BNL--47920

DE93 001491

FACE: FREE-AIR CO_2 ENRICHMENT FOR PLANT RESEARCH IN THE FIELD

George R. Hendrey

August 1992

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

TABLE OF CONTENTS

FOREWORD: Roger Dahlman and Stephen Rawlins
ACKNOWLEDGEMENTS: George R. Hendrey
INTRODUCTION: George R. Hendrey

SECTION I: THE FREE-AIR EXPOSURE SYSTEM

Chapter 1. Global Greenhouse Studies: Need for a New Approach to Ecosystem Manipulation. (Hendrey, G. R.)

Chapter 2. The DOE/USDA FACE Program: Goals, Objectives and Results through 1989 (Hendrey, G. R.)

Chapter 3. Field Techniques for Exposure of Plants and Ecosystems to Elevated CO_2 and Other Trace Gases. (Allen, L. H., Jr., B. Drake, H. H. Rogers and J. Shinn)

Chapter 4. Free-Air CO_2 Enrichment Field Experiments: A Historical Perspective. (Allen, L. H., Jr.)

Chapter 5. Brookhaven National Laboratory Free-air Carbon Dioxide Enrichment Facility. (Lewin, K. F., G. R. Hendrey and Z. Kolber)

Chapter 6. Performance Analysis of the BNL FACE Gas Injection System. (Lipfert, F., Y. Alexander, G. R. Hendrey, K. F. Lewin and J. Nagy)

Chapter 7. FACE Facility Engineering Performance in 1989. (Nagy, J., K. F. Lewin, G. R. Hendrey, F. Lipfert and M. Daum)

Chapter 8. Distribution of Carbon Dioxide within and above a Cotton Canopy Growing in the FACE System. (Hileman, D. R., N. C. Bhattacharya, P. P. Ghosh, P. K. Biswas, L. H. Allen, Jr., K. F. Lewin and G. R. Hendrey)

Chapter 9. A Comparison of the Uniformity of an Elevated CO_2 Environment in Three Different Types of Open-Top Chambers. (Hileman, D. R., P. P. Ghosh, N. C. Bhattacharya, P. K. Biswas, L. H. Allen, Jr., G. Peresta and B. A. Kimball)

SECTION II: BIOLOGICAL RESPONSES

Chapter 10. Responses of Cotton Foliage to Short-term Fluctuations in CO_2 Partial Pressures. (Evans, L. S. and G. R. Hendrey)

Chapter 11. Growth and Yield of Cotton Exposed to Free-Air CO_2 Enrichment (FACE). (Mauney, J. R., K. F. Lewin, G. R. Hendrey and B. A. Kimball)

Chapter 12. Influence of Elevated CO_2 on Leaf Starch of Field-Grown Cotton. (Hendrix, D. L.)

Chapter 13. Responses of Photosynthesis and Stomatal Conductance to Elevated Carbon Dioxide in Field-grown Cotton. (Hileman, D. R., N. C. Bhattacharya, P. P. Ghosh, P. K. Biswas, K. F. Lewin and G. R. Hendrey)

Chapter 14. Cotton Leaf and Boll Temperatures in the 1989 FACE Experiment. (Kimball, B. A., P. J. Pinter, Jr. and J. R. Mauney)

Chapter 15. Evaluating Cotton Response to Free Air Carbon Dioxide Enrichment with Canopy Reflectance Observations. (Pinter, P. J., Jr., R. J. Anderson, B. A. Kimball and J. R. Mauney)

Chapter 16. Cotton Root Response and Rhizosphere to Free-Air Carbon Dioxide Enrichment. (Rogers, H. H., S. A. Prior and E. G. O'Neill)

SECTION III: COST

Chapter 17. Cost Comparisons Among Free-Air CO_2 Enrichment, Open-Top Chamber, and Sunlit Controlled-Environment Chamber Methods of CO_2 Exposure. (Kimball, B. A.)

Subject Index

Appendix I: Weather, Soils, Cultural Practices, and Cotton Growth Data from the 1989 FACE Experiment in IBSNAT Format. (Kimball, B. A., R. L. La Morte, G. J. Peresta, J. R. Mauney, K. F. Lewin and G. R. Hendrey)

Appendix II-A: Glossary. (Kimball, B. A., R. L. La Morte, G. J. Peresta, J. R. Mauney, K. F. Lewin and G. R. Hendrey)

Appendix II-B: Soils Data Sources. (Kimball, B. A., R. L. La Morte, G. J. Peresta, J. R. Mauney, K. F. Lewin and G. R. Hendrey)

Appendix II-C: List of Data File Names. (Kimball, B. A., R. L. La Morte, G. J. Peresta, J. R. Mauney, K. F. Lewin and G. R. Hendrey)

Appendix II-D: The 1989 FACE Data Files in IBSNAT Format. (Kimball, B. A., R. L. La Morte, G. J. Peresta, J. R. Mauney, K. F. Lewin and G. R. Hendrey)

FOREWORD

In 1981, Dave Slade, a visionary at DOE, formulated interdisciplinary research to investigate effects of increasing atmospheric CO_2 on both climate and biology. From the beginning there was a clear recognition that direct effects of CO_2 on biology could be important because of the central role it plays in the physiology, metabolism and growth of plants.

Later, under the leadership of Fred Koomanoff, the DOE CO_2 Program further recognized the importance of the direct effects of CO_2 on plants by initiating a modest research program to address it. Roger Dahlman was asked to organize research on this topic. With guidance from the scientific community, a focused, field-oriented research program was initiated with the objectives to:

- obtain field data on yield and productivity of principle crop and native species in relation to CO_2 concentration and other key environmental variables;
- determine fundamental effects on plant physiology and growth when plants are subjected to elevated CO_2 over long time periods; and
- evaluate ecosystem responses to CO_2.

Substantial progress has been made toward achieving these objectives through integrated cooperative programs bridging across several scientific and engineering disciplines. New data have been obtained on the physiology and growth of plants subjected to elevated CO_2. Innovative approaches for conducting long-term experiments on plants in natural ecosystems have been developed.

Further progress will require experimental techniques to maintain elevated CO_2 concentrations within natural systems for long periods of time at costs that are reasonable. The Free-Air CO_2 Enrichment (FACE) approach described in this book represents one successful new technology for achieving this objective. It provides an approach for enriching relatively large areas of vegetation with CO_2 for extended periods of time, at less cost per unit experimental area than any other known technique. Engineered and developed by the Brookhaven National Laboratory, the FACE experimental system takes advantage of microscale meteorological conditions to maintain desired CO_2 concentrations over areas of hundreds of square meters.

This book describes the results of experiments with cotton, funded jointly by DOE and USDA Agricultural Research Service, report the feasibility of the general approach, engineering testing, detailed performance data, and examples of biological response from year-long experiments. Readers will find the FACE system to be an example of the application of modern technology to field experimentation. The "FACE machine," an environmental analogue to sophisticated machines required for particle physics and structural biology experiments, enables a vast number of detailed observations and experiments with crop and ecological systems that previously were beyond the reach of agronomists, plant physiologists and ecologists. It provides the experimental means for addressing ever more sophisticated questions about CO_2 effects in outdoor environments,

including transpiration and plant water relations; photosynthesis and carbon metabolism; molecular controls on plant biochemistry; plant-insect and plant-disease interactions; and the relationship between direct CO_2 effects and other changing environmental influences such as light, temperature, water and nutrient availability.

In looking to the future, the FACE system could be the forerunner for large-scale integrated environmental research that makes possible sophisticated experiments capable of increasing our understanding of complex living systems; where an array of specific measurements elucidate fundamental biological mechanisms; where multiple, sustained observations are possible in simulated environments that could exist in the future. Combinations of advanced technologies assembled around a FACE system could open new opportunities to address questions at the frontier of biological science. The high-tech field experimental approaches initiated with FACE are poised to contribute to a number of global change research interests defined in the U.S. Global Change Research Program and the International Geosphere-Biosphere Program.

The first phase of FACE research has clearly demonstrated feasibility (proof of concept), and has produced useful experimental data. The FACE approach continues to attract international interests as a means to address biological questions ranging from molecular biology to plant community dynamics, to global carbon balance. This document proudly shares the accomplishments of the many scientists, engineers and research planners at the first important milestone in FACE system research.

Roger C. Dahlman
Office of Health and
Environmental Resources
U.S. Department of Energy

Stephen Rawlins
Agricultural Research Service
U.S. Department of Agriculture

ACKNOWLEDGEMENTS

The FACE Program at Brookhaven National Laboratory is supported by the US Department of Energy, Office of Health and Environmental Research, under DOE contract Nr. DE-AC02-76CH00016, Dr. Roger Dahlman, Technical Representative. Support has also been provided through the USDA Agricultural Research Service, Dr. Stephen Rawlins, National Program Leader. The Editor and contributing authors wish to express their appreciation to Dr. Dahlman for his continuing support and effective guidance of this program, and to Dr. Rawlins for his continued support and efforts on behalf of the program within USDA.

The involvement of BNL in the development of a free-air CO_2 enrichment system occurred at the suggestion of Dr. Lance Evans (Manhattan College) with whom BNL has had a long-standing collaborative relationship in plant effects research. In 1985, Lance saw an opportunity to try a new approach to controlled fumigation of plants in an open field setting and worked with the BNL team to develop the BNL FACE system.

Dr. Roy Rauschkolb, Director of the Maricopa Agricultural Center (MAC) of the University of Arizona, has provided great assistance to the FACE project by making space available within the excellent research facilities at MAC. His staff, particularly Jeanne Schmidt, has assisted FACE investigators with meetings and conferences, as well as daily mail and message services for several dozen visitors associated with FACE over entire crop seasons. Special thanks go to Mr. Terry Freeze and to Mississippi Chemical Corporation for facilitating the experiments at Yazoo City, MS.

Miss Sharon Zuhoski has provided valuable assistance in dealing with many office tasks relating to the FACE program, including setting up facilities and logistics for annual meetings. In addition, she has done much of the work in getting the various contributions to this book in shape and in a common format. I am especially indebted to Dr. Frederick Lipfert for providing timely assistance with editorial tasks.

Dozens of research associates, technicians and students contributed to setting up the FACE experiments, data acquisition and data reduction. Finally, it is the contributing authors who have made the FACE Program an outstanding example of cooperative, integrated research in field biology.

George R. Hendrey
Upton, NY

INTRODUCTION

George R. Hendrey
Editor

This book is organized into three sections. The first section deals with program rationale, management, history engineering and performance of free-air CO_2 exposure. The second section presents results of field experiments using a new free-air exposure system. The third section covers cost. While attempting to minimize overlapping topics among chapters and sections, some topics are discussed in differing detail or from a different point of view by various chapter authors.

In 1986, Brookhaven National Laboratory (BNL), collaborating with Lance Evans (Manhattan College), began the development of a system for exposing plants in the field to controlled, elevated concentrations of CO_2, as part of the Carbon Dioxide Research Program of the United States Department of Energy (DOE). The BNL system adopted the acronym FACE, for Free Air Carbon Dioxide Enrichment (this acronym had been coined earlier by L.H. Allen, Jr., as applied generically to all such open-field release systems, see Chapter 4). Building on preceding efforts by investigators in Europe to develop well controlled free-air fumigation systems, especially the work of Andrew McLeod in England, BNL's FACE design was intended to provide a means of evaluating the effects of CO_2 enrichment on plants, free from interference from confining chambers. This initial development project evolved into the FACE Program, a full-scale biological field research effort with support from DOE and the United States Department of Agriculture (USDA), and has received the active participation of 31 investigators from 15 different research units (Chapter 2).

While the FACE Program was initially motivated by the desire to predict the effects of higher ambient CO_2 concentrations on plants, another important mission has developed: to contribute to an evaluation of global climate change, *per se*. This follows from the fact that the flux of CO_2 between the atmosphere and plant biomass and soil carbon is biologically regulated; as a result, the exchange rates and mass storage may change in response to increases in atmospheric CO_2 (see Chapter 1). Thus, the FACE Program has two principal missions: to evaluate the effects of global CO_2 change on plants and ecosystems, and to evaluate how plant-atmosphere interactions may regulate the rate of increase of CO_2 in the atmosphere, thereby contributing to regulation of global climate change.

This book is intended to present the rationale underlying the FACE Program, to document the historical development of free-air controlled fumigation systems (Chapters 3 and 4), to describe the apparatus developed by BNL for the FACE Program, and to provide a compendium of research results achieved through 1989. These results include the performance of BNL's FACE system in the field and biological data describing the effects of enriched CO_2 on field-grown cotton, as observed in FACE experiments. Chapter 2 summarizes this information, along with the FACE Program goals and objectives, and provides some ideas about future direction of the program.

A clarification may be in order concerning terminology. Chapters 3 and 4 describe various means of exposing plants to altered gaseous environments, including the developmental history of open-field gaseous release systems. In this context, which emphasizes the period up to 1986, "FACE" is a generic term

for all such systems. However, in all other chapters, "FACE" refers specifically to the BNL FACE design, as described in Chapters 5 and 6.

Chapter 3 discusses the various ways in which plants can be exposed to experimental manipulations of their gaseous environments, including chambers of various types as well as open-field release techniques. This is the background against which the BNL FACE project was conceived. Chapter 4 then focuses specifically on the historical development of open-field release systems of various types, including those developed to study the effects of toxic air pollutants on plants.

A great deal of effort has been expended in the FACE Program to design the FACE system, and to document its performance, *vis a vis* the ability to control CO_2 within experimental plots. Persons interested in these engineering aspects will want to study Chapters 5-7. In Chapter 5 the mechanical and conceptual design of the BNL FACE system and its control algorithm are presented in sufficient detail so as to allow others to independently assemble the hardware and control system for a similar system. The fluid mechanical design principals as deduced from theory and experiments, engineering data, and performance analysis, all essential to scaling new FACE designs for experiments in various types of vegetation, are presented in Chapter 6. Documentation of the engineering performance of the system is presented in Chapter 7. FACE system component reliability is also presented and analyzed quantitatively.

Just how stable are CO_2 concentrations within FACE plots? An analysis of variation in control of the FACE systems, including statistical distributions of data measured at the center of the plots is given in Chapter 7. Chapters 7 and 8 also present the results of a series of different experiments by two teams of investigators to evaluate the spatial distribution of CO_2 within the experimental plots. Some of these data are used to document the frequency and extent of "extreme" events of elevated CO_2 occurring with FACE. Spatial variation in FACE systems is reported in Chapters 7 and 8. A comparison of CO_2 concentration stabilities among different types of open top chambers is presented in Chapter 9. The performance of these OTCs is then compared to CO_2 control within FACE systems in Chapters 2 and 7. Chapter 10 presents the results of some special experiments conducted on cotton in growth chambers to evaluate the importance of biological responses to such short-term fluctuations.

Chapters 11-16 present experimental results on cotton obtained in 1989 at Maricopa, Arizona, at a CO_2 level of 550 μmol mol^{-1}; these findings are summarized in Chapter 2. Cotton yield responses to elevated CO_2 are presented in Chapter 11, and leaf starch data are discussed in Chapter 12. Photosynthetic rates and stomatal conductance data are compared between elevated CO_2 (FACE) and control plots in Chapter 13; leaf and boll temperature data are compared in Chapter 14. Canopy reflectance data are evaluated as a tool for monitoring cotton responses to enriched CO_2 in Chapter 15, and Chapter 16 discusses below-ground processes including root and rhizosphereresponses.

The economics of various types of fumigation systems are compared in Chapter 16. Finally, information on the COTCO2 model being developed by the FACE program and data file listings together with IBSNAT file formats and a glossary are presented in appendices to the book.

SECTION I: THE FREE-AIR EXPOSURE SYSTEM

GLOBAL GREENHOUSE STUDIES: NEED FOR A NEW APPROACH TO ECOSYSTEM MANIPULATION

George R. Hendrey
Department of Applied Science
Brookhaven National Laboratory
Upton, NY 11973

I. INTRODUCTION

The world is changing in ways that can we describe as change progresses but that cannot be predicted very well. Radiative and chemical properties of the atmosphere, global climate, and global ecology are dynamic and measurable, but they are also linked to each other in complex and poorly understood ways (Raval and Ramanathan 1989; Wuebbles 1988; Hicks 1989; Houghton and Woodwell 1989). While many of the physical and biological sub-processes are understood and modeled in great detail, predictive capabilities are poor if the linkages are not understood. Fortunately, linking of complex models across scientific disciplines (e.g. atmospheric chemistry-climate-agronomy-economics) to analyze large scale interactions has begun (Adams *et al.* 1990).

There is no consensus as to either how or how much global climate might change as a consequence of alterations in atmospheric chemistry (Cess *et al.* 1989; Schneider 1990; Lindzen 1990) or whether changes in either atmospheric chemistry or climate bode net good or net ill for mankind (Lindzen 1990). One cannot now predict reliably how simultaneous changes in both chemical or climate drivers will alter the biosphere by changing biomass accumulation, species diversity or ecosystem structure.

Lest the atmospheric physicists and chemists feel too smug about their "more precise" sciences, they should reflect on the dominant role played by ecosystems in regulating surface albedo, gas concentrations of the atmosphere through storage of labile carbon and its exchange with the atmosphere in the forms of radiatively active trace gases, and sulfur compounds. If we can't improve our predictive abilities for ecosystem responses to changes in the global atmosphere, then resultant changes in bio-regulation of variables such as these can not be predicted, and dependent physical and chemical processes cannot be quantitatively predicted with long-term accuracy. These biological response issues must be addressed if ever we are to obtain acceptable predictive capabilities for global change. Addressing such issues requires the cooperation of many scientific disciplines and an integrating framework of explicit mathematical models. Developing this sweeping vision of integrated scientific endeavor, however, begins with small steps.

The small step that is the subject of this book is a new method for conducting experiments on the effects of atmospheric gases on plants and ecosystems. This method relies on the controlled release of a fumigant into the

open air in such a way as to maintain stable concentrations over experimental plots that are hundreds of square meters in size, while at the same time, causing no perceptible change to the micro climate of the plants. Because the method has first been applied to experiments on the effects of CO_2, it is called Free-Air Carbon dioxide Enrichment, and has come to be known by its acronym **FACE**.

The technological means of conducting field experiments is only part of the story, particularly when they are rather expensive in comparison to other types of ecological studies. Why do we need FACE? What questions is it meant to address? How does it relate to global change? In discussing these questions, this chapter presents the justification for conducting FACE experiments. Subsequent chapters treat in detail the historical development of FACE, the design and performance of the FACE system developed by Brookhaven National Laboratory (BNL) and early biological results of our cooperative field experiment on cotton through 1989.

Although comprehensive reviews of the literature on the effects of CO_2 enrichment on plants can be found elsewhere (Strain and Cure 1985; Musselman and Fox 1991 *inter alia*) this chapter will also discuss some of the key experiments in detail in order to illustrate the need for a new approach to ecosystem manipulations represented by FACE.

A. The global greenhouse

The 1990 global average atmospheric CO_2 concentration was 355 microliters per cubic meter (μmol mol^{-1}) and it is rising at the rate of 1.8 μmol $mol^{-1}y^{-1}$. This concentration compares to about 280 $\pm$10 μmol mol^{-1} prior to the industrial age (pre-1800) (IPCC 1990). At this rate of increase, atmospheric CO_2 is expected to be double the pre-industrial level in the first half of the next century. This change in atmospheric CO_2 concentration follows the general trend in emissions of CO_2 from fuel combustion and other human activities, including cement manufacturing, deforestation and plowing of virgin soils. In addition to CO_2, other radiatively active gases are released by man, including chlorofluorocarbons, methane and oxides of nitrogen. These increases, with CO_2 being the most important, are presumed to be the drivers of global climate changes that may alter world-wide patterns of temperature, precipitation and sea level with unquantified consequences for man. The increases in the radiatively active gases due to human activities and the environmental consequences of such increases are popularly known as the "greenhouse" problem.

B. Global CO_2 budget uncertainties

The concentration of CO_2 in the atmosphere is controlled by several grand processes that operate on very different time scales. Use of fossil fuel, land clearing and tillage of soil appear to have increased atmospheric CO_2 at the unprecedented rate of about one third in a century, and will double it in one and a half centuries. Oceanic geochemistry may respond to this increase over decades to millennia to establish a new steady state equilibrium, thereby mitigating anthropogenic emissions to some extent in the short term. Biological processes also have the potential to remove CO_2 to long-term storage at an intermediate rate, decades to centuries. (Consider that biological processes were responsible for initial removal of most CO_2 from the proterrozoic atmosphere and creation of

free oxygen in the atmosphere.)

Emissions of CO_2 to the atmosphere due to all fuel combustion processes totaled 5.7 ±0.5 billion tons of carbon per year ($GtCy^{-1}$) 1987, plus 1.5 ±1.0 $GtCy^{-1}$ due to deforestation (IPCC 1990). The principal sinks for atmospheric CO_2 are oceanic uptake and terrestrial plant photosynthesis. The net annual sink for carbon in the oceans is estimated to be 2.0 ±0.8$GtCy^{-1}$ (IPCC 1990) although Tans *et al.* (1991) estimate that it may be as low as 1 $GTCy^{-1}$.

While photosynthesis by land plants and respiratory emissions due to all terrestrial biological processes are about 110 $GtCy^{-1}$ (Post, et al 1990) direct estimates of global terrestrial photosynthetic uptake and respiratory releases of CO_2 have such large uncertainties, about ±10 $GtCy^{-1}$, that they are not considered to be credible estimators for deriving net flux values of CO_2 between the known terrestrial, oceanic and atmospheric pools of carbon. In fact, the uncertainty on these numbers is about the size of all anthropogenic emissions of CO_2. Thus, the balance of global respiratory emissions and photosynthetic uptake is not known with the precision with which the emissions by man have been inventoried. Small changes in these large numbers, perhaps directly driven by anthropogenic release of CO_2 and/or climate change, could be important determinants of the future rate of change of CO_2 in the atmosphere.

Indirect estimates of sink rates are currently used to derive the global carbon balance. Usually global carbon budgets are constructed by accounting for carbon pools in the atmosphere, numerous terrestrial and oceanic compartments and estimated fluxes between these compartments. But uncertainties remain large and the debate within the scientific community concerning the relative roles of marine versus terrestrial biota as sinks for atmospheric carbon is contentious. One prominent oceanographer recently stated "But the important part is terrestrial, not marine", and "My contention is that marine organisms have played no role whatsoever [as a sink for anthropogenic CO_2 from the atmosphere] and that they are unlikely to become more than minor players in the future" (Broecker 1991). Thus, the need to quantifythe current 'sink strength' for atmospheric CO_2 not only into terrestrial biota of today, but also of the future, is underscored.

Virtually all of the attempts to calculate mass balances to account for the fate of CO_2 emissions are fraught with uncertainties and assumptions that are difficult to verify. Consequently, various carbon budget models give widely differing allocations among sinks and sources of CO_2. Post *et al.* (1990) used two different approaches to analyze net terrestrial carbon flux to the atmosphere over the period 1800 to 1980, reconstruction and deconvolution. One approach resulted in an estimated net positive flux while the other one yielded a net negative flux. Analyses by Tans *et al.* (1990) indicate that the terrestrial system uptake currently exceeds respiratory sources by 2±0.6 $GtCy^{-1}$; Houghton and Skole (1990) estimated a net terrestrial sink of 2.5 $GtCy^{-1}$.

C. Climate change

Changing the chemical composition of the atmosphere on a global scale will alter the radiative properties of the atmosphere. CO_2 absorbs energy in the infra-red (IR) range of the spectrum, the range in which a significant portion of solar energy absorbed by the earth is re-radiated back into space. This absorption of IR increases the total solar energy retained by the earth thereby warming the atmosphere, the oceans and the land surface. CO_2 contributes 61% of

the radiative forcing due to increased "greenhouse" gases since the pre-industrial era. This has resulted in an increase net energy input to the world of 2.9 watts per square meter. Other important contributors include methane (17%), nitrous oxide (4%), and chlorofluorocarbons (12%). Changes in stratospheric water vapor and ozone, driven by anthropogenic activities, may also contribute significantly. Together, these gases have increased radiative forcing by 4.6 Wm^{-2} since pre-industrial times. While CO_2 is not the most effective of these gases in absorbing infrared energy, because of the quantity emitted, it is the most significant of the anthropogenic gases *vis-a-vis* climate change (IPCC 1990).

While there are differences of opinion as to the extent to which global climate is changing due to forcing by the "greenhouse" gases, there is agreement that global mean temperature has increased by 0.5°C over the past century. The decade of the 1980s was the warmest on record, and 1990 was the warmest year on record . Global mean temperature is predicted to increase by 3 °C over the next century if a "business as usual" scenario is followed (IPCC 1990; Jones and Wigley 1991)).

The predicted distribution of global warming is not uniform but increases with latitude. This non-uniformity is likely to lead to other changes in global climate, particularly in patterns of precipitation. If precipitation and other climate variables change then plant communities and the ecosystems they support will change in response with a lag period of decades.

D. Global greenhouse effects on plants

Changes in the concentration of CO_2 in the atmosphere also have the potential to alter both the physiological functioning of plants and the structure of plant communities. This is important for several reasons, two of which are of obvious, immediate interest to man. First, the rate and location of food and fiber production may change in ways that affect their quality and quantity. Together with plant responses to "greenhouse" effects on climate, these changes may have serious economic and political repercussions. Second, plants of the world exert a strong feedback control on atmospheric CO_2. Attempts to predict climate change without understanding this feedback regulation as a quantitative function of anticipated ranges of atmospheric CO_2, will lack credibility. Thus, assessments of political and economic consequences of the "greenhouse" problem based on deficient analyses of climate change will be subject to serious criticism.

Warming of the planet will increase rates of evaporation and a first order effect on plants would be to increase transpiration (ET). An important second order effect of increasing temperature would be to increase the ratio of photo respiratory loss of carbon to photosynthetic gain at a particular CO_2 concentration, but increasing CO_2 has the opposite effect. The net result of rising temperature and greater availability of CO_2 is an overall increase in net photosynthesis at the expense of photorespiration (Long 1991). There is a considerable body of literature on the effects of CO_2 enrichment on individual species of plants, particularly for crop species, and some literature on the effects on ecosystems (see below). Increasing the concentration of CO_2 at a particular temperature will have a significant fertilizing effect on most plants, at least for plants not taken above their temperature optima (Idso *et al.* 1987). Also, photosynthesis may not be stimulated by increased CO_2 at ambient

temperatures below 18 °C (Sage and Sharkey 1987). However, as global CO_2 and temperature continue to rise simultaneously, the combined effect will be to increase net photosynthesis (Long 1991) particularly in temperate and warmer climates (Mooney *et al.* 1991).

II. CO_2 ENRICHMENT STUDIES

Numerous studies of CO_2 enrichment of plants grown as monocultures in greenhouses and various other forms of controlled environment enclosures have shown that C_3 plants, and to a lesser extent C_4 plants, respond to CO_2 enrichment by increasing net photosynthesis, and that total biomass increases in terms of annual increment on an areal basis, compared to unenriched plants. With a doubling of CO_2 over the present ambient concentration, carbon exchange measurements in most C_3 plants increase by 30 to 40% and net photosynthesis increases by 50 to 100%. This literature is extensively reviewed elsewhere (Kimball 1983; Strain and Cure 1985; Trabalka, 1985; Lawlor and Mitchell 1991). In many of these controlled environment studies, plants exhibited an adaptation to increased CO_2, a topic discussed in more detail below.

A wide variety of plants also have been exposed to elevated CO_2 in the field, through the use of open top chambers (OTC). Virtually all of these plants had a substantial increase in biomass of fruit, shoots and roots in response to CO_2 enrichment. Although the extent of the increase in response is highly variable among cultivars and species, it averages about 35% in dry biomass from a doubling of CO_2 for a single season (Kimball 1983). For example, tree seedlings (Pinus virginiana, Quercus alba and Liriodendron tulipifera) increased in dry weight 37% to 90% over a 40-week exposure to 690 μmol mol^{-1} CO_2 (Luxmore *et al.* 1986). In the most extreme case, sour orange trees have been grown at 600 μmol mol^{-1} CO_2 in OTCs in Phoenix AZ. Total biomass of the enriched trees, including both above and below ground components, has tripled compared to the increase observed in OTC-grown controls at ambient CO_2 over a two and one-half year exposure period (Idso *et al.* 1991).

In a multidisciplinary study integrating climate models, crop growth models and economic models, Adams *et al.* (1990) examined the potential effects of increasing atmospheric CO_2 to 600 - 660 μmol mol^{-1} on agricultural production in the U.S., using a suite of climate and crop models. Their preliminary assessment predicted significant changes in crop yields, due primarily to increased temperatures and decreased precipitation with a concomitant increase in the need for crop irrigation. The negative impact of these effects were largely offset by the beneficial effect of increased atmospheric CO_2, including improved water use efficiency. If these beneficial effects extend to natural ecosystems, then an increasing rate of CO_2 absorption by the terrestrial biosphere with increasing CO_2 availability is indicated.

A. Chamber plants differ from field-grown plants

Although the use of controlled climate chambers provide stable, repeatable conditions for plant experimentation, there is wide recognition that chamber-grown plants can be physiologically and morphologically different from plants grown in the open field. Lawlor *et al.* (1991), in reviewing the literature on CO_2 enrichment, noted that plant growth conditions in controlled environment chambers differed markedly from natural conditions: light levels were often low

and constant, with spectral differences from ambient light; temperatures were often high and constant over the day period; light and temperature were poorly coupled; water relations were complicated by high humidity, low wind speed and regular watering in small amounts; nutrition was regularly applied in small amounts; and rooting volume was typically very small.

To avoid problems associated with controlled environmental chambers, OTCs were designed to be placed in the field where plants would have "natural" conditions. But, OTCs also fail to provide an experimental environment free of chamber effect: **"the climatological effect of the (open-top) chamber often confounds the biophysical impact of the trace gas under investigation"** (Ham *et al.* 1991). Typically, OTCs are about 2 °C warmer than ambient, light is attenuated by about 10-15%, and wind speeds are low and steady in contrast to great variability in the ambient environment, thus protecting the plants from physical stresses. These changes can significantly alter leaf temperature, transpiration and latent heat flux. Chamber effects on the plant micro-environment resulted in a significant growth enhancement in Scirpus dominated communities. (Ham *et al.* 1991; Drake *et al.* 1989). Hileman *et al.* (Chapter 9, this book) examined differences in CO_2 control among several types of open top chambers during our experiments at Yazoo City, MS, in 1987. The design features of the OTCs were found to influence the ability to control CO_2 concentrations. OTCs that lacked a frustum on the top had greater internal variability than an OTC with a frustum.

Such problems with experimental protocols point to obvious deficiencies in attempting to assess natural ecosystem responses to environmental perturbations by studying communities or species grown in artificial media in pots, in greenhouses or other chambers. Inherent deficiencies of such experiments include limited rooting space in pots, edge effects in chambers, and unnatural conditions of light, temperature air flow, soil structure and nutrients. These differences may provide observations that are unrealistic, *vis-a-vis* plants in their natural setting.

B. Adaptation: a paradigm for achieving wrong conclusions

The effect of the experimental approach on the outcome of the experiment is illustrated by reports of an apparent "adaptation" by plants to elevated CO_2. This is a critical issue in discussions of global change since it has been suggested (Bazzaz and Fajer 1992) that such adaptation might limit the role of plants as sinks for rising CO_2.

Numerous studies find an adaptation, or homeostatic adjustment, of plants to higher levels of CO_2. This adaptation is ascribed to a variety of mechanisms like "down-regulation", the internal adjustments in enzyme concentrations such as RUBP carboxylase/oxygenase; or excess accumulation of starch in the chloroplasts thus causing physical impairment of function and suppression of sucrose synthesis and interference with steps in cyclical phosphorelation. Ontogenetic processes following from these biochemical responses under CO_2 enrichment could result in reduced photosynthetic capacity at the plant level due to altered development of photosynthetic organs (discussed in Bazzaz 1990; Bazzas and Fajer 1992; Long and Drake 1991). Mechanisms explaining possible adaptation have also been thought to be complicated by interactions with other plant environmental conditions (Lawlor and Mitchell 1991). However, translocation of photosynthate from the production site at the chloroplast requires a sink

elsewhere in the plant and it is likely that limited sink capacity greatly contributes to carbohydrate accumulation in leaves (Cure and Acock 1986) which seems to be the proximal cause of the apparent adaptation.

Arp (1991) found a strong statistical correlation between this adaptation as reported in the literature and the size of the pots used during studies in which adaptation was observed. In contrast to pot and controlled environmental chamber-grown plants, plants exposed to elevated CO_2 in the field maintain a high photosynthetic capacity with continued increase in CO_2 level.

The evaluation of adaptation also will be influenced by other environmental conditions which occur during the experiment. Measurements made at light saturated levels of photosynthesis probably do not reflect overall plant response, since much of a plant's photosynthetic apparatus within the canopy is operating above the compensation point but well below the light-saturated level. Long-term exposure of the sedge Scirpus olneyi to CO_2 enrichment did not result in any detectable acclimation in photosynthetic capacity under light-limiting conditions generally prevailing within the canopy (Long and Drake 1991).

Long-term experiments on CO_2 enrichment using temperature regulated closed chambers placed over natural stands of tussock tundra on permafrost in Alaska (Oechel et al 1992), did report a homeostatic adjustment of the plant community. Even with the addition of nutrients, the community did not maintain initially high rates of photosynthesis observed with CO_2 enrichment to 675 μmol mol^{-1} (Oberbauer *et al.* 1986, Grulke *et al.* 1990). These results are puzzling. At the low temperatures of these experiments, generally in the range 5 to 15 °C, and low light levels of the Arctic, one should not expect to see much, if any, effect of CO_2 enrichment in either short or long-term experiments (Long 1991). Methodological problems such as leakage of ambient air into the chambers, if leaks were present, could give spuriously low CO_2 concentrations early that would be interpreted as high CO_2 uptake rates. Speculation on possible problems with this experiment will continue until the results are independently confirmed.

In short, critical review of the literature finds that the conditions under which CO_2 enrichment experiments and measurements are executed are determinants of the experimental outcome and of subsequent interpretation of the results when discussed in the context of future global change. Except for the puzzling results of the Arctic CO_2 enrichment experiment, there is little support for the notion that field-grown plants or natural ecosystems will adapt to higher CO_2 concentrations with down-regulation of photosynthetic capacity, thereby limiting the role of terrestrial vegetation as a sink for atmospheric CO_2.

III. ROLE OF TERRESTRIAL PLANTS IN REGULATING ATMOSPHERIC CO_2

While essentially all of the recent research on CO_2 interactions with plants is aimed at describing the effects of global CO_2 enrichment on plants, the reverse view is also of great importance: that is, **what is the effect of changing plant communities of the world on the concentration CO_2 in the atmosphere?** In the discussion above the importance of plants as components of the annual CO_2 cycle and as a sink for atmospheric CO_2 was presented for contemporary conditions. But what is likely to happen as global CO_2 increases?

A. Plants as a near-term sink for anthropogenic CO_2

If fertilization of global plant growth is occurring in this manner, as

seems likely, then inventories of plants, as well as distributions among C_3 and C_4 types are quite likely to change as CO_2 changes, albeit with a significant time lag. Furthermore, increasing net photosynthesis with rising CO_2 is accompanied by an increase in water use efficiency (WUE) apparently due to decreased stomatal conductance at higher CO_2 concentrations. WUE increases of 33% to 240% are reported from field studies, although the use of open top chambers may have influenced such observations (Lawlor and Mitchell 1991) These responses to CO_2 enrichment should lead to expansion of plant biomass in more xeric areas due to increased water use efficiency and increased production of carbon stored in soil (Lawlor and Mitchell 1991; Mooney *et al.* 1991). Increased annual carbon storage may exert a gradually increasing negative feedback on atmospheric CO_2 over decades to centuries as the global inventory of plants and soil carbon adjusts to new conditions. Thus, it is likely that the global rate of net photosynthesis and carbon storage by terrestrial plants will increase as CO_2 increases in the atmosphere.

B. Beta functions

How can such a global fertilization be documented and quantified? Several approaches have been tried, including application of a multiplier representing fertilization to global biomass, analyses of annual cycles in atmospheric CO_2, and by difference in trying to close global carbon budgets.

In their analysis of partitioning of atmospheric CO_2 among elements of a six-compartment model of the world, Bacastow and Keeling (1973) calculated the amount of CO_2 taken into terrestrial plant matter as the product of biotic standing stock times a biotic growth factor, ß. This concept of a "Beta Factor", defined as an adjustable parameter reflecting the degree of CO_2 fertilization, has been used by other investigators in trying to close global carbon budgets.

It has been realized for several years that the annual oscillation in CO_2 concentration of the atmosphere (12.7 GT of carbon in 1988 at Mauna Loa observatory) is due primarily to carbon exchange with the terrestrial biosphere and not with the other large reservoir, the ocean (Woodwell 1987; Tucker *et al.* 1986). Kohlmaier *et al.* (1989) observed that the amplitude of the seasonal atmospheric CO_2 cycle measured at several atmospheric monitoring stations has been increasing over the past several decades. They elegantly modeled biotic and abiotic factors contributing to difference between the relative increases in annual peaks, minus annual troughs, in CO_2 concentrations measured at Mauna Loa Observatory. Their estimated annual increment in storage of CO_2 in the terrestrial biosphere (photosyntheses minus all respiratory releases) due to all causes was 0.6 to 2.0 Gt yr^{-1}. In addition to fertilization by increasing atmospheric CO_2, deposition of nitrate, phosphate and sulfate from the atmosphere were estimated to contribute 10% to this value, and it also may have been influenced by long-term trends in global temperature during the years of record. CO_2 fertilization appeared to account for from 8% to 64% of the integral amplitude increase in the seasonal CO_2 signal at Mauna Loa between 1958 and 1988. Their "CO_2 fertilization factor", ß, lying in the range 0.15 to 0.60, implies that a 1.5% to 6% change in net primary production would occur with a 10% increase in atmospheric CO_2 (Kohlmaier, *et al.* 1989). This range estimate for ß has an uncertainty factor of 4, while the estimate of biotic carbon sequestration ranges up to about one third of anthropogenic CO_2 emissions.

A hypothesis (Tans *et al.* 1990) based on recent data for CO_2 emissions,

latitudinal differences in atmospheric CO_2 and estimates of fluxes between the atmosphere, ocean and land, is that a terrestrial sink may exist at mid-northern latitudes. Essentially, this analysis balanced the global carbon budget via CO_2 fertilization proportional to net primary production. They estimate that the (global) oceans provide a sink of not more than 1.0 $GtCy^{-1}$, while terrestrial vegetation at high northern and temperate latitudes have a net absorbtion between 2.0 to 3.4 $GtCy^{-1}$, depending on size of emissions in boreal and tropical regions. Recognizing that this net sink due to the fertilization of vegetation according to such estimates is equal to half of the total anthropogenic emission of carbon globally, the importance of the fertilization effect to global CO_2 budgeting, and therefore to global climate predictions, is clear.

Over decades, successional changes in terrestrial ecosystems caused by CO_2 fertilization should favor those species most benefited by increasing CO_2, with an accelerating effect on the global rate of net photosynthesis. This is the general mechanism by which the fertilization effect would exert a non-linear negative feedback control on the processes of global change. At the same time, release of carbon from terrestrial storage pools due to global warming is also likely to increase, having a positive feedback on atmospheric CO_2 (Houghton and Woodwell 1989). We cannot now predict quantitatively the net outcome of these two processes as changes in global atmospheric chemistry and climate proceed. It is likely that the result will be different from the current net exchange, resulting in a new state of control of atmospheric CO_2 by the biosphere. One may debate the extent to which the difference between carbon emissions, terrestrial sinks and the amount remaining in the atmosphere are accounted for by oceanic uptake (Broecker *et al.* 1985; Broecker 1991; Houghton and Woodwell, 1989), but the fact is that our state of knowledge about terrestrial uptake of carbon and its release is insufficient for predicting the change of carbon in the atmosphere of the future.

Estimates of CO_2 fertilization effects, or biotic growth factors b, such as those produced by the studies cited above, are static in nature. That is, they provide a linear relationship between increasing global plant storage of carbon with increasing CO_2. As cited above, they are applied to a planetary inventory of plant matter and an estimate of global net photosynthesis to obtain an estimate of carbon uptake at a higher concentration of CO_2. Reynolds *et al.* (1992), using a mechanistic plant growth model (GEPSI), developed a response surface for relative growth rates in response to changes in CO_2 and N availability for a chaparral stand. This surface, expressed as percent change in stand biomass with changing CO_2, was very non-linear, or dynamic. Dynamic response functions describing the fertilization of CO_2 on plants, ecosystems and carbon storage may provide more accurate estimates for global analysis.

Dynamic beta functions need to be incorporated into models contributing to analyses of global climate change. However, the modeling process must include a suite of models accurately representing the fertilization process beginning at the level of plant physiology. Currently, there is much interest within the plant research community in physiological responses of ecosystems to CO_2 enrichment including: examination of potential up-regulation or down-regulation of the A/Ci curves; inhibition of dark respiration; allocation and partitioning of photosynthate within the plant and the mechanisms regulating these processes; net storage of and turnover of subsurface carbon; and the potential effects of warming and changes in water availability on all of these processes. Thus, a dynamic beta function expressing the sum of these processes for a canopy, or

summed for all canopies globally, is central to understanding global CO_2 fluxes and the balance of carbon storage among various global compartments. It needs to be evaluated at several levels from physiological to ecosystem, and it needs to be studied in as natural a setting as possible.

IV. ECOSYSTEM LEVEL CO_2 ENRICHMENT EXPERIMENTS

Few CO_2 enrichment experiments have been conducted on intact, natural plant communities and, of those that have been reported, all used some form of enclosure.

A. Tussock tundra

Oechel and colleagues exposed Arctic tussock tundra, *in situ*, to 600 μmol mol^{-1} CO_2 in temperature-controlled enclosures over a period of three years. An initial stimulation of the dominant species, the C_3 cotton grass Eriophorum vaginatum, was apparent but photosynthesis declined over two to three weeks. Tillering by this grass was strongly stimulated, while root biomass actually decreased over the length of the experiment. Although whole system carbon storage was initially stimulated, homeostatic adjustment by the tussock tundra ecosystem was complete within three years. Both low temperature and nutrient availability may have been factors limiting the increase in photosynthesis due to CO_2 enrichment of this Arctic system (Tissue and Oechel 1987; Mooney *et al.* 1991).

B. Salt marsh

In contrast to the lack of continuing long-term response in the tussock tundra experiment, temperate wetland communities enclosed in open top chambers show little sign of homeostatic adjustment to long-term exposure to elevated CO_2. Stands of the C_4 grass Spartina patins and the C_3 sedge Scirpus olney were exposed to ambient and ambient plus 340 μmol mol^{-1} CO_2 in OTCs in a Chesapeake Bay salt marsh. Productivity and biomass of the C_3 sedge in particular increased. Both C_3 and C_4 plants exhibited other responses, including reduced evapotranspiration and respiration. Overall, net carbon sequestering doubled in the Scirpus community and increased by 25% in the Spartina community. Root biomass increased by 85% in the Spartina community. After three years of growth in elevated CO_2 there was no evidence of acclimation in photosynthetic capacity at light limited conditions (Drake 1989; Long and Drake 1991; Mooney *et al.* 1991). Experiments currently underway with OTCs in grasslands generally parallel the findings reported in wetlands (C. Owensby 1991, pers. comm.).

C. Soil nutrient status

Experimenters like to think that they can account for all variables associated with their experiments. This is probably close to true *in vitro* but, as one moves toward systems of increasing complexity, the ability even to identify, not to mention quantify, all of the variables becomes more problematic, and control becomes difficult. The nutrient status of soils is a case in point, particularly in natural ecosystems. Nutrient supply can strongly influence sinks for photosynthate, and overall plant response to CO_2 enrichment is largely

regulated by sink strength (discussed in Mooney *et al.* 1991).

Unfortunately, there is little published information other than the studies cited above on the interaction of nutrient availability and CO_2 enrichment on intact, natural ecosystems. Nevertheless, this is currently a "hot" topic for discussion. The allocation of photosynthate to various plant activities under nutrient rich and nutrient limited conditions was addressed by several reports presented at the International Workshop on CO_2 and the Biosphere, held at the International Agriculture Center at Wageningen, Netherlands, in November 1991. Publications of reports presented there should occur in 1992. This topic is very important to the interpretation of the large number of CO_2 enrichment studies reported in the literature and that are likely to be conducted over the next few years.

Preliminary information has been published from a study aimed at evaluating the interactions of soil nutrient availability and CO_2 enrichment is currently under way (Pitelka 1992). This study exposes two conifers grown in OTCs, loblolly pine grown in North Carolina on moist soils with both low nitrogen and phosphorous, and ponderosa pine grown in Sierra Nevada foothills of California under drier, nitrogen limiting conditions. Controlled environment studies are run in parallel to help define the nature of the CO_2 and nutrient interaction. Three levels of CO_2 are used and two or three levels of nutrients, in East and West sites, respectively. Preliminary results from seedling loblolly pine grown for five months indicate little or no response to CO_2 enrichment unless the soil was enriched with both nitrogen and phosphorous. Ponderosa pines seemed to be stimulated by CO_2 enrichment at five months at all nutrient levels, but this stimulation was not apparent at eight months. This response is quite different from the growth enhancement observed under nutrient rich agricultural conditions typical of almost all of the CO_2 enrichment experiments published to date. If the lack of stimulation persists, and is verified in other experiments, then it would seem less likely that terrestrial biota might mitigate the rate of increase in the concentration of atmospheric CO_2.

Summarizing the currently available data from CO_2 enrichment experiments on plants within intact ecosystems: water use efficiency increases, there is an increase in the carbon-to-nitrogen ratio, and environmental temperature and nutrient status of the soil influence the extent of the response. The differences in outcome of the two CO_2 enrichments of intact, natural ecosystems are of significance to the global carbon flux issue. While nutrient limitation of the Arctic community may have been a factor in homeostatic adjustment over three years, the short growing season, widely varying temperatures associated with Arctic summer conditions, and low soil temperatures limit the usefulness of that study *vis-a-vis* understanding temperate or tropical forest response over the long term.

V. CHANGES IN COMMUNITY COMPOSITION

Has increased atmospheric CO_2 over the past 150 years created a grand experiment, *de facto*, within which the entire biosphere is the subject? The potential for differential responses of C_3 and C_4 plants, as well as the differential fertilization responses among species within these groups in natural communities, strongly suggests that the composition of natural communities will shift as global CO_2 increases in ways that cannot be predicted with our current state of knowledge (reviewed in Bazzaz 1990; and Mooney *et al.* 1991). Several

attempts have been made to detect contemporary ecosystem responses to the 21% increase in CO_2 that have already occurred. Errors in measurement at the ecosystem level, annual variability in climate, interactions with herbivores that differ from year to year, and changing concentrations of atmospheric oxidants all contribute to difficulty in detecting a signal of natural ecosystem responses to historic changes in CO_2 concentrations (Mooney *et al.* 1991). But careful analysis of plant census data accumulated over large regions and over long periods of time may provide some evidence for plant community adjustments induced by global changes in CO_2.

Over the past century a ubiquitous increase in the abundance of woody C_3 plants such as creosote bush, at the expense of C_4 plants such as the prairie grasses, occurred across the extremely heterogeneous Western U.S., from tall grass prairie to desert grassland, according to Mayeux, *et al.* (1990).). Their data are taken from vegetation surveys over the period 1850-1990 across a 2000 km transect from the Southeastern mixed forests of central Alabama to the desert grasslands on western New Mexico. Analogous shifts in community composition seem to be occurring throughout similar biomes of the world, including reports from Central America, South America, Africa, India and Australia (reviewed in Mayeux *et al.* 1990). "Traditional" explanations for this shift include increasing drought, introduction of livestock grazing and over grazing, increased seed dispersal by roving livestock, climate change, control of wildfires, and combinations of these factors. The authors, in discussing these alternative explanations for the shift from C_4 to C_3 vegetation, state that this occurred over a wide range of annual precipitation (1250 to 250 mm yr^{-1}) in the U.S., and that no individual or combination of these potential explanations could account for the ubiquity of the observed succession, both in the U.S. and globally. They hypothesize that changes in atmospheric CO_2 concentration must be responsible. This is of interest because it seems to be the first discussion of systematic structural changes observed in natural ecosystems in response to anthropogenically induced changes in global atmospheric CO_2. The argument of Mayeux, *et al.* however, remains inferential. One way to evaluate the inference would be to conduct large-scale and long-term studies of CO_2 enrichment on intact sections of these natural ecosystems.

A. Need for improved C-flux experiments

Mooney *et al.* (1991) note that there is an urgent need for direct experimentation on intact ecosystems in order to observe (among other variables) adjustments to net ecosystem fluxes of carbon. They recommend well replicated studies in each of the worlds six major biomes (tundra, boreal forest, temperate forest, tropical forest, grassland and desert) with spatial and temporal scales appropriate to the ecosystem being tested. "Even a single-species tree plantation may require plots of at least 10m x 20m ... [and] must run for at least a decade to allow a response trajectory to be determined" (Mooney *et al.* 1991).

The International Geosphere Biosphere Program (IGBP 1990) has among its objectives the development of the capacity to predict the effects of changes in CO_2, climate and land use on terrestrial ecosystems, and how these effects can lead to feedbacks to the physical climate system. "The top priority is for large-scale experiments involving free-air CO_2 enrichment studies (FACE)" at the patch scale in order to provide data on how CO_2 fluxes between plants and the

atmosphere might change with the chemical climate. IGBP recommends that experiments should be planned for 3 - 5 years for perennial grasslands and 10 to 15 years or longer for forests. "The interaction between CO_2 and water supply is an important requirement"(IGBP 1990). The FACE system provides an experimental approach within which to observe simultaneously changes in growth rates, morphology, biomass and yield; instantaneous-to-annual gross- and net primary production, and respiration; fluxes of water, nutrients and energy; water use efficiency; carbon allocation; and decomposition. FACE plots can be large enough to allow sampling above and below ground without compromising the utility of the plot. Ultimately, the IGBP envisions making continental-scale predictions for several properties, such as albedo, evapotranspiration, carbon storage and release, etc. For such analyses, the IGBP also aims to estimate the distribution of terrestrial carbon pools within continents to predict how they might change under given scenarios of global change. Central to such sweeping analyses is the problem of transferring the quantification of biological functions observed at one level to other levels that differ in spatial scale by several orders of magnitude.

VI. THE ECOLOGICAL SCALING PROBLEM

In a review of responses of natural ecosystems to increased CO_2, Bazzaz (1990) reported on studies at the physiological level of individuals and presumed consequences to populations, community and ecosystem levels. Plants react differently; the same species or cultivar response varies due to interactions among CO_2 and light, nutrients, temperature, humidity, micro-scale turbulence, subsurface microbial processes, water availability, etc. The naturally occurring **gestalt** of these variables for a particular ecosystem is difficult, if not impossible, to synthesize in the laboratory, or to maintain in an open top chamber. Yet, realistic experiments are required that provide data aggregating plant responses up to the ecosystem level, and an analytical framework is required within which to extrapolate field data from the ecosystem to the biome and even global levels.

Thus, the need for realistic field experiments seems to be confounded both by experimental artifacts imposed by the treatment method and by the lack of a transfer framework for information from plots a square meter in size to biomes measured in thousands of square kilometers. Our dilemma is that we cannot obtain realistic field data without manipulating ecosystems and we cannot enclose an ecosystem without thereby altering its structure or function. There is hope of solving the gordian knot of ecosystem analysis by combining both "top-down" and "bottom-up" approaches.

In the approach suggested by Stewart *et al.* (1989), the world is divided organizationally from top downward into biomes, and ecosystems are selected spanning the probable range of environmental factors within biomes. At this level, critical decisions must be made in order to limit the expense of the overall program, selecting those ecosystems within biomes significant to the global carbon flux issue (including vegetation factors, soil fertility, climate, and disturbance) for direct observation (or experimentation). Within ecosystems, representative sites are selected for experimentation. Analysis of biome responses to the experimental treatment (e.g. CO_2 fluxes and carbon storage) would then incorporate a range in variability that may be modeled as functions of the environmental factors used for stratification. Extrapolation of results

REFERENCES

1. Adams RM, Rosenzweig C, Peart RM, Ritchie JT, McCarl BA, Glyer JD, Curry RB, Jones JW, Boote KJ, Allen, LH Jr. (1990) Global climate change and US agriculture. Nature 345:219-224.

2. Allen LH (1990) Plant responses to rising carbon dioxide and potential interactions with air pollutants. J. Environ. Qual. 19:(1) 15-34.

3. Arp WJ (1991) Effects of source-sink relations on photosynthetic acclimation to elevated CO_2. Plant, Cell and Environment 14:869-875.

4. Bacastow R, Keeling CD (1973) Atmospheric carbon dioxide and radiocarbon in the natural carbon cycle: II. Changes from A.D. 1700 to 2070 as deduced from a geochemical model. pp. 86-135 in Woodwell, G.M. and E.V. Pecan Carbon and the Biosphere. Proc. 24th Brookhaven Symposium in Biology. Brookhaven National Laboratory, Upton, NY 11973.

5. Bazzaz FA (1990) The response of natural ecosystems to the rising global CO_2 level. Annu. Rev. Ecol. Syst. 21:167-196.

6. Bazzaz FA, Fajer ED (1992) Plant life in a CO_2-rich world. Scientific American. January 1992:68 74.

7. Broecker WS (1991) Global change and oceanography programs. (Letters) Science 254:1566.

8. Cess RD, Potter FL, Blanchet JP, Boer GJ, Ghan SJ, Kiehl JT, Le Treut H, Li Z-X, Liang X-Z, Mitchell JFB, Morcrette J-J, Randall DA, Riches MR, Roeckner E, Schlese U, Slingo, A, Taylor KE, Washington WM, Wetherald RT, Yagi I (1989). Interpretation of cloud-climate feedback as produced by 14 atmospheric general circulation models. Science245:513-516.

9. Drake B (1989) Elevated Atmospheric CO_2 Concentration Increases Carbon Sequestering in Coastal Wetlands. Carbon Dioxide Research Program, OHER, Dept of Energy, Wash. DC

10. Drake BG, Leadley PW, Arp WJ, Nassiry D, Curtis PS (1989). An open top chamber for field studies of elevated atmospheric CO_2 concentration on saltmarsh vegetation. Functional Ecology 3:363-371

11. Drake BG (1989) Elevated Atmospheric CO_2 Concentration Increases Carbon Sequestering in Coastal Wetlands. Carbon Dioxide Research Program, OHER, Dept of Energy, Wash. DC.

XX. Grulke NE, Riechers GH, Oechel WC, Hjelm U, Jaeger C (1990). Carbon balance in tussock tundra under ambient and elevated atmospheric CO_2. Oecologia 83:485-494.

12. Ham JM, Ownsby CE, Coyne PI (1991) Simulating confounding CO_2 and chamber effects within open-top chambers. p. 18 In Agronomy Abstracts. Amer. Soc. Agron., Madison, WI. Additional information is contained in an unpublished manuscript with the same title made available at the 1991 annual meeting Amer Soc. Agronomy, Denver, CO.

13. Hendrey GR, Lewin KF, Lipfert F, Kolber Z, Daum, M (1988a) Free-air carbon dioxide enrichment (FACE) facility development: I. Concept, prototype design and performance. BNL-42338, Brookhaven National Laboratory, Upton NY 11973, 36 pp.

14. Hendrey GR (1988b) Controlling Carbon Dioxide Concentrations in Free air experiments. Carbon Dioxide Research Division, Office of Basic Energy Sciences, U.S. Dept. of Energy, Washington, DC 20545.

15. Hendrey, GR, Lewin KF, Kolber Z, Daum M (1988c) Control of ozone concentrations for plant effect studies. BNL 43589. Brookhaven National Laboratory, Upton, NY 11973. 38 pp.

16. Hendrey GR, Lewin KF, Lipfert F, Kolber Z, Daum M (1988a) Free-Air Carbon Dioxide Enrichment (FACE) Facility Developmentrr: I. Concept, Prototype Design and Performance. Response of Vegetation to Carbon Dioxide: Series No.045. U.S. Dept of Energy, Washington, DC. 36 pp.

17. Hendrey GR, Kimball BA (1990) FACE: Free-air carbon dioxide enrichment: Application to field-grown cotton. GPO 1991-514-579. 18 pp.

18. Hendrey GR, Kimball BA (1990). FACE: Free-air carbon dioxide enrichment program summary. GPO 513-040 1-M. 4 pp.

19. Hicks BB (1989) The ocean as a source and sink for atmospheric trace constituents. Final Report of SCOR Working Group 72. Unesco technical papers in marine science Nr. 56. 20 pp.

20. Houghton RA, Skole DL (1990) The long term flux of carbon between terrestrial ecosystems and the atmosphere as a result of changes in land use. Research project of the month summary (July 1990), Carbon Dioxide Research Program, U.S. Dept. of Energy, Washington, DC.

21. Houghton RA, Woodwell GM, (1989) Global climatic change. Scientific American 260:36-44.

22. Idso SB, Kimball BA, Anderson MG, Mauney JR, (1987) Effects of atmospheric CO_2 enrichment on plant growth: The interactive role of air temperature. Agriculture, Ecosystems and Environment 20:1-10.

23. Idso SB, Kimball BA (1991) Doubling CO_2 triples growth rate of sour orange trees. DOE Research Summary 13. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, Oak Ridge TN. 4pp.

24. Idso SB, Kimball BA, Allen SG (1991) CO_2 enrichment of sour orange trees: two and a half years into a long-term experiment. Plant Cell Environment, in press.

25. IGBP (1989) IGBP Report No. 11.Internat. Council of Scientific Unions, Stockholm.

26. IGBP (1990) The initial core projects. International Geosphere-biosphere Program Report NO. 12.Internat. Council Scientific Unions, Stockholm.

27. Jones PD, Wigley TML (1991) The global temperature record for 1990. Research Summary No. 10. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, Oak Ridge TN. 4.pp.

28. Kimball BA (1983) Carbon dioxide and agricultural yield: an assemblage and analysisof 430 prior observations. Agronomy Journal 75:779-782.

29. Kohlmaier GH, Sire E-O, Janecek A, Keeling CD, Piper SC, Revelle R (1989) Modelling the seasonal contribution of a CO_2 fertilization effect of the terrestrial vegetation to the amplitude increase in atmospheric CO_2 at Mauna Loa Observatory. Tellus 41B: 487-510

30. Lawler DW, Mitchell RAC The effects of increasing CO_2 on crop photosynthesis and productivity - a review of field studies. Plant, Cell and Environment 14:807-818

31. Lindzen RS (1990) Some coolness concerning global warming. Bull. Amer. Meteorol. Soc. 71:288-299.

32. Lipfert FW, Daum ML, Hendrey GR, Lewin KF (1989) Fluid mechanics and spatial performance of FACE arrays. BNL-43476. Brookhaven National Laboratory, Upton, NY 11973, 38 pp.

33. Long SP (1991) Modification of the response of photosynthetic productivity to rising temperature by atmospheric CO_2 concentratons: Has its importance been underestimated? Plant, Cell and Environment 14:729-739.

34. Long SP, Drake, BG (1991) Effect of the long-term elevation of CO_2 concentration in the field on the quantum yield of photosynthyesis of the C_3 sedge, *Scirpus olneyi*. Plant Physiol. 96: 221-226.

35. Luxmore RJ, Norby ??, O'Neill EG (1986) Seedling tree responses to nutrient stress under atmospheric CO_2 enrichment. pp.178-183 in Forest Plants and Forest Protection 18th IUFRO World Congress Division 2:1.

36. Mayeux H, Johnson HB, Polley HW, Global change and vegetation dynamics. Chapter 7, *in* Noxious Range Weeds, L.F. James, J.O. Evans, M.H. Ralphs and R. D. Child, *Eds*. Westview Press, Boulder, CO_2.

37. Mooney HA, Drake BG, Luxmore RJ, Oechel WC, Pitelka LF (1991) Predicting ecosystem responses to elevated CO_2 concentrations. BioSci. 41:96-104.

38. Musselman RC, Fox DJ (1991) A review of the role of temperate forests in the global CO_2 balance. J. Air Waste Manage. Assoc. 41:798-807.

XX. Oberbauer SF, Sionet N, Hastings SJ, Oechel WC (1986). Effects of CO_2 enrichment and nutrition on growth, photosynthesis, and nutrient concentration of Alaskan tundra plant species. Can. J. Bot. 64:2993-2998.

XX. Oechel WC, Reichers G, Lawrence WT, Prudhomme TI, Grulke N, Hastings SJ (1992) 'CO_2LT' an automated, null-balance system for studying the effects of elevated CO_2 and global climate change on unmanaged ecosystems. Functional Ecology 6:86-100

39. Pitelka L (1992) Forest response to carbon dioxide. EPRI Journal Jan/Feb 1992:38-41

40. Raval A, Ramanathan V (1989) Observational determination of the greenhouse effect. Nature 342:758-761.

41. Reynolds JF, Hilbert DW, Kemp PR (1992). Scaling ecophysiology from the plant to the ecosystem: A conceptual framework. *in*, J. Ehlering, C. Field, *eds*., Scaling Processes Between Leaf and Landscape Levels. Academic Press.

42. Sage RF, Sharkey TD (1987) The effect of temperature on the occurence of O2 and CO_2 insensitive photosynthesis in field grown plants. Plant Physiol. 658-664.

43. Schneider SH (1990) The global warming debate heats up: An analysis and perspective. Bull. Amer. Meteorol. Soc. 71:1292-1304.

44. Stewart JWB, Aselmann I, Bouwman AF, Desjardins RL, Hicks BB, Rodhe H, Schimel DS, Svensson BH, Wassermann R, Whiticar MJ, Yang W-X (1989) Group report Extrapolation of flux measurements to regional and global scales. pp. 155-174 in M.O. Andreae and D.S. Schimmel, eds, Exchange of Trace Gases Between Terrestrial Ecosystems and the Atmosphere. Wiley & Sons.

45. Strain BR, Cure JD (1985) Direct effects of increasing carbon dioxide on vegetation. DOE/ER-0238, U.S. Department of Energy, Washington DC. 286 pp.

46. Tans PP, Fung, IY, Takahashi T (1990) Observational constraints on the global atmospheric CO_2 budget. Science 247: 1431-1438

47. Tissue DL, Oechel WC (1987) Physiological response of *Eriophorum vaginatum* to field elevated CO_2 and temperature in the Alaskan tussock tundra. Ecology 68:401-410.

48. Trabalka ?? (1985) Atmospheric Carbon Dioxide and the Global Carbon Cycle. DOE/ER-0239, US Dept. of Energy, Wash. DC, 316 pp

49. Walker BH (1990) A framework for modelling the effects of climate change and atmospheric change on terrestrial ecosystems. pp.1-22 in Global Climate Change IGBP Report Nr. 11. Internat. Council of Scientific Unions, Stockholm, 108 pp.

50. Woodwell GM (1978) The carbon dioxide question. Scientific American 238:34-43.

51. Wuebbles DJ, Connel PS, Grant KE, Penner JE (1988) The role of atmospheric chemistry in climate change. J. Air Pollut. Control Assoc.

THE DOE/USDA FACE PROGRAM: GOAL, OBJECTIVES AND RESULTS THROUGH 1989

George R. Hendrey
Department of Applied Science
Brookhaven National Laboratory
Upton, NY 11973

I. INTRODUCTION

A principal reason for assembling all of the materials presented in this book is to provide a compendium of information about the experimental system developed by Brookhaven National Laboratory, and about the biological studies for which it has been used. The information reported in this book on the responses of cotton to CO_2 enrichment as observed in field experiments at Yazoo City, MS and Maricopa, AZ, are certainly not intended to be definitive. Rather, these reports are preliminary observations and indicative of the types of observations obtained in FACE experiments through 1989. Since the primary purpose of the book is to present the status of the FACE Program, inclusion of highlights of these biological data, in the context of a few key questions, is of interest here.

As discussed in Chapter 1, a justification for investigating the effects of CO_2 enrichment on plants and ecosystems is that the role of terrestrial plants in mitigating the rise in atmospheric CO_2 in our time may be very significant, but it cannot be quantified accurately enough with our present knowledge to allow acceptable predictions about the concentration of atmospheric CO_2 over the next century. It follows that without reliable predictions of future CO_2 concentrations, changes in global climate driven by changing CO_2 also cannot be predicted reliably. In order to provide improved estimates of the interactions between terrestrial plants and the atmosphere, *vis-a-vis* exchange of carbon and water, and to describe the molecular to physiological mechanisms regulating these exchanges, the United States Department of Energy (DOE) and the U.S. Department of Agriculture (USDA) have been conducting a cooperative research effort, called the Free-Air CO_2 Enrichment (FACE) Program.

The FACE Program has three principal goals. These are to:

1. Design, assemble, operate and evaluate a free-air CO_2 enrichment system that maintains sufficiently steady CO_2 concentrations so that the fluctuations in CO_2 cause no perceptible effect on plants grown

within the experiment;

2. Provide reliable field data about the effects of CO_2 enrichment on crops and other plant communities to be used to develop and evaluate mechanistic plant growth models which can contribute to predicting the effects of future CO_2 concentrations and climate changes on plant growth and water use;
3. Contribute to an evaluation of global CO_2 fluxes and carbon balances between vegetation and the atmosphere under conditions of elevated atmospheric CO_2.

II. OBJECTIVES

In order to meet the goals stated above, specific objectives were set for the initial phases of FACE system development, field testing and experiments. These objectives were to:

1. Design, construct and demonstrate the FACE system and document its performance.
2. Establish the effective spatial operating range of the FACE system.
3. Document the biological responses of cotton to CO_2, including interactions with other environmental variables.
4. Establish criteria for CO_2 concentration fluctuations based on the transient responses of plants.
5. Develop a dynamic model for cotton plant growth that can predict the effects of climatic change and increasing atmospheric CO_2 concentrations.

III. PROJECT STATUS AS OF 1989

Our progress on the first three objectives through 1989 is detailed in subsequent chapters of this book, and a summary is presented below. The BNL FACE system, described in detail by Lewin, *et al.* in Chapter 5, consists of a circular array of vertical vent pipes (VVP) connected to a toroidal plenum through which air enriched in CO_2 (or some other fumigant) is released. Several configurations of the basic system have been tested with plenum diameters of 15-27 m. The array diameter can be changed by inserting an extender pipe between the VVP and the plenum or by increasing the diameter of the plenum. A fan located adjacent to the plenum is used to force ambient air through the plenum torus and out the VVPs. Pure CO_2 is metered into the fan air intake, based on demand. The CO_2 metering valve is controlled by a proportional-integral-differential (PID) algorithm that includes terms for wind speed, measured CO_2 concentration at the center of the array, and various performance statistics modified by a term proportional to wind speed. Spatial control is evaluated by measurement of gas concentrations at many points within the FACE array over various time periods.

The first BNL prototype system (Hendrey *et al.* 1988a), developed between July 1986 and February 1987, used SO_2 as a controlled gas because of the ease of detection, and the fact that with ambient concentration at about 10 nano moles per mole, very little SO_2 was needed for the demonstration phase. We were able to maintain SO_2 measured at the center of a 15 m-diameter prototype array at 40

±8 nano mol mol^{-1} at least 80% of the time, during a 72-h test at Brookhaven National Laboratory, Long Island. In subsequent studies using this prototype array, we also demonstrated the ability to control the concentration of ozone at 200 nano mol mol^{-1} ± 40 nano mol mol^{-1} better than 96% of the time, with a standard deviation of 18 nano mol mol^{-1}. At a set point of 150 nano mol mol^{-1} O_3, deviations from the 120-180 nano mol mol^{-1} criterion range occurred less than 9% of the time, with a standard deviation of 22 nano mol mol^{-1}. "Spike" concentration were of short duration, less than 1-min, and rarely exceeded the set point by as much as 100% (Hendrey *et al.* 1988c).

From 1987 through 1991 the BNL FACE system was used in field trials both in Yazoo City, MS, and at Maricopa, AZ. Tests were conducted in active agricultural fields planted in cotton grown according to standard agronomic practices for the regions. Cotton, a C_3 plant, was chosen because it is actually a woody perennial grown as an annual. Thus, from a modeling point of view, cotton is a paradigm for other woody plants. Because of its high economic value it has been the subject of much agronomic research; there is a large body of information on cotton, including responses to availability of water and nutrients, and CO_2. USDA has developed growth models of cotton used for agronomic management.

FACE can operate effectively over bare ground, over grass, and over a crop ranging in height from 0 to 200 cm with both open and closed canopies. Control of CO_2 concentrations, measured 10 cm above the canopy at the center of the FACE array, is essentially the same in all of these situations and the vertical gas profiles within the canopies are approximately uniform over the controlled plot area. The initial CO_2 mass-flow distribution has been tailored for the lower transport velocities inside the canopy and the enhanced mechanical turbulence there helps promote rapid mixing. The system provides good control of CO_2 over a wide range of wind velocities.

In general, increasing wind velocity decreases variance about the target CO_2 concentration because system time lags (transport of gas from the peripheral VVPs to the sample intake port in the center of the plot) are reduced (see Chapter 7). Poorest control (but well within the control criteria parameters) occurs at low or variable wind velocities. Below 0.4 m s^{-1} our wind vane cannot determine wind direction reliably. Our strategy then is to open every other VVP and flood the field with CO_2 with concentration controlled by feedback from the measured concentration.

One measure of the utility of the FACE system is in the size of the experimental plots having acceptable concentrations of CO_2. Definition of "acceptable concentration" is somewhat arbitrary and was arrived at by consensus of FACE experimenters and reviewers as ± 20% of the target concentration for 1-min averages at the center of the array. This value was selected with the assumptions that: (1) deviations of the concentrations from the set point are symmetrical so that there is no bias toward net higher or lower values; and (2) the duration of such deviations is short, less than a minute, so that overall plant response is not altered by either the direction or amount of the deviation.

Since CO_2 is injected into the plot with an average concentration of about 25,000 μmol mol^{-1}, further dilution to the desired enrichment level must occur rapidly and thoroughly within a few meters of downwind travel. This rapid mixing is aided by the CO_2 injection jets of the BNL FACE design, most of which are lateral to the wind. Because of the normal variation of wind direction,

diurnally and over a growing season, this mixing zone becomes effectively annular in shape and defines the useful outer periphery of the FACE plot. Studies of emitter jet penetration (width of annulus) were carried out using a sonic anemometer. Under conditions of very low ambient wind velocity (<0.2 m s^{-1}) at a distance of 1-2 m from the emitter port, we were unable to distinguish emitter jet velocities from ambient winds. Jets from adjacent emitters also intersect at about this distance, as observed from the plumes of smoke introduced into the plenum (see Chapter 6). Thus, the outer 2 m of the radius of the FACE system is a region of dilution of injected CO_2 with the ambient air, and intersection and blending of the adjacent jet plumes.

The credibility of experiments using any type of fumigation system depends greatly on the ability of the system to provide a controlled treatment. It is noted by Allen (Chapter 3) that free-air release systems prior to 1983 experienced concentration excursions equal to 3 to 5 times the mean CO_2 concentration about 10% of the time. At a median concentration of 550 μmol mol^{-1}, this would be in the range 1650 to 2750 μmol mol^{-1}. The 1-min average CO_2 concentration measured at the center of the FACE array at Maricopa in 1989 was within $\pm$10% of the 550 μmol mol^{-1} target concentration better than 88% of the time, and it was within $\pm$20% of the target concentration better than 98% of the time. What do the "extreme" events of elevated CO_2 look like in the BNL FACE system? Short-term spikes exceeding twice the mean CO_2 concentration within the "sweet spot" constituted about 0.44% (72) of the observations from a population of 16,404 1-s grab-sample observations from 27 continuous sampling points in a three-dimensional sampling array through and around the "sweet spot".

Several different tracer studies and multiple port sampling studies have been conducted to evaluate spatial variability. Array diameters ranging from 16 m to 27 m have been tested, so far. Three dimensional non-uniformity has improved (compare measurements reported by Nagy *et al.* in Chapter 7 [1989 data from Arizona] and by Hileman *et al.* in Chapter 8 [1988 data from Mississippi]). Just how stable are CO_2 concentrations within FACE plots? Since the variation at different averaging periods are critical to determining the credibility of the experimental conditions, three different experiments by two sets of investigators were carried out on FACE systems in 1988 and 1989. Variation of grab samples over the area of the entire FACE plot was generally less than 20% of the set point measured at the center of the plot (Chapters 7 and 8). In the central 12-m diameter area of the plot, the "sweet spot" from which biological samples were taken, season-long average spatial variation was within about $\pm$5% of the mean concentration within the entire volume of this "sweet spot" (Chapter 7). These findings may be contrasted with the results of measurements of CO_2 uniformity within the three different types of open-top chambers made by Hileman *et al.* (Chapter 9). Variation of the mean CO_2 concentration over time exceeded 100 μmol mol^{-1} in three types of OTCs tested. Spatial variation within the OTCs ranged from 4% to 17% of the concentration measured at the center of OTCs. Even the best of these, a round OTC with a frustum, had variations in CO_2 concentration over time that exceeded 100 μmol mol^{-1} at some sample points. In <u>most</u> cases when a frustum was not used the mean CO_2 range exceeded 50% of the mean elevation above ambient. Use of a frustum improved control considerably and CO_2 never exceeded 10% deviation from the mean. Spatial variability of CO_2 in the FACE arrays is comparable to that observed in other open-top chambers (OTCs) as well. Drake *et al.* (1989) found CO_2 concentrations to differ by about 12% within OTCs in a <u>Scirpus</u> community.

The long-term response of the plants grown within the controlled area of the FACE plots also is indicative of growing conditions and CO_2 control. The uniformity of plant response within FACE arrays indicates that as much as 18 m and perhaps 20 m of the 22 m diameter may be used for sampling plant responses (Mauney *et al.* Chapter 11). Hendrix (Chapter 12) concludes that leaf starch content may be used to evaluate the uniformity of the biological response within the FACE system. Grid-based sampling showed that increased leaf starch occurred more-or-less throughout the area delineated by the FACE ring, with a sharp boundary evident. Figure 12-1 shows scatter in the leaf starch measurements both inside and out of the FACE treatment area. We therefore assume that this "noise" may be due to non-uniformities in water treatment or soil properties or to the measurements themselves, rather than to variability in CO_2 (which would be unlikely to be stationary in time).

Will short-term spikes in CO_2 concentrations such as those observed in the FACE array effect net photosynthesis? The results of some special experiments conducted on cotton in growth chambers to determine responses to such short-term fluctuations are presented by Evans *et al.* in Chapter 10. These experiments indicate that excursions within the range of observations made in the FACE system have little effect if they last for less than 60 s.

IV. COST OF FACE EXPERIMENTS

CO_2 costs are likely to vary widely for different FACE experiments in different locations. Prices of CO_2 in the United States, in quantities sufficient to run four FACE arrays, vary from a low of $25 per ton to well over $100 per ton. In Yazoo City, MS, CO_2 was produced as a by-product of the Mississippi Chemical Company's (MCC) fertilizer factory located 2 km from the FACE field experiment. MCC provided the CO_2 at no cost to an intermediary CO_2 vendor who charged $35 per ton for recovery, scrubbing and delivery to the FACE site. Cooperation of industrial sponsors can be a valuable asset. At Maricopa, AZ, CO_2 was obtained at $68 per ton in 1989 and $70 per ton in 1990. At Brookhaven National Laboratory on Long Island, the current price for CO_2, at 5 tons per day, is $149 per ton.

Early considerations of FACE systems focused on the economics of increasing agronomic yields and thus were more concerned with gas usage and the associated costs than with its distribution in space and time (Chapter 4). To function as a useful research tool, however, a FACE system must provide a well controlled gas distribution (as uniform in space and time as possible), with operating costs a somewhat secondary consideration. Although BNL's FACE design may use more CO_2 than projected by some of the early facilities, its overall operating cost per unit of plant research area compares favorably, because of the economy of scale in a research setting. Our experience through 1991 is that operation of the FACE experiments, including 2.5 full-time operators, CO_2, electricity, logistics and miscellaneous parts and equipment, costs $450-$650 m^{-2} of controlled plot area.

In order to make reasonable decisions about program direction, an assessment of relative costs of various CO_2 fumigation methods is presented by Kimball in Chapter 16. The costs of setting up and operating a facility with systems like the BNL FACE arrays are compared to soil-plant-air-research (SPAR) systems and to open top chambers. A facility with 4 FACE units operating in a split-plot experiment may cost about $300,000 to set up. Similar costs for 8 OTCs total about $200,000 and about $350,000 for a facility with 8 SPAR units. Operating

costs for these three facilities under CO_2 enrichment in an experiment with eight treatments in a 6-month growing season with 24-h day^{-1} enrichment to 300 μmol mol^{-1} above ambient are estimated to be $451,000 for FACE, $133,000 for OTCs and $141,000 for the SPAR facility. While the FACE systems have a higher overall operating cost, the economy of scale makes their cost per unit of land area, or per unit of biological material, a fraction of that of the other systems. The cost of producing a unit of plant material for FACE, OTC and SPAR units, respectively are in the ratio 1:4:18.

V. HIGHLIGHTS OF BIOLOGICAL RESPONSES

Do FACE experiments confirm the types of plant responses to CO_2 enrichment observed in OTCs and other chamber experiments? Cotton accumulates starch within leaves during the day. At night, this stored starch is used for a variety of growth process and respiration. Previous work in OTCs has shown that leaf starch content in cotton increases substantially with CO_2 enrichment. In 1988 in the FACE experiments at Yazoo City, Hendrix (Chapter 12) observed that in plants receiving 600 μmol mol^{-1} CO_2 enrichment, leaf starch increased dramatically, from about 12 gm^{-2} leaf area to about 15 to 18 gm^{-2} leaf area. Similar patterns, albeit with lower levels of starch accumulation, also were observed in the FACE experiment with the 550 μmol mol^{-1} CO_2 enrichment in Maricopa, in 1989.

The large plot size of FACE experiments allowed extensive destructive harvesting throughout the period of plant growth. Harvest data on growth responses, final biomass and yield of cotton grown under 550 μmol mol^{-1} CO_2, presented by Mauney (Chapter 11), are similar to observations made in other CO_2 enrichment experiments. In 1989 at Maricopa, AZ, FACE plots had 45% greater dry weight than control plots 112 days after planting. At final harvest, the difference had narrowed to 20%. Increase in root biomass was as much as 85% greater with CO_2 enrichment. These data indicate that FACE-grown plants respond at the leaf and canopy levels in a similar fashion to CO_2 enriched plants grown in enclosures.

A critical question emerging from virtually all types of CO_2 exposure experiments on plants is: **How will water use by plants in their native habitats be altered by CO_2 enrichment?** This question is of considerable interest since if transpiration is reduced per plant while plant productivity rises due to the enrichment, then water use efficiency will rise. This could allow more plant growth per hectare in water-short regions, and it may convey a competitive advantage to C_3 over plants (see discussion of plant community succession, in Chapter 1). Because all types of enclosures alter the micro climate regime of the enclosed plants, plant water relations are difficult to evaluate in enclosures. Net leaf photosynthesis was measured by Hileman *et al.* (Chapter 13) during the experiments at Yazoo City, MS, using a leaf cuvette attached to a portable infrared gas analyzer. Stomatal conductance was obtained from the rate of water vapor change within the cuvette. Although photosynthesis was as much as 33% higher in the CO_2 enriched plots (600 μmol mol^{-1}) than in ambient plots, differences were not significant due to high variability among plots. Moreover, stomatal conductance did not differ among plots. This was something of a surprise since earlier work in controlled environments and field chambers has shown that cotton responds to CO_2 enrichment with a reduction in stomatal conductance. Hileman, *et al.* conclude that under field conditions, with a sufficient supply of nutrients and water, cotton can maximize photosynthesis by

maintaining normal stomatal opening rather than conserve water. But this type of response was not observed in the experiments at Maricopa.

Does CO_2 enrichment affect vegetation temperatures? Kimball and Pinter (Chapter 14) note that most plant models assume plant temperatures are the same as air temperatures. If plants are warmed to some degree as a consequence of CO_2 enrichment, then metabolic processes will be altered as a result. Earlier work (e.g. Idso *et al.* 1987) demonstrated that plants receiving CO_2 enrichment were significantly warmer than unenriched plants. This is attributed to the partial stomatal closure that is known to occur in C_3 plants exposed to elevated CO_2 concentrations, thereby reducing transpiration rates. A reciprocal relationship can be expected between stomatal conductance and transpiration, such that as plants respond to CO_2 enrichment by increasing stomatal resistance, cooling by transpiration decreases and leaf temperature increases (Lawlor and Mitchell 1991). In the FACE experiments at Maricopa, CO_2 enriched leaf temperatures averaged 1.4°C below air temperature through the day. However, CO_2-enriched foliage temperature, compared to foliage in ambient plots, increased by 1.°C over the first month of growth, and averages 0.80 °C warmer than leaves at ambient CO_2 over the whole season. Cotton bolls tended to be warmer by 1.9 °C than adjacent leaves, presumably due to the lower density of stomata compared to the stomatal density of leaves. Kimball and Pinter conclude that partial stomatal closure and concomitant reduction in transpiration resulted in increased temperatures.

Why do Hileman *et al.* and Kimball and Pinter come to differing conclusions regarding the effects of CO_2 enrichment on stomatal conductance? Transpiration rate is a function of humidity and boundary layer; boundary layer is dependent on wind speed and direction (Lawlor and Mitchell 1991). Perhaps the very humid and wet conditions in the OTCs in Mississippi compared to the low humidity conditions and natural wind movement of FACE in the Arizona desert are responsible. Here is an issue of importance to both the design of field experiments and to model development, with implications for the future of dry grazing lands as the global atmospheric concentration of CO_2 continues to rise. In any event, such water relation data can be readily obtained in FACE experiments, whereas they may be viewed as unrealistic if obtained within an enclosure.

Does the size of the FACE plot lend itself to efficient data acquisition by remote sensing? Spectral reflectance from cotton was measured by Pinter *et al.* (Chapter 15) using a hand-held radiometer, in visible and near-infrared (NIR) wave lengths. Ratios of red to NIR reflectance and the normalized difference (ND = NIR minus red reflectances, divided by their sum) were obtained. These indices were compared to samples of plant biomass and leaf area index obtained by destructive harvests throughout the growing season. Such remote sensing techniques can be obtained very rapidly with a low investment in equipment and labor, and without damage to the experimental plants. Differences, apparently due to the CO_2 treatment, were evident at all spectral bands measured. But estimates of canopy variables made by spectral measurements and analyses differed from harvest data. Foliage reflectance was sensitive to variables such as mite infestations and to covering of leaves by honeydew produced by white flies. Work is continuing to refine the radiometric techniques for application to analysis of plant responses to CO_2 enrichment. In these FACE experiments radiometric measurements of plant responses to the CO_2 enrichment treatment did provide season-long data that were very useful for management of the experiment. Pinter *et al.* conclude in their preliminary analyses that the relationship between plant

biomass and spectral vegetation indices is a function of the availability of CO_2.

How will plants allocate the "extra" production occurring because of CO_2 enrichment? Among the most interesting observations made within the FACE experiments is the response of the root and rhizosphere system. Because FACE provides such a large experimental plot area, intensive destructive extraction of root core samples could go on during the experiment without ruining the experimental plots. Rogers *et al.* (Chapter 16) report on two samplings, one at six weeks after planting and one at 14 weeks, at the end of the growing season. At crop harvest in 1988 at Maricopa, CO_2 enriched plots had a 20% increase in lateral roots and increased root weight density by 33%. There were indications of increased bacterial populations and microbial activity. They interpret increasing root density and stable mycorrhizal infection as amounting to greater mycorrhization for the plants. In 1989, taproot volume and dry weight increased by 73% and 83%. Other measures of root development increased by as much as 100%. Clearly, the CO_2 treatment was associated with massive root proliferation. The data of Rogers, *et al.* are the first documentation of such subsurface responses to CO_2 enrichment for an agro-ecosystem, and the first to be taken in the context of a well integrated biological study within which so much collateral data on the responses to CO_2 enrichment are available.

VI. FUTURE DIRECTIONS

Although this book deals with the initial phases of the FACE Program through 1989, work has continued through 1991. Full-scale experiments were conducted at the Maricopa Agricultural Center (MAC) in 1990 and 1991 using the four FACE arrays in a multivariate field experiment with two levels of water treatment at each of two levels of CO_2, ambient and 550 μmol mol^{-1}. The results of this work were not fully available at the time this book was sent to the publisher. In 1992 at MAC wheat will be grown in the FACE arrays. Efforts in the FACE Program, however, are shifting toward development of FACE systems for other types of ecosystems. In cooperation with the New Zealand Ministry of Forests and Fisheries, we are developing a FACE facility for exposing pasture lands to CO_2 enrichment. BNL is cooperating with investigators at Duke University in the development of a prototype FACE system for forests.

VII. FACE EXPERIMENTS IN A FOREST

Forest ecosystems occupy an important fraction of the planet's terrestrial biomass. Of the estimated 625 $\pm$205 GtC stored in global plant biomass, forests account for about 75%, and for about 66% of photosynthesis (Woodwell 1978; Post *et al.* 1990).

It takes several centuries for this carbon to cycle, but the net flux in any year is influenced by climatological factors. It is also quite likely that the net flux will be influenced by the steadily increasing concentration of CO_2 in the atmosphere (Strain and Cure 1985). Climate change and increasing CO_2 may alter both the rate of net uptake, and the sign, in ways that are not now predictable. Forest stand dynamics (e.g. growth rates of individual species, inter specific competition) will be influenced by CO_2 and climate changes. While there are several valid models of forest dynamics, they lack realistic field data for either parameterizing or for evaluating their performance in predicting the effects of changing CO_2 concentrations on carbon storage.

Carbon storage due to experimental CO_2 enrichment to 600-660 μmol mol^{-1} in sour orange trees grown over three years in OTCs has been as high as three times the rate of uptake in parallel control chambers, with no indication of adaptation or down regulation (Idso and Kimball 1991). It should be noted that this experiment occurred under agronomic conditions, with adequate water and excess nutrients, conditions quite uncommon for most of the forest soils of the world. Nevertheless, if a fraction of this increase in CO_2 uptake occurs in natural systems, particularly in forests, it suggests that the worlds plants may be able to provide a negative feedback on the increase in CO_2. But the time scale for ecosystem response via development of active biomass sufficient to alter the balance of CO_2 remaining in the atmosphere is certainly decades and likely to be on the order of 10^2 years (Graham *et al.* 1990). A means is needed to evaluate the effects of the increase in atmospheric CO_2 on the net storage of carbon globally, and in terrestrial systems in particular. This may be accomplished by various types of models, but the models need to be realistically parameterized and evaluated against realistic and credible field data. The FACE Program plans to initiate work on the development of free-air exposure systems for forest canopies.

Studies using the 3-dimensional gas dispersion model developed for analysis of the FACE system (Lipfert *et al.* Chapter 6) indicate that fumigation of the upper portion of a forest canopy may also be feasible.

How does fumigating a forest canopy differ from our previous experience and how do we plan to cope with it? Our plan to demonstrate FACE in a forest canopy involves raising the present array configuration to canopy height and extending the vertical extent of CO_2 coverage as required. This entails the following tasks, including changes in design and operation of the prototype FACE system.

Several alternative experimental protocols and designs are conceivable for conducting FACE Experiments In Forests (FEIF). Whether FEIF is initiated in a stand of seedlings or in a mature canopy, eventually the latter situation will have to be dealt with in a long-term forestry research program. Thus, it is important to learn at an early stage how well CO_2 can be controlled in a mature canopy. Studies using a 3-dimensional gas dispersion model developed for analysis of the FACE system indicate that fumigation of the upper portion of a forest canopy is feasible. Preliminary engineering studies indicate that CO_2 use will increase by about 40-60% if CO_2 is controlled in a 5 m deep cylindrical section 23 m in diameter at the top of a forest canopy (Lipfert *et al.* 1992). Further evaluation of FEIF is needed including development and testing of a FEIF prototype in a forest. In 1991 we intend to build a forest FACE prototype at Duke University in Durham, NC, to evaluate both the ability to control gas concentrations in the forest canopy and the amount of gas required. Anticipated studies with the forest FACE prototype will address the following problems:

1. Increase the vertical extent of coverage. With an annual crop, the vertical dimension changes over time as the crop matures. We can tailor the initial flow distribution accordingly with no particular difficulty, by changing the height of the emitter jets. Extending this control strategy to taller canopies should just be a matter of using the proper amount of gas.
2. Modify the design of gas distribution and control systems. Moving the system off the ground will cause some loss in efficiency since CO_2 will diffuse out of the bottom of the array. A possible way to improve the vertical distribution is to operate two separately controlled FACE arrays, stacked one on

top of the other. Since we can independently control the initial gas distribution in each, and can use two (or more) locations to control CO_2, we should have sufficient flexibility to optimize this requirement. Since control is based on gas concentration, transport from one control area into another does not cause a problem; the receiving area simply reduces demand for incremental CO_2.

3. Adjust the position and density of emitter jets in the vertical planes. The array height will increase, but we plan to keep the diameter about the same. Wind speeds at the top of the forest canopy may be higher. Higher wind speeds will decrease the travel time from gas release to feedback concentration sensing. Our experience with increasing wind speeds is that the system responds more-or-less linearly; more gas is needed but control improves. Higher winds often are accompanied by less vertical motion since the rate of CO_2 spreading is proportional to travel distance, the horizontal distribution should not change appreciably, depending on the turbulence level. We can tailor the vertical distribution by rearranging the CO_2 injection jet locations.

4. Adjust the control algorithm to achieve stable control and improve efficiency of gas use. The scale of turbulence may increase, both absolute magnitude and the scales of eddies, commensurate with the canopy height. In previous FACE designs, the turbulence scale was of the order of 1-2 m, so that only a small portion of the array was affected by each burst. The FEIF FACE array will be about the same diameter as previous FACE arrays. The system response time is variable but has been of the order of 10-45 s and was able to deal satisfactorily with a wide range of turbulence conditions both in the Arizona desert with a very long fetch, and in a Mississippi site with short fetches complicated by trees and leaves. Increased isotropic turbulence gives us better mixing. Mechanically induced turbulence should have scales determined approximately by individual tree-top sizes. At the top of a forest canopy, we expect larger and longer bursts. If they are as long as 100-200 s, we expect to be able to "ride the waves" and maintain control, by improving response times, for example, or by sampling at more than one location for feedback purposes. We expect that this topic will occupy a substantial portion of our development resources under the proposed project.

VIII. SUMMARY

The FACE system is a tool for studying the effects of CO_2 enrichment on vegetation and natural ecosystems and the exchange of carbon between the biosphere and the atmosphere. FACE experiments are conducted in a true field setting without any chamber effect. FACE studies were conducted in an agronomic setting using cotton because the plant and field conditions are relatively uniform, thus permitting and evaluation of FACE performance. Cotton is a woody perennial with well-known physiological characteristics and a high level of response to CO_2 enrichment. It is therefore a convenient subject for experimentation.

The BNL FACE system was shown to be reliable in field experiments conducted in 1987-1989, providing effective control of CO_2 concentrations in an open field setting without any type of confinement of ambient air. The system operates effectively over plant canopies ranging in stature from bare ground to 200 cm with both open and closed canopies. Control of CO_2 concentrations over large plots is within the criterion range $\pm$20% of set point for 1-min averages at least

80% of the time in all of these situations over both vertical and horizontal profiles. The area under effective control is described, approximately, by the diameter of the FACE array minus 4 m and is as large as 380 m^2 in the largest configuration tested to date (Hendrey 1992). In 1989 a 12-m diameter "sweet spot" in the center of the FACE array had season-long average CO_2 concentrations throughout the volume from ground level to the top of the canopy that were within the range of 94% to 104% of the target concentration. Operating costs for a four-array FACE system are approximately \$450-650 m^{-2} of usable plot area under effective CO_2 control.

Cotton grown under CO_2 enrichment showed significant increases in biomass accumulation, both above ground and below ground. Soil respiration also increased in CO_2 enriched plots. Enriched plants matured earlier and, in general, had greater agronomic yields. Water use efficiency increased with CO_2 enrichment.

The FACE system as reported here has had two years of successful biological experimentation. Results from these experiments are intended for use in evaluating both the effects of CO_2 on plants and ecosystems, and on the feedback processes operating between the biosphere and atmosphere that are the primary, short-term regulators of atmospheric CO_2 concentrations.

IX. ACKNOWLEDGMENTS

This research has been supported by the Carbon Dioxide Research Program of the U.S. Department of Energy, Environmental Sciences Division.

REFERENCES

1. Drake BG, Leadley PW, Arp WJ, Nassiry D, Curtis PS (1989) An opentop chamber for field studies of elevated atmospheric CO_2 concentration on saltmarsh vegetation. Functional Ecology 3:363-371

2. Grahm RL, Turner MG, Dale VH (1990) How increasing CO_2 and climate change affect forests. BioScience 40:575-587.

3. Hendrey GR, Lewin KF, Lipfert F, Kolber Z, Daum M (1988a) Free-air carbon dioxide enrichment (FACE) facility development: I. Concept, prototype design and performance. BNL-42338, Brookhaven National Laboratory, Upton NY 11973, 36 pp.

4. Hendrey GR, Lewin KF, Kolber Z, Daum M (1988c) Control of ozone concentrations for plant effect studies. BNL 43589. Brookhaven National Laboratory, Upton, NY 11973. 38 pp.

5. Hendrey GR, Lewin KF, Nagy J (1992) Free air carbon dioxide enrichment: development, progress, results. Vegetatio (in press).

5. Idso SB, Kimball BA (1991) Doubling CO_2 triples growth rate of sour orange trees. DOE Research Summary 13. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, Oak Ridge TN. 4pp.

6. Lawlor DW, Mitchell RAC (1991) The effects of increasing CO_2 on crop photosynthesis and productivity - a review of field studies. Plant, Cell and Environment 14:807-818.

7. Lipfert F, Alexander Y, Hendrey GR, Lewin KL (1992) Application of free-air CO_2 enrichment (FACE) technology to a forest canopy: A simulation study. BNL-47392. Brookhaven National Laboratory, Upton, NY 11973.

8. Post WM, Peng T-H, Emmanuel WR, King AW, Dale VH, DeAngelis DL (1990) The global carboncycle. American Scientist 78:310-326.

9. Strain BR, Cure JD (1985) Direct effects of increasing carbon dioxide on vegetation. DOE/ER-0238, U.S. Department of Energy, Washington DC. 286 pp.

10. Woodwell GM (1978) The carbon dioxide question. Scientific American 238:34-43.

FIELD TECHNIQUES FOR EXPOSURE OF PLANTS AND ECOSYSTEMS TO ELEVATED CO_2 AND OTHER TRACE GASES

Leon Hartwell Allen, Jr.
U.S. Department of Agriculture
Agricultural Research Service
University of Florida
Gainesville, FL 32611-0840

Bert G. Drake
Smithsonian Environmental Research Laboratories
P.O. Box 28,
Edgewater, MD 21037

Hugo H. Rogers
U.S. Department of Agriculture
Agricultural Research Service
Auburn University
Auburn, AL 36831

Joseph H. Shinn
Lawrence Livermore National Laboratory
Livermore, CA 94550

I. INTRODUCTION

Carbon dioxide (CO_2) concentration of the atmosphere has varied considerably over geological time. Ice core data from the USSR Vostok Station showed that the Earth's atmospheric CO_2 ranged from as low as 180 to 200 μmol mol^{-1} during the last two glacial maxima (13,000 to 40,000 and 130,000 to 160,000 years before present, Barnola *et al.* 1987). However, following the rapid glacial melting, the concentration rose quickly to about 260 to 270 μmol mol^{-1}. Since around 1700 AD, the CO_2 concentration has increased from about 270 μmol mol^{-1} to 315 μmol mol^{-1} in 1958 and 355 μmol mol^{-1} in 1991.

Recognition of the importance of CO_2 for photosynthesis and growth of green plants had a long period of development during the 18th century (review by Krikorian 1975). Stephan Hales showed that wood could generate many times its volume of air. Joseph Priestley first recognized that the action of green plants could reverse the process of animal respiration and of combustion. Jan Ingenhousz elaborated further the findings of Priestley. However, these early workers were more interested in the uptake of oxygen than in the uptake of CO_2.

The importance of CO_2 for growth of green plants became clear during the early 19th century. According to de Saussure (1804), peas exposed to 8% CO_2 grew better than those in ambient air. The effect of the concentration of CO_2 (as well as light and temperature) on photosynthesis of green leaves was quantified by Matthaei (1904) and Blackman and Matthaei (1905).

behavior of small particles of matter (Downs 1980). A major advantage of the phytotron is that multiple chambers or rooms may be used to create matrices of environmental variables. A matrix of three CO_2 concentrations and three temperatures, for example, requires the use of nine growth rooms. With only two chamber replicates of each condition, this experiment would require 18 growth chambers. Within each growth room, subcells of light intensity or quality, soil nutrients or water status, or certain other environmental manipulations are possible. Separate rooms are needed for each photoperiod or thermoperiod, but if plants are grown on wheeled carts that may be moved from room to room, the number of environmental variables can be greatly increased. Few plant laboratories have such extensive plant growth facilities.

Carlson and Bazzaz (1980) reported competition experiments in which they used inexpensive growth chambers on wheels. These chambers were small enough for artificial lighting, but mobile so that they could be moved into the greenhouse for use with natural light. Thus they combined some of the best features of growth cabinets, namely, environmental control, with relatively high photosynthetic photon flux density as may be found in a greenhouse. The growth chambers were developed to house experiments to study the effects of various gases, including CO_2, on plants grown under several conditions.

Naturally sunlit crop growth chambers based on "closed-loop", air circulation systems with computer-managed environmental controls, such as those developed at Florence, South Carolina (Phene *et al.* 1978; Baker *et al.* 1982) and at Gainesville, Florida (Jones *et al.* 1984a; 1984b) have proven very useful for detailed crop studies. These units are sometimes referred to as SPAR (Soil-Plant-Atmosphere Research) chambers. At Clemson University, Mississippi State University, and the University of Florida, these systems have been used for short- and long-term experiments on responses of cotton, maize, soybean, wheat, citrus, tomato, and rice to CO_2-enriched atmospheres. Subambient levels of CO_2, spanning concentrations that existed during the previous ice age 15,000 to 40,000 years before present, have been studied at Gainesville using soybean (Bisbal 1987; Allen *et al.* 1990a; 1991) and rice (Baker *et al.* 1990a; 1990b; 1990c). These systems, because they are closed, lend themselves to the study of water use and water-use efficiency by crop species as a function of temperature, humidity, and CO_2 concentration throughout diurnal cycles and throughout the season (Jones *et al.* 1985a; 1985b; 1985c; Allen *et al.* 1985b). The chambers are divided into two parts, an upper plant canopy chamber and a lower root zone compartment in which soil water content, water use, and root growth can be measured. The upper chambers are covered with clear glazing, allowing plant exposure to sunlight, and the root compartments are deep enough to allow a more field-like rooting volume than pots can provide.

Interactions of CO_2 concentration with other variables, especially temperature, vapor pressure deficit, and soil water content, have frequently been studied at Gainesville and at Mississippi State. Rhizobium nitrogen fixation of soybean as a function of CO_2 treatment was investigated at Clemson University (Reardon *et al.* 1990).

Greenhouses offer at least partial control over the vagaries of the weather outside and enable an additional crop to be grown in the wintertime in climates where none would be possible in field plots. Only in greenhouses has it been economically practical to use CO_2 enrichment to increase the productivity of crops, and in cooler climates, such as the northeastern United States, it is a

recommended horticultural practice (Wittwer and Honma 1969). Numerous CO_2 enrichment studies have been conducted in greenhouses since the beginning of the 20th century. Kimball (1983a, 1983b) reviewed over 140 reports and extracted more then 770 observations of the yields or biomass production with CO_2 enrichment of 56 plant species. The majority of these data were obtained from studies conducted in greenhouses. Kimball's analysis of these disparate data indicated an average 36% increase of the weight of crop yield for a doubling of CO_2, which shows that CO_2 enrichment is indeed very beneficial to the greenhouse industry.

A new application of the use of greenhouses was tried by Oechel and coworkers (Prudhomme *et al.* 1984; Oechel and Strain 1985; Tissue and Oechel 1987), who designed small greenhouses capable of tracking ambient temperature and humidity while maintaining setpoint CO_2 concentration to study the effect of elevated CO_2 on Arctic tundra. The computer control feature of SPAR systems would easily permit them to track ambient CO_2 concentrations, air temperature, and humidity (as long as the ambient air humidity is well below saturation), although they have been used mainly to follow preprogrammed setpoints rather than setpoints of the changing atmospheric environment.

Open-top field chambers as described by Heagle *et al.* (1973, 1979; 1989) Buckenham *et al.* (1981), Ashenden *et al.* (1982), and Hogsett *et al.* (1985) have had extensive use as plant exposure units both in air pollution and in CO_2 effects studies in the field. These systems have been used to expose potted plants, annual crops, and trees to a variety of aerial pollutants and CO_2, and they are currently in use at a number of laboratories in North America and Europe. Hardy and Havelka (1975) first used a square-wall, open-top enclosure to expose soybeans to atmospheres enriched with CO_2 for the purpose of studying the effect of increased photosynthate production on symbiotic nitrogen fixation. Rogers *et al.* (1983b) adapted the basic cylindrical open-top chamber system to generate large-scale CO_2 test atmospheres in the field. Kimball *et al.* (1983) and Nakayama and Kimball (1988) used a square-wall, open-top chamber with 0.2 m diameter perforated polyethylene ducts between rows of cotton. Drake *et al.* (1989) developed an open-top chamber system for CO_2 enrichment of saltmarsh vegetation that recirculated part of the input air. Computerized control and data acquisition systems have been developed (e.g., Nystrom *et al.* 1982; Weigel and Jäger 1988b; Mejer *et al.* 1988).

The need to study CO_2 effects on vegetation in a natural field environment has led to the concept of artificially elevating CO_2 by release through an array of pipes. The history of this free-air CO_2 enrichment (FACE) approach can be traced to studies by crop scientists (Kretchman 1969; 1970; Baker *et al.* 1970; Allen 1973; Harper *et al.* 1973a; 1973b; 1973c; Baker and Lambert 1980). Field experience with this method is reported in the thesis studies of Harper (1971) and Allen (1973), and technical aspects were extensively reviewed by Allen (1979).

The FACE approach had much in common with methods developed by air pollution ecologists. A grid release system to study air pollutant effects in vineyards for the French Ministry of Agriculture was described by de Cormis *et al.* (1975). The U.S. Environmental Protection Agency Zonal Air Pollution System (ZAPS) released air pollutants through a pipeline network in a prairie grassland (Lee and Lewis 1975; Lee *et al.* 1978). The U.S. Department of Energy's Argonne National Laboratory developed its own ZAPS capability (Miller *et al.* 1980), as

did the University of British Columbia, Canada (Runeckles *et al.* 1981; 1990), the University of Nottingham School of Agriculture, U.K. (Greenwood *et al.* 1982), and the U.K. Central Electricity Research Laboratories (McLeod *et al.* 1983). A related open-air fumigation system to provide linear gradients of exposure to a pollutant with air exclusion methods was designed by Shinn *et al.* (1977) and modified by Laurence *et al.* (1982) and by Reich *et al.* 1982). McLeod and Fackrell (1983) and McLeod and Baker (1988) reviewed methods of open-air fumigation.

The topic of "methods for exposure of plants and ecosystems to elevated CO_2 and other trace gases" was discussed thoroughly by Drake *et al.* (1985) and by Weigel and Jäger (1988a). This current chapter is an update of the earlier contribution to a U.S. Department of Energy report prepared by Drake *et al.* (1985). The main advances have been in the new, emerging technology of free-air CO_2 enrichment (FACE).

II. LEAF CUVETTES

There are so many cuvette designs for single-leaf gas exchange measurements that an exhaustive discussion of advantages and problems of each one is beyond the scope of this chapter. Representative examples of different cuvette designs developed during the past three decades can be found in Musgrave and Moss (1961); Mooney *et al.* (1971); Šesták *et al.* (1971); Bingham and Coyne (1977); Sinclair *et al.* (1979); DeJong *et al.* (1981); Field *et al.* (1982); Huck *et al.* (1983); and Valle *et al.* (1985a; 1985b).

The major design problem of leaf cuvettes is the same as for whole-plant growth chambers, namely, how to control the environment around the leaf. Thus, a leaf cuvette for measuring gas exchange is only one part of a system which can be subdivided into (1) control of gas composition and the environment around the leaf, (2) measurement of various physical parameters such as changes in gas concentrations, and (3) collection and evaluation of data. Bloom *et al.* (1980) discuss the effects of materials on water vapor and CO_2 in the gas-exchange circuit. In recently developed systems for use outdoors (e.g., Sinclair *et al.* 1979; Field *et al.* 1982; and Valle *et al.* 1985a; 1985b) computers have been used in mobile field laboratories to integrate all subsystems as well as to manage data and provide either machine-readable or hard copy of results.

The simplest leaf cuvette systems have measured only CO_2 assimilation. Water vapor loss and CO_2 assimilation, however, must be measured simultaneously to make the analysis of data required to evaluate separately the effect of elevated CO_2 treatment on the supply of CO_2 through stomata to intercellular spaces and the biochemical responses of photosynthesis. Von Caemmerer and Farquhar (1981) have summarized the necessary calculations, a discussion of the physical aspects of gas exchange in leaves can be found in Šesták *et al.* (1971), and the interpretation of gas analysis data is discussed by Sharkey (1985).

Cuvette systems for measuring gas exchange between the leaf and its environment are either open or closed. In flow-through, open-exhaust systems, air of known composition passes once over the leaf, and the change in CO_2 and water vapor concentration caused by the leaf is determined. In closed-circulation systems, air is stirred continuously around the leaf, and CO_2, water vapor, and other variables of interest are controlled by compensation for exchange between the leaf and the surrounding air. Single flow-through systems

may ultimately be the simplest to design and control, but they require a high degree of sensitivity in measurement of CO_2 concentration and dewpoint temperature. For example, to determine the flux of CO_2 across the epidermis, Sinclair *et al.* (1979) used a flow-through cuvette system with an IRGA to measure the drop in CO_2 concentration of air as it passed over the leaf. In closed systems, a null-balance approach is used, and the change in concentration of water vapor and CO_2 in the chamber is determined from the rate of injection of water vapor and CO_2 required to maintain a set point concentration. Field *et al.* (1982) used a closed system and measured the change in pressure across an injection capillary required to maintain CO_2 concentration within the chamber at a set point which was measured by a gas analyzer used in absolute mode.

The leaf gas exchange system (Figure 3-1) described by Sinclair *et al.* (1979) would be well adapted for use in studies of the effect of prolonged exposure to elevated CO_2 levels on photosynthesis, although it was not used for that purpose. This system was used in field studies to track environmental temperature, humidity, and solar radiation, as well as to measure continuously both water vapor and CO_2 exchange of up to 39 cuvettes concurrently.

The leaf cuvette consisted of two disks of clear Teflon[1] separated by a pair of chrome-plated brass rings. The leaf was inserted between rows of monofilament line on each ring. Leaf temperature was controlled so as to track ambient temperature by passing the air supply line through a water jacket in the rim of the chamber. In the study of Sinclair *et al.* (1979), the effect of the chamber on the plants was evaluated on leaves enclosed in the chamber for 6 weeks. There were no visually apparent effects of the chamber nor were there any effects detected in the data on the photosynthetic response when compared with data obtained on neighboring leaves that were of similar age but which had grown outside the chamber. However, leaves inside the chamber did not have insect damage, and senescence was delayed compared with other leaves in the same canopy. Sinclair and Allen (1982) and Sinclair *et al.* (1983) used this system for studying response of citrus to environmental variables.

A system similar to the one employed by Sinclair *et al.* (1979) was used by Valle *et al.* (1985a; 1985b) and Allen *et al.* (1990b) for studying long-term responses of soybean (Glycine max [L.] Merr., cultivar Bragg) leaves to elevated CO_2. The cuvettes were used to measure photosynthesis and gas exchange in up to 12 leaves of plant canopies that were being grown in elevated CO_2 in outdoor, sunlit controlled-environment chambers. Managing a leaf gas exchange system with cuvettes mounted inside large (but not walk-in) outdoor plant growth chamber systems is much more difficult than managing cuvettes outdoors.

III. CONTROLLED ENVIRONMENT CHAMBERS FOR WHOLE-PLANT CANOPIES

A. Phytotrons

Integration of environmental control systems and a broad spectrum of controlled environmental variables distinguish phytotrons from greenhouses or

---

[1]Teflon is a registered trademark.

adjust circulation patterns. Air temperature in the chambers was regulated by passing the circulated air around a 600 W heating element and through expansion coils of a refrigeration system. Plants humidify the air rapidly, so humidity control was achieved by condensing moisture from the air.

Pure commercial CO_2 was metered into the chambers to elevate normal ambient CO_2 concentration to the level desired, and air was sampled from the chambers through a system of valves and flowmeters. CO_2 concentration within each chamber was controlled individually. When lamps and sunlight were used together, the plants could be supplied with 2000 μmol m^{-2} s^{-1} photosynthetic photon flux density.

C. Continuous-flow Stirred Tank Reactors

A widely used plant exposure chamber system in air quality and gas kinetics work (i.e., uptake by and release from plants) is the continuous stirred tank reactor or CSTR (Rogers *et al.* 1977). The unique feature of this chamber technique is that it provides direct kinetic data, as well as a uniform and readily characterizable environment. A CSTR system for continuously monitoring not only pollutant uptake, but also transpiration, photosynthesis, and respiration has been developed recently (Marshall and Ferman 1988). This system incorporated improved control technology compared to previous CSTR systems used for air pollutant studies (Heck *et al.* 1979). Although used mostly indoors, CSTR systems could be adapted for outdoor use.

D. Outdoor, Sunlit Controlled-Environment Chambers

Sunlit controlled-environment chambers based on "closed-loop" air circulation systems with computer-managed environmental controls were developed in the late 1950s and early 1960s. These chambers usually had Mylar[3] polyester film walls. Nondispersive IRGAs allowed rapid measurement of CO_2 concentration, and these analyzers in combination with metered CO_2 allowed direct and continuous measurement of photosynthetic CO_2 exchange rates. Transpiration rates were measured by collecting condensate from air conditioning cooling coils. These chambers were used successfully for measuring photosynthesis and transpiration as a function of CO_2 concentration, light, temperature, and soil moisture conditions (e.g., Musgrave and Moss 1961; Moss *et al.* 1961; Baker and Musgrave 1964, Egli *et al.* 1970). These systems were the predecessors to the units with large controlled root-zone containers as well as canopy-zone chambers (Phene *et al.* 1978; Parsons *et al.* 1980; Baker *et al.* 1982), which have been further modified for improved systems for CO_2-effect studies (Jones *et al.* 1984b; Acock *et al.* 1985b).

Details of the design, functioning, and use of these recently improved chambers have been reported by Jones *et al.* (1984a; 1984b; 1985a; 1985b; 1985c). A sketch showing the overall layout of this system is shown in Figure 3-2. This system was based on the original SPAR (soil-plant-atmosphere-research) units reported by Phene *et al.* (1978) and Parsons *et al.* (1980).

---

[3]Mylar is a registered trademark.

These SPAR chambers were designed to provide accurate, flexible control of dry-bulb temperature, CO_2 concentration, and humidity of the canopy air, as well as control and measurement of soil water and root conditions. In contrast to open flow-through systems, the air in SPAR systems was monitored and controlled. Specific methods and equipment for controlling chamber conditions varied, but were generally based on (1) sensors that measured temperature, CO_2, and humidity (e.g., copper-constantan thermocouples, IRGAs, and dewpoint hygrometers, respectively), (2) feedback mechanisms such as thermostats or loops in computer logic that compared sensed with desired conditions; and which (3) actuated control devices such as heaters that were regulated to produce the desired temperature treatment conditions, CO_2 injection valves for replacing CO_2 as it was used in photosynthesis, and cooling-coil flow-valves for regulating dewpoint temperature.

Air in these SPAR chambers was circulated through the canopy from top to bottom and then out through ducts, where the air was reconditioned before flowing back into the canopy chamber. Sensors, air sampling ports, and control devices were located within the ducts so that the air circulated to the top of the canopy had the experimentally prescribed setpoints of temperature, CO_2 concentration, and humidity level. Measurement of plant canopy response in a closed chamber system was directly linked to the control of chamber conditions. Changes in CO_2 and humidity levels within the chamber were driven by canopy CO_2 and H_2O gas exchange processes. Thus, except during occasional operational problems such as excessive condensation in sampling lines or on chamber walls (during cold winter events) or failure of air sampling pumps, successful control actions provided a mirror image of canopy net photosynthesis and transpiration, and the operation of a closed chamber system implicitly provided measurements of canopy response.

Each SPAR chamber described by Jones *et al.* (1984b) consisted of an acrylic plastic top 2.0 by 1.0 m in cross section by 1.5 m tall (volume, 3.0 m^3) secured to a 1.0-m-deep steel lysimeter filled with a fine sand soil. For single mainstem crops like soybean, the soil compartment could be sealed from the aerial compartment by growing the plants through slits in the floor, and filling those slits with closed-cell foam as soon as the plants were large enough. However, other similar systems may vary in size and in the rooting medium (e.g., Acock *et al.* 1985b). The SPAR systems were designed with deep rooting volumes to prevent the plants from becoming "root-bound". However, when these systems were used for studying paddy rice, the depth of the flooded vats were reduced to 0.6 m (Baker *et al.* 1990a; 1990b; 1990c). Because of the growth habit of rice (tillering), the soil compartment could not be sealed from the aerial compartment.

The SPAR chamber system described by Jones *et al.* (1984b) provided measurements of canopy photosynthetic CO_2 exchange rate and transpiration rate at 5-min intervals. Air samples from each chamber were analyzed for CO_2 on a 5-min cycle. Quantitative carbon balance was computed from the amount of CO_2 injected during each 5-min interval adjusted for the change in chamber CO_2 concentration from the beginning to the end of the 5-min period. If the concentration increased slightly, then the photosynthetic rate based on CO_2 injection was adjusted downward, and vice versa. The amount of CO_2 injected during each 20-s interval within the 5-min period could be adjusted based on measured incoming solar radiation. This frequent adjustment of CO_2 injection provided an accurate control of CO_2 to the setpoint. Transpiration was obtained from a tipping bucket raingauge measurement every 5 min. The design of SPAR

chamber systems for continuous, ongoing measurements of photosynthetic rate and transpiration rate, coupled with their computer setpoint controls, provides unique research capabilities and opportunities for investigating interactions of CO_2 with temperature, humidity, and solar radiation effects on photosynthesis, water use, growth, and productivity of plants.

Recent experiments using sunlit controlled environment chambers have focused on short- and long-term effects of elevated CO_2 on soybean growth and yield, photosynthesis, transpiration, and water-use efficiency (Jones *et al.* 1984a; 1985b; Allen *et al.* 1985b), as well as on interactions between elevated CO_2 concentrations and temperature (Jones *et al.* 1985a) and a moisture stress (Jones *et al.* 1985c). These are examples of the types of direct CO_2 effects and coupled climate or soil-water interactions that can be obtained in sunlit controlled environment chambers. These systems offer a high level of environmental control with a reasonable approximation to field sunlight and soil conditions. Yields of crops grown in SPAR systems (such as soybean and rice) have been very similar to crops grown outdoors in other experiments. Direct comparisons with outdoor crops are not usually possible, especially when the chambers are operated with fixed setpoints of temperature and humidity.

E. Field Tracking Chambers

The small, field tracking chamber used in studies of Arctic ecosystems (Prudhomme *et al.* 1984; Tissue 1984; Oechel and Strain 1985; Tissue and Oechel 1987) had a 127-mm (0.5-in) polyvinyl chloride tubing frame covered with 0.8-mm clear plastic sheeting sealed to a galvanized sheet-metal frame, which was sunk 10 to 15 cm into the soil (Figure 3-3). The chamber enclosed a surface area of 1.65 m^2. Carbon dioxide concentrations inside the enclosure were continuously monitored and maintained at 340 μmol mol^{-1} CO_2, representing ambient, or at an elevated level of 680 μmol mol^{-1}. Concentrations were maintained by either adding pure CO_2 gas or scrubbing the chamber air through soda lime.

Air temperature within the chamber was maintained at the desired ambient levels. A temperature controller set to track ambient air temperature activated a compressor unit connected to a heat exchanger inside the chamber. The fans inside the chamber operated continuously to ensure adequate mixing of the air and CO_2. The entire system was powered by a 6.5 kW generator. Temperatures of the air, moss surface, Betula nana leaves and Eriophorum vaginatum stem base, and the soil at 2-cm and 10-cm depths both inside and outside the chamber were measured using thermocouples.

The mass of CO_2 going into the chamber was calculated from the flow rate and the time that CO_2 was injected. The mass of CO_2 removed was calculated based on volume of air removed, its CO_2 concentration, and the length of time that the chamber air was scrubbed. The difference between the mass of CO_2 injected and that removed to maintain setpoint ambient or elevated CO_2 levels in the chamber was the net carbon uptake by the community. This measure was expressed as community production as CO_2 exchanged per square meter per day.

The field tracking chambers are actually a subset of the outdoor, sunlit controlled environment chambers. They are very similar to SPAR chambers, except the field tracking chambers were used over natural vegetation whereas the SPAR chambers included a large contained, controllable soil volume.

IV. GREENHOUSES

Greenhouses are structured frames covered with nearly transparent glazing such as glass, fiber glass, polyvinyl chloride, acrylic, polycarbonate, or polyethylene. Because they are manufactured by numerous commercial firms, they are relatively inexpensive compared with custom-built, one-of-a-kind structures. Although constant temperatures are not maintained, greenhouses are usually equipped with heaters and ventilation systems (forced or natural, evaporatively cooled or not) to prevent excessively low or high temperatures. Controls have various degrees of sophistication, but generally provide separate day and night minimum temperature set points to control the heater and a maximum temperature set point to turn on the ventilation. Humidity is usually not controlled, except possibly for some nighttime ventilation at flow rates much smaller than are used for daytime temperature control. Artificial light is generally not used except for the control of photoperiod using low-intensity incandescent light.

Kimball (1983a) listed ways that greenhouse environments differ from the open field and Kimball (1986b) reviewed data available from the literature on the interactions of CO_2 enrichment effects with several environmental variables. The most obvious difference between greenhouse and open field environments is that temperatures can be modified in the former, usually with gas burners for heating or evaporators for cooling. As in the commercial industry, this feature allows experiments to be done during seasons when it is too cold for crops to grow outside. Furthermore, CO_2 appears to stimulate plant vegetative growth more at the higher ranges of temperatures over which plants are normally grown than at the lower ranges (Allen SG *et al.* 1990).

Another difference between the environment inside a greenhouse and that outside is the considerably lower light intensity inside. Greenhouse coverings typically transmit two-thirds to three-fourths of the available sunlight. Also, greenhouse experiments are often conducted during winter when light levels are only one-third to one-tenth of summer open-field intensities. From theoretical consideration of CO_2 effects on photosynthesis, Kimball (1986b) concluded one could expect stimulation of growth by elevated CO_2 compared with growth at present ambient CO_2 concentration at very low and very high light levels with a midrange minimum. Actual observations of growth and yield of CO_2-enriched plants at a range of light intensities did not exhibit any definite discernible pattern within experimental variability (Kimball 1986b). To a first approximation, greenhouse results should apply to the field, but the available data do not support that prediction.

Greenhouses generally have higher humidity and lower windspeed than outside. Thus, greenhouse crops can generally be described as having grown under a milder environment with respect to water relations, and they often appear more luxuriant than their shorter, thicker leaved, field-grown counterparts. In his review, Kimball (1986b) concluded that most of the previous experiments on the interaction between CO_2 and water stress showed that the stimulation of plant growth with CO_2 enrichment was as large or larger under water stress conditions as it was under well-watered conditions at present normal ambient CO_2 concentration. Thus, from a water relations standpoint, one could expect responses in the field to be as large as or larger than in a greenhouse. Soil moisture depletion studies can be done in a greenhouse, but the control of the development of tissue water stress is difficult. When large soil volumes are

used, stress may develop more slowly than in the field. In small containers, however, stress may develop more rapidly than in the field. Because the wind flow, radiation regime and humidity are generally different than in the field, it is particularly difficult (and the uncertainty is large) to extrapolate greenhouse water-use measurements to the field situation. Most of these comments apply to salinity stress as well (Kimball 1986b).

Because most of the prior CO_2-enrichment experiments in greenhouses were conducted using nonlimiting nutrient levels, conclusions based on them probably do not apply to the nutrient-limited unmanaged biosphere. Low nutrient level was the only environmental restraint that appeared to generally limit the relative response of plants to CO_2 enrichment (Kimball 1986b). Future farmers will need to adjust fertilizer rates to take advantage of the stimulation of yield by the increased atmospheric CO_2.

The economics of research are not the same as those of horticultural production. For research purposes, expensive refrigeration may be justified to control temperature (and even humidity) of closed, CO_2-enriched greenhouses and growth chambers. Alternatively, injecting large amounts of CO_2 during ventilation of greenhouses may also be justified. This approach uses much CO_2 but little electrical energy. Furthermore, Monteith *et al.* (1983) controlled greenhouse temperatures easily in the United Kingdom as long as they were above outside temperatures, and maintained CO_2 by controlled injection.

V. OPEN-TOP VENTILATED CHAMBERS

Air flow properties around open-top ventilated chambers, particularly near the large opening at the top of the transparent walls, has been an ongoing concern in the development and use of this field technique for exposure of plants to CO_2 or gaseous air pollutants. Ordway (1969) provided an aerodynamicists qualitative analysis of the "Odum Cylinder" approach to measurement of CO_2 exchange in a forest (Odum and Jordan 1970). Ordway pointed out several actual and potential problems with a cylindrical chamber. First (from mean-flow hydrodynamics), a vortex would form near the base of the chamber on the upwind side and coil around both sides of the chamber, forming a horseshoe-shaped vortex when viewed from above. Second, a nonuniform penetration and entrainment of air into the opening at the top would be expected, which could lead to uneven mixing and a nonuniform concentration distribution of gases (e.g. CO_2). Third, Ordway pointed out that air flow through the vegetation would be unnatural. Ordway (1969) failed to point out the importance of atmospheric turbulence or gustiness on the penetration of eddies into the top of the chamber. The concerns about turbulent exchange in and out of the top of the cylinders, as opposed to strict mass flow incursions, led to several wind-tunnel evaluations of open-top chambers. These wind tunnel studies were conducted with and without baffles or constrictions at the top to reduce the incursion of ambient air (Davis and Rogers 1980; Davis *et al.* 1983). Baldocchi *et al.* (1989) designed a wind tunnel study to measure flow in and out of cylindrical chambers located in a scaled-down model forest. These wind tunnel scale chambers had various top size openings (25%, 50%, and 75%) with frusta having 30, 45, and 60° angles of elevation. In the wind tunnel conditions, little incursion of air occurred when the percentage opening was only 25%. Incursion of air from above increased with increasing angle and increasing opening of the frustum. Baldocchi *et al.* (1989) concluded

that decreasing the size of the open top and decreasing the angle of the frustum would minimize turbulent incursion losses through the outlet of open-top chambers.

L.H. Allen (unpublished) found that air flow through an open-top chamber could be influenced greatly under high windspeed conditions. When high wind gusts were directed toward the intake of fans of an open-top chamber such as illustrated in Figure 3-4, mass flow into the open-top chamber would be increased. The variability of flow through the open-top chambers under windy conditions was greatest when the filter density (filter resistance) was lowest.

Open-top chambers have ranged in size from the very unwieldy Odum Cylinder (18 m diameter x 20 m height) to the very useful and practical chamber (0.8 m diameter x 1.0 m height) used in saltmarsh vegetation (Drake *et al.* 1989). Few measurements of actual performance in the field have been made, and those may vary considerably depending on the size and shape of the structure. Chapter 9 of this volume documents enriched CO_2 concentration and air flow measurements within three types of open-top chambers.

The open-top chamber used by Rogers *et al.* (1983a; 1983b; 1983c; 1984a; 1984b) was an open-ended, transparent cylinder roughly 3 m in diameter by 2.4 m high (Figure 3-4). A high rate of ventilation was assumed to keep the inside temperature and humidity close to those of the outside air. When air in the chamber was mixed with fresh air at normal ambient CO_2 concentration blowing over the top of the chamber, it was difficult to maintain a desired concentration near the top of the plant canopy. Accordingly, a frustum was added to the top of the chamber (Figure 3-4) which reduced the size of the top opening to one-half of the ground area inside the chamber (Rogers *et al.* 1984a). The chambers consisted of a structural aluminum frame covered by panels of clear polyvinyl chloride plastic film. The bottom panel was doubled-walled; the inside wall was perforated by 2.5-cm holes to serve as a duct to distribute the CO_2-air mixture uniformly into the chamber. Air to this duct was supplied from an axial fan mounted in a sheet metal plenum box with a particulate filter. Pure CO_2 was injected into the plenum box ahead of the fan to ensure thorough mixing.

The open-top chamber system performed well in generating and maintaining large-scale test atmospheres in the field and presented no major difficulties once in place. Provisions for delivery of large amounts of liquid CO_2 and electrical power needs were solvable problems. The liquid CO_2 receiver was the best method to store and supply the large quantities of CO_2 (1×10^6 g d^{-1}) needed for a study of approximately 35 chambers. Good separation of treatment CO_2 concentration was obtained for each treatment level up to and even higher than 600 μmol mol^{-1} above ambient. Ambient CO_2 levels and levels inside chambers with no added CO_2 were virtually the same.

A small open-top chamber system (1.0 m in height and 0.8 m in diameter) with a recirculation mixing blower has been used for measurement of CO_2 effects in salt-marsh vegetation since 1986 (Curtis *et al.* 1989a; 1989b; 1990; Drake *et al.* 1989; 1990; Long and Drake 1991; and Leadley and Drake 1992). These studies have shown that a C_3 sedge responded to elevated CO_2, 660 vs 350 μmol mol^{-1}, with increased growth, increased shoot densities, and reduced green shoot % N with unchanged % C (which resulted in a 20 to 40% increase in the shoot tissue C/N ratio). However, litter C/N was unaffected. Root dry mass increased 83% over a two-year period. No evidence for decreased acclimation in photosynthetic capacity that would counteract CO_2 stimulation was found. No effect of elevated

CO_2 on Spartina patens or Distichlis spicata (C_4 grasses) was found. Chamber effects *per se* on plant response was not very noticeable. In contrast, soybean has been observed to show chamber effect responses (Rogers *et al.* 1984a; 1986; Acock *et al.* 1985a).

There have been a number of studies that have evaluated the microenvironment within open-top chambers and how it differs from that of unenclosed crop canopies (Heagle *et al.* 1973, 1979; 1989; Mandl *et al.* 1973; Kats *et al.* 1976; Shinn *et al.* 1976; Heck *et al.* 1979; Olszyk *et al.* 1980; Thompson 1981; Weinstock *et al.* 1982; Unsworth 1984a, 1984b; Last 1986; Fangmeier 1986; Unsworth 1986; Adaros *et al.* 1989a; Drake *et al.* 1989; Flesch and Grant 1992). With respect to temperature, some report that air temperature within the canopy of plants inside the chamber does not differ from air temperature in the canopy of plants not enclosed by the chambers. Kats *et al.* (1976) found no difference up to 38°C; Heagle *et al.* (1979) found less than 1°C difference; Mandl *et al.* (1973) found no difference greater than 1°C over the range of 16° to 29°C; and Olszyk *et al.* (1980) found no difference greater than 2°C. Heagle (1989) reported mean chamber air temperatures to be 0.6, 2.2, and 2.8°C above ambient on cloudy, cold days, on partly cloudy, cool days, and on sunny, warm days, respectively. Drake *et al.* (1989) reported that night-time temperatures in their salt-marsh chambers were 2°C higher than outside because of heat from blowers. Air temperatures were generally from 1.2 to 2.7°C higher in chambered vegetation in the daytime, particularly in a Scirpus olneyi (C_3) community. Air speed was variable, ranging from 1.6 to 0.1 m s^{-1}. Average air speeds in other larger open-top chambers have been reported from 0.3 to 0.8 m s^{-1} (Heagle *et al.* 1979; Olszyk *et al.* 1980; Weinstock *et al.* 1982). Flesch and Grant (1992) reported that air speed ranged from 0.28 to 1.33 m s^{-1} and turbulent intensity ranged from 0.15 to 0.61 in their open-top chamber measurements. Musselman *et al.* (1986) reported average daytime chamber and ambient air temperatures of 26.2 ± 1.6 and 23.7 ± 1.8°C, respectively, for a closed-top ventilated field chamber, with temperatures at various locations being within 1 to 1.5°C of each other. Nighttime temperatures were usually 1 to 2°C warmer inside the chamber. Fangmeier *et al.* (1986) measured diurnal cycles of temperature and found the values to be about 1°C higher inside open-top chambers than outside near midday. Adaros *et al.* (1989a) found a maximum rise of air temperature in their open-top chambers to be 3.6 and 1.4°C under day and night conditions, respectively, but daily mean temperature increases were only 1°C. During the winter period, barley was observed to survive in open-top chambers, but not in the open air (Adaros *et al.* 1989b).

Solar radiation is attenuated by the walls of the chamber. Olszyk *et al.* (1980) found a reduction of photosynthetically active photon flux density of 10.3%; Heagle *et al.* (1979; 1989) reported a reduction of total solar radiation of about 12 to 15%; and Adaros *et al.* (1989a) found irradiance to be decreased by 22 to 28%. Relative humidity within the chambers is higher than it is within the canopy of plants outside the chambers, which results in a reduction in daily water use of significant amounts (Olszyk *et al.* 1980). Fangmeier *et al.* (1986) measured diurnal cycles of relative humidity and found increases to range from nil to about 10%. Relative humidity increased by up to 12% by day and decreased by 15% by night in measurements by Adaros *et al.* (1989a).

Shinn *et al.* (1976) discussed problems associated with maintaining homogeneous pollutant gradients across the chambers, desiccation of some plants, and problems with adequate irrigation. Heagle (1989) found that the ozone

concentration differences at various sampling positions within an open-top chamber were about 0.008 μmol mol^{-1} when the mean concentration was 0.15 μmol mol^{-1}, a 5% maximum difference.

Although solar radiation is attenuated by the largely transparent walls of open-top chambers, the flux density of net radiation inside the chambers is considerably higher than outside in the morning and midday hours. As pointed out by Unsworth (1986), net radiation (Rn) is given by the radiant energy balance equation, Rn = St - r x St + Ld - Lu, where St is downwelling solar radiation, r is canopy reflectivity (assumed to be 0.2), Ld is downwelling long wavelength radiation, and Lu is upwelling long wavelength radiation. Unsworth (1986) provided typical values of these radiant flux densities inside and outside chambers at noon for a cloudless spring or summer day. The values of St, r x St, Ld, Lu, and Rn were 800, 160, 350, 450, and 540 W m^{-2}, respectively, for outside conditions, and 760, 150, 500, 450, and 660 W m^{-2}, respectively, for chamber conditions. The increase in Ld within the chamber thus more than compensates for the decrease of St within the chamber, and results in an increase of Rn of about 20% (Unsworth 1986). Thus, it is primarily the increase of downwelling long wavelength radiation from the walls of the chamber (emitting at near air temperature conditions) that causes increase of foliage temperatures inside open-top chambers. It seems probable that, under similar chamber ventilation rates, temperature increases in comparison to outside conditions would be greatest when emissivity of the wall material is large (transmissivity to Ld is low) and when sky conditions are clear with low water vapor content (which would give low values of Ld of sky radiation). To our knowledge, a detailed study of all these relevant factors has not been conducted for open-top chambers. However, this information may be available in greenhouse energy balance studies (e.g., Kimball 1986a).

Unsworth *et al.* (1984a; 1984b) found the boundary layer resistance of leaves and canopy (to water vapor and O_3 transfer, respectively) of soybean inside the open-top chamber to be similar to boundary layer resistance for soybean crop canopies obtained during the day using micrometeorological methods (Wesely *et al.* 1982). Flesch and Grant (1992) pointed out that greater differences in boundary layer resistances may exist between chamber and field conditions in low air speed spaces of the chambers, or when chamber conditions are compared with field windspeed conditions above 1.8 m s^{-1}. Dunin and Greenwood (1986) compared daily evapotranspiration from a lysimeter containing 6 eucalyptus trees surrounded by a ventilated chamber (open-top, tapered chamber, 11 m in height with 15 x 15 m square base and 2.5 m circular upper outlet). Evaporation determined by inflow-outflow gas analysis was 96% of the lysimeter measurements. During most measurement periods, evaporation was slightly lower (about 7%) than Bowen ratio--energy balance measurements of the surrounding forest. When windspeeds were low (outside), the ventilated chamber evaporation exceeded the Bowen ratio--energy balance measurements by 18%. Similar results were found for evaporation from a lupine crop (Dunin *et al.* 1989), although daily average vapor losses from the ventilated chambers were 5% higher than from the Bowen ratio--energy balance technique, with the largest value being 28% higher. The chambers used in this experiment had tapered entry and exit bays arranged to give a horizontal air flow rather than a vertical air flow. Leuning and Foster (1990) compared transpiration rates of a 7-year-old eucalyptus tree in their ventilated chamber with the Penman-Monteith equation applied to single leaves, and to a leaf energy

budget method. Not surprisingly, the transpiration rates of the ventilated chamber were about 30% lower than that computed by the Penman-Monteith equation for single leaves, probably due to questions of scaling from leaf to whole tree canopy.

Although open-top ventilated chambers appear to provide quite reasonable evapotranspiration measurements, Dunin and Greenwood (1986) point out that their findings may not apply to chambers of different design nor to different vegetation. Also, Dunin *et al.* (1989) point out that inferences in plant control of evaporation can be misleading in chamber experiments. Nevertheless, relative evapotranspiration rates of canopies under different CO_2 treatments should be quite valid.

Do differences observed between the microenvironment of plant canopies inside and outside open-top chambers lead to effects on yield? Mandl *et al.* (1973) saw no significant differences between the rates of germination or the final dry weights of pinto beans inside or outside open-top chambers compared at ambient CO_2 concentrations. Howell *et al.* (1979) reported that yields of plants inside the chambers were sometimes greater than and sometimes less than yields of plants grown outside the chambers. Heagle *et al.* (1979) reported that the chambers often produced plants that were taller than the same species outside the chambers, but that yields were rarely different from crops in the field without chambers around them. Plant height increases inside chambers may be due to the lack of sufficient mechanical stress due to wind gusts (Biddington 1986) or to other factors such as decreased solar radiation (particularly UV-B) or increased humidity. In a later paper they reported no apparent chamber effects for 1979 but a significant effect on mean pod weight in soybean in 1980. Heggestad *et al.* (1980) reported that significant differences were found in approximately 25% of the 24 comparisons made between mean values of biological parameters of snap bean such as height, fresh weight, pod weight, and number of pods of plants grown without chambers around them and plants within open-top chambers, but there was no distinct trend in favor of either group. Olszyk *et al.* (1980) came to a similar conclusion, namely, that differences existed between growth statistics inside and outside the chambers, but they tended to be random rather than systematic. This led the authors to conclude that such differences were not directly attributable to the effects of the chamber on physiological or developmental processes. Weinstock *et al.* (1982) also reported that they could find no differences between physiological processes such as stomatal resistance, transpiration, and water potential or the relationship between physiological and microclimate parameters. Rogers *et al.* (1986) found large chamber effects for soybean. Acock *et al.* (1985a) were not able to successfully match GLYCIM model predictions to chamber-grown soybeans using external micrometeorological data. Olszyk *et al.* (1992) reported that canopy volume of Valencia orange trees (Citrus sinensis [L.] Osbeck) was 104% greater after growth for 51 months in nonfiltered air of open top chambers in comparison with ambient air. Total harvestable fruit for the last 3 years of the study was 98% greater in the chambered treatment than in the nonchambered control. Protection from damaging wind could have contributed to the beneficial effects of chambers on these citrus trees.

Olszyk *et al.* (1986) compared system exposure effects (air exclusion, open-top ventilated field chambers, and closed-top ventilated field chambers) with outside plots during an ozone exposure experiment with alfalfa across the growing season of two years. The air exclusion system itself had no effect on alfalfa

response parameters. Open-top chambers caused lower weights, greater heights, and greater O_3 injury in nonfiltered open-top chambers compared with outside plots during three summer harvests in 1983. However, weights were increased by the open-top chamber for the October 1983 harvest. During 1984, the closed-top ventilated chambers generally increased dry weight and height with respect to both other systems.

Although direct comparisons with simultaneous field plantings of soybean were not made, the leaf size and plant height were generally larger, and mainstem strength generally lower ("viney") than outside plantings in SPAR chamber (Jones *et al.* 1984a; 1985a; 1985b; 1985c). However, morphological characteristics reported by Baker *et al.* (1990a; 1990b) for rice grown in SPAR chambers were similar to field plants reported elsewhere. Curtis *et al.* (1989a) reported a significant chamber effect on biomass of a C_3 saltmarsh sedge, Scirpus olneyi, but not on C_4 saltmarsh grasses or mixed communities. Probably the most extreme example of a chamber effect was reported by Kirkham *et al.* (1990) for closed-top ventilated chambers under rangeland conditions. They found that total aboveground dry weights of tall grass prairie plants grown in their chambers were more than 2-fold greater than weights of outside control plants.

Thus, the conclusion to be drawn is that the climatological differences imposed on plants by chambers can result in either insignificant differences or great differences in growth or yield. The extent of the observed differences are probably related to the natural outside environment under which the plants are being grown (e.g., arid vs. humid, windy vs. calm, hot vs. cold), as well as the species being studied and the chamber system being used.

VI. PORTABLE FIELD CHAMBERS

Rapid, short-term measurements of canopy evapotranspiration was developed by Reicosky and Peters (1977) using a portable field chamber technique. This technique has also been applied to canopy photosynthetic CO_2 exchange measurements in subsequent studies (Boote *et al.* 1980; Ingram *et al.* 1981; Jones *et al.* 1982; Boote and Bennett 1982; Daley *et al.* 1983; Zur *et al.* 1983; Boote *et al.* 1984; Garrity *et al.* 1984; Boote *et al.* 1985; Jones *et al.* 1986; Meyer *et al.* 1987; Albrecht *et al.* 1989). The portable field chamber developed at Gainesville, Florida (Jones *et al.* 1982; Zur *et al.* 1983; Boote *et al.* 1984) had a nondispersive infrared gas analyzer and a mirror-type dewpoint hygrometer for measuring carbon dioxide and humidity (dewpoint temperature), respectively. The portable chamber top was 1.033 m^3 in volume which was formed by an aluminum frame covered with Mylar film. During operation, the chamber was clamped onto a base for measurements over a duration of 1 to 2 min. A 30-cm fan was used to circulate air within the transparent chamber. Air was pumped through 0.6 cm diameter tubing at 8 ℓ min^{-1} for a short distance to the infrared gas analyzer and dewpoint hygrometer located in a small van. Part of the flow (0.8 ℓ min^{-1}) was diverted through the infrared gas analyzer. Output from the two analyzers, along with air temperature (from a copper-constantan thermocouple) and photosynthetically active radiation were recorded on strip-chart recorders. Photosynthetic CO_2 uptake rates and transpiration rates were measured from the slopes of the time rate of change of CO_2 concentration and humidity after the rates had stabilized (15 to 20 seconds after enclosure of the portable chamber). Temperature increases were about +1.5°C per min and CO_2 concentration decreases

were about -60 μmol mol^{-1} per min in this chamber. This technique has also been used for measurements of CO_2 uptake rates and transpiration rates in FACE studies (D.R. Hileman, personal communication).

VII. AIR EXCLUSION SYSTEMS

Air exclusion systems were developed for exposure of crop plants to pollutant gases in the field. These systems were designed to replace the air within the plant canopy with air that had been filtered and enriched with a pollutant to a specified concentration. The essential features are large volume capacity blowers connected to large inflatable air exclusion tubes (0.15 to 0.32 m in diameter) with suitable exhaust ports that can be placed between rows of a crop. Hogsett *et al.* (1987a; 1987b) reviewed the performance and description of several of these facilities. The first system was described by Jones *et al.* (1977) for excluding ambient SO_2 from crops. This system was successful in excluding up to 85% of ambient SO_2. Another system was designed not only to exclude ambient air but also to inject O_3 or H_2S into the blower distribution system for exposure of plants in the field (Shinn *et al.* 1976; 1977; Shinn 1979; Bennett *et al.* 1980). Furthermore, this system could establish a linear gradient of gaseous pollutants along the air exclusion tubes. Also, the exposure plots were surrounded by a 0.6 m high barrier to help minimize the incursion of outside air into the plot. A similar system was designed to expose row crops to O_3, SO_2, and HF in multiple pollutant exposures (Laurence *et al.* 1982; Reich *et al.* 1982). Thompson and Olszyk (1985) designed another system for a variety of uses including ambient air exclusion, or for linear gradients of ambient air or SO_2. The response of plants with this system has been compared with open-top ventilated chambers and closed-top ventilated chambers (Olszyk *et al.* 1986).

Air exclusion systems have not been used for CO_2 enrichment studies, but in principle they would be very adaptable for this purpose, both with or without a linear gradient exposure. The open-top chamber system reported by Nakayama and Kimball (1988) comes very close to being an air exclusion system since they used large ducts for distributing CO_2 enriched air between rows of cotton in large rectangular open-top chambers with a large area-to-height ratio.

VIII. ENVIRONMENTAL GRADIENT

A small tunnel formed by a polyethylene cover on hoops was used by Kretchman (1969; 1970) to enrich strawberries with CO_2 (see Allen 1979). Carbon dioxide was injected into a blower air stream to provide enriched air at one end of the tunnel. Temperature and humidity was not measured along the length of the tunnel.

A temperature gradient tunnel was developed as an indoor plant growth cabinet facility (Grime *et al.* 1989). This system can quickly provide sets of temperature responses for small stature plants. The facility is computer controlled and can create a temperature gradient over the range of 10 to 35°C and also inject steam for humidification. However, the levels of photosynthetically active radiation were only about 125 μmol (photons) m^{-2} s^{-1}, far below typical summertime midday values of more than 2000 μmol (photon) m^{-2} s^{-1}. The small size and low light conditions limit the usefulness of such a facility for meaningful CO_2 effects research.

A controlled-environment tunnel for CO_2 gradient studies is under development by Mayeux *et al.* (1992). Air is moved unidirectionally along five 7.6-m segments. Plants are grown under transparent covers in a soil volume that is 0.76 m deep and 0.45 m wide. Each soil container is partitioned into 0.6 m segments so that water and nutrients can be controlled along the direction of air flow. At the end of each 7.6 m segment, air passes through chilled-water heat exchangers and electrical resistance heaters for control of humidity and air temperature. The tunnel makes a 180° turn at the end of each 7.6 m working segment to allow the whole system to fit inside a 9.5 m by 8.5 m greenhouse that can itself be heated and cooled. The CO_2 of the air flow is depleted progressively by photosynthesis of plants grown in the tunnel chamber. The system produces a gradient of CO_2 from entry to exit of the whole tunnel system. Carbon dioxide depletion down to 150 to 200 $\mu mol\ mol^{-1}$ can be achieved by adjusting the blower speed depending upon real-time measurements of CO_2 and light. A micrologger-controller system manages the blower speed and air conditioning equipment at the entry to each segment of the tunnel system in order to maintain desired levels of CO_2, air temperature, and air humidity. Although used so far only for investigating effects of subambient gradients of CO_2 on rangeland plants, the system of Mayeux *et al.* (1992) can easily be adapted for the study of superambient gradients of CO_2 by incorporating either fixed-rate or variable-rate CO_2 injection at the entry of the controlled-environment tunnel.

Greenhouse-size environmental-gradient tunnels have been under development in Japan (Horie *et al.* 1991). One such greenhouse tunnel is about 30 m long by about 3 m wide and about 2 m in height. Natural solar energy is used to create a temperature gradient in the greenhouse tunnel. Air flow through the greenhouse tunnel is controlled by three reversible-flow fans at one end of the structure. One, two, or all three of the fans can be operated to control the air flow rate and air residence time, and hence the air temperature gradient, from one end to the other of the greenhouse tunnel. At nighttime, the direction of the fans are reversed and heat is added to the system with a burner to maintain a similar gradient of air temperature with respect to the ambient air temperature. This system is used to track ambient air temperature conditions, with the warmer end of the tunnel maintained at a consistently higher temperature than the cooler end of the tunnel. Overhead fans were used over four segments along the greenhouse tunnel to prevent vertical gradients of temperature from developing. Air temperature was sensed throughout the tunnel.

Carbon dioxide by temperature interaction effects on rice were studied by injecting CO_2 at a controlled rate into the air flow of a companion greenhouse tunnel. Under the tunnel system and operating conditions established by Horie *et al.* (1991), a decrease of CO_2 concentration of about 10% was observed from the entry to the exit of the tunnels. Since both CO_2 uptake rate of the plants and the temperature rise in the tunnel system are driven by solar radiation, the increase in air flow required to maintain the desired temperature gradient along the tunnel also helps maintain the supply of CO_2 along the length of the tunnel. Horie *et al.* (1991) did indeed find CO_2 X temperature interaction effects on rice.

Both the controlled-environment tunnel systems of Mayeux *et al.* (1992) and the environment-tracking, greenhouse environmental-gradient tunnel system of Horie *et al.* (1991) provide additional methods for conducting CO_2 X temperature studies on crops and short ecosystems beyond those of the SPAR chamber systems

discussed earlier. The greenhouse environmental-gradient tunnel has an unnatural solar and long wavelength radiation environment, but the air flow through and above the canopy should come closer to approximating outdoor wind profile conditions than any system other than free-airstream CO_2-enrichment systems.

IX. OPEN FIELD RELEASE INCLUDING RECENT FREE-AIR CO_2 ENRICHMENT TECHNIQUES

A. General considerations

The free-air CO_2 enrichment (FACE) methodology is a "real-world" approach that may provide the best test for the effect of the impending global atmospheric CO_2 enrichment on natural and managed ecosystems (Allen *et al.* 1985a; Drake *et al.* 1985; Shinn and Allen, 1985; Hendrey *et al.* 1988a; 1988b). A brief review of FACE-type methodology, or plume exposure systems, applied to air pollution studies in the field was given by Hogsett *et al.* (1987a; 1987b), and has been summarized in Chapter 4 of this book. The theoretical pros and cons of various FACE methodology (Shinn and Allen 1985; Allen *et al.* 1985a) are presented below. Recent advance in FACE technology by Brookhaven National Laboratory (BNL FACE) using closely controlled release of pre-diluted CO_2 through a circular array of vertical vent pipes represent a new approach in CO_2 vegetation effects research. These advance are also discussed in Chapters 1, 2, 5, 6, and 7 of this book.

The general FACE approach to CO_2 enrichment uses a distribution system of pipes or plenums designed to provide elevated CO_2 to the ambient air of the plant canopy. Gases emitted from the distribution system are diluted rapidly close to the release points primarily by horizontal advection and secondarily by vertical turbulent eddy diffusion. Entrainment of air by emission jets and continuous mixing by turbulence smooths out both temporal and spatial variations in CO_2 concentration. Because mean horizontal transport of CO_2 is much greater than vertical diffusion by eddy transport, an approximate "box budget" of mass can be used to make first-order estimates of horizontal mass transport of CO_2. The distribution system could be designed for either (1) area-source emissions (ground-level or elevated-height), (2) upwind vertical vent pipe emissions (circular or square array), or (3) a combination of area-source and upwind vertical vent pipe distribution systems. The objective is to avoid the need for an enclosure or chamber around the plant canopy.

The major differences between FACE-type techniques and either outdoor controlled-environment chambers or open-top field chambers are that FACE techniques in general eliminate the following chamber effects: (1) reduction of the solar radiation environment (and changes in the diffuse/direct beam ratio) by the transparent chamber walls and support structures (including further reduction of solar UV-B radiation by many glazing materials), (2) unnatural wind flow, turbulence, and micrometeorological patterns of temperature, humidity, and long wavelength energy exchange, and (3) disturbed soil water patterns, especially with open-top chambers, associated with diversion of natural rainfall by the chamber walls. FACE systems use real field soil for the rooting medium, which is sometimes not used for chambered CO_2 enrichment studies or even open top chambers. The direct chamber effects include slight reductions in photosynthetic rates due to lower light levels, and changes in rates of development and growth due to temperature and soil-plant-air water relationships. In many cases, plant morphology may be changed due to the absence or reduction of solar UV-B

radiation, or to changes in thigmomorphogenesis or seismomorphogenesis factors due to insufficient movement or mechanically-induced stress (Biddington 1986) in the constant, but low wind and low turbulence, airflow environment of most chambers.

B. Scaling considerations

For designing FACE-type experiments it would be very useful to have a set of scaling rules for adjusting release characteristics to the height and density of the plant canopy. Such rules will depend explicitly on the type of FACE system that is used. For example, based on the data of Allen (1975, 1979) Shinn and Allen (1985) showed that a single line source of pure CO_2 in a FACE-type release in a maize field required a downstream distance about 7 to 20 times the height of vegetation (H) before horizontal CO_2 concentration gradients became vanishingly small. Shinn and Allen (1985) and Drake *et al.* (1985) adapted 10 H as a minimum scaling factor for horizontal distances that should be considered for FACE-type CO_2 exposure systems. Air pollution exposure systems designed for short crops tend to exceed this minimum approximation. The U.S. Environmental Protection Agency Zonal Air Pollution System (ZAPS) utilized plots with dimensions of 73 m by 85 m, or about 100 H on each side, for a prairie grassland (Lee *et al.* 1978). The U.S. Department of Energy's Argonne National Laboratory used air pollution exposure plots with dimensions of 29 m by 27 m, about 50 H on each side, for a soybean crop (Miller *et al.* 1980). The U.K. Central Electricity Research Laboratories (CERL) designed a circular plot array of 27 m in diameter, or about 30 H, for a wheat crop (McLeod and Fackrell 1983; McLeod *et al.* 1983; 1985; McLeod and Baker 1988). Based on both theoretical and experimental work, Shinn and Allen (1985) estimated that a plot would need to have a minimum area of magnitude 100 H^2, perhaps larger if wind direction changes are also considered using this type of control system. This approximation suggested that plot might be about 100 m^2 for a 1-m-height wheat field, 484 m^2 for a 2.2-m-height maize field, 48,400 m^2 (4.48 ha) for a 22-m-height forest, and 160,000 m^2 (16 ha) for a 40-m-height forest for a ground-level area source release of CO_2.

The plot area of the BNL circular FACE array of vertical vent pipes (VVP) is 380 m^2 for a cotton crop which grew to about 1.5 m in Yazoo City, Mississippi in 1987 and 1988, and to about 1 m in Maricopa, Arizona in 1989. These are the only FACE studies in which both temporal and spatial control of CO_2 concentrations are well documented. Also, the degree of control and shape of release from the BNL VVP FACE system is a significant advance over the ground-level area source release discussed above. The tight control over CO_2 concentrations achieved by this system, due to both the configuration of release equipment and the 1-s time step monitoring and feedback control subsystems, show that a new height scaling rule is needed. The earlier estimates of 100 H^2 seem to be excessively large for very tall vegetation and too small for very short vegetation.

A large study area is an advantage when part of the sampling problem is to obtain representative plant material from populations. Obtaining a CO_2 enrichment study area with sufficient size is especially a problem in forests or most natural ecosystems. Ecological studies of effects of elevated CO_2 on cycles of litter production, organic matter accumulations, soil respiration, nutrient cycling, aboveground competition, and phenology require a large area of uniform

exposure or treatment. A requirement of a large area with replication of experiments, however, becomes a logistics problem with large numbers of samples to process and analyze and higher associated costs, especially in natural ecosystem studies. FACE techniques do provide much more plant material than open-top chambers that are typically 0.8 to 13 m^2 in plot area, depending upon vegetation type and height or SPAR chambers typically 2 m^2 in plot area.

The concentration of CO_2 in a large area supplied through a network of pipes without feedback control will depend inversely upon wind speed, directly upon the release rate (source) of CO_2 (Allen 1975; McLeod and Fackrell 1983; Shinn and Allen 1985), and inversely with vegetation height when mass continuity is taken into account (Hanna *et al.* 1982). To maintain CO_2 concentration constant on the average, however, the delivery rate must be increased at higher wind speeds and decreased at lower wind speeds, which requires a feedback mechanism based upon wind speed to be included in the FACE design (see Chapter 7, this book).

C. Early FACE system experience

Experience has shown that in pipeline release systems including the U.K. CERL pollutant SO_2 release system, early FACE-type releases, and ZAPS, there were persistent vertical and horizontal gradients in the mean concentrations obtained by averaging measurements over periods of minutes to tens of minutes. Harper *et al.* (1973b) observed that when mean increases (ΔC) in CO_2 of about 100 $\mu mol\ mol^{-1}$ were obtained near the top of a cotton crop during ground-level, area-source releases, the vertical mean gradients near the release pipe (at ground level) were about 20 $\mu mol\ mol^{-1}\ cm^{-1}$. Although the observed vertical concentration variability is a drawback for ground-level, area-source releases, Drake *et al.* (1985) suggested that some reasonably constant mean CO_2 concentration could be maintained by clever design of distributed, multilayer, pipeline networks and vertical standpipe releases, coupled with a feedback system of detection and flow controls. Such a control system would increase the complexity of design, however, and it may also require a custom design for each experimental site to account for vegetation height and density. The BNL FACE systems seems to be a simpler solution to the problem, at least for crops.

Observations by air pollution ecologists prior to 1983 showed that downstream concentrations resulting from SO_2 gas injection in essentially uncontrolled open release systems tended to have a log-normal frequency distribution. McLeod and Fackrell (1983) compared the results of air pollutant concentration observations by the French Ministry of Agriculture, the U.S. Environmental Protection Agency, the University of Nottingham, the U.S. Department of Energy, the U.K. Central Electricity Research Laboratories, and linear-gradient systems. All of them had a log-normal frequency distribution of concentration at a point for nearly any sample-averaging time scale (a few minutes to a few hours). The geometric standard deviation was such that 10% of the time the observed concentrations were about 3 to 5 times greater than the median concentration for any given location in the grid (Shinn and Allen 1985). On the basis of these earlier studies, if CO_2 enrichment (ΔC) of 300 $\mu mol\ mol^{-1}$ were specified for a FACE-type system, then about 10% of the time the CO_2 concentration would be expected to exceed 900 to 1500 $\mu mol\ mol^{-1}$. Most of these excursions in the CO_2 concentration would be of short duration under typical daytime turbulence conditions (Allen 1973; Desjardins *et al.* 1978). Furthermore,

large variations in average CO_2 concentration from point to point might be anticipated, depending on proximity to the CO_2 release lines or points and on vertical height and horizontal distance downwind in the release array (e.g., experimental data, Allen 1973; model predictions, Allen 1975 and Allen *et al.* 1985a).

Such wide concentration variations could lead to problems of data interpretation in experiments where physiological mechanisms are the subject of investigation. Geometric fluctuations could possibly render certain in situ physiological measurements, such as stomatal diffusion resistance, photosynthetic rate, and water stress, questionable because they depend on quasi-steady-state conditions. Moreover, variation in long-term average concentration with height or horizontal space may make it difficult to specify the exact CO_2 enrichment level throughout the enriched volume, although modelling (Chapter 7 of this book; Allen and Beladi 1990) can be used to predict these distribution of CO_2 concentration. Natural variations in wind direction help to decrease the problem of horizontal CO_2 concentration gradients.

D. BNL FACE

Most of the problems with such large fluctuations in CO_2 concentrations in FACE systems appear to have been solved. Improvements in FACE technology that have been developed by BNL have greatly decreased the range of gas concentrations that were observed by others during CO_2 releases (see Chapter 7, Fig. 7-7) to smaller relative values than those observed in early SO_2 release experiments. The reasons for the smaller range of concentrations are: (1) predilution of gases before emission from the array to about 3% CO_2 (depending on windspeed), (2) vertical vent pipe injection jet design for entraining and mixing with the air stream, (3) rapid updating and correction of CO_2 release rates with a PID algorithm (Chapters 5, 6, and 7) based on rapid, direct measurements of wind speed, wind direction, and CO_2 concentration at the center of a vertical vent pipe distribution array, and (4) the fact that CO_2 is being released into a relatively stable background concentration of about 355 μmol mol^{-1}.

E. Scaling requirements for area-source releases

Shinn and Allen (1985) provided the earliest estimates of requirements for scaling up the CO_2 requirements and cost estimates for conducting FACE-type experiments in tall vegetation. Those estimates are based on FACE technologies prior to the improvements demonstrated by the BNL FACE system. The horizontal scale requirement for a ground-level, area-source FACE array is a symmetric plot with a minimum area of 100 H^2 where H is the height of the vegetation (Shinn and Allen 1985). Scaling up from a 2.2-m-tall maize field to a 22-m-tall forest would require about 100 times the plot area (48,400 m^2 compared with 484 m^2) assuming fumigation of the entire column from ground to crown. The source Q (mass of CO_2 per unit area per unit time) would not need to be increased to scale up from maize to forest, when x scales with H. Using Allen's (1975) estimate for Q of 833 kg ha^{-1} h^{-1}, to increase CO_2 by 100 μmol mol^{-1} the maize plot of 0.0484 ha requires 40 kg h^{-1}, but the forest plot of 4.84 ha would require 100 times more, 4000 kg h^{-1} (Drake *et al.* 1985; Shinn and Allen 1985).

If the 833 kg ha^{-1} h^{-1} rate of CO_2 were applied to a ground-level, area-source release on one 4.8-ha forest plot to attain a 100 μmol mol^{-1} increase in concentration above present ambient level, the consumption of CO_2 would be about 17.5×10^6 kg per year for a 12 h per day, 365 day per year release. A CO_2 treatment of 300 μmol mol^{-1} would require about 52.5×10^6 kg per year. A simple experimental design with one of each of the above treatments would require about 70×10^6 kg per year. Clearly, scale-up to forests using the earlier FACE technologies would become a logistics problem and the calculated daily consumption of 384 Mg would require large, liquid CO_2-holding reservoirs. About 30 CO_2 receivers, each the size of a tank truck (13 Mg), would be depleted each day in this scenario. Thus the need for improvement in FACE technology provided by the BNL FACE system is dramatically illustrated. Further study of the application of this new BNL FACE technology to forests is also needed to provide an assessment of whether or not such forest experiments are practical.

F. Real-world dispersion: forests

In real-world forests, CO_2 dispersion plumes from emitters are likely to meander considerably in comparison with plumes in shorter vegetation. Fluorescent particle releases from point sources as measured by Leo J. Fritschen *et al.* (1969; 1970a; 1970b) in a University of Washington experimental forest showed examples of extremely variable patterns of dispersion. Scaling up equipment for tall forests may make operation and maintenance much more difficult than for short vegetation.

Because larger plot areas may be required for tall forests, costs of CO_2 enrichment would be higher than for short crops, although the cost per unit ground area for a given level of enrichment may be similar. Costs obviously would vary linearly with wind speed. Since recent research suggests that elevated CO_2 may suppress dark respiration rates (Gifford *et al.* 1985; Reuveni and Gale 1985; Bunce 1990; Amthor 1991), 24 h per day releases may be required.

For 270 m x 270 m simulations in a 40-m forest (Allen and Beladi 1990) with CO_2 releases of 1,667 kg ha^{-1} h^{-1} from the upwind backup vertical vent pipe source and 1,667 kg ha^{-1} h^{-1} from the area-source, the amount of CO_2 released would be 24,300 kg h^{-1} and the cost of CO_2 (at $39 per ton) would be $948 per hour, or 291,600 kg d^{-1} of CO_2 at a cost of $11,372. For 365 days, this gives 1.064×10^8 kg of CO_2 at a cost of $4.15 million per year. If a decreased area (100 m x 100 m) were sufficient, the amounts and costs of CO_2 would be divided by 713. If smaller forest plot sizes are adequate say 213 m^2 equal to those used by Odum in his studies of a tropical forest in Puerto Rico (Odum and Jordan 1970) then 3.1×10^5 kg of CO_2 would be used per year at a cost of $12,000. Clearly, the range is determined by the size of the plot.

Likewise, for 13.5 m x 13.5 m grassland simulations (Allen and Beladi 1990) with CO_2 injections of 1,852 kg ha^{-1} h^{-1} from the upwind backup vertical vent pipe release and 1,852 kg ha^{-1} h^{-1} from the area-source release, the amount of CO_2 released would be 67.5 kg h^{-1} and the CO_2 cost would be $2.63 per hour, or 810 kg d^{-1} at a cost of $31.59. For 365 days, this gives 295,650 kg of CO_2 at a cost of $11,530 per year.

An elevated-height, area-source release used in conjunction with an upwind leading edge vertical vent pipe release should provide the maximum uniformity of mean CO_2 concentration over the canopy and within the canopy according to these

simulation analyses. This was also the conclusion of McLeod and Fackrell (1983) and McLeod *et al.* (1983; 1985). However:

a. More emitters over the canopy volume targeted for enrichment would increase the short-term CO_2 fluctuations.

b. The CO_2 injection control technology would increase in complexity, although presumably a modified controller could command injection of both the vertical vent pipe array and a circular, elevated-height, uniform-emission, area-source array.

c. A controlled injection, vertical vent pipe circular array seems to be the best arrangement for controlling CO_2 concentration and for economy in use of CO_2. At any given point in time, substantial gradients of CO_2 concentration along the mean wind path across the circular array may exist, but variable wind direction throughout a long-term period of enrichment may avoid a CO_2 gradient effect.

Scale up problems such as dispersion variability, larger equipment for injection of CO_2, and perhaps more complex control systems will make FACE studies in tall forest systems more difficult than in short vegetation systems.

Significant progress has been made since 1987 by Brookhaven National Laboratory on development of a circular array of vertical vent pipes for use as a FACE system in fields of cotton (see Chapters 5, 6, and 7). Most of the chapters of this book deal with the development and performance of this new BNL FACE system, and with the methodology and experimental findings of these studies of CO_2 enrichment effects on cotton obtained with this system. .The new BNL FACE concepts for larger sized forest vegetation include injection of CO_2 into the crown space only with vertical vent pipe emission systems (personal communication by G.H. Hendrey, June 1992). This approach should reduce the area-to-height requirements very significantly for FACE experiments in tall vegetation, although the open trunk space at the bottom of the crown space will allow some CO_2 losses downward as well as upward. The area requirement proposed by Shinn and Allen (1985) of 100 H^2 is likely to be much too great for very tall vegetation, and much too small for very short vegetation, and new scaling criteria need to be developed.

X. SUMMARY

To learn how crop plants, native plants, and ecosystems will respond as atmospheric CO_2 continues to increase will require additional research using approaches described in this chapter. Advantages and disadvantages of the various methods discussed are summarized in Table 3-2. The primary benefit of controlled environments in elevated CO_2 research lies with the ability to formulate, test, and improve hypotheses of organism response to environmental conditions. Environmental factors can be manipulated singly or in combinations to critically examine basic effects on organisms. The final confirmation of hypotheses generated from controlled environment studies may require field trials before prediction of field responses from laboratory experimentation can be validated.

Some of the problems of field vs. laboratory growth chamber responses of plants to aerial environments were discussed in phytotron studies by Van Volkenburgh and Davies (1977) at Duke University and by Raper and Downs (1976) at North Carolina State University. More recent studies show that limited rooting volume (small pot size) may be just as serious a problem for interpretation of responses to CO_2 as the unnatural aerial environment of chambers, due to small pot size effects on reduction of overall plant size (Bonzai Effect), root/shoot ratios, and relative growth response to CO_2 (Arp 1991; Thomas and Strain 1991). For example, elevated CO_2 caused enhanced branching of soybean roots (Del Castillo *et al.* 1989) and increased partitioning of dry weight to fine roots of trees, especially in poor soil conditions (Norby *et al.* 1985).

In all studies of the effects of elevated CO_2 on plants that have been carried out in controlled environments, however, the growth environment differs from the natural environment of plants. Our ability to use present knowledge to predict the probable future effects of CO_2 enrichment of the atmosphere is limited by our ability to account for the differences these test environments produce on plants grown in them as compared with plants grown in the open. Thus, the disadvantage of using controlled environments for studying the effects of elevated CO_2 on plant responses is the uncertainty of extrapolating results from chamber environments to field environments. This uncertainty may increase, especially when restricted rooting volume containers are used for long-term studies.

Requirements for research in controlled environments have forced the realization that the light intensity provided in standard commercially available growth chambers is inadequate for many plants. Photosynthetic photon flux density (PPFD) available in growth chambers is typically in the range of 300 to 700 μmol m^{-2} s^{-1}, but most plants require at least two to three times more photosynthetic energy to respond completely to CO_2 enrichment. High-intensity discharge lamps provide the PPFD required and have been installed in many CO_2 research facilities. Although these better light sources are becoming available, they are expensive to add to existing commercial growth units that were engineered for lower energy inputs. Overheating of plants and desiccation of the air will almost certainly result unless the capacity of the refrigeration systems is also increased.

Greenhouses have a place in CO_2 enrichment research undertaken to understand the response of crops to the open field situation. To a first approximation, some environmental control is possible and the relative stimulation of vegetation by CO_2 is roughly the same over a range of light, temperature, and humidity. In addition, the light quality and intensity in greenhouses more closely approximates natural levels than those in indoor controlled environment facilities. However, using greenhouses for elevated CO_2 studies has the same type of disadvantage that applies to using controlled environments, namely, that the differences in environment between the greenhouse and the natural, unobstructed environment are a source of inaccuracy that is difficult to estimate.

Sunlit controlled-environment chambers and open-top chambers give plants exposure to 80 to 100% of natural full sunlight, although there are some differences in the quality of light in the ultraviolet and near-infrared regions. Furthermore, the reduction of windflow and turbulence inside chambers may

influence water loss for both systems. Certain species may also respond to the sheltering effect of the chamber by changes in morphology.

A general conclusion regarding open-top chambers is that the microenvironment around the plant canopy is more humid and slightly warmer than outside the chambers. Surano and Shinn (1984) found that the seasonal rate of increase of growing degree days was higher in open-top chambers than for companion plots outside the chambers. Some differences have been reported (cited previously) between growth of plants within the chambers and plants not enclosed by chambers in the field when both were exposed to the same atmospheric gas composition. These differences require that control chambers (without elevated CO_2) be included in the experimental design. The chamber effect can be included in the interpretation of results by comparison between growth of the crop or ecosystem being studied in an unenclosed plot and an enclosed plot with normal ambient air supplied to the plants. In the opinion of some researchers these chambers remain the most convenient, if not the best, currently available technology for studying plant responses to a CO_2-enriched atmosphere in the field.

The FACE approach has the advantages of least interference with solar radiation and natural wind flow, as well as providing for a natural below-ground environment. Its disadvantages include some spatial and temporal variations in CO_2 concentrations, and greater technical difficulty (except compared to the control technology of sunlit, outdoor controlled-environment systems). At present, it appears that costs of CO_2 might make FACE expensive for tall vegetation depending on plot size. It is practical for investigating the effects of elevated CO_2 on short crops, forages, pastures, or grasslands (Allen *et al.* 1985a).

Recent analysis of plot area vs costs of CO_2 and cost of total scientific commitment by Kimball (Chapter 17) shows a considerable advantage for FACE techniques. The FACE plot areas are much larger than those of open-top chambers or outdoor controlled environment chambers. Therefore, more experimental work can be conducted by a larger number of scientists. Considered as a total research program, the costs for CO_2 itself becomes a smaller component of the total costs of conducting research.

XI. CONCLUSIONS AND RESEARCH TECHNIQUE RECOMMENDATIONS

There are many technical difficulties in conducting research on CO_2 enhancement. Available facilities include greenhouses, phytotrons, outdoor controlled-environment chambers, leaf cuvettes, open-top chambers, air exclusion systems, free-air releases, and variations of these systems. All of these approaches have advantages and disadvantages. Environmental control allows the study of environmental factors alone and in combination. Environmental control, however, induces uncertainty in the extrapolation of results to the variable natural environments. Controlled environments have space, size, and cost limitations.

Field chambers and open-air releases allow the study of the effects of CO_2 under field conditions and offer the best available approaches to investigating plant responses to CO_2 under variable "real-world" conditions. The use of FACE techniques for validation studies of a cotton crop exposed to atmospheric CO_2 enhancement has been accomplished. Entire ecosystem responses to CO_2 enrichment

should be further investigated using FACE. Each of the other techniques discussed has an appropriate place, summarized as follows, in CO_2 research:

1. Use controlled environments to study the effects of separate environmental factors (such as temperature, humidity, soil water, photoperiod, irradiance, etc.) and their interactions on the CO_2 response of organisms and ecosystems.

2. Use single-leaf cuvettes to study basic details of CO_2 and other environmental changes on photosynthesis and other physiological properties of leaves. This technique is important in quantifying upward regulation and downward regulation of photosynthesis over long time periods of exposure of the whole plant system. Branch chambers may offer some advantages (and disadvantages) of both leaf cuvettes and open-top chambers.

3. Use controlled-environment plant growth chambers to study long-term effects of continuous CO_2 enrichment on whole plants throughout their life cycles. Formulate hypotheses and test understanding by controlling and varying factors singly and in combinations.

4. Use phytotron chambers and refrigerated greenhouses to obtain multiple factor controls and to gain space required for larger experiments. At northerly cool latitudes, use heated greenhouses for CO_2-effect interaction studies with temperature and soil-water using idealized diurnal cycles of temperature where the control temperatures are to be maintained above the outside temperatures.

5. Use portable field chambers for short-term measurement of canopy photosynthetic and transpiration rate, and for an inexpensive approach to the development of basic hypotheses.

6. Use sunlit, controlled-environment chambers and field tracking chambers to study canopy and ecosystem responses to a combination of variable and controlled-field environments. These responses include continuous CO_2 exchange and transpiration measurements.

7. Use open-top chambers to study vegetation and ecosystem responses under field conditions that approach those of the natural outdoors. Evaporation and CO_2 uptake capabilities have been included in some of these chamber systems.

8. Continue the development of both controlled-environment chamber tunnels and field-tracking, greenhouse environmental-gradient tunnels for CO_2-effect interaction studies with temperature, soil moisture, and soil nutrients.

9. Continue to develop the unique capability of FACE techniques for validation studies of whole crop, forest, or entire ecosystem responses to atmospheric CO_2 enhancement. Use leaf cuvettes for documenting leaf level and stomatal responses, portable field chambers for short-term photosynthetic and transpiration measurements, and open-top chambers for growth and yield comparisons within FACE plots, and for quantifying the expression of the "chamber effect" by plants.

There is a need to integrate previous knowledge gained from experiments into whole ecosystem responses (Mooney *et al.* 1991). FACE techniques may allow such an approach without disturbing the natural system although "scaling up" to tall vegetation ecosystems may be complex. The greenhouse environmental-gradient tunnel concept could be used to investigate CO_2 X temperature interactions. Clever aerodynamic design with controlled-direction air entry scoops and air exit vents could both decrease the power requirements for ventilation of large greenhouse environmental-gradient tunnels and prevent the possibility of air flow reversals during windy conditions. A large facility such as this could be

adapted for use in ecosystems research. Also, perhaps a large greenhouse tunnel on rails could be developed and operated to allow direct natural rainfall on the environmental-gradient site. Finally, many of these field exposure systems could also be used to investigate interactions of global CO_2 increases with regional or local air pollutant effects on vegetation (Allen 1990).

ACKNOWLEDGEMENTS

We wish to gratefully acknowledge the contributions to this chapter made by the following people: Drs. F.A. Bazzaz, P.H. Jones, B.A. Kimball, R.J. Luxmoore, W.C. Oechel, T.I. Prudhomme, B.R. Strain, R.R. Valle, and K.F. Heimburg. This contribution is revised and updated from a U.S. Department of Energy report by Drake *et al.* (1985).

REFERENCES

1. Acock B, Acock MC, Reddy VR, Baker DN (1985a) Response of Vegetation to Carbon Dioxide, Series no. 011. The simulation, with GLYCIM, of soybean crops grown in the field and at various CO_2 concentrations in open-top chambers during 1982. Mississippi Agricultural and Forestry Experiment Station, Mississippi State, MS. Joint program of the U.S. Dept. of Energy and the U.S. Dept. of Agriculture, Washington, 47 pp.

2. Acock B, Reddy VR, Hodges HF, Baker DN, McKinion JM (1985b) Photosynthetic responses of soybean canopies to full-season carbon dioxide enrichment. Agron J 77:942-947.

3. Adaros G, Weigel H-J, Jäger H-J (1989a) Environment in open-top chambers and its effect on growth and yield of plants I. Measurement of microclimatic parameters. Gartenbauwissenschaft 54:165-171.

4. Adaros G, Weigel H-J, Jäger H-J (1989b) Environment in open-top chambers and its effect on growth and yield of plants II. Plant responses. Gartenbauwissenschaft 54:252-256.

5. Albrecht KA, Bennett JM, Prine GM (1989) Growth and gas exchange of rhizoma peanut (Arachis glabrata Benth.) subjected to water deficit. Proceedings of the XVI International Grassland Congress, Nice, France, pp 495-496.

6. Allen LH Jr. (1973) Crop Micrometeorology: A. Wide-Row Light Penetration. B. Carbon Dioxide Enrichment and Diffusion. Ph.D. Thesis, Cornell University, Ithaca, New York. University Microfilms Dissertation Abstract No. 73-14,716.

7. Allen LH Jr. (1975) Line-source carbon dioxide release. III. Prediction by a two-dimensional numerical diffusion model. Boundary-Layer Meteorol 8:39-79.

8. Allen LH Jr. (1979) Potentials for carbon dioxide enrichment. In Barfield BJ, Gerber JF (eds) Modification of the Aerial Environment of Crops. Monograph No. 2, American Society of Agricultural Engineers, St. Joseph, Missouri, pp 500-519.

9. Allen LH Jr. (1990) Plant Responses to rising carbon dioxide and potential interactions with air pollutants. J Environ Qual 19:15-35.

10. Allen LH Jr., Beladi SE, Shinn JH (1985a) Modeling the feasibility of free-air carbon dioxide release for vegetation response research. 17th Conference on Agriculture and Forest Meteorology and Seventh Conference on Biometeorology and Aerobiology, May 21-24, 1985, Scottsdale, Arizona. American Meteorology Society, Boston, Massachusetts, pp 161-164.

11. Allen LH Jr., Jones PH, Jones JW (1985b) Rising atmospheric CO_2 and evapotranspiration. In National Conference on Advances in Evapotranspiration.

ASAE Publ. 14-85, American Society of Agricultural Engineers, St. Joseph, Michigan, pp 13-27.

12. Allen LH Jr., Bisbal EC, Campbell WJ, Boote KJ (1990a) Carbon dioxide effects on soybean developmental stages and expansive growth. Soil Crop Sci Soc Fla Proc 49:124-131.

13. Allen LH Jr., Valle RR, Mishoe JW, Jones JW, Jones PH (1990b) Soybean leaf gas exchange responses to CO_2 enrichment. Soil Crop Sci Soc Fla Proc 49:192-198.

14. Allen LH Jr., Bisbal EC, Boote KJ, Jones PH (1991) Soybean dry matter allocation under subambient and superambient levels of carbon dioxide. Agron J 83:875-883.

15. Allen LH, Jr., Beladi SE (1990) Response of vegetation to carbon dioxide--057. Free-air CO_2 enrichment (FACE): Analysis and evaluation of enrichment arrays for the study of the response of plants to rising atmospheric CO_2. 1983-1989 Report. Plant Stress and Protection Laboratory, USDA-ARS in cooperation with the University of Florida, Gainesville. Joint Program of U.S. Dep. of Energy and U.S. Dep. of Agriculture, Agricultural Research Service, Washington.

16. Allen SG, Idso SB, Kimball BA, Baker JT, Allen LH Jr., Mauney JR, Radin JW, Anderson MG (1990) Effects of Air Temperature on Atmospheric CO_2-Plant Growth Relationships. Prepared for U.S. Dept. of Energy, Office of Energy Research, Office of Health and Environmental Research, Carbon Dioxide Research Program, Washington and U.S. Dept. of Agriculture, Agricultural Research Service, Washington.

17. Amthor JS (1991) Respiration in a future, higher-CO_2 world. Plant Cell Environ 14:13-20.

18. Arp WJ (1991) Effects of source-sink relations on photosynthetic acclimation to elevated CO_2. Plant Cell Environ 14:1004-1008.

19. Ashenden TW, Tabner PW, Williams P, Whitmore ME, Mansfield TA (1982) A large-scale system for fumigating plants with SO_2 and NO_2. Environ. Pollut. 63:21-26.

20. Baker DN, Musgrave RB, (1964) Photosynthesis under field conditions. V. Further plant chamber studies of the effects of light on corn (Zea mays L.). Crop Sci 4:127-131.

21. Baker DN, Harper LA, Hesketh JD, Box JE Jr. (1970) Carbon dioxide and the photosynthesis of field crops: A metered release in cotton. Report No. 1. Southern Branch, Soil and Water Conservation Research Division, USDA Agricultural Research Service and Mississippi Agricultural Experiment Station, State College, Mississippi.

22. Baker DN, Lambert JR (1980) The analysis of crop responses to enhanced atmospheric CO_2 levels. In Workshop on Environmental and Societal Consequences

of a Possible Climate Change (CONF-7904143). U.S. Department of Energy, Washington. Available from NTIS, Springfield, Virginia, pp 275-294.

23. Baker DN, Allen, LH Jr., Lambert JR (1982) Effects of increased CO_2 on photosynthesis and agricultural productivity, Series no. 013. Volume 2, Part 6 of Environmental and Societal Consequences of a Possible CO_2-Induced Climate Change. DOE/EV/10019-6 (Vol. 2 of 2). U.S. Dept. of Energy, Carbon Dioxide Research Division, Washington. Avail. from NTIS, Springfield, VA.

24. Baker JT, Allen LH Jr., Boote KJ (1990a) Growth and yield responses of rice to carbon dioxide concentration. J Agric Sci, Cambridge 115:313-320.

25. Baker JT, Allen LH Jr., Boote KJ, Jones P, Jones JW (1990b) Developmental responses of rice to photoperiod and carbon dioxide concentration. Agric For Meteorol 50:201-210.

26. Baker JT, Allen LH Jr., Boote KJ, Jones P, Jones JW (1990c) Rice photosynthesis and evapotranspiration in subambient, ambient, and superambient carbon dioxide concentrations. Agron J 82:834-840.

27. Baldocchi DD, White R, Johnston JW (1989) A wind tunnel study to design large, open-top chambers for whole-tree pollutant exposure experiments. J Air Pollut Control Assoc 39:1549-1556.

28. Barnola JM, Raynaud D, Korotkevich YS, Lorius C (1987) Vostok ice core provides 160,000-year record of atmospheric CO_2. Nature 329:408-414.

29. Bennett JP, Barnes K, Shinn JH (1980) Interactive effects of H_2S and O_3 on the yield of snap beans (Phaseolus vulgaris L.). Environ Exp Bot 20:107-114.

30. Biddington NL (1986) Mechanically-induced stress in plants. SPAN 29:38-40.

31. Bingham GE, Coyne PI (1977) A portable, temperature-controlled steady state porometer for field measurements of transpiration and photosynthesis. Photosynthetica 11:148-160.

32. Bisbal EC (1987) Effects of Subambient and Superambient CO_2 Levels on Growth, Development, and Total Nonstructural Carbohydrate of Soybean. M.S. Thesis, University of Florida, Gainesville.

33. Blackman FF, Matthaei GLC (1905) Experimental researches in vegetable assimilation and respiration IV. A quantitative study of carbondioxide assimilation. Proc Roy Soc London B 198:402-460.

34. Bloom AJ, Mooney HA, Björkman O, Berry J (1980) Materials and methods for carbon dioxide and water vapor exchange analysis. Plant Cell Environ 3:371-376.

35. Boote KJ, Jones JW, Smerage GH, Barfield CS, Berger RD (1980) Photosynthesis of peanut canopies as affected by leafspot and artificial defoliation. Agron J 72:247-252.

36. Boote KJ, Bennett JM (1982) Teaching techniques in crop water relations, gas exchange, and growth analysis. J Agron Educ 11:13-16.

37. Boote KJ, Bennett JM, Jones JW (1984) Canopy Photosynthesis: Apparent, net, or gross? In Sybesma C (ed) Advances in Photosynthesis Research, Vol. IV. Martinus Nijhoff/Dr W. Junk, The Hague

38. Boote KJ, Jones JW, Bennett JM (1985) Factors influencing crop-canopy CO_2 assimilation of soybean. In Shibles R (ed) World Soybean Research Conference III Proceedings. Westview Press, Boulder, Colorado, pp 780-788.

39. Bowman WD, Strain BR (1987) Interaction between CO_2 enrichment and salinity stress in the C_4 nonhalophyte Andropogon glomeratus. Plant Cell Environ 10:267-270.

40. Buckenham AH, Parry MA, Whittingham CP, Young AT (1981) An improved open-topped chamber for pollution studies on crop growth. Environ Pollut 62:475-482.

41. Bunce JA (1990) Short- and long-term inhibition of respiratory carbon dioxide efflux by elevated carbon dioxide. Ann Bot 65:637-642.

42. Carlson RW, Bazzaz FA (1980) Elevated CO_2 concentrations differentially increase growth, photosynthesis, and water use efficiency of plants. In Singh JJ, Deepak A (eds) Environmental and Climatic Impact of Coal Utilization. Academic Press, New York, pp 608-623.

43. Clough JM, Peet MM, Kramer PJ (1981) Effects of high atmospheric CO_2 and sink size on rates of photosynthesis of a soybean cultivar. Plant Physiol 67:1007-1010.

44. Cummings MB, Jones CH (1918) The aerial fertilization of plants with carbon dioxide. Vermont Agr. Exp. Station Bull. 211.

45. Cure JD, Rufty TW, Israel DW (1988) Phosphorus stress effects on growth and seed yield responses of nonnodulated soybean to elevated carbon dioxide. Agron J 80:897-902.

46. Curtis PS, Drake BG, Leadley PW, Arp WJ, Whigham DF (1989a) Growth and senescence in plant communities exposed to elevated CO_2 concentrations on an estuarine marsh. Oecologia 78:20-26.

47. Curtis PS, Drake BG, Whigham DF (1989b) Nitrogen and carbon dynamics in C_3 and C_4 estuarine marsh plants grown under elevated CO_2 in situ. Oecologia 78:297-301.

48. Curtis PS, Balduman LM, Drake BG, Whigham DF (1990) Elevated atmospheric CO_2 effects on belowground processes in C_3 and C_4 estuarine marsh communities. Ecology 71:2001-2006.

49. Daley PF, Cloutier CF, McNeil JN (1983) A canopy porometer for photosynthesis studies in field crops. Can J Bot 63:290-295.

50. Davis JM, Rogers HH (1980) Wind tunnel testing of open top field chambers for plant effects assessment. J Air Pollut Control Assoc 30:905-908.

51. Davis JM, Riordan AJ, Lawson RE Jr. (1983) Wind tunnel study of the flow field within and around open-top chambers used for air pollution studies. Boundary-Layer Meteorol 25:193-214.

52. de Cormis L, Bonte J, Tisne A (1975) Experimental technique for determining the effect on vegetation of sulfur dioxide pollutants applied continuously in subnecrotic doses. Pollution Atmospherique 17:103-107.

53. DeJong TM, Drake BG, Pearcy RW (1981) Gas exchange responses of Chesapeake Bay tidal marsh species under field and laboratory conditions. Oecologia 52:5-11.

54. Del Castillo D, Acock B, Reddy VR, Acock MC (1989) Elongation and branching of roots on soybean plants in a carbon dioxide-enriched aerial environment. Agron J 81:692-695.

55. DeLucia EH, Sasek TW, Strain BR (1985) Photosynthetic inhibition after long-term exposure to elevated levels of atmospheric carbon dioxide. Photosynth Res 7:175-184.

56. Desjardins RL, Allen LH Jr., Lemon ER (1978) Variations of carbon dioxide, air temperature, and horizontal wind within and above a maize crop. Boundary-Layer Meteorol 14:369-380.

57. Downs RJ, Hellmers H, Kramer PJ (1972) Engineering problems in the design and operation of phytotrons. American Society of Heating, Refrigerating and Air-Conditioning Engineers Journal, June 1972:47-55.

58. Downs RJ, Hellmers H (1975) Environment and the Control of Plant Growth. Academic Press, New York. Downs RJ (1980) Phytotrons. Bot Rev 46:447-489.

59. Downs RJ (1980) Phytotrons. Bot Rev 46:447-489.

60. Drake BG, Rogers HH, Allen LH Jr. (1985) Methods of exposing plants to elevated carbon dioxide. In Strain BR, Cure JD (eds) Direct effects of increasing carbon dioxide on vegetation. DOE/ER-0238, U.S. Dept. of Energy, Carbon Dioxide Research Division, Washington, pp 11-31.

61. Drake BG, Leadley PW, Arp WJ, Nassiry D, Curtis PS (1989) An open top chamber for field studies of elevated atmospheric CO_2 concentration on saltmarsh vegetation. Funct Ecol 3:363-371.

62. Drake BG, Arp WJ, Balduman L, Cousimano R, Dacey J, D'Abundo D, Hogan K, Long S, Pockman WT, Utley P, Villegas AC, Whigham D (1990) Response of

Vegetation to Carbon Dioxide--055. Effects of elevated CO_2 on Chesapeake Bay wetlands. V. Ecosystem and whole plant responses. Program of the U.S. Dept. of Energy, Carbon Dioxide Research Division, Office of Energy Research, Washington

63. Dunin FX, Greenwood EAN (1986) Evaluation of the ventilated chamber for measuring evaporation from a forest. Hydrological Processes 1:47-62.

64. Dunin FX, Nulsen RA, Baxter IN, Greenwood EAN (1989) Evaporation from a lupin crop: A comparison of methods. Agric For Meteorol 46:297-311.

65. Egli DB, Pendleton JW, Peters DB (1970) Photosynthetic rate of three soybean communities as related to carbon dioxide levels and solar radiation. Agron J 62:411-414.

66. Evans LT (ed) (1963) Environmental Control of Plant Growth. Academic Press, New York.

67. Fangmeier A, Gnittke J, Steubing L (1986) Transportable open-tops for discontinuous fumigations. In Microclimate and plant growth in open-top chambers. Air Pollution Research Report 5, Commission of the European Communities, Directorate-General for Science, Research and Development, Environment Research Programme, Freiburg 17-19 September 1986, pp 102-112.

68. Field C, Berry JA, Mooney HA (1982) A portable system for measuring carbon dioxide and water vapor exchange of leaves. Plant Cell Environ 5:179-186.

69. Flesch TK, Grant RH (1992) Wind flow within open-top chambers and the gas exchange implications. J Environ Qual 21:49-56.

70. Fritchen LJ, Driver CH, Avery C, Buffo J, Edmonds R, Kinerson R (1969) Dispersion of air tracers into and within a forested area: 1. Research and Development Technical Report ECOM-68-G8-1. Prepared by University of Washington, Seattle, for U.S. Army Electronics Command, Atmospheric Sciences Laboratory, Ft. Huachua, Arizona.

71. Fritchen LJ, Driver CH, Avery C, Buffo J, Edmonds R, Kinerson R, Schiess P (1970a) Dispersion of air tracers into and within a forested area: 2. Research and Development Technical Report TR ECOM-68-G8-2. Prepared by University of Washington, Seattle, for U.S. Army Electronics Command, Atmospheric Sciences Laboratory, Ft. Huachua, Arizona.

72. Fritchen LJ, Driver CH, Avery C, Buffo J, Edmonds R, Kinerson R, Schiess P (1970b) Dispersion of air traces into and within a forested area: 3. Research and Development Technical Report ECOM-68-G8-3. Prepared by University of Washington, Seattle, for U.S. Army Electronics Command, Atmospheric Sciences Laboratory, Ft. Huachua, Arizona.

73. Garrity DP, Sullivan CY, Watts DG (1984) Rapidly determining sorghum canopy photosynthetic rates with a mobile field chamber. Agron J 76:163-165.

74. Gifford RM, Lambers H, Morison JIL (1985) Respiration of crop species under CO_2 enrichment. Physiologia Plantarum 63:351-356.

75. Greenwood P, Greenhalgh A, Baker CH, Unsworth MH (1982) A new method for exposure of field crops to sulphur dioxide. In Unsworth MH, Ormrod DP (eds) Effects of Gaseous Air Pollution in Agriculture and Horticulture. Butterworth Scientific, London, pp 452-453.

76. Grime, JP, Hall W, Hunt R, Neal AM, Ross-Fraser W, Sutton F (1989) A new development of the temperature-gradient tunnel. Annals of Botany 64:279-287.

77. Hanna SR, Briggs GA, Hosker RP Jr. (1982) Handbook on Atmospheric Diffusion. (DOE/TIC-11223). U.S. Department of Energy, Washington, Available from NTIS, Springfield, Virginia, pp 57-58.

78. Hardy RWF, Havelka VD ((1975) Photosynthate as a major factor limiting N_2 fixation by field-grown legumes with emphasis on soybeans. In Nutman PS (ed) International Biological Programme. 7. Symbiotic Nitrogen Fixation in Plants. Cambridge University Press, Cambridge.

79. Harper LA (1971) Mass and Energy Transfer Between the Atmosphere and Two Plant Canopy Types. Ph.D. Dissertation, University of Georgia, Athens, Georgia. University Microfilms Dissertation Abstracts No. 72-2488.

80. Harper LA, Baker DN, Box JE Jr. (1973a) Fertilize the air over a field? Crops and Soils Magazine 26(2):8-9.

81. Harper LA, Baker DN, Box JE Jr., Hesketh JD (1973b) Carbon dioxide and the photosynthesis of field crops: A metered carbon dioxide release in cotton under field conditions. Agron J 65:7-11.

82. Harper LA, Box JE Jr., Baker DN, Hesketh JD (1973c) Carbon dioxide and the photosynthesis of field crops. A tracer examination of turbulent transport theory. Agron J 65:574-578.

83. Heagle AS, Body DE, Heck WW (1973) An open top field chamber to assess the impact of air pollution on plants. J Environ Qual 2:365-368.

84. Heagle AS, Philbeck RB, Rogers, HH, Letchworth MB (1979) Dispensing and monitoring ozone in open top field chambers for plant effects studies. Phytopathology 69:15-20.

85. Heagle AS, Philbeck RB, Ferrell RE, Heck WW (1989) Design and performance of a large, field exposure chamber to measure effects of air quality on plants. J Environ Qual 18:361-368.

86. Heck WW, Krupa SV, Linzon SN (eds) (1979) Handbook of Methodology for the Assessment of Air Pollution Effects on Vegetation. Air Pollution Control Association, Pittsburgh.

87. Heggestad HE, Heagle, AS, Bennett JH, Kock EJ (1980) The effects of photochemical oxidants on the yield of snap beans. Atmos Environ 14:317-326.

88. Hendrey GR, Lewin KP, Lipfert F, Kolber Z, Daum M (1988a) Response of Vegetation to Carbon Dioxide--045. Free-air carbon dioxide enrichment (FACE) facility development: I. Concept, prototype design and performance. Div. of Environmental Biotechnology, Dept. of Applied Science, Brookhaven National Lab., Upton, NY. Program of the U.S. Dept. of Energy, Carbon Dioxide Research Div., Washington.

89. Hendrey GR, Lipfert FW, Kimball BA, Hileman DR, Bhattacharya NC (1988b) Response of Vegetation to Carbon Dioxide--046. Free air carbon dioxide enrichment (FACE) facility: II. Field tests at Yazoo City, MS, 1987. Prepared by Brookhaven National Lab., USDA Water Conservation Lab., and Tuskegee University. Program of the U.S. Dept. of Energy, Carbon Dioxide Research Div., Washington.

90. Hofstra G, Hesketh JD (1975) The Effects of temperature and CO_2 enrichment on photosynthesis in soybean. In Marcelle R (ed) Environment and Biological Control of Photosynthesis. Dr W. Junk N.V., The Hague, pp 71-80.

91. Hogsett WE, Tingey DT, Holman SR (1985) A programmable exposure control system for determination of effects of pollutant exposure regimes on plant growth. Atmos. Environ. 19:1135-1145.

92. Hogsett WE, Olszyk D, Ormrod DP, Taylor GE Jr., Tingey DT (1987a) Air Pollution Exposure Systems and Experimental Protocols: Volume 1: A Review and Evaluation of Performance. EPA/600/3-87/037a. Environmental Research Laboratory, Office of Research and Development, U.S. Environmental Protection Agency, Corvallis, Oregon.

93. Hogsett WE, Olszyk D, Ormrod DP, Taylor GE Jr., Tingey GE (1987b) Air Pollution Exposure Systems and Experimental Protocols: Volume 2: Description of Facilities. EPA/600/3-87/037b. Environmental Research Laboratory, Office of Research and Development, U.S. Environmental Protection Agency, Corvallis, Oregon.

94. Horie T, Nakano J, Nakagawa H, Wada K, Kobayashi M, Kim H, Seo M (1991) Effects of elevated CO_2 concentration and temperature on growth and yield of rice. 1. Temperature-gradient tunnel for CO_2 and temperature treatments. Japan J Crop Sci 60:(extra issue 2)127-128 (In Japanese).

95. Houpis JLJ, Costella MP, Cowles S (1991) A branch chamber for fumigating Ponderosa pine to atmospheric pollution. J Environ Qual 20:467-474.

96. Howell RK, Kock EJ, Rose LP Jr. (1979) Field assessment of air pollution induced soybean yield losses. Agron J 71:285-288.

97. Huck MG, Ishihara K, Peterson CM, Ushijma T (1983) Soybean adaptation to water stress at different stages of growth. Plant Physiol 73:422-427.

98. Ingram KT, Herzog DC, Boote KJ, Jones JW, Barfield CS (1981) Effects of defoliating pests on soybean canopy CO_2 exchange and reproductive growth. Crop Sci 22:741-745.

99. Jones HC, Lacasse NL, Liggett WS, Weatherford F (1977) Experimental air exclusion system for field studies of SO_2 effects on crop production. EPA-600/7-77-122, U.S. Environmental Protection Agency, Washington.

100. Jones JW, Barfield CS, Boote KJ, Smerage GH, Mangold J (1982) Photosynthetic recovery of peanuts to defoliation at various growth stages. Crop Sci 22:741-746.

101. Jones JW, Zur B, Bennett JM (1986) Interactive effects of water and nitrogen stresses on carbon and water vapor exchange of corn canopies. Agric For Meteorol 38:113-126.

102. Jones P, Allen LH Jr., Jones JW, Boote KJ, Campbell WJ (1984a) Soybean canopy growth, photosynthesis, and transpiration responses to whole-season carbon dioxide enrichment. Agron J 76:633-637.

103. Jones P, Jones JW, Allen LH Jr., Mishoe JW (1984b) Dynamic computer control of closed environmental plant growth chambers. Design and Verification. Trans ASAE 27:879-888.

104. Jones P, Allen LH Jr., Jones JW (1985a) Responses of soybean canopy photosynthesis and transpiration to temperature in different CO_2 environments. Agron J 77:242-249.

105. Jones P, Allen LH Jr., Jones JW, Valle R (1985b) Photosynthesis and transpiration responses of soybean canopies to short- and long-term CO_2 treatment. Agron J 77:119-126.

106. Jones P, Jones JW, Allen LH Jr. (1985c) Seasonal carbon and water balances of soybeans grown under stress treatments in sunlit chambers. Trans ASAE 28:2021-2028.

107. Kats G, Thompson CR, Koby WC (1976) Improved ventilation of open top chambers. J Air Pollut Control Assoc 26:1089-1090.

108. Kimball BA (1983a) Carbon dioxide and agricultural yield: An assemblage and analysis of 430 prior observations. Agron J 75:779-788.

109. Kimball BA (1983b) Carbon Dioxide and Agricultural Yield: An Assemblage and Analysis of 770 Prior Observations. (WCL Report 14). U.S. Water Conservation Laboratory, Phoenix.

110. Kimball BA (1986a) A modular energy balance program including subroutines for greenhouses and other latent heat devices. ARS-33, U.S. Dept. of Agriculture, Agricultural Research Service, U.S. Water Conservation Lab., Phoenix, AZ.

111. Kimball BA (1986b) CO_2 Stimulation of growth and yield under environmental restraints. In Enoch HZ, Kimball BA (eds) Carbon Dioxide Enrichment of Greenhouse Crops. CRC Press, Boca Raton, Florida, pp 53-67.

112. Kimball BA, Mauney JR, Guinn G, Nakayama FS, Pinter PJ Jr., Clawson KL, Reginato RJ, Idso SB (1983) Response of Vegetation to Carbon Dioxide, Series no. 021. Effects of increasing atmospheric CO_2 on the yield and water use of crops. U.S. Water Conservation Laboratory and the Western Cotton Research Laboratory USDA. ARS, Phoenix. Program of the U.S. Dept. of Energy, Carbon Dioxide Research Division and the U.S. Dept. of Agriculture, Agricultural Research Service, Washington.

113. Kirkham MB, Kanemasu ET, Harbers GW, Reed DW, He H, Theisen RD, Bolger TP, Goodrum DE, Ballou LK, Lawlor DJ, Nie D, Lu WP (1990) Response of Vegetation to Carbon Dioxide, Series no. 056. Rangeland-plant response to elevated CO_2. Program of the U.S. Dept. of Energy, Carbon Dioxide Research Division, Office of Energy Research, Washington.

114. Kramer PJ, Hellmers H, Downs RJ (1970) SEPEL: New phytotrons for environmental research. BioScience 20:1201-1208.

115. Kretchman DN (1969) CO_2 Enrichment of Outdoor Crops (An Interim Report). Ohio Agricultural Research and Development Center, Department of Horticulture, Wooster, Ohio.

116. Kretchman DN (1970) CO_2 Enrichment of Outdoor Crops (Interim Report III). Ohio Agricultural Research and Development Center, Department of Horticulture, Wooster, Ohio.

117. Krikorian AD (1975) Excerpts from the history of plant physiology and development. In Davies PJ (ed) Historical and Current Aspects of Plant Physiology: A Symposium Honoring F.C. Steward. New York College Agric Life Sci, Cornell Univ, Ithaca, NY.

118. Langhans R (ed) (1978) A Growth Chamber Manual: Environmental Control for Plants. Comstock Publishing Association, Cornell University Press, Ithaca, New York.

119. Last FT (ed) (1986) Microclimate and plant growth in open-top chambers. Air Pollution Research Report 5, Commission of the European Communities, Directorate-General for Science, Research and Development, Environment Research Programme, Freiburg 17-19 September 1986, pp 16-29.

120. Laurence JA, Maclean DC, Mandl RH, Schneider RE, Hansen KS (1982) Field tests of a linear gradient system for exposure of row crops to SO_2 and HF. Water Air Soil Pollut 17:399-407.

121. Leadley PW, Drake BG (1992) Open top chambers for exposing a grassland community to elevated ambient CO_2 concentration and for measuring net ecosystem

gas exchange. In Proceedings of the International Workshop on CO_2 and Biosphere, Nov. 15-19, 1991, Wageningen, Vegetario.

122. Lee JJ, Lewis RA (1975) Field experimental component. In Lewis RA, Lefohn AS (eds) The Bioenvironmental Impact of a Coal-Fired Power Plant, 1st Interim Report (EPA-600/3-76-002). U.S. Environmental Protection Agency, Washington. Available from NTIS, Springfield, Virginia, pp 95-101.

123. Lee JJ, Preston EM, Lewis RA (1978) A System for the Experimental Evaluation of the Ecological Effects of Sulphur Dioxide. In Proceedings of the 4th Joint Conference on Sensing of Environmental Pollutants. American Chemical Society, Washington, pp 40-53.

124. Leuning R, Foster IJ (1990) Estimation of transpiration by single trees: Comparison of a ventilated chamber, leaf energy budgets and a combination equation. Agric For Meteorol 51:63-86.

125. Long SP, Drake BG (1991) Effect of the long-term elevation of CO_2 concentration in the field on the quantum yield of photosynthesis of the C_3 sedge Scirpus olneyi. Plant Physiol 96:221-226.

126. Mandl RH, Weinstein LH, McCume DC, Kevemeg M (1973) A cylindrical, open top chamber for the exposure of plants to air pollutants in the field. J Environ Qual 2:371-376.

127. Marshall JD, Ferman MA (1988) An exposure facility for examining the physiological basis of air pollutant effects on plant growth. Atmos Environ 22:2525-2533.

128. Matthaei GLC (1904) Experimental researches on vegetable assimilation and respiration III--On the effect of temperature on carbon dioxide assimilation. Phil Trans London B 197:47-105.

129. Mayeux HS, Johnson HB, Polley HW, Dumesnil MJ, Spanel GA (1992) A controlled environment chamber for growing plants across a subambient CO_2 gradient. Funct Ecol 6:(In Press).

130. McLeod AR, Fackrell JE (1983) A Prototype System for Open-Air Fumigation of Agricultural Crops. 1: Theoretical Design. (TPRD/L/2474/N83). Central Electricity Research Laboratories, Central Electricity Generating Board, Technology Planning and Research Division, Leatherhead, United Kingdom.

131. McLeod AR, Alexander K, Hatcher P (1983) A Prototype System for Open-Air Fumigation of Agricultural Crops. 2: Construction and Description (TPRD/L/2475/N83). Central Electricity Research Laboratories, Central Electricity Generating Board, Technology Planning and Research Division, Leatherhead, United Kingdom.

132. McLeod AR, Fackrell JE, Alexander K (1985) Open-air fumigation of field crops: Criteria and design for a new experimental system. Atmos Environ 19:1639-1649.

133. McLeod AR, Baker CK (1988) The use of open field systems to assess yield responses to gaseous pollutants. In WW Heck, OC Taylor, DT Tingey (ed) Assessment of crop loss from air pollutants. Elsevier Applied Science, London. pp 181-210.

134. Mejer G-J, Speckmann H, Paul W, Weigel H-J, Jäger H-J (1988) Zur Ökotoxikologie von Luftschadstoffen III. Erfassung und Verabeitung von Schadstoff- und Klimamessdaten einer Pflantzenbegasungsanlage aus open-top-Kammern. Landbauforschung Volkenrode 38:141-150.

135. Meyer WS, Reicosky DC, Barrs HD, Shell GSG (1987) A portable chamber for measuring canopy gas exchange of crops subject to different root conditions. Agron J 79:181-184.

136. Miller JE, Sprugel DG, Muller RN, Smith JJ, Xerikos PH (1980) Open-air fumigation system for investigating sulphur dioxide effects on crops. Phytopathology 70:1124-1128.

137. Monteith JL, Marshall B, Saffell RA, Clarke D, Gallagher JN, Gregory PJ, Ong CK, Squire GR, Terry A (1983) Environmental control of a glasshouse suite for crop physiology. J Exp Bot 34:309-321.

138. Mooney HA, Dunn EL, Harrison AT, Morrow PA, Bartholomew B, Hays RL (1971) A mobile laboratory for gas exchange measurements. Photosynthetica 5:128-132.

139. Mooney HA, Drake BG, Luxmoore RJ, Oechel WC, Pitelka LF (1991) Predicting ecosystem responses to elevated CO_2 concentrations. BioScience 41:96-104.

140. Moss DN, Musgrave RB, Lemon ER (1961) Photosynthesis under field conditions. III. Some effects of light, carbon dioxide, temperature, and soil moisture on photosynthesis, respiration, and transpiration of corn. Crop Sci 1:83-87.

141. Musselman RC, McCool PM, Oshima RJ, Teso RR (1986) Field chambers for assessing crop loss from air pollutants. J Environ Qual 15:152-157.

142. Musgrave RB, Moss DN (1961) Photosynthesis under field conditions. I. A portable, closed system for determining net assimilation and respiration of corn. Crop Sci 1:37-41.

143. Nakayama FS, Kimball BA (1988) Soil carbon dioxide distribution and flux within the open-top chamber. Agron J 80:394-398.

144. Norby RJ, Luxmoore RJ, O'Neill EG, Weller DG (1985) Plant Response to Elevated Atmospheric CO_2 with Emphasis on Belowground Processes (ORNL/TM-9426). Oak Ridge National Laboratory, Oak Ridge, Tennessee.

145. Nystrom SD, Hendrickson RC, Pratt GC, Krupa SV (1982) A computerized open-top field chamber system for exposing plants to air pollutants. Agric. Environ. 7:213-221.

146. Odum HT, Jordan CF (1970) Metabolism and evaporation of the lower forest in a giant plastic cylinder. In HT Odum, RF Pigeon (ed) A tropical rain forest: A study of irradiation and ecology at El Verde, Puerto Rico, Book 3. U.S. Atomic energy commission, Oak Ridge, Tn. pp I.165-I.189.

147. Oechel WC, BR Strain (1985) Native species responses to increased atmospheric carbon dioxide concentrations. In BR Strain, JD Cure (ed) Direct effects of increasing carbon dioxide on vegetation. DOE/ER-0238, U.S. Department of Energy, Carbon Dioxide Research Division, Washington, pp 117-154.

148. Olszyk DM, Bytnerowicz A, Kats G, Dawson PJ, Wolf J, Thompson CR (1986) Crop effects from air pollutants in air exclusion systems vs. field chambers. J Environ Qual 15:417-422.

149. Olszyk DM, Tibbitts TW, Hertsberg WM (1980) Environment in open-top field chambers utilized for air pollution studies. J Environ Qual 9:610-615.

150. Olszyk DM, Takemoto BK, Kats G, Dawson PJ, Morrison CL, Wolf Preston, J Thompson CR (1992) Effects of open-top chambers on 'Valencia' orange trees. J Environ Qual 21:128-134.

151. Ordway DE (1969) An aerodynamicist's analysis of the Odum cylinder approach to net CO_2 exchange. Photosynthetica 3:199-209.

152. Paez A, Hellmers H, Strain BR (1983) CO_2 enrichment, drought stress, and growth of Alaska pea plants (Pisum sativum L.). Physiol Plant 58:1161-165.

153. Parsons JE, Dunlap JL, McKinion JM, Phene CJ, Baker DN (1980) Microprocessor based data acquisition and controlled software for plant growth chambers (SPAR system). Trans ASAE 23:589-595.

154. Patterson DT, Flint EP (1980) Potential effects of global atmospheric CO_2 enrichment on the growth and competitiveness of C_3 and C_4 weed and crop plants. Weed Sci 28:71-75.

155. Phene CJ, Baker DN, Lambert JR, Parsons JE, McKinion JM (1978) SPAR--A soil-plant-atmosphere-research system. Trans ASAE 21:924-930.

156. Potvin C, Strain BR (1985) Effects of CO_2 enrichment and temperature on growth in two C_4 weeds, Echinochloa crysgali and Eleausine indica. Can J Bot 63:1495-1499.

157. Prudhomme TI, Oechel WC, Hastings SJ, Lawrence WT (1984) Net ecosystems gas exchange at ambient and elevated CO_2 concentrations in the tussock tundra at Toolik Lake, Alaska: An evaluation of methods and initial results. In McBeath JH (ed) Potential Effects of Carbon Dioxide Induced Climatic Changes In Alaska.

Proceedings of a Conference (Miscellaneous Pub. 8-31). School of Agriculture and Land Resources Management, University of Alaska, Fairbanks, Alaska, pp 155-162.

158. Raper CD Jr., Downs RJ (1976) Field phenotype in phytotron culture: A case study for tobacco. Bot Rev 42:317-343.

159. Reardon JC, Lambert JR, Acock B (1990) Response of Vegetation to Carbon Dioxide, Series no. 016. The influence of carbon dioxide enrichment on the seasonal patterns of nitrogen fixation in soybeans. USDA-ARS Crop Simulation Research Unit, Mississippi State, MS and Agricultural Engineering Department, Clemson University, SC Joint Program of the U.S. Dept. of Energy, Carbon Dioxide Research Division, and U.S. Dept. of Agriculture, Agricultural Research Service, Washington.

160. Reich PB, Amundson RG, Lassoie JP (1982) Reduction in soybean yield after exposure to ozone and sulfur dioxide using a linear gradient exposure technique. Water Air Soil Pollut 17:29-36.

161. Reicosky DC, Peters DB (1977) A portable chamber for rapid evapotranspiration measurements on field plots. Agron J 69:729-732.

162. Reuveni J, Gale J (1985) The effect of high levels of carbon dioxide on dark respiration and growth of plants. Plant Cell Environ 8:623-628.

163. Rogers HH, Jeffries HE, Stahel EP, Heck WW, Ripperton LA, Witherspoon AM (1977) Measuring air pollutant uptake by plants: A direct kinetic technique. J Air Pollut Control Assoc 27:1192-1197.

164. Rogers HH, Bingham GE, Cure JD, Smith JM, Surano KA (1983a) Responses of selected plant species to elevated carbon dioxide in the field. J Environ Qual 12:569-574.

165. Rogers HH, Heck WW, Heagle AS (1983b) A field technique for the study of plant responses to elevated carbon dioxide concentration. J Air Pollut Control Assoc 33:42-44.

166. Rogers HH, Thomas JF, Bingham GE (1983c) Response of agronomic and crop species to elevated atmospheric carbon dioxide. Science 220:428-429.

167. Rogers HH, Cure JD, Thomas JF, Smith JM (1984a) Influence of elevated CO_2 on growth of soybean plants. Crop Sci 24:361-366.

168. Rogers HH, Sionit N, Cure JD, Smith JM, Bingham GE (1984b) Influence of elevated carbon dioxide on water relations of soybeans. Plant Physiol 74:233-238.

169. Rogers HH, Cure JD, Smith JM (1986) Soybean growth and yield response to elevated carbon dioxide. Agric Ecosystems Environ 16:113-128.

170. Runeckles VC, Palmer KT, Trabelski H (1981) Effects of field exposure to SO_2 on Douglas Fir, Agropyron spicatum, and Lolium perenne. Silva Fennica 15:405-415.

171. Runeckles VC, Wright EF, White D (1990) A chamberless field exposure system for determining the effect of gaseous air pollutants on crop growth and yield. Environ. Pollut. 63:61-77.

172. Šesták Z, Čatský J, Jarvis PG (eds) (1971) Plant Photosynthetic Production: Manual of Methods. Dr W. Junk N.V. Publishers, The Hague.

173. Sharkey TD (1985) Photosynthesis in intact leaves of C_3 plants: Physics, physiology, and rate limitations. Bot Rev 51:53-105.

174. Shinn JH, Clegg BR, Stuart, ML, Thompson SC (1976) Exposure of field grown lettuce to geothermal air pollution--Photosynthetic and stomatal responses. J Environ Sci Health Part A 11 (10 and 11):603-612.

175. Shinn JH, Clegg BR, Stuart ML (1977) A Linear-Gradient Chamber for Exposing Field Plants to Controlled Levels of Air Pollutants (Report UCRL 80411). Lawrence Livermore National Laboratory, Livermore, California.

176. Shinn JH (1979) Problems in assessment of air pollution effects on vegetation. In Pfaffling JR, Ziegler EN (eds) Advances in Environmental Sciences and Engineering. Gordon and Breach Science Publishers, New York, pp 88-105.

177. Shinn JH, Allen LH Jr. (1985) An Evaluation of Free-air Carbon Dioxide Enrichment (FACE) as a Field Method for Investigation of Direct Effects of Carbon Dioxide on Plants (UCRL-93635 Report for the U.S. Dept. of Energy, Carbon Dioxide Research Division). Lawrence Livermore National Laboratory, Livermore, California.

178. Sinclair TR, Allen LH Jr. (1982) Carbon dioxide and water vapor exchange by leaves of field-grown citrus trees. J Exp Bot 33:1166-1175.

179. Sinclair TR, Allen LH Jr., Cohen M (1983) Citrus blight effects on carbon dioxide assimilation. J Am Soc Hort Sci 108:503-506.

180. Sinclair TR, Johnson MN, Drake GM, Van Houtte RC (1979) Mobile laboratory for continuous, long-term gas exchange measurements of 39 leaves. Photosynthetica 4:446-452.

181. Sionit N, Mortensen DA, Strain BR, Hellmers H (1981) Growth response of wheat to CO_2 enrichment and different levels of mineral nutrition. Agron J 73:1023-1027.

182. Sionit N, Patterson DT (1984) Responses of C_4 grasses to atmospheric CO_2 enrichment. I. Effects of irradiance. Oecologia 65:30-34.

183. Sionit N, Patterson DT (1985) Responses of C_4 grasses to atmospheric CO_2 enrichment. II. Effects of water stress. Crop Sci 25:533-537.

184. Surano KA, Shinn, JH (1984) A Field Study of Elevated Atmospheric CO_2 Effects on Yield Water-Use Efficiency, and Dry Matter Partitioning in Zea mays. (UCRL 90771 Report for the U.S. Dept. of Energy, Carbon Dioxide Research Division). Lawrence Livermore National Laboratory, Livermore, California.

185. Teskey RO, Dougherty PM, Wiselogel AE (1991) Design and performance of branch chambers suitable for long-term ozone fumigation of foliage in large trees. J Environ Qual 20:591-595.

186. Thomas RB, Strain BR (1991) Root restriction as a factor in photosynthetic acclimation of cotton seedlings growing in elevated carbon dioxide. Plant Physiol 96:627-634.

187. Thompson CR (1981) Fluid Dynamic Study of Open-Top Greenhouse (Final Report, Contract #SICV70287). State Wide Air Pollution Research Center, University of California, Riverside, California.

188. Thompson CR, Olszyk DM (1985) A Field Air-Exclusion System for Measuring the Effects of Air Pollutants on Crops. EPRI EA-4203. Final Report for Project 1908-3. Electric Power Research Institute. Palo Alto, California.

189. Tibbitts T, Kozlowski TT (eds) (1979) Controlled Environment Guidelines for Plant Research. Academic Press, New York.

190. Tissue DL (1984) Physiological and Growth Responses of Eriophorum vaginatum to Elevated Carbon Dioxide and Temperature in the Alaskan Tundra. M.S. Thesis, San Diego State University, San Diego, California.

191. Tissue DL, Oechel WC (1987) Physiological response of Eriophorum vaginatum to field elevated CO_2 and temperature in the Alaskan tussock tundra. Ecology 68:401-410.

192. Unsworth MH, Heagle AS, Heck WW (1984a) Gas exchange in open-top field chambers I. Measurement and analysis of atmospheric resistance to gas exchange. Atmos Environ 18-373-380.

193. Unsworth MH, Heagle AS, Heck WW (1984b) Gas exchange in open-top field chambers II. Resistance to ozone uptake by soybeans. Atmos Environ 18:381-385.

194. Unsworth MH (1986) Principles of microclimate and plant growth in open-top chambers. In Microclimate and plant growth in open-top chambers. Air Pollution Research Report 5, Commission of the European Communities, Directorate-General for Science, Research and Development, Environment Research Programme, Freiburg 17-19 September 1986, pp 16-29.

195. Valle R, Mishoe JW, Campbell WJ, Jones JW, Allen LH Jr. (1985a) Photosynthetic responses of 'Bragg' soybean leaves adapted to different CO_2 environments. Crop Sci 25:333-339.

196. Valle R, Mishoe JW, Jones JW, and Allen LH Jr (1985b) Transpiration rate and water use efficiency of soybean leaves adapted to different CO_2 environments. Crop Sci 25:477-482.

197. van Bavel CHM, McCree KJ (1975) Design and use of phytotrons in crop productivity studies. Phytotronic Newsletter 10:16-22.

198. van Volkenburgh E, Davies WJ (1977) Leaf anatomy and water relations of plant growth in controlled environments and in the field. Crop Sci 17:353-358.

199. von Caemmerer S, Farquhar GD (1981) Some relationships between the biochemistry of photosynthesis and the gas exchange of leaves. Planta 153:376-387.

200. Weigel H-J, Jäger H-J (1988a) Zur Ökotoxikologie von Luftschadstoffen I. Experimentalle Verfahren zur Schadstoffexposition von Pflantzen. Landbauforschung Volkenrode 38:103-115.

201. Weigel H-J, Jäger H-J (1988b) Zur Ökotoxikologie von Luftschadstoffen II. Aufbau und Funktionsweise einer Expositionsanlage aus open-top Kammern zur Untersuchung von Immissionswirkungen auf Pflantzen. Landbauforschung Volkenrode 38:182-195.

202. Weinstock L, Kender WJ, Musselman RC (1982) Microclimate within open-top air pollution chambers and its relation to grapevine physiology. J Am Soc Hort Sci 107:923-929.

203. Went FW (1957) Environmental Control of Plant Growth. Chronica Botanica Vol. 17. Ronald Press, New York.

204. Wesely ML, Egtmon JA, Stedmon DH, Yalvao ED (1982) Eddy correlation measurement of NO_2 flux. Atmos Environ 16:815-820.

205. Wittwer SH, Robb W (1964) Carbon dioxide enrichment of greenhouse atmospheres for food crop production. Econ Bot 18:34-56.

206. Wittwer SH, Honma S (1969) Greenhouse Tomatoes: Guidelines for Successful Production. Michigan State University Press, East Lansing, Michigan.

207. Wittwer SH (1986) Worldwide status and history of CO_2 enrichment--An overview. In Enoch HZ, Kimball BA (eds) Carbon dioxide enrichment of greenhouse crops. CRC Press, Boca Raton, Florida, pp 3-15.

208. Wray SM, Strain BR (1986) Response of two old field perennials to interactions of CO_2 enhancement and drought stress. Am J Bot 73:1486-1491.

209. Zur B, Jones JW, Boote KJ (1983) Field evaluation of a water relations model for soybean. I. Validity of some basic assumptions. Agron J 75:272-280.

LIST OF FIGURES

Figure 3-1. Leaf chamber for field measurement of photosynthesis. After Sinclair *et al.* (1979).

Figure 3-2. Closed system computer-controlled plant environments for CO_2 enrichment study. Plant canopy chamber system described by Jones *et al.* (1984a; 1984b; 1985a; 1985b; 1985c). Leaf chamber system described by Valle *et al.* (1985a; 1985b).

Figure 3-3. Schematic diagram of the field tracking chamber used to measure community CO_2 exchange of tussock tundra at Toolik Lake, Alaska; (1) Compressor, (2) YSI 71A controller, (3) external thermistor, (4) internal thermistor, (5) heat exchanger and fans, (6) chamber, (7) on/off solenoid, (8) flow meter, (9) carbon dioxide cylinder, (10) timers, (11) CO_2 control circuit, (12) ADC infrared gas analyzer, (13) pump, (14) scrub pump, (15) soda lime. After Prudhomme *et al.* (1984).

Figure 3-4. Open-top field chamber. (A) filters, (B) plenum, (C) blower, (D) air duct, (E) port of injection of CO_2, (F) single-layer wall, (G) double-layer wall with perforations for air entry. After Rogers *et al.* (1983b).

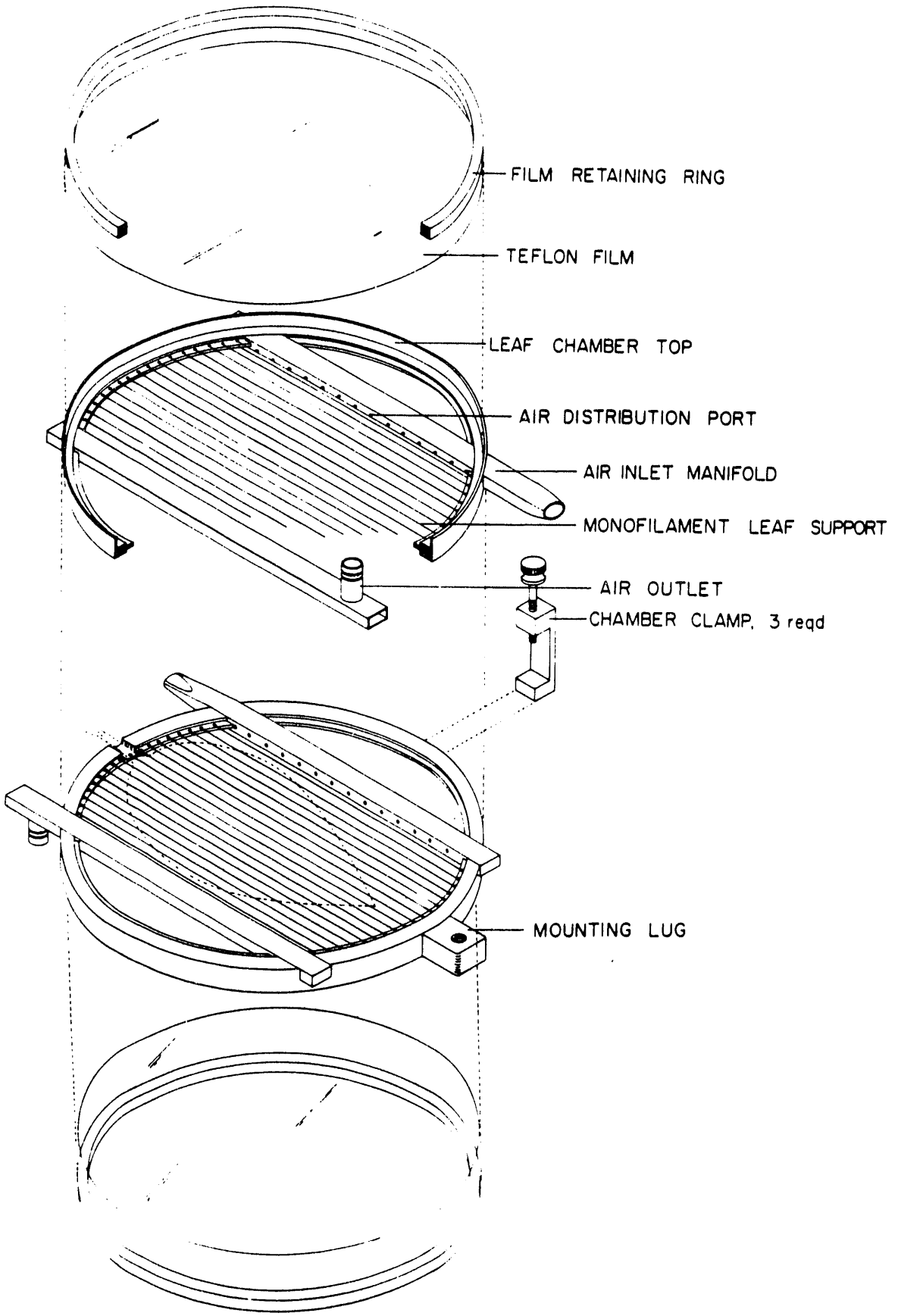
Table 3-1
Environmental Specifications (Minimal Requirements) for
Controlled Environments Designed for CO_2 Research

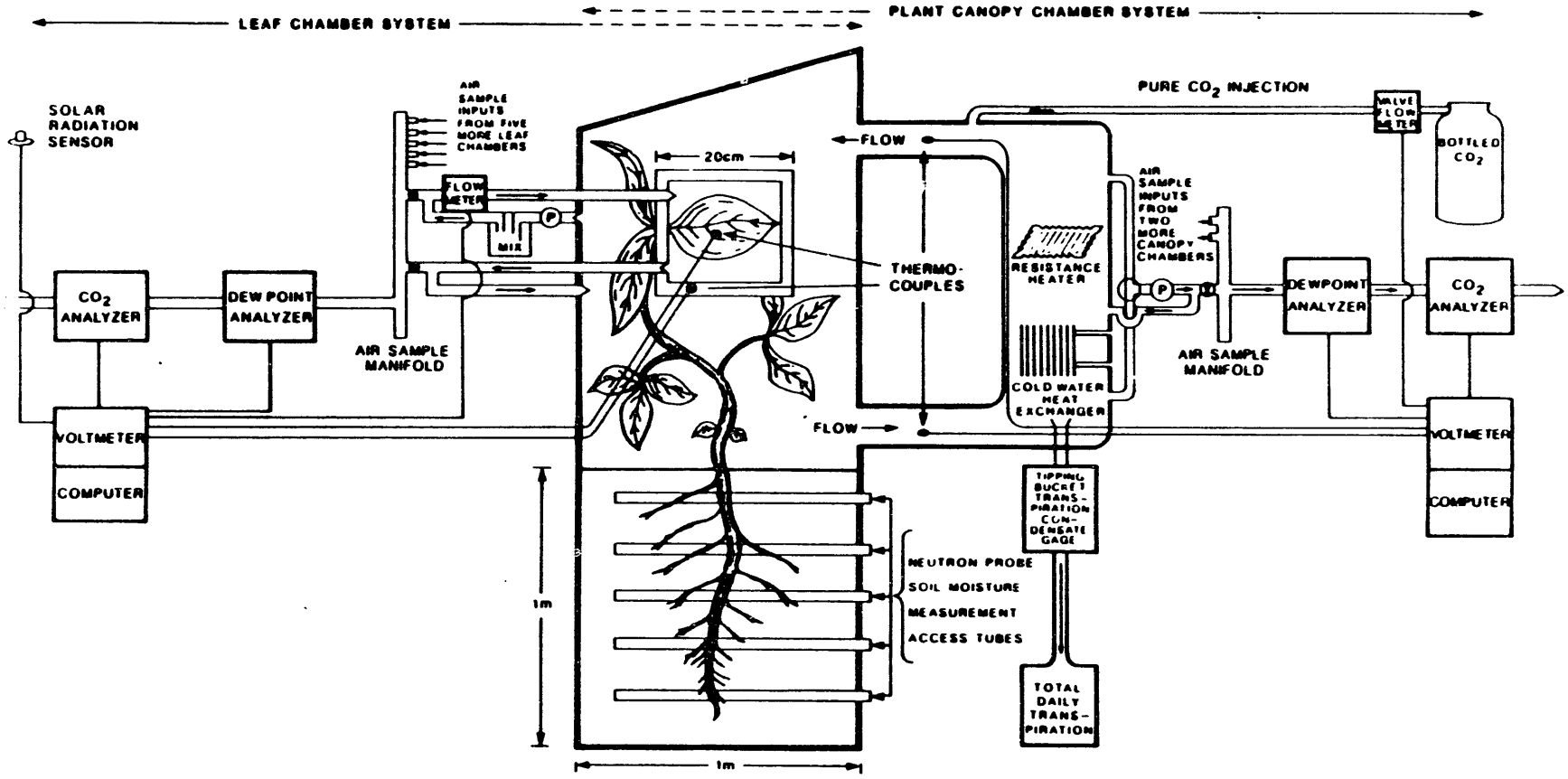
Parameter	Units
Photosynthetic Photon Flux Density	0-2000 μmol m^{-2} s^{-1}
Photoperiod	A range of 0-24 h of light continuously programmable in square or sine wave patterns. Outdoor chambers or field tracking chambers would receive natural photoperiods
Air Temperature	5° to 40°C
Thermoperiod	0-24 h phase-separated from photoperiod but in similar wave patterns
Air Water Vapor Pressure	Controllable to give a vapor pressure deficit of 0.2 to 5 MPa. Practically, this is highly dependent upon air temperature.
Air Velocity	0-3 m s^{-1} continuously adjustable
CO_2 Concentration	0-2500 μmol mol^{-1}. Practically, 100 to 1000 μmol mol^{-1}.

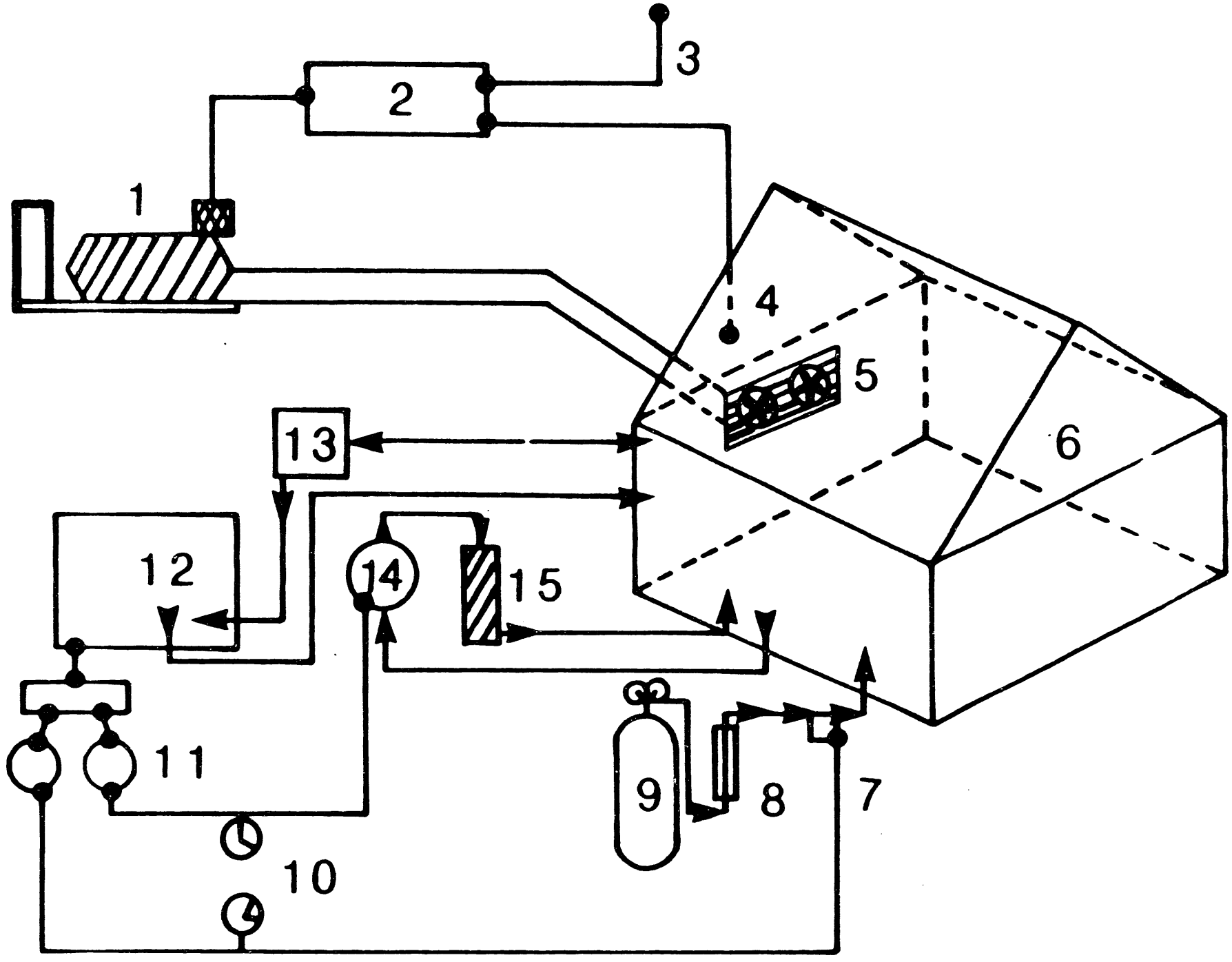
Table 3-2
Advantages and Disadvantages of the Methods Described in This Chapter
(from Allen 1979; Baker *et al.* 1982; Drake *et al.* 1985)

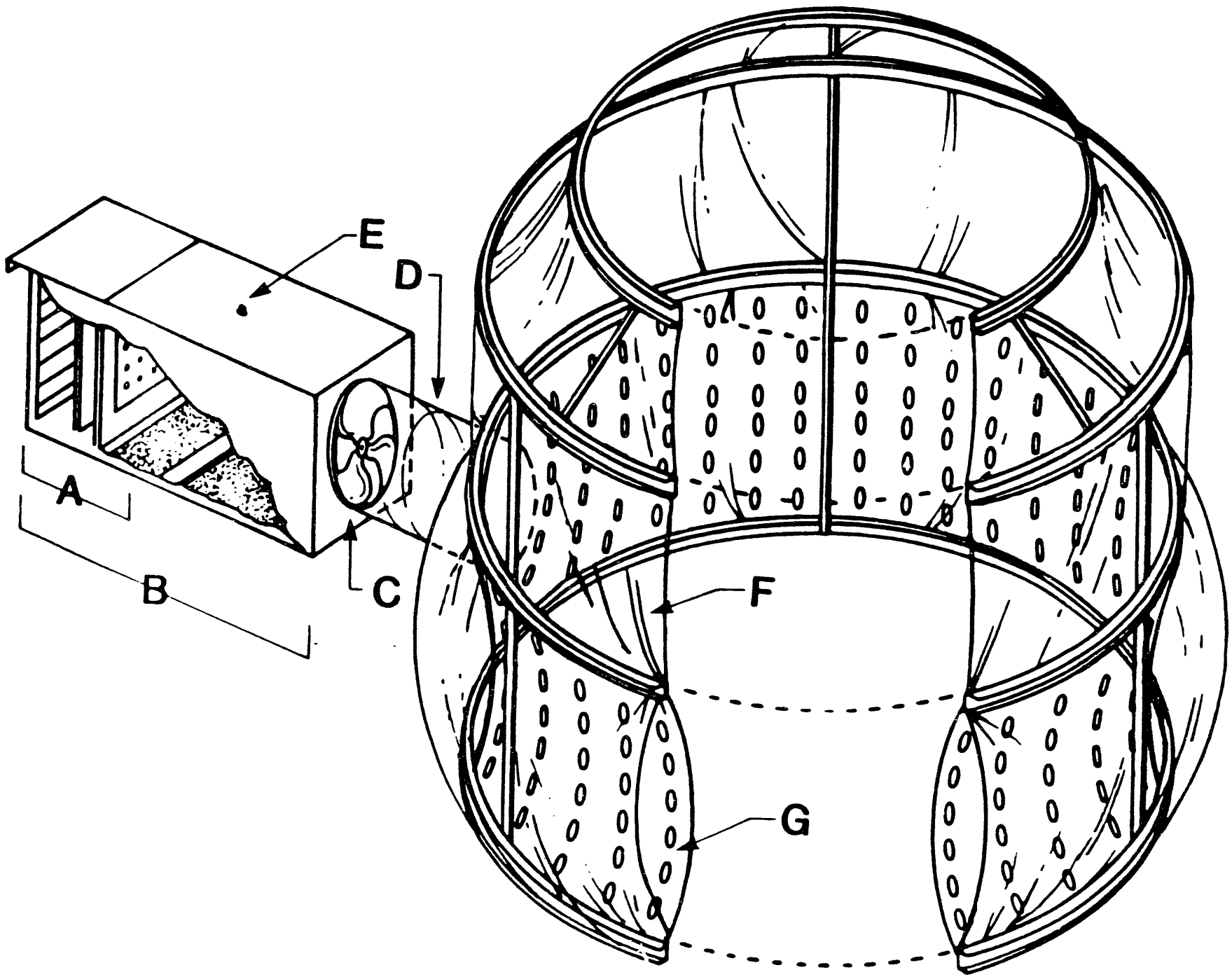
Method	Advantages	Disadvantages
Leaf Chamber	Single-leaf gas exchange kinetics obtainable. Can be used alone or in combination with long-term exposed plants.	No whole plant response such as growth; natural environment difficult to duplicate.
Phytotron	Create and control many desired environments; repeat experiments; many environmental conditions possible; biological factors controlled; interactions of CO_2 with temperature and vapor pressure.	Difficult to extrapolate to natural conditions; environmental factors usually constant; plant size limitations; plant root volume limitations; less than sunlight. Usually not set up for carbon uptake and transpiration.
Portable Greenhouse Chambers	Small, inexpensive to build; can be used with either natural sunlight or artificial light.	Same as for most controlled environments.
Sunlit Controlled Environments (e.g., SPAR)	High light, similar to natural irradiance; variable conditions; provides for continuous integrated measurements of carbon and water balance; root zone similar to field; control to specified setpoints or track the ambient environment; temperature and humidity; same advantages as phytotron.	Complex control; chamber effects (humidity, temperature, wind gradients); limited replication usually; expensive per unit.

Greenhouse	Present data base on CO_2 large; natural sunlight; large area of plant material.	Difficult to maintain (CO_2) under some conditions; difficult to maintain temperature and humidity; difficult to extrapolate results to the field.
Field Tracking Chamber	Permits study of natural vegetation; track natural variation in the environment; whole ecosystem effects; integrated measurements of carbon and water balance.	Complexity of control functions in a remote setting; possible chamber effects; expensive per unit.
Open-Top Chambers	Can be used to study crops and natural vegetation in situ; natural sunlight; closely approximates natural environment; ease of establishing elevated CO_2 concentrations.	Gradients in humidity and wind produce chamber effects; growth differs inside from outside; many sample chambers needed to deal with natural variability of ecosystems.
Portable Field Chambers	Small, inexpensive to build; can be moved easily from plot to plot; can be adjunct with FACE system for snapshot of carbon and water exchange; good for relative measurements.	Not a long term exposure facility; modifies environment as soon as placed on crop.
Air Exclusion System	Other than FACE, closest to natural environmental conditions.	Complex feedback control; large air exclusion tubes interferes with access; only for row crops.
Tunnels	Can establish CO_2 and temperature gradients for interaction studies.	Possible chamber effects; gradients may be variable.
Free-Air CO_2 Enrichment (FACE)	Closest to natural environmental conditions; provides large area of plant material for measurements and sampling.	Complex feedback control; spatial gradients in CO_2; short-term variability in CO_2; large areas needed; cost may be high for tall vegetation.


FILM RETAINING RING
TEFLON FILM
LEAF CHAMBER TOP
AIR DISTRIBUTION PORT
AIR INLET MANIFOLD
MONOFILAMENT LEAF SUPPORT
AIR OUTLET
CHAMBER CLAMP, 3 reqd
MOUNTING LUG


LEAF CHAMBER SYSTEM
PLANT CANOPY CHAMBER SYSTEM
SOLAR RADIATION SENSOR
AIR SAMPLE INPUTS FROM FIVE MORE LEAF CHAMBERS
FLOW METER
MIX
20cm
FLOW
PURE CO_2 INJECTION
VALVE FLOW METER
BOTTLED CO_2
CO_2 ANALYZER
DEW POINT ANALYZER
AIR SAMPLE MANIFOLD
THERMO-COUPLES
RESISTANCE HEATER
AIR SAMPLE INPUTS FROM TWO MORE CANOPY CHAMBERS
DEWPOINT ANALYZER
CO_2 ANALYZER
COLD WATER HEAT EXCHANGER
AIR SAMPLE MANIFOLD
VOLTMETER
COMPUTER
FLOW
TIPPING BUCKET TRANS-PIRATION CON-DENSATE GAGE
VOLTMETER
COMPUTER
1m
NEUTRON PROBE SOIL MOISTURE MEASUREMENT ACCESS TUBES
TOTAL DAILY TRANS-PIRATION
1m


1
2
3
4
5
6
7
8
9
10
11
12
13
14
15


E
D
A
B
C
F
G

FREE-AIR CO_2 ENRICHMENT FIELD EXPERIMENTS: A HISTORICAL OVERVIEW

Leon Hartwell Allen, Jr.
U.S. Department of Agriculture
Agricultural Research Service
Department of Agronomy
University of Florida
Gainesville, FL 32611-0840

I. INTRODUCTION AND BACKGROUND

During the last century the chemical composition of the global atmosphere has changed. These changes will continue in the future with exacerbated speed. Burning of fossil fuels releases gases to the atmosphere that influence plant photosynthesis and growth. One of these gases is carbon dioxide (CO_2) which is essential for photosynthesis. Higher future levels of CO_2 in the atmosphere are expected to increase plant photosynthetic rates and crop growth. On the other hand, gases such as SO_2, NO_x, and tropospheric oxidants produced as a direct or indirect result of burning of fossil fuels are known to adversely affect plant leaves, photosynthetic rates, and growth.

Several types of plant exposure systems have been developed to investigate the impacts of steadily rising levels of global atmospheric CO_2 concentrations, as well as episodic and chronic local and regional levels of toxic gaseous air pollutants. These systems have included: leaf chambers; controlled-environment plant growth cabinets; greenhouses, open-top field chambers; sunlit, controlled-environment plant growth chambers; field air exclusion systems; and free-airstream gas enrichment (or plume) systems. Each of these research systems has its advantages and disadvantages in providing information on plant responses to gaseous treatments. Early investigators recognized that chambers interfered with natural micrometeorological conditions of windflow and radiation exchange (especially solar UV-B, but also general solar irradiance level and thermal energy exchange). Concerns about these factors led to attempts to study effects of CO_2 and air pollutants under field conditions with minimal modification of the aerial environment of plants. More recently, there has been a growing recognition that root-zone volume (i.e., pot size) may be as important, if not more important, as any other factor in assessing plant response to CO_2, air pollutants, or any other treatment (Thomas and Strain 1991; Arp 1991). Thus, the need for adequate rooting volume may be another reason for conducting carbon dioxide enrichment experiments in the open field.

Early efforts at development of free-airstream CO_2 enrichment evolved from a different motivation (and a different set of investigators) than free-air pollution studies. The motivation of possible crop yield increases and economic gain of CO_2 fertilization stimulated early FACE experiments. Several factors led to the original studies. Increased yields of greenhouse crops summarized by Wittwer and Robb (1964) suggested that CO_2 fertilization of the aerial

environment was economic. Furthermore, carbon dioxide fertilization was practiced by glasshouse growers over the last 200 years using breakdown of organic materials which provided CO_2 concentrations of 2,000 to 5,000 μmol mol^{-1} for several months (H. Z. Enoch, pers. comm., 1992; Enoch and Kimball, 1986). In the field, crop production in small plots was increased by fertilizing with CO_2. Some agriculturalists even applied frozen CO_2 as "dry ice" in the field. D. N. Baker (USDA-ARS at Mississippi State University, Mississippi), and other scientists recognized that there were large, high-purity geologic reservoirs and industrial sources of CO_2 that could be used in a field release system.

As time elapsed, a different motivation developed for FACE experiments. The US Department of Energy (DOE) assumed a leading role among USA federal agencies to assess the impacts of CO_2 released from burning of fossil fuels (as a part of assessment of overall federal energy policy options). In the early 1980's, a large, long-term program was undertaken by DOE to assess the impact of rising CO_2 on vegetation. The early studies were conducted in sunlit, controlled-environment soil-plant-atmosphere research (SPAR) chambers, open-top field chambers, growth cabinets of phytotrons, and leaf chambers. In several circumstances, a large "chamber effect" on plants was observed in open-top field chambers in comparison to nonchambered plants, but the relative contribution of modified temperature, humidity, solar radiation, and windspeed was not clearly identified or quantified. These concerns led to a new thrust to develop free-air CO_2 enrichment facilities for studying the effects of future levels of CO_2 under natural micrometeorological conditions.

The motivation for free-air (or plume) studies of gaseous air pollution effects on vegetation arose from observations that SO_2, NO_x, and tropospheric oxidants cause visible damage to crops and forests. Enrichment systems, including open-air systems, for studying adverse effects of air pollutants were developed by a different set of investigators in the air pollution research community than in the CO_2-effects research community. However, the technologies (and to some extent, investigators) have partially merged in the development of the FACE system used for CO_2 enrichment experiments described in other chapters of this book.

II. EARLY CHRONOLOGY OF FREE-AIR CO_2 ENRICHMENT

Perhaps the earliest experiments with CO_2 fertilization in the field were carried out in 1922 and 1923 by Lundegårdh (1927). In 1922, CO_2 was produced from decomposing manure isolated from the soil by asphalted felt placed in furrows dug between the rows of sugarbeet plants. In 1923, a gaseous, ground-level release system was devised with distribution tubes placed 1 m apart. Lundegårdh (1927) states:

> "For this purpose five 100-sq m plots were provided with systems of iron tubes, perforated and connected with a steel flask containing pure carbon dioxide.... Five plots of the same size served as controls; all were cultivated with the same crop and were otherwise uniformly treated. The results ... show a clear positive effect of the gas."

Sugarbeet roots produced 19% more under CO_2 enrichment in 1922. In 1923, sugarbeet roots produced 16% more under a 15% increase in CO_2 concentration (from

about 284 to 328 μmol mol^{-1}) whereas oat produced 30% more for a doubling of CO_2 concentration from about 282 to 594 μmol mol^{-1} during the July 28 to August 17 period. No details were provided on the air sampling height used or the release protocol followed by Lundegårdh (1927).

In 1968, field CO_2 release experiments were initiated at the Ohio Agricultural Research and Development Center (OARDC) and continued in 1969 and 1970 (Kretchman 1969; 1970). These experiments were funded in part by a supplier of liquid CO_2, Liquid Carbonics, to determine economic benefits of elevated CO_2 in several crops (strawberry, cantaloupe, cucumber, snap bean, pepper, cabbage, tomato, potato, grape, muskmelon, and sweet corn). However, some of the experiments were conducted using combustion of natural gas from a CO_2 generator.

Most of the experiments reported by Kretchman (1969; 1970) were conducted in 2- to 6-row field plots with 2-row sweet-corn windbreaks or 0.6 m wide wheat strip windbreaks. Five- to 10-row plots of tomato and potato were cropped with snow-fence windbreaks. Allen (1979) aggregated and summarized some of the data from Kretchman. During the 1969 growing season, the total CO_2 release rate ranged from about 14 x 10^4 kg ha^{-1} for snap bean to 57 x 10^4 kg ha^{-1} for potato. The calculated release rates were 360 kg ha^{-1} h^{-1} for 15 h d^{-1} releases (5:30 a.m. to 8:30 p.m.). The CO_2 was delivered to the field along the rows in 7.9-mm polyethylene tubing perforated at 0.3 m spacing with 1.6 mm holes. Although few CO_2 concentration measurements were reported by Kretchman (1969), the following general conclusions were reached.

1. CO_2 concentrations ranged from 300 to 1450 μmol mol^{-1} within the plant canopy of strawberry, with the majority of readings less than 500 μmol mol^{-1}.
2. Levels of CO_2 were higher within than above the plant canopies of all crops receiving CO_2 enrichments.
3. Higher levels of CO_2 were found in cucumber, cantaloupe, and tomato canopies. Only on the calmest days were higher levels than normal recorded in the cabbage, pepper, and snap bean. (Presumably, these latter canopies were much more open.)

The micrometeorological instrumentation and the spatial CO_2 sampling system were not adequate for this study to draw any conclusions regarding CO_2 control other than the fact that CO_2 concentrations within and above the plant canopy were extremely variable.

Allen (1979) also aggregated the Kretchman (1969; 1970) weighted yield increases for CO_2-enriched treatments. Percentage yield increases of 3, 18, 9, 5, 12, 14, 11, and 14 were computed for strawberry, cantaloupe, cucumber, snap bean, pepper, cabbage, tomato, and potato, respectively, in 1969 and 11, -3, and 3 for tomato, muskmelon and cucumber, respectively, in 1970. The non-weighted average yield increase was 9%. Part of the lack of increase in response could have been due to inadvertent CO_2 increases in the non-enriched treatment plots which were frequently adjoining the enriched plot treatments. Based on yield responses and costs of installation of equipment and distribution of CO_2, Kretchman concluded that the economics of field CO_2 enrichment were not favorable for enhancement of agricultural yield.

In 1969, experiments were conducted on ground-level, area-source field releases of CO_2 by USDA-ARS and Mississippi State University at Starkville,

Mississippi, in cotton, and by USDA-ARS and the University of Georgia at Watkinsville, Georgia, in Coastal Bermudagrass (Baker *et al.* 1970; Harper 1971; Harper *et al.* 1973a; 1973b). The area-source consisted of a grid of 12.7 mm pipe delivery tubes laid out in a 76 m x 76 m array. CO_2 was transported to the site by a tanker truck and delivered to the field through a steam heat exchanger. The CO_2 gas flow rate was recorded by a commercial natural gas meter.

Release rates in cotton were constant at 223 kg ha^{-1} h^{-1}. Fetch ranged from 38 m to the north and south, and 53 m to the west in this rectangular grid. CO_2 concentration profiles showed typically a concentration of about 900 μmol mol^{-1} near ground level which decreased sharply to about 500 μmol mol^{-1} at 3/4 of canopy height. The September 18, 1969 data (Baker *et al.* 1970; Harper 1971; Harper *et al.* 1973a; 1973b) showed a large tendency for vertical exchange up to at least 4 m, where CO_2 concentrations ranged from 390 to 425 μmol mol^{-1}. This vertical mixing was probably driven by buoyancy which was enhanced by short, small cotton plants with LAI = 2.34 which intercepted only 62% of incoming solar radiation at noontime. In a later study with taller cotton that intercepted nearly all solar radiation, the enrichment above background at a height of 3 m was only about 15 μmol mol^{-1} (Baker and McKinion 1971). Apparently, open rows with soil exposed to solar radiation can generate considerably more buoyant vertical exchange of CO_2 released at ground level than a closed plant canopy.

From the studies in cotton, Harper *et al.* (1973a) estimated a 7 to 25% recovery of applied CO_2 and predicted a daily net photosynthate production increase of 33%.

Experiments with a horizontal line source release were conducted by USDA-ARS and Cornell University in Ithaca, New York (Allen 1973; Allen, 1974; Allen *et al.* 1974). These experiments were used as the basis for development of a 2-dimensional CO_2 dispersion model based on horizontal wind flow transport and vertical eddy diffusivity. This study was primarily a tracer study. It consisted of a single line source 100 m in length with ports every 1 m apart. CO_2 was released at ground level when the wind direction was perpendicular to the line source and CO_2 samples vs. height were collected 15 m and 45 m downwind of the line-source release. CO_2 was collected at 10 heights within and above the crop (0.1, 0.6, 1.2, 1.8, 2.4, 3.0, 3.6, 4.2, 4.8 and 6.0 m) by an air sampling and storage system composed of 40 storage units. This system was designed to fill 20 of the units simultaneously (10 units from each of the two sampling sites) while the other 20 units were being analyzed sequentially. The air was stored in laminated polyethylene-aluminum-Mylar bags housed in 8-liter glass jars. Twenty bags were filled at a rate of about 0.2 l min^{-1} over a 30-min period while the other 20 bags were being analyzed and purged. The air samples from each site were analyzed sequentially at 75-s intervals. This sampling system provided mean-value CO_2 concentration profiles at two sites to use in development of a 2-dimensional line source model that could be expanded to multiple line sources to create an effective area source (Allen 1973; 1974).

Using a linear increase in CO_2 uptake rate with increasing CO_2 concentration, Allen (1975a) computed a maximum efficiency of capture of <u>applied</u> CO_2 of about 6.5% for an area source release rate of 1400 kg CO_2 ha^{-1} h^{-1}. This efficiency was somewhat less than that computed by Harper *et al.* (1973a). Apparently the model of Allen (1975a) allowed greater losses of CO_2 by turbulent diffusion and mass transport.

The rapid loss of CO_2 emitted from a line source led to studies of area-source CO_2 releases under a 0.81-ha porous shade cloth structure by USDA-ARS and Cornell University in a soybean field at Ithaca, New York (Allen 1973; Allen 1975a; 1975b). This experiment did not increase the concentration of CO_2 above the canopy very much (Allen 1973), but it did cause a reduction in the rate of CO_2 loss from the canopy grown under shade cloth. The shade cloth tent caused a "chamber effect"; the average plant height was increased from 0.9 m to 1.2 m, and leaf area index increased from 3.7 to 4.5. This "chamber effect" may have been due to several factors, such as reduction of solar radiation flux density to 0.7 of the amount above the shade cloth tent. Furthermore, measurements on August 22, 1971 showed that windspeed (at a height of 1.5 m) was decreased from 1.8 to 0.6 m s^{-1}, humidity (at a height of 0.4 m) was increased from 14 to 19 mmol (H_2O) mol^{-1} (air), and temperature near midday (at a height of 0.4 m) was decreased from 34 to 31°C.

Broecker and Takahashi (1979) proposed "A New Technique for Determining Agricultural Growth Enhancement Caused by Fossil Fuel CO_2." The main idea was to release CO_2 into a plant canopy over the entire growth season and attempt through a feedback system (release rate coupled to wind velocity) to eliminate large temporal changes in CO_2 concentration. The key to their idea was to use CO_2 gas derived from a biogenic source which would give it a biogenic $\delta^{13}C$ of about -26‰ in comparison with an ambient air value of about -7 or -8‰. Broecker and Takahashi proposed to use the $\delta^{13}C$ content of plant components at the end of the season to provide a measure of the excess CO_2 concentration experienced by the plants over the season. This technique was not implemented as proposed, but a similar method for the use of carbon isotopes to estimate incorporation of added CO_2 by greenhouse-grown tomato plants was employed by Enoch *et al.* (1984).

III. SIMULATIONS OF ELEVATED ATMOSPHERIC CO_2 EFFECTS

Waggoner (1969) calculated responses of plants to outdoor CO_2 enrichment using an electrical resistance analog of CO_2 fluxes within leaves and within the plant-canopy air-space. These resistance analogs were solved using a digital computer. Waggoner showed that CO_2 had to be elevated at the top of the canopy, as well as the bottom, in order to increase photosynthetic rates. His simulator predicted a 40% increase in photosynthetic rates when elevating CO_2 from 300 to 600 μmol mol^{-1} and a 7% increase when elevating CO_2 from 315 to 344 μmol mol^{-1}. Using several sets of real soybean crop data, Allen *et al.* (1987) predicted a 53% increase in midday relative photosynthetic rate when doubling CO_2 from 315 to 630 μmol mol^{-1} and a 7% increase when elevating CO_2 from 315 to 345 μmol mol^{-1}.

Uchijima and Inoue (1970) published a CO_2 canopy transport model which was similar to the model of Allen (1974; 1975a), but it included an explicit photosynthetic CO_2 uptake function and a light attenuation function. It was not used to predict CO_2 fluxes under CO_2 enrichment conditions. However, with slight modifications, this model would provide an excellent, simple simulator of CO_2 uptake and losses under enrichment conditions.

Allen *et al.* (1971) simulated the response of plants to a ground-level, area-source release of CO_2 at 225 and 450 kg ha^{-1} h^{-1} under a range of plant heights, leaf angles, leaf area indices, and windspeed conditions. For the LAI = 4.0 canopies, increased CO_2 uptake ranged from 6 to 28%, with the highest

increases being at low windspeeds. However, the efficiency of uptake, the ratio of the increased CO_2 uptake rate to the CO_2 enrichment rate, ranged from 2.3 to 6.2%. This simulation was directed toward assessment of field releases of CO_2 for stimulating economic responses of plants, rather than for evaluating global increases in atmospheric CO_2.

Takami and van Bavel (1975) developed a model to compare with experimental ground-level, area-source CO_2 release data in a 24 m x 24 m plot of cotton. Their model predicted that concentration of CO_2 at any x,y point should be proportional to the release rate and inversely proportional to windspeed. In other words, in order to maintain a constant concentration at any x,y point, the ground-level, area-source release rate would have to be increased in direct proportion to windspeed. Takami and van Bavel (1975) also investigated effects of canopy parameters. In general, sparse canopies lost CO_2 faster than dense canopies, and smooth canopies retained CO_2 deeper within the canopies. Takami and van Bavel also fit their model to the data of Harper (1971) and found a better fit to the dense bermudagrass canopies than to the sparse, short cotton canopy. (The sparse, short, open canopy probably had a greater exchange due to thermal buoyancy).

Modeling of crop response to CO_2 in the early 1970's was mainly concerned with the question of field fertilization with CO_2 for increased productivity and economic benefit. However, Lister (1974), Lister and Lemon (1976), and Lemon (1977) reported SPAM model simulations of sugar beet and maize responses to global CO_2 concentrations of 400 μmol mol^{-1} in comparison to 315 μmol mol^{-1} under three diffuse solar radiation regimes.

The three solar radiation regimes were 10% diffuse (very clear sky), 30% diffuse (moderately turbid atmosphere) and 60% diffuse (very turbid atmosphere). Total solar radiation was decreased in relationship to the increase of the diffuse component. These simulations were run at 0800, 1000, 1200, 1400, and 1600 using weather data from a typical summer sunny day at Ithaca, New York (August 18, 1968), and the data aggregated into total daily CO_2 uptake. Lemon (Table 1, 1977) summarized the results of these simulations, which showed that sugar-beet, a C_3 plant, had about 20% more photosynthesis predicted for a 400 μmol mol^{-1} exposure, whereas maize, a C_4 plant, had only about a 5% calculated increase in photosynthetic rate.

IV. CONCEPTION AND GESTATION OF FACE

Several studies (Kretchman 1969; 1970; Baker *et al.* 1970; Allen *et al.* 1971; Harper 1971; Harper *et al.* 1973a; 1973b; Allen 1973; Allen *et al.* 1974; Allen 1974; 1975a; 1975b; Takami and van Bavel 1975) provided information that showed that ground-level, area-source CO_2 enrichment would not be feasible for enhancing economic crop production. After the paper of Lemon (1977) little attention was given to field-scale CO_2 enrichment research until a meeting was held at Athens, Georgia, May 23-28, 1982 on "Rising Atmospheric Carbon Dioxide and Plant Productivity: An International Conference," (Lemon 1983) under the auspices and support of AAAS, USDA-ARS, DOE, EPA, the Gas Research Institute, the Electric Power Research Institute, the National Science Foundation, the National Academy of Sciences, and the Weyerhaeuser Foundation. At this meeting Enoch described several large underground geologic reservoirs of CO_2 which could be used for a controlled enrichment of air surrounding a crop or a stand of trees. He also

suggested that plant growth rates, water loss rates, and other physiological processes could be studied over several growing seasons while the CO_2 fertilization continued. He predicted that such experiments would be expensive and difficult to undertake (p. 17, Lemon 1983).

Enoch pointed out that many of the underground CO_2 reservoirs are owned by oil companies who will pump CO_2 into old oil fields as one method of enhanced oil recovery. Also, coal gasification plants would produce massive amounts of CO_2. Currently, other industries also generate large amounts of CO_2. Finally, preliminary experiments on a small scale could indicate whether or not large scale CO_2 enrichment studies of crops and forest would be a worthwhile undertaken.

While at this conference Enoch circulated a questionnaire to the participants entitled "Response to the use of open air CO_2 enrichment facilities" and obtained 22 responses. Twenty responders indicated a "yes" or a "maybe" to the question "Would your field of research benefit if you were to use such facilities?"

The origin of the acronym FACE for "free-air CO_2 enrichment" had its beginnings at this conference. L.H. Allen, Jr. inserted the words "free airstream CO_2 enrichment" in the place of "open air CO_2 enrichment" facilities in the questionnaire.

Immediately prior to the International Conference at Athens, Georgia, a manuscript had been prepared by Enoch and co-authors entitled "A Proposal to Test the Effect of Future Atmospheric Carbon Dioxide Levels--Now" (Enoch *et al.* 1977). This manuscript, which remains unpublished, was submitted to NATURE in November 1982. The authors recommended that "CO_2 research facilities should be conducted near inexpensive sources of CO_2 (industrial or geologic sources) permitting outdoor area release of CO_2 for prolonged periods to a managed ecosystem with forest, horticultural, and agronomic plant species as well as unmanaged ecosystems." This manuscript is presented in its entirety with the permission of Herbert Z. Enoch as APPENDIX B in Allen and Beladi (1990).

On June 4, 1982, Boyd R. Strain and Herbert Z. Enoch communicated to Dr. Roger C. Dahlman, of the U.S. Department of Energy, ideas for a "Preliminary Proposal for Creating Elevated CO_2 Concentrations in the Open Air Over Managed and Unmanaged Vegetation." On August 18, 1982, several researchers involved in the VEGETATION RESPONSE Area of the USDOE Carbon Dioxide and Climate Program discussed a feasibility study for field scale CO_2 enrichment using geologic or anthropogenic CO_2 sources at a research meeting with Roger Dahlman held at Raleigh, North Carolina. The researchers attending that meeting included B. Acock, J.R. Allen, L.H. Allen, Jr., D.N. Baker, G.E. Bingham, A.S. Heagle, W.W. Heck, H.F. Hodges, F. Mowry, H.H. Rogers, B.R. Strain, and several other researchers from North Carolina. During this meeting, many advantages and disadvantages of open-field CO_2 enrichment were discussed, and the need for a feasibility study was stated. The primary concerns were (a) costs of large amounts of CO_2 required and (b) temporal and spatial (vertical and horizontal) variability of CO_2 (e.g., discussions by Allen 1979, Baker DN *et al.* 1982). After this conference, a revised proposal entitled "Proposal for Determining the Feasibility of Elevating Open-Air CO_2 Concentrations for Evaluating Effects on Managed and Unmanaged Vegetation" was prepared by L.H. Allen, Jr. on September 17, 1982. This proposal was later submitted to Roger Dahlman of the Carbon

Dioxide Research Division on January 4, 1983. This proposal is reproduced in its entirety as APPENDIX A in the report by Allen and Beladi (1990).

During late 1982, Roger Dahlman developed a plan with Joseph H. Shinn of Lawrence Livermore National Laboratory to provide a feasibility analysis, including cost estimates, for elevating CO_2 concentration in the open air as a method for evaluating the effects of rising CO_2 on vegetation. Shinn had a good working knowledge of open air "plume" exposure experiments conducted in the air pollution research community. Part of this feasibility analysis effort involved a joint study with USDA-ARS in Gainesville, Florida, entitled "Feasibility Study of Elevating Open Air CO_2 Concentration for Evaluating Effects on Vegetation, Phase I, Part 1," (initiated April 25, 1983).

Four reports were prepared for DOE as a part of the LLNL-ARS effort. The first of these was an unpublished report to DOE on August 8, 1983 entitled "A PRAGMATIC REVIEW OF FEASIBILITY OF ELEVATING OPEN AIR CO_2 CONCENTRATIONS FOR EVALUATING EFFECTS ON VEGETATION: SCOPE AND COST REPORT." This report was circulated among a number of researchers for comment. The comments were incorporated in another unpublished report to DOE entitled "FREE-AIR CO_2 ENRICHMENT (FACE): A FEASIBILITY STUDY, Progress Report--Summary of Significant Findings, October 1983," by J.H. Shinn and L.H. Allen, Jr. The use of the acronym "FACE" was suggested by L.H. Allen, Jr. to J.H. Shinn while this report was being prepared. The term grew out of the use of "free airstream CO_2 enrichment" by Allen on Enoch's May 1982 questionnaire. Allen suggested the term FACE to Shinn in 1983 although it had been used previously in the meteorological literature in conjunction with the "Florida Area Cumulus Experiment", a cloud-seeding experiment conducted in southern Florida. To my knowledge no more cloud-seeding publications from the southern Florida study have appeared in the literature since we adopted the acronym FACE. The October 1983 report by Shinn and Allen included several important suggestions by several reviewers (B.A. Kimball, R.J. Norby, G.M. Woodwell, C.D. Murphy, E.T. Kanemasu, R.L. Desjardins, A.E. Lugo, H.Z. Enoch, G.H. Heichel, and F. Mowry). The primary concerns of the ecological research community was that such an experiment should also address as many facets as possible of the carbon cycle under long-term CO_2 enrichment conditions. Two other published reports on the feasibility and analysis of FACE were also prepared and published later (Shinn and Allen 1985; Allen, Beladi, and Shinn 1985). These reports, especially the one by Shinn and Allen (1985), were cited and used extensively in the DOE "State-of-the Art" CO_2 reports (Drake *et al.* 1985).

V. OPEN AIR "PLUME" STUDIES WITH GASEOUS AIR POLLUTANT RELEASE SYSTEMS

Since J.H. Shinn was involved in toxic air pollutant research, it is appropriate at this point to digress from FACE and review chronological progress made in air pollution exposure systems. The "Plume" or free-air exposure systems for gaseous dry deposition research have been reviewed in two excellent detailed reports by Hogsett *et al.* (1987a; 1987b) with the help of 24 invited participants to an International Workshop on Standardization of Exposure Systems and Protocol, Corvallis, Oregon, January 27-28, 1986.

The first published plume system was in France by de Cormis *et al.* (1975). This facility consisted of an array of vertical tubes with emitters 2.75 m high located in a grid every 4.5 m in a 32 x 64 m exposure plot, which was used to

expose small trees to SO_2. Windspeed was measured. Sulfur dioxide concentration varied by about 25% vertically between 0.5 and 2.5 m at the routine air sampling site, but horizontal variability was about 240% and temporal variability about 100%.

The USEPA designed a plume system to use with the Colstrip Project in Montana (Lee *et al.* 1975; Lee and Lewis 1976; Preston and Lee 1982; and Laurenroth *et al.* 1983). This facility consisted of emitters positioned 0.75 m above ground in a 3.1 m spacing in 85 x 73 m plots which were used to expose native grasses to SO_2. The concentration of SO_2 varied by up to 300% across plots. Use of the system under all wind speeds and directions resulted in large horizontal and spatial variability.

The USEPA Plume system was modified and tested by the Argonne National Laboratory to simulate fumigation (and acid rain) episodes of gases from coal-burning power plants on crops (Miller *et al.* 1980; 1981; Irving and Miller 1981; 1984). Gases included SO_2, NO_2, NO_2 + SO_2, and O_3. However, this exposure system was operated as an elevated line source maintained at 0.3 m above the canopy with releases conducted only when the wind was more or less perpendicular to the length of the pipe. Holes were drilled at 0.76 m intervals along the 37 m lengths of pipe. The plot widths were only 6.1 m, so concentrations of SO_2 were found to vary only 5 to 10% across the plots, but SO_2 decreased 34% from the top of the plant canopy to the soil when measurements were made. Hourly-average SO_2 concentrations were found to vary about 50%. During a series of SO_2 releases in 1978, concentration averages and standard deviations across 5 systems were 234 ± 131, 262 ± 131, 498 ± 210, 655 ± 367, and 943 ± 498 $\mu g\ SO_2\ m^{-3}$.

Moser *et al.* (1980) exposed arctic lichens to SO_2 using a very small plume exposure system with a 1 m long horizontal emitter tube with holes each 0.1 m. The concentration of SO_2 has ranged from 2700 $\mu g\ m^{-3}$ near the emitter pipe to 173 $\mu g\ m^{-3}$ at a distance of 4.1 m downwind from the emitter pipe. Variation of concentration at sampling points was 50 to 70%.

Runeckles *et al.* (1981) described an SO_2 field exposure system used at the University of British Columbia (Vancouver) similar to the Lee *et al.* (1975) system. The plots were 10 x 12 m, with a gridwork of emitter points at 1.0 m intervals. Sulfur dioxide varied 5-15% across the plots, but vertical and temporal variability were not given. Throughout the season, concentration distributions were log-normal.

A 20-m square exposure plot facility was established at the University of Nottingham, England for exposing SO_2 to gases (Greenwood *et al.* 1982; Baker CK *et al.* 1982). The emitter pipes were arranged 0.2 m above the plant canopy as the sides of a 20-m square with emitter points every 1 m along the length. Dispensing from each pipe on the four sides was controlled independently by wind direction and wind speed monitoring equipment. Dispensing, monitoring, and data storage were computer controlled. Sulfur dioxide was diluted in a chamber with ambient air before being released to the field.

A circular plume distribution system for SO_2, NO_2, and O_3 exposure was designed and tested by the Central Electricity Research Laboratories, Leatherhead, England (McLeod and Fackrell 1983; McLeod *et al.* 1983; 1985; McLeod and Baker 1988). The exposure plots consisted of a 27-m circle of 24 emitters located 0.5 m above ground, with emitters located within the circle at 3-m grid spacing at a height of 1.5 m. Wind speed and wind direction were measured, but not used for control. Sulfur dioxide concentrations varied by more than 40% from

a 1.4 m height to the ground, by less than 7% across the 9-m diameters central plot, and by less than 10% with time within the plot (sampling time interval and sampling duration not specified). This system has the advantage of a circular array which should give good exposure regardless of wind direction.

The National Park Service, Denver, Colorado, contracted for design and test of a plume system with Northrop Services, Inc. (1983). The system was designed to be controlled by a computer feedback system based on wind speed and wind direction, but the emitters were not designed to make optimum use of this capability. The emitters were located every 0.5 m along three 15-m long PVC pipes which could be placed either horizontally or vertically. Air dilution of the emitted gas was provided by a 2.8 m^3 min^{-1} capacity blower. Pollutant samples could be analyzed from a number of points by a series of sampling ports controlled by solenoid valves. Pollutant concentration varied 5-fold over 10 days of fumigation testing.

A computer-controlled plume system was built and tested for use with vegetation in an area with predominately westerly wind direction in the Mojave desert near Daggett, California (Thompson *et al.* 1984). The research plots were 3.1 x 7.6 m, with horizontal emission tubes at 0.45 and 0.70 m above ground with perforation emitters 0.15 m apart. The emission system was designed to operate only when the wind direction was within a specified angle from the west (perpendicular to the emission tubes). A dedicated sampling point in the plot was used to control SO_2 emission via a mass-flow controller. Snow fence (1 m in height) was used to help channel the dispersed air pollutant. Variability among hourly-average concentrations has ranged up to 70% per treatment, and from 40% to 90% horizontally across entire plots. This system was designed to be used only where wind direction is relatively constant. With feedback control, it has the capability of improving control at the sampling point, but will always be subject to a concentration gradient along the direction of wind flow.

Another system was described in Hogsett (1987b) which was designed for fumigation of a forest (T.M. Roberts, personal communication, 1985). The plots were designed to be 50 m in diameter with 4 quarter-circle controlled sections with emitters at heights of 1.0 and 2.5 m. This system was designed to expose trees to SO_2 and O_3 for up to 5 years. Mass flow controllers on SO_2 supply tanks, computer-controlled ozone generators, and solenoid valves at each emitter will be used to control injection of pollutants.

Of the systems described for dispersal of air pollutants, the system designed by McLeod *et al.* (1983; 1985) probably came closest to providing the type of dispersal needed for large area CO_2 enrichment plots. The systems ranged from constant-emission systems to those with some sort of wind speed and wind direction inputs into the control of emission. The horizontal, vertical, and temporal variations reported for the systems in this section may or may not be comparable among plume exposure systems, because of the way that gases were sampled, and the way that data were recorded and aggregated for analyses.

VI. BIRTH AND GROWTH OF THE BNL FACE SYSTEM

In January of 1985, Lance S. Evans, representing a team from Brookhaven National Laboratory), in a letter to L. Hartwell Allen, Jr., Donald N. Baker, Roger C. Dahlman, George R. Hendrey, Keith F. Lewin, Hugo H. Rogers, Norman J. Rosenberg, and Joseph H. Shinn, called for a consortium of scientists and the

U.S. Department of Energy to evaluate various approaches for carbon dioxide enrichment experiments, and to design an open-air field approach (free-air carbon dioxide enrichment, or FACE) that would supply a relatively constant CO_2 concentration without changing the crop microclimate. Lance Evans had spent considerable time during the previous year examining aspects of free-air CO_2 enrichment with all of the above-mentioned CO_2-effects researchers and the BNL team for about a year had been seeking support for development of a FACE system from the CO_2 program at DOE. This letter helped move the concept of free-air CO_2 enrichment from a feasibility analysis phase into an active pilot study phase. Roger Dahlman responded that the interest and participation of the BNL team in conceptualizing field CO_2 experimental approaches was welcome. He also emphasized that ongoing FACE feasibility studies needed to be completed prior to initiating a new program (reports by Shinn and Allen 1985; Allen *et al.* 1985; and discussed in Drake *et al.* 1985 included micrometeorological feasibility and cost estimates of FACE experiments.)

Jackson R. Mauney of the U.S. Western Cotton Research Laboratory in February 1986 organized a "CO_2 Working Group Meeting" at Mississippi State University to discuss the possibility of setting up an outdoor field enrichment system using industrial or geologic sources of CO_2. The group visited the Shell Oil CO_2 Wellhead Processing Plant at the Jackson Dome geologic CO_2 deposit in Rankin County, Mississippi and the Mississippi Chemical Corporation (MCC) Ammonia Manufacturing Plant in Yazoo City, Mississippi. Those attending the meeting in Yazoo City were: Tom Parry, Terry Freeze, Gene Triggs, Jerry Irvin, Philip Dixon, Hugh Adams, and Carl Wallace (all of Mississippi Chemical Corporation), Joe Shinn, Paul Daley, and Kris Surano (Lawrence Livermore National Lab), Jack Mauney and Bruce Kimball (USDA-ARS, Phoenix, AZ), Don Baker (USDA-ARS, Mississippi State, MS), L.H. Allen, Jr. (USDA-ARS, Gainesville, FL), J.T. Baker (University of Florida, Gainesville, FL), Keith Lewin (Brookhaven National Lab) and Lance Evans (Manhattan College and Brookhaven National Lab), Ed Kanemasu (Kansas State University), and Roger Dahlman (U.S. Dept. of Energy). At this meeting the BNL team outlined ideas on how a new FACE-type system might operate. After much discussion, the decision was reached that the facilities at Yazoo City would be the best location for various types of free-air release systems because of the immediate access of desirable Delta farmland near the MCC facility that could be used to grow a cotton crop in a CO_2 enriched atmosphere using CO_2 from the MCC facility.

Lance Evans distributed a draft document in March 1986, entitled "Proposed Open-Field Exposure System" to incorporate in an overall research proposal. This report included wind speed and wind direction data for the Yazoo City plant of MCC. Roger Dahlman distributed a report of the study tour in April 1986 which covered the February CO_2 working group meeting. Among the items discussed was an open-air CO_2 delivery system that could accommodate rapidly changing environmental conditions. The proposed design included a circular field plot surrounded by CO_2 release points which were regulated based on meteorological conditions. The BNL team was to provide additional design information and performance data from experiments with air pollutant gases based on a circular delivery system.

Roger Dahlman also reviewed the topic of CO_2 sources for open-air experiments which had been discussed at MCC. The CO_2 available at MCC was a by-product of ammonia synthesis by the Haber-Bosch process and was 100% pure. An

unused 700 to 800 tons of CO_2 were being discharged daily to the atmosphere. The idea of experiments near MCC were well received by Tom Parry (President of MCC). Jack Mauney agreed to coordinate a proposal for a field study using ground-level line-source CO_2 releases and open top chambers. Lance Evans and Keith Lewin of BNL expressed a strong interest to cooperate in the study and suggested using a new FACE system that would be designed by a team at BNL. It was agreed that a proposal including the three types of FACE release systems would be prepared and that a scientific panel would be convened to review these research plans.

In May 1986, George R. Hendrey, leader of the BNL team transmitted to Roger Dahlman plans and timetables for the construction and operation of a free-air CO_2 enrichment (FACE) experiment near Yazoo City, MS, with CO_2 releases planned to begin in May 1987. A proposal to develop a 15-m diameter FACE system prototype was submitted to DOE by Hendrey in June. This was approved and work began in September 1986.

In July 1986, Jack Mauney circulated a research proposal prepared by Donald Baker and Bruce Kimball (Need for FACE..., Chapter 1), Jack Mauney (Design of Experiments...Chapter 2), and Lance Evans (CO_2 Delivery System...Chapter 3). In August Lance Evans and Keith Lewin, representing the BNL team, conducted site visits to German, Dutch, and British field exposure systems which were either in operation or under development. The visits helped to establish the type of system that was eventually designed and developed by Brookhaven National Laboratory. Although several sites based control on wind conditions, the system designed by McLeod *et al.* (1985) provided the best model for design of the eventual BNL FACE system.

In September 1986, a final draft of a research proposal to the U.S. Department of Energy was prepared by USDA-ARS, BNL, and Tuskegee University. This proposal was entitled "Responses of crop plants to free-air CO_2 enrichment (FACE) for field plantings, with principal investigators J.R. Mauney, L.S. Evans, B.A. Kimball, and P.K. Biswas, and collaborators of H.H. Rogers, L.H. Allen, Jr., K.F. Lewin, and D.R. Hileman.

In order to achieve evaluations and suggestions by knowledgeable scientists, Roger Dahlman organized an external DOE peer review panel to review the proposed research and to continue to meet annually and review the research progress. The first peer review meeting was held on December 7-9, 1986. The members of this peer review panel originally were Edwin Kanemasu (Chair), Boyd Strain, Kenneth King, George Thurtell, and Marvin Wesely. At this meeting the BNL team (Evans, Hendrey and Lewin) presented data from the prototype FACE system which they had begun assembling in September of the same year. These data demonstrated that over a 72 hour period which included substantial variability in microclimate conditions, SO_2 concentrations could be held to within $\pm$20% of a setpoint better than 80% of the time without the extreme excursions observed in other FACE-type systems. As a consequence of this demonstration, the peer reviewers recommended that development of a FACE system for an experiment with cotton be given high priority, and that a program manager be selected. Shortly thereafter, Dahlman requested that Hendrey be the FACE Program Coordinator.

During the spring of 1987, the FACE technique pilot study got underway at the MCC site near Yazoo City, Mississippi. Considerable field preparation (land-leveling, improvement of surrounding drainage, measurements to water table, and ground penetrating radar) was conducted. The 1987 pilot study consisted of a single 22-m diameter array of vertical vent pipes for injecting CO_2. This system

had several important features; a blower box, in which CO_2 was injected (and prediluted to about 30,000 μmol mol^{-1}, depending upon wind speed and turbulence) and delivered through a large torus about 0.3 m in diameter to the vertical vent pipes; and a computer which controlled the release of CO_2 based on wind direction (which allowed only the upwind-component vertical vent pipe valves to be opened), windspeed, and a feedback algorithm based on concentration measured at the center of the array. These and later studies have been summarized by Hendrey (1987) and by Hendrey *et al.* (1988a, 1988b, 1988c). A spatial evaluation of CO_2 concentrations as a function of height and distance from the center of the ring was conducted by L.H. Allen, Jr. and D.R. Hileman (see Chapter 8). Also, studies of the variability of CO_2 concentration and wind were conducted in 3 types of open-top chambers: cylindrical, cylindrical with frustum of cone partial cap, and square wall (Chapter 9).

An annual review of research progress by the peer review panel has continued each year. The FACE experiment was expanded to four arrays in 1988 at Yazoo City, Mississippi (Hendrey *et al.* 1988d). After two years at Yazoo City, where experiments were conducted at some distance from any research institution and from scientific investigators, the research team decided to search for a location close to an institution that could provide investigators and facilities. The earlier foresight of H.H. Rogers prevailed, since he had contended in several early FACE meetings that it was easier to bring CO_2 to a group of investigators than it was to bring investigators to a site some distance from research institution support. A site review was conducted by Jack Mauney, George Hendrey, and Keith Lewin. Alternate sites near Yazoo City and Stoneville, Mississippi; near Monroe, Louisiana; Muleshoe, Texas; West Side Field Station of the University of California in the San Joaquin Valley; and Maricopa Agricultural Center of the University of Arizona near Phoenix were considered. Maricopa was selected because it was the best of the candidate sites, water application could be controlled, and it was near the U.S.D.A. Western Cotton Research Lab and Water Conservation Lab with the support of the University of Arizona's laboratory facilities and spacious field site. Three experiments on response of cotton to elevated CO_2 have been conducted, in 1989, 1990, and 1991, at the Maricopa site. The studies at Yazoo City, Mississippi, and Maricopa, Arizona will be topics of chapters in this book, and future publications. The fruition of the FACE concept is largely due to the superior efforts of personnel of the Brookhaven National Lab under the leadership of George R. Hendrey, Head, Biosystems and Process Sciences Division.

VII. CONCLUDING REMARKS

Numerous persons had a significant input into the background of effort that led to FACE. Sylvan Wittwer has been an effective spokesperson for the benefits of CO_2 fertilization since 1964 (Wittwer and Robb 1964). Don Baker pressed for field studies of CO_2 enrichment since 1968, with the possibility of deriving economic benefit (Baker *et al.* 1970; Baker and Lambert 1980). Herbert Enoch raised the consciousness of field enrichment studies as a technique for evaluating plant response to rising atmospheric CO_2 (Lemon 1983). Joseph Shinn analyzed the possibilities of FACE using his background knowledge of "plume exposure" studies of the air pollution research community (Shinn and Allen 1985). L.H. Allen, Jr. provided dispersion modeling information to the free-air

enrichment questions (Allen 1975a; 1979; Allen and Beladi 1990). Lance Evans provided the "jump start" that moved FACE out of the analysis phase into the action phase. Jack Mauney identified potential industrial cooperators and set the vehicle in motion to initiate a real FACE study. George Hendrey provided the leadership and facilities of Brookhaven National Laboratory to develop a FACE system. Keith Lewin provided essential engineering design and development expertise, and more than any other individual, made the whole system work in the field. And finally, Roger Dahlman and the U.S. Department of Energy provided necessary funding.

The other contributors and beneficiaries of this technology constitute a much larger list. However, the above individuals, from my historical perspective, constituted the ongoing core up through the first two years of work at Yazoo City, Mississippi. Research publications based on data collected at Maricopa since 1989 will speak for themselves. They represent the "present", rather than a historical perspective, at this point in time.

Part of the material in this chapter was presented at the 83rd Annual Meeting of the American Society of Agronomy, Crop Science Society of America, and Soil Science Society of America, October 27 - November 1, 1991 at Denver, Colorado, in "Symposium -- Free Air Gas Enrichment", chaired by Bruce A. Kimball [L.H. Allen, Jr. (1991) Free-air gas enrichment field experiments -- Historical perspective. Agronomy Abstracts 83:13].

REFERENCES

1. Allen LH Jr. (1973) Crop micrometeorology: A. Wide-row light penetration. B. Carbon dioxide enrichment and diffusion. Ph.D. Thesis, Cornell University, Ithaca, New York. 366 p. Univ. Microfilm Diss. Abstr. No. 73-14,716.

2. Allen LH Jr. (1974) Line source carbon dioxide release. II. Two-dimensional numerical diffusion modeling. Agron. J. 66:616-220.

3. Allen LH Jr. (1975a) Line source carbon dioxide release. III. Predictions by a two-dimensional numerical diffusion model. Boundary-Layer Meteorol. 8:39-79.

4. Allen LH Jr. (1975b) Shade-cloth microclimate of soybeans. Agron. J. 67:175-181.

5. Allen LH Jr. (1979) Potentials for carbon dioxide enrichment. In BJ Barfield and JF Gerber (eds), Modifying the Aerial Environment of Crops. Monograph No. 2, Amer. Soc. of Agric. Engineers, St. Joseph, MI, pp 500-519.

6. Allen LH Jr., Beladi SE (1990) Response of Vegetation to Rising Carbon Dioxide--057. Free-air CO_2 enrichment (FACE): Analysis of gaseous dispersion arrays for the study of rising atmospheric CO_2 effects on vegetation. Plant Stress and Protection Research Unit, USDA-ARS in cooperation with the Institute of Food and Agricultural Sciences, University of Florida, Gainesville. Joint Program of the U.S. Department of Energy and the U.S. Department of Agriculture, Washington.

7. Allen LH Jr., Beladi SE, Shinn JH (1985) Modeling the feasibility of free-air carbon dioxide releases for vegetation response research. In 17th Conf. on Agric. and Forest Meteorology, Scottsdale, Arizona, 21-24 May 1985, Amer. Meteorol. Soc., Boston, pp 161-164.

8. Allen LH Jr., Boote KJ, Jones JW, Jones PH, Valle RR, Acock B, Rogers HH, Dahlman RC (1987) Response of vegetation to rising carbon dioxide: Photosynthesis, biomass, and seed yield of soybean. Global Biogeochemical Cycles 1:1-14.

9. Allen LH Jr., Desjardins RL, Lemon ER (1974) Line source carbon dioxide release: I. Field experiment. Agron. J. 66:609-615.

10. Allen LH Jr., Jensen SE, Lemon ER (1971) Plant response to carbon dioxide enrichment under field conditions: A simulation. Science 173:256-258.

11. Arp WJ (1991) Effects of source-sink relations on photosynthetic acclimation to elevated CO_2. Plant Cell Environ. 14:869-875.

12. Baker CK, Unsworth MH, Greenwood P (1982) Leaf injury on wheat plants exposed to the field in winter to SO_2. Nature 299:149-151.

13. Baker DN, Harper LA, Hesketh JD, Box JE Jr. (1970) Carbon dioxide and the photosynthesis of field crops. A metered release in cotton. Report No. 1, Southern Branch, Soil and Water Conservation Research Division, USDA-ARS, and Mississippi Agricultural Experiment Station, State College, MS.

14. Baker DN, McKinion JM (1971) Annual Report, Boll Weevil Research Laboratory, Southern Branch, Soil and Water Conservation Research Division, USDA-ARS, in cooperation with the Mississippi Agricultural Experiment Station, State College, MS.

15. Baker DN, Lambert JR (1980) The analysis of crop responses to enhanced atmospheric CO_2 levels. In Carbon Dioxide Effects Research and Assessment Program--009. Workshop on environmental and societal consequences of a possible CO_2-induced climate change, Annapolis, Maryland, April 2-6, 1979. CONF-7904143, Office of Health and Environmental Research, U.S. Dept. of Energy, Washington, pp 275-294.

16. Baker DN, Allen LH Jr., Lambert JR (1982) Effects of increased CO_2 on photosynthesis and agricultural productivity. Vol. II. Part 6. Environmental and societal consequences of a possible CO_2-induced climate change. DOE/EV/10019-6. U.S. Department of Energy, Washington.

17. Broecker WS, Takahashi T (1979) A new technology for determining agricultural growth enhancement caused by fossil fuel CO_2. Unpublished document, pers. comm.

18. de Cormis L, Bonte J, Tisne A (1975) Technique experimentale permettant l'etude de l'incidence sur la vegetation d'une pollution par le dioxyde de soufre appliquee en permanence et a dose subnecrotique. Pollut. Atmos. 66:103-107.

19. Drake BG, Rogers HH, Allen LH Jr. (1985) Methods of exposing plants to elevated carbon dioxide. In BR Strain and JD Cure (ed) Direct effects of increasing carbon dioxide on vegetation. DOE/ER-0238. U.S. Dept. of Energy, Carbon Dioxide Research Div., Washington, pp 11-31.

20. Enoch HZ, Carmi I, Rounick JS, Magaritz, M (1984) Use of carbon isotopes to estimate incorporation of added CO_2 by greenhouse-grown tomato plants. Plant Physiol. 76:1083-1085.

21. Enoch HZ, Kimball BA (ed) (1986) Carbon dioxide enrichment of greenhouse crops, vol. 1, Status and sources. CRC Press, Boca Raton, FL.

22. Enoch HZ, Baker DN, Acock B, Idso SB, Mergen F, Reifsnyder WF, Allen LH (1977) "A proposal to test the effect of future atmospheric carbon dioxide levels -- now." Appendix B in Allen and Beladi 1990 (ref. 6 above).

22. Greenwood P, Greenhalgh A, Baker C, Unsworth M (1982) A computer controlled system for exposing field crops to gaseous air pollutants. Atmos. Environ. 16:2261-2266.

23. Harper LA (1971) Mass and energy transfer between the atmosphere and two plant canopy types. Ph.D. Dissertation, University of Georgia, Athens, GA. Univ. Microfilms Diss. Abstr. No. 72-2488.

24. Harper LA, Baker DN, Box JE Jr., Hesketh JD (1973a) Carbon dioxide and the photosynthesis of field crops: A metered carbon dioxide release in cotton under field conditions. Agron. J. 65:7-11.

25. Harper LA, Box JE Jr., Baker DN, Hesketh JD (1973b) Carbon dioxide and the photosynthesis of field crops. A tracer examination of turbulent transfer theory. Agron. J. 65:574-578.

26. Hendrey GR (1987) Free Air Carbon Dioxide Enrichment (FACE) Facility Development--Progress Report. BNL-40305 Informal Report, July 1987. Dept. of Applied Science, Brookhaven National Lab., Upton, NY.

27. Hendrey G, Lewin K, Kolher Z, Daum M (1988a) Control of Ozone Concentrations for Plant Effect Studies. BNL-43589 Informal Report, September 1988. Report to National Council of the Paper Industry for Air and Stream Improvement. Dept. of Applied Science, Brookhaven National Lab., Upton, NY.

28. Hendrey GR, Lewin KF, Lipfert F, Kolher Z, Daum M (1988b) Response of Vegetation to Carbon Dioxide--045. Free-air carbon dioxide enrichment (FACE) facility development: I. Concept, prototype design and performance. Div. of Environmental Biotechnology, Dept. of Applied Science, Brookhaven National Lab., Upton, NY. Program of the U.S. Dept. of Energy, Carbon Dioxide Research Div., Washington.

29. Hendrey GR, Lipfert FW, Kimball BA, Hileman DR, Bhattacharya NC (1988c) Response of Vegetation to Carbon Dioxide--046. Free air carbon dioxide enrichment (FACE) facility development: II. Field tests at Yazoo City, MS, 1987. Prepared by Brookhaven National Lab., USDA Water Conservation Lab., and Tuskegee University. Program of the U.S. Dept. of Energy, Carbon Dioxide Research Div., Washington.

30. Hendrey GR, Lewin KF, Lipfert F, Daum M, Kolber Z, Evans LS (1988d) Free-air carbon dioxide (FACE) facility development III. Operation and performance of multiple FACE arrays at Yazoo City, 1988. Dept. of Applied Science, Brookhaven National Lab., Upton, NY.

31. Hogsett WE, Olszyk D, Ormrod DP, Taylor GE Jr., Tingey DT (1987a) Air Pollution Exposure Systems and Experimental Protocols. Volume 1: A Review and Evaluation of Performance. EPA 600/3-87/037a. Environmental Research Laboratory, Office of Research and Development, U.S. Environmental Protection Agency, Corvallis, OR.

32. Hogsett WE, Olszyk D, Ormrod DP, Taylor GE Jr., Tingey DT (1987b) Air Pollution Exposure Systems and Experimental Protocols. Volume 2: Description of Facilities. EPA 600/3-87/037b. Environmental Research Laboratory, Office of Research and Development, U.S. Environmental Protection Agency, Corvallis, OR.

33. Irving PM, Miller JE (1981) Productivity of field-grown soybeans exposed to acid rain and sulfur dioxide alone and in combination. J. Environ. Qual. 10:473-478.

34. Irving PM, Miller JE (1984) Synergistic effect on field-grown soybeans from combinations of sulfur dioxide and nitrogen dioxide. Can. J. Bot. 62:840-846.

35. Kretchman DW (1969) CO_2 enrichment of outdoor crops. An interim report. Ohio Agricultural Research and Development Center, Dept. of Hort., Wooster, OH, 67 p.

36. Kretchman DW (1970) CO_2 enrichment of outdoor crops. Interim report III. Ohio Agricultural Research and Development Center, Dept. of Hort., Wooster, OH, 22 p.

37. Laurenroth WK, Milchunas DG, Dodd JL (1983) Response of a grassland to sulfur dioxide and nitrogen additions under controlled SO_2 exposure. Environ. Exp. Bot. 23:339-346.

38. Lee JJ, Lewis RA, Body DE (1975) A field experimental system for the evaluation of the bioenvironmental effect of sulfur dioxide. In D Wilson and F Clark (eds). Proceedings of the Fort Union Coal Field Symposium. Volume 5, Montana Academy of Science, Billings, Montana, pp 608-620.

39. Lee JJ, Lewis RA (1976) Field experimental component. In RA Lewis and AS Lefohn (eds). The Bioenvironmental Impact of a Coal-Fired Power Plant. First Interim Report, Colstrip, Montana -- December 1974, U.S. Environmental Protection Agency, Corvallis, OR, EPA-600/3-76-002, pp 95-101.

40. Lemon E (1977) The land's response to more carbon dioxide. In NR Anderson and A Malahoff (eds). The fate of fossil fuel CO_2 in the ocean. U.S. Office of Naval Research, Symposium Series in Oceanography. Plenum Publishing Corp., New York, pp 97-130.

41. Lemon ER (ed) (1983) CO_2 and plants: The response of plants to rising levels of atmospheric carbon dioxide. AAAS Selected Symp. 84. Westview Press, Boulder, CO.

42. Lister RA (1974) The effects of increasing atmospheric carbon dioxide and particles on plant photosynthesis. Ph.D. Thesis, Cornell University, Ithaca, NY, 159 p. Univ. Microfilms Diss. Abstr. No. 75-4257.

43. Lister RA, Lemon ER (1976) Interactions of atmospheric carbon dioxide, diffuse light, plant productivity, and climate processes--model predictions. In Atmospheric-Surface Exchange of Particulate and Gaseous Pollutants. ERDA Symposium Series 38:112-135 (Jan. 1976) CONF-740921, NTC, U.S. Dept. of Commerce, Springfield, VA.

44. Lundegårdh H (1927) Carbon dioxide evolution of soil and crop growth. Soil Sci. 23:417-449.

45. McLeod AR, Fackrell JE (1983) A Prototype System for Open-Air Fumigation of Agricultural Crops. 1. Theoretical Design. Central Electricity Generating Board, Technology Planning and Research Division. Report TPRD/L/2474/N83. Leatherhead, United Kingdom.

46. McLeod AR, Alexander K, Hatcher P (1983) A Prototype System for Open-Air Fumigation of Agricultural Crops. 2. Construction and Description. Central Electricity Generating Board, Technology Planning and Research Division. Report TPRD/L/2475/N83. Leatherhead, United Kingdom.

47. McLeod AR, Fackrell JE, Alexander K (1985) Open-air fumigation of field crops: Criteria and design for a new experimental system. Atmos. Environ. 19:1639-1649.

48. McLeod AR, Baker CK (1988) The use of open field systems to assess yield response to gaseous pollutants. In WW Heck, OC Taylor, DT Tingey (eds). Assessment of Crop Loss from Air Pollution. Elsevier, New York. pp 181-210.

49. Miller JE, Sprugel DG, Smith HJ, Xerikos PB (1980) Open-air fumigation system for investigation of sulfur dioxide effects on crops. Phytopathology 70:1124-1128.

50. Miller JE, Prepejchal W, Smith HJ (1981) Relative sensitivity of field corn hybrids to ozone: A field study. Report No. ANL-81-85-III. Argonne National Laboratory, Illinois, pp 30-36.

51. Moser TJ, Nash TH, Clark WD (1980) Effects of long-term field sulfur dioxide fumigation of Arctic caribou forage lichens. Can. J. Bot. 58:2235-2240.

52. Northrop Services Inc. (1983) Work Assignment 5. Air quality related values. Air pollution fumigation studies, No. 1. SP4162-83-08. Research Triangle Park, North Carolina, 34 p.

53. Preston EM, Lee JJ (1982) Design and performance of a field exposure system for evaluation of the ecological effect of SO_2 on native grassland. Environ. Monit. Assess. 1:213-228.

54. Runeckles VC, Palmer KT, Trabelsi H (1981) Effects of field exposures to SO_2 on Douglas fir, Agropyron spicatum, and Lolium perenne. Silva Fennica. 15:505-515.

55. Shinn JH, Allen LH Jr. (1985) An evaluation of free-air carbon dioxide enrichment (FACE) as a field method for investigation of direct effects of carbon dioxide on plants. UCRL-93635. Lawrence Livermore National Laboratory, Livermore, CA. Prepared for U.S. Dept. of Energy, Carbon Dioxide Research Div., Washington.

56. Takami S, van Bavel CHM (1975) Distribution of carbon dioxide released in a field crop. J. Agric. Meteorol. (Japan) 31:29-42.

57. Thomas RB, Strain BR (1991) Root restriction as a factor in photosynthetic acclimation of cotton seedlings grown in elevated carbon dioxide. Plant Physiol. 96:627-634.

58. Thompson CR, Olszyk DM, Kats G, Bytnerowicz A, Dawson PJ, Wolf JW (1984) Effects of O_3 or SO_2 on annual plants of the Mojave Desert. J. Air Pollut. Contr. Assoc. 34:1017-1022.

59. Uchijima Z, Inoue K (1970) Studies of energy and gas exchange within crop canopies. (9) Simulation of CO_2 environment within a canopy. J. Agr. Meteorol. (Japan) 26:5-18.

60. Waggoner PE (1969) Environmental manipulations for higher yields. In JD Eastin, FA Haskins, CY Sullivan, CHM van Bavel (eds). Physiological Aspects of Crop Yield. Amer. Soc. of Agron., Madison, WI pp 343-373.

61. Wittwer SH, Robb WM (1964) Carbon dioxide enrichment of greenhouse atmospheres for food crop production. Econ. Bot. 18:34-56.

BROOKHAVEN NATIONAL LABORATORY
FREE AIR CARBON DIOXIDE ENRICHMENT FACILITY

Keith F. Lewin, George R. Hendrey and Zbigniew Kolber
Department of Applied Science
Brookhaven National Laboratory
Upton, NY 11973

I. INTRODUCTION

When evaluating the effects of gases on crops, forests or other ecosystems, the experimenter is faced with the problem of trying to produce an exposure regime in which only the variables chosen to be investigated are altered, while other features of the remaining edaphic environment remain in a natural state. This type of experiment has often been hampered by an inability to create an experimental environment free of artifacts introduced by the structures and equipment used to expose the target ecosystem to the test gas. These are generally described as "chamber effects" and include changes in wind velocity, humidity, temperature, light quality or intensity, and soil variables. In the quest for a more realistic experimental design, researchers have moved their plant fumigation studies from the highly controlled and unnatural environment of the greenhouse or growth chamber to open-top chambers. The primary benefit of this shift has been to reduce experimental artifacts associated with soil variables. Many of the other limitations of chambers have remained, as discussed by Unsworth and Mansfield (1980).

The elimination of chamber effects has been attempted by the use of exposure protocols in which a fumigant is released into ambient air without the use of a containment structure. The historical development of free air exposure systems is reviewed in Chapters 3 and 4 by McLeod *et al.* (1985). A drawback to free air systems has been the inability to rigorously control the concentration of the gas being tested. With ground-level gas release systems, concentrations of more than double the desired exposure concentration have frequently occurred under still-air conditions, even when data are averaged over periods as long as an hour (Chapter 3, and Bruce Kimball, pers. comm.). While some experimental designs call for variation of the treatment concentration in order to mimic the stochastic nature of pollutant concentrations, control of short-term variations has proven elusive.

In this chapter we describe the design and operation of a Free Air Carbon Dioxide Enrichment (FACE) facility which was established at the University of Arizona Maricopa Agricultural Center at Maricopa, Arizona, during 1989. This facility is capable of exposing large numbers of field-grown plants to elevated levels of atmospheric carbon dioxide for all daylight hours between seedling emergence and physiologic maturity. The design of the exposure system used at this site offers significant improvements over those used in previous chamberless fumigation experiments. It has been used with crop canopies ranging from bare earth to 1.75 meters tall and with leaf area indexes up to 6. While specifically designed for carbon dioxide enrichment experiments, the same design has been successfully operated using sulfur dioxide and ozone as the fumigants.

II. DESIGN OBJECTIVES

The major objective for the design of the Brookhaven National Laboratory (BNL) FACE Facility was to develop a chamberless system that would maintain a set, elevated CO_2 concentration with minimal variability. After examining the various methods used to experimentally fumigate unenclosed field plots, we concluded that a cylindrical array of emitters, similar to the design used by Mooi and van der Zalm (1985a, 1985b) and McLeod *et al.* (pers. comm.) would be the most appropriate. Our design achieved this cylindrical shape by emitting the test gas from multiple ports located on a circular array of vertical vent pipes which are connected at their bases to a common toroidal plenum. This emitter port arrangement results in the merging of individual plumes within a few meters of injection, providing a quasi two-dimensional concentration field which decays only slightly in the down-wind direction. The normal variability in wind direction tends to smooth out the long term average concentrations around the annular array. Gas concentration variability has been reduced by using high rates for sampling the parameters used by the control algorithm and for adjusting the control signals. Control calculations are based on measurements of wind speed, wind direction, and test gas concentration, taken at one-second intervals. The release rate of the test gas is also adjusted every second and the selection of vent pipes to release the test gas is updated every four seconds.

III. ARRAY HARDWARE

The BNL FACE Facility is presently configured to study the effects of carbon dioxide enrichment on cotton (*Gossypium hirsutum* L.). It has four independently controlled circular treatment arrays, each having its own sampling instrumentation, carbon dioxide flow controller and high volume blower to supply ambient air for predilution of the CO_2. Four control plot areas are situated at least 100 m from the nearest treatment array in order to minimize contamination of the control plots by the carbon dioxide released from the treatment arrays (Figure 5-1). Each of the treatment arrays has 32 vertical vent pipes, with each vent pipe containing multiple gas emitter ports. Each vent pipe in an array is connected to a common

22 m diameter toroidal distribution plenum through an individually controlled ball valve (Figure 5-2). A high-volume blower (Buffalo Forge, Model 35-V) draws ambient air through two 60 x 60 x 5 cm glass fiber filter packs to remove coarse particles and injects it into the plenum at a rate of about 50 m^3 per minute with a pressure of about 1.2 kPa (4.8 inches H_2O) above ambient. The pure carbon dioxide is mixed with the ambient air by placing the outlet from the CO_2 flow controller directly in front of the blower intake. This arrangement uses the turbulence created by the fan blades to thoroughly mix the CO_2 with the ambient air prior to the mixture's entry into the plenum.

The amount of CO_2 metered into the air stream entering the plenum is based on wind speed and gas concentration sampled at the center of the array. An empirically derived proportional, integrative, differential (PID) control algorithm adjusts the amount of test gas introduced into the plenum. Another algorithm, which considers both wind direction and speed, controls which vent pipes emit this CO_2 enriched air. These two algorithms work together to maintain the desired concentration within the central area of the FACE array while minimizing CO_2 usage. Minimizing CO_2 usage reduces not only operating costs but also the probability of contaminating adjacent treatment and control areas

The 22 m diameter plenum is assembled from polyvinyl chloride (PVC) pipe with an internal diameter of 30 cm. The vent pipes are made from PVC pipe with an internal diameter of 5 cm and are each 2.2 m long. Each vent pipe has 15 emission ports, with each port having a diameter of 2 cm. The ports are placed in five groups of three ports each in evenly spaced horizontal rows. The grouped ports are arranged so that the center port faces the center of the circular array, with the adjacent ports angled from the center port in the same plane by 60 degrees on each side. The rows of ports are vertically spaced 50 cm apart along the length of the vent pipe, with the lowest hole positioned about 20 cm above the soil surface. An electrically controlled, pneumatically actuated, quarter-turn ball valve with a port diameter of 5 cm is located between the torus and each vertical vent pipe, allowing each pipe to be independently controlled. Individual ports or rows of ports are manually opened or closed as needed to accommodate changes in the height and density of the plant canopy. In the 1989 growing season, the emitting port configuration was changed five times.

IV. CARBON DIOXIDE SUPPLY COMPONENTS

Liquid carbon dioxide is stored at the site in a 48,000 kg capacity insulated tank. Tank pressure is maintained at 1725 kPa (250 psig), which keeps the CO_2 in a liquid state. A refrigeration unit and a heater are used to maintain this pressure regardless of demand. Under normal operation, liquid CO_2 is fed to heat exchangers which vaporize the CO_2 as needed. The heat exchangers at this site use water at ambient temperature as the source of heat. This water can be drawn from either an irrigation canal or a pond located next to the vaporizers. The vaporizing system is configured as two independent modules, either of which can supply sufficient CO_2 for normal operations. This arrangement allows for

maintenance to be performed on the vaporizing system without shutting off the CO_2 supply to the experiment. The modules can also operate together to meet high CO_2 demands. In order to reduce energy costs for refrigerating the liquid CO_2 in the tank, gaseous CO_2 is shunted from the tank to the gas supply line if tank pressure exceeds 1795 kPa above ambient (260 psig). When the facility is in daily operation, this arrangement eliminates the need for operating either the refrigeration or heating units provided for regulation of tank pressure.

The gaseous CO_2 is channeled through 5 cm internal diameter (ID) steel piping to the edge of the field site, adjacent to the control trailer. There it passes through four pressure regulators, one for each treatment array, which reduce the line pressure from tank pressure to 105 kPa above ambient (15 psig). Each regulator is equipped with both manual and electrically actuated shut off valves. The CO_2 gas, now under low pressure, is piped out to the individual arrays using 5 cm ID polyethylene tubing.

At each fan housing, the gas is fed into a mass flow controller which regulates flow based on signals received from the control program. The flow rate can be regulated from 0 to 190 L s^{-1} (0-400 SCFM). Since the outlet of the flow controller is positioned just in front of the blower intake and the fan draws air in at a constant rate, the actual CO_2 concentration varies in direct proportion to demand for CO_2, while the total flow of enriched air through the plenum remains constant.

V. WIND MONITORING COMPONENTS

The concentration of CO_2 within a FACE array is a function of its rate of release, wind speed and turbulence. The gas control system is designed to maintain CO_2 releases that are always upwind of the center of the FACE array. This is achieved by measuring wind direction using a wind direction sensor (Climatronics model 101871) positioned above the canopy at the center of each array. The algorithm controlling the vent pipe ball valves uses the signal from this sensor to keep the vent pipe valves on the upwind side of the array open. Since the wind direction sensor is insensitive to changes in direction at wind speeds below 0.4 m s^{-1}, at wind speeds below this threshold alternate vent pipe valves are opened around the entire array. The system then operates without directional control. The vent pipe valve opening patterns at both above and below the 0.4 m s^{-1} threshold are shown in Figure 5-3.

Wind speed is measured with a cup anemometer (Climatronics model 100075) located adjacent to the direction sensor at each array. Minimum detectable wind speed is 0.3 m s^{-1}.

VI. CO_2 CONCENTRATION MONITORING COMPONENTS

A non-dispersive infrared (NDIR) CO_2 analyzer (Siemens Ultramat model 21P) is placed adjacent to each array to continuously monitor the gas concentration at each experimental plot. Air is sampled from the center of the array, with the inlet height adjusted as needed to keep the sampling port between 5 and 25 cm above the canopy. The sampled air is

pumped at 2.5 l/min through approximately 17 meters of 4.3 mm ID polyethylene tubing before it reaches the analyzer. The time for the sample to traverse this distance, along with measurement delays inherent in the analyzer, results in a total delay of 7 to 10 seconds between when the air sample enters the sampling tube and when the resulting concentration is delivered to the control program.

The Siemens CO_2 analyzer has an accuracy of 1% of its full scale range of 0 - 1000 μmol mol^{-1}, or 10 μmol mol^{-1}. The output signal from the analyzer can be read with a resolution of 1 μmol mol^{-1}. Any changes which may have occurred to the absolute carbon dioxide concentration as the air sample passed through the sampling tubing were well below the accuracy of the analyzer and not discernible from normal instrument variability.

VII. CONTROL PROGRAM AND HARDWARE

It is not possible to achieve acceptable control of CO_2 by simply making its release directly proportional to wind velocity, due to the time delay between release of the CO_2 at the mass flow controller and its distribution within the control area of the array, and due to variations in ambient turbulence. For this reason, a custom control program was written which allows complex interactions between the sampling and control hardware. An extensive operator interface is provided which allows the system operator to view both the present and historical operation of the system in either textual or graphic modes. The operator can also adjust many of the integration and weighting functions from the keyboard, so that the system can be fine tuned while operating and adjusted as needed during the experiment. Provisions are also made for data backup onto removable media, reporting alarms and accessing the control program from a remote terminal.

The control program collects information from several sensing devices and uses this information to formulate output signals which control the fumigation system. Analog signals from the wind sensors, the CO_2 flow controller and the CO_2 analyzer located at each array are passed to a circuit board containing 16 analog-to-digital (A/D) converters (Metrabyte model MAI-16) coupled by a 50-conductor ribbon cable to an interface board (Metrabyte model MID-64) in an Intel 80286 based microcomputer. These signals are the inputs to a modified PID algorithm which has the form:

$$F_{total} = F_{integ} + F_{prop} + F_{diff} + F_{wind}$$

where:

$$F_{integ} = F_{integ} - a_{integ} * e \quad = \quad F_0 - a_{integ} \int_0^t e \, dt$$

$$F_{prop} = - a_{prop} * L_{45}(e)$$

$$F_{diff} = - a_{diff} * L_{45}(de/dt)$$

$$F_{wind} = L_{900}(F_{total}) * [L_{20}(u) - L_{900}(u)] / [L_{900}(u) - a_{wind}]$$

In these equations, F_{total} represents the output signal to the CO_2 flow controller. F_{integ}, F_{prop}, F_{diff} and F_{wind} represent the parts of the total flow control signal supplied by the integral, proportional, differential and wind speed (u) components of the algorithm. The difference between the actual gas concentration and the set point (error) is represented by "e". The scaling factors a_{integ}, a_{prop}, a_{diff} and a_{wind} allow the operator to change the relative contribution of each component in the algorithm. L_t signifies a low pass filter with a time constant of "t" seconds applied to the argument.

The first three terms are a standard PID algorithm using negative feedback. The first term, F_{integ}, is the dominant one and represents the long term CO_2 demand due to changes in vertical dispersion, wind speed, emitting port configuration, and array diameter. The next two terms, F_{prop} and F_{diff}, represent short-term adjustments. Their size and sign depend on the magnitude and direction of the error and the rate at which the error is changing. A low pass filter with a 45-second time constant is used to prevent the control system from chasing very short term variations.

The last term, F_{wind}, is not part of a standard PID algorithm. It anticipates changes in gas demand due to changes in wind speed. The software accomplishes this by accumulating 15-minute averages of wind speed and gas demand. More or less gas is released depending on whether the short term average wind speed is greater or less than the long term average. The a_{wind} parameter accounts for the fact that gas demand is not strictly proportional to wind speed. Some gas input would be required even at zero wind speed due to diffusion and vertical dispersion of the gas out of the experimental plot area.

This algorithm is solved independently for each array and is sent from the microprocessor to digital-to-analog converters (Metrabyte model MAO-8) which send corresponding voltage signals to the appropriate CO_2 mass flow controllers. The microprocessor also passes signals derived from the wind direction algorithm through solid-state relay interfaces (Metrabyte model MAI-32) to actuate solenoid valves which control the pneumatically actuated ball valves on the vent pipes. Other signals derived from the control program are passed through solid-state relay interfaces (Metrabyte model MAI-16) to switch the blowers and CO_2 supply lines on and off at operator-specified times.

VIII. SYSTEM PERFORMANCE

Prior testing of the facility components and design concepts at Brookhaven National Laboratory and at a field site in Yazoo City, Mississippi, during the period 1986 - 1988 established this as a functional and highly reliable FACE system. Similar designs have been used for the control of sulfur dioxide and ozone concentrations over a grass meadow as well as control of carbon dioxide in cotton (Hendrey *et al.* 1988a, 1988b, 1988c). With all gases tested, the system has been able to maintain one-minute average gas concentrations within 20% of the set point for greater than 90% of the operating time. Temporal and spatial variability of the carbon dioxide concentrations in the experimental plot

areas within the treatment arrays will be discussed in greater detail in subsequent chapters.

Adjustments and improvements made in the design and operation of the system as a result of these prior studies resulted in even better system performance at the Maricopa site. In 1989, an analysis of carbon dioxide concentration data collected once each minute at the top of the canopy in the center of each exposure plot showed that over the entire treatment period, the four arrays each maintained one minute average gas concentrations within 20% of the 550 μmol mol^{-1} target for greater than 97% of the total operating time and within 10% of the target concentration for greater than 86% of the time.

These improvements also increased the operational reliability of the FACE facility, which is critical if it is to be used by a large group of researchers for long-term biological studies. In the 1989 experiment, arrays 1, 2 and 4 were never shut down or out of control for as much as an entire day between the time fumigation of the plots started and the conclusion of carbon dioxide treatments at crop maturity. Overall, arrays 1, 2 and 4 were operating properly for better than 96% of the treatment period. Array 3, which was classified at the start of the experiment as the least critical array for continuous treatment, due to its designation as the "engineering studies array", operated for 92% of its potential exposure time between its start up and the conclusion of CO_2 exposures. All four arrays exceeded the design criteria of operating for greater than 90% of the potential exposure period once the treatments were begun. A detailed examination of the operational reliability of the facility is presented in Chapter 6.

IX. CONCLUSIONS

The BNL FACE Facility can provide a useful and reliable research platform for studying the effects of elevated atmospheric carbon dioxide levels on plant growth in an open-field setting. Since it uses a chamberless design, the fumigation system does not impose a discernible chamber effect on the plants grown in the test plots. The incorporation of a microcomputer-based control system using short time steps for sampling and control signals provides a high degree of control over the gas concentration within the experimental plots.

Although designed for the exposure of cotton plants to elevated levels of carbon dioxide, the fumigation system has been successfully operated using both sulfur dioxide and ozone as the test gases. Future plans include the introduction of water stress as a coincident experimental variable, studying the effect of larger array diameters on control and the adaptation of the present design to other plant species and ecosystems.

REFERENCES

1. Hendrey GR, Lewin KF, Kolber Z, Daum M (1988a) Control of ozone concentrations for plant effect studies. Brookhaven National Laboratory Informal Report No. 43589 Upton, New York.

2. Hendrey GR, Lewin KF, Lipfert F, Kolber Z, Daum M (1988b) Response of vegetation to carbon dioxide. Free air carbon dioxide enrichment (FACE) facility development: I. Concept, prototype design and performance. Series Report No. 45, Carbon Dioxide Research Division, Office of Basic Energy Sciences, U.S. Department of Energy, Washington.

3. Hendrey GR, Lipfert F, Kimball BA, Hileman DR, Bhattacharya NC (1988c) Response of vegetation to carbon dioxide. Free air carbon dioxide enrichment (FACE) facility development: II. Field tests at Yazoo City, MS, 1987. Series Report No. 46, Carbon Dioxide Research Division, Office of Basic Energy Sciences, U.S. Department of Energy, Washington.

4. McLeod AR, Fackrell JE, Alexander K (1985) Open-air fumigation of field crops: Criteria and design for a new experimental system. Atmospheric Environment 19:1639-1649.

5. Mooi IJ, van der Zalm AJA (1985a) Research on the effects of higher than ambient concentrations of SO_2 and NO_2 on vegetation under semi-natural conditions: The developing and testing of a field fumigation system; process description. First Interim Report to the Commission of the European Communities, EEC Contract ENV-677-NL. January - December 1983. Research Institute for Plant Protection, Wageningen, Netherlands.

6. Mooi IJ, van der Zalm AJA (1985b) Research on the effects of higher than ambient concentrations of SO_2 and NO_2 on vegetation under semi-natural conditions: The developing and testing of a field fumigation system; Execution. Second Interim Report to the Commission of the European Communities, EEC Contract ENV-677-NL. January - December 1984. Research Institute for Plant Protection, Wageningen, Netherlands.

7. Unsworth MH, Mansfield JA (1980) Critical aspects of chamber design for fumigation experiments on grasse. Envir. Pollut. 23:115-120.

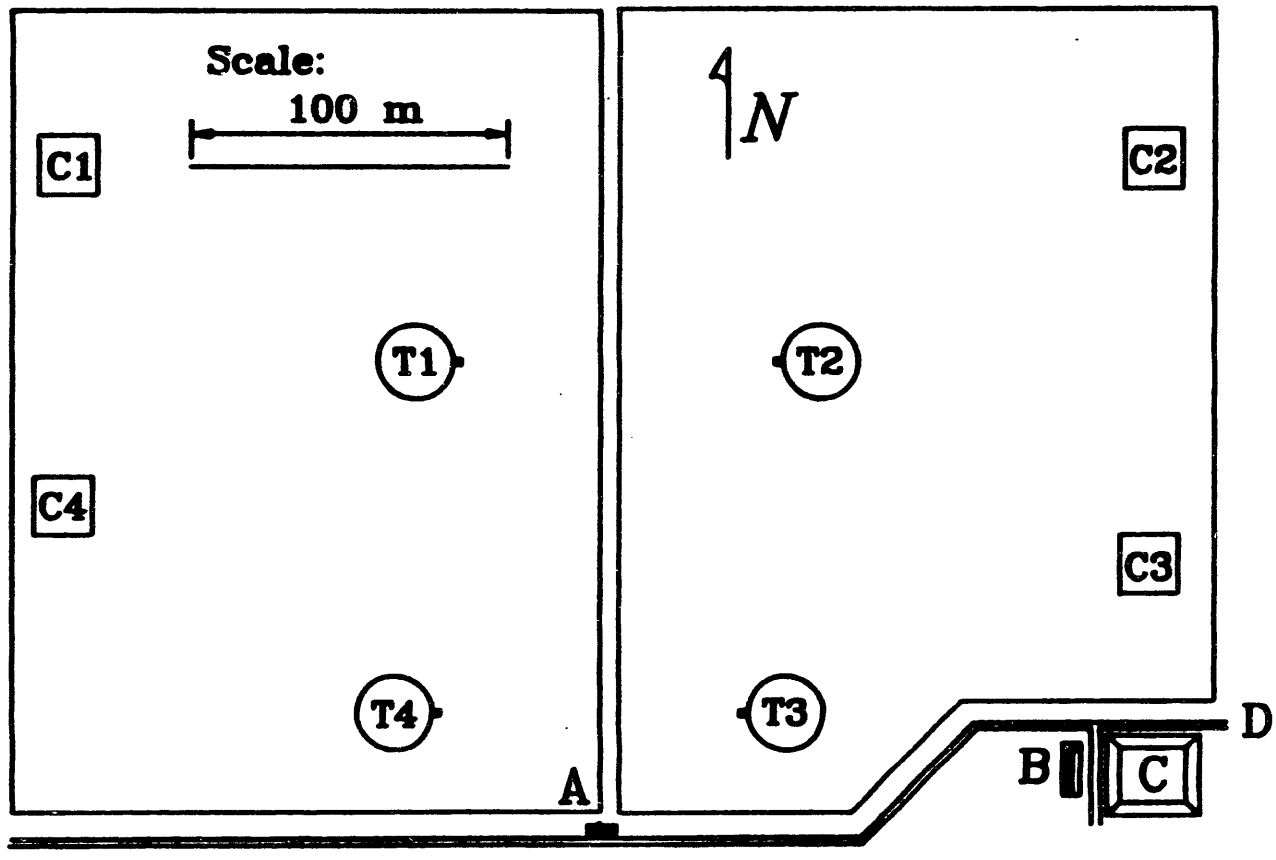
LEGENDS

Figure 5-1. Diagram of the FACE Facility at Maricopa, AZ showing: A - the central control trailer, B - CO_2 storage reservoir and vaporizers, C - water storage pond and D - irrigation canal. T1 through T4 and C1 through C4 represent the treatment arrays and the control areas, respectively.

Figure 5-2. Major components of an individual treatment array. The fan housing contains the high volume blower, particulate filters, CO_2 flow controller and CO_2 concentration analyzer.

Figure 5-3. Vent pipe valve opening patterns for a treatment array when wind speed is either above or below the 0.4 m s^{-1} detection limit of the wind direction sensor.

Fig 5-1



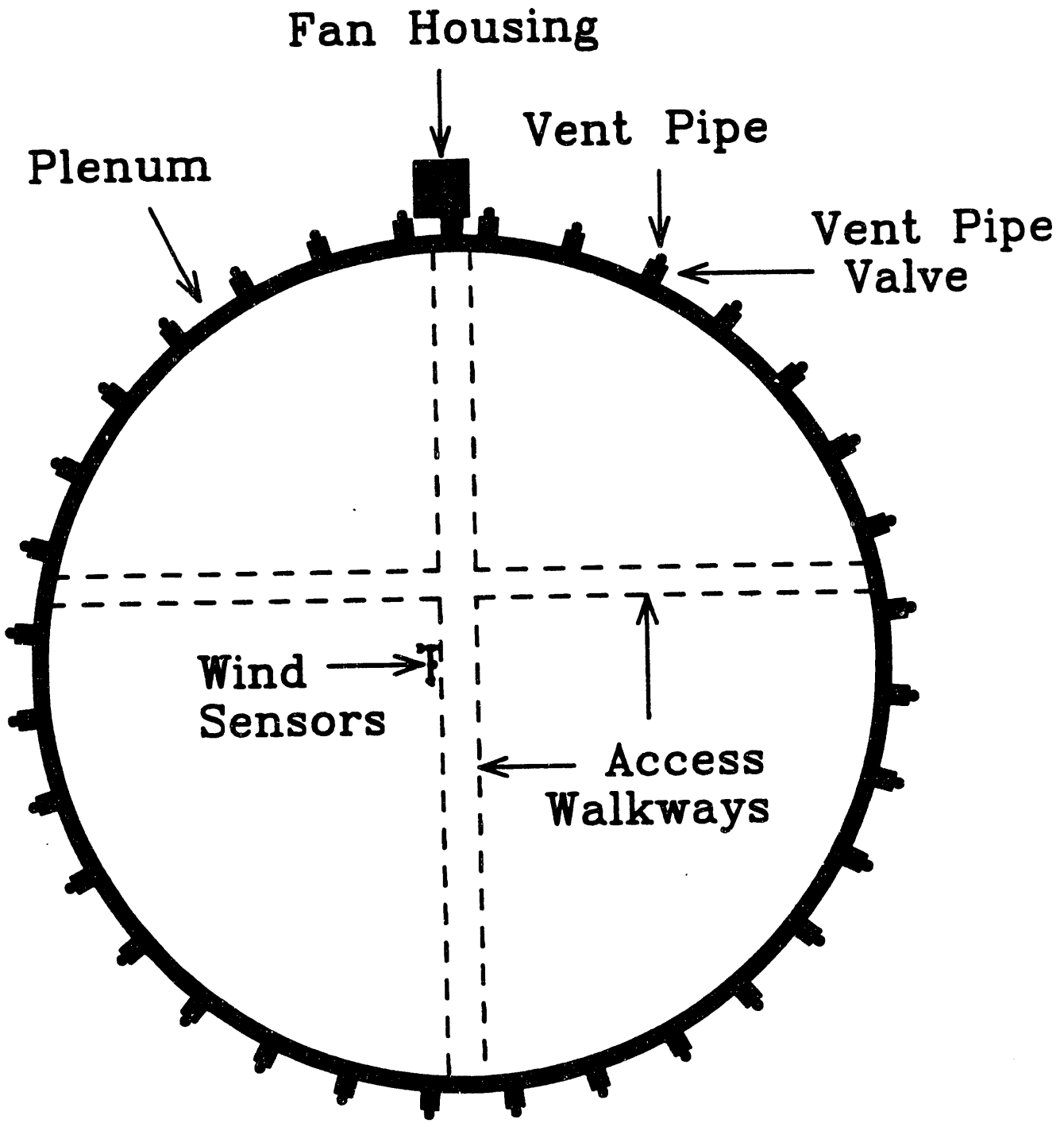

Fan Housing
Vent Pipe
Plenum
Vent Pipe
Valve
Wind
Sensors
Access
Walkways

Fig 5-2

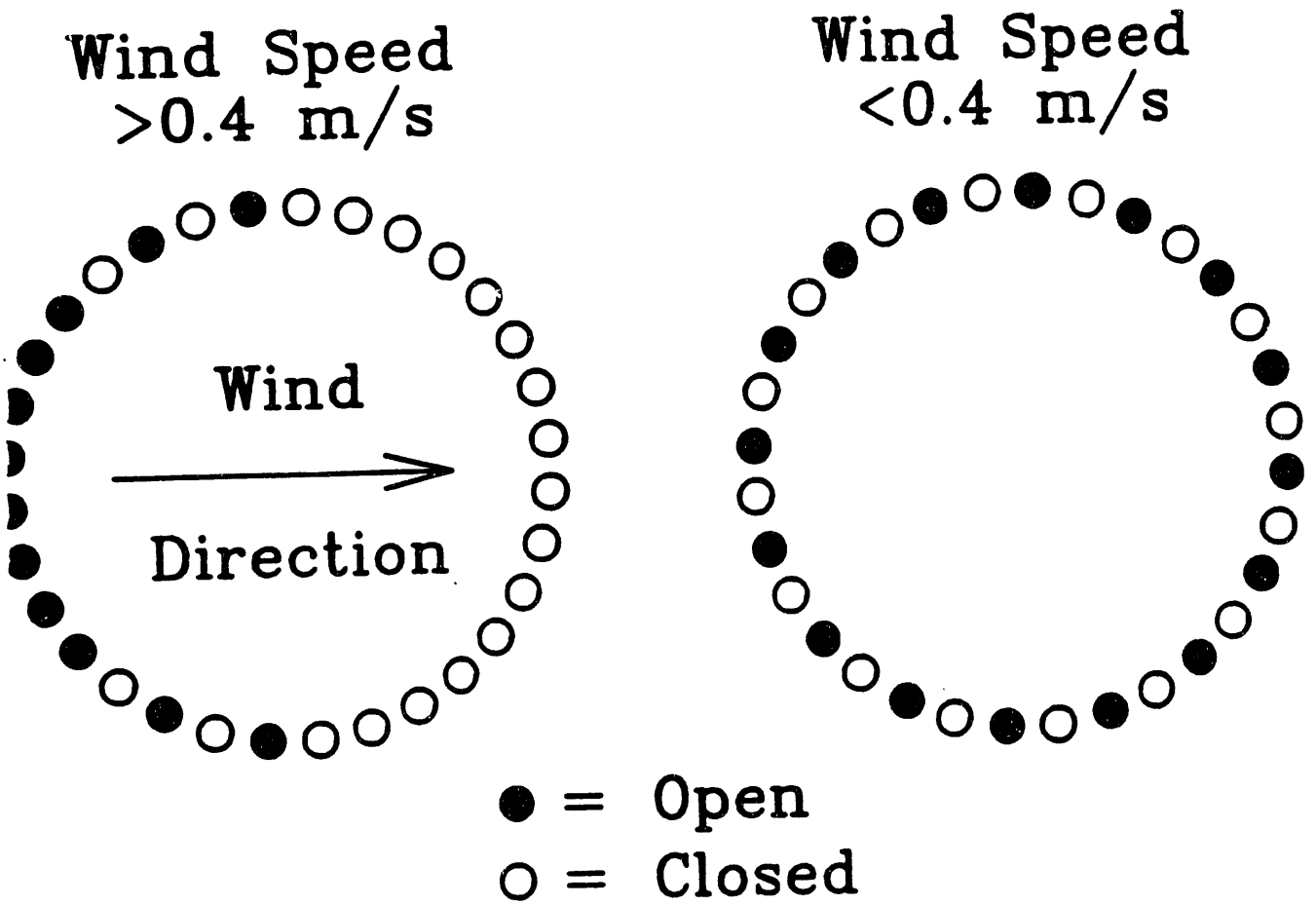


Fig 5-3

PERFORMANCE ANALYSIS OF THE BNL FACE GAS INJECTION SYSTEM

Frederick W. Lipfert, Yehudah Alexander, George R. Hendrey, Keith F. Lewin and John Nagy*
Department of Applied Science
Brookhaven National Laboratory
Upton, NY 11973

*Israel Institute for Biological Research
Department of Mathematics
70450 Ness Ziona, Israel

I. INTRODUCTION

As described elsewhere in this volume, the criteria for successful operation of a FACE-type crop fumigation system include the spatial uniformity of the gas injected over the crop growing area, the efficiency of gas usage, and the overall cost of the system. Efficiency of gas usage is important not only from a cost standpoint, but also to reduce the distances required to preclude interference between replicate FACE arrays or control plots. The details of the FACE design and analyses of the important fluid mechanical concepts are described below. A more detailed description of the hardware was given in Chapter 5. Additional FACE performance and CO_2 distribution data are given in Chapter 7.

II. GENERAL DESIGN PRINCIPLES

The BNL FACE system operates with two fluids: the carrier gas (ambient air) and the injection gas (CO_2 for the purposes of this chapter, although other experiments have been performed with SO_2 and with ozone). There are a number of interacting criteria to consider in designing such a system. For example, sizing the air handling components as large as possible reduces pressure drops due to frictional losses but increases hardware costs and the physical blockage presented to the wind. Also, low internal flow rates increase the system residence time, which may be undesirable from the standpoint of stability of the control system.

The air handling system might be simplified if the injection gas were emitted at essentially 100% concentration, but this would require dilution by three orders of magnitude between the injection point and the experimental plot. The early experiments reported by Allen in Chapter 4 showed how difficult this task could be. Even if such large amounts of atmospheric dilution could be achieved upstream of the desired area, it would be extremely difficult to prevent further dilution from taking place within the experimental plot, which would lead to unacceptably large spatial gradients within the plot. One solution to this problem is pre-dilution of the injection gas upstream of the injection points,

i.e., within the air handling system. However, this concept also has limits. For example, the need for atmospheric mixing could be completely eliminated if the injection gas were emitted directly at the desired plant exposure concentration. For an array 2 m high and 22 m in diameter and an average wind speed of 1 m s^{-1}, this would require a flow rate of 44m^3 s^{-1} (2640 m^3 min^{-1}), which would correspond either to very large pipe sizes or very high velocities. Dissipation of high injection velocities down to the level of normal wind speeds would inevitably result in further dilution and unacceptable spatial concentration gradients.

A reasonable compromise between these two design extremes is to split the difference, i.e., to accomplish roughly half of the dilution (in terms of ratios) as pre-dilution and half in the atmosphere. For an experiment involving an increment of 200 μmol mol^{-1} of CO_2 above ambient, this means injecting at a concentration of $(200 * 10^{-6})^{0.5}$ or about 1.4%. The air flow required to do this at a mean wind speed of 1 m s^{-1} is 2640*0.014 or about 40 m^3 min^{-1}. If the dilution in momentum is to match the dilution in concentration, the injection jets should operate at (1/0.014)*mean wind speed, or about 70 m s^{-1}. This establishes the approximate pressure head requirements for the fan or blower.

The cross-wind uniformity of the injection gas can be enhanced by increasing the number of injection points distributed in the plane normal to the wind. For a situation with essentially random wind directions, a circular array has the advantage of treating all directions alike. Thus, the limit to cross-wind uniformity may be set by the amount of wind blockage created by the vertical vent pipes. Use of lateral (inclined) as well as radial injection ports in the BNL FACE system effectively triples the number of vent pipes without imposing additional blockage or hardware expense. Also, the interaction of jets inclined to the wind promotes more rapid mixing.

In addition to the requirement for horizontal uniformity of the injection gas, there is also a requirement for vertical uniformity. With a low growing crop or a very open canopy, this is less critical than it might be with a dense canopy. The transport wind speeds within a dense canopy are a fraction of the undisturbed wind speed, which can lead to pooling of the injection gas and can create regions of very high concentration. The solution to this problem has been found to be a vertically-tailored gas injection profile, which can be accomplished by proper design of the vertical vent pipes.

These are the main design features of the BNL FACE System which, in conjunction with the feedback-control system, allowed us to succeed in spite of the fundamental difficulties discussed by Allen in Chapter 4.

III. FACE COMPONENTS, FUNCTIONS, AND CHARACTERISTICS

The BNL FACE system consists of a blower or fan to move the air, a toroidal plenum chamber, an array of 32 vertical vent pipes spaced uniformly around the ring, each 2.25 m in length with an on/off valve, and various sensors and control equipment as described in Chapter 3. The toroidal plenum chamber is referred to as a FACE ring, whereas the complete assembly is referred to as a FACE array.

A. Air supply

The carrier gas is supplied by a fan (Buffalo Forge Model 35-V) which

supplies nominally 50 $m^3 min^{-1}$ (1750 cfm) at about 1.2 kPa (4 in-H_2O) back-pressure above ambient. The factors controlling back pressure include the internal diameters of the valving and vertical vent pipes and the diameter and numbers of injection ports that are open at a given time. As back-pressure increases, the fan output flow decreases, as shown in Figure 6-1; the concave-upward lines emanating from the origin represent the squared dependence of pressure drop on velocity (flow) within the system, and their intersections with the fan characteristic curve (the upper concave-downward line) represent points of steady-state operation. The flow-pressure characteristic operating curve for the fan was taken from the manufacturer's specification.

B. Air handling system

The FACE plenum chamber torus has an internal diameter of 30 cm; as a result, the air-CO_2 mixture travels at a maximum speed of 12 m s^{-1}. Upon entering the torus, the flow divides into two portions and is discharged incrementally through the vent pipes; thus the velocity averaged over the entire plenum is about 3 m s^{-1}. The average travel time is about 6 sec during normal wind speed operation (12 pipes operating) and about 5 sec during the higher flow condition that results with every other pipe open around the ring (16 pipes operating) during low wind conditions. These times are shorter than typical wind travel times through the array and of the same order as the time required to withdraw a sample and measure its CO_2 concentration. These velocities are sufficiently low that pressure drop is negligible in this part of the system and the static pressure is not depressed because of the moving air.

The internal diameter of the valves and vertical vent pipes is 5 cm, so that the total internal flow area with 12 pipes open is 236 cm^2, or about 1/3 that of the plenum. At the entrance to each vent pipe, the internal flow velocity is about 35 m s^{-1} (neglecting friction), which is fast enough to cause pressure losses and a drop in the local static pressure. The pressure equivalent of this velocity level is about 0.5 kPa (2.7 in H_2O). The losses occur due to friction with the walls and because of the abrupt right-angle bend and the valve. These losses could be reduced by enlarging the elbow and valve diameter, but at a considerable increase in hardware costs.

The air-CO_2 mixture is discharged through the injection ports, which are located in groups of three at five different elevations on each vent pipe. The vent pipes have constant internal diameters, so that as flow is discharged, the internal velocity drops and the static pressure increases, according to Bernoulli's equation. Higher internal static pressure allows increased velocity of jet discharge, so that the amount of air-CO_2 mixture discharged increases from bottom to top of the vent pipe, i.e., with height above ground. The total available discharge port area per pipe is 513 cm^2, with all ports open. However, the system is almost never operated in this mode; only two or three rows of open ports are normally used. Furthermore, flow through this kind of relatively sharp-edged orifice results in a contraction of streamlines so that the effective maximum total discharge area is only about 330 cm^2. With three or fewer rows of ports open, the injection ports become the limiting flow area in the system. The theoretical velocity of discharge of the air-CO_2 mixture with two rows of ports open is about 39 m s^{-1}; in practice, there is a velocity profile across the port with higher jet velocities near the center. Although detailed fine-scale

velocity traverses across the open ports have not been made (in part because of the relatively large size of the hot-wire anemometer probe), peak velocities have been measured in the range 20-40 m s^{-1} under various operating conditions.

The sources of pressure drop in the system are the jet discharge, the flow turning in the elbows, and the frictional losses across the valve and in the vertical vent pipes. Since the jet discharge ports are drilled by hand and are not finely machined, there may be some additional losses due to rough edges, burrs, etc. Figure 6-2 shows how the system behaves with different numbers of ports open, taking into account the approximate pressure drops and the characteristic of the blower. Decreasing the number of ports open thus not only changes the locations of the injection jets but also increases the initial CO_2 concentration, since the air flow is reduced.

c. Jet discharge characteristics

The flow through each discharge port depends on the local static pressure drop across the orifice, with the further constraint that the sum of the flows through all ports must equal the output of the blower. As discussed above, this internal pressure distribution changes with height as the internal momentum of the pipe flow is dissipated.

At the lowest row of injection ports, the flow is extremely three-dimensional since the ports are located quite near the 90° bend and the streamlines are still curved at this point. The actual flow conditions near the bend can only be roughly approximated using the simple equations of one-dimensional pipe flow. The static pressure there is the lowest of any point in the system, because of the high overall flow velocity and the losses through the bend. The ports are located on the low-pressure (concave) side of the bend, which further reduces the outflow there. This results in less driving force behind the jet and thus reduced mass flow, more upward momentum than horizontal, and a sharp upward angle to the jets (Figure 6-3), as desired to prevent excess gas at the bottom of the canopy.

For the remaining four rows of ports, the angle of the discharge jet with respect to horizontal can be estimated by assuming that the vertical component is conserved as given from the internal velocity prior to reaching the open port, and by calculating the discharge velocity based on the local static pressure. Given the upward velocity component and the combined exit velocity, the angle may be estimated. This can be an iterative procedure, since the total mass flow through all the open ports must match the fan characteristic performance curve (Figure 6-2).

Figure 6-4 shows the results of such a calculation for the case of all discharge ports open. On the right of the figure is a schematic of a vertical vent pipe and the plenum cross-section; the jet angles and the internal static pressures are indicated. The plenum pressure for this case is 1.2 kPa (3.9 in-H_2O); the difference between that value and 0.64 kPa (2.13 in-H_2O) represents losses in the system. Jet and internal velocities are compared on the left side of the figure. Measurements were made with a Kurtz hot-wire anemometer (Model 1440 M), traversing manually across the ports to find the maximum value. The calculated values represent average velocities, hence they are usually lower than the measured values. The internal velocities were measured by inserting the hot-wire probe through one of the open ports, which would have had a slight effect

on the flow because of cross-sectional blockage; this effect was ignored. The measured internal velocities decrease with height and the jet velocities increase, as predicted.

D. Jet trajectories

The behavior of the injected gases after discharge into the atmosphere may be predicted from the conservation laws of fluid mechanics (conservation of mass, momentum, and energy) and from the equations of jet and plume behavior in a turbulent medium. It is convenient to consider two different scales of analysis: the jet scale pertains to about 100 jet diameters downwind, or roughly 2 m; the array scale pertains to the balance of the array. There is also a far-field scale to consider, mainly from the perspective of interference between adjacent rings.

The analysis of a single turbulent jet in a crossflow has been considered by many authors in classical fluid mechanics (see for example Abramovich 1960; Krausche 1963; Schlicting 1960). However, as seen in Figure 6-5, the BNL FACE design features many intersecting jets; such interactions have received comparatively little theoretical or experimental attention. Presumably, when two intersecting jets are otherwise identical, the opposing lateral components of momentum cancel and the axial components add, so that the combined mass flow travels approximately in the radial direction. In Figure 6-5, the (non-intersecting) jet vectors have been arbitrarily set at 2 m in length; the effects of wind in deflecting the jet trajectories have not been shown, for simplicity. In such a zero-wind case, adjacent jets would interact after about 1.2 m of travel, as shown; with wind, this interaction would occur further downwind, if at all. In Figure 6-5 also, when one considers that under low-wind conditions, every other vent pipe is open, which increases the separation distance and slightly reduces jet velocities, the probability of significant jet interaction is reduced even more.

As a turbulent jet travels downwind, it entrains ambient air by means of fluid viscosity and shear at the jet-ambient interface. The resulting exchange of mass, momentum, and energy result in further dilution of the CO_2 and eventual alignment of the jet with the wind direction. Note that as shown in Figure 6-5 (for the case of 12 pipes open), each vent pipe has a least one jet more-or-less aligned with the wind; the axial momentum ratio of the ensemble is 0.46 (46% of the total initial jet momentum is directed downwind). This calculation did not consider the upward velocity components of the injection jets.

One of the important parameters of turbulent jet analysis is the velocity ratio (V_j/V_o), where V_j is the jet velocity and V_o is the undisturbed (ambient) wind speed. Since jet velocities are of the order of 30 m s^{-1} or more and wind speeds tend to be low (ca. 1 m s^{-1}) at the FACE sites of interest, we have assumed a value of 30 for this parameter, which is in the upper range of the available experimental data. Figure 6-6 shows how the jets deflect as they travel downwind, depending on their initial angles. Note the large difference in scale between downwind and crosswind directions in Figure 6-6. According to these calculations, the maximum cross-wind penetration is less than 2.5 m; one should also keep in mind that jets of this diameter cease to exist as distinct observable entities after about 1-2 m of travel (see photographs below).

Comparing Figures 6-5 and 6-6, and starting with a centrally-located vent

pipe, one can see that the jets from side-opening ports will penetrate about to the position of the adjacent pipe centerline, neglecting interactions (the vent pipes are spaced 2.15 m apart around the ring). Interactions should result in the cancellation of opposing lateral momenta, thus curtailing jet penetration. In the case of every other pipe being open, the lateral jet penetration places the jets from the side-opening ports at about the locations of the non-operational vent pipes.

Jet deflection occurs in the vertical plane as well. Figure 6-7 depicts the trajectories (for the jets aligned with the wind in the horizontal plane) for the case of three rows of open ports. These calculations are based on a uniform wind profile and do not account for turbulence induced by the canopy. They show that the jets level off within 3 m or so and become well-mixed with one another by the center of the array.

Wind speed profiles at Maricopa are shown in Figure 6-8 (data courtesy of Dr. Bruce Kimball). A typical profile is superimposed on the jet field in Figure 6-9, and indicates the necessity of accounting for variable wind conditions at the array scale.

IV. VENT PIPE FLOW SIMULATOR EXPERIMENTS

Because of the difficulty in making detailed fluid mechanical measurements in the field environment, a vent pipe flow simulator was constructed and evaluated in a laboratory setting at BNL. The simulator consisted of a 2.5 m long section of 30 cm plenum pipe connected to a blower, with two vertical vent pipes, essentially identical to those of the field FACE system including the discharge ports, and a variable intake flow throttle arrangement which was used to control back-pressure and flow rate (Figure 6-10). The blower used in this simulator was somewhat larger than 1/16 of the FACE system; this required operating with an intake throttle in order to simulate FACE air flow rates and pressures. Plenum pressure, measured on a water manometer, was used to maintain operating conditions which corresponded to the field configurations of FACE.

This simulator was fitted with static pressure taps, which were used to determine the flow distribution, together with hot-wire velocity measurements. Chemically-colored (mainly ZnCl) smoke was introduced through the blower intake and photography was used to study the jet flow patterns under various conditions. Operating with the full blower capacity provided somewhat stronger jets for the purpose of qualitative visualization. For some experiments, a black back-drop cloth was used to heighten the contrast of the white smoke against the building background. The thermal effect of the smoke was checked by measuring jet exit temperature and found to be negligible. Operating with smoke was limited to outdoor conditions; early morning times with relatively stable air and low wind speeds gave the best results. Some of the tests were run adjacent to a building in order to minimize wind effects. Others were run in a parking lot where the apparatus was manually oriented to maintain the plenum section perpendicular to the wind. Video photography was also used.

In general, the simulator tests verified the theoretical flow distribution and jet trajectory calculations. Even indoors in quiescent air, it was difficult to detect the jet velocity with a sensitive hot-wire anemometer after about 1.5 m travel. The outdoor smoke tests (Figure 6-11), showed that jets with an upwind component quickly bent over and followed the travel of the wind.

Figure 6-12 shows a close-up of opposing jet interaction, in which the jets issue from the full vent pipe diameter rather than from the normal injection ports. The description given above seems to be accurate, in that the two jets merge into one with a common direction (influenced by the wind in this case).

The three-dimensionality of the system was also clearly evident from these tests. Figure 6-13 shows how the upward velocity component decreases with height of the injection ports along the vent pipe (right-hand vent-pipe). In Figure 6-14, the vent pipes have been rotated 90° in order to allow visualization from the side of what would normally be the top view. The six jets have merged into a cloud within 1-2 m.

One of the FACE injection configurations used early in the growing season requires injection primarily from the bottom ports, in order to efficiently fumigate newly emerging plants. We learned from these simulator tests that when these jets impinge on the plenum, the flow follows around the plenum pipe and fills the "cavity," which is sheltered from the wind (Figure 6-15). This is an example of the Coanda effect, which is used in fluidic control systems. The result is to efficiently fumigate down to the ground, in spite of the potential wind barrier imposed by the plenum. The upward velocity component from the lower injection ports may also be seen from this photograph; these two effects create enhanced vertical mixing for the lower jets.

An additional configuration investigated with the simulator rig involved the use of 7.5 cm long plastic nozzle extension tubes (Figure 6-16). These tubes fit snugly inside the jet ports, and effectively eliminate the vertical momentum of the jet discharge. They also increase jet velocity because of the blockage effect of the tube wall thickness. Figure 6-16 allows a comparison of the jets with and without these extensions. With the extensions U(upper row), there is a zone of laminar-like flow before turbulence effects begin to dominate the dispersion. Without the extension tubes, turbulent flow is seen immediately. These tubes were evaluated in FACE field experiments, which will be reported separately elsewhere.

V. A SIMPLE MATHEMATICAL MODEL OF GAS DISPERSION WITHIN THE FACE ARRAY

Various analytical methods of fluid mechanics have been applied to the BNL FACE design, for the purposes of understanding its characteristics and of predicting performance under varying conditions and sizes of arrays. An early attempt was made by Allen *et al.* (1985), using a two-dimensional numerical eddy diffusivity model for FACE-type simulations involving grasslands and tropical forests. This model framework was later used by Allen (1990) in an attempt to simulate the current application of FACE to a cotton crop.

Lipfert *et al.* (1989) used a one-dimensional representation based on urban-scale area sources as a device for comparing the performance of the entire array (as a single entity) over time and for different array sizes. However, this representation is not capable of addressing spatial variability within the array, which is one of the topics of primary interest.

FACE is a three-dimensional system; the initial mass flow distribution varies with height, and the use of a circular array in an assumed two-dimensional wind field results in a distinct cross-wind spatial pattern within the array. Attempts to represent this detailed configuration in fewer than three dimensions are unlikely to be adequate. Recognizing this, we are investigating

dimensions are unlikely to be adequate. Recognizing this, we are investigating the use of superimposed multiple jets in a Gaussian framework to represent specific FACE configurations of interest.

In this context, the Gaussian jet dispersion model serves as a device for representing the detailed CO_2 injection arrangement of interest, while subjecting each jet to a common diffusion environment. The net effect (the horizontal CO_2 distribution) is obtained by superimposing all the jets. With 12 vent pipes and all rows of ports open, this requires the superposition of 180 Gaussian jets, each carrying the appropriate fraction of the total mass flow. Steady winds are assumed so that each jet plume is assumed to travel in a straight-line trajectory. The initial jet deflections are ignored for these simulations, which are intended for the array scale, and the virtual origin of each jet is estimated based on the jet trajectory data discussed above.

A. Results for single vs. multiple jets in a single plane

Only relatively simple applications of this simulation technique are presented here, based on arbitrary meteorological conditions, constant with height (i.e., effects of the canopy are not considered). Some sample outputs are shown in Figures 6-17 through 6-18, which focus on the difference in uniformity between a finite array of multiple jets and the "equivalent" single jet; these comparisons illustrate the benefits in concentration uniformity that derive from the use of multiple jets. The parameters of this problem are the height of injection above ground (z), which will vary as the crop grows, the locations where the gas concentration (CO_2) is monitored, and the distance downwind from the injection point where CO_2 is controlled to meet the desired enrichment level. Most of the results shown below are for the vertical plane of symmetry through the center of the array. For these simulations, 9 identical jets were arrayed around the periphery of the circular array, but lateral injection was not accounted for.

Figure 6-17 shows downwind concentration profiles in the vertical plane of symmetry with gas injected at 0.5 m above ground. The concentration at the surface (z=0) is shown in Figure 6-17a; The upper and lower design limits correspond to $\pm$ 20% from 550 μmol mol^{-1}, assuming a background of 350 μmol mol^{-1}. We define the concentration control point at the center of the array, for all heights. At z=0, the multiple jet case falls within design limits over virtually the entire array, while the equivalent single jet overshoots upwind and undershoots downwind. At z=0.5, which corresponds to the jet axis (Figure 6-17b), very high concentrations occur upwind for both single and multiple jet simulations.

Figure 6-18 presents similar Gaussian simulation results for the case of injection at z=1 m above ground. At the surface, the multiple jet case undershoots for $x < -6$ m; the single jet case is only slightly less uniform. At mid-height (z=0.5, Figure 6-18b), the multiple jet case is quite uniform over most of the array, in sharp contrast to the single jet case. At z=1, corresponding to the jet centerline (Figure 6-18c), very high initial concentrations are seen as in Figure 6-17(b).

With injection at z=2 m, corresponding to a mature crop (Figure 6-19), the zone of uniformity is moved further downwind at the lower sampling heights (z=0, 0.5, and 1, [Figures 6-19(a-c)]), but at z=1.5 (Figure 6-19d), the concentrations

are quite uniform for the multiple jet case. As before, upwind concentrations are quite high in the plane of jet injection.

These simulations show that the jets should be placed about 0.5 m above the canopy to maintain the most uniform downwind concentration fields (neglecting velocity profile effects and nonaxial jet trajectories), and that there could be pockets of low upwind concentrations at the lower elevations. However, these simulations are based on only a single row of jets and neglect the effects of the canopy and of the laterally injected jets in providing accelerated mixing in the region upwind of the control point.

B. Results for multiple jets in three planes

Figure 6-20 presents CO_2 concentration profiles along a downwind vertical slice through the plane of symmetry. The three rows of injection jets are located at z=0.75, 1.25, and 1.75 m; the downwind CO_2 concentration profiles are located at z=0.5, z=1, z=1.5, and z=2, with an assumed control point at z=1.5 These results show that downwind of about x= -5, the spatial variability in CO_2 is within our design objectives of $\pm$ 20% of the target concentration.

The 3-dimensional Gaussian model simulations show that actual FACE performance may be represented reasonably well with a simple closed form model. Future work with this simulation model is aimed at incorporating canopy effects, by virtue of vertical variations in velocity and diffusion profiles.

VI. EFFICIENCIES OF FREE-AIR GAS FUMIGATION DEVICES

In this section, we develop some non-dimensional groups of parameters for the purpose of characterizing performance in terms of usage of enrichment gas. These nondimensional groups are then used as figures of merit and allow the required flow rates of CO_2 to be predicted based on the geometry of the device, the wind speed, and the incremental gas concentration desired. The parameters chosen to comprise a useful nondimensional group must not only have the correct dimensions, they must also represent an appropriate physical relationship. The term "efficiency," as used in this chapter, refers to the physical distribution of gas and not to its uptake by plants, as considered by Allen in Chapter 4.

A. Design parameters

In order to make comparisons on a common basis, some experimental design parameters must be specified. One of the most important is the degree of temporal and spatial uniformity required in the enrichment gas concentration fields. For example, temporal uniformity in open-top chambers (OTCs) depends on the degree to which incursions of atmospheric air are allowed to intrude from the top. As discussed below, the primary control mechanism for this problem is increasing the gas through-flow rate, which increases the usage of enrichment gas.

In contrast, open-field enrichment or fumigation systems rely on atmospheric dispersion to distribute the enrichment gas as uniformly as possible across the experimental plots. The ability to maintain temporal uniformity depends on the control system and associated sensors; spatial uniformity is more dependent on the geometry of the system and the details of the gas injection hardware. There

is a fundamental conflict between the desired degree of spatial uniformity and the efficiency of gas usage; if the experimental area is "flooded" with gas at the proper concentration, a high degree of uniformity will be achieved, but the gas diffusing into adjacent areas at lower concentrations will essentially be wasted.

This concept is illustrated in Figures 6-21 and 6-22, which are based on steady-state two-dimensional Gaussian diffusion and uniform atmospheric conditions. We assume a point source of CO_2 well upwind of the test plot; atmospheric dispersion creates a spatial distribution of CO_2 similar to the curves shown in Figure 6-21. Because of this distribution, not all of the test plot can be exposed to the same concentration level. For this example, we assume that it is desired to enrich the "natural" CO_2 level by 200 μmol mol^{-1}, and we consider various levels of error about this increment, in terms of spatial increments about the resulting total concentration (550 μmol mol^{-1}), in either direction. In this simple hypothetical example, a square plot is superimposed on the Gaussian concentration field (Figure 6-21); as the tolerance for error increases, a larger portion of the Gaussian pattern becomes usable (i.e., less of the emitted CO_2 is "wasted") and the relative plot dimensions can be increased (i.e., the plot can be located closer to the CO_2 source). This trade-off is given in Figure 6-22, which shows that gas utilization initially rises sharply with allowable error, with a break and leveling off for errors greater than about 10%. Since concentrations decrease with downwind distance as well, this criterion should be applied at the center of the plot, perpendicular to the wind, so that the total degree of spatial nonuniformity across the square plot would be somewhat larger than shown in Figure 6-21.

Of course, this simple illustration does not comprise a practical open-field fumigation or enrichment system. For a 20 m plot, for example, fumigated by a single gas release point, the plot would have to be about 100 m downwind in order to allow sufficient cross-wind dispersion. However, a wind direction shift of 6-10° would cause the plume to miss the target completely. The solution to this problem has been found by several investigators to lie with multiple gas injection points and close coupling between injection and experimental plot.

The gas flow rate required by an open-field enrichment system designed to maintain constant concentrations will scale directly with the mean wind speed and the area of enrichment. As discussed below, wind speed also controls the flow rate required through an OTC. In theory, one might wish to couple the chamber ventilation rate directly to corresponding atmospheric conditions, so as to mimic the undisturbed evapotranspiration rates and thus reduce the degree of artificiality of the experiments. Such designs are not in practical use, however, in part because the "transparent" enclosures inevitably alter the radiation environment.

B. Performance of open-top chambers

Baldocchi *et al.* (1989) conducted systematic wind tunnel tests of OTCs and developed some useful design criteria. They found that the opening of an OTC should be less than the typical turbulence length scale, and that the exit velocity should exceed one standard deviation of the vertical wind speed in order to prevent 84% of the outside air incursions from entering. These formulae translate into an optimum exit diameter/height ratio of about 0.24, and a minimum

diameter criterion seems a bit small for practical field designs (for a crop of, say, 1 m canopy height), we assume that the more practical solution will be to increase the exit velocity, u_e. We take $u_e/u = 0.33$ as a practical guideline with the aim of achieving uniformity within ± 10%.

A non-dimensional group describing the performance of an OTC would be $\chi d^2u/Q$, where χ is the chamber concentration increment over ambient, d is the plot or chamber diameter, u is the wind speed at canopy height, and Q is the fumigation (or enrichment) gas flow rate. Since this flow rate is also given by the product of the exit velocity (u_e) and area (d_e^2), we find that the minimum flow to achieve this performance is given by $(u/u_e)(d/d_e)^2$. For a typical OTC design with a frustum top with about 50% area restriction, the value of $\chi d^2u/Q$ would be about 6 (4.7 for a circular cross section). This parameter may be thought of as an efficiency measure, since it represents the chamber concentration achievable with a given flow rate of enrichment or fumigation gas.

C. Performance of other open-field release (FACE) systems

Although several different open-field system designs have been reported in the literature (See Chapter 4), gas usage has not been one of the performance parameters of recent interest. When fumigating with a trace gas such as SO_2 or ozone, the economics of supply are not likely to be of concern. However, the system efficiency is also relevant to the degree of gas carry-over into adjacent plots, a problem that has been mentioned by Runeckles *et al.* (1990). The data given by Allen in Chapter 4 on rates of gas supply per unit area for some of the early systems imply higher rates of gas utilization, but no data are given on spatial or temporal uniformity, which are required for a meaningful comparison.

D. Comparison of the BNL FACE design with OTCs

We have measured the performance of BNL's FACE system in terms of the parameter $\chi Au/Q$ under various atmospheric conditions and configurations, where A is the plant growing area under enrichment. Values of this parameter are highest (most efficient use of CO_2) under low turbulence conditions, such as in the early morning and late afternoon, but generally are in the range 5-10 (Figure 6-23). On this basis, we would conclude that the gas utilization performance of FACE is essentially equivalent to a well-designed OTC, on the basis of equivalent plant growing areas. However, Allen's data (Chapter 4) on surface release of pure CO_2 from a line source imply considerably more efficient gas utilization, albeit with larger concentration gradients. BNL's FACE system was designed to maintain temporal concentration variability of 1-min averages within ± 20% at the center of the plot (Lipfert *et al.* 1989a); tracer tests and traverses have shown that the spatial variability also lies within this range (see Chapter 7 and Lipfert *et al.* 1989b).

E. Theoretical consideration of the vertical dimension

Use of the horizontal plot area as a generalized design parameter does not account for the vertical dimension of the system, which can be important for an optimized system and varies during the growing season of an annual crop. An alternative efficiency parameter would thus be $\chi dhu/Q$, where d is the cross-wind

alternative efficiency parameter would thus be χdhu/Q, where d is the cross-wind plot dimension and h is the canopy height.

Theoretical Gaussian plume relationships can be used to estimate some figures of merit for this parameter. For example, downwind of a single point source located at z=0 (ground level), the centerline concentration χ is given by Turner (1970):

$$\chi(x,y,z;H) = \frac{Q}{2\pi\,\sigma_y\,\sigma_z\,u}\ \exp\ -\ \frac{1}{2}\left(\frac{y}{\sigma_y}\right)^2 \left\{\exp\left[-\frac{1}{2}\left(\frac{z-H}{\sigma_z}\right)^2\right] + \exp\left[\frac{1}{2}\left(\frac{z+H}{\sigma_z}\right)^2\right]\right\} \quad [1]$$

assuming no losses at the ground (or in the canopy). Here x,y,z represent along-wind, cross-wind, and vertical coordinates, σ_y and σ_z are the plume spreading parameters in horizontal and vertical directions, respectively, and H is the gas injection height. This equation can be used to explore the geometric relationships inherent in steady-state Gaussian diffusion, using an upwind "virtual source" as a paradigm for the distributed multiple jet injection systems that are actually employed in practical open-field enrichment systems. We compute a normalized concentration field, χu/Q, and then the non-dimensional efficiency parameters χAu/Q and χdhu/Q based on assumed system geometries, for comparison with actual FACE performance measured in the field. We assume a circular array of 24 m diameter and 2 m height.

There are three cases of interest with respect to the turbulence assumptions:

a. the base case, in which horizontal and vertical turbulence are assumed to be equal (isotropic). Standard deviations are assumed to be linear with distance from the virtual source.

b. enhanced vertical turbulence, for example, because of thermals due to solar insolation (vertical dispersion is twice as fast as horizontal).

c. enhanced, nonlinear horizontal turbulence, in which the initial dispersion increases faster (horizontal standard deviation is assumed to vary with the square root of distance).

In all of these calculations, the upwind virtual source displacement distance is an arbitrary parameter used for convenience. Figure 6-24 presents a crossplot of the results of these parametric calculations, which can be used for qualitative purposes only. As was shown in Figure 6-22 (which was based on two-dimensional profiles), the efficiency of gas utilization increases with the allowable concentration error (the undershoot errors for these cases are about twice as large as the overshoot errors). The maximum concentration occurs at the centerline of the upwind edge of the array; the minimum occurs at the downwind

outer radius. When vertical turbulence is enhanced, the relative efficiency drops due to loss of gas in the vertical (i.e., out the "top"). In contrast, enhanced horizontal turbulence (faster initial mixing) improves the relative performance, since the gas is spread over the horizontal extent of the array in a shorter distance and thus the relative upward losses are reduced.

F. FACE observations of χdhu/Q

Data from cotton grown at Maricopa, AZ during 1989 are used to provide field efficiency data for comparison with the theoretical Gaussian plume estimates given in Figure 6-24. The configuration used here consisted of four 23-m circular arrays of vertical injection ports, with CO_2 injected at heights from 0.75 to 2.25 m above ground depending on canopy height. For the purposes of this data presentation, CO_2 usage was averaged over the four arrays and hourly averages were used for wind speeds and CO_2 flow rates for each of the four systems. The systems were controlled to provide a constant experimental CO_2 value of 550 μmol mol^{-1}; we assumed that the average background was 360 μmol mol^{-1}, thus neglecting the tendency towards substantially higher background CO_2 values during evening and early morning hours.

Figure 6-25 presents the 1989 FACE efficiency data. As predicted, efficiencies drop at midday due to increased vertical turbulence. The sharply increased values at 6 AM in July, August, and September are probably due to high background CO_2 (released from the vegetation). The efficiency changes during the growing season are minimal, and point to an increase with time. Thus, any effects imposed by the canopy appear to be beneficial, probably because of enhanced horizontal turbulence.

The overall levels of the efficiency parameter χdhu/Q are in the range 0.2 to 0.4, which compare well with the theoretical values derived from the single Gaussian plume paradigm (Figure 6-24), at the upper range of (spatial) concentration error tolerance.

VII. CONCLUSIONS

The two-fluid FACE system developed by BNL offers a compromise between injection of pure CO_2 (as done in some of the early designs discussed by Allen in Chapter 4) and use of CO_2 fully premixed to the desired concentration level. The former imposes severe mixing problems and the latter requires very large hardware components. The use of lateral injection jets greatly improves initial mixing and effectively triples the number of vertical vent pipes. The relatively high internal velocities used in the vent pipes result in a tailored initial vertical distribution profile that effectively circumvents the potential problem of gas pooling in the lower portions of the canopy. These design concepts have been proven by theory and with laboratory experiments and flow visualization photography.

The Gaussian dispersion model developed to characterize the flow distribution within the array is useful for optimization studies, since it provides a three-dimensional picture of the flow using simple mathematics.

The costs of fumigation and enrichment gas can become a major factor in large-scale ecological experiments of the type envisioned as part of future research on the effects of global climate change; this factor has not been previously considered in detail. Large-scale open-top chambers must maintain appreciable through-flow rates in order to prevent incursions of ambient air from

dimensional gas usage parameter χAu/Q for OTCs of about 5-6. Values for χAu/Q for BNL's open-field FACE system are comparable, ranging from slightly lower values during midday to higher values for morning and evening hours. When variability in the vertical extent of gas enrichment (or fumigation) is taken into account, FACE performance is about as expected from theoretical considerations derived from a Gaussian plume paradigm. Fumigation gas usage has not been reported for other recent open-field system designs.

ACKNOWLEDGMENTS

This research was supported by the U.S. Department of Energy, Atmospheric and Climate Research Division, Office of Health and Environmental Research. Dr. Roger Dahlman was the project officer. A portion of this material was presented at the 9th World Clean Air Conference, Montreal, Canada, September 1992.

REFERENCES

1. Allen LH Jr., Beladi SE, Shinn JH (1985) Modeling the feasibility of free-air carbon dioxide releases for vegetation response research, Proc. 17th Conf. on Agricultural and Forest Meteorology, Am.Met. Soc., Boston, pp. 161-164.

2. Allen LH Jr. (1990), personal communication.

3. Baldocchi DB, White R, Johnston JW (1989) A wind tunnel study to design large, open-top chambers for whole-tree pollutant exposure experiments, J.APCA 39:1549-1556.

4. Lipfert FW, Hendrey GR, Lewin KF, Daum ML (1989) FACE: A free-air facility for fumigation with gaseous air pollutants, presented at environmental testing in the 90'S, 20th International Conference of the ICT, Karlsruhe, FRG, June 27-30, 1989.

5. Lipfert FW, Daum ML, Hendrey GR, Lewin KF (1989) Fluid mechanics and spatial performance of FACE arrays, BNL 43727, prepared for U.S. Dept. of Energy Series: Response of Vegetation to Carbon Dioxide #046, Nov. 1988. Also presented at the 1989 ASA Agronomy Conference, Las Vegas, Oct. 19, 1989.

6. Runeckles VC, Wright EF, White D (1990) A chamberless field exposure system for determining the effects of gaseous air pollutants on crop growth and yield, Environ.Poll. 63:61-77.

7. Turner DB (1970) Workbook of Atmospheric Dispersion Estimates, AP-26, U.S. Environmental Protection Agency, Research Triangle Park, NC 27711.

Figure Captions

Figure 6-1. Pressure-flow characteristic of the FACE air supply fan, showing operating points with 12 and 16 vertical ventpipes in service (all discharge ports open).

Figure 6-2. Pressure-flow characteristic of the FACE air supply fan, showing operating points with 12 vertical ventpipes in service and various numbers of discharge ports open.

Figure 6-3. Photograph of FACE discharge jets using smoke visualization.

Figure 6-4. Schematic of the FACE jet injection arrangement used at Yazoo City, MS. The vertical axis represents height above ground; measured and calculated jet (symbols) and internal pipe (lines) velocities are shown on the left. Static pressures and jet angles are shown on the left, for each of the five rows of discharge ports. The lower circle represents the plenum and its static pressure and internal velocity.

Figure 6-5. FACE jet schematic (plan view). Jet trajectories are indicated in the absence of wind deflection, although the open pipe configuration corresponds to wind speeds > 0.4 m s^{-1}.

Figure 6-6. Parametric calculations of FACE jet trajectories for various inclination angles, assuming the jet/wind velocity ratio = 30. Crosswind coordinate is greatly extended in order to show trajectory details.

Figure 6-7. Theoretical vertical spreading of FACE jets, shown in true coordinates. Different line legends correspond to boundaries and centerlines from three different injection heights. Jet/wind velocity ratio = 30.

Figure 6-8. Measured daytime velocity profiles above cotton at Maricopa, AZ.

Figure 6-9. Vertical cross-section in extended vertical coordinates showing measured wind profile superimposed on theoretical jet trajectories and boundaries.

Figure 6-10. Photograph of the FACE engineering simulator, positioned for outdoor testing with smoke. This configuration has the jets discharging away from the plenum. The apparatus is mounted on casters to facilitate positioning perpendicular to the wind.

Figure 6-11. Photographs of outdoor smoke tests.

Figure 6-12. Smoke visualization of the interaction of two obliquely-opposed jets under quiescent wind conditions. Note that smoke is discharged from the full ventpipe diameter here in order to better visualize the effect. In the actual FACE configuration, such interactions would occur after the jets had decayed further.

Figure 6-13. Photographs of outdoor smoke tests.

Figure 6-14. 90° rotated view (effectively looking down) of the FACE gas injection system, showing interaction of the obliquely opposed jets and merging of all jets into a cloud within about 1-2 m.

Figure 6-15. Three views of jet simulator tests showing Coanda effect due to lower jets impinging on plenum.

Figure 6-16. Comparison of FACE jets with plastic extension nozzles fitted (upper row) with the normal configuration (lower row).

Figure 6-17. Results of Gaussian simulation modeling, with jets located at z=0.5 m. (a) concentrations at the surface (z=0). (b) concentrations in the plane of injection (z=0.5).

Figure 6-18. Results of Gaussian simulation modeling, with jets located at z=1.0 m. (a) concentrations at the surface (z=0). (b) concentrations at z=0.5, (c) concentrations in the plane of injection (z=1.0).

Figure 6-19. Results of Gaussian simulation modeling, with jets located at z=2.0 m. (a) concentrations at the surface (z=0). (b) concentrations at z=0.5, (c) concentrations at z=1.0, (d) concentrations at z=1.5, (e) concentrations in the plane of injection (z=2.0).

Figure 6-20. Simulation of three rows of 12 CO_2 injection jets at z=0.75,1.25, and 1.75 m, with mass flows in the ratio 80, 100, and 120% of nominal. The corresponding wind speeds for each row are 1, 1.5, and 2 m s^{-1}. Background CO_2 is 350 μmol mol^{-1}.

Figure 6-21. Gaussian plume concentration profiles yielding a mean incremental enrichment concentration of 200 μmol mol^{-1}, with specified tolerances about the total concentration of 550 μmol mol^{-1}.

Figure 6-22. Relationship between allowable spatial variability in enrichment gas concentration and the percentage of the plume mass flow that is utilized (two-dimensional case).

Figure 6-23. Typical measured values of the efficiency parameter $\chi Au/Q$ for the BNL FACE system.

Figure 6-24. Parametric calculations of theoretical gas usage efficiencies for a 24 m diameter plot fumigated by a single Gaussian plume at H=2 m, for various turbulence assumptions.

Figure 6-25. CO_2 usage of the BNL FACE system, measured at Maricopa, AZ in 1989.

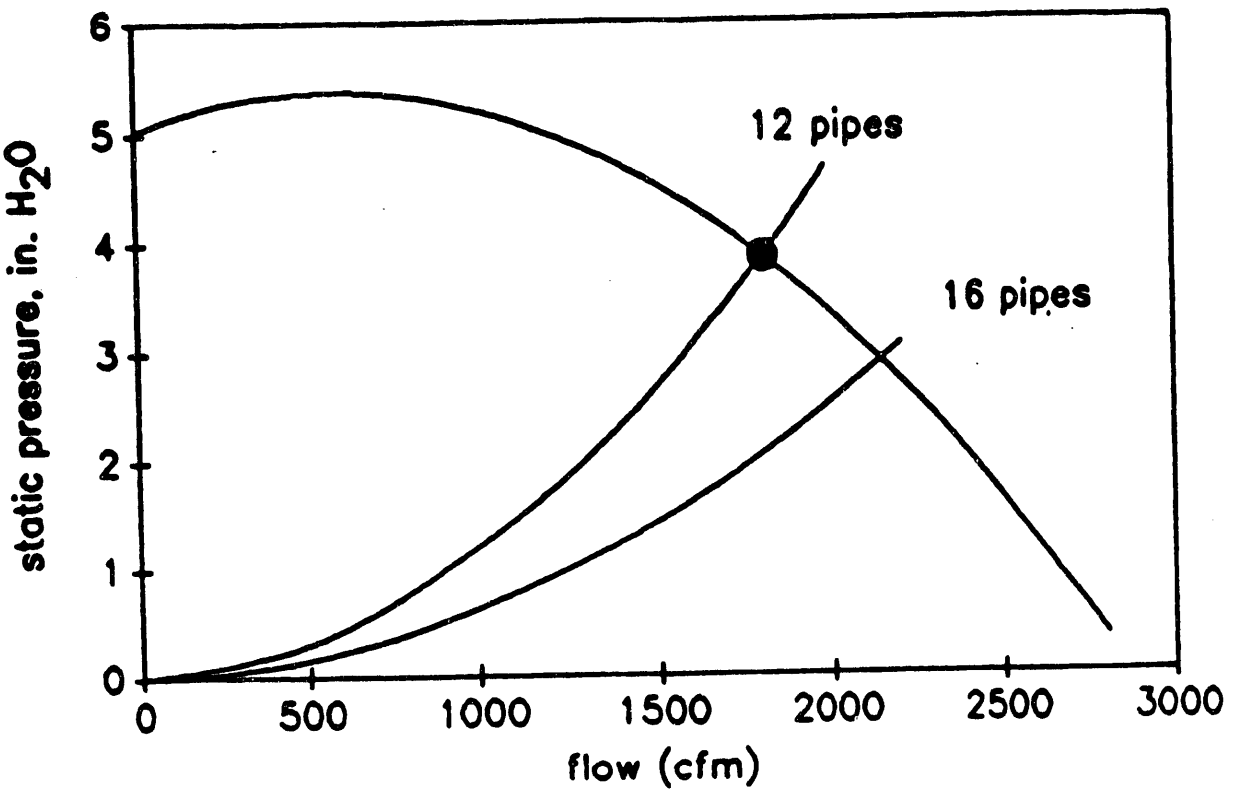


Figure 6-1. Pressure-flow characteristic of the FACE air supply fan, showing operating points with 12 and 16 vertical ventpipes in service (all discharge ports open).

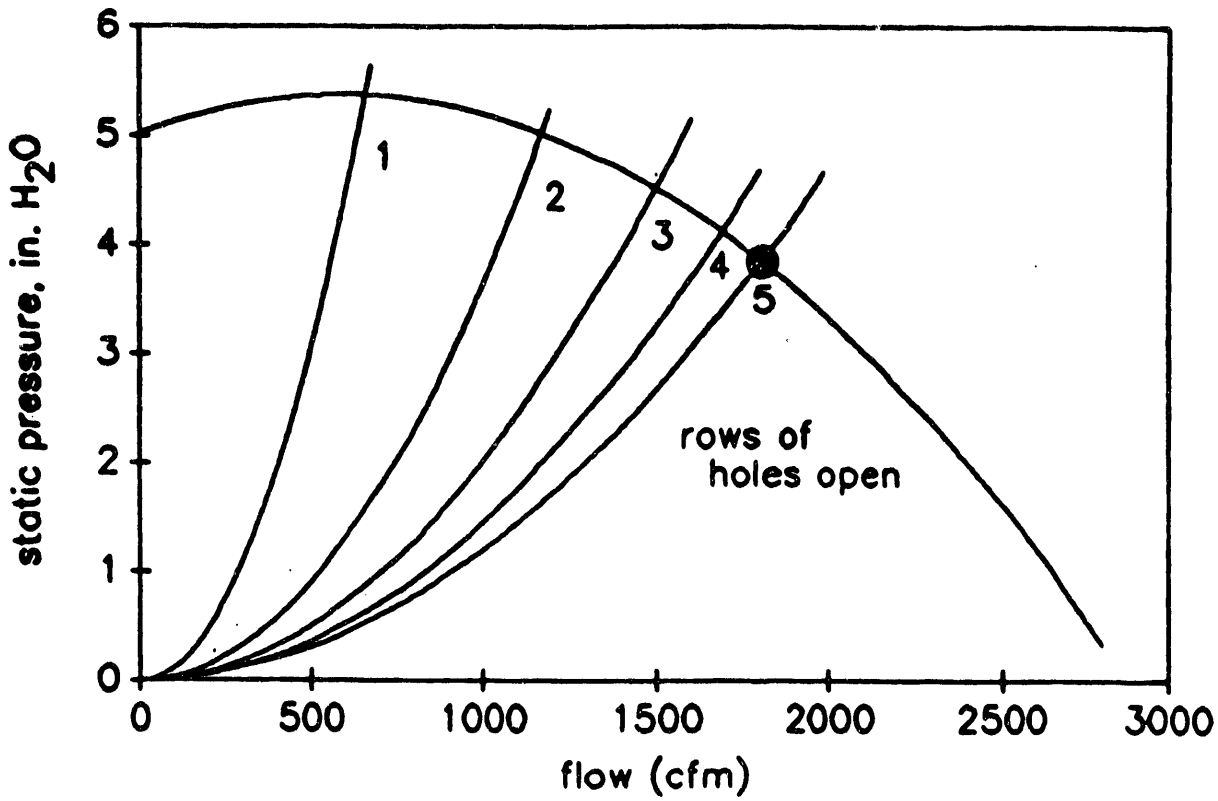


Figure 6-2. Pressure-flow characteristic of the FACE air supply fan, showing operating points with 12 vertical ventpipes in service and various numbers of discharge ports open.

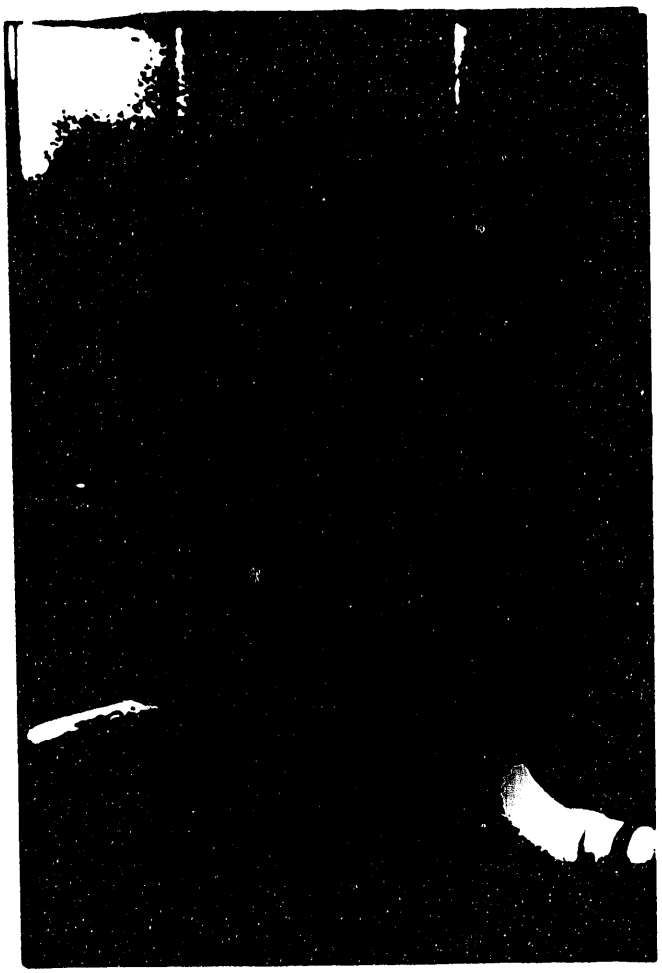


Figure 6-3. Photograph of FACE discharge jets using smoke visualization.

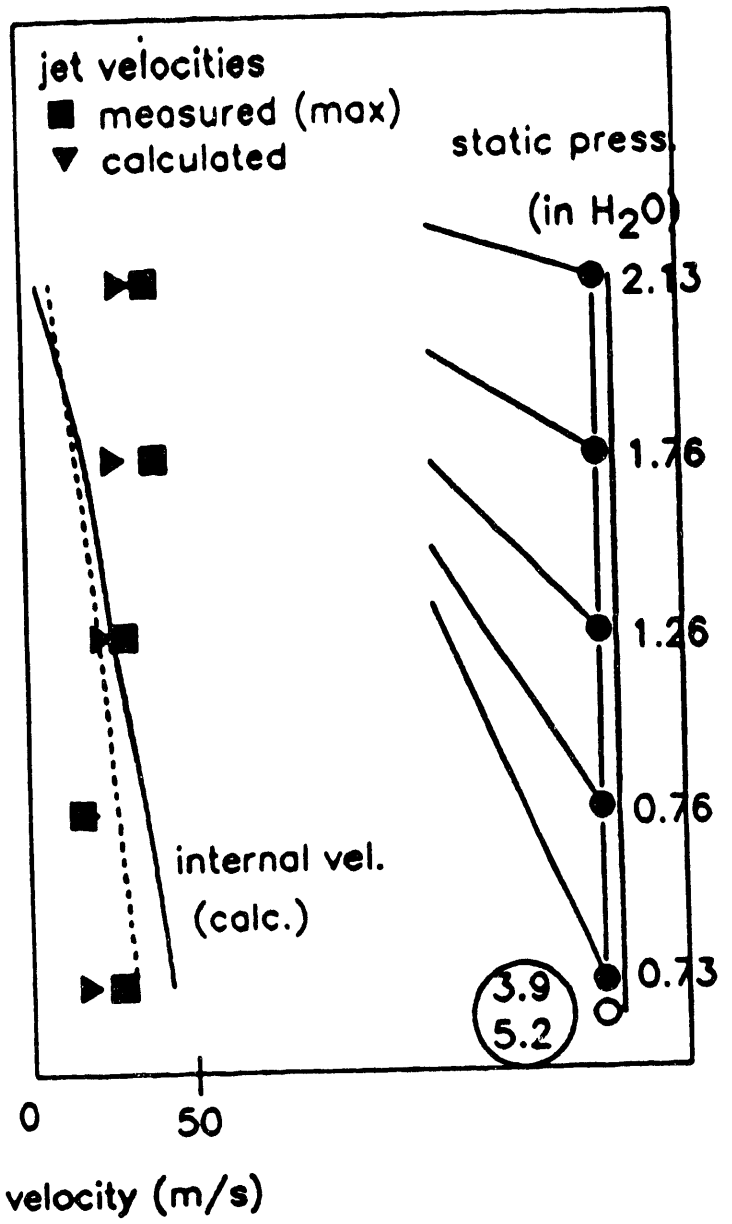


Figure 6-4. Schematic of the FACE jet injection arrangement used at Yazoo City, MS. The vertical axis represents height above ground; measured and calculated jet (symbols) and internal pipe (lines) velocities are shown on the left. Static pressures and jet angles are shown on the left, for each of the five rows of discharge ports. The lower circle represents the plenum and its static pressure and internal velocity.

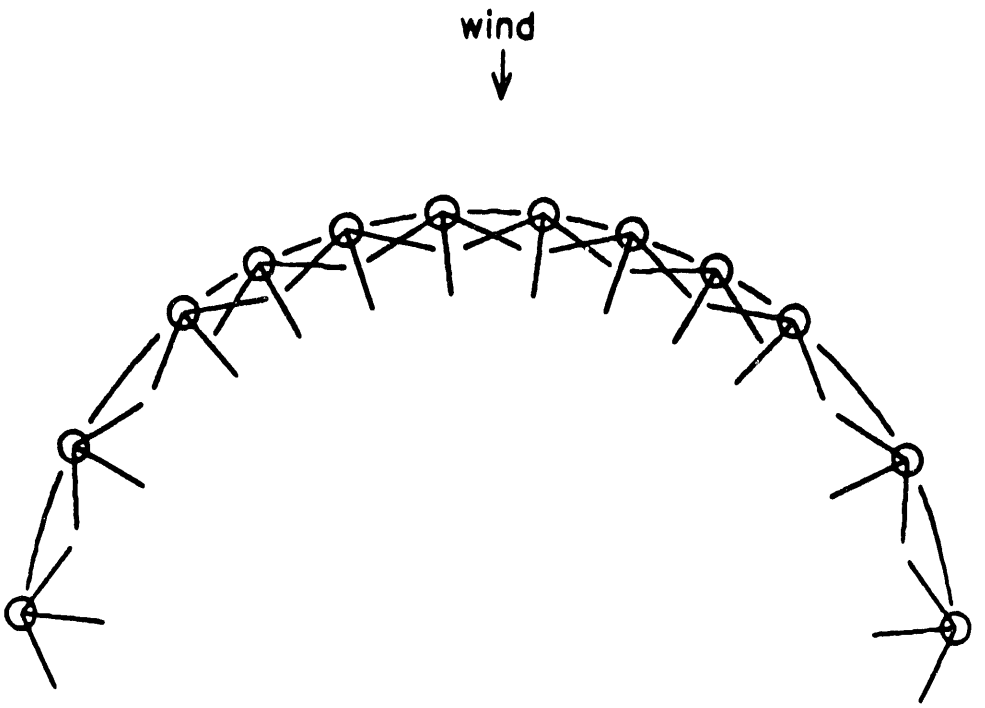


Figure 6-5. FACE jet schematic (plan view). Jet trajectories are indicated in the absence of wind deflection, although the open pipe configuration corresponds to wind speeds > 0.4 m s^{-1}.

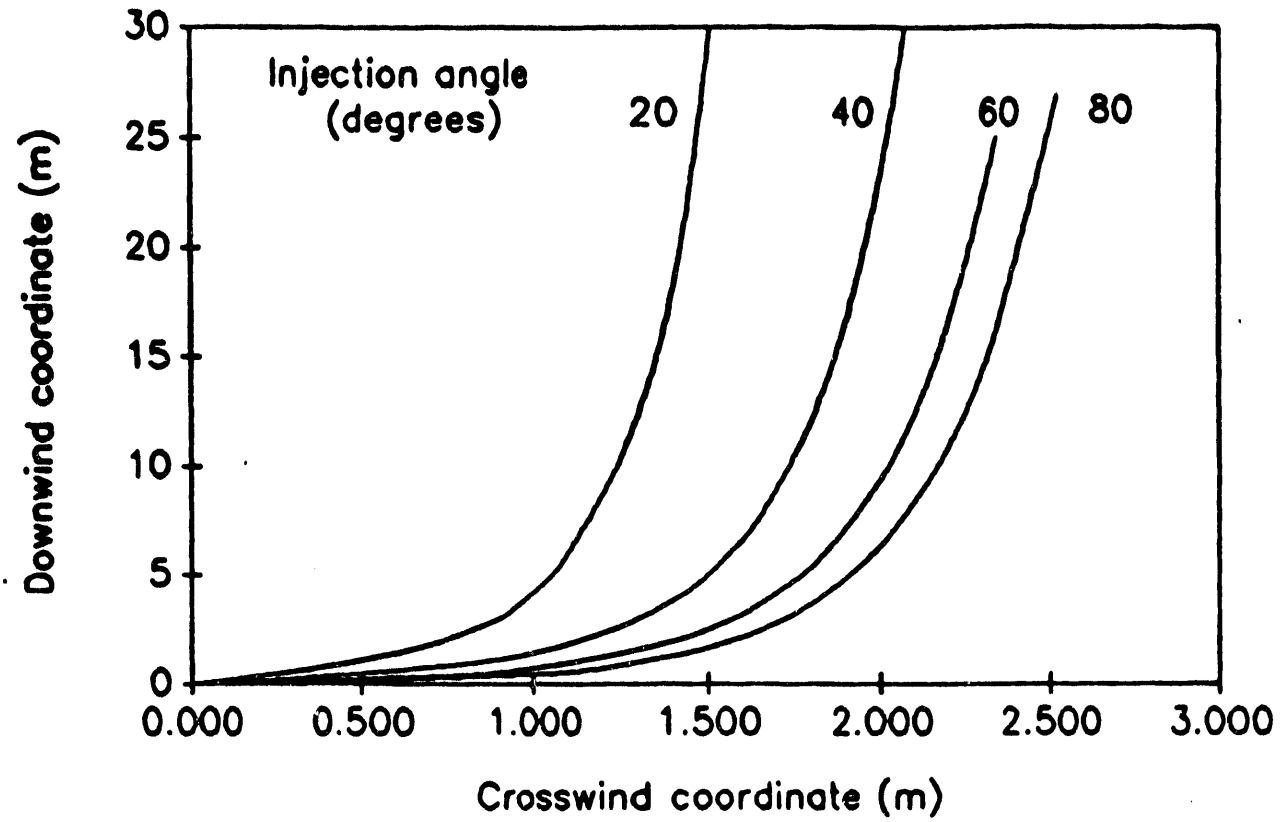


Figure 6-6. Parametric calculations of FACE jet trajectories for various inclination angles, assuming the jet/wind velocity ratio = 30. Crosswind coordinate is greatly extended in order to show trajectory details.

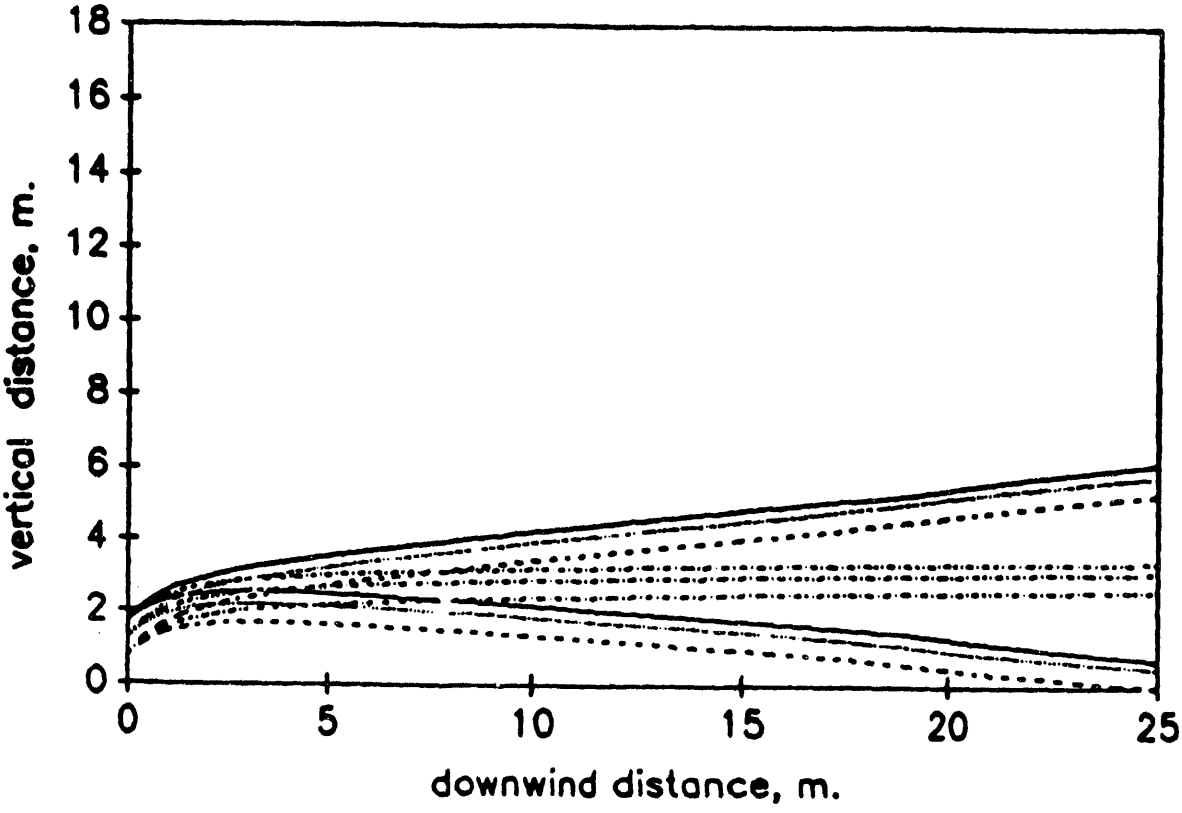


Figure 6-7. Theoretical vertical spreading of FACE jets, shown in true coordinates. Different line legends correspond to boundaries and centerlines from three different injection heights. Jet/wind velocity ratio = 30.

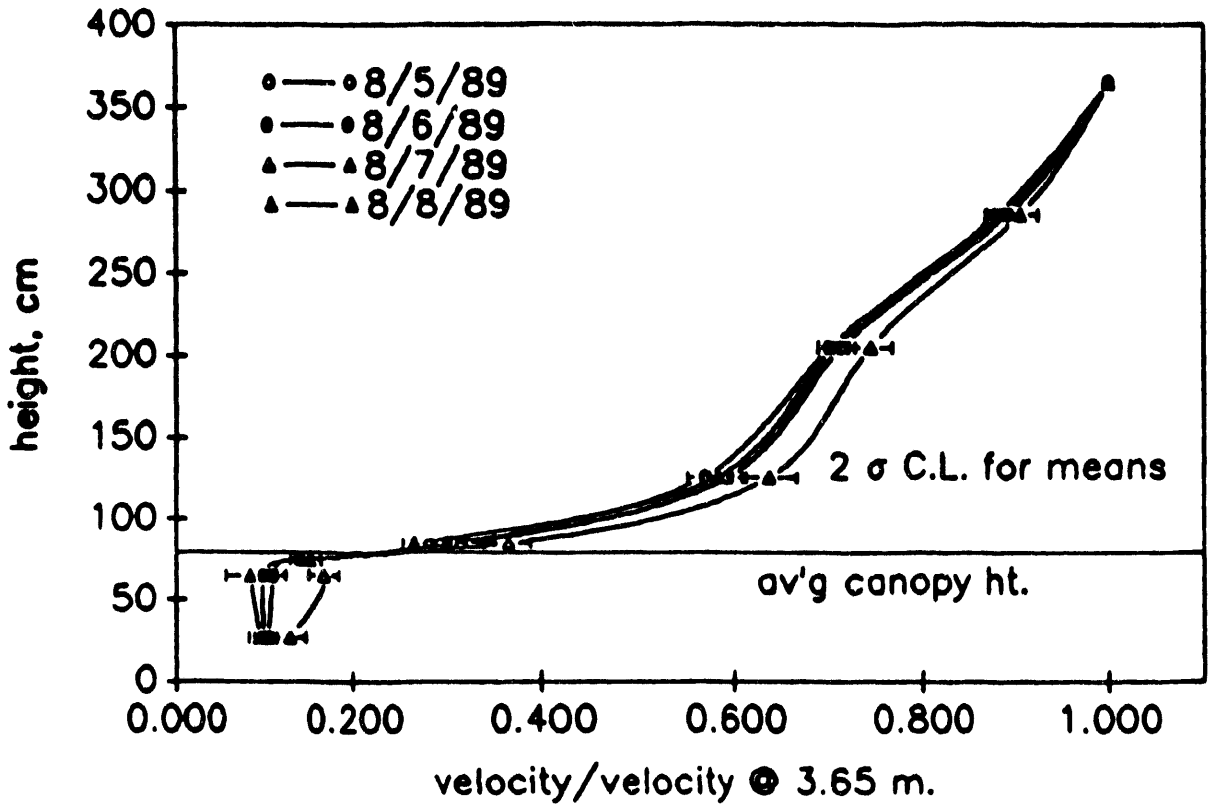


Figure 6-8. Measured daytime velocity profiles above cotton at Maricopa, AZ.

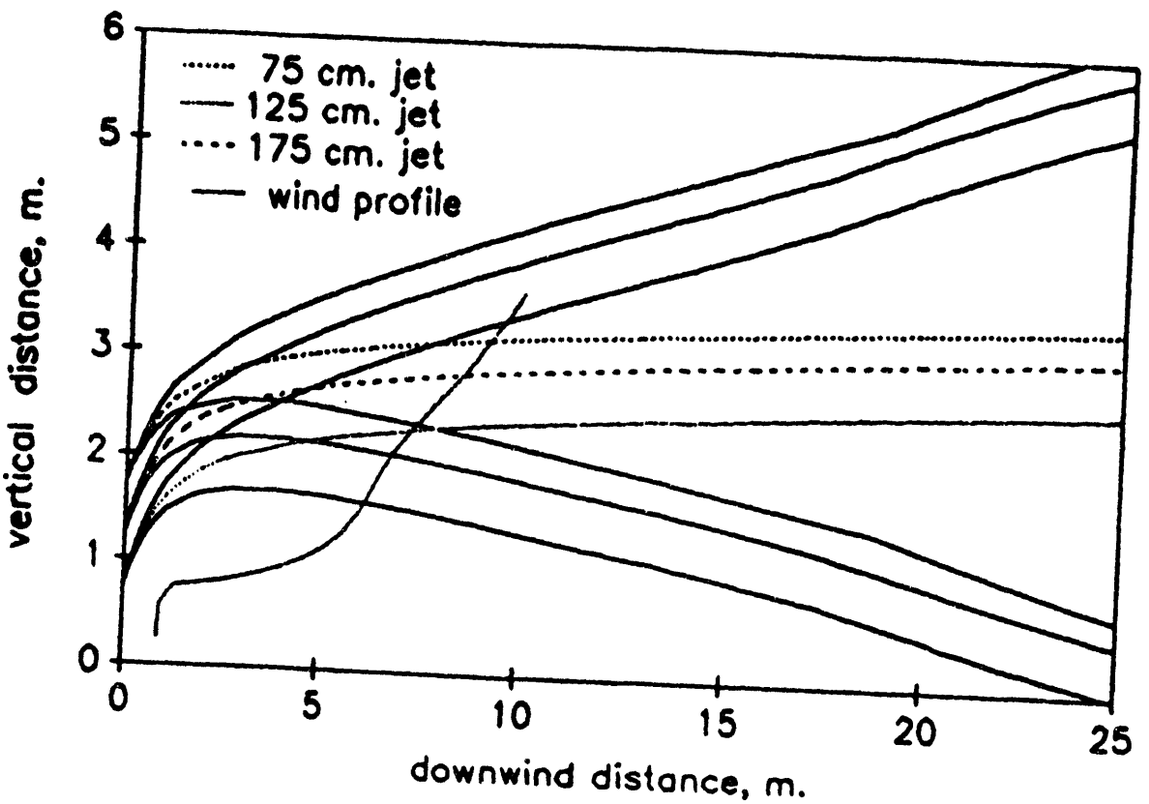


Figure 6-9. Vertical cross-section in extended vertical coordinates showing measured wind profile superimposed on theoretical jet trajectories and boundaries.

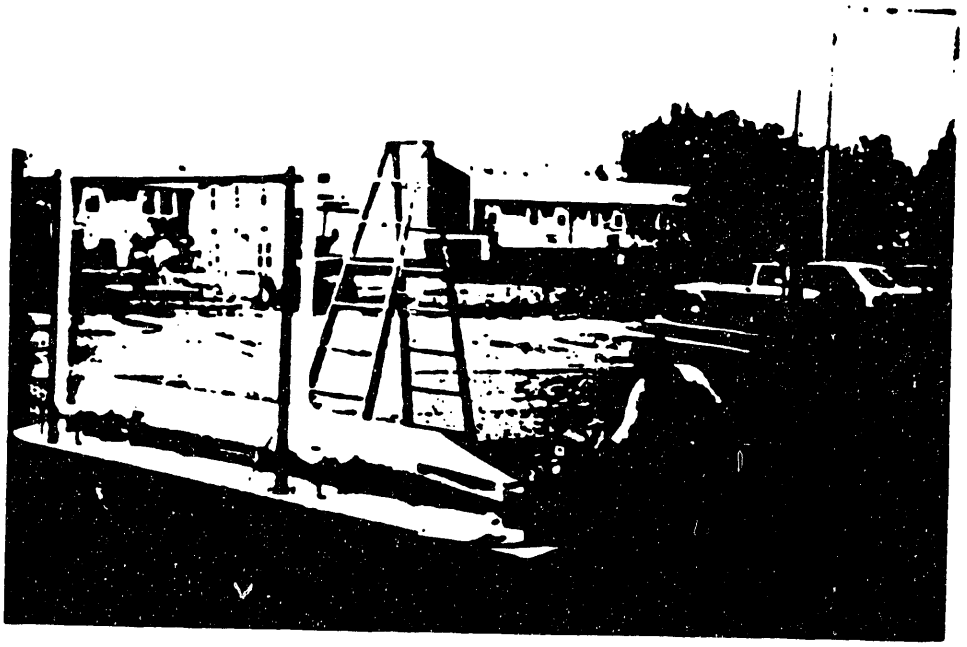


Figure 6-10. Photograph of the FACE engineering simulator, positioned for outdoor testing with smoke. This configuration has the jets discharging away from the plenum. The apparatus is mounted on casters to facilitate positioning perpendicular to the wind.

Figure 6-11. Photographs of outdoor smoke tests.

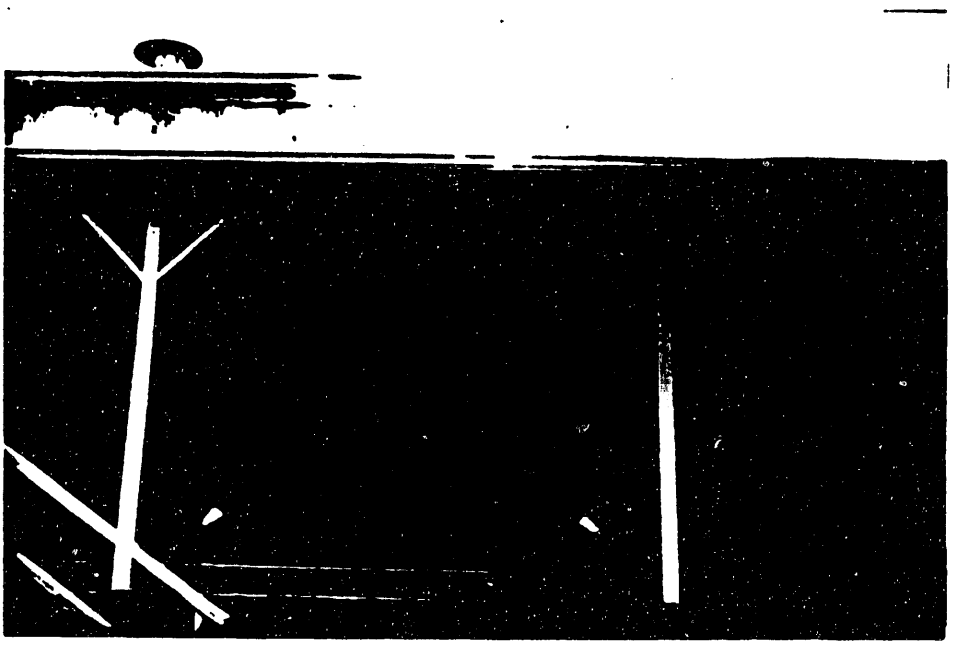


Figure 6-12. Smoke visualization of the interaction of two obliquely-opposed jets under quiescent wind conditions. Note that smoke is discharged from the full ventpipe diameter here in order to better visualize the effect. In the actual FACE configuration, such interactions would occur after the jets had decayed further.

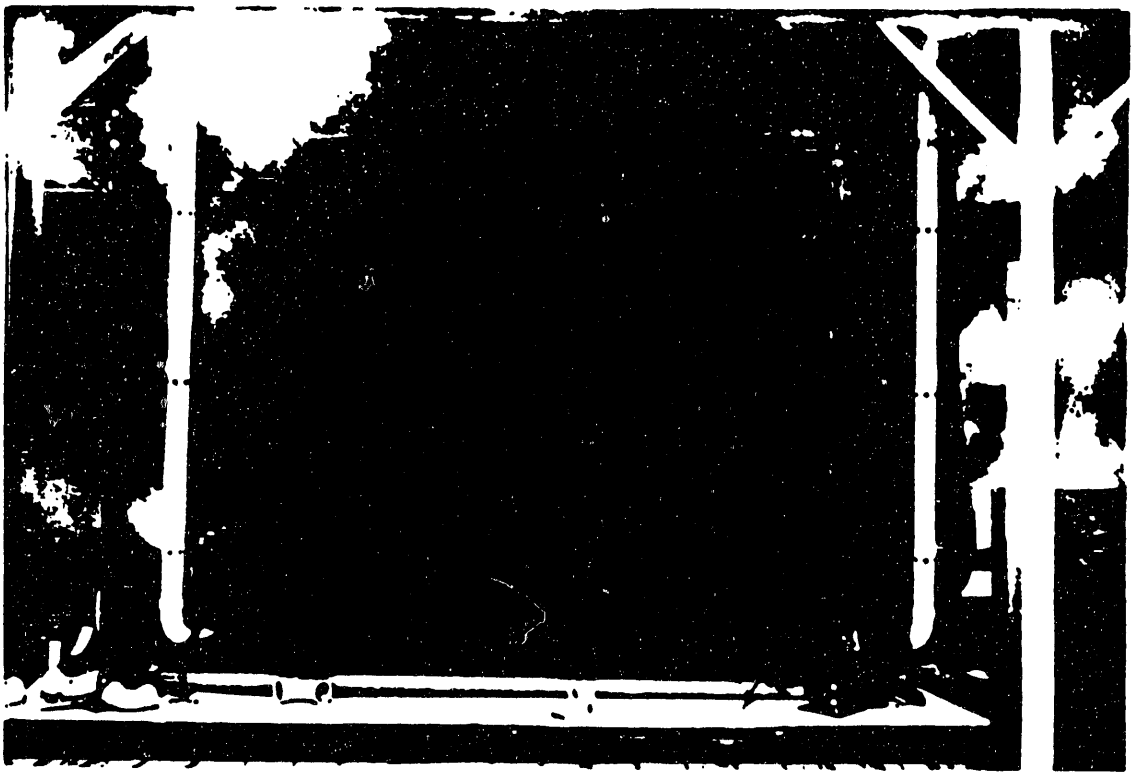


Figure 6-13. Photographs of outdoor smoke tests.

Figure 6-14. 90° rotated view (effectively looking down) of the FACE gas injection system, showing interaction of the obliquely opposed jets and merging of all jets into a cloud within about 1-2 m.

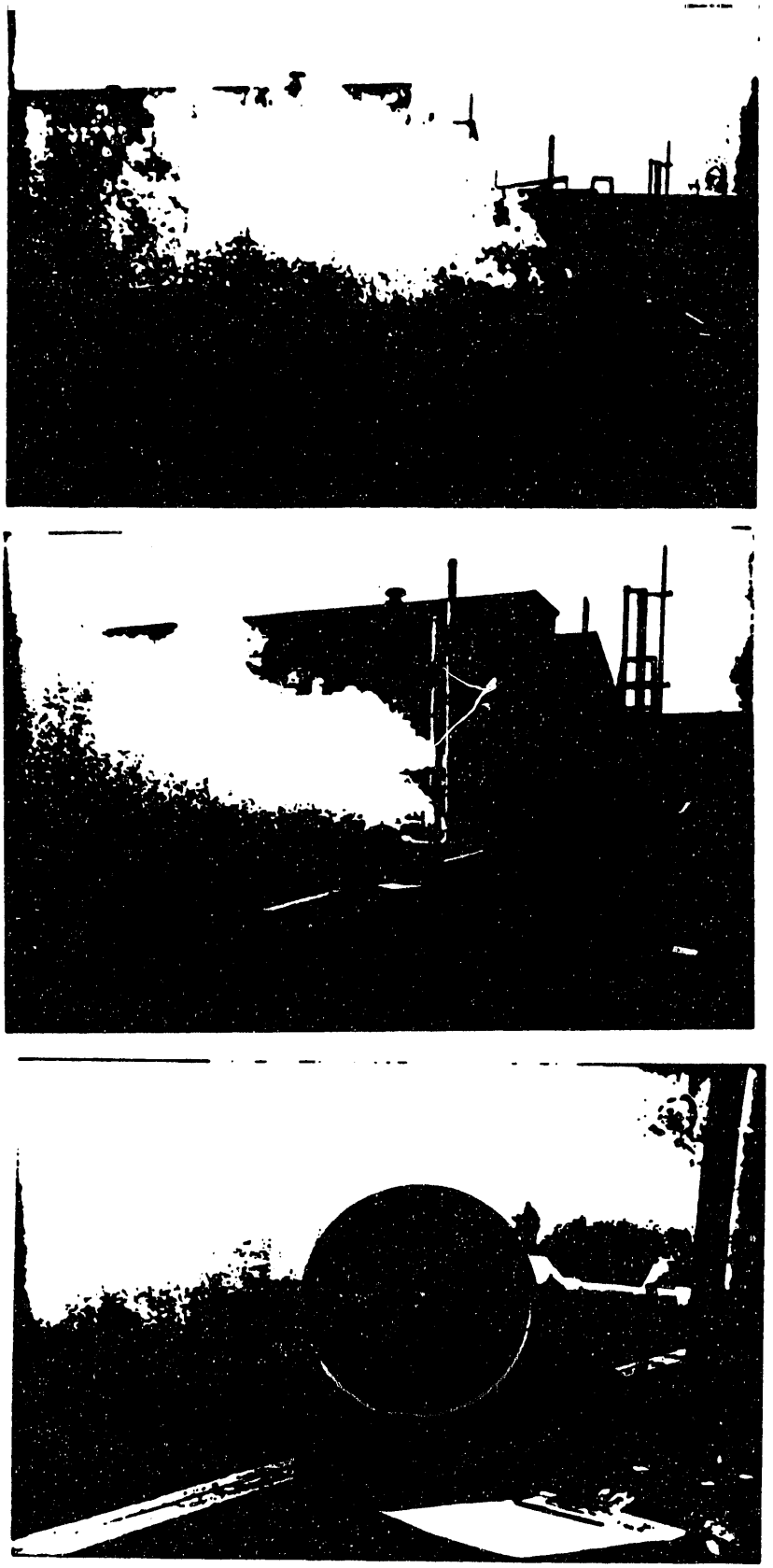


Figure 6-15. Three views of jet simulator tests showing Coanda effect due to lower jets impinging on plenum.

Figure 6-16. Comparison of FACE jets with plastic extension nozzles fitted (upper row) with the normal configuration (lower row).

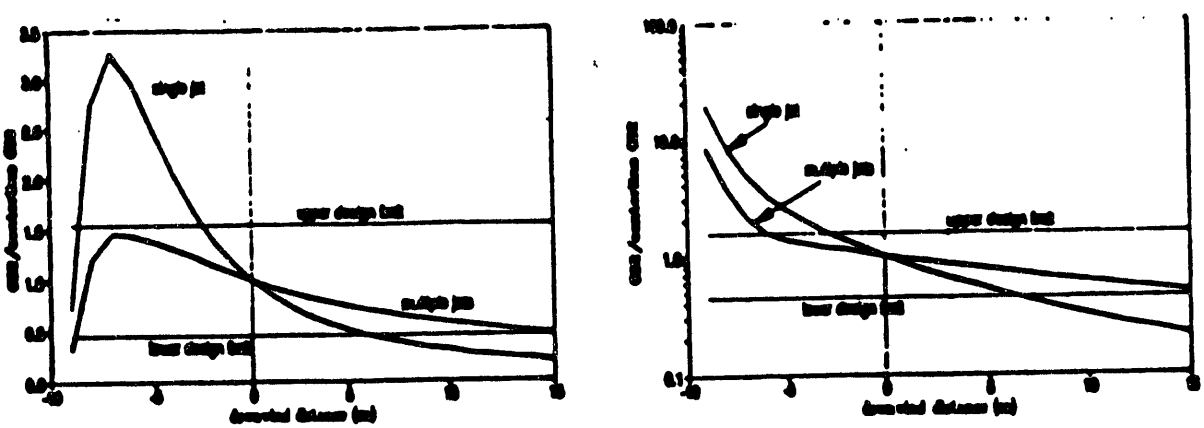


Figure 6-17. Results of Gaussian simulation modeling, with jets located at z=0.5 m. (a) concentrations at the surface (z=0). (b) concentrations in the plane of injection (z=0.5).

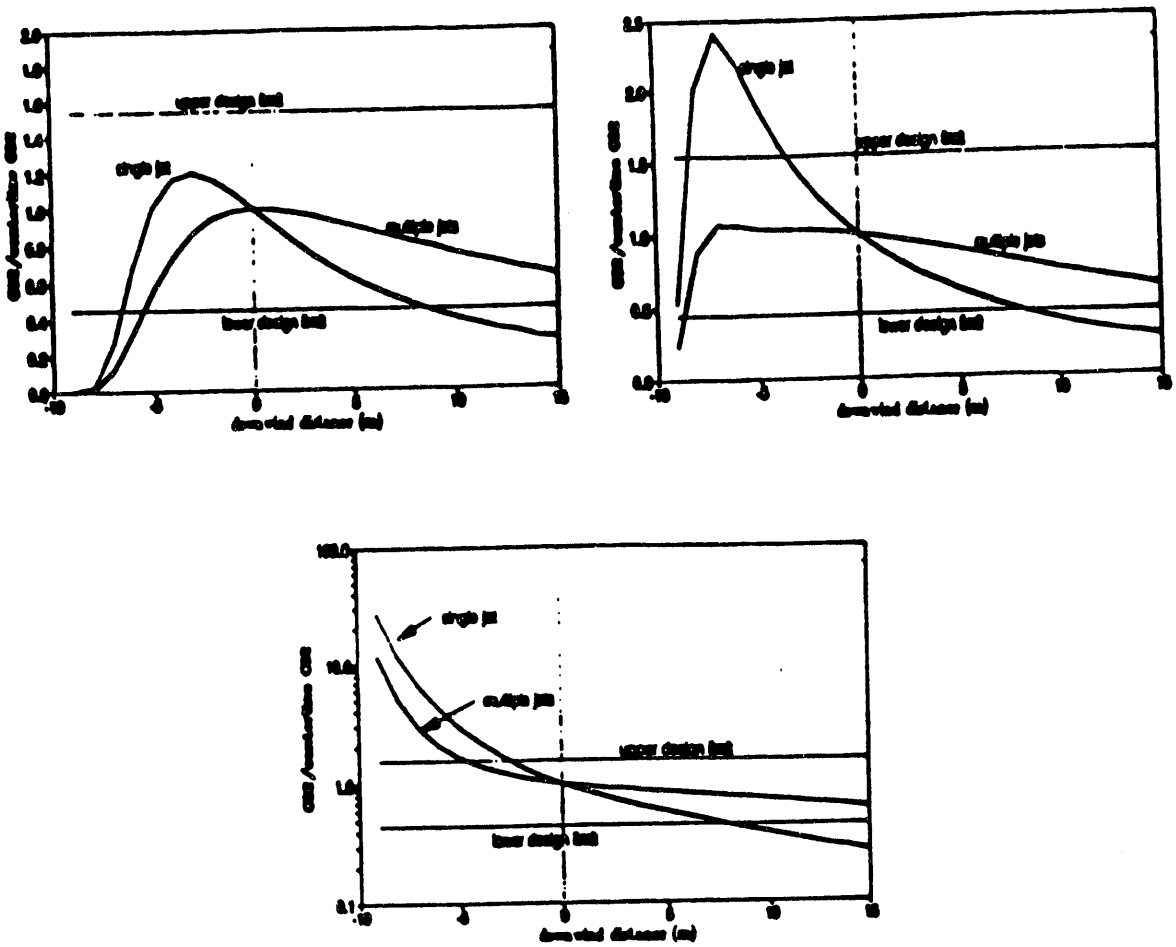


Figure 6-18. Results of Gaussian simulation modeling, with jets located at z=1.0 m. (a) concentrations at the surface (z=0). (b) concentrations at z=0.5, (c) concentrations in the plane of injection (z=1.0).

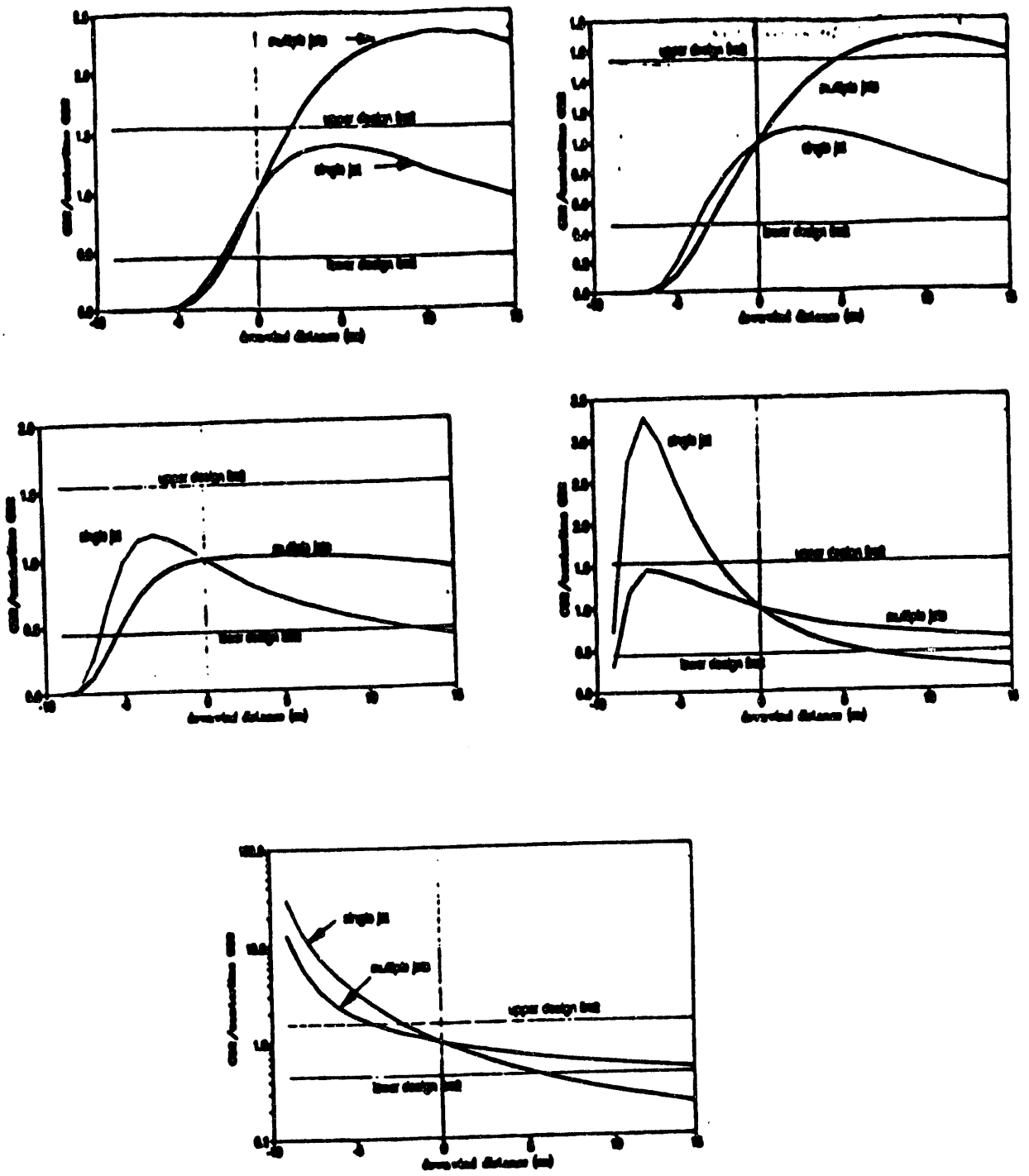


Figure 6-19. Results of Gaussian simulation modeling, with jets located at z=2.0 m. (a) concentrations at the surface (z=0). (b) concentrations at z=0.5, (c) concentrations at z=1.0, (d) concentrations at z=1.5, (e) concentrations in the plane of injection (z=2.0).

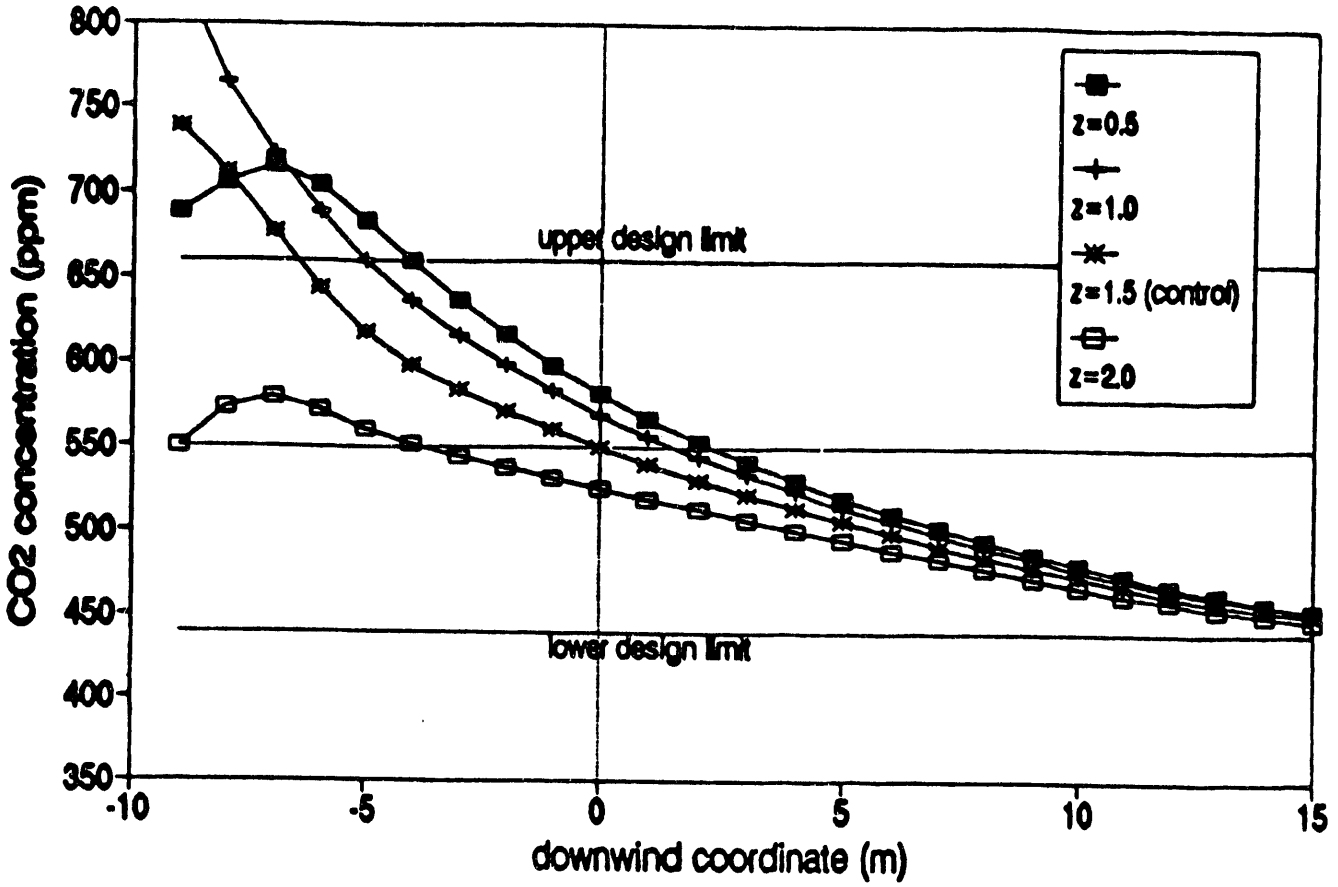


Figure 6-20. Simulation of three rows of 12 CO_2 injection jets at z=0.75,1.25, and 1.75 m, with mass flows in the ratio 80, 100, and 120% of nominal. The corresponding wind speeds for each row are 1, 1.5, and 2 m s^{-1}. Background CO_2 is 350 μmol mol^{-1}.

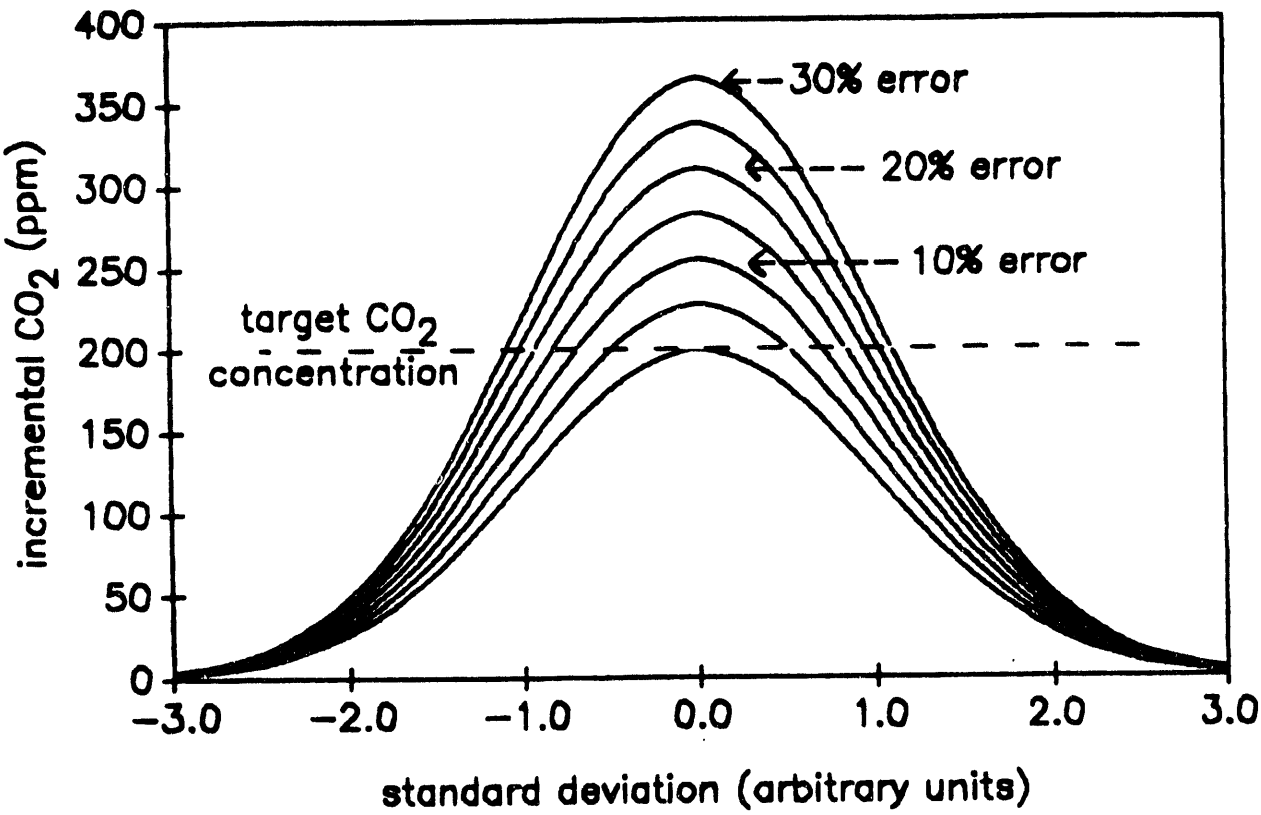


Figure 6-21. Gaussian plume concentration profiles yielding a mean incremental enrichment concentration of 200 μmol mol^{-1}, with specified tolerances about the total concentration of 550 μmol mol^{-1}.

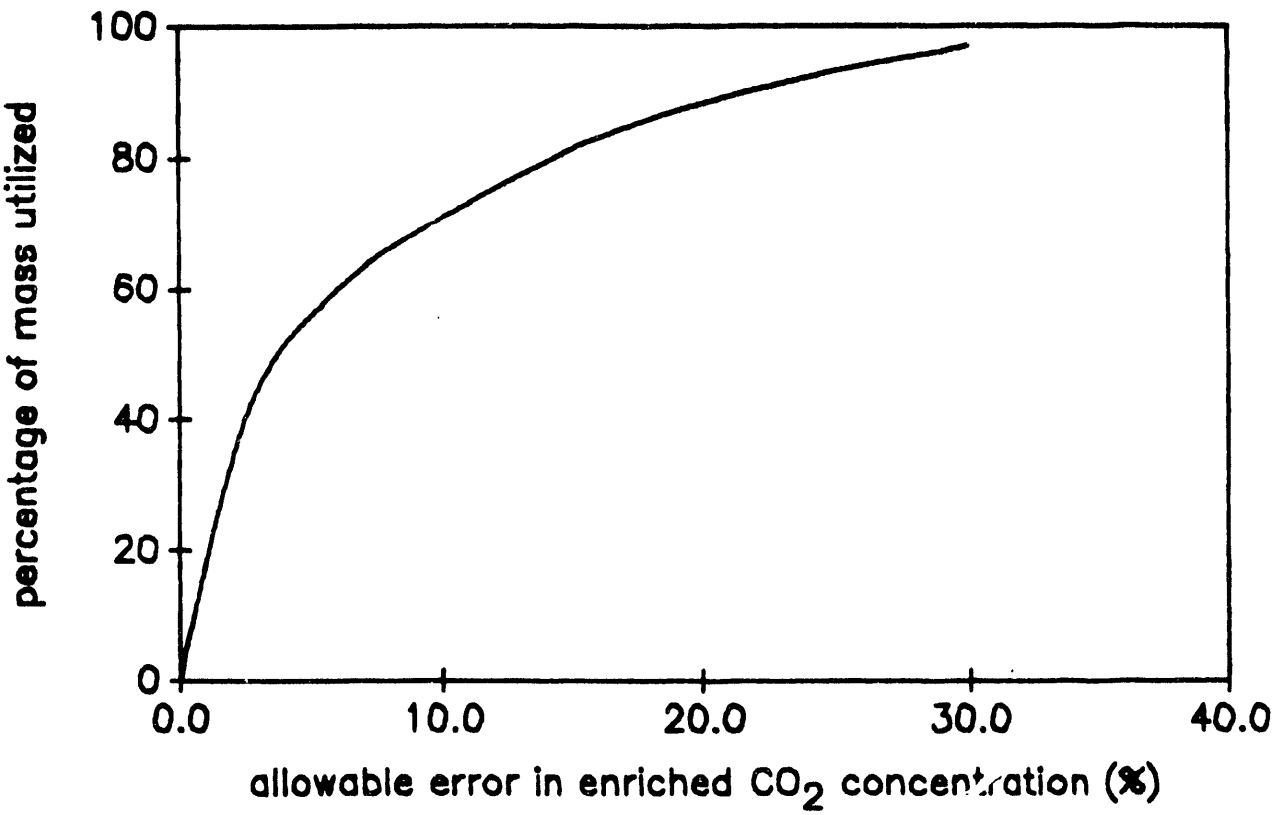


Figure 6-22. Relationship between allowable spatial variability in enrichment gas concentration and the percentage of the plume mass flow that is utilized (two-dimensional case).

6-23

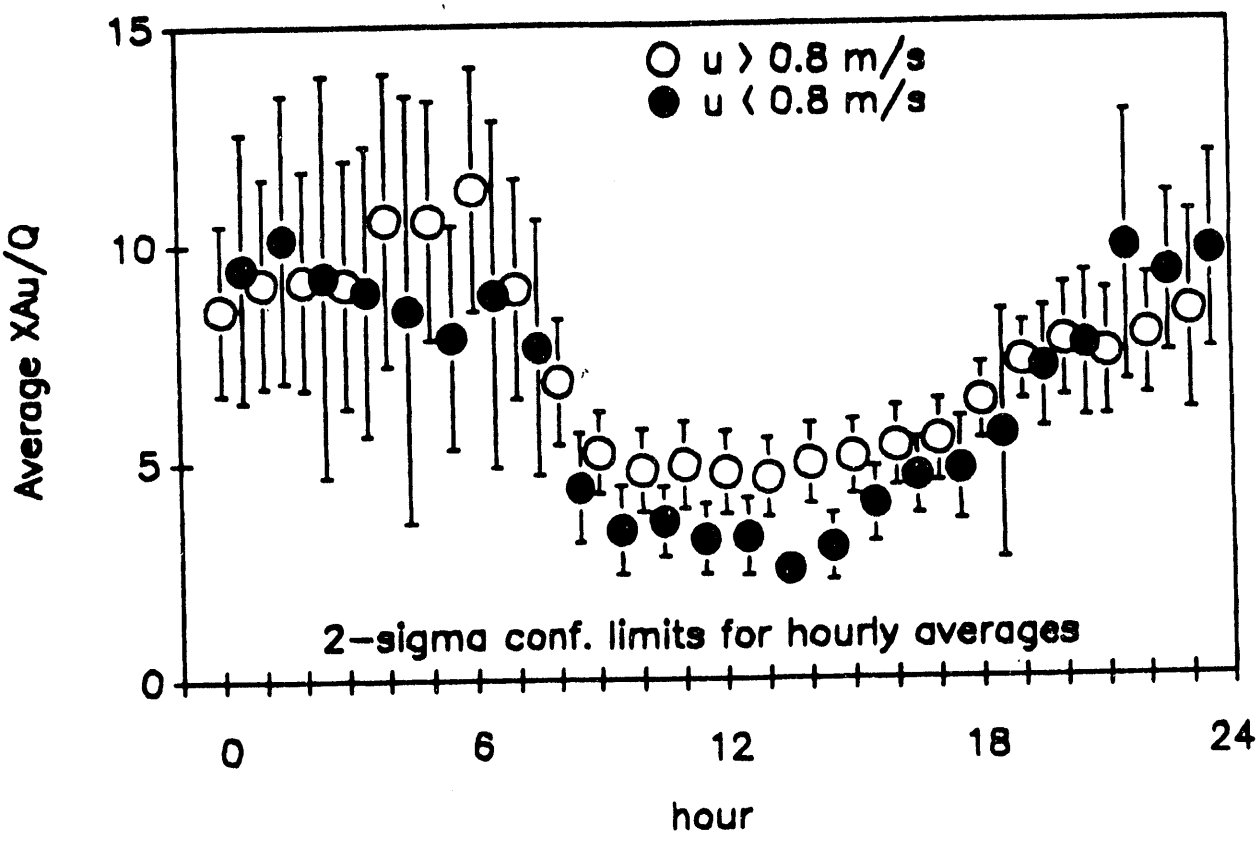


Figure 6-23. Typical measured values of the efficiency parameter χAu/Q for the BNL FACE system.

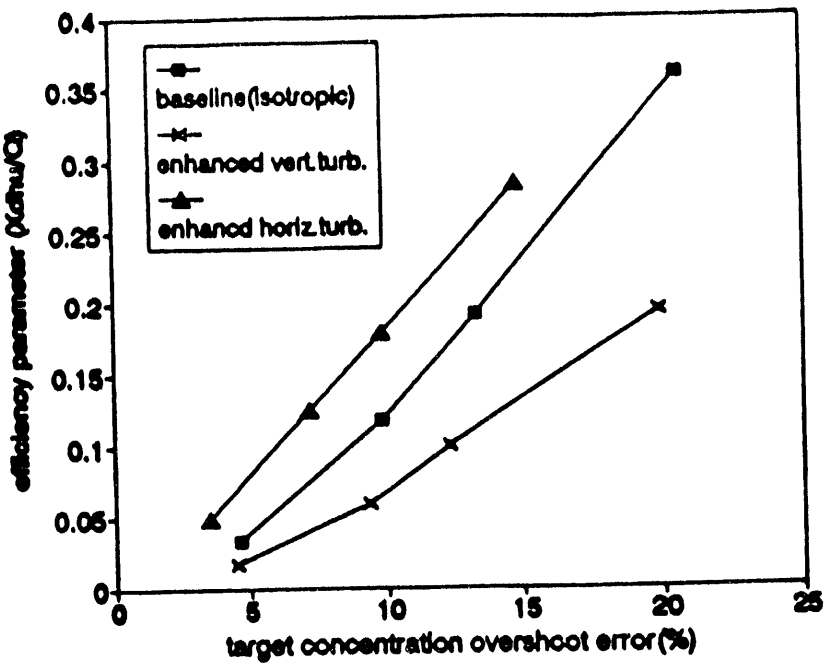


Figure 6-24. Parametric calculations of theoretical gas usage efficiencies for a 24 m diameter plot fumigated by a single Gaussian plume at H=2 m, for various turbulence assumptions.

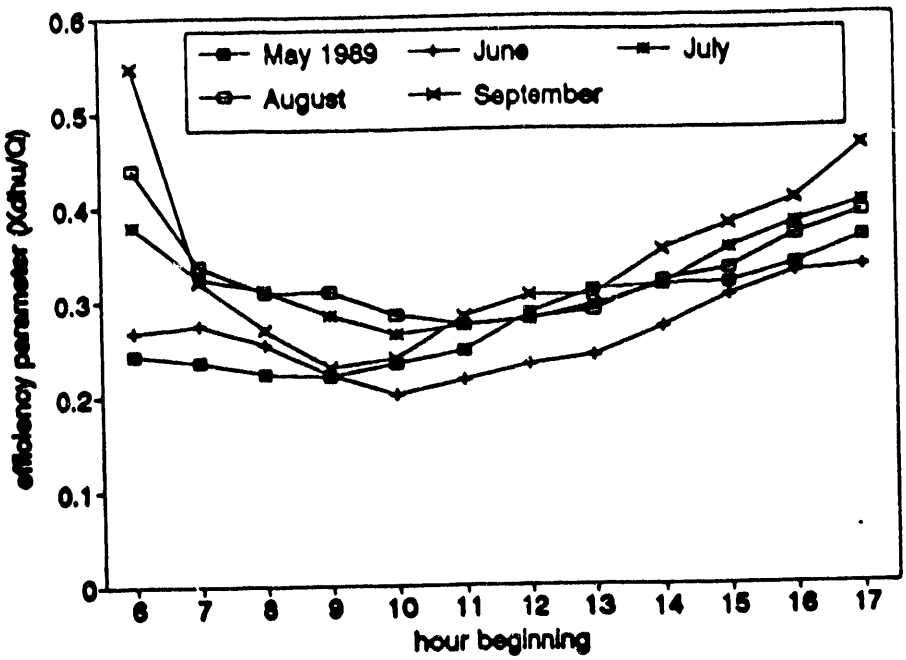


Figure 6-25. CO_2 usage of the BNL FACE system, measured at Maricopa, AZ in 1989.

FACE FACILITY ENGINEERING PERFORMANCE IN 1989

John Nagy, Keith F. Lewin, George R. Hendrey,
Frederick W. Lipfert and Mary L. Daum
Department of Applied Science
Brookhaven National Laboratory
Upton, NY 11973

I. INTRODUCTION

This chapter summarizes FACE facility engineering performance during the 1987-1989 operating period. There are two general areas of system control. The first is reliability of subsystems and components. The second is maintenance of temporal and spatial control of the CO_2 concentration within the experimental plot. Data from 1987, 1988, and 1989 are presented to illustrate spatial variability in CO_2 within the FACE array. The first section addresses system reliability, that is, failures of hardware components or subsystems resulting in inability of the facility to function as designed. This is distinct from CO_2 control performance, defined as the ability to hold a preset concentration level when all hardware is functioning.

Generally, elevated CO_2 treatment ceased in order to effect a repair to one or more arrays. Some types of failure, however, can cause over-treatment or wide variation in treatment level if left uncorrected. Failures can be common to all arrays (e.g., the CO_2 vaporizer) or specific to one array (e.g., a gas analyzer). The following section documents the system reliability as a percentage of available running time and assigns fraction of downtime to specific components and subsystems. Reliability varied in 1989 from 92% (Array 3) to 97% (Array 1).

Factors influencing CO_2 control performance can be divided into two parts: efficiency, that is the amount of CO_2 needed to maintain an elevated concentration level, and control, the long-term and short-term ability to maintain the target concentration. Both of these factors are strongly affected by the micrometeorology encountered at a site during an experiment. Therefore, wind conditions at Maricopa for the 1989 experiment are summarized first. This provides the context within which to interpret CO_2 use and concentration control. The average wind speed during 1989 CO_2 treatment was 1.0 m s^{-1}, resulting in an average CO_2 use of 1,400 kg per day per array. Long-term (daily average) concentration control was within several μmol mol^{-1} of the 550 μmol mol^{-1} set point (approximately 200 μmol mol^{-1} above ambient). One-min average CO_2 concentrations lay within 55 μmol mol^{-1} (±10%) of the set point 88% of the time, and within 110 μmol mol^{-1} (±20%) 98% of the time.

II. SYSTEM RELIABILITY

Downtime is defined as failure of a subsystem or hardware component such that the system fails to meet design specifications. During downtime there may

be under-enrichment, over-enrichment, widely varying enrichment, or even stable enrichment at the set point, depending on the nature of the failure, current conditions, whether the problem has been detected by the control software or the operator, and whether the operator has taken any temporary mitigating action. For example, CO_2 concentrations return to ambient if CO_2 stops flowing, over-enrichment occurs if a CO_2 proportional mass flow valve fails fully open, and no change happens if wind direction control fails but the wind does not change direction. In the latter case, even if wind direction is changing, the operator has the option of manually opening every other vertical vent pipe valve around an array. Under these conditions the CO_2 concentration control is good but at the expense of markedly increased CO_2 use (decreased efficiency).

Four independent CO_2 treatment arrays were in place at Maricopa in 1989. However, all four arrays shared certain subsystems for reasons of economy, space, and available maintenance time. Failure of a shared subsystem results in impaired operation of all arrays (common mode failure). A detailed breakdown of downtime due to shared resources is given below. Common mode failure accounted for 29% (Array 3) to 84% (Array 1) of all downtime for the arrays. This range is partly due to the fact that the other arrays were kept running at the expense of Array 3 (designated the "engineering studies array") if replacement parts could be obtained from the latter. Downtime in terms of total array-hours in 1989 was about equally divided between common mode failure and problems with individual arrays (Table 7-1).

Total downtime varied between 3% (Array 1) and 8% (Array 3) of the scheduled time available. As discussed below, many of the problems were due to commissioning an experiment at a new site, hardware or software design faults which were correctable, or the operator learning curve. Array 3 was not turned on until about 20 days after the others due to the unavailability of a CO_2 gas analyzer. This period for Array 3 has not been assigned as downtime counted against system reliability.

A. Common mode failures

Subsystems shared by all arrays which caused problems in 1989 were (1) the CO_2 gas supply, (2) the control computer, (3) the air compressor, (4) the field-to-trailer multiplexed data transmission, and (5) the multiplexed vent pipe valve control circuitry. Only failures in the first three were significant problems (Table 7-2).

CO_2 liquid is vaporized near the CO_2 storage tank and then transported through a high pressure line to a manifold for distribution to the separate arrays. Most of the downtime attributed to this subsystem was due to startup of new equipment at the very beginning of the experiment. Some was due to operator error in that the clock which turns on the vaporizer in the morning was not set correctly.

One computer and data acquisition system runs all arrays. None of the downtime can be attributed to hardware failure of any computer system component. The primary problem in this area was the lack of robustness of the software. Increasing the software's user tolerance and adding various alarms to notify the operator of possibly abnormal conditions has greatly reduced the period of downtime caused by computer system malfunction. A residual, and possibly unsolvable concern, is that of incorrect settings entered by an operator.

A centrally located compressor supplied air to the pneumatically actuated vent pipe valves and purge gas for the CO_2 analyzer cases. The immediate effect of losing compressed air on CO_2 concentration control depends on current conditions. The large fraction of downtime attributed to the air compressor is due primarily to the fact that the compressor failure was not immediately detected. In one case the compressor was shut off by an operator but not restarted and in the others a fuse had blown. Control performance alarms have addressed the problem indirectly but a direct signal showing the presence of compressed air is needed.

B. Array specific downtime

The only significant contributor to downtime by components in each array was the CO_2 mass flow control valve, which accounted for 82% of array specific downtime (Table 7-3). This is a DC-motor actuated, rotary ramp valve using a resistance-type flow sensor. The valve opens to the extent needed to satisfy the CO_2 flow demanded by a control signal. The most prevalent cause of failure of this component was the galling of mating surfaces. Hardfacing one of the mating surfaces has subsequently improved reliability of these devices to almost 100%.

III. WIND CONDITIONS

Understanding the meteorological conditions under which a FACE experiment operates is necessary to interpret data on CO_2 use and control performance. Enriched gas is introduced only at the upwind edge of an array. A horizontal wind component is required to transport the gas across the array. The horizontal component must be relatively strong compared to vertical components to ensure spatial uniformity and good concentration control. Changes in wind conditions during the season complicate analysis of CO_2 use and control performance due to their correlation with other important variables, including ambient CO_2 concentration, solar radiation, canopy height, height of CO_2 sampling intake and wind sensors, and the number and vertical position of open ports on the vent pipes.

A. Wind speed

Wind speeds in Field 27 at the Maricopa Agricultural Center during 1989 were much lower than those reported in historical records due to difference in the height of the sensors. Wind data used here are taken from the center of the FACE arrays by the wind measurement subsystems (see Chapter 5). Daily average wind speeds from 0600 to 1800 hours ranged from 1.5 to 3.5 m s^{-1} but dropped below 1.0 m s^{-1} at the end of May and the beginning of June for most of the remainder of the season (Figure 7-1). Along with the decrease in average wind speed, the fraction of time defined as "calm" for the purposes of this experiment increased from a low of 2% in May to 30% in September (Table 7-4). All together calm periods amounted to 19% of the running time.

For this experiment, "calm" is defined as wind speeds below 0.4 m s^{-1} and has real, operational effects. Below this speed, the wind direction sensors are insensitive to direction changes. Since the wind cannot be assigned to any given sector under these low wind conditions, every other vent pipe is opened around

the whole array. Although control is little effected in this mode, CO_2 use increases by a factor of about 2.5 compared to operating with directional control.

B. Wind direction

Wind direction showed distinct patterns both in terms of sector frequency and wind speed from a sector. Winds from the south to the west were more frequent and were generally stronger than winds from the north to east. Since gas is ejected only from the upwind side, except under calm conditions, and spatial uniformity depends on wind speed, non-random winds introduce the possibility of spatial CO_2 bias within an array, primarily on a southwest-northeast axis, depending on time of day.

C. Diurnal patterns

Meteorological conditions demonstrated fairly consistent diurnal patterns throughout the experiment, higher wind speeds occurring later in the day (Table 7-5). Averaged over the season, periods of calm dropped from 26% early in the morning to 14% in the late afternoon. The wind direction also shifted during the day from the south and southeast in the morning to the west in the afternoon (Figure 7-2).

IV. CO_2 USE

The diameter of all four arrays, as measured at the vent pipes, was 23 meters in 1989. Under the meteorological conditions encountered between May 20 and September 18, CO_2 use averaged about 1,400 kg of CO_2 per day per array (Figure 7-3).

CO_2 demand is not strictly proportional to wind speed; vertical dispersion plays an important role. Even if horizontal wind speed were zero, some CO_2 input is required to maintain the concentration at the central gas analyzer at the set point. Vertical turbulence varies with meteorological conditions, so the relation between CO_2 demand and wind speed is not 1:1. To illustrate this effect, the hourly average CO_2 release rate and wind speed were computed separately for each month (Figure 7-4). The curve for each month as it progresses through the hours of the day traces an inverted U-shape. From early morning to midday, average wind speed increases but CO_2 use increases by a proportionally higher amount. Winds continue to increase during the afternoon but CO_2 use per unit wind speed decreases. CO_2 use per unit wind speed is lowest at the beginning and end of the day when the sun is lowest on the horizon. It is greatest during midday when the intense Arizona sun is creating turbulence in the atmosphere. A simple empirical expression which fits the gross features of the data is

$$F = 0.3 + 1.1 * u + 0.8 * \sin(h)$$

where F is the CO_2 flow rate in kg min^{-1} for a 23-meter array, u is the wind speed in m s^{-1}, and h is the solar altitude (the angle of the sun above the horizon). Rapid changes in wind direction or speed, besides being an indicator of

atmospheric turbulence, also directly influence CO_2 demand; demand is less when both wind speed and direction are steady.

V. CO_2 TREATMENT CONCENTRATION LEVELS

Over the course of the season when enhanced CO_2 treatment was scheduled, the CO_2 concentration was 544 to 548 μmol mol^{-1} depending on array (including downtime). When the system was functioning properly as designed, the treatment average was within 1 μmol mol^{-1} of the 550 μmol mol^{-1} set point (Table 7-6).

Daily average CO_2 treatment was very close to the set point for most of the running period (Figure 7-5). Commissioning problems with the CO_2 supply effected Arrays 1 and 4 at the very beginning. Array 3 suffered from loss of its mass flow control valve for three days late in June and its CO_2 pressure regulator for part of a day in September. Daily average CO_2 levels in September tended to be high due to ambient concentration levels which exceeded the set point for the hour 0600-0700. See especially September 4 (day 247) in Figure 7-5 in this regard.

VI. SHORT TERM CO_2 CONCENTRATION CONTROL PERFORMANCE

As demonstrated above, the FACE system controls CO_2 concentration very close to the set point when viewed over long time periods, e.g. day or season. Shorter time periods may be of biological significance. Short-term performance is measured by calculating the fraction of time that CO_2 concentrations measured just above the crop canopy at the center of the FACE plot (e.g., samples taken every second, 1-min average, 5-min average) deviate by more than certain amounts (e.g., 20%, 10%, or 2%) from the set point. In the case of a set point of 550 μmol mol^{-1}, 10% and 20% of the set point correspond to ±55 μmol mol^{-1} (495 to 605 μmol mol^{-1}) and ±110 μmol mol^{-1} (440 to 660 μmol mol^{-1}) respectively. The design criterion was to hold the 1-min average within 20% of set point for over 80% of the time. This criterion was easily fulfilled even under the adverse control conditions encountered at Maricopa in 1989.

Table 7-7 shows the fraction of time the 1-s sample and 1-min average gas concentrations deviated more than 10% and 20% from the set point. Downtime is not included in these results. The 1-min average deviation was greater than 20% for less than 2% of the time, an order of magnitude better than the design criterion. It was within 10% for 88% of the time. Since all arrays demonstrated similar short-term control capability under all conditions, the remaining results are presented combining data from all four arrays.

A. Dependence on wind speed

Control performance varied with wind speed (Table 7-8). In general, low wind speeds are associated with relatively greater variability in wind speed and direction and during the daytime, with relatively higher vertical turbulence. Control was markedly poorer under calm conditions (wind speed less than 0.4 m s^{-1}) when every-other VVP was open around the full circle of the FACE array, than for the other wind speed categories when directional control was used on VVP openings. Above 0.4 m s^{-1}, average performance gradually improves except for an inexplicable deterioration in Array 4 above 4.0 m s^{-1}. The one-dimensional

presentation in Table 7-8 averages over other important influences, such as solar radiation, and is not necessarily an indication of what performance would be at another site with different meteorological conditions.

B. Dependence on wind direction

Although the FACE arrays are radially symmetric, short-term control performance appears correlated with wind direction (Tables 7-9 and 7-10). The reason control is poorer from the north and east is because winds from those directions were weaker and more variable. Control under southerly winds was better because those winds are associated with early morning atmospheric stability as opposed to westerly winds which predominate later in the day.

C. Diurnal variation

In general, control was worse in the middle of the day, averaged over all other variables (Figure 7-6). Again, this is due to the increased vertical turbulence induced by solar energy input. Performance was poorer for the first hour of running (0600-0700) compared to the second hour in 1989. The control algorithm is adaptive and learns how to adjust CO_2 flow rates (see Chapter 5), primarily from conditions and operating performance over the previous 15 min. In the case of a scheduled shutdown such as from 1800 to 0600 hours, the control program picks up where it left off the previous evening. It takes a few minutes to adjust to the morning conditions. For purposes of system startup, it would have been better to have stored a knowledge base of operating parameters versus current conditions. Low wind speed exacerbated the problem but higher atmospheric stability kept it from being even worse.

VII. GAS DISTRIBUTION WITHIN THE FACE ARRAY

Three separate types of experimental protocols were used to investigate the distribution of CO_2 within the FACE array at Yazoo City, MS and Maricopa, AZ (not including studies reported in Chapter 8 of this book). First, a multiport sampler was used to document CO_2 concentrations at various locations and times. This device samples the air from 12 fixed locations within the FACE plot sequentially, each sample being processed in turn by the same CO_2 analyzer. As a result, this investigation did not permit simultaneous determinations at all locations and thus the covariables include wind speed as well as the CO_2 concentration set point (Yazoo City, only). Second, tracers were released from the CO_2 injection ports and then sampled simultaneously at a large number of preset locations within the array and downwind. Three such tracer tests were performed in 1987, and three separate tracers were released during each test, each tracer having different release (and thus averaging) times. The intent was to release the tracers during times of relatively constant wind conditions and thus to provide a "snapshot" of the dispersion. The tracer tests document the dispersion of the **incremental** CO_2 released from FACE, over and above existing ambient. The multiport sampler (CO_2) data are presented in terms of the **total** CO_2 level, including ambient background. Referenced to a target concentration of 550 μmol mol^{-1}, the percentage differences in tracer concentrations thus should be about three times as large as the percentage differences in total CO_2

(background + increment), under the same conditions. See Lipfert *et al.* 1989 for more details on these experiments. A second type of multiport sampler, the MP3S discussed (in footnote 1 below), was used in tests at Maricopa in 1989. The final technique measures the CO_2 concentrations as a function of position at the same time from all nodes in the multiport matrix. Collapsed plastic bags are placed in evacuated, sealed buckets. These are attached to the sampling cups and the bags are allowed to fill at a controlled rate. After filling, a gas analyzer sequentially determines the CO_2 concentration in each bag. The technique, called a "bucket test," thus provides a snapshot of the 3-dimensional distribution of CO_2 concentrations (see footnote 2, below).

A. 1987 Multiport sampler results

These data were taken during the FACE experiment at Yazoo City, MS during the period August 25-28, 1987. Since wind conditions varied during these tests, the distributions within the FACE array are presented in terms of the radius from the center of the ring, rather than as a function of the distance downwind from the injection point, as would be more appropriate from the standpoint of the fluid mechanical behavior. In addition, data were taken at three different heights above ground: "top" = 175 cm; "middle" = 85-90 cm; "bottom" = 5-10 cm aboveground. Three different CO_2 concentration set points were employed: 500, 600, and 700 μmol mol^{-1} (approximately 140, 240, and 340 μmol mol^{-1} above ambient, respectively). Part of the experimental objective was to determine whether the distributions were sensitive to variations in the set point (target concentration), since the amount of gas injected and dispersed varied by about a factor of 2.5 over the range in set points.

A further experimental variable is the gas concentration averaging time. Data were recorded for one second and then aggregated to longer averaging times, up to one hour. Naturally, the variability is much greater for the shorter averaging times. Wind speed also plays a role, and its variability must be accounted for in interpreting the multiport sampler results. Pending definition of the minimum time increment that is biologically relevant (see Chapter 10), we have used arbitrary levels in presenting the FACE test results.

Figure 7-7 presents the deviations from the set point (expressed as a fraction of the "target" or set point), as a function of height and radius. Various values of wind speed and set point concentration are encompassed in these data, as well as both upwind and downwind locations at a given location, expressed as radius from the center of the ring. The observation time used is five minutes, for each sample location, and an electrical integration circuit was used to give a signal averaging time of 33 seconds. Each data point on Figure 7-7 is thus the average of the data taken during the 5-min period. The lines on the graphs are best-fit second-order least-squares regressions for the data points shown. The data indicate only minimal differences according to height above ground, although there is considerable scatter. On average, the radial distribution is essentially flat out to a radius of about 4 m rising to about 10% above target at 6.5 m radius. The individual 5-min points are within $\pm$20% of target in this region. On this basis, the usable diameter within the FACE array in 1987 was estimated to be 13 m.

In 1987 FACE was controlled so that half of the vertical vent pipes (16) were opened in a semi-circular arc at wind speeds >0.4 m sec^{-1}. For this reason

the concentration tended to rise near the edges of the ring because the injection pipes were effectively spaced closer together, when projected onto a plane perpendicular to the wind direction. In order to reduce this problem the configuration was changed in 1988 to provide "feathering" of opening of the vents at either end of the arc (see Fig. 3, Chapter 5).

Figure 7-8 displays this same information with the CO_2 set point concentration as a parameter, averaged over the three heights. The same conclusions hold regarding the usable area of the ring, and no systematic variations are seen due to set point level. If the percentage deviations were referenced to the incremental C02 concentration rather than to the set point, the percentage deviations would be about double those shown in the figures, on average.

The preceding graphs display the total range in scatter but do not directly indicate the distribution of readings within that range; Figures 7-9 and 7-10 display frequency distributions which provide this information. The 5-min mean concentrations are within $\pm$20% of the set point all of the time for radii less than about 6 m, and 50% of the time at the maximum radius (8-9 m), as shown in Figure 7-9. The concentration ranges (maximum - minimum) within the 5-min time blocks (Figure 7-10) meet the precision criterion ($\pm$20% [corresponding to the range value of 0.4] 80% of the time) out to about 5-m radius, but this range is not symmetric about the set point.

The final graph in this series, Figure 7-11, shows the effect of averaging time on the range of deviations, for locations near the center of the ring (up to 4 m radius). The 1-s readings, on the left of the graph, have an average range of about 80% (plus or minus 40%). Since there is a large number of these readings (from 1500 to 3900 at the various locations shown) which reduces the uncertainty of the means, these five data points are tightly grouped. The middle set of points, which correspond to Figures 7-8 to 7-10, have an average range of about 30%, and the 5-min data, on the right, average about 10%. The linear regression line through these three groups of data indicates that the (extrapolated) average range in 60-min deviations would be about 4%, but achievement of this degree of control uniformity over an extended period of time would be dependent on the meteorological conditions experienced.

B. 1987 Tracer test results

Three different tracer tests were performed in 1987 on the FACE experiment at Yazoo City using three separate perfluorocarbon tracers. Perfluorocarbon compounds can be detected in extremely minute quantities, down to about 10^{-15} mol ℓ^{-1} (see Dietz 1987 for a description of this methodology). During these tests, a fixed array of detector tubes was deployed at the same locations used for the multiport sampling. Each tracer was released through the FACE gas injection system for the length of time prescribed by the detection limit for that particular perfluorocarbon compound. The detector tubes, which are passive air sampling devices, were opened before the tracer release and closed afterwards. The relative variation in tracer concentrations within the array gives a measure of the dispersion within the array. In addition, detector tubes were deployed upwind and downwind of the array, to provide data on background levels of the tracers and on the downwind decay.

The tracer data are extremely useful in describing the FACE three-

dimensional flow fields, since they can provide snapshots in time with all locations sampled simultaneously. The three tracer compounds, denoted PMCP, PMCH, and PDCH, were released for 1, 5, and 25 min, respectively. The analytical laboratory reported difficulty with the 1-min data, and since this time increment is of the same order as the transit time through the array for low windspeeds, these data were not regarded as particularly useful. Two types of data presentations follow:

1. Statistics of the variability of tracer within the central area of the FACE array (the so-called "sweet spot," 6.5 m radius), given in Table 7-11.

2. Plots of the downwind and crosswind variability of tracer concentrations, resolved into a rectangular coordinate system approximately aligned with the average wind during the tracer release. The crosswind variability is limited to a swath 13 m wide perpendicular to the wind direction, and is presented in terms of the deviation from the "sweet spot" average of the data points within this swath at a given downwind distance from the upwind edge of the array.

Table 7-11 confirms that the vertical concentration gradients during these tests were modest (but variable). In most cases, the bottom level was slightly depleted, rather than over-enriched as predicted by theory (Chapter 4). The overall standard deviations decreased as the tracer release (averaging) time increased, as expected. The variability among the three tests was about the same, although Test 2 was somewhat less variable than the others.

The wind direction-resolved plots, Figures 7-12, 7-13, and 7-14, show a stronger downwind concentration decay during Tests 1 and 3 than for Test 2. This may relate to wind direction at the Yazoo City location, since northerly winds pass over an elevated levee obstruction north of the field before encountering the array. Analysis of 1988 data from the FACE tests at Yazoo City found FACE array performance differences within the field that related to distance from this obstruction.

Figure 7-15 plots the PDCH tracer data from Test 2 as a function of radius, for comparison with the CO_2 plot (Figure 7-8). The tracer data are seen to be considerably more variable, but the comparison becomes more reasonable when the background CO_2 is taken into account.

The upwind-downwind concentration variability is expected to be systematic, moving with wind direction. This means that the gradients will tend to average out if the wind is not consistently out of a particular direction. The crosswind variability is more likely to be random, as evidenced by deviations from the best fit (2nd order) regression lines shown. However, the overall deviation of the incremental enrichment indicated by the tracer experiments in 1988 is likely to be in the range $\pm$25% to $\pm$40% of the increment (80% of the time), which is within the $\pm$20% design goal when the background CO_2 is accounted for.

The tracer data taken downwind of the array were aligned approximately with the wind, but this is difficult to achieve since wind shifts cannot be predicted and the bulk of the measurements were planned for the region inside the array. The data are presented in semilog format, consistent with an exponential decay downwind of the array. At a distance of about 100 m (about 5 array diameters),

the tracer has decayed by about an order of magnitude (Figure 7-16). This would correspond to a CO_2 increment of about 20 μmol mol^{-1}. The variability about the regression line on Figure 7-16 indicates the cross-wind variability in downwind decay.

C. 1989 multiport sampler data

A multiport selectable sequencing sampler (MP3S) was set up within FACE Array 3 at Maricopa from 26 July to 18 September 1989.[1] This system was arranged with 21 sample ports placed at the nodes of a square grid with 4.5 m spacing in each of three layers centered in the FACE plot. The four corner nodes of each layer were omitted. The bottom layer of sample ports was placed at height of the rows but within the furrows. The middle layer was at 0.5 m above ground from 26 July to 13 September and at 0.8 m from 13 to 18 September. The top layer was 1.0 m above ground from 26 July to 13 September and 1.6 m from 13 to 18 September. Over the period 26 July to 18 September 1-s grab-samples were taken sequentially by layer in discontinuous periods of observation. The sampling protocol included a purge period of at least a 10-s between samples. Within each of the three layers, the nine central sampling nodes correspond roughly to the 12-m diameter "sweet spot" from which biological samples were collected (see Chapter 11). The total number of observations made in each of these central three 3-node by 3-node areas were 5,381 (bottom layer), 5,437 (middle layer) and 5,586 (top layer). The deviations of each sample from the mean value of its plane is plotted for all 16,404 of the samples collected from the 27 sample nodes in the central volume of the FACE treatment (Fig. 7-17). Out of all of these 1-s grab samples 72, or 0.44% exceeded 1,100 μmol mol^{-1} (2 times the target value).

The deviation of the season-long CO_2 concentration average of each of the nodes from the season-long average of its layer, is plotted in Figures 7-18a-c. Winds at the Maricopa site were predominantly westerly. But the average wind direction associated with the measurements is from the southwest. Sample nodes, indicated by plus signs in the figures, impinge upon the FACE distribution plenum ring at each of the 8 outermost end points of the rows of nodes. These sample intakes were within a meter of the VVP emitter jets. It is likely that the westerly sample points were actually impacted by emission jets from time to time, thus causing the high average values on that side of the array.

Deviations within the "sweet spot" volume described by the central 27 nodes with respect to the season-long average within the "sweet spot"are less than $\pm$5%. The effect of the dominant westerly wind direction is to impose a slight CO_2 gradient across the FACE plot. This gradient is altered by either the height above ground or position with respect to development of the canopy, or both.

---

[1]The MP3S has 72 3-way valves that may be switched in any order or combination. Sampling tubes (0.625 cm id PVC 30 m long) run from a remote location to each of the valves. The valves are connected to a vacuum exhaust manifold through which all sample tubes are connected. In this way air flow is continuously maintained in all of the sample tubes. A PC-based control program sequences through the ports, diverting a sample line to a Binos infra-red gas analyzer. Transit time from sample line intake through the Binos is 7 s.

These up-wind to down-wind differences across the "sweet spot" were about 9%, 6%, and 4% respectively for the bottom, middle and top layers. It should be possible to plan sampling strategies within the controlled area to minimize possible effects of such gradients.

D. 1989 bucket tests

Two bucket test[2] runs were made at Maricopa on August 3, 1989. The first began at 0800 MST and had a fill time of 1 h. The second began at 1400 MST and had a fill time of 5 min. During these tests winds were from the S to SSW directions. Wind speeds were low, averaging 0.3 and 0.7 m s^{-1}, respectively. Figure 7-19(a) depicts the results for the lowest layer (0.1 m) for the morning test as a contour plot. The figure as a whole shows slight buildup of CO_2 near ground level. The distribution is fairly uniform except for higher values on the upwind (southwest) side. Figures 7-19(b) and (c) show the middle and highest layers at 0.5 and 1.0 m respectively. The upper node at the ring center had a value of 573 μmol mol^{-1} for this 1-h test. Spatial uniformity is excellent at the top of the canopy.

Figures 7-20(a), (b), and (c) show the same series of results for the 5-min afternoon test. The upper node at the center measured 556 μmol mol^{-1}. However, there is less spatial uniformity. There is a noticeable drop off in concentration from SW towards NE. Nodes nearest the south and west sides in the upper layer have concentrations of 650 to 950 μmol mol^{-1}; elsewhere in the array, concentrations are 550 to 650 μmol mol^{-1}. The approximate range of concentrations across the "sweet spot" are presented in Table 7-12.

VIII. Summary

Following prototype development of the first BNL FACE system on Long Island in 1986, the first full-scale (22-m diameter) FACE array was built at Yazoo City, MS, in 1987. Three additional arrays were built (with some modification of the configuration of all four arrays) in 1988 in Yazoo City. In 1989 the four arrays were moved to Maricopa, AZ. The FACE system has proven to be very reliable with 3 to 7% of available experimental time lost to system failures in 1989 in the various arrays. Analysis of modes of failure and component failures are presented.

Wind speed, direction and stability are the most important variables governing CO_2 distributions within the FACE arrays. For this reason, detailed

---

[2]In these "bucket" tests sample tubes from the MP3S system were connected to individual Mylar balloons (10-ℓ capacity) via a syringe needle through a serum cap on a 10-cm long section of PVC tube sealed to the inside of the balloon. Each balloon was contained in a bucket with the sample line passing through an air-tight lid. A second section of PVC tube connected the inside of the bucket to the MP3S valves. By turning on a vacuum pump connected to the MP3S exhaust manifold, all of the buckets could be evacuated thus drawing air into the sample balloons. After filling, the balloons were removed and the samples analyzed separately on either a Binos or Simmens IRGA.

analyses of system control deviations as a function of these variables are presented. A statistical model relating CO_2 use to wind speed and solar altitude (a surrogate for stability) is derived that may be helpful in evaluating CO_2 use for FACE experiments planned for other locations.

System reliability and control improved with changes in engineering features between 1987 and 1989. Over the entire 1989 growing season, omitting times when the FACE systems were not functioning properly, average CO_2 concentrations measured at the center of the arrays were within 1 μmol mol^{-1} of the 550 μmol mol^{-1} target concentration. Averaging over all four arrays and all periods of operation, the 1-s observations measured at the center of the FACE arrays remained within $\pm$20% of 550 μmol mol^{-1} for 88% of the time. The corresponding 1-min average was within $\pm$10% for 88% of the time and within $\pm$20% for 98% of the time.

Studies of spatial control within one of the arrays demonstrated the general acceptability of control of CO_2 concentrations in a central plot of 12-m diameter. Experiments using tracers and multi-port monitoring of the spatial distribution of CO_2 showed that this area constituted a "sweet spot" within which CO_2 concentrations were $\pm$20% of the target CO_2 concentration at least 80% of the time. A 63-port selectable sequencing sampler was set up as a three-dimensional sampling system. Over 16,000 observations of 1-s grab samples were taken with this multiport sampler. Average values at each sampling node showed that spatial variability of CO_2 concentrations throughout the volume of the "sweet spot" in 1989 varied by less than $\pm$5%. Of these 1-s grab samples 0.44% exceeded twice the target concentration of 550 μmol mol^{-1} but 110 μmol at the top of the canopy. Grab-samples taken in "bucket tests" averaging over 5-min found a wind-dependent gradient across the "sweet spot" that was as high as 160 μmol. However, those ranges are still within the design criteria.

Table 7-1
Downtime summary, number of hours as a percentage of scheduled treatment time. Scheduled hours includes 12 hours per day from May 20 (Arrays 1, 2, and 4) or June 10 (ArraY 3) through September 18.

	Array 1	Array 2	Array 3	Array 4
Common Mode	38.17 (2.6%)	38.17 (2.6%)	29.83 (2.5%)	38.17 (2.6%)
Ring Specific	7.50 (0.5%)	25.17 (1.7%)	71.66 (5.9%)	13.58 (0.9%)
TOTAL	45.67 (3.1%)	63.33 (4.3%)	101.49 (8.4%)	51.75 (3.5%)

Table 7-2
Downtime due to common mode failure. Scheduled hours includes 12 hours per day from May 20 through September 18. (Arrays 1, 2 and 4)

Subsystem	Hours	Percentage of all common mode failure	Percentage of time scheduled
Air Compressor	15.17	40	1.04
CO_2 Supply	9.75	26	0.66
Computer	9.42	25	0.64
VVP Controls	2.33	6	0.16
Data Transmission	1.50	4	0.10
TOTAL	38.17	100	2.60

Table 7-3
Downtime effecting only one array, [Number of hours].

	Array 1	Array 2	Array 3	Array 4	Total
Mass Flow Valve	1.83	24.00	63.75	7.25	96.83
CO_2 Supply	3.25	0	4.50	4.33	12.08
Gas Analyzer	0	0	2.83	0.33	3.16
Miscellaneous	2.42	1.17	0.58	1.67	5.84
TOTAL	7.50	25.17	71.66	13.58	117.91
% scheduled treatment time	0.5	1.7	5.9	0.9	

Table 7-4

Fraction of calm wind conditions expressed as percentage of time with winds less than 0.4 m s^{-1}. Data for May cover the period May 20 to May 31. Data for September cover September 1 to 18.

Time (MST)	May	Jun	Jul	Aug	Sep	ALL
0600-0700	3	14	26	33	43	27
0700-0800	2	10	25	31	45	25
0800-0900	3	12	21	26	37	21
0900-1000	3	14	23	20	34	20
1000-1100	4	17	26	23	32	22
1100-1200	3	12	20	24	26	19
1200-1300	1	7	21	22	22	17
1300-1400	1	8	19	22	23	16
1400-1500	1	6	18	20	19	15
1500-1600	1	3	15	24	24	15
1600-1700	2	1	12	21	24	13
1700-1800	0	1	16	23	30	15
ALL HOURS	2	9	20	24	30	19

Table 7-5

Hourly average wind speed [m s^{-1}] by month. Data for May cover the period May 20 to May 31. Data for September cover September 1 to 18.

Time (MST)	May	Jun	Jul	Aug	Sep	ALL
0600-0700	1.58	0.85	0.65	0.58	0.48	0.71
0700-0800	1.80	1.03	0.73	0.63	0.47	0.81
0800-0900	1.80	1.04	0.82	0.75	0.60	0.89
0900-1000	1.72	0.98	0.73	0.80	0.65	0.88
1000-1100	1.84	0.99	0.70	0.76	0.69	0.87
1100-1200	1.92	1.14	0.75	0.74	0.82	0.94
1200-1300	2.40	1.28	0.76	0.75	0.82	1.02
1300-1400	2.81	1.35	0.82	0.78	0.87	1.09
1400-1500	3.11	1.51	0.89	0.82	0.94	1.19
1500-1600	3.30	1.71	0.97	0.79	0.96	1.26
1600-1700	3.08	1.79	0.95	0.86	0.94	1.28
1700-1800	3.11	1.75	0.92	0.76	0.75	1.21
ALL HOURS	2.40	1.29	0.81	0.75	0.75	1.01

Table 7-6
Average daytime CO_2 exposure (μmol mol^{-1}).

	Array 1	Array 2	Array 3	Array 4
Target (set point)	550	550	550	550
When under control(1)	549.7	549.4	549.6	549.5
All periods(2)	548	548	544	547

(1) Mean of 1-min average CO_2 concentration readings over the entire treatment period for all time when the control system was functioning properly and was adding CO_2 to the array.

(2) Includes all periods when the system should have been adding CO_2 to an array from start up to September 18.

Table 7-7

Fraction of time CO_2 concentration averages deviated from set point for 1-s samples and 1-min averages. Samples taken once per second represent a few seconds concentration average due to the inherent response time limitations of the apparatus.

	1-second Sample		1-minute Average	
Array	by > 10%	by > 20%	by > 10%	by > 20%
1	0.390	0.121	0.133	0.021
2	0.396	0.122	0.132	0.018
3	0.391	0.122	0.110	0.017
4	0.385	0.118	0.105	0.015
ALL	0.390	0.121	0.121	0.018

Table 7-8
Fraction of time CO_2 concentration averages deviated from set point versus wind speed for 1-s samples and 1-min averages.

Wind Speed	1-second Sample		1-minute Average	
[m s^{-1}]	by > 10%	by > 20%	by > 10%	by > 20%
0-0.4	0.497	0.212	0.255	0.051
0.4-1.0	0.388	0.120	0.113	0.013
1.0-2.0	0.346	0.081	0.062	0.006
2.0-4.0	0.321	0.061	0.056	0.004
4.0+	0.306	0.049	0.082	0.016
ALL	0.390	0.121	0.121	0.018

Table 7-9

Fraction of time CO_2 concentration averages deviated from set point versus wind direction for 1-s samples and 1-min averages.

Wind	1-second Sample		1-minute Average	
Direction	by > 10%	by > 20%	by > 10%	by > 20%
Calm	0.497	0.212	0.255	0.051
North	0.441	0.150	0.144	0.016
East	0.409	0.128	0.113	0.012
South	0.331	0.082	0.068	0.009
West	0.355	0.088	0.082	0.008
ALL	0.390	0.121	0.121	0.018

Table 7-10

Fraction of time 1-min average CO_2 concentration deviated by more than 10% from set point, versus wind speed and direction.

Wind Direction	< 0.4 m s^{-1}	0.4-1 m s^{-1}	1-2 m s^{-1}	2-4 m s^{-1}	> 4 m s^{-1}
Calm	0.255	---	---	---	---
North	---	0.150	0.127	0.144	---
East	---	0.135	0.077	0.049	---
South	---	0.083	0.049	0.051	0.076
West	---	0.115	0.054	0.056	0.084
All	0.255	0.113	0.062	0.056	0.082

Table 7-11

Statistics of the tracer tests at Yazoo City, MS.
Tracer Test 1. Sept. 25, 1987, 16:40-17:05, winds: N-NW at 0.7-0.9 ms^{-1}.
Tracer Test 2. Sept. 27, 1987, 17:50-18:15, winds: SE at 1-3 ms^{-1}.
Tracer Test 3. Sept. 29, 1987, 15:05-15:30, winds: W-NW at 1-4 ms^{-1}.
Average tracer concentrations are expressed as percentage of the average over the sweet spot at the top sampling location.

	Tracer		
	PMCP (1-min)	PMCH (5-min)	PDCH (25 min)
Tracer Test 1			
Top	100	100	100
Middle	104	125	111
Bottom	108	111	101
Overall Std. Dev.	56	33	16
Tracer Test 2			
Top	100	100	100
Middle	98	92	95
Bottom	85	79	85
Overall Std. Dev.	34	24	24
Tracer Test 3			
Top	100	100	100
Middle	85	107	101
Bottom	94	101	99
Overall Std. Dev.	55	32	24

Table 7-12

Approximate ranges of variation of CO_2 concentrations observed within the central 12-m diameter area of FACE Array 3 during 60-min and 5-min bucket tests. These ranges are obtained by interpolation of isolines presented in Figures 18 and 19.

Layer	60-min	5-min
Top	25	110
Middle	62	160
Bottom	50	150

FIGURE CAPTIONS

Figure 7-1. Daily average wind speed in (m s^{-1}) for the hours 0600 to 1800, May 19 to September 18, 1989. Measurements are taken at the center of each array at heights from approximately 1.5 to 2.5 m depending on time of year.

Figures 7-2a to 7-7d. Wind direction frequency and average magnitude by hour of day. Each figure represents pooling of all wind data for a given time-of-day interval for the whole treatment period. The height of a bar is proportional to the frequency of wind from the indicated sector. At the top of a bar is the mean wind speed for winds from that sector. Calm is defined as wind speed less than 0.4 m s^{-1}. (a) 0600-0900 MST, (b) 0900-1200 MST, (c) 1200-1500 MST, (d) 1500-1800 MST.

Figure 7-3. CO_2 use in megagrams (metric tonnes) per day per array at Maricopa, Arizona, from 0600 to 1800 MST May 19 to September 18, 1989. Arrays were 23 m in diameter.

Figure 7-4. CO_2 demand (kg min^{-1}) versus wind speed in (m s^{-1}). Averages are computed for each hour of the day for each month (May is not shown). (See text for interpretation of graph.)

Figures 7-5a to 7-5d. Daily average (0600-1800 MST) of 1-min integral CO_2 gas concentration (μL/L = μmol mol^{-1}. (a) Array 1, (b) Array 2, (c) Array 3, (d) Array 4.

Figures 7-6a to 7-6e. Fraction of time which the 1-min CO_2 concentration deviates by more than ±10% (55 μmol mol^{-1}) from the set point of 550 μmol mol^{-1}. Short-term CO_2 concentration control performance showed strong diurnal and seasonal variation. (a) May, (b) June, (c) July, (d) August, (e) September.

Figure 7-7. Average distribution of CO_2 within the FACE array at Yazoo City, MS, 1987, averaged over set point concentrations of 500, 600, and 700 μmol mol^{-1}.

Figure 7-8. Average distribution of CO_2 within the FACE array at Yazoo City, MS, 1987, averaged over vertical sampling heights of 5-10 cm, 85-90 cm and 175 cm above ground.

Figure 7-9. Frequency distribution of mean CO_2 concentrations within the FACE array at Yazoo City, MS, 1987, as a function of sampling location (distance from the central control point).

Figure 7-10. Frequency distribution of the range in 33-s average CO_2 concentrations within the FACE array at Yazoo City, MS, 1987, as a function of sampling location (distance from the central control point).

Figure 7-11. Effect of averaging time on CO_2 concentration variability at Yazoo City, MS, 1987, for various sampling locations within the FACE array.

Figure 7-12. Tracer data from Test 1, PDCH tracer (25 min.). Yazoo City, MS, September 1987. Plotted against downwind time.

Figure 7-13. Tracer data from Test 2, PDCH tracer (25 min.). Yazoo City, MS, September 1987. Plotted against downwind distance.

Figure 7-14. Tracer data from Test 3, PDCH tracer (25 min.). Yazoo City, MS, September 1987. Plotted against downwind distance.

Figure 7-15. Tracer data from Test 3, PDCH tracer (25 min.). Yazoo City, MS, September 1987. Test 2 data plotted against radius.

Figure 7-16. Tracer data from Test 2 downwind of the array, PDCH tracer (25 min.). Yazoo City, MS, September 1987.

Figure 7-17. Frequency distribution of CO_2 concentration measurements made by the MP3S system. The dotted line represents all 1-s grab samples in the central 9 nodes of the top layer (1.0 m) of the plot for the period July 26 to September 18, 1989. The solid line represents the corresponding value of the FACE CO_2 concentration control port. Observations are grouped in increments of 10 μmol mol^{-1}.

Figure 7-18. Isolines of percent setpoint for CO_2 concentration 1-s grab samples averaged over all MP3S samples at each node from the season-long average of the sampling layer. Vent pipe positions are indicated by solid dots. The central circle designates the 12-m diameter "sweet spot". (a) bottom layer; (b) middle layer; (c) top layer.

Figure 7-19. Bucket test contout plots (μmol mol^{-1}) for August 3, 1989, 0800-0900 MST. Sampling period was 60 min. (a) 0.1 meter above ground level; (b) 0.5 meters; (c) 1.0 meters.

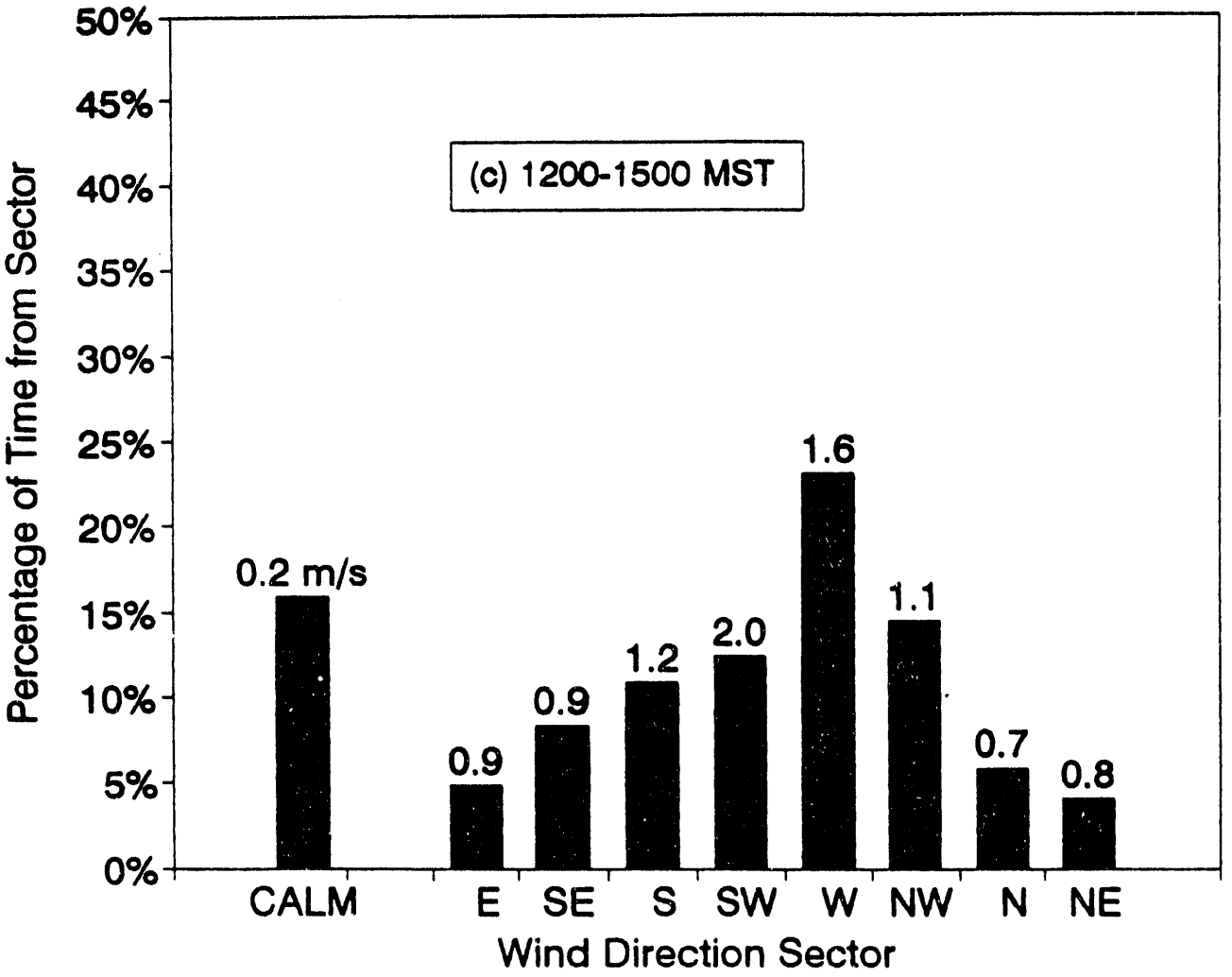
Figure 7-20. Bucket test contour plots (μmol mol^{-1}) for August 3, 1989, 1400-1405 MST. Sampling period was 5 min. (a) 0.1 meters above ground level; (b) 0.5 meters,; (c) 1.0 meters.

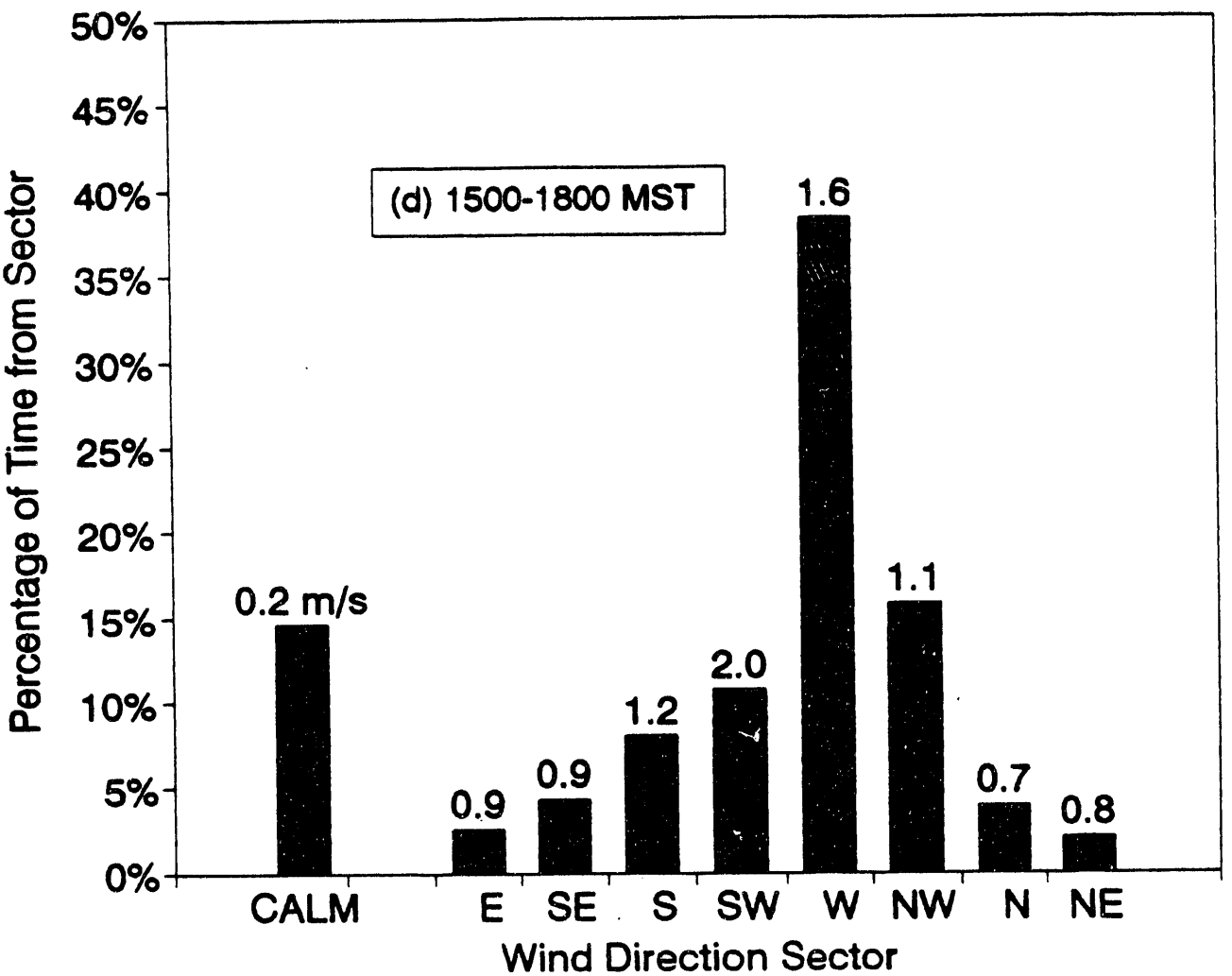
References

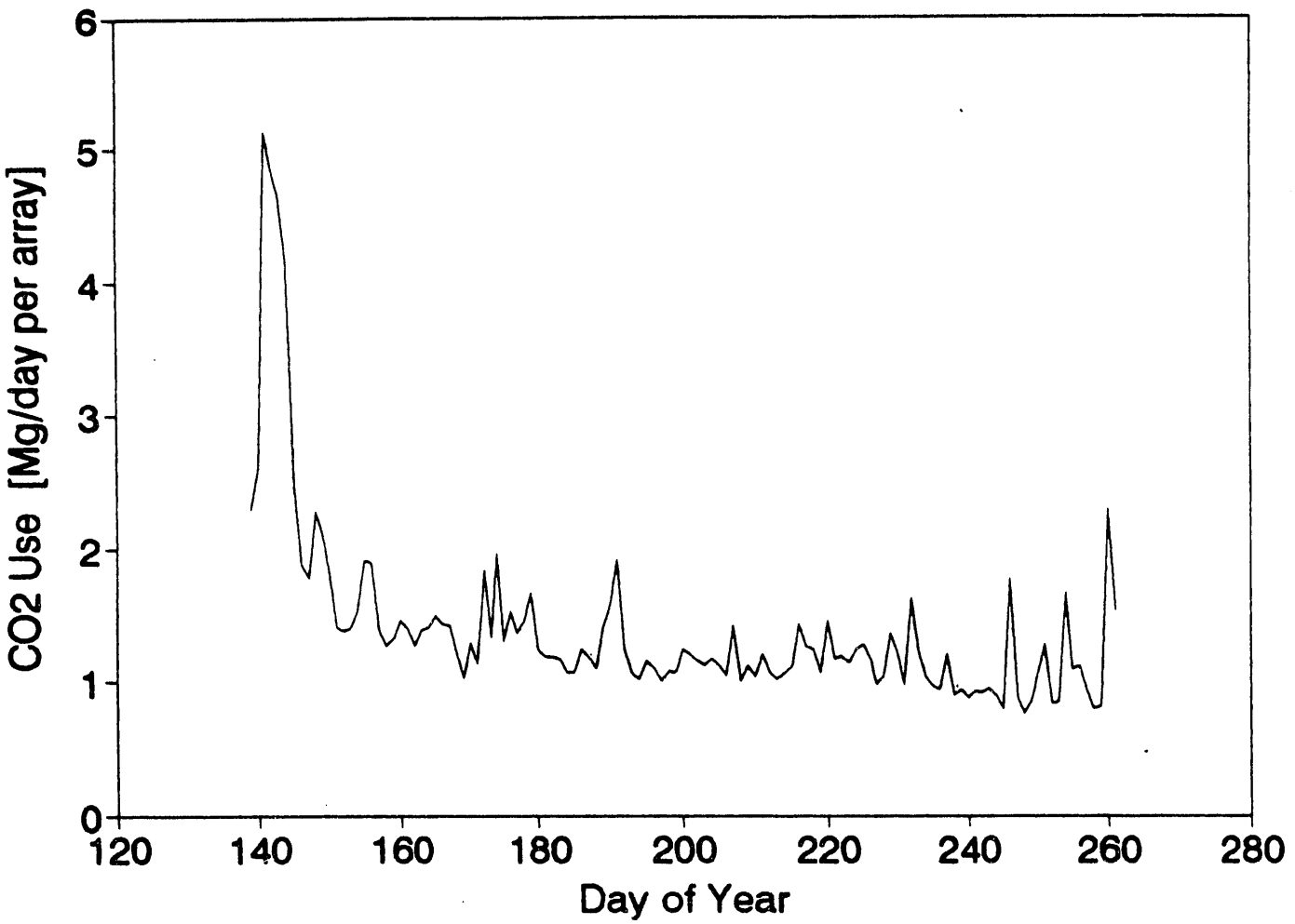
1. Allen LH Jr (1975) Lime-Source Carbon Dioxide Release. III: Predictions by a Two- Dimensional Numerical Diffusion Model. Boundary-Layer Met. 8:39- 79.

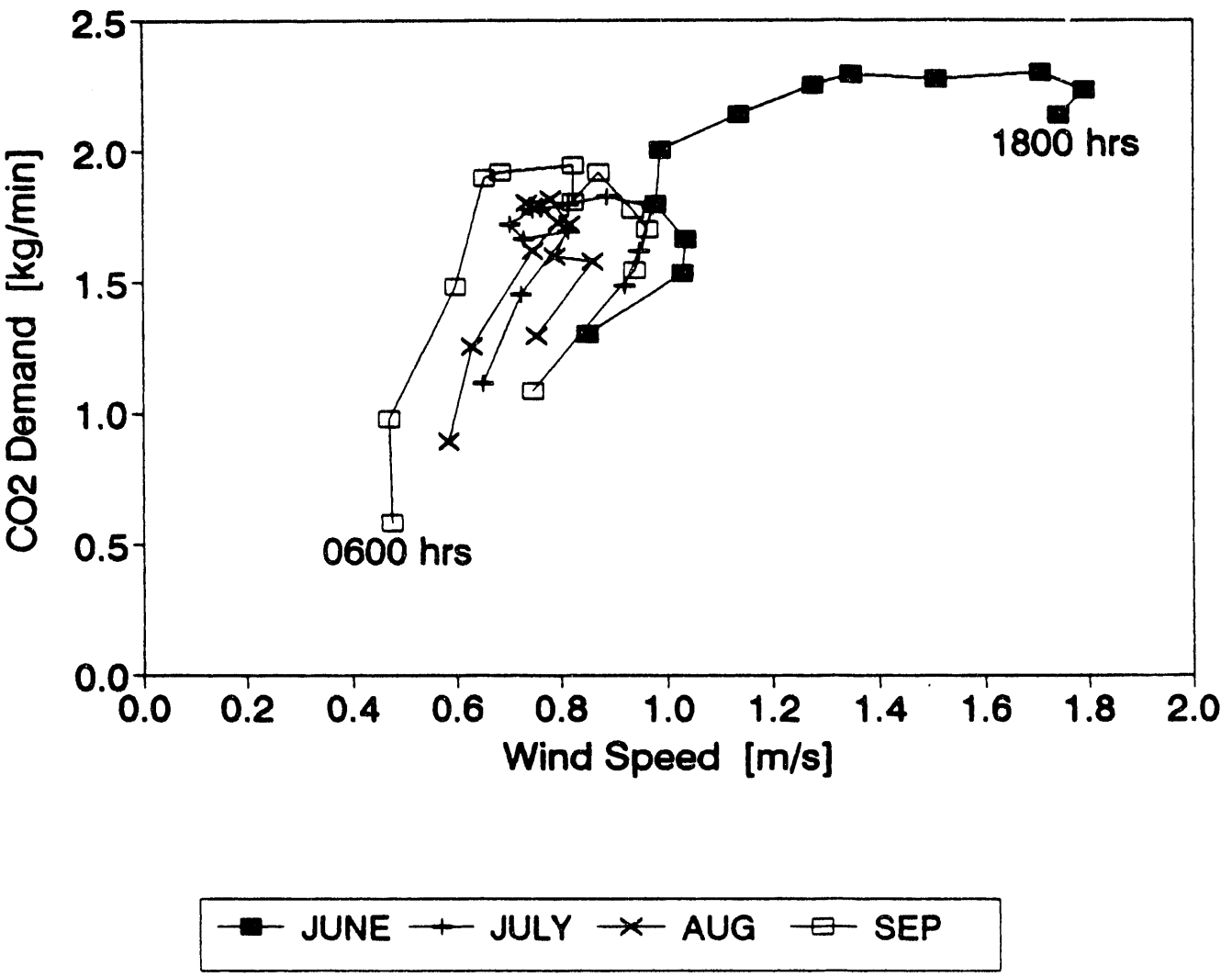
2. Dietz RN (1987) Perfluorocarbon Tracer Technology, in Regional and Long Range Transport of Air Pollution. Ed. by S. Sandroni, Elsevier, pp. 215-297.

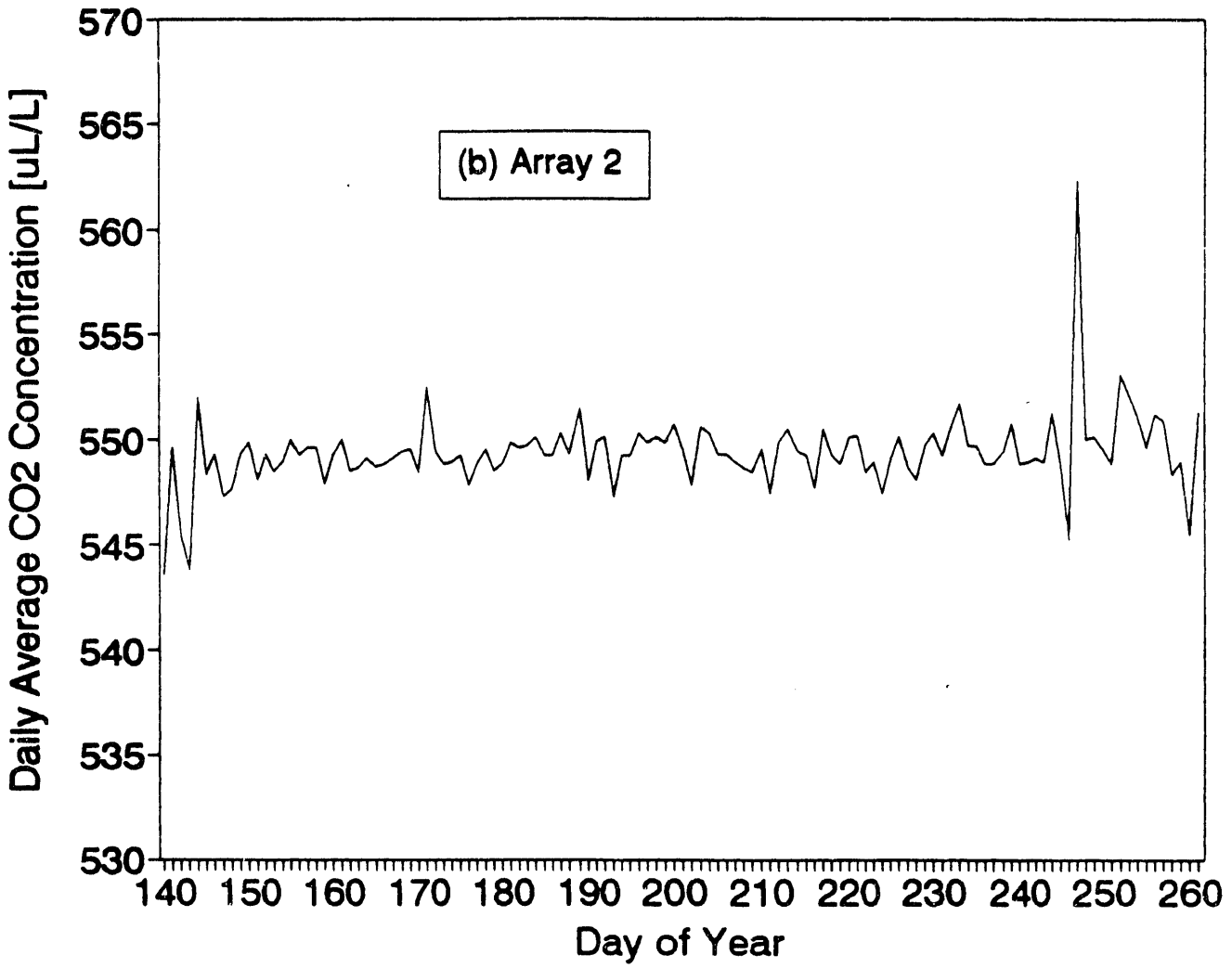
3. Lipfert FW, Daum ML, Hendrey GR, and Lewin KF (1989) Fluid Mechanics and Spatial Performance of FACE Arrays, BNL 43727, prepared for U.S. Dept. of Energy Series: Response of Vegetation to Carbon Dioxide #046, Nov. 1988. Also presented at the 1989 ASA Agronomy Conference, Las Vegas, Oct. 19, 1989.

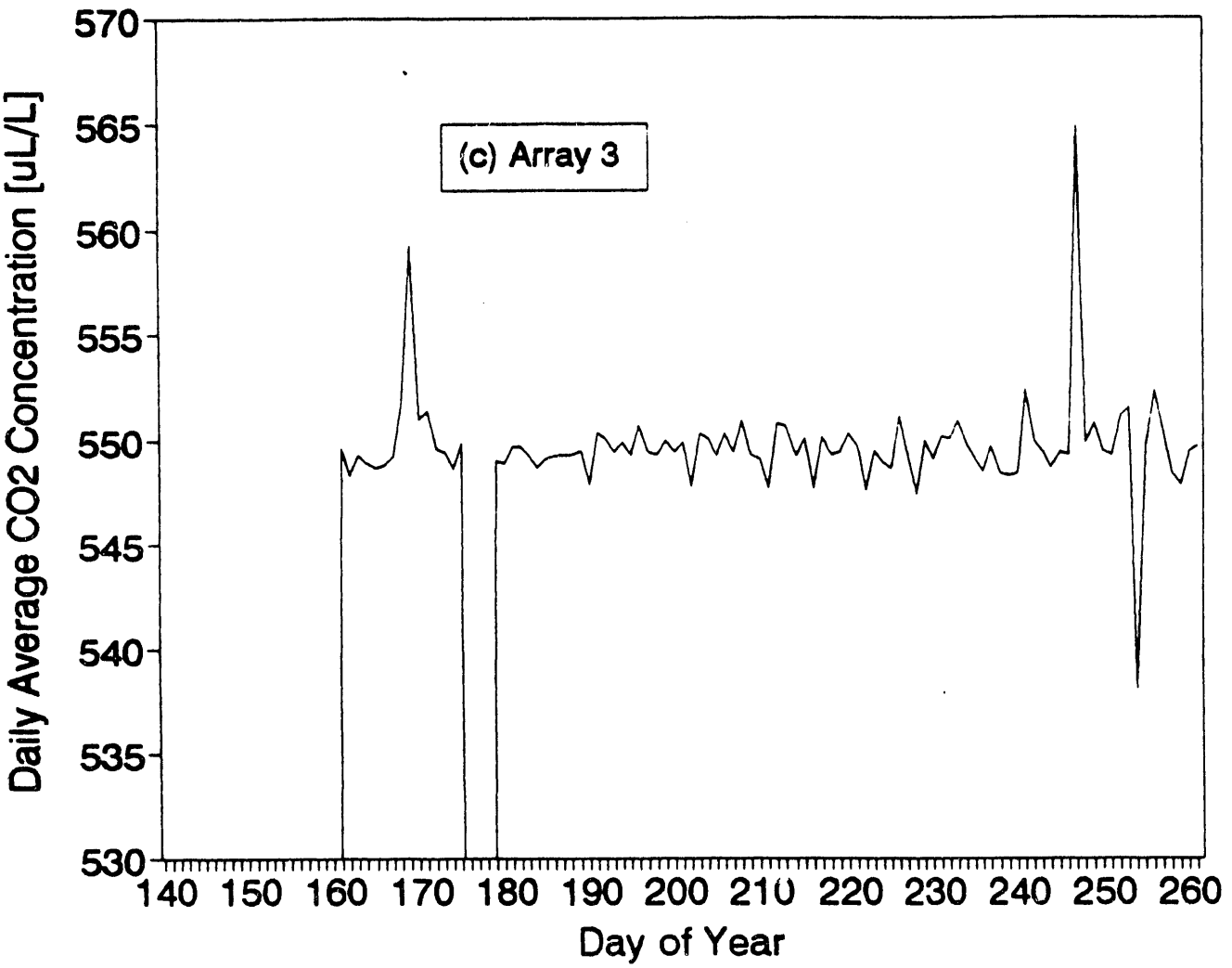

(c) 1200-1500 MST
Percentage of Time from Sector
50%
45%
40%
35%
30%
25%
20%
15%
10%
5%
0%
0.2 m/s
0.9
0.9
1.2
2.0
1.6
1.1
0.7
0.8
CALM
E
SE
S
SW
W
NW
N
NE
Wind Direction Sector

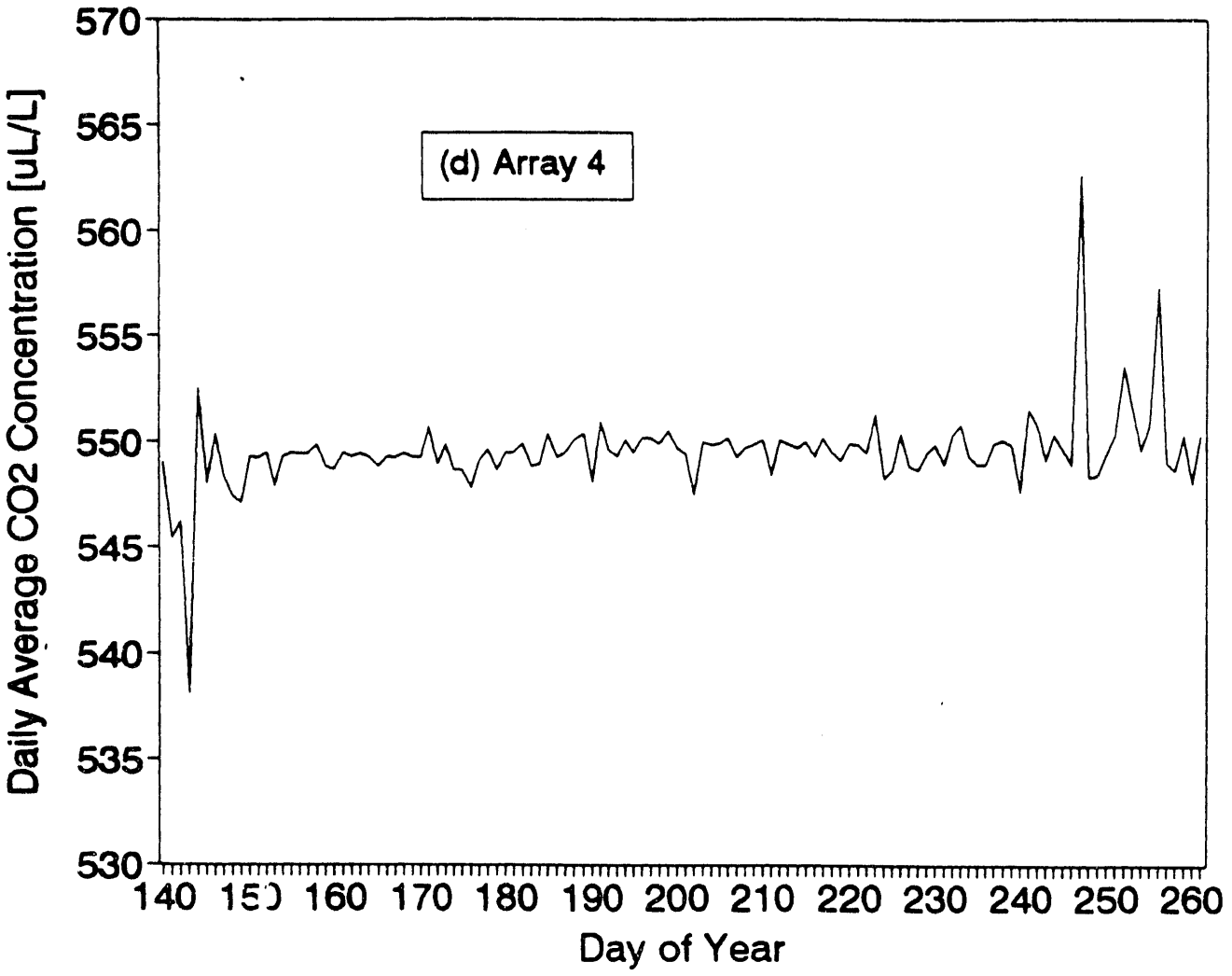

(d) 1500-1800 MST
Percentage of Time from Sector
50%
45%
40%
35%
30%
25%
20%
15%
10%
5%
0%
0.2 m/s
0.9
0.9
1.2
2.0
1.6
1.1
0.7
0.8
CALM
E
SE
S
SW
W
NW
N
NE
Wind Direction Sector

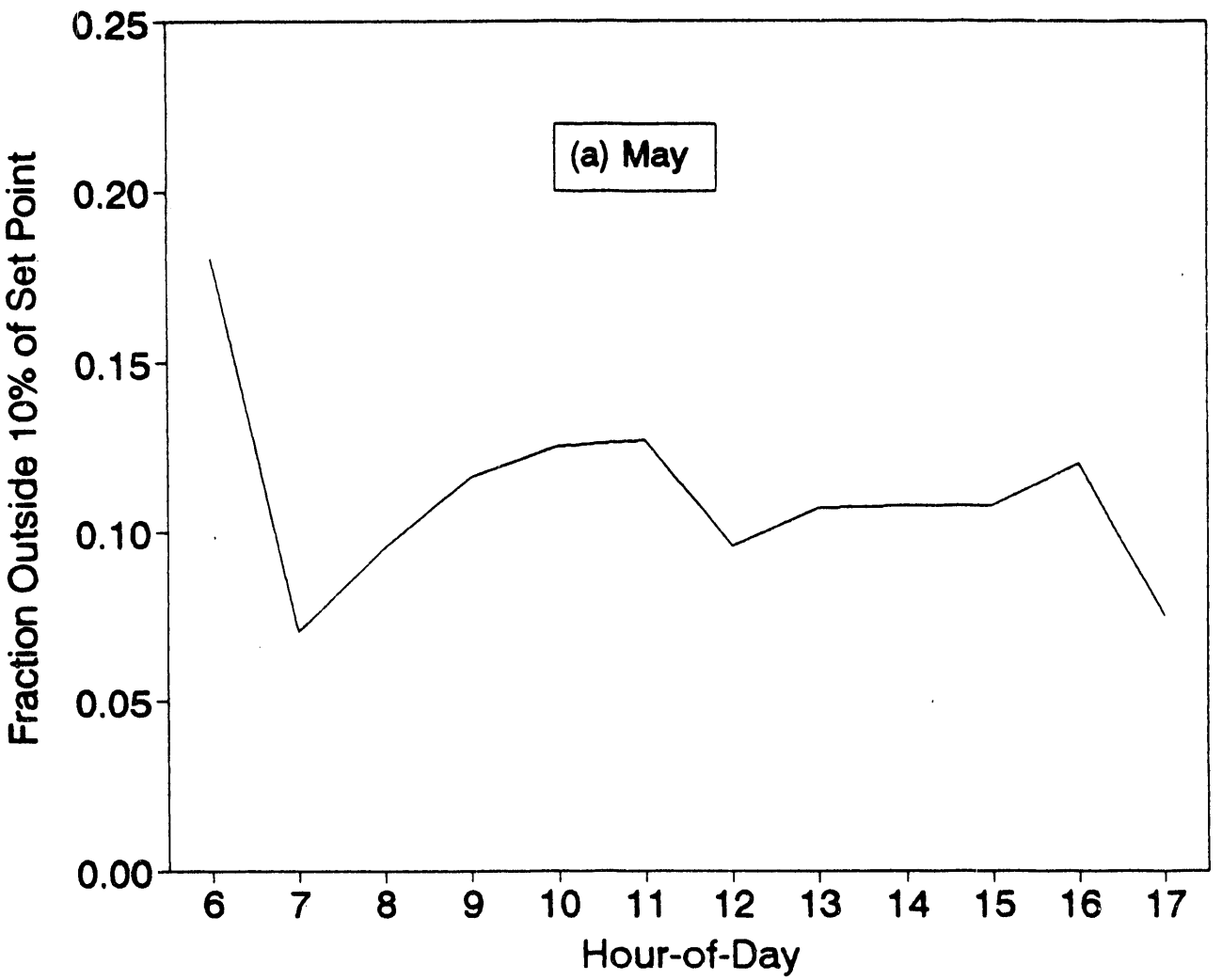

6
5
4
3
2
1
0
CO2 Use [Mg/day per array]
120
140
160
180
200
220
240
260
280
Day of Year

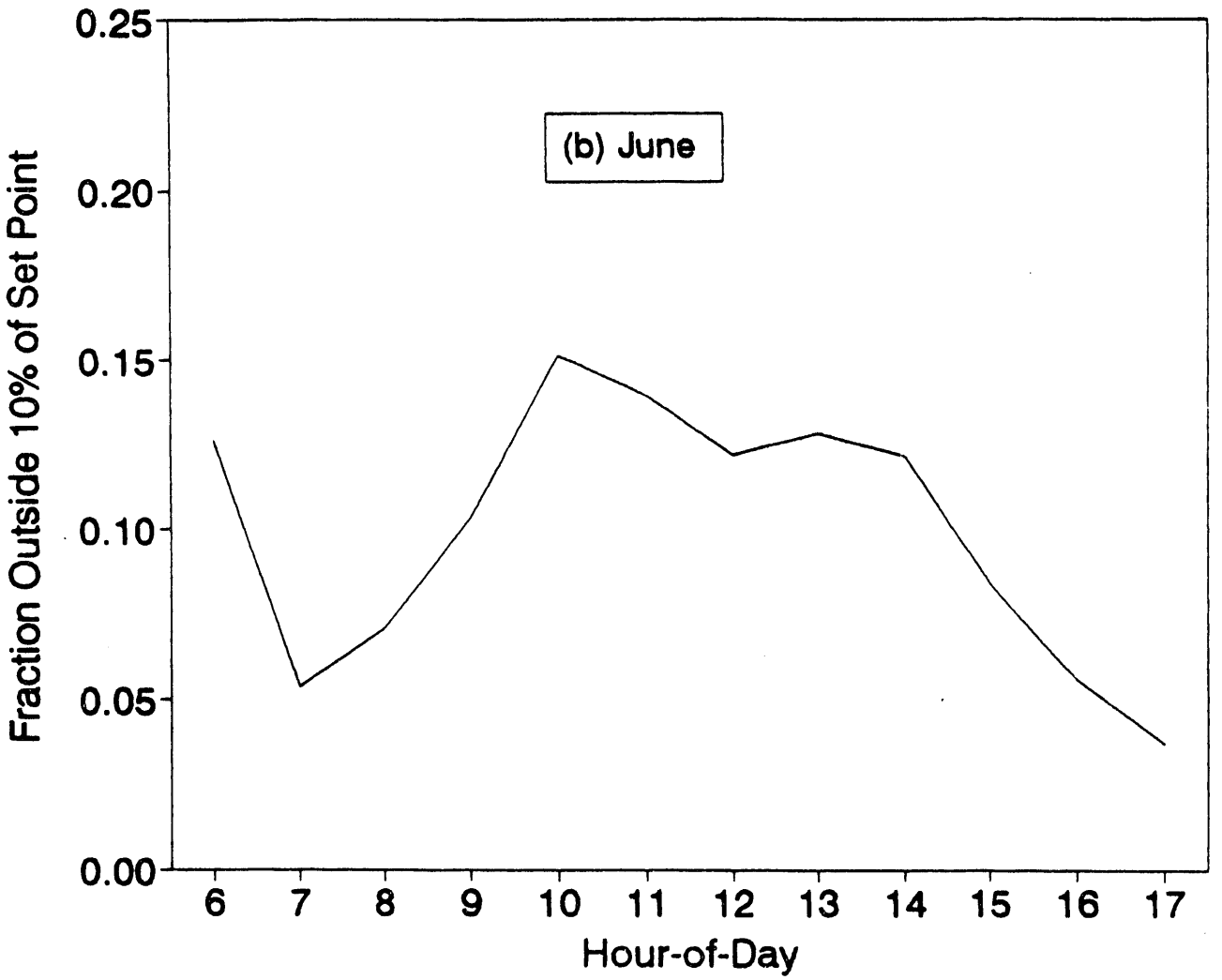

2.5
2.0
1.5
1.0
0.5
0.0
CO2 Demand [kg/min]
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
Wind Speed [m/s]
1800 hrs
0600 hrs
JUNE
JULY
AUG
SEP

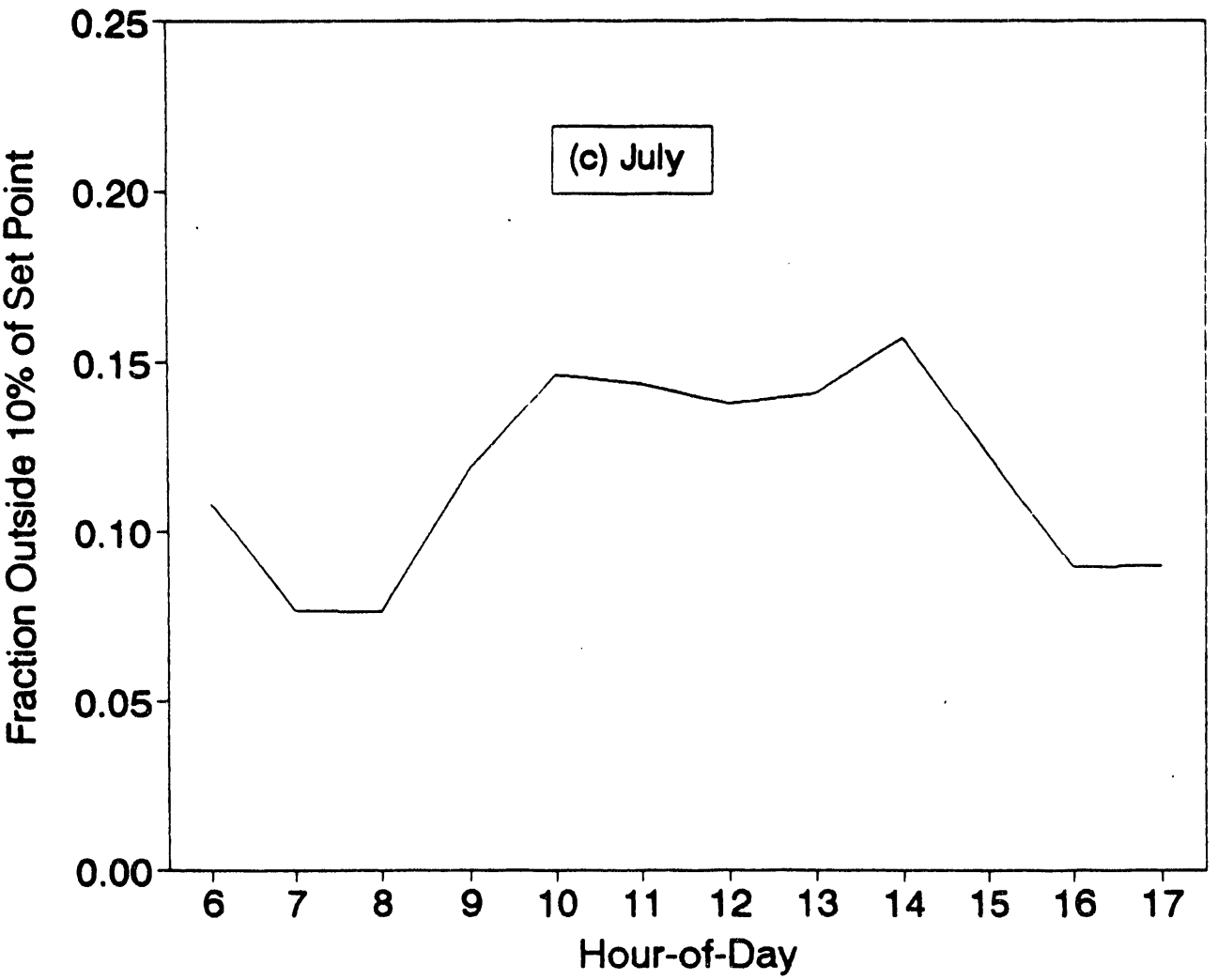

(b) Array 2
Daily Average CO2 Concentration [uL/L]
570
565
560
555
550
545
540
535
530
140 150 160 170 180 190 200 210 220 230 240 250 260
Day of Year

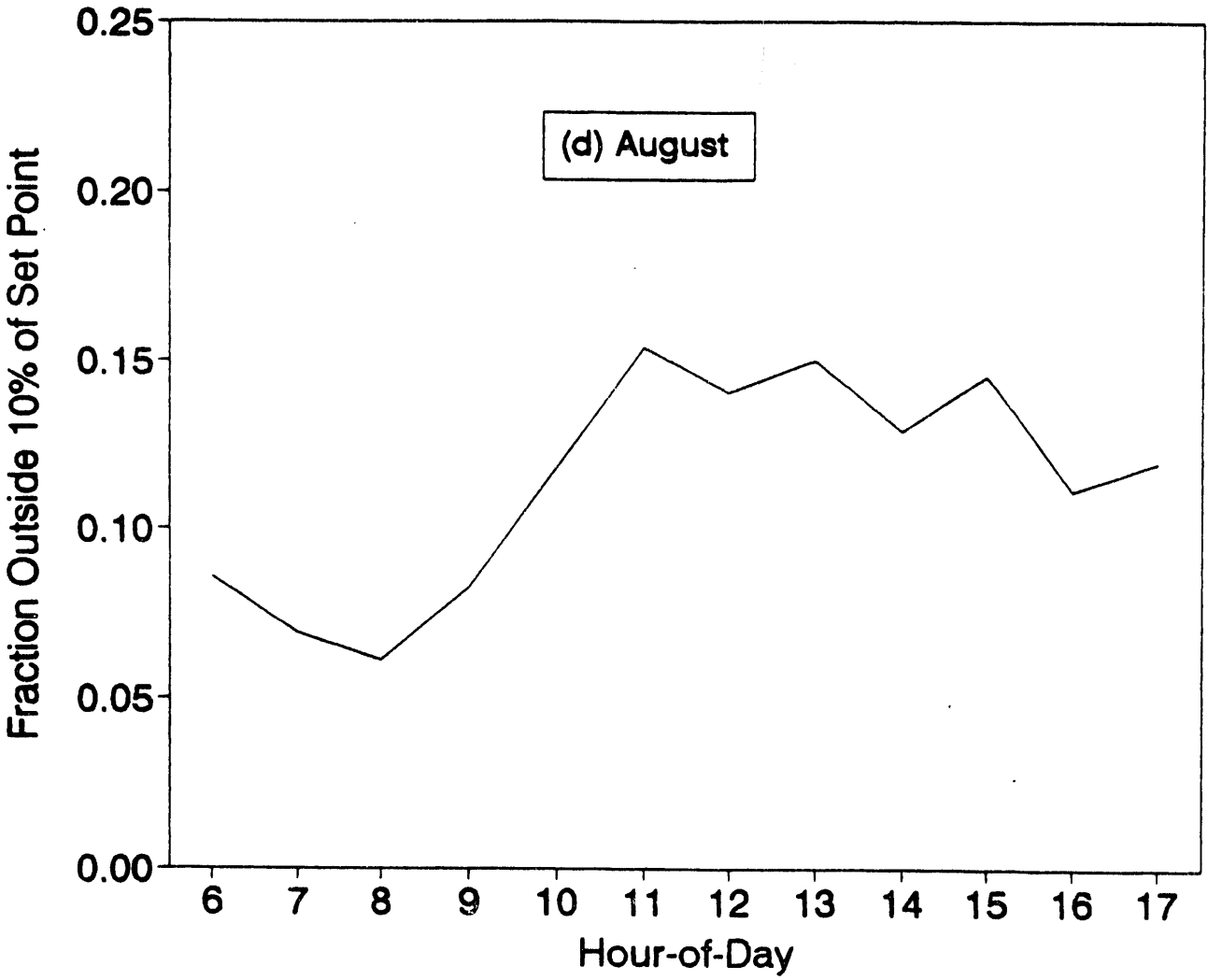

(c) Array 3
Daily Average CO2 Concentration [uL/L]
570
565
560
555
550
545
540
535
530
140 150 160 170 180 190 200 210 220 230 240 250 260
Day of Year

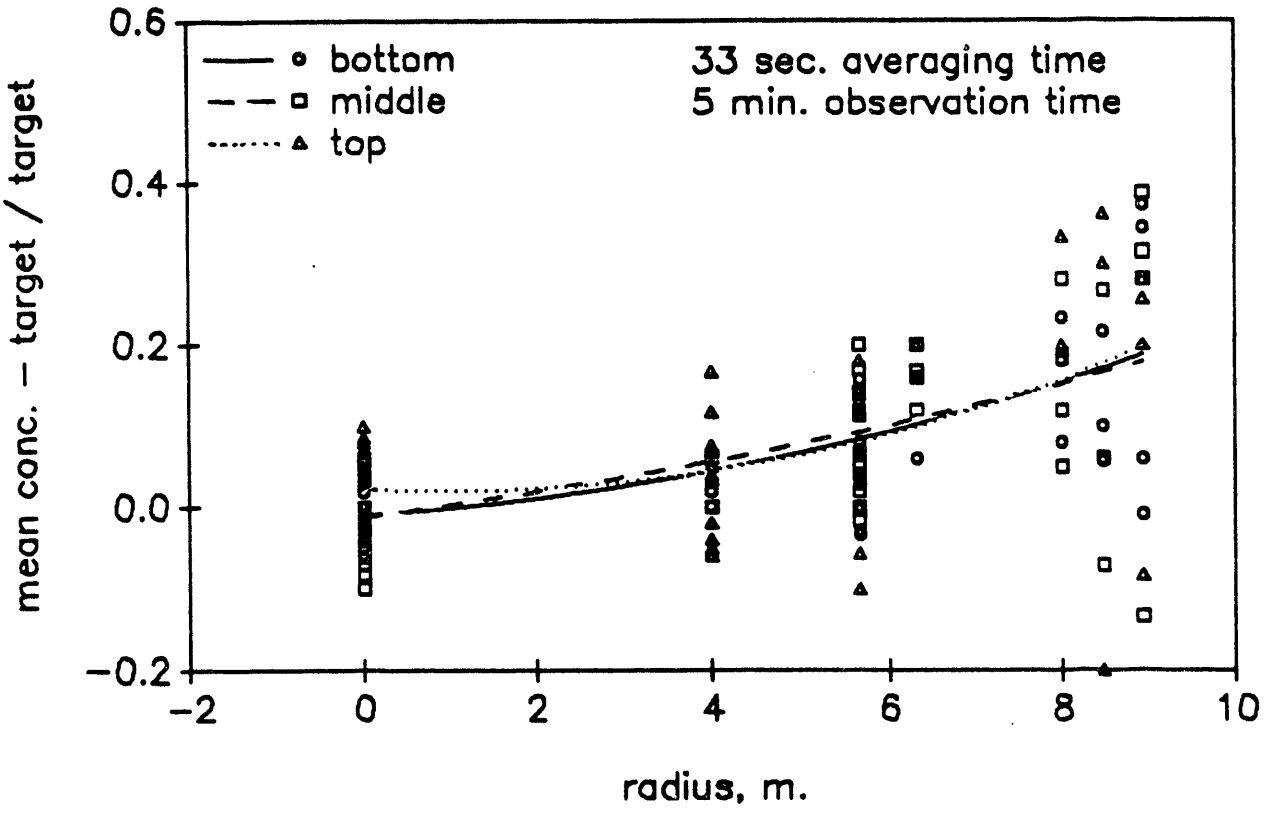

(d) Array 4
Daily Average CO2 Concentration [uL/L]
570
565
560
555
550
545
540
535
530
140
150
160
170
180
190
200
210
220
230
240
250
260
Day of Year

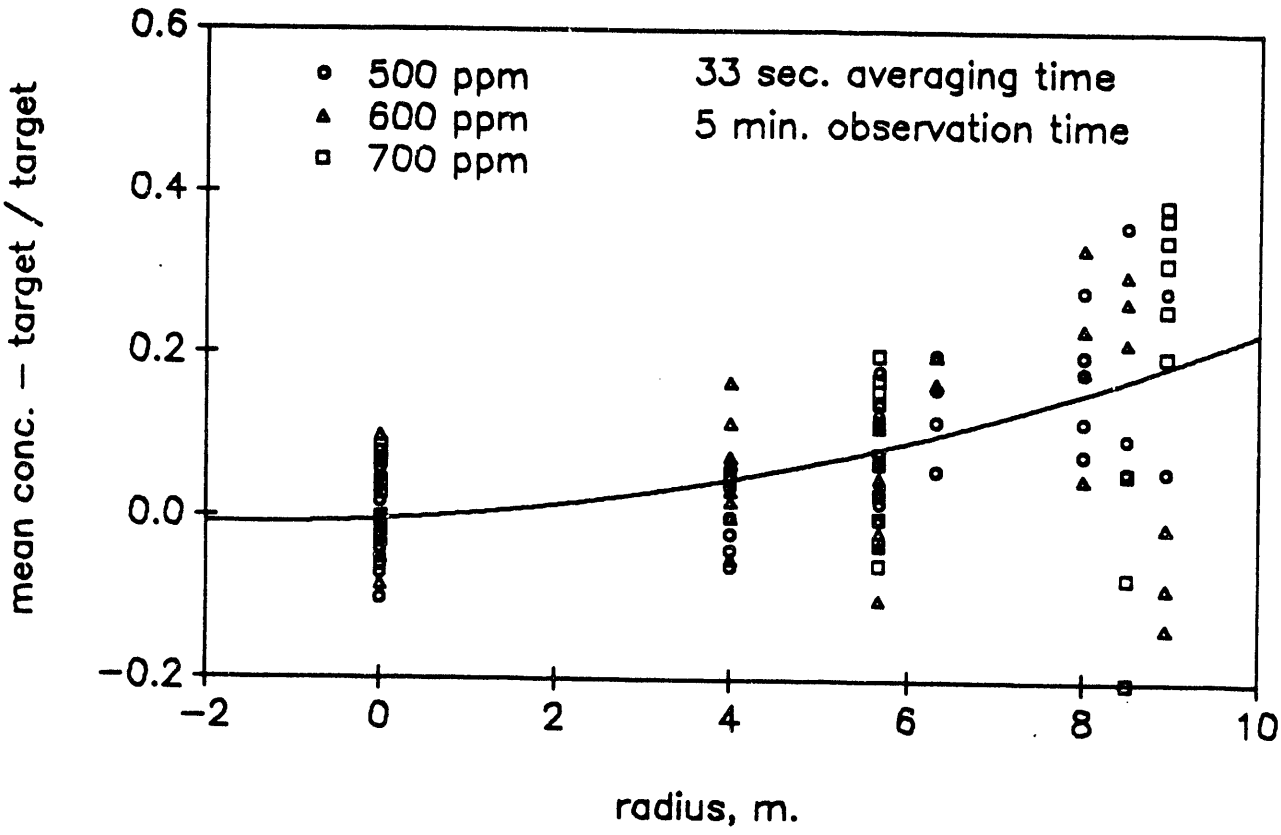

(a) May
Fraction Outside 10% of Set Point
0.25
0.20
0.15
0.10
0.05
0.00
6
7
8
9
10
11
12
13
14
15
16
17
Hour-of-Day

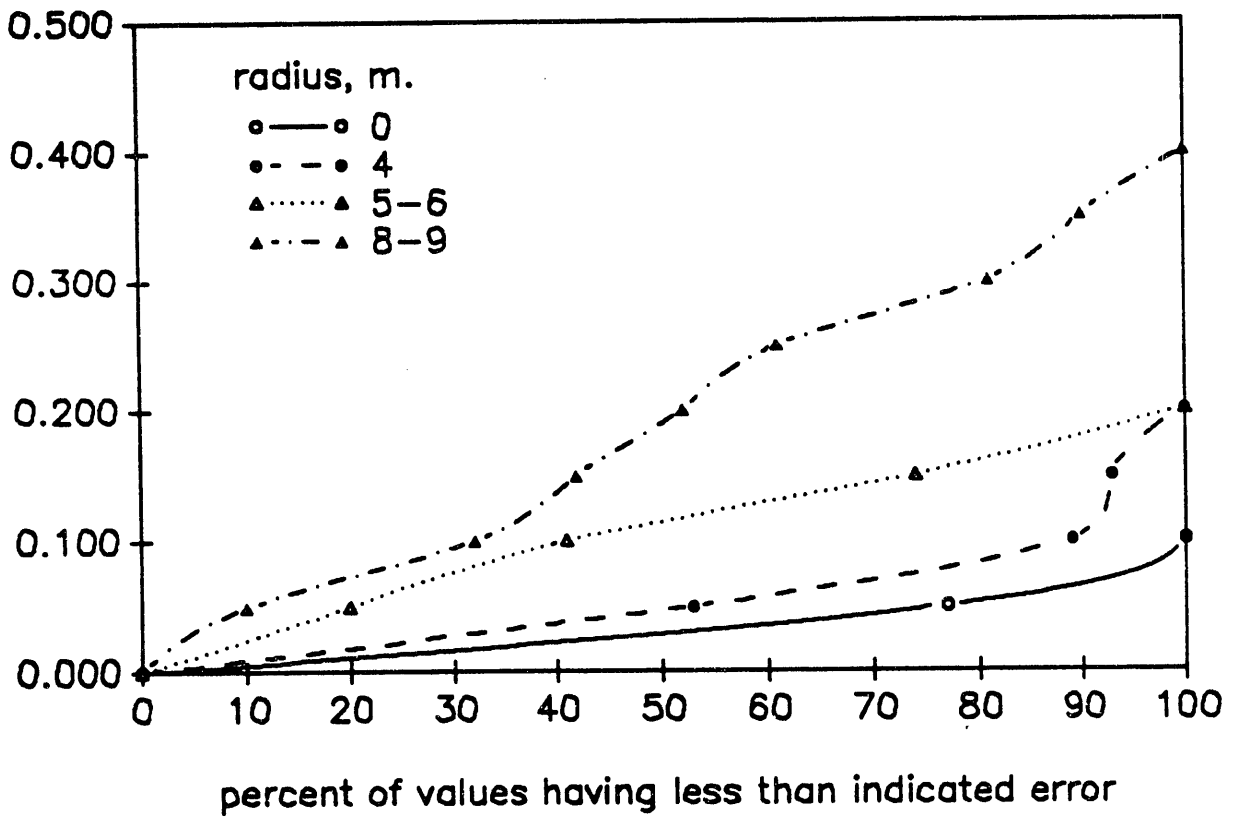

(b) June
Fraction Outside 10% of Set Point
0.25
0.20
0.15
0.10
0.05
0.00
6
7
8
9
10
11
12
13
14
15
16
17
Hour-of-Day

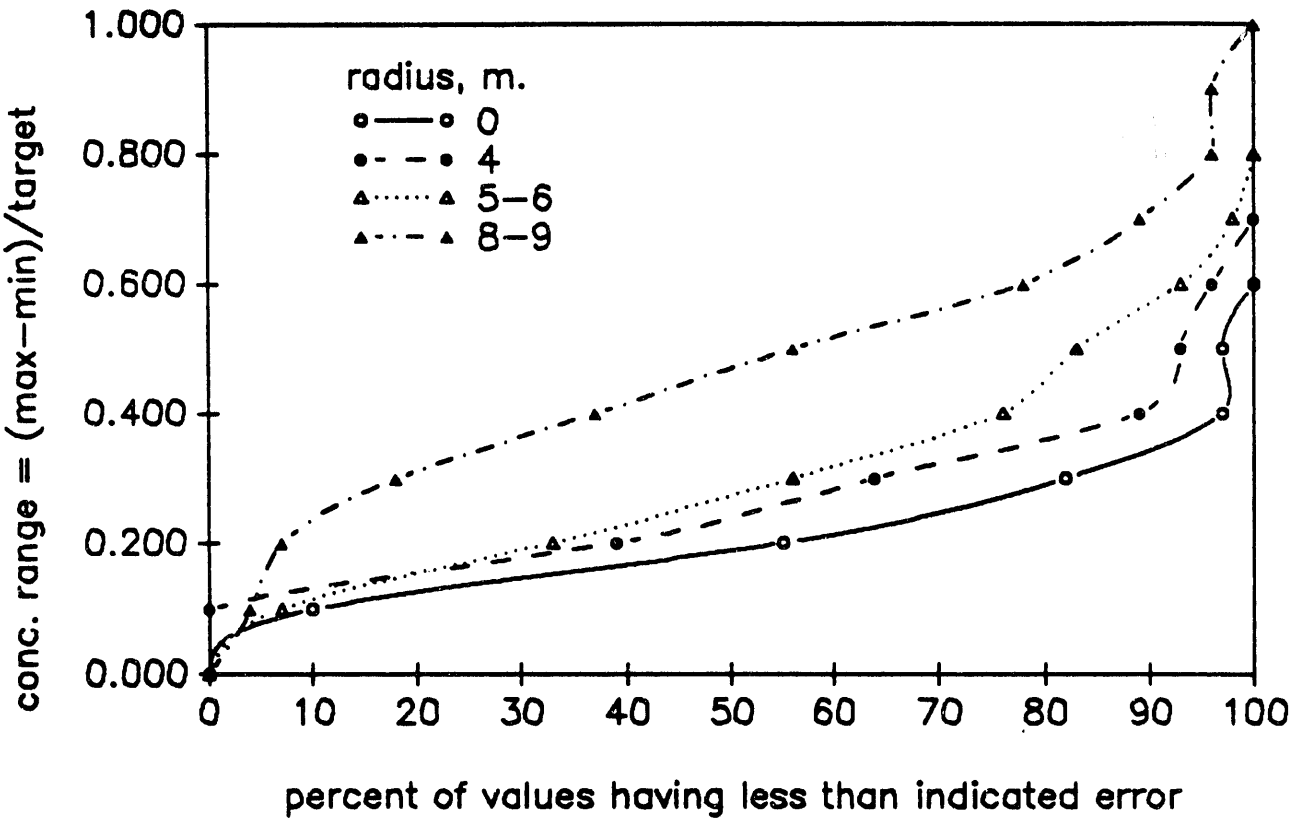

(c) July
Fraction Outside 10% of Set Point
0.25
0.20
0.15
0.10
0.05
0.00
6
7
8
9
10
11
12
13
14
15
16
17
Hour-of-Day

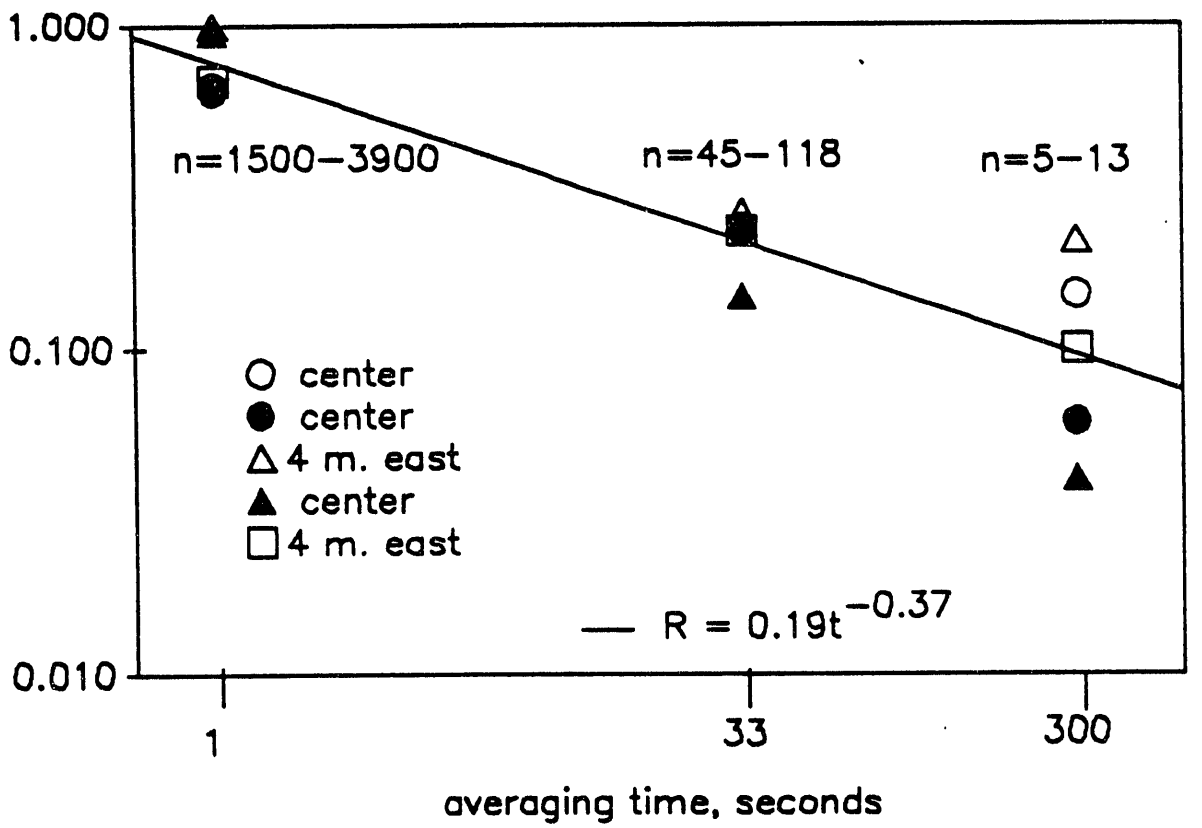

(d) August
Fraction Outside 10% of Set Point
0.25
0.20
0.15
0.10
0.05
0.00
6
7
8
9
10
11
12
13
14
15
16
17
Hour-of-Day

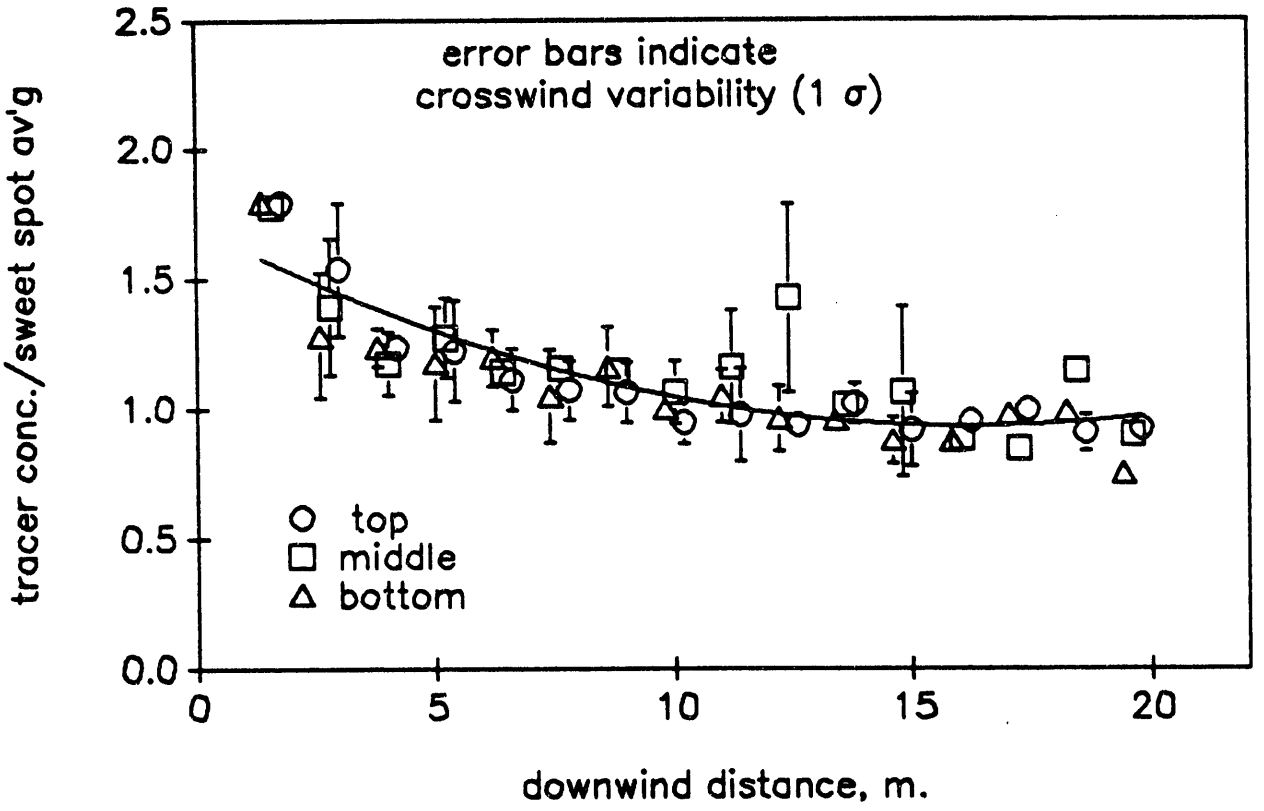

0.6
0.4
0.2
0.0
−0.2
−2
0
2
4
6
8
10
bottom
middle
top
33 sec. averaging time
5 min. observation time
mean conc. − target / target
radius, m.

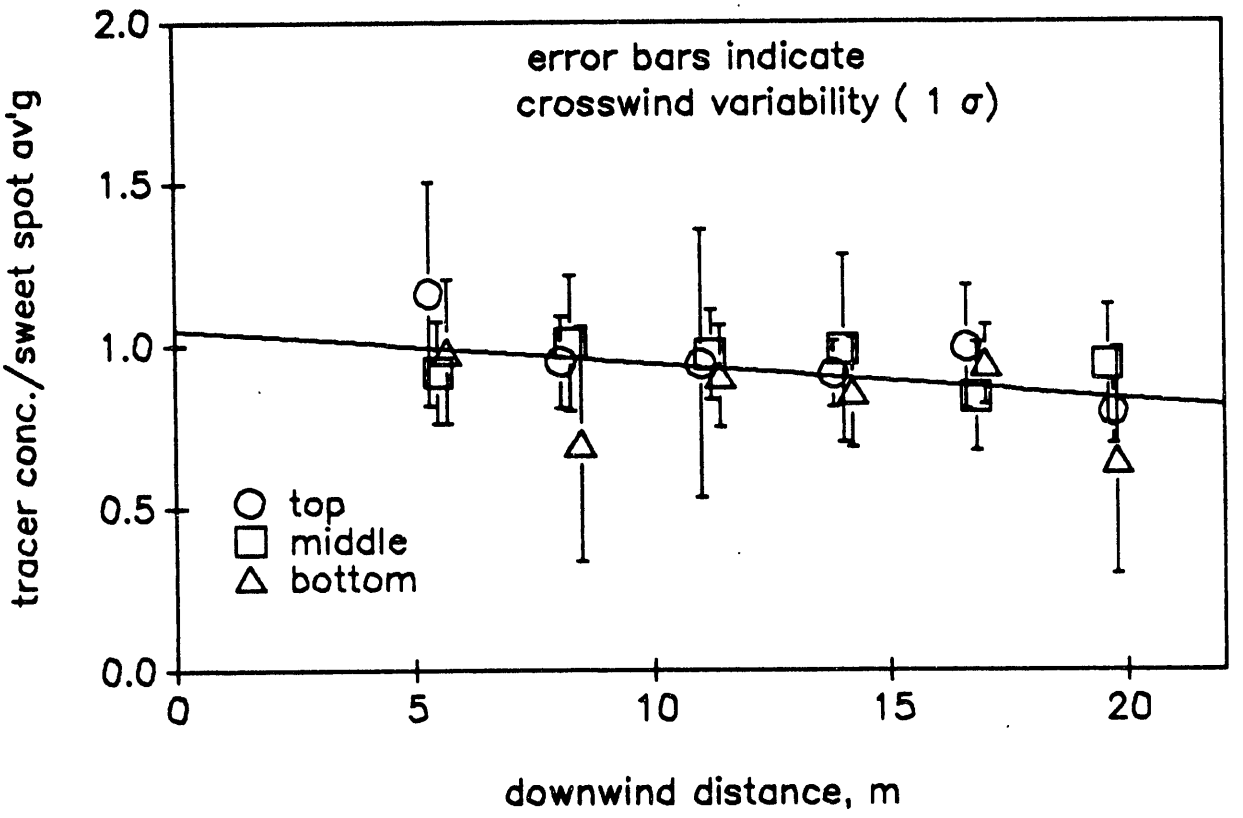

0.6
0.4
0.2
0.0
−0.2
−2
0
2
4
6
8
10
500 ppm
600 ppm
700 ppm
33 sec. averaging time
5 min. observation time
mean conc. − target / target
radius, m.

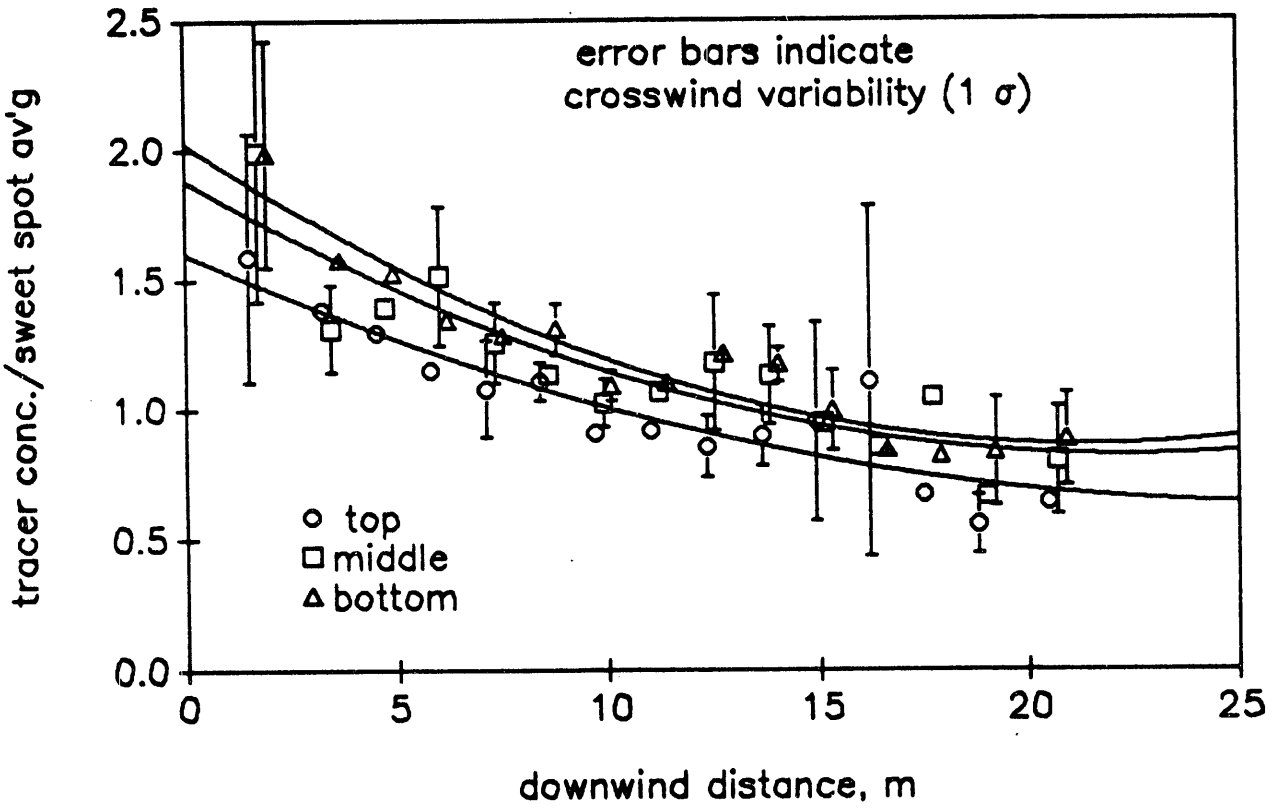

0.500
0.400
0.300
0.200
0.100
0.000
radius, m.
0
4
5–6
8–9
0
10
20
30
40
50
60
70
80
90
100
percent of values having less than indicated error

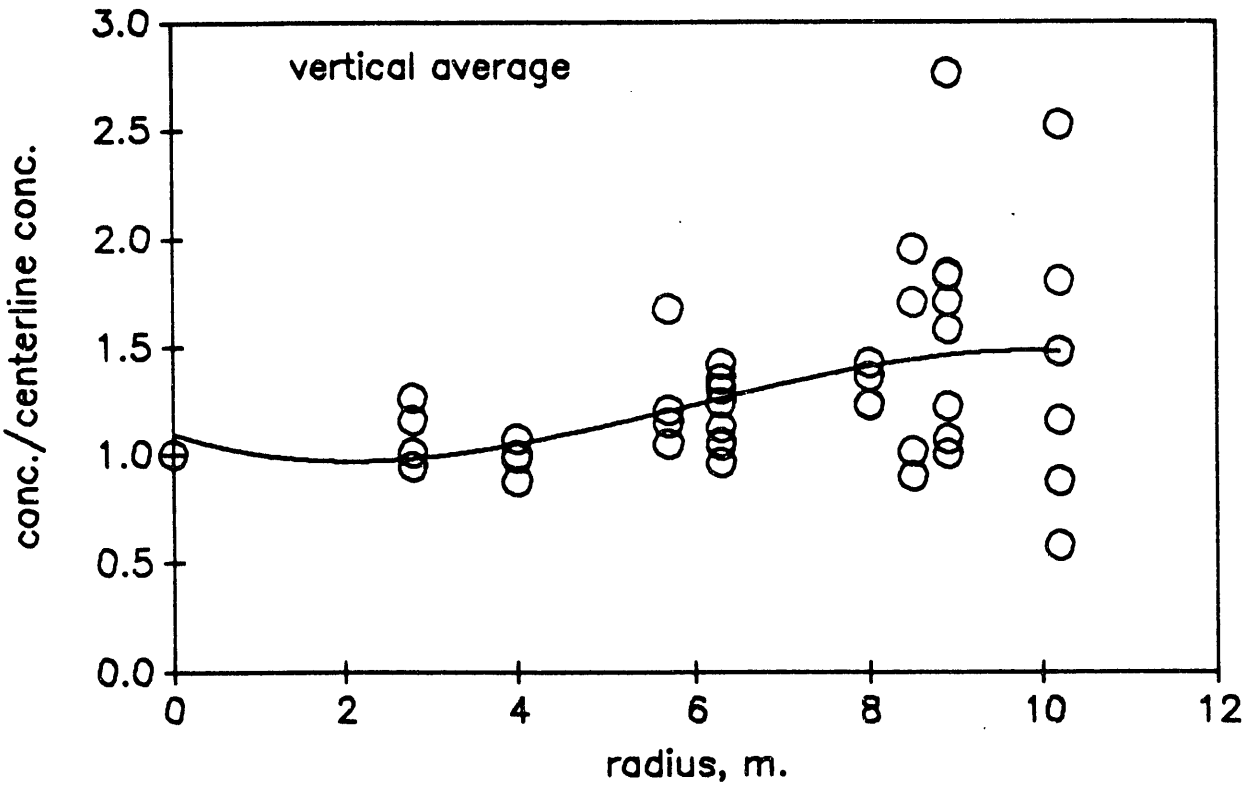

1.000
0.800
0.600
0.400
0.200
0.000
conc. range = (max−min)/target
radius, m.
0
4
5–6
8–9
0
10
20
30
40
50
60
70
80
90
100
percent of values having less than indicated error

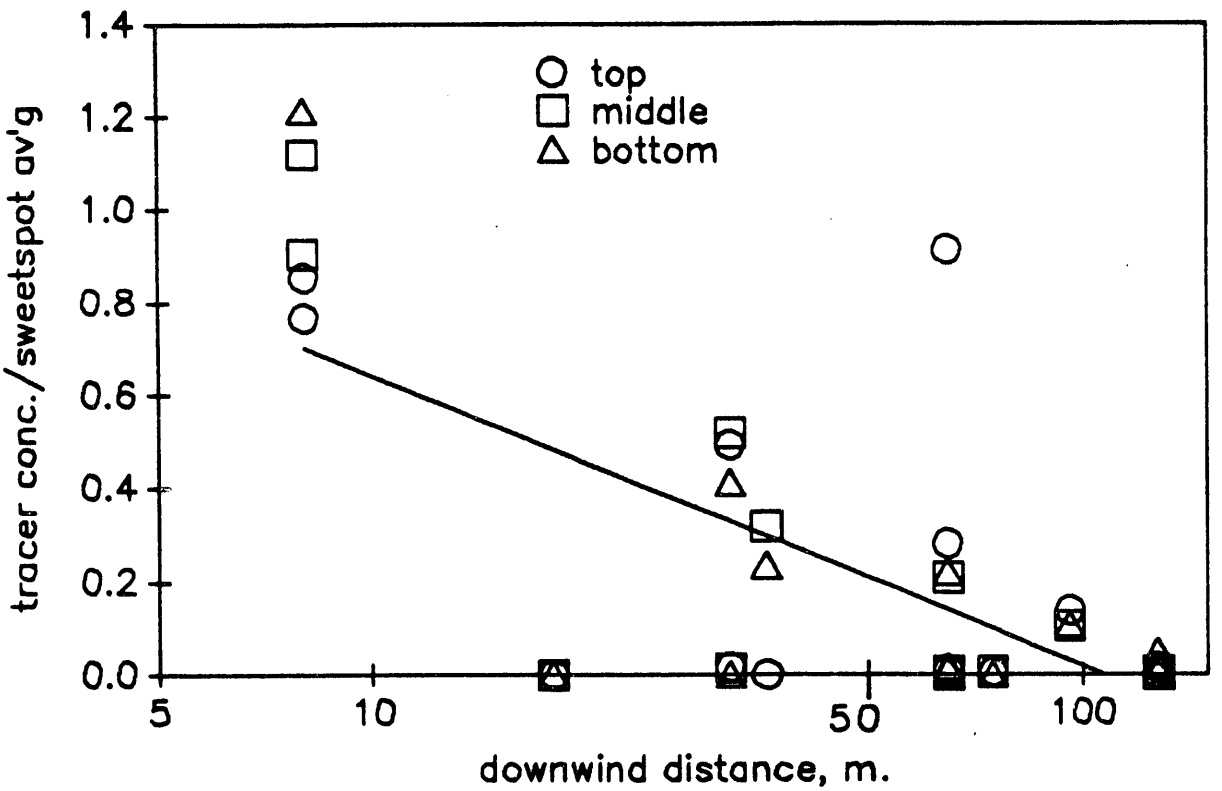

1.000
0.100
0.010
n=1500–3900
n=45–118
n=5–13
center
center
4 m. east
center
4 m. east
R = 0.19t^−0.37
1
33
300
averaging time, seconds

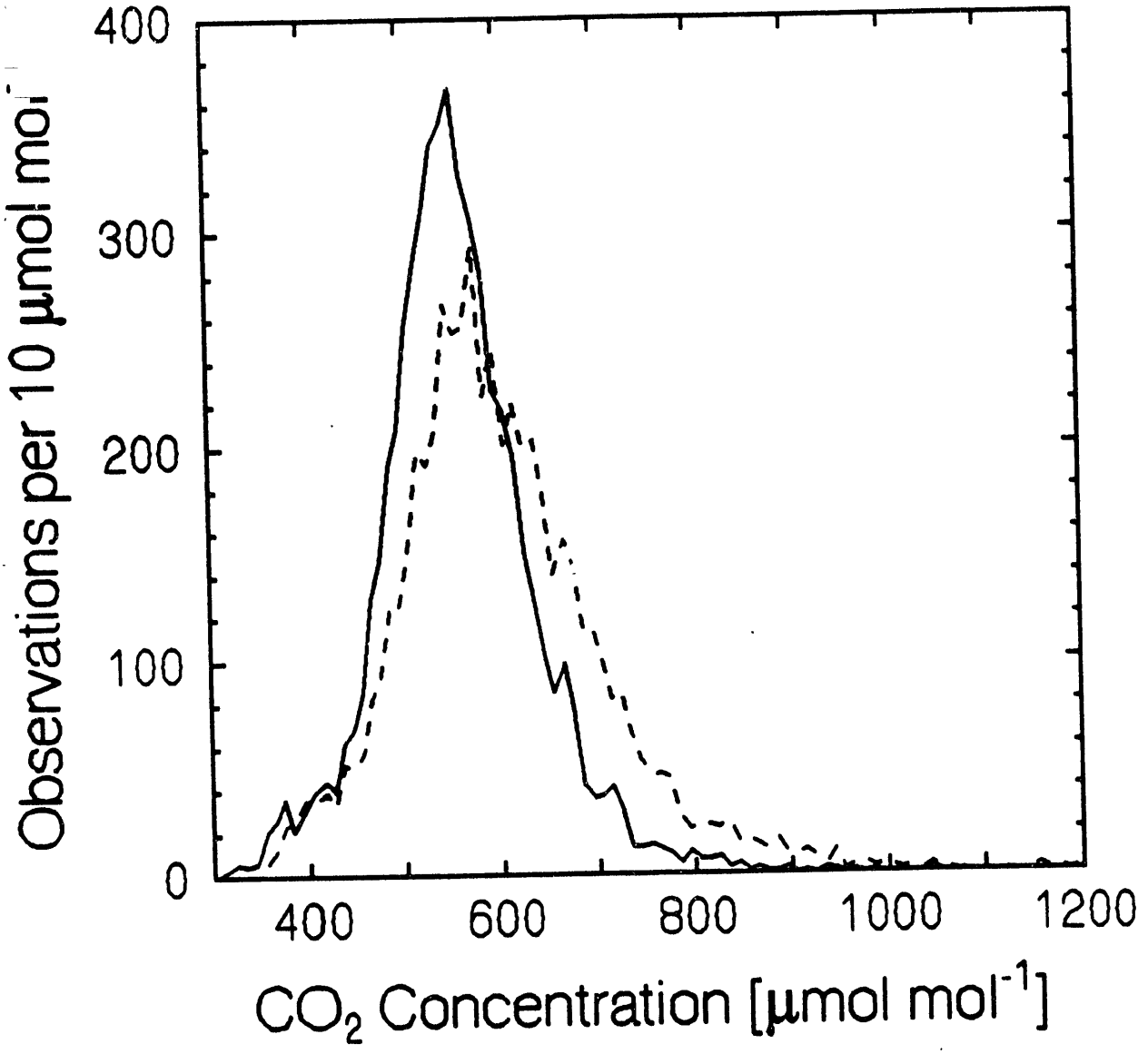

error bars indicate
crosswind variability (1 σ)
tracer conc./sweet spot av'g
2.5
2.0
1.5
1.0
0.5
0.0
0
5
10
15
20
top
middle
bottom
downwind distance, m.

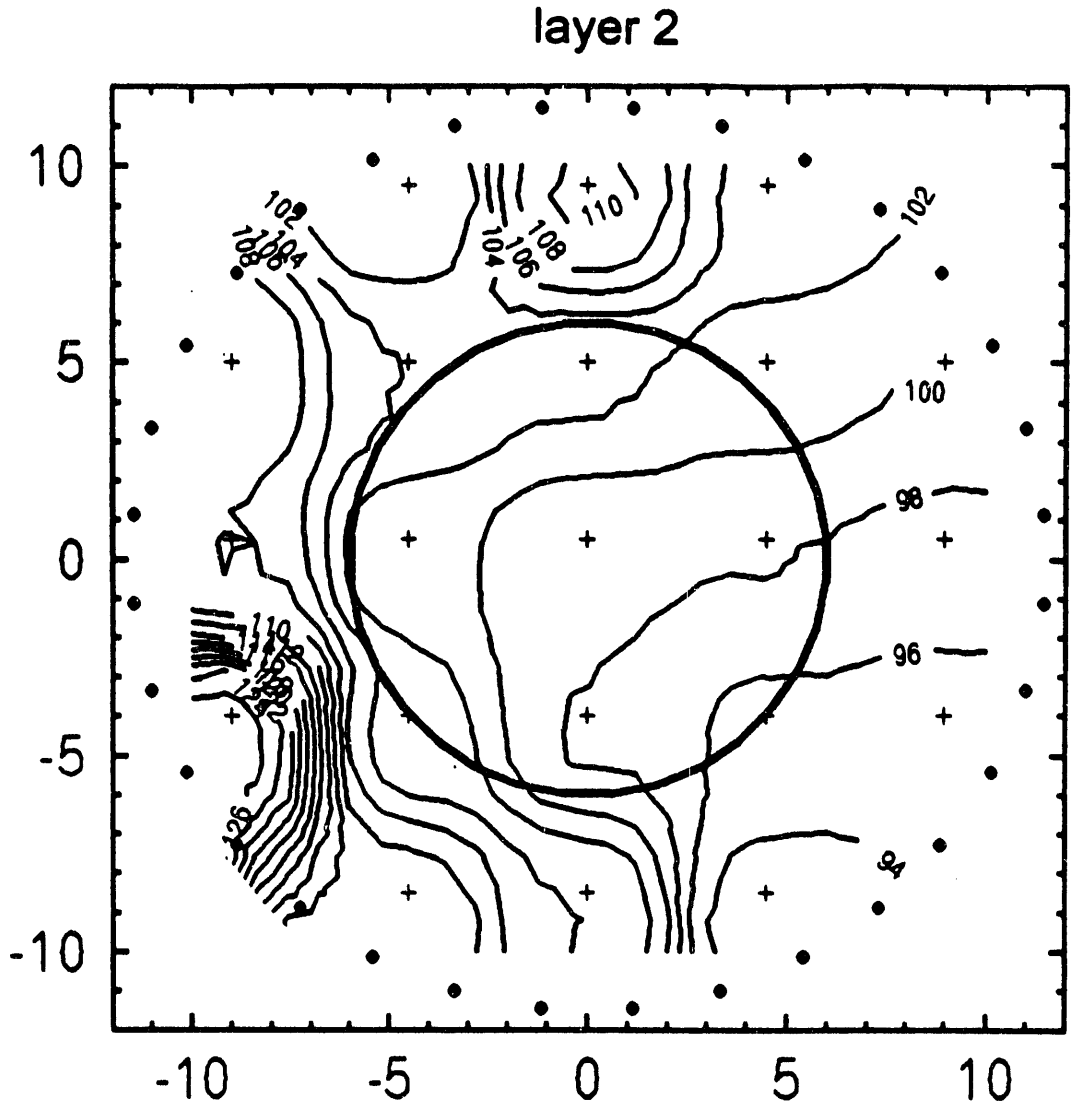

error bars indicate
crosswind variability (1 σ)
tracer conc./sweet spot av'g
2.0
1.5
1.0
0.5
0.0
top
middle
bottom
0
5
10
15
20
downwind distance, m

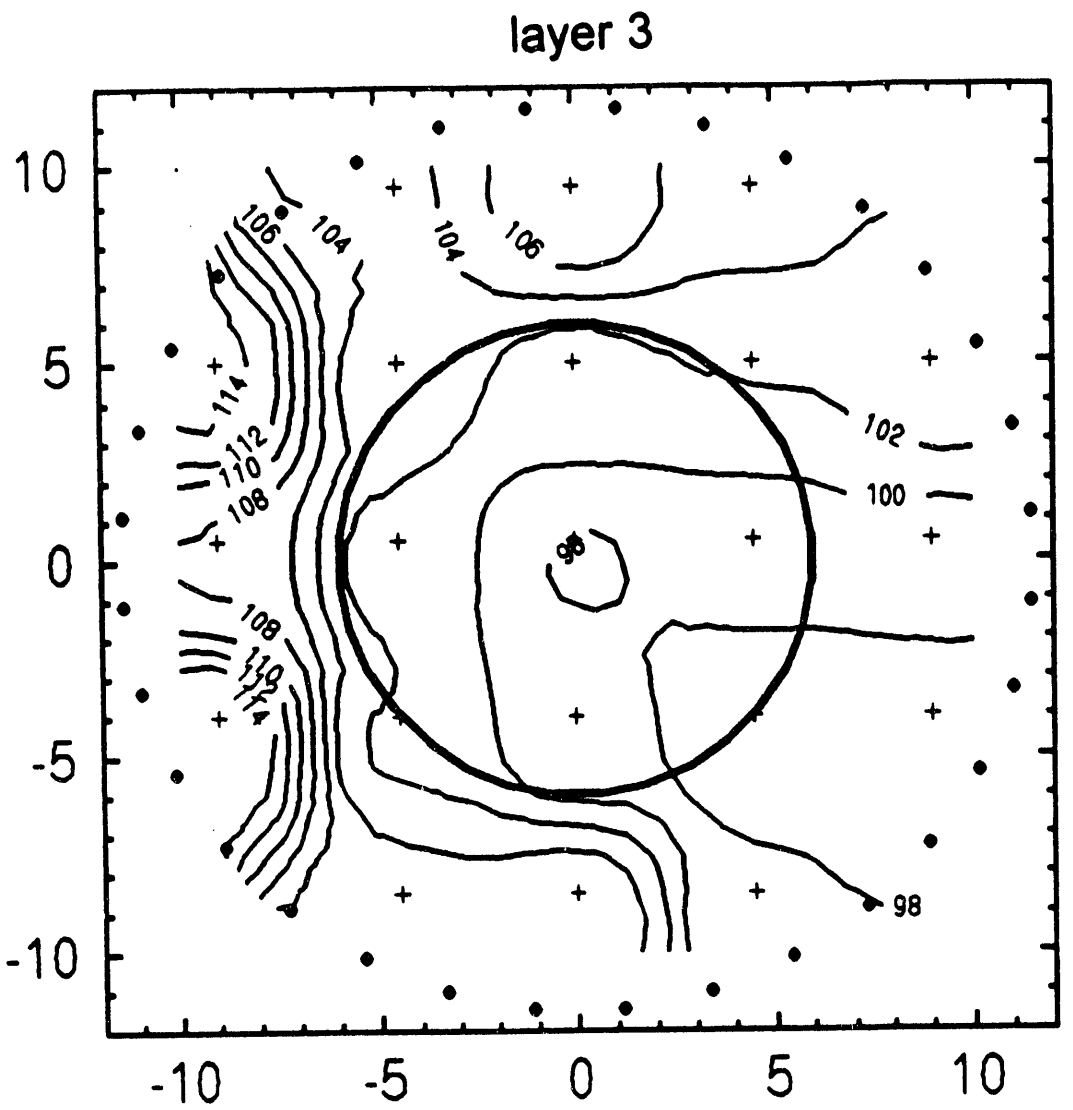

error bars indicate
crosswind variability (1 σ)
top
middle
bottom
tracer conc./sweet spot av'g
downwind distance, m
0.0
0.5
1.0
1.5
2.0
2.5
0
5
10
15
20
25

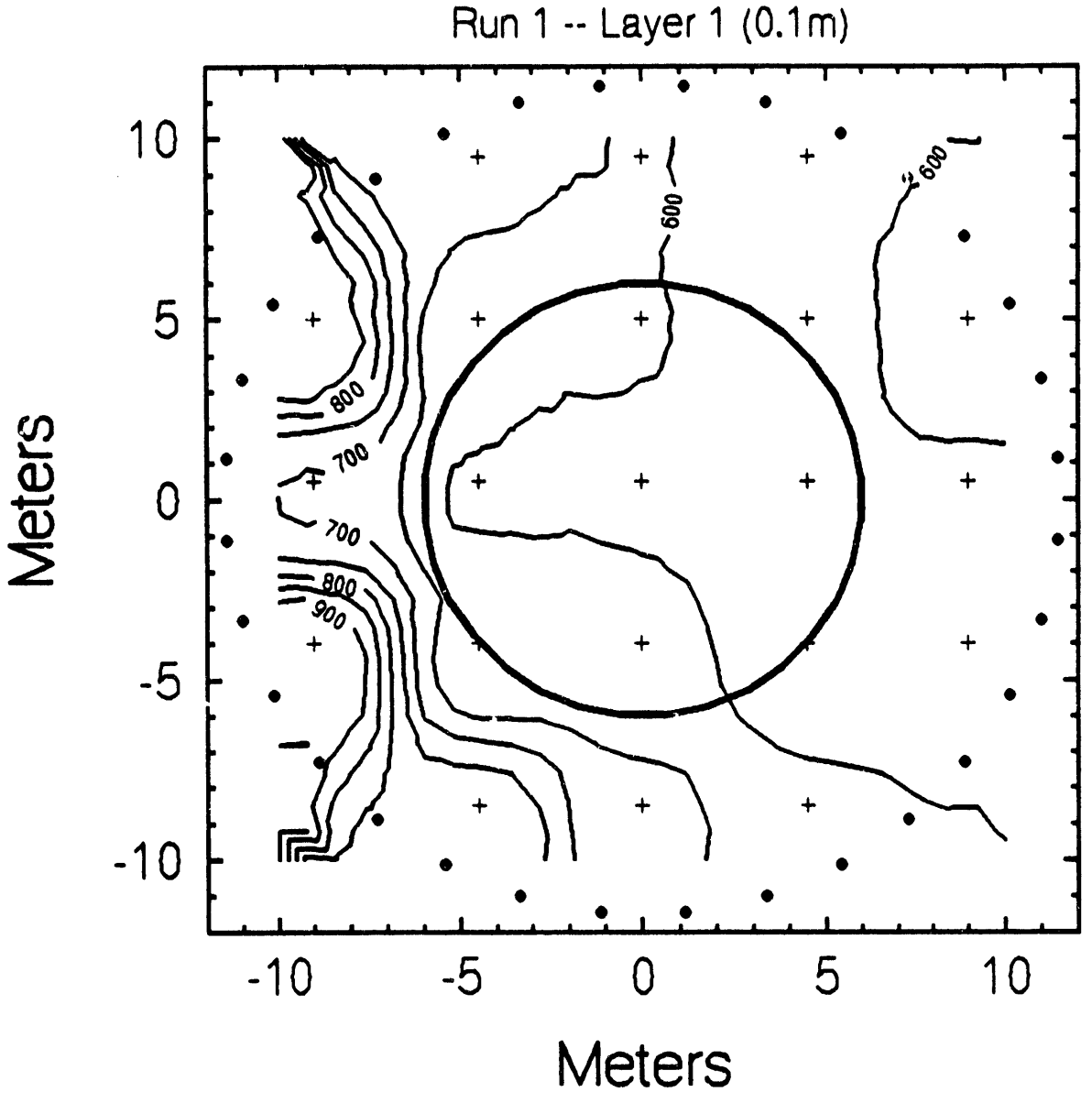

vertical average
conc./centerline conc.
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0
2
4
6
8
10
12
radius, m.

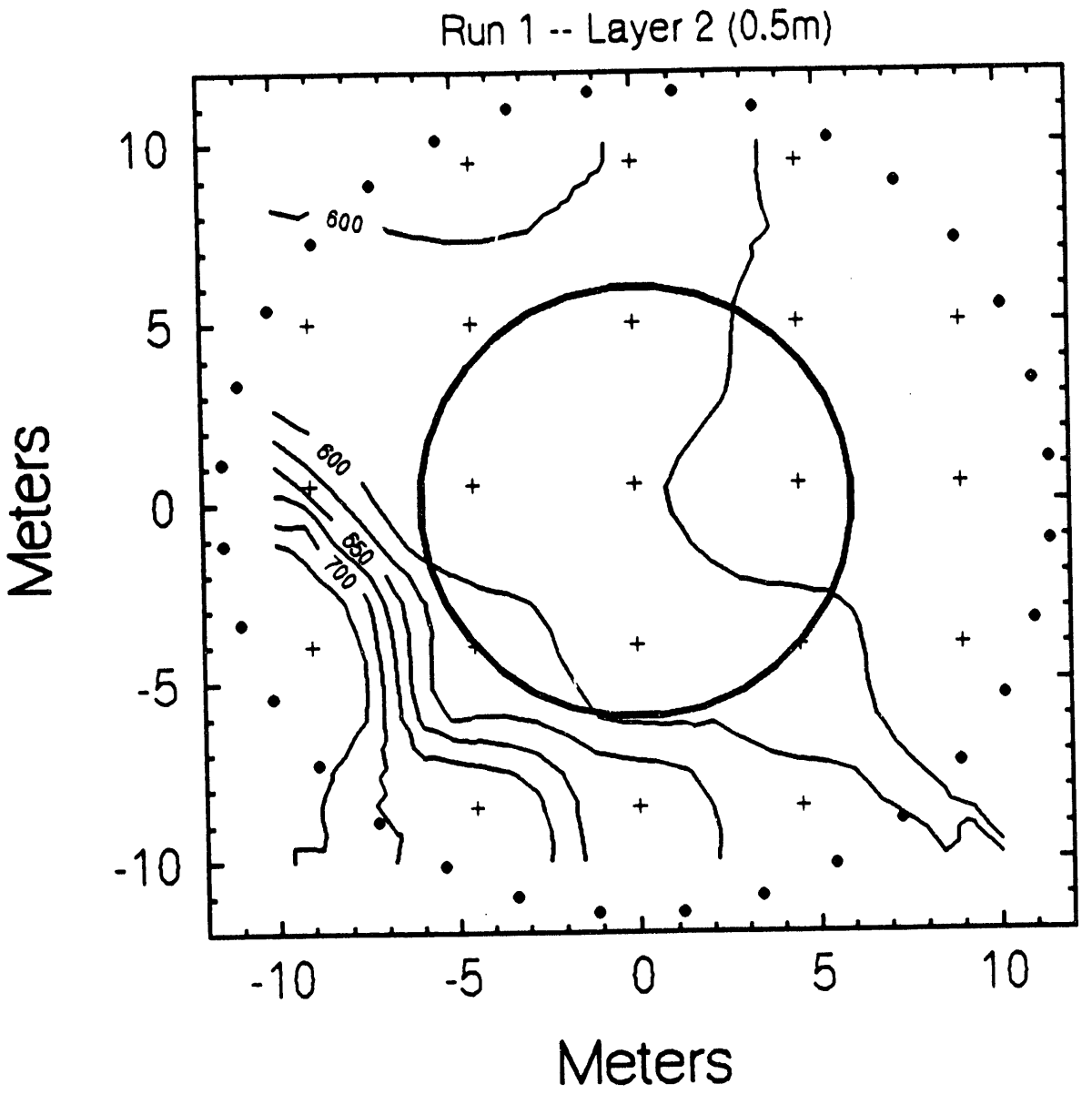

1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
tracer conc./sweetspot av'g
top
middle
bottom
5
10
50
100
downwind distance, m.

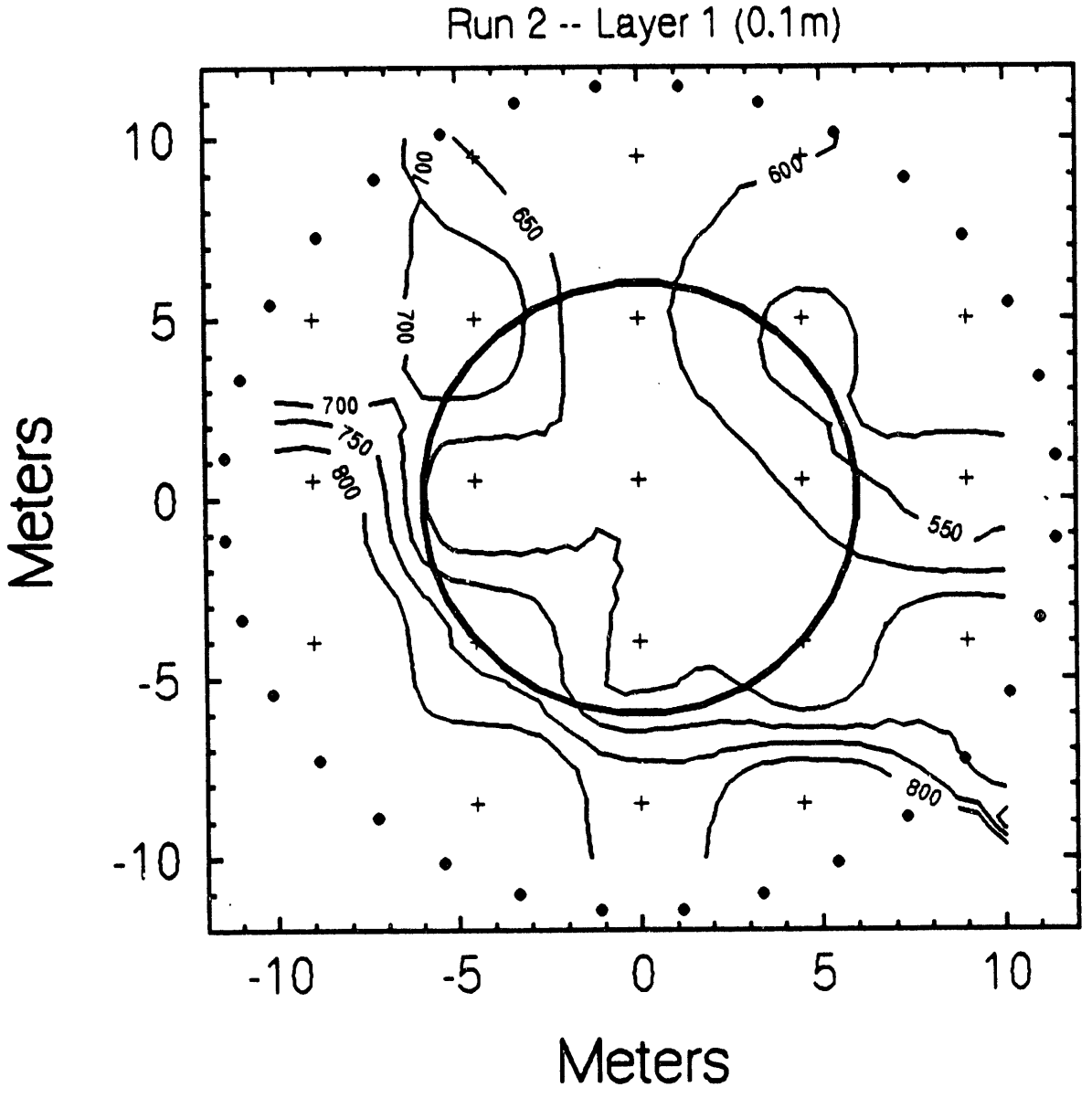

400
300
200
100
0
Observations per 10 µmol mol
400
600
800
1000
1200
CO2 Concentration [µmol mol-1]

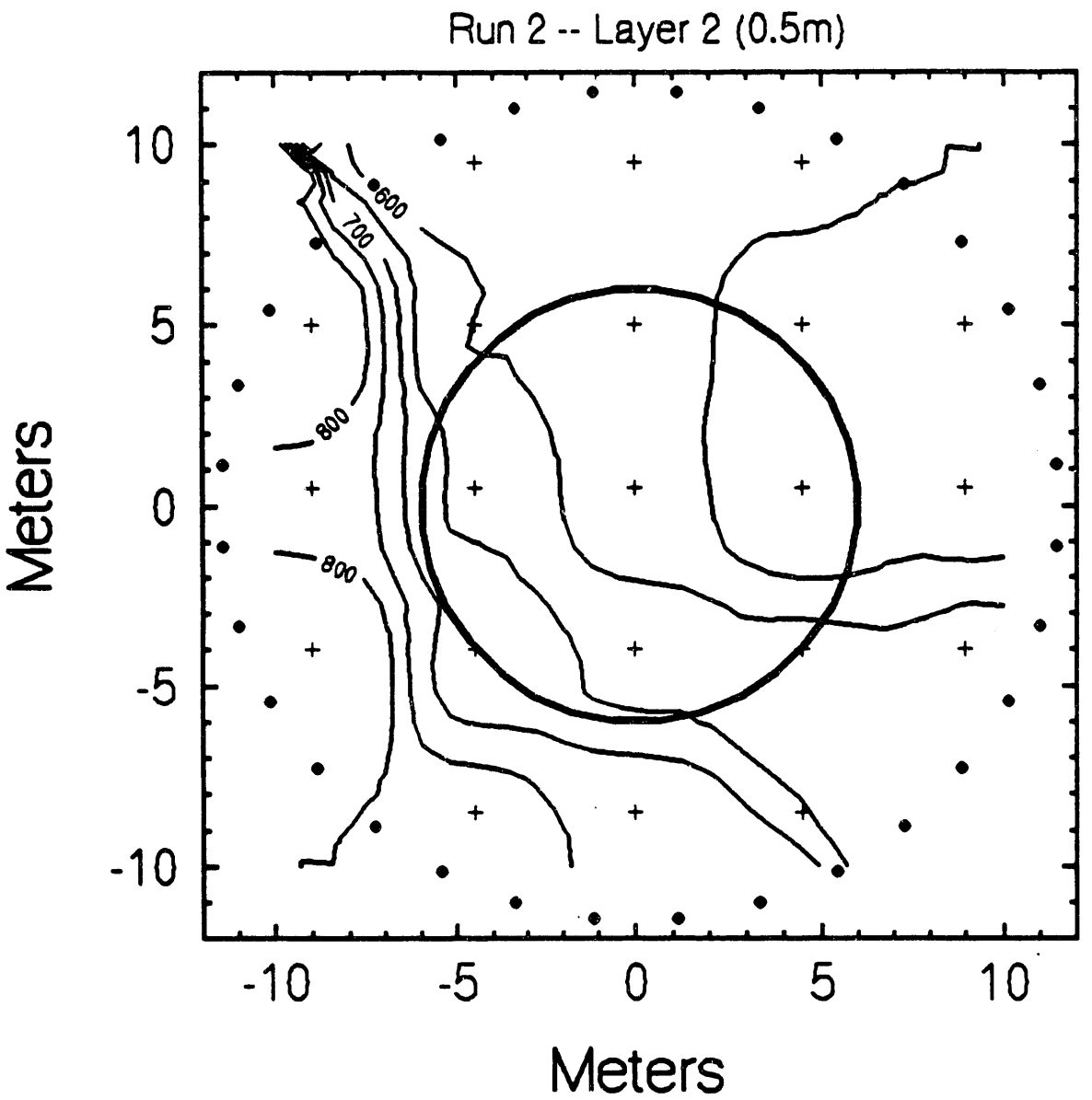

layer 2
10
5
0
-5
-10
-10
-5
0
5
10
102
104
106
108
110
102
100
98
96
94
126

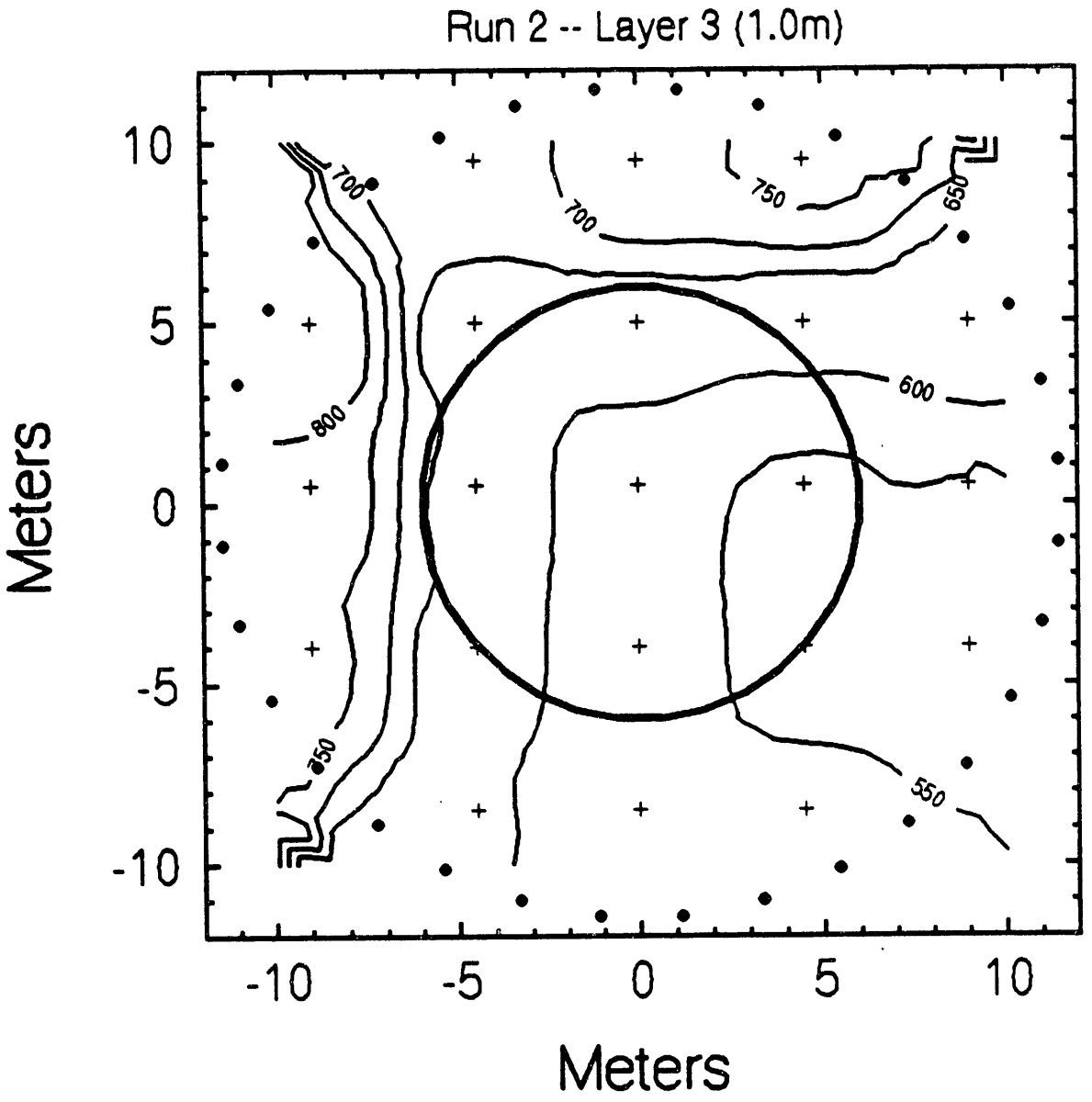

layer 3
10
5
0
-5
-10
-10
-5
0
5
10
106
104
104
106
114
112
110
108
108
110
112
114
102
100
98
98


Run 1 -- Layer 1 (0.1m)
Meters
Meters
10
5
0
-5
-10
-10
-5
0
5
10
600
600
800
700
700
800
900


Run 1 -- Layer 2 (0.5m)
10
5
0
-5
-10
Meters
600
600
650
700
-10
-5
0
5
10
Meters


Run 2 -- Layer 1 (0.1m)
Meters
Meters
10
5
0
-5
-10
-10
-5
0
5
10
700
650
600
700
700
750
800
550
800


Run 2 -- Layer 2 (0.5m)
Meters
Meters
10
5
0
-5
-10
-10
-5
0
5
10
600
700
800
800


Run 2 -- Layer 3 (1.0m)
Meters
Meters
10
5
0
-5
-10
-10
-5
0
5
10
700
700
750
650
600
800
550
550

DISTRIBUTION OF CARBON DIOXIDE WITHIN AND ABOVE A COTTON CANOPY GROWING IN THE FACE SYSTEM

D.R. Hileman[1], *N.C. Bhattacharya*[1*], *P.P. Ghosh*[2] *and P.K. Biswas*[2]
[1]Department of Biology and [2]Department of Plant and Soil Science
Tuskegee University
Tuskegee, AL 36088
[1*]Present address: USDA-ARS
Western Cotton Research Laboratory
4135 E. Broadway
Phoenix, AZ 85040

L.H. Allen, Jr.
USDA-ARS
University of Florida
Gainesville, FL 32611

K.F. Lewin and G.R. Hendrey
Department of Applied Science
Brookhaven National Laboratory
Upton, NY 11973

I. INTRODUCTION

In order to conduct meaningful biological experiments using the FACE system, it is important to have a relatively uniform CO_2 environment within the FACE ring. Continuous computer logging of the CO_2 concentration at the center of the ring has shown that the CO_2 level at this position stays near the set point most of the time (Chapter 7).

During the initial field trials of the FACE system at Yazoo City, MS, in 1987, tracer dispersion studies within the FACE ring had suggested that the CO_2 concentration on the edges of the ring parallel to the wind might be higher than at the center. This could be due to the interception of more vertical vent pipes by the wind on the sides of the ring than along the upwind edge. Based on this information, the pattern of which vent pipes were open, relative to the wind direction, was altered (Figure 8-1). One of our objectives was to determine if the distribution of CO_2 was now adequately uniform across the FACE ring. In addition, the possibility existed that CO_2 levels within the canopy might exceed the setpoint due to lower wind speeds within the canopy than above the canopy. In order to address these concerns, we sampled the CO_2 concentration both vertically and horizontally within a cotton (*Gossypium hirsutum* L.) canopy growing in a FACE ring.

II. METHODS

Measurements of CO_2 concentration were conducted within a FACE ring in a cotton field in Yazoo City, MS in 1988. The field was laid out with 4 FACE plots and 3 control plots. FACE plots were maintained at a CO_2 concentration of 550 μmol mol^{-1}, from 18-26 July and at 600 μmol mol^{-1} from 27 July until the end of the growing season. Measurements of CO_2 distribution were conducted in FACE plot 3 because it was the farthest from obstructions that might affect the wind flow pattern. The rows were planted in an east-west orientation. During the measurements winds were mainly out of the east or west.

A. Sampling system

Air within the FACE ring was sampled using two separate sampling systems simultaneously. Air samples were drawn in through twenty-eight 50-m sample lines of 6-mm O.D. polyallomer (Impolene, Imperial Eastman) tubing. Sixteen of the 28 sample lines were attached to a 16-port sampler and a Binos model 4b1 infrared gas analyzer (IRGA). The remaining sample lines were attached to a 12-port sampler and a Beckman model 865 IRGA. Both sampling systems were designed to allow selection of one line at a time to be diverted through the IRGA. In each sampling system, the gas from the selected sample line was diverted to a pump and then through the sample side of the IRGA. The pumps pulled in sampled air at a rate of 1.5 to 2.0 l min^{-1}. Bleeder valves were installed between the pumps and the IRGAs to reduce the flow into the IRGAs to 1.0 l min^{-1}. The bleeder valves and flow meters were adjusted so that the time required for a gas sample to reach the IRGA from the plot was identical in the two sample systems. Gas from the lines not being sampled was routed to a larger pump which provided continuous flushing of the 50-m sample lines. The IRGAs were calibrated using tanks of standard gasses. Quadratic regressions were fitted to the calibration data.

The signals from the IRGAs were passed through electronic signal integrators, which provided a 67% attenuation over a 1-min period. The raw and the integrated signals were recorded on strip chart recorders. The raw signals of the two IRGAs differed greatly in the frequency of their fluctuations, due to a large difference in their sample cell sizes. However, the variation in the integrated signals of the two IRGAs was nearly identical.

Individual samples were recorded for 5-min periods. Data were collected from the strip charts by reading 8 points from the integrated signal taken 18 s apart, starting 2.5 min after the start of the sampling. This allowed for the flushing of the sample cell (25 s) and a 94% attenuation of the previous sample's signal. In rare cases, the difference in CO_2 concentration between successive samples was large enough that integrated sample was still being affected by the previous sample after 2.5 min. In these cases, the raw signal was read instead of the integrated signal.

Sample lines were attached to wooden stakes located within the FACE ring. The ends of the sample lines were sometimes placed inside 3.8 l plastic containers to buffer the temporal variations in the CO_2 concentration. The buffering reduced the variation in the raw signals, but electronic signal integration masked any differences caused by the presence of the sample buffers. During analysis, the data was pooled without regard to the presence or absence of sample buffers.

B. Sampling patterns

Two different patterns of sampling points were used. To sample horizontal variation in CO_2 distribution, one sample point was located at the center of the FACE ring and 24 sample points were located in concentric circles with radii of 4, 6 and 8 m (Figure 8-2a). Sample points were located 120 cm above the ground. At the time of the measurements (29 July - 1 August), the cotton canopy was 100-110 cm tall. Each sampling system was used in turn to monitor the CO_2 concentration above the canopy at the center of the ring, while the other system was used to sample other areas of the ring. This allowed the data to be expressed as deviations from the CO_2 concentration at the center of the ring, eliminating the effects of temporal fluctuations in the CO_2 concentration.

Vertical variation in CO_2 distribution was sampled at the center of the FACE ring and at 4 locations at a radius of 6 m. from the center (Figure 8-2b). Sample points were located at heights of 50, 80, 140 and either 110 or 225 cm above the ground. At the time of the measurements (2-10 August), the canopy was 120-130 cm tall. At each sampling location, one sample system was used to monitor the CO_2 concentration at the 140 cm height while the other system was used to sample the other heights, eliminating the effects of temporal fluctuation and horizontal variation in CO_2 concentration. Data were adjusted for differences between the various sampling locations based on the mean CO_2 concentrations at the 140 cm height. During the sampling of the vertical profiles, some of the holes in the vertical vent pipes were covered in an attempt to achieve a more uniform vertical distribution of CO_2.

During both types of sampling, samples were periodically drawn from identical locations just above the canopy into both sampling systems. The differences observed in these readings were used to correct the data for differences in the two sampling systems. One additional sample point was located on the upwind side of the FACE ring for periodic monitoring of the ambient CO_2 concentration. Wind speed and direction were sampled continuously at the edge of the FACE ring and logged into the computer system that was controlling the FACE system. Wind direction remained relatively constant during the day, but occasionally shifted by a large amount. When this happened, the points taken during the unusual wind direction were resampled after the wind reverted to its normal direction.

III. RESULTS AND DISCUSSION

A. Horizontal variation

A typical horizontal distribution of CO_2 above the canopy is shown in Figure 8-3. The CO_2 concentration was greater on the upwind side of the ring than on the downwind side, due to mixing of the CO_2-enriched air with ambient air. In general, the deviations in CO_2 concentration from the value at the center of the ring were smaller at 4 m from the center than at 6 or 8 m. The concentration at 8 m was more variable than at 6 m, but the average deviations were similar at the two distances.

All of the data from five sampling cycles, taken over four days, were pooled and corrected for wind direction (Figure 8-4). The curved shape exhibited by the combined data points is due to the decrease in CO_2 concentration from the upwind side to the downwind side of the FACE ring. The data show that the concentration of CO_2 at 4 m from the center rarely differed by more than 50 μmol mol^{-1} from the concentration at the center. However at 6 and 8 m, the deviation

in CO_2 concentration from the value at the center frequently reached 100 μmol mol^{-1}. There is no evidence of a buildup of CO_2 on the sides of the ring, and thus the current pattern of open vent pipes appears to be satisfactory.

Table 8-1 summarizes all of the horizontal CO_2 distribution data. The magnitude of the deviations in CO_2 concentration from the concentration at the center of the ring was the same at 6 and 8 m, but was 55 and 61% greater at 6 and 8 m than at 4 m. In addition, the percentage of the data points where the deviation from the center exceeded 50 μmol mol^{-1} was 7-8 times greater at 6 and 8 m than at 4 m. The standard deviation of the actual CO_2 levels increased with increasing distance from the center. These data indicate that the CO_2 concentration was more variable at 8 m than at 6 m, but the average magnitude of the deviations from the value at the center of the ring was no greater at 8 m than at 6 m (Figure 8-3).

B. Vertical variation

The vertical vent pipes in the FACE system contained 5 sets of 3 holes. The sets of holes were spaced 50 cm apart, from 25 to 225 cm above the ground. When all of the holes were open, the CO_2 concentration increased as the sample height decreased (Figure 8-5a). The CO_2 concentration at the 50 cm height exceeded the concentration just above the canopy (140 cm) by 100 to 200 μmol mol^{-1}. Apparently, the reduced wind speed below the canopy allowed a build-up of CO_2. When two holes at 25 cm and one hole at 75 cm were covered, the build-up of CO_2 below the canopy was lower, but the CO_2 concentration at 50 cm still exceeded the concentration above the canopy by 50 to 100 μmol mol^{-1} (Figure 8-5b). When all three holes at 25 cm and one hole at 75 cm were covered, the CO_2 concentration did not differ among the sample heights (Figure 8-5c).

The CO_2 concentration in the upper canopy (110 cm), where most of the leaves were located, did not differ from the concentration just above the canopy (140 cm), even when no holes were covered (Figure 8-5a,b). Since most of the photosynthesis takes place in the upper canopy, biological impact of the build-up of CO_2 below the canopy (50 cm), may be minimal.

Regardless of which holes were covered, the CO_2 concentration above the canopy at the upwind sampling locations exceeded the concentration at the center by up to 100 μmol mol^{-1} (Figure 8-5). The CO_2 concentration at the downwind sampling locations was often lower than the concentration at the center, but usually by no more that 50 μmol mol^{-1}. These differences show evidence of an exponential decay of the CO_2 concentration due to mixing of ambient and CO_2-enriched air as the air moves from the upwind to the downwind side of the FACE ring.

Most of the data on vertical distribution of CO_2 was taken when the wind was predominantly out of the east or west, parallel to the rows. However, on one day, the wind shifted during the day, resulting in the three sample cycles being taken under northwest, north and northeast wind conditions (Figure 8-6). The cycles taken under northwest (Figure 8-6a) and northeast (Figure 8-6c) wind conditions, showed CO_2 distribution patterns similar to those shown in Figure 8-5, which also were taken under northwest and northeast wind conditions. However, the CO_2 distribution was different when the wind was out of the north, perpendicular to the rows (Figure 8-6b). The differences in CO_2 concentration among the sampling locations were greater under north wind conditions. Also, the CO_2 concentration in many locations was lower than the concentration at the

center of the ring above the canopy. This indicates that when the wind is perpendicular to the rows, the propagation of CO_2 across the ring is reduced. Wind direction and row orientation must be considered when modifying the number of open holes on the vertical vent pipes.

The vertical CO_2 distribution data is summarized in Table 8-2. The values represent the average over all five sampling locations of the deviations (both positive and negative) in CO_2 concentration from the concentration at the center of the FACE ring above the canopy (140 cm). Regardless of the number of holes that were covered, the mean deviation in CO_2 concentration increased as sample height decreased. At 50 cm, the deviation in CO_2 concentration was significantly greater when no holes were covered than when holes were covered at 25 and 75 cm. Covering holes at 25 and 75 cm had no significant effect on the CO_2 concentration at sample heights above 50 cm.

The highest set of holes on the vent pipes was at 225 cm. Air samples taken at 225 cm indicate a surprisingly small effect of mixing with ambient air (Table 8-2). This indicates that it may not be necessary to emit CO_2 at heights up to a meter above the canopy, as was done in this experiment.

It should be noted that the wind speed was significantly higher when 4 holes were covered than when no holes were covered (Table 8-2). The differences in CO_2 elevation under the canopy may be due in part to differing wind speeds, rather than solely to the changes in the number of holes covered. More data, under similar wind conditions, is needed to separate these two effects.

IV. CONCLUSIONS

With all of the holes in the vertical vent pipes of the FACE system open, CO_2 concentrations below a full canopy can be several hundred $\mu mol\ mol^{-1}$ above the desired CO_2 level. Reductions in the number of open holes can be used to obtain a more uniform vertical distribution of CO_2.

The vertical distribution of CO_2 in a FACE ring will be affected by plant height and the degree of canopy closure. It is likely that the covering of the lower holes in the vertical vent pipes is not necessary early in the season. It may also be possible to cover some of the upper holes early in the season and reduce CO_2 usage while maintaining the CO_2 environment around the plants.

The one unavoidable non-uniformity in the CO_2 environment within a FACE ring is the decrease in CO_2 concentration from the upwind to the downwind side of the ring. This difference frequently reached 100 $\mu mol\ mol^{-1}$. If the wind direction varies either uniformly or randomly, the long-term effect of this CO_2 gradient should be minimal. However, the distribution of wind direction is frequently skewed. This means that plants on the predominantly upwind side of the FACE ring will be exposed to a higher average CO_2 concentration than the plants on the predominantly downwind side.

Logistical and sampling concerns dictate that many of the plant response measurements made in FACE plots must be restricted to segments of the plots. If measurements are consistently made on one side of the ring, the results may not be representative of the target CO_2 concentration. Locating measurements on different sides of replicate FACE plots would overcome this problem, but would introduce greater variability among plots for these measurements.

Experiments are being conducted to evaluate the possibility of enlarging the FACE ring in order to allow for more experimental plant material. If wind direction is skewed, the upper limit of the size of the FACE ring might be

determined by the acceptable amount of variation in the season-long average CO_2 average concentration. Efforts to model both the performance of the FACE system and the responses of plants to elevated CO_2 are being undertaken as part of the overall FACE project. These models can be used along with existing data on wind direction to help identify a practical upper limit to the size of the FACE ring.

It is apparent that when cotton is grown in the FACE system, it is necessary to monitor the CO_2 concentration at various heights and locations in the canopy throughout the season. In addition, the use of the FACE system on other crops and ecosystems will require periodic three-dimensional sampling of CO_2 in order to adjust the distribution of emission holes. Other species, with different growth patterns and architectures, will likely have different affects on the movement of the CO_2-enriched air emitted by the FACE system.

V. ACKNOWLEDGEMENTS

We thank Clay McConnell and the Mississippi Chemical Company for their assistance and for permission to conduct this experiment in their field. This research was supported in part by the Department of Energy (contract no. DE-FG05-86ER-60498) and the Tuskegee University George Washington Carver Agricultural Experiment Station.

Table 8-1
Variation in CO_2 concentration above a mature cotton canopy at different distances from the center of a FACE ring.

Date	Cycle	Distance from Center (m) 4	6	8
Mean of Absolute Values of Deviations from Center (μmol mol^{-1} CO_2)				
29 July	1	24	44	52
30 July	1	32	49	36
31 July	1	41	66	45
31 July	2	24	43	56
1 August	1	32	38	59
Mean		31	48	50
Pct. Deviations from Center $\geq$ 50 μmol mol^{-1}				
All Data		5	38	40
Standard Deviation of CO_2 Concentration (μmol mol^{-1})				
29 July	1	30	53	85
30 July	1	39	56	51
31 July	1	60	53	52
31 July	2	35	45	62
1 August	1	33	40	77
Mean		39	49	65

Table 8-2

Mean deviation of CO_2 concentration (μmol mol^{-1}) in a mature cotton canopy (120-130 cm tall) from the concentration at the 140 cm height at the center, as affected by sample height and the number of vertical vent pipe holes covered. Values are means of five sampling locations (center and 6 m north, east, south and west). Wind direction was generally parallel to the rows. At each sample height, mean values followed by the same letter do not differ at the 0.05 level (Duncan's multiple range test).

Date	Cycles	Holes Covered*	Wind Speed ($m\ s^{-1}$)	Sample Height (cm)				
				225	140	110	80	50
2 August	2	0,0	1.24[b]	--	24[a]	36[a]	49[a]	142[a]
3 August	2	2,1	1.22	--	18	14	36	69
5 August	3	2,1	1.52	-31	11	23	41	99
Mean		2,1	1.37[ab]	-31[a]	15[a]	19[a]	39[a]	84[b]
6 August	4	3,1	1.78	-15	32	--	49	68
8 August	3	3,1	2.06	--	33	45	53	85
9 August	2	3,1	2.47	-56	-5	--	22	69
10 August	2	3,1	2.45	-10	32	--	52	58
Mean		3,1	2.19[a]	-27[a]	23[a]	45[a]	44[a]	70[b]

*Number of holes in each vertical vent pipe covered at the 25 and 75 cm heights, respectively.

FIGURE LEGENDS

Figure 8-1. Relationship between wind direction and the dispensing of CO_2 through vertical vent pipes in the FACE system.

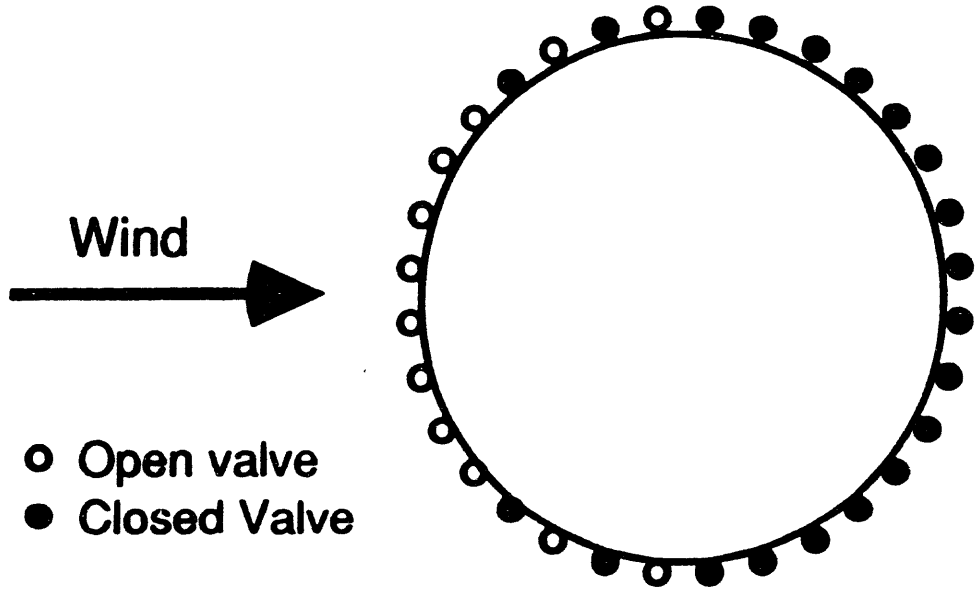
Figure 8-2. Arrangement of sampling points for determination of: (a) horizontal and (b) vertical distribution of CO_2 within the FACE system. Sample heights were: (a) 120 cm and (b) 50, 80, 110, 140 and 225 cm. Canopy heights were (a) 100-110 cm and (b) 120-130 cm.

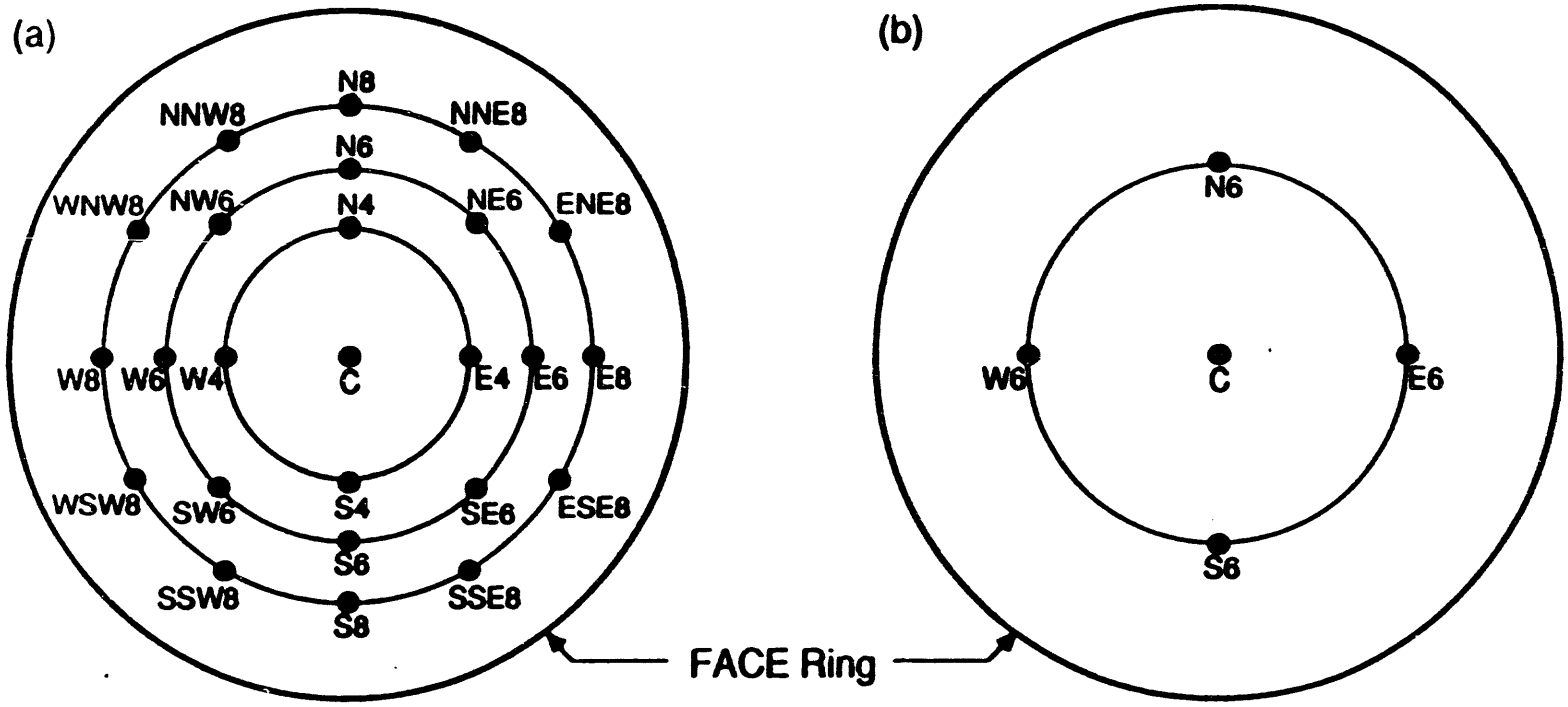
Figure 8-3. Typical variation in CO_2 concentration above a mature cotton canopy at different distances from the center of a FACE ring. Values are expressed as deviations from the CO_2 concentration at the center of the ring. Points are means of 2 replicate 2.5-min samples taken on 31 July. Wind was out of the WSW at 1.48 m s^{-1}.

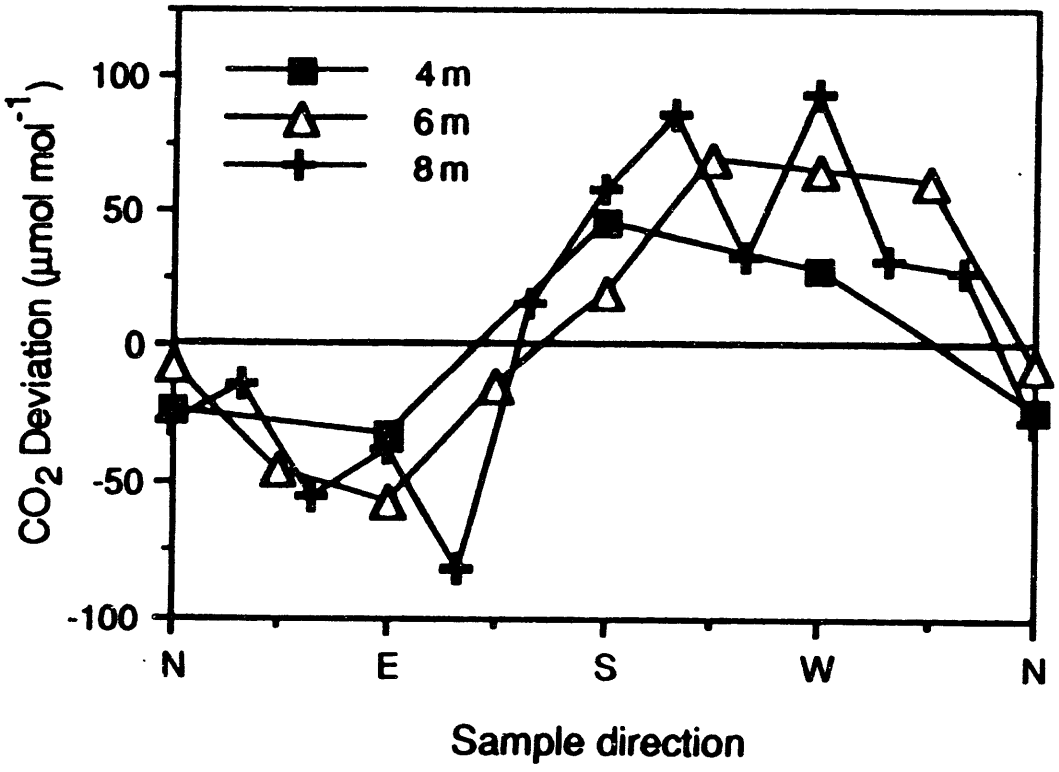
Figure 8-4. Relationship between wind direction, sampling location and CO_2 concentration above a mature cotton canopy within a FACE ring. Points are individual 2.5 min samples taken during the period 29 July to 1 August.

Figure 8-5. Vertical variation in CO_2 concentration within a FACE ring containing a mature cotton canopy (120-130 cm tall), as affected by the number of vertical vent pipe holes covered. Values are means of 2-4 replicate 2.5-min samples. Dates and wind directions and speeds were: (a) 2 August, NW, 1.24 m s^{-1}, (b) 5 August, ENE, 1.52 m s^{-1}, and (c) 6 August, ENE, 1.78 m s^{-1}.

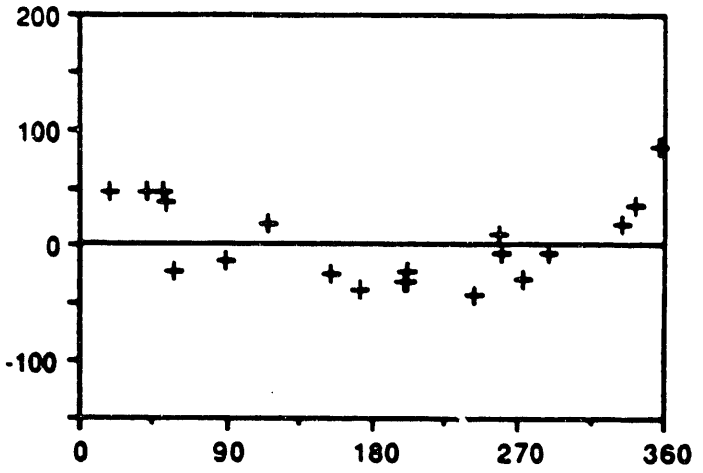
Figure 8-6. Vertical variation in CO_2 concentration within a FACE ring containing a mature cotton canopy (120-130 cm tall), as affected by wind direction. Values are single 2.5-min samples taken on 3 August. Two holes at 25 cm and 1 hole at 75 cm were covered.


Wind
Open valve
Closed Valve

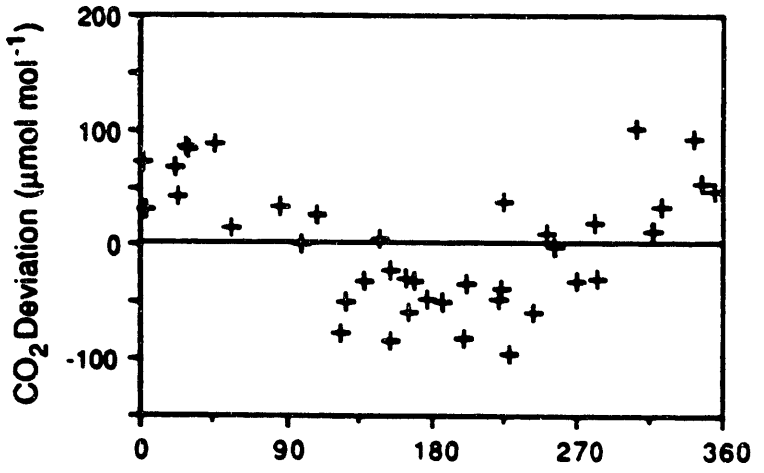

(a)
N8
NNW8
NNE8
N6
WNW8
NW6
N4
NE6
ENE8
W8
W6
W4
C
E4
E6
E8
WSW8
SW6
S4
SE6
ESE8
S6
SSW8
SSE8
S8
(b)
N6
W6
C
E6
S6
FACE Ring


4 m
6 m
8 m
100
50
0
-50
-100
CO_2 Deviation (µmol mol^{-1})
N
E
S
W
N
Sample direction

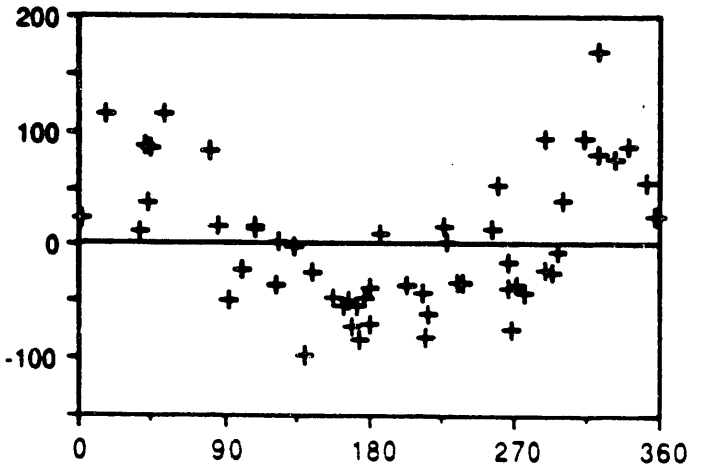
(a) 4 m from Center



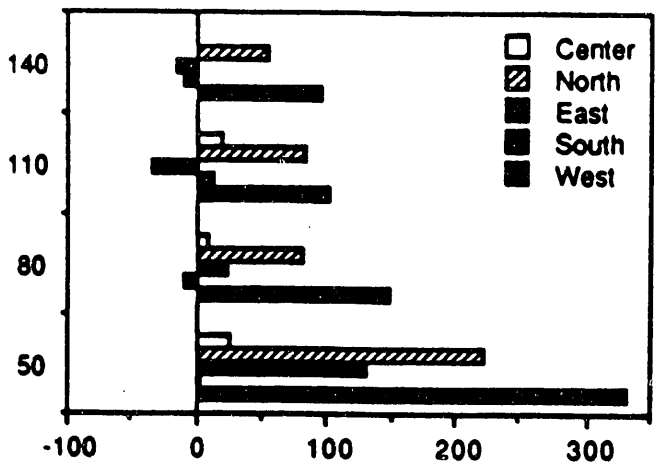
(b) 6 m from Center



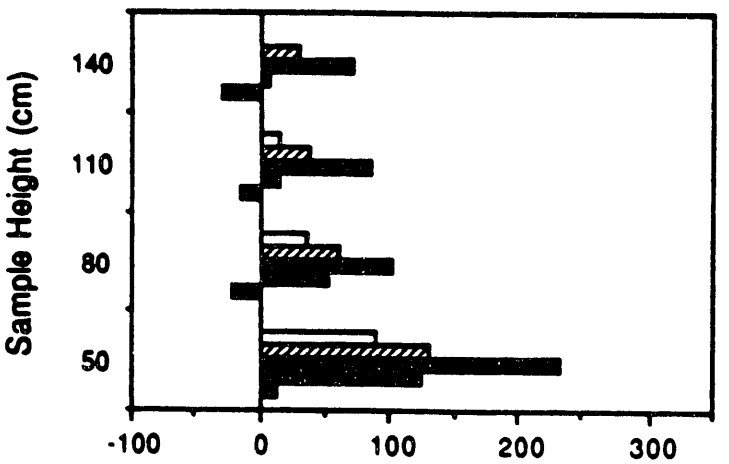
(c) 8 m from Center



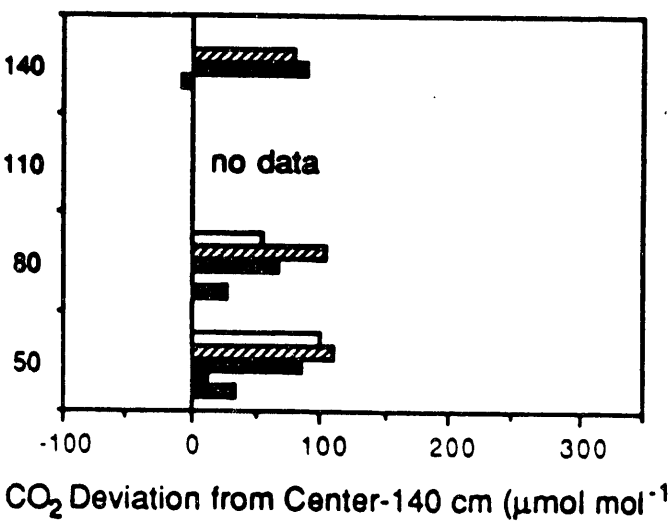
(a) Holes covered: none



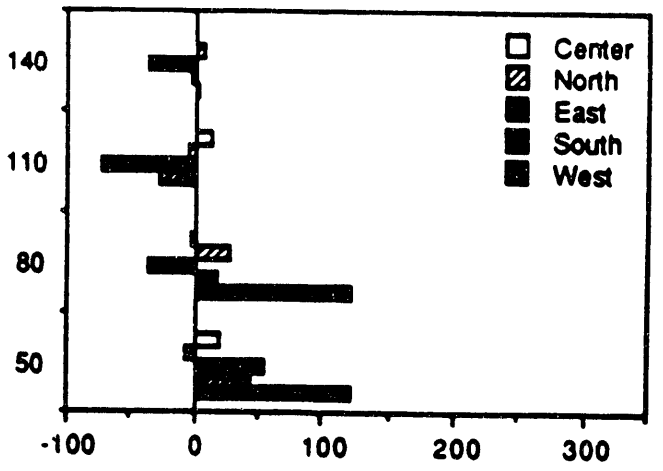
(b) Holes Covered: 2 at 25 cm, 1 at 75 cm



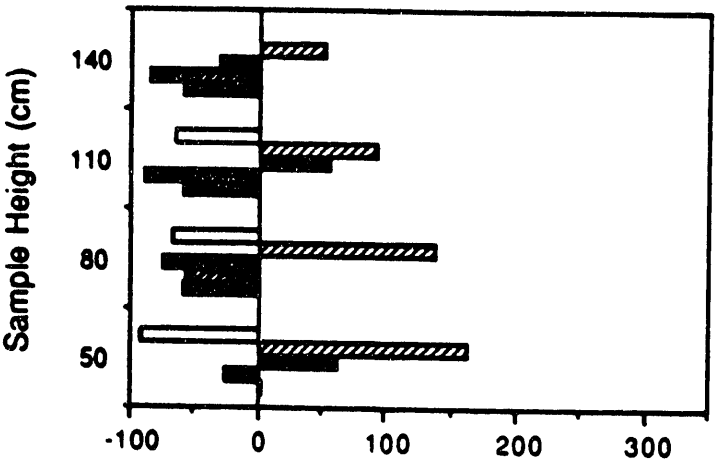
(c) Holes covered: 3 at 25 cm, 1 at 75 cm



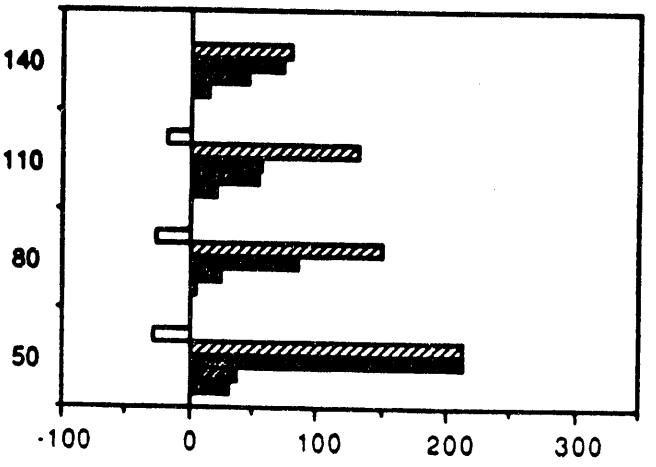
(a) WNW Wind, 1.07 m s^{-1}



(b) N Wind, 1.29 m s^{-1}



(c) ENE Wind, 1.31 m s^{-1}



CO_2 Deviation from Center-140 cm (μmol mol^{-1})

A COMPARISON OF THE UNIFORMITY OF AN ELEVATED CO_2 ENVIRONMENT IN THREE DIFFERENT TYPES OF OPEN-TOP CHAMBERS

D.R. Hileman[1], P.P. Ghosh[2], N.C. Bhattacharya[2] and P.K. Biswas[2]*
[1]Department of Biology and [2]Department of Plant and Soil Science
Tuskegee University
Tuskegee, AL 36088
[*]Present address: USDA-ARS
Western Cotton Research Laboratory
4135 E. Broadway
Phoenix, AZ 85040

L.H. Allen, Jr.
USDA-ARS
University of Florida
Gainesville, FL 32611

G. Peresta[f] and B.A. Kimball
USDA-ARS
U.S. Water Conservation Lab
Phoenix, AZ 85040
[f]Present address: Smithsonian Environmental Research Center,
P.O. Box 28
Edgewater, MD 21037

I. INTRODUCTION

The Free-Air Carbon dioxide Enrichment (FACE) system is designed to provide an elevated CO_2 atmosphere in a more natural environment than is possible with open-top chambers, sunlit controlled environment units (Phene *et al.* 1978) or growth chambers. One of the concerns with the proposed FACE system, however, is the variability in CO_2 concentration caused by shifts in wind speed and direction. Variabilities of CO_2 concentrations observed within the FACE systems used at Yazoo City, MS, and Maricopa, AZ, are discussed in Chapters 8 and 7, respectively. We felt that it would be beneficial to characterize the uniformity of the CO_2 environment in open-top chambers, so as to provide a basis for comparison of the FACE system to the open-top chamber system.

Several different types of open-top chambers have been used in CO_2 studies. The earliest of these was a cylindrical, open-top chamber (Heagle *et al.* 1973, Rogers *et al.* 1983b). Rogers *et al.* (1984) added a 45° truncated cone or frustum to this chamber, in order to minimize the ingress of wind-driven ambient air, thus achieving more constant CO_2 levels. A shorter, less expensive, square chamber has also been used (Nakayama and Kimball 1988). This chamber provides 27% more area inside the chamber, and the shorter walls increase the amount of

sunlight available to the crop canopy. We compared the uniformity of the CO_2 environment within each of these three types of chambers in the same field on the same days.

In most studies involving open-top chambers, the CO_2 concentration is monitored by a single sample tube placed inside a volume buffer (e.g. a 3.8 l beverage container) in the center of the chamber. In this study, to compare the uniformity of the CO_2 environment within the chambers, we placed unbuffered sample tubes in various locations within each type of chamber.

II. MATERIALS AND METHODS

The experiment was conducted in an agricultural field containing a crop of cotton (*Gossypium hirsutum* L.) in Yazoo City, Mississippi. The crop was planted on 7 May 1987. The experiment was conducted on 26 and 27 September, when the crop was about 1.5 m tall. The crop had lost most of its leaves due to spraying with a defoliant in preparation for harvesting.

A. Open-top chambers

Three different types of open-top chambers were used: round without frustum, round with frustum, and square. The round chambers (Heagle *et al.* 1973, Rogers *et al.* 1983b) consisted of cylindrical aluminum frameworks 3 m in diameter and 2.4 m high, covered with 0.20 mm clear PVC plastic film. The bottom halves of the chambers were double walled; the inside wall was perforated and served as a duct to distribute air uniformly. Ambient air was supplied to the ducts by a 560 W axial fan mounted in a sheet metal plenum box with a filter. The fan provided about three air changes per min (Rogers *et al.* 1983a). Carbon dioxide was injected into the plenum box between the filter and the fan. The area of the top opening of one round chamber was reduced by about 50% with 45° frustum (Rogers *et al.* 1984).

The square chamber was identical to those used by Nakayama and Kimball (1988), except that ours was 0.3 m shorter. Our chamber was 1.7 m high and 3.0 m on each side. Plastic-coated steel cables were strung between the tops of five 1.83 m steel fence posts located at the corners and at the edge of the door. Clear, low density polyethylene film (0.15 mm thick, 2 m high) was hung from the cables, forming the sides of the chamber. Ambient air was supplied by a 373 W evaporative cooler fan with dry pads. Air from the cooler fan passed into a large duct that acted as a manifold for four smaller perforated pipe-shaped ducts, which lay on the ground inside the chamber between the rows of cotton, discharging their air downward toward the soil. Identical evaporative cooler fans provided about four air changes per min in 3.0 x 3.0 x 2.0 m high square chambers (Nakayama and Kimball 1988). Carbon dioxide was injected on the intake side of the evaporative cooler.

The frameworks of the round chambers were installed in the field in mid-August, but the plastic coverings were not installed until 26 September. The square chamber was installed on 25 and 26 September. All three chambers were oriented so that the duct entry was on the west side and the door was on the east side.

B. Dispensing and sampling of carbon dioxide

Liquid CO_2 was stored in a 50-ton tanker-trailer receiver adjacent to the field site. Gaseous CO_2 was dispensed from the tanker-trailer through low density polyethylene tubing to a bank of flow meters located near the chambers. Carbon dioxide passed from the flow meters to the open-top chambers through 0.95 cm (3/8") polyallomer (Impolene, Imperial Eastman) tubing. The flow rates were set at a level that was expected to yield elevations of about 300 μmol mol^{-1} CO_2 above ambient. Near the end of the measurements, when it was observed that CO_2 concentrations in the square chamber were much lower than in the round chambers, the flow rate to the square chamber was increased by an arbitrary amount in an effort to achieve more equal CO_2 elevations in the three chambers. Only one set of data was taken for the square chamber at the higher flow rate. In the tables, these data are labelled as high CO_2. Subsequent data calculations revealed that the ranges of CO_2 elevations (averaged over all sample points) on 27 September for the various chambers were 160-230 (round), 260-270 (round with frustum), 130-160 (square-low CO_2 flow) and 200 μmol mol^{-1} (square-high CO_2 flow).

Five 2.5-m wooden stakes were placed in each chamber. One stake was placed in the center of the chamber; the other four stakes were placed 1 m north, south, east and west of the center stake (0.5 m from the chamber wall). Sample lines were taped to the wooden stakes. There were no volume buffer containers on the ends of the sample lines. Three different arrangements of sample lines were used. (1) Horizontal variation was sampled near the top of the canopy by placing one sample line at a height of 120 cm (100 cm in the square chamber) on each stake. (2) Horizontal variation within the canopy was sampled by placing one sample line at a height of 60 cm on each stake. (3) Variation in a vertical, east-west plane was sampled by placing one sample line at 120 cm (100 cm in the square chamber) and one sample line at 60 cm on the east, center and west stakes.

The sample lines were attached to a custom-made solenoid switching device which allowed any combination of the sample lines to be sampled. Air was drawn through the selected sample lines by a diaphragm pump located between the mechanical switching device and a Beckman 865 infrared gas analyzer. Most of the air flow bypassed the analyzer, with 6.0 l min^{-1} flowing through the sample cell. The gas analyzer was calibrated at the beginning and end of each day using standard gases.

Measurements were made on 26 September using the 120 cm height sampling arrangement and various sampling protocols. On 27 September measurements were made in each chamber using each of the three sampling arrangements and a standardized sampling protocol. The sample lines were sampled sequentially two times with each line being sampled for 2 min during each pass. The complete sampling of one arrangement of the sample lines for one chamber took about 26 min, and the two replicates of each sample point were taken about 12 min apart. On 27 September, at the completion of the sampling of each arrangement of the sample lines, ambient air was sampled at a site remote from the chambers and 2.5 m above the ground.

After the east-west sample had been taken in the round chamber with a frustum, the PVC covering on the frustum was quickly removed and the chamber immediately resampled, thus providing a comparison of the same chamber under similar conditions both with and without a frustum.

C. Data analysis

Data points were extracted from the strip charts every 12 s, starting 16 s after switching sample lines. Flushing of sample lines plus analyzer volume to 95% response took 8-12 s. Wind speed and direction at one min intervals were obtained from a recording anemometer mounted 2 m above the ground about 50 m east of the open-top chambers. Due to the distance between the anemometer and the open-top chambers, we felt that precise, instantaneous correlations between wind and CO_2 data would not be accurate. Therefore, we averaged the wind speed and direction for each 26 min sample period.

III. RESULTS

At a sample height of 100-120 cm, CO_2 levels were generally highest in the round chamber with the frustum and lowest in the square chamber (Figure 9-1a). Variation was greatest in the square chamber and least in the round chamber with the frustum. Ambient wind speeds were similar during the sampling of this height in all three chambers. In both the square chamber and the round chamber without the frustum, the variation was the greatest at the north and west sampling points. Also, the CO_2 levels were the lowest at the north, west and center sampling points in the square chamber and at the west sampling point in the round chamber without a frustum. Apparently the southeast wind was causing ingress of ambient air from above in the northwest part of the chambers. The round chamber with the frustum showed no evidence of a wind direction effect.

Levels of CO_2 at the 60 cm height in the three chambers followed the same pattern as at 100-120 cm. Carbon dioxide levels were highest in the round chamber with the frustum and lowest in the square chamber (Figure 9-1b), but the differences between the chambers were not as great as at 100-120 cm. At the 60 cm height, variation was the greatest in the round chamber without the frustum and the least in the round chamber with the frustum. However, the wind speed was lower during the sampling of the square chamber than during the sampling of the other two chambers. The highest variation in the round chamber without the frustum occurred at the west sampling point, possibly due to ingress of ambient air caused by the southeast wind. However, the other two chambers showed the highest variation in the center sampling position.

When the sample tubes were arranged in a vertical, east-west plane, CO_2 levels increased from west to east in all but the round chamber with the frustum (Figure 9-2). This was likely due to the effects of the southeast wind. It is also possible that structural differences between the east end of the chamber (which contained the door) and the west end of the chamber (which contained the air entry ducts) played a role. However, the possibility of higher flow rates through duct holes at the west end and the possibility of leaks around the door both should lead to higher CO_2 values at the west end of the chamber, not at the east end as was observed. In the east-west sampling arrangement, variation was lower in the round chamber with the frustum than in the other chambers (Figure 9-2). There were no clear differences in the degrees of variation between the 60 and 120 cm heights and between the east and west sides of the chambers.

When the round chamber with a frustum had its frustum panel removed, the average CO_2 level (corrected for the change in ambient CO_2) decreased by 17%, and the average CO_2 elevation above ambient decreased by 38% (Figure 9-2). Also, variation increased substantially when the frustum panel was removed. The

average wind speed differed by only 6% between the two sampling periods.

Table 9-1 summarizes the results of all of the experiments. In this analysis, in the east-west sample arrangement, the 60 cm sample in the center of the chamber was omitted since it was not present in all experiments. This left 5 sample points in every experiment. In Table 9-1, range refers to the mean of the ranges of the CO_2 values from the 5 sample points. Deviation from mean refers to the mean of the deviations of the CO_2 concentrations at the 5 sample points from the mean of those 5 points. Thus, the range values are measures of variation over time, and the deviation from mean values are measures of the variation among the sample points within the chamber. The data of 27 September are also expressed as a percentage of the elevation in CO_2 concentration above ambient, to take into account the differences in CO_2 enrichment in the chambers. Ambient data were not taken on 26 September.

In general, variation was significantly lower in the round chamber with a frustum than in the other two chambers (Table 9-1). This was true both for variation over time (range) and for variation among sample points (deviation). The round chamber without a frustum had significantly less variation at the 100-120 cm height than did the square chamber. However, variability at 60 cm and in the east-west plane did not differ between these two chambers.

IV. DISCUSSION

Much of the variation in CO_2 levels in open-top chambers is due to changing ambient wind speeds. In this experiment, the three different open-top chambers and the sample points within the chambers were sampled sequentially, thus introducing wind speed and direction as confounding factors. However, wind direction was always out of east, southeast or south. Also, with only two exceptions, the wind velocity was relatively constant within each sampling arrangement (Table 9-1). Wind speeds during the two days of sampling were typical for the area.

Despite the variability caused by changing winds, some clear trends are apparent in these data. In all three types of chambers tested, variation over time (range in Table 9-1) was much greater than variation among points (deviation). Fluctuations of over 100 μmol mol^{-1} occurred at some sample points in all three chambers. In most cases when a frustum was not used, the mean CO_2 range exceeded 50% of the mean CO_2 elevation above ambient (Table 9-1). However, the mean CO_2 deviation among sample points within a chamber never exceeded 35% of the mean CO_2 elevation above ambient, and in the round chamber with a frustum, it never exceeded 10%.

Many experiments using open-top chambers use a volume buffer in the sample line to dampen the variations. While this permits more accurate control of the average levels of CO_2 in the chambers, it obscures the widely fluctuating conditions that the plants are experiencing. In our measurements, the sample cell in the gas analyzer served as a volume buffer. Therefore, the plants are experiencing even wider fluctuations than we are reporting here.

The shape of the chamber did not have a large effect on the degree of variation in CO_2 concentration. Variation, both over time (range) and among sample points (deviation), did not differ between the square and round (no frustum) chambers, except at the 100-120 cm sampling level (Table 9-1). At the 100-120 cm height, both types of variation were greater in the square chamber than in the round chamber without a frustum. This difference may be due to the

difference in chamber height. The square chamber that we used was 0.3 m shorter than the chambers utilized by Nakayama and Kimball (1988), and 0.7 m shorter than the round chamber (no frustum) used here. The square chamber also had a larger top opening than the round chamber (9.0 m^2 vs. 7.1 m^2). Both of these differences could lead to greater penetration of ambient air into the square chamber than into the round chamber.

It is also possible that the difference in CO_2 variation between the square and round (no frustum) chambers may be due to the different air delivery systems employed by the two chambers. In the square chamber, the air is projected down onto the soil surface from tubes lying on the ground. In the round chamber, the air is projected approximately horizontally from the bottom half (1.2 m) of the side walls towards the center of the chamber. Therefore, at a height of 1 m, wind-driven intrusions of ambient air are more likely to encounter, and mix with, forced currents of CO_2-enriched air in the round chamber than in the square chamber. This could lead to less variation in the CO_2 concentration in the round chamber. More study is needed, using chambers of equal height and area, to determine whether the greater variation in the square chamber is due to its shorter height or to its air delivery system.

The addition of the frustum to the round chamber greatly decreased the variation, both at a given sample point and among sample points. This was probably due to the deflection of the ambient wind upward by the frustum and to the 50% reduction in the size of the top opening (Rogers *et al.* 1984), which gave a smaller area for wind to penetrate the chamber and which doubled the average exit velocity of the air.

Wind direction had a clear effect on the CO_2 levels in the square chamber and the round chamber without the frustum. The downwind sides of the chambers exhibited lower CO_2 levels and greater variation than the upwind sides (Figures 9-1 and 9-2). Carbon dioxide levels and variation in the round chamber with the frustum were not affected by wind direction.

When the same rate of CO_2 injection into the fan box was used for all three chambers, the square chamber maintained the lowest CO_2 concentration and the round chamber with a frustum maintained the highest CO_2 concentration (Table 9-1). The difference between the round chambers with and without a frustum is likely due to the exclusion of wind by the frustum.

The difference in CO_2 concentration between the round chamber without a frustum and the square chamber is probably due to a combination of effects. As discussed above, the shorter walls and larger top opening of the square chamber may have allowed for greater penetration of ambient air. However, the greatest cause of the lower CO_2 concentration in the square chamber was probably the differences in the speed with which the fans pushed air into the chambers. We did not measure the rate of the air entering the chambers, but calculations based on the chamber volumes and published turnover rates for the chambers indicated that the fan used in the square chamber delivered about 40% more air than the fans used in the round chambers. When chambers sampled under equal wind conditions were compared, the mean difference in CO_2 enrichment observed between the square chamber and the round chamber without a frustum was 50%.

The square and round (without frustum) open-top chambers differ in at least five fundamental ways: (1) shape, (2) area, (3) height, (4) air delivery system, and (5) wall material. These differences affect all aspects of the microclimate inside the chamber. Our study dealt only with differences in CO_2 levels. Differences in CO_2 levels within the chambers are probably due to the combined

effects of differences in height, area and the air delivery system. More study is needed to separate these effects. The addition of a frustum to the round chamber greatly reduces the variation in CO_2 levels within the chamber. However, the frustum also excludes some additional light and some precipitation.

While the fluctuations in the CO_2 concentration within open top chambers are likely to be much less than the fluctuations in the FACE system, the fluctuations in both systems are large enough to be of concern. The critical question that needs to be addressed with further study is: How do plants respond to fluctuating CO_2 concentrations? Are the responses of plants to an elevated, but rapidly fluctuating, CO_2 concentration equal to the responses in an elevated, but constant, CO_2 concentration? How does the frequency of fluctuations affect the response of the plants to elevated CO_2? Studies are needed that address these questions, for both physiological responses of individual leaves and for growth responses of whole plants.

VI. SUMMARY

Carbon dioxide levels were determined at various points inside three different types of open-top chambers (square, round without frustum and round with frustum), to compare the variability in CO_2 concentrations among the different types of chambers. At similar rates of injection of CO_2 into the fan housings of the three chambers, CO_2 levels were highest in the round chamber with a frustum and lowest in the square chamber. The lower enrichment levels in the square chamber were most likely due to greater air movement by the fan.

Variability in CO_2 concentration was lowest in the round chamber with a frustum. Variability was similar in the round (without frustum) and square chambers, except at the upper heights, where variability was somewhat greater in the shorter, square chamber. These trends were true both for variability from point to point within chambers and for variability over time. In both the square chamber and the round chamber without a frustum, CO_2 levels were frequently lower and more variable in the downwind side of the chamber than in the upwind side. The round chamber with the frustum showed no evidence of a wind direction effect.

VI. ACKNOWLEDGEMENTS

We thank Keith Lewin for providing the wind data as well as for his technical advice, cooperation and support. We also thank Clay McConnell and the Mississippi Chemical Company for permission to conduct this study in their field. This research was supported in part by the Department of Energy (contract no. DE-FG05-86ER-60498) and the Tuskegee University George Washington Carver Agricultural Experiment Station.

REFERENCES

1. Heagle AS, Body DE, Heck WW (1973) An open top field chamber to assess the impact of air pollution on plants. J Environ Qual 2:365-368.

2. Nakayama FS, Kimball BA (1988) Soil carbon dioxide distribution and flux within the open-top chamber. Agron J 80:394-398.

3. Phene CJ, Baker DN, Lambert JR, Parsons JE, McKinion JM (1978) SPAR--a soil-plant-atmosphere research system. Trans ASAE 21:924-930.

4. Rogers HH, Bingham GE, Cure JD, Smith JM, Surano, KA (1983a) Responses of selected plant species to elevated carbon dioxide in the field. J Environ Qual 12:569-574.

5. Rogers HH, Heck WW, Heagle AS (1983b) A field technique for the study of plant responses to elevated carbon dioxide concentrations. J Air Pollut Control Assoc 33:42-44.

6. Rogers HH, Cure JD, Thomas JF, Smith JM (1984) Influence of elevated CO_2 on growth of soybean plants. Crop Sci 24:361-366.

Table 9-1

Variation in CO_2 concentrations (μmol mol^{-1}) inside open top chambers taken on 26-27 September 1987, in a cotton field. Values are the means of 5 sample locations. Elevation is the mean enrichment above ambient. Range is the mean of the 5 range values. Deviation from mean is the mean deviation of the CO_2 concentration at the 5 sample points from the mean of those 5 points. Values in each sample height group in each column followed by the same letter are not significantly different at the 0.05 level according to Duncan's multiple range test.

			Range		Deviation from Mean		
Chamber	Date	Elevation (μmol mol^{-1})	(μmol mol^{-1})	Pct. of Elevation	(μmol mol^{-1})	Pct. of Elevation	Wind $\pm$ S.E. (m s^{-1})
Sample Height = 100-120 cm (Center, North, East, South, West)							
Square	9/26	---	109^{bc}	--	62^{a}	--	0.71$\pm$.05
Square	9/26	---	171^{a}	--	32^{bc}	--	1.19$\pm$.07
Square	9/27	129^{b}	105^{bc}	97^{a}	41^{ab}	34^{a}	1.16$\pm$.09
Round	9/26	---	158^{ab}	--	13^{cd}	--	1.35$\pm$.09
Round	9/26	---	83^{cd}	--	13^{cd}	--	1.55$\pm$.06
Round	9/27	228^{a}	81^{cd}	37^{b}	15^{cd}	7^{b}	1.23$\pm$.09

Table 9-1. (continued)

Round-Frustum	9/26	---	3[e]	--	4[d]	--	1.26±.10
Round-Frustum	9/27	266[a]	34[ab]	13[b]	8[cd]	3[b]	1.32±.13
		Sample Height = 60 cm (Center, North, East, South, West)					
Square	9/27	145[b]	98[ab]	73[ab]	28[a]	19[a]	1.17±.07
Round	9/27	195[b]	153[a]	81[a]	29[a]	16[ab]	2.53±.13
Round-Frustum	9/27	255[a]	68[b]	28[b]	15[a]	6[b]	2.29±.15
		Sample Heights = 60 cm (East, West) and 100-120 cm (East, Center, West)					
Square	9/27	164[c]	92[ab]	61[a]	34[bc]	22[ab]	1.79±.12
Square	9/27	133[c]	71[ab]	59[a]	42[ab]	33[a]	2.43±.11
Square-High CO_2	9/27	226[b]	104[a]	47[ab]	54[a]	25[ab]	2.11±.13
Round	9/27	158[a]	113[a]	76[a]	27[bc]	18[bc]	2.51±.16
Round-FR*	9/27	171[c]	84[ab]	55[a]	37[ab]	22[ab]	2.35±.10
Round-Frustum	9/27	275[a]	51[b]	19[b]	16[a]	6[b]	2.50±.14

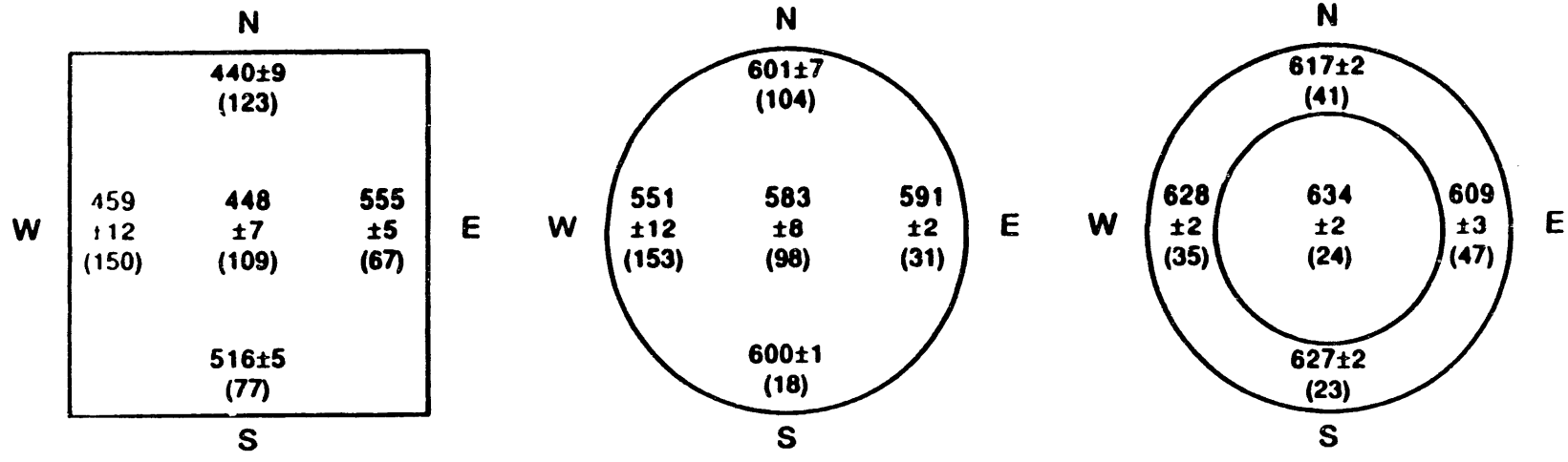
*FR = Frustum panel removed for measurements.

FIGURE LEGENDS

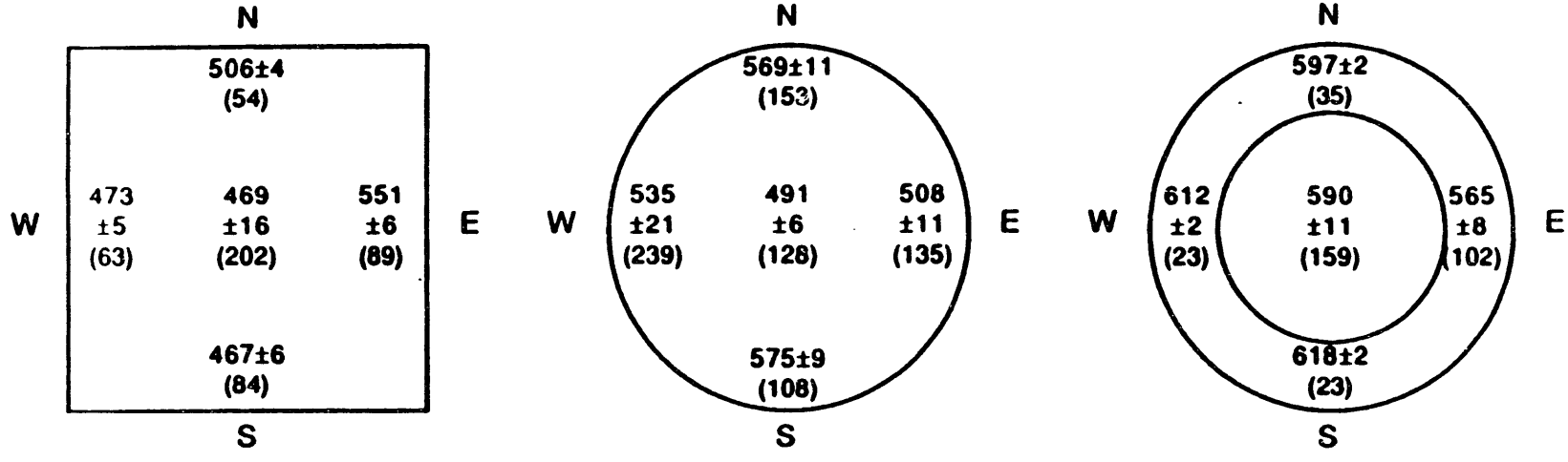
Figure 9-1. Horizontal variation in carbon dioxide levels (μmol mol^{-1}) in three different open-top chambers at heights of 60 and 120 cm (60 and 100 cm in the square chamber). Values represent the means ± S.E. (range in parentheses) of 16-19 readings taken every 12 s over two 2-min periods 12 min apart. The chambers contained a mostly-defoliated cotton crop, and were oriented such that the door faced east and the air duct entry faced west. Wind was out of the E to SE. Wind speeds (mean ± S.E.) during the sampling at 100-120 cm were 1.16±.09 (square), 1.23±.09 (round without frustum) and 1.32±.13 (round with frustum) m s^{-1}. Wind speeds during the sampling at 60 cm were 1.17±.07 (square), 2.53±.13 (round without frustum) and 2.29±.15 (round with frustum) m s^{-1}.

Figure 9-2. Variation in the east-west plane of carbon dioxide levels (μmol mol^{-1}) in three different open-top chambers. Values were taken at heights of 60 and 120 cm (60 and 100 cm in the square chamber). Wind was out of the E to SE. Wind speeds during sampling were 2.43±.11 (square), 2.51±.16 (round without frustum), 2.50±.14 (round with frustum) and 2.35±.10 (round with frustum removed) m s^{-1}. Other details are given in Figure 9-1.

(a) 100-120 cm



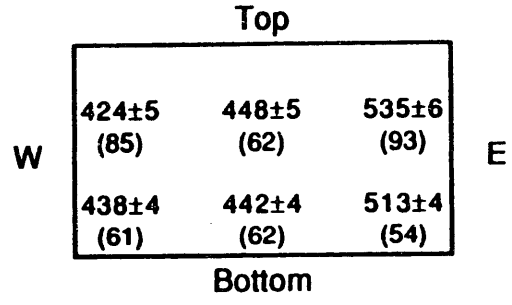
(b) 60 cm



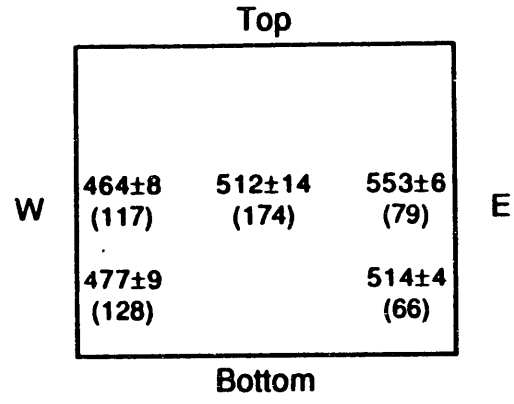
Square

Round — Without Frustum

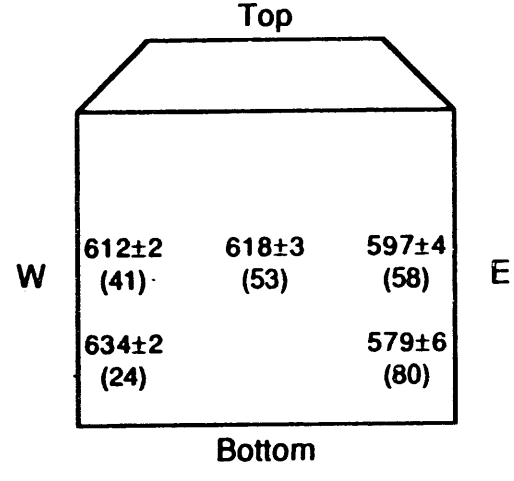
Round — With Frustum



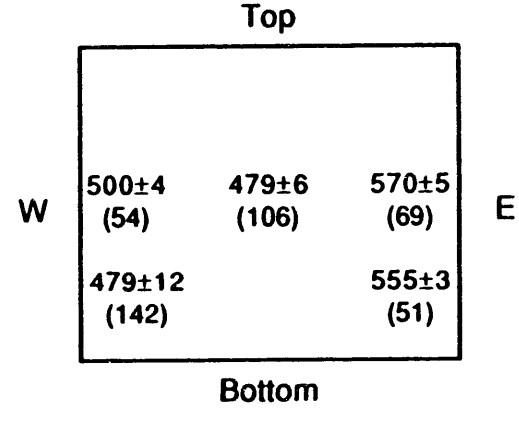
Square



Round — Without Frustum



Round — With Frustum



Round — Frustum Removed

SECTION II: BIOLOGICAL RESPONSES

RESPONSES OF COTTON FOLIAGE TO SHORT-TERM FLUCTUATIONS IN CO_2 PARTIAL PRESSURES

Lance S. Evans
Laboratory Plant Morphogenesis
Manhattan College
Bronx, NY 10471

George R. Hendrey
Department of Applied Science
Brookhaven National Laboratory
Upton, NY 11973

I. INTRODUCTION

Global atmospheric carbon dioxide partial pressures are increasing, with a projected doubling during the 21st century. Determination of the effects of elevated levels of CO_2 partial pressures on vegetation in both agricultural fields and natural ecosystems is the topic of a major research effort which is now underway (Dahlman 1985 and Chapter 1). One goal of this effort is to predict plant growth under elevated levels of CO_2 as well as natural conditions of temperature, rainfall, humidity, etc. Due to the cost of CO_2 and difficulty in controlling CO_2 partial pressures in free-air carbon dioxide experiments, little research has been conducted under natural conditions.

A major objective of the DOE carbon dioxide research program is the prediction of biological effects of increasing atmospheric CO_2 to aid in the understanding of changing future climates. Models are desired that account for effects of environmental factors (i.e., climate, soil) and variable CO_2 on plant physiology and growth, which can be applied to different cropping and ecological systems. Reliability of such models can be evaluated best by comparison of model predictions with experimental data measured from plants grown under representative natural conditions.

The Vertical Vent Pipe (VVP) System to distribute CO_2 in an open field that is the subject of this book has been developed and tested for several years. This facility produces CO_2 partial pressures that are usually within 10% of set values more than 90% of the exposure time (one min. averages). However, there are occasions in which the CO_2 partial pressures for short periods (less than 20 s) may be considerably higher than the desired partial pressures. At present there are few data relating plant responses to short-term fluctuations in CO_2 partial pressures. The experiments reported herein were performed to determine CO_2 uptake and retention following:

(1) a rapid, sustained increase in CO_2 partial pressure (CO_2 pulse experiments).

(2) a decrease in CO_2 partial pressure after this rapid, sustained increase in CO_2 partial pressure (CO_2 pulse-chase experiments).

(3) oscillations in CO_2 partial pressure over a two-hour period in which the oscillations in CO_2 varied with cycle durations of one, two, five, and ten min (CO_2 oscillation experiment).

Pulse experiments provide information about the rate of CO_2 fixation during a step elevation in CO_2 partial pressures. Pulse-chase experiments indicate the rate as which radiolabeled CO_2 in leaves may be metabolized after such CO_2 pulses. These two types of experiments are necessary to interpret results of oscillation experiments in which the effects of variable and constant CO_2 partial pressures carbon uptake are determined. These studies should provide insight to the degree to which plants respond to short-time fluctuations in external CO_2 partial pressures.

II. MATERIALS AND METHODS

A. Plant material

Seeds of cotton (*Gossypium hirsutum* L.) cv. Delta Pine 77 were germinated and grown in a greenhouse potting soil composed of Promix®. Plants were grown under greenhouse conditions. Supplemental lighting was used to extend the photoperiod in the autumn to 16 hours of light. All plants were kept in the greenhouse until 24 hours before experimentation in which plants were transferred to the growth chamber. In all cases, the youngest most fully expanded leaf of leaves 5 through 8 was used for experimentation.

B. Growth chamber conditions

The interior of the plant Growth Chamber (Environmental Growth Chamber, Chagrin Falls, OH) measured 4.6 m by 3.1 m. Light was controlled by a Tipptronic Control Console. Lights were activated from 0700 to 2400 hr daily. Air temperature in the chamber was controlled at 32 ± 1°C. Fans moved air through the chamber so the calculated air exchange air rate was once each 1.5 min.

C. Field growth conditions

In addition, cotton seeds were also planted in one meter rows in an agricultural field at Brookhaven National Laboratory, Upton, NY on May 30, 1989. Standard fertilizer and cultural practices were followed so that plant growth was rapid. As in the growth chamber experiments, the youngest most fully expanded leaf of leaves 5 through 8 only were used in experimentation.

D. Leaf chamber design

The leaf chambers used in these experiments were constructed by the Aquebogue Machine Shop, Aquebogue, NY. The basic design of the chamber was similar to that

described by Naylor and Teare (1975). It is a symmetrical, two piece, plexiglass, clamp-on leaf cuvette. Notable differences in the design of the leaf chamber are that upper and lower Plexiglas portions held depressions of 10 mm to make a leaf chamber depth of 20 mm without consideration for depth from the rubber pads. Closed-cell neoprene pads specifically designed for the Parkinson Leaf Chamber (P.K. Morgan Col, Inc., Andover, MA) were used to make a gas-tight seal fore leaves during the fumigation process. With pads in place the effective height of the leaf chamber was 25 mm. The area of leaf within the chamber was 625 mm and volume of the leaf chamber was 15.6 cm^3. Within both the top and bottom portions of the leaf chamber the gas intake orifice was 6.25 mm i.d. Intake air was channeled through three, 3.1 mm-diameter holes in the Plexiglas so that the intake air reached all areas of the chamber uniformly. Similar channels were made for exhaust gas to reach a 6.25 mm inside diameter exit port.

E. CO_2 administration systems

1. Specifications of Gases

The carbon dioxide used to enrich the growth chamber environment was industrial grade "bone dry" CO_2 metered into the chamber environment near the air intake fan. All other nonradioactive research gases were custom mixtures of CO_2 in air (Scott Research Laboratories, Inc., South Plainfield, NJ) in which the CO_2 was stated by the supplier to be within 5 μmol mol^{-1} of the desired partial pressure. This was verified by analysis using a Binos (Leybold-Heraens Co., Hanau, FRG) CO_2 analyzer. To standardize the CO_2 analyzer, custom CO_2 gases at partial pressures of 350, 700, 1050 μmol mol^{-1} (all three gases were prepared and analyzed according to EPA protocol specifications for standard reference material (SRM) traceable to NPS standards; MG Industries, Langhorn, PA) were used. Checks with these gases were made weekly.

The radioactive gas mixtures were synthesized using $^{14}CO_2$ (New England Nuclear Division of Dupont Chemical Company) for each of the two mixtures used, 25 mCi of 58 mCi Mol^{-1} CO_2 was added to an evacuated cylinder. Thereafter, a nonradioactive gas mixture from Scott Research Laboratories at 700 μmol mol^{-1} was added. The partial pressure and level of radioactivity were determined before experimentation began. The CO_2 partial pressure of the growth chamber environment and in the CO_2 administration systems were monitored constantly with the Binos analyzer.

2. Constant CO_2 Partial Exposure System

The CO_2 administration system for the constant CO_2 partial pressure exposure was similar to that of Naylor and Teare (1975). The most notable difference between the system used herein and that of Nylor and Teare (1975) was the administration of an ambient partial pressure (≈360 μmol mol^{-1}) or CO_2 enriched (≈700 μmol mol^{-1}) gas for a two-hour period before administration of the radiolabeled gas. In addition, a high-precision brass needle valve (Model 4170 Series, Matheson, East Rutherford, NJ) was present between the gas regulator and the flowmeter (Manostat Cat. #9144). A humidifier (in which gas was bubbled through distilled water) insured that the relative humidity was about 79%.

A flowmeter (Flow tube #FT23A00, #52-315-1-1, Scott Research Lab., Inc., South Plainfield, NJ) as present on the $^{14}CO_2$ supply line, before the one-way check valve. The check valve (400 V, Matheson, East Rutherford, NJ) insured that the $^{14}CO_2$ would not be altered due to the overpressure from the $^{12}CO_2$ chamber were monitored three times during each exposure. A relative humidity and temperature sensor (Rotronic Hygroshop GT, Model GTL; Zurich, Switzerland) was used for these measurements. The hygrometer was calibrated against standard salt solutions.

3. Short-Term Pulse and Pulse-Chase Experiments

For short-term pulse and pulse-chase experiments, plants were exposed to either ambient (360 μmol mol^{-1}) or CO_2 enriched (700 μmol mol^{-1}) preconditioning environments in the growth chamber for at least 24 hours prior to radiolabeling. Leaf chamber flow rates of the nonradioactive gas averaged 1,040 m min^{-1}, about 8 times the velocity used by Naylor and Teare (1975). This provided an average air flow velocity of 167 cm min^{-1} through the leaf chamber. For these studies the nonradioactive gas consisted of 3,000 μmol mol^{-1} $^{12}CO_2$ in air. The radioactive gas consisted of 10μmol mol^{-1} $^{14}CO_2$ in 20% O_2 and 80% N_2. To make overall partial pressures of 450, 750, 1,150, and 1,800 μmol mol^{-1} CO_2 the flow rates of the two gases above were varied.

For pulse-chase experiments, plants were exposed to preconditioning environments of either ambient CO_2 or CO_2 enrichment at 700 μmol mol^{-1} followed by pulses of radioactivity labeled CO_2 as for the pulse experiments. Leaves were then allowed to return to the preconditioning environment. Leaves were sampled at various time periods after returning to the preconditioning environment.

4. Variable CO_2 Partial Pressure System

The CO_2 administration system for variable CO_2 partial pressure exposures has some similarities to the constant CO_2 partial pressure exposure system. In this system, the CO_2 partial pressures were varied from ambient levels (360 μmol mol^{-1}) to 1090 μmol mol^{-1}. The major difference in the gas streams was the presence of a three-way valve (Valve #VSD17670, 1/32 to 3/32 orifice size, 10 watts, Skinner Electric Valve, New Britain, CT) that switched between two gas sources. This valve was activated by an automatic timer (GRALAB 625, GRALAB Instrument Division, Dimco-Gray Company, Centerville, OH). Gas pressure on the off side was released through an air-bubbling water bath so that the pressures in the two gas flow systems did not change during the exposure period.

5. Variable vs Constant Partial Pressures System Experiments

Experiments were designed to determine the effects of variable and constant CO_2 partial pressures on plant uptake of CO_2. Two identical leaf chambers were used: one for a constant CO_2 treatment at 700 μmol mol^{-1}, and the other for a cycling CO_2 treatment. These experiments began with a 2-hour treatment prior to introduction of $^{14}CO_2$. The cycling treatment provided changes from 360 to 1,090 μmol mol^{-1}. The cycle duration for the two hour exposure period was varied from 1, 2, 5, and 10 min exposures in which the durations of exposure to 360 and 1,090 μmol mol^{-1} were adjusted to provide a CO_2 dose that was equal to the 700 μmol mol^{-1} dose provided by the constant gas flow system. During the last cycle (after the

two hour exposure period), both systems were exposed to 13 ml m^{-1} of $^{14}CO_2$. A $^{12}CO_2$ flow rate of 1.04 ℓ min^{-1} was maintained throughout these experiments.

6. Evaluation of Radioactivity in Tissues

Leaf tissues exposed to radiolabeled $^{14}CO_2$ were dipped in liquid N_2 within 3 s of treatment termination. Immediately thereafter, six leaf punches, each 6 mm in diameter from the exposed area were placed in protocol (New England Nuclear Research Products, Boston, MA) and agitated overnight to enhance tissue digestion. Liquid scintillation fluid (Aquasol, New England Nuclear Research Products, Boston, MA) was added and samples were counted for five min repeatedly in a Beckman Liquid Scintillation LS 3150T (Beckman Instruments, Irvine, CA) counter until stable counts were obtained. Quench Corrections were made with the use of ^{14}C quench standards.

7. Statistical Procedures

For comparisons between constant and variable CO_2 gas flow systems, slight differences in the operation of the two flowmeters of the non-radioactive gases as well as the two leaf chambers were compensated for by systematically rotating the sequence of flowmeters and leaf chambers to obtain the four possible combinations in replicate treatments. Since there may have been minor differences in the two flowmeters of the radioactive gas, the two gas lines were systematically alternated from one system to the other after each set of four combinations described above. For each of the time periods tested (cycle durations of 1, 2, 5, and 10 min) a total of 16 replicates were performed. Three series of experiments with 16 replicates were performed. For pulse and pulse-chase experiments at least ten replicates were made.

Statistical analyses were run on data from pulse and pulse-chase experiments to determine lines of best fit and to provide standard deviations about means. For data from the constant versus variable dose experiments, ratios of DPM's of variable/constant were converted to log transformed values for ANOVA analyses to estimate errors and establish statistical probabilities that the ratios are different from 1.00.

III. RESULTS

A. Characteristics and performance

1. Vertical Light Intensity Characteristics

Light intensities varied little during the experimental period within the growth chamber since fixtures were maintained weekly as necessary. The light intensities at the light bank level at the top of leaf chamber, in leaf chamber, and through the leaf chamber without a leaf present, were 1,000, 850 and 685, μE m^{-2} s^{-1}. Light intensity in the leaf chamber was relatively low compared with full sunlight and is comparable with light intensities of cotton leaves in the shade below the top of the canopy.

2. Relative Humidity and Gas Temperature Characteristics

Relative humidity and gas temperatures were monitored three times during each 2 h preconditioning period. Each monitoring period lasted 5 min for each leaf chamber. Relative humidity, with the distilled water humidifier in place, was controlled at 79 ± 2% during all runs. Gas temperature averaged 30.1 ± 1.1 C.

3. Variability in Gas Flow Rates

Gas flow rates were set during the first ten min of each 2 h preconditioning period. They were checked three times during each run and were within 5% of desired flow rates at all times. If necessary, adjustments were made to provide exact flow rates just prior to $^{14}CO_2$ exposures.

4. Rate of Change of CO_2 Partial Pressure Experiment

Rate of change of CO_2 partial pressure in the variable gas flow system was rapid. When the input gas was changed from 360 to 1,090 μmol mol^{-1} or vise versa it took an average of 3, 4, and 5 s to reach 50, 75, and 95% of the ending CO_2 concentration.

B. Response of leaves to short pulses of CO_2

The responses of plant leaves to pulses of $^{14}CO_2$ were determined on plants preconditioned to ambient (≈700 μmol mol^{-1} CO_2 environments. Figure 10-1 shows the response to $^{14}CO_2$ pulse treatments following a 24 hour preconditioning environment of ambient CO_2 partial pressures. Pulse treatments of 450 and 750 μmol mol^{-1} CO_2 had little effect at pulse durations of 5 to 15 s, but plant uptake of CO_2 to the 1,150 μmol mol^{-1} treatment began to increase after 15 s exposure. Plants exposed to 1800 μmol mol^{-1} CO_2, however, had an 8-fold increase in carbon uptake compared to the less extreme treatments, even at the shortest pulse periods.

The responses of cotton foliage to $^{14}CO_2$ pulses after exposure to a CO_2 enriched environment are shown in Figure 10-2. Uptake apparently declined with the 450 μmol mol^{-1} pulse treatment compared to the other treatments. For the 750 and 1,150 μmol mol^{-1} pulse treatments, uptake values increased slightly with increased pulse length. Although uptake was greater for the 1,800 μmol mol^{-1} treatment at all pulse durations, the greatest increase in uptake for this treatment occurred from 30 to 60 s.

Similar labeling experiments using the same leaf chambers were conducted with field-grown plants at Brookhaven National Laboratory in July of 1989. These plants were about one-half meter in height and had not closed their rows yet which provided full sunlight to leaves exposed to radioactive CO_2. CO_2 uptake in field-grown plants was similar to that of plants grown in the growth chamber (Figure 10-3).

C. Retention of radiolabel after exposure to $^{14}CO_2$

Pulse-chase experiments were performed to the degree to which cotton foliage retained or respired incorporated $^{14}CO_2$. For these experiments plants were

preconditioned at ambient CO_2 partial pressures then exposed to $^{14}CO_2$ for pulse periods of 1 or 5 min at 450, 750, 1,150, or 1,800 μmol mol^{-1} CO_2 partial pressures. Plant tissues were sampled after chase periods of up to 15 min after $^{14}CO_2$ exposure. After a 5 min exposure treatment to $^{14}CO_2$, the amount of ^{14}C retained did not change significantly over the 0 to 15 min chase period (Figure 10-4).

D. Variable vs constant CO_2 partial pressure experiments

Oscillation experiments were performed to determine if rates of $^{14}CO_2$ uptake differed between plants exposed constant CO_2 and variable CO_2 partial pressures. Analysis of variance of the log transformed (Sokal and Rohlf, 1981) data show foliage exposed to the variable treatments had 6, 13, 18, and 27% more carbon uptake for cycle durations of 1, 2, 5, and 10 min, respectively. Compared with foliage of plants exposed to constant CO_2 partial pressures (Table 10-1). For leaves exposed to oscillation durations of 2, 5, and 10 min, the percent difference values were significantly different from 1. In all cases, except at one minute, the differences between variable and constant were significant at $p < 0.02$. Regression analyses of percentage increase of variable versus constant and cycle duration demonstrated a significant ($p = 0.038$) relationship of $y = 7.95 + 1.92(x)$ (Figure 10-5).

IV. DISCUSSION

Response to CO_2 pulses were related to both the extent of the change and the duration of CO_2 enrichment. For plants preconditioned to 360 μmol mol^{-1} CO_2 the response to 450 to 750 μmol mol^{-1} did not differ until the pulse length was 60 s. However, a 30 s pulse at 1,150 μmol mol^{-1} caused a significant increase in carbon uptake. The 1,150 μmol mol^{-1} pulse is a factor of 3 greater then the ambient CO_2 partial pressure to which plants were preconditioned.

In the short-term pulse experiment, CO_2 incorporation rates were similar over pulse periods of zero to 15 s at 700 μmol mol^{-1} CO_2 partial pressure. A markedly higher CO_2 incorporation rate occurred when the external CO_2 partial pressure was 1,800 μmol mol^{-1}. This pattern of response occurred with plants exposed in growth chamber and field conditions.

Plants conditioned to 700 μmol mol^{-1} CO_2 had higher carbon uptake rates than did plants conditioned to 360 μmol mol^{-1} CO_2. However, plants at the higher partial pressure responded less to the various pulse treatments. Plants conditioned at 360 μmol mol^{-1} CO_2 experienced greater incremental increases in CO_2 partial pressures during pulses compared with plants exposed to 700 μmol mol^{-1}.

The present studies did not address the physiological or biochemical mechanisms by which cotton foliage respond to the changes in external CO_2 partial pressures. Previous research has shown that during short-term (minute) exposures to elevated partial pressures of CO_2, the rate of light-saturated CO_2 assimilation in C_3 plants is primarily limited by the capacity to regenerate inorganic phosphate from phosphorylated photosynthetic products (Sharkey, 1985; Sivak and Walder 1987; Sage and Sharkey, 1987; Lebate and Leegood, 1988). An inorganic phosphate regeneration limitation of photosynthesis is characterized by a lack of sensitivity of net CO_2 fixation rate to changes in ambient partial pressure CO_2. However, at subsaturating light intensities, the limiting step seems to be

the rate of RuBP regeneration (von Caemmerer and Farquhar, 1981; Sharkey, 1985; Sage, 1990). Short-term exposure to elevated CO_2 causes the activation state of Rubisco to decline regardless of whether RuBP regeneration or the availability of inorganic phosphate are limiting photosynthesis. Lower Rubisco activation sates reduce CO_2 fixation rates which, in turn, reduce rates of electron transport and triose phosphate production and utilization. We speculate that plants exposed to the constant treatment of 700 μmol mol^{-1} CO_2 may have photosynthetic rates limited by Rubisco activity. In contrast, plants exposed in the variable CO_2 regimen may have photosynthesis limited by Rubisco activity when at 360 μmol mol^{-1} but they are RuBP or inorganic phosphate limited at 1,090 μmol mol^{-1} CO_2 partial pressures. The alteration in limitations may result in greater overall photosynthetic rates as shown in the oscillation experiments.

The experiments performed herein were designed to determine CO_2 incorporation responses to fluctuating CO_2 partial pressures (Figure 10-6). Although the ambient CO_2 is thought to be relatively constant, wide fluctuations occur. Most notably there are marked diurnal fluctuations in which the CO_2 partial pressures can reach 1,200 μmol mol^{-1} during calm nights (Reicosky, pers. comm.). However, recent data obtained during the daytime at canopy level in a cotton field in Maricopa shows that ambient CO_2 partial pressures may vary by as much as 100 μmol mol^{-1} over relatively short time periods (Alexander, personal communication).

The BNL FACE experimental system also shows some large, rapid fluctuations in CO_2 partial pressures. However, a very small fraction of these oscillations are both longer than 1 min and exceed 20% of the intended experimental treatment value (550 μmol mol^{-1}). Changes in CO_2 partial pressures of 200 to 300 μmol mol^{-1} over a period of 5 to 20 s are not uncommon but fluctuations of 300 μmol mol^{-1} for periods greater than 30 s are quite rare. Daytime CO_2 distribution spectra observed within the FACE array are quite similar to that observed in ambient settings (Alexander, personal communication). It should be cautioned that these fluctuations in both ambient and FACE CO_2 partial pressures are recorded values in which long sampling lines may tend to average or dampen wider fluctuations. If these values are representative of instantaneous CO_2 partial pressure profiles then the results of the present study suggest that fluctuations of not more than 30 s to 1 min are of little consequence to overall CO_2 assimilation rates.

The results of the experiments performed herein show that foliage of cotton does not alter assimilation rate significantly when external CO_2 partial pressures change by as much as a factor of 3 for 30 s. In general, there was little evidence of significant changes in carbon uptake when cotton plants were exposed to pulses of CO_2 that were two times higher than preconditioning CO_2 partial pressures. This observation is reinforced by comparisons of CO_2 uptake under oscillating versus constant CO_2 partial pressure conditions. Taken together these results suggest that photosynthesis is not sensitive to fluctuations in CO_2 partial pressure that occur in the ambient environment or in the FACE plots. We speculate that a regularly oscillating CO_2 partial pressure regimen for oscillation periods longer than one minute can increase carbon uptake by providing an alternation between RuBP and Rubisco limitations.

REFERENCES

1. Dahlman RC (1985) Modeling needs for predicting responses to CO_2 enrichment: plants, communities, and ecosystems. Ecol. Modeling 29: 77-116.

2. Labate CA, Leegood RC (1988) Limitation of photosynthesis by changes in temperature. Fractions affecting the response of carbon dioxide assimilation to temperature in barley leaves. Planta 173: 519-527.

3. Naylor DG, Teare ID (1975) An improved, rapid field method to measure photosynthesis with $^{14}CO_2$. Agron, J. 67: 404-406.

4. Raschke K (1972) Saturation kinetics of the velocity of stomatal closing in response to CO_2. Plant Physiol. 49: 229-234.

5. Sage RF (1990) A model describing the regulation of ribulose-1, s-bisphosphate carboxylase, electron transport, and triose phosphate use in response to light intensity and CO_2 in C_3 plants. Plant Physiol. 94: 1728-1734.

6. Sage RF, Sharkey TD (1987) The effect of temperature on the occurrence of O_2 CO_2 insensitive photosynthesis in field-grown plants.
Plant physiol. 84: 658-664.

7. Sharkey TD (1985) Photosynthesis in intact leaves of C_3 plants. Physics, Physiology and rate limitations. Bot. Rev. 51: 53-105.

8. Sivak MN, Walker DA (1987) Oscillations and other symptoms of limitation of <u>in vivo</u> photosynthesis by inadequate phosphate supply to chloroplasts. Plant Physiol. Biochem. 25: 636-648.

9. Von Caemmerer S, Farquhar GD (1981) Some relationships between the biochemistry of photosynthesis and the gas exchange of leaves. Planta 153: 376-387.

10. Sokal RR, Rohlf RJ (1981) Biometry 2nd Ed. W.H. Freeman, Inc., San Francisco.

Table 10-1

Source of Variation	d.f.	Mean Squares Cycle Duration (min) 1	2	5	10
Chamber	1	0.0027	0.0738	0.0043	0.0008
Treatment	1	0.0012	0.0035	0.0066	0.0000
Chamber X Treatment	1	0.0494	0.0012	0.0123	0.0183
Error	12	0.0920	0.0048	0.0094	0.0267
Correction Term	1				
Total	16				
Log transformed Mean Sum of Squares Ratio Values		0.0255	0.0536	0.0725	0.1025
Ratios Variable/Constant		1.06	1.131	1.182	1.266
Level of Significance		N.S.	99%	99%	98.5%

FIGURE CAPTIONS

Figure 10-1. CO_2 uptake rate of cotton leaves as a function of time at various CO_2 partial pressures. Plants were preconditioned for 24 hours at 360 μmol mol^{-1} CO_2. Circles: 450 μmol mol^{-1}; Diamonds: 750 μmol mol^{-1}; Squares: 1,150 μmol mol^{-1}; Triangles: 1,800 μmol mol^{-1}.

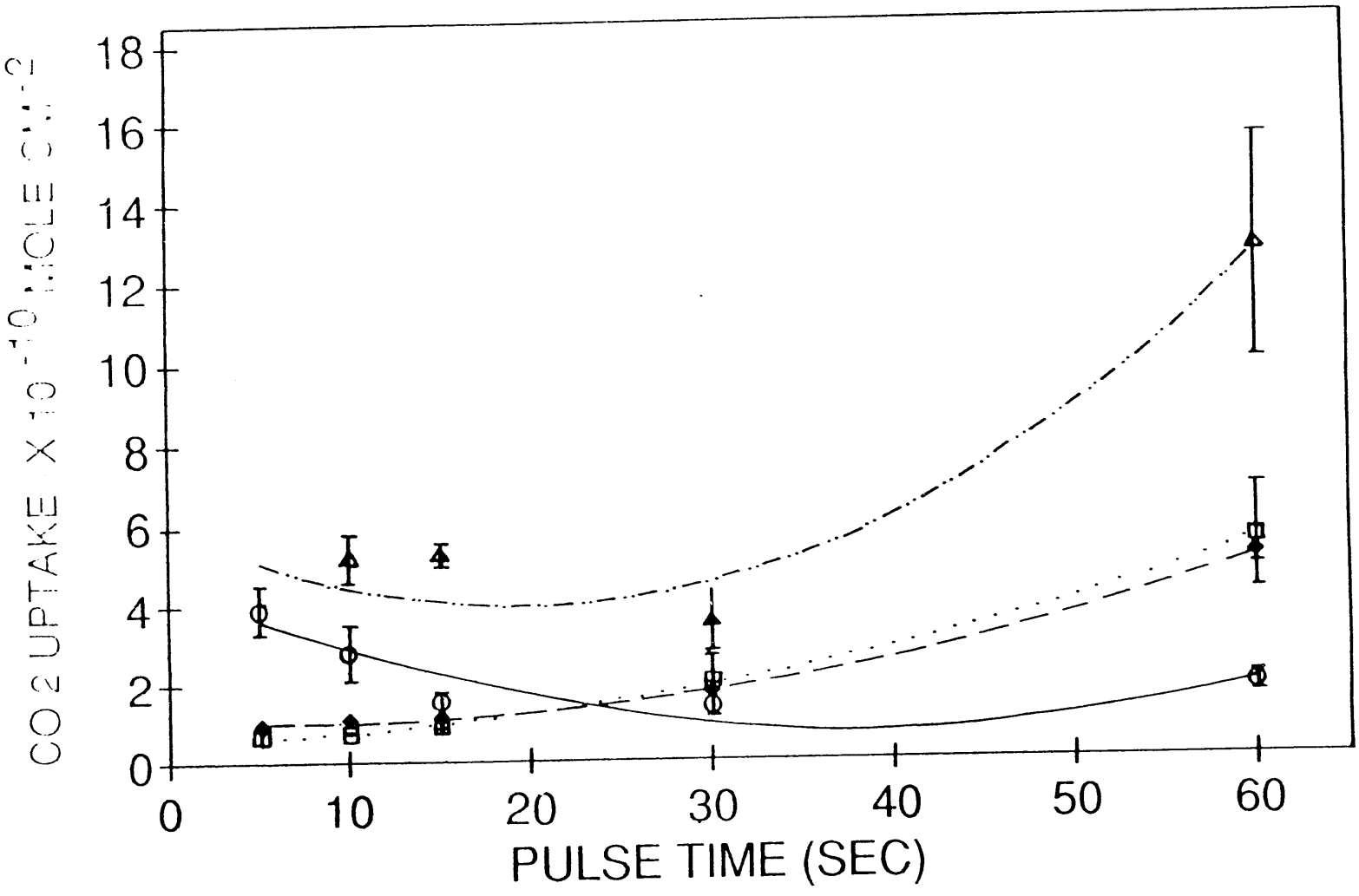
Figure 10-2. CO_2 uptake rate of cotton leaves as a function of time at various CO_2 partial pressures. Plants were preconditioned for 24 hours at 700 μmol mol^{-1} CO_2. Circles: 450 μmol mol^{-1}; Squares; 1,150 μmol mol^{-1}; Triangles: 1,800 μmol mol^{-1}.

Figure 10-3. CO_2 uptake rate of cotton leaves as a function of time at various CO_2 partial pressures. Plants were grown in an agricultural field at ambient CO_2 partial pressures. Circles: 450 μmol mol^{-1}; Diamonds: 750 μmol mol^{-1}; Squares: 1,150 μmol mol^{-1}; Triangles: 1,800 μmol mol^{-1}.

Figure 10-4. Amounts of radioactive CO_2 retained in leaves of cotton plants after a five minute exposure to $^{14}CO_2$. The CO_2 partial pressure was varied from 450 to 1,800 μmol mol^{-1}. Circles: 450 μmol mol^{-1}; Diamonds: 750 μmol mol^{-1}; Squares: 1,150 μmol mol^{-1}; Triangles; 1,800 μmol mol^{-1}.

Figure 10-5. Relationship between percentage increase in $^{14}CO_2$ incorporation of variable versus constant exposure systems as a function of the duration of the variable CO_2 partial pressure. Regression analyses show that the line of best fit $(y=7.95 + 1.92(x))$ is significant $(p=0.038)$.

Figure 10-6 Persistence of CO_2 concentration fluctuations within the FACE array at Maricopa, AZ, 1989. The average concentration deviation is plotted against the length of time involved; regression lines are fit through deviations taken from the same data set. Positive and negative deviations are plotted separately. (Normally in any FACE operation only a single 1-s observation of CO_2 concentration is logged out of each minute. In 1989 at Maricopa we stored all 1-s observations during seven mid-day periods from July-Sept. lasting an hour or longer. All deviations greater than $\pm$ 20% of 550 μmol mol^{-1} observed in these seven periods are represented here.)


CO2 UPTAKE X 10 -10 MOLE CM-2
18
16
14
12
10
8
6
4
2
0
0
10
20
30
40
50
60
PULSE TIME (SEC)

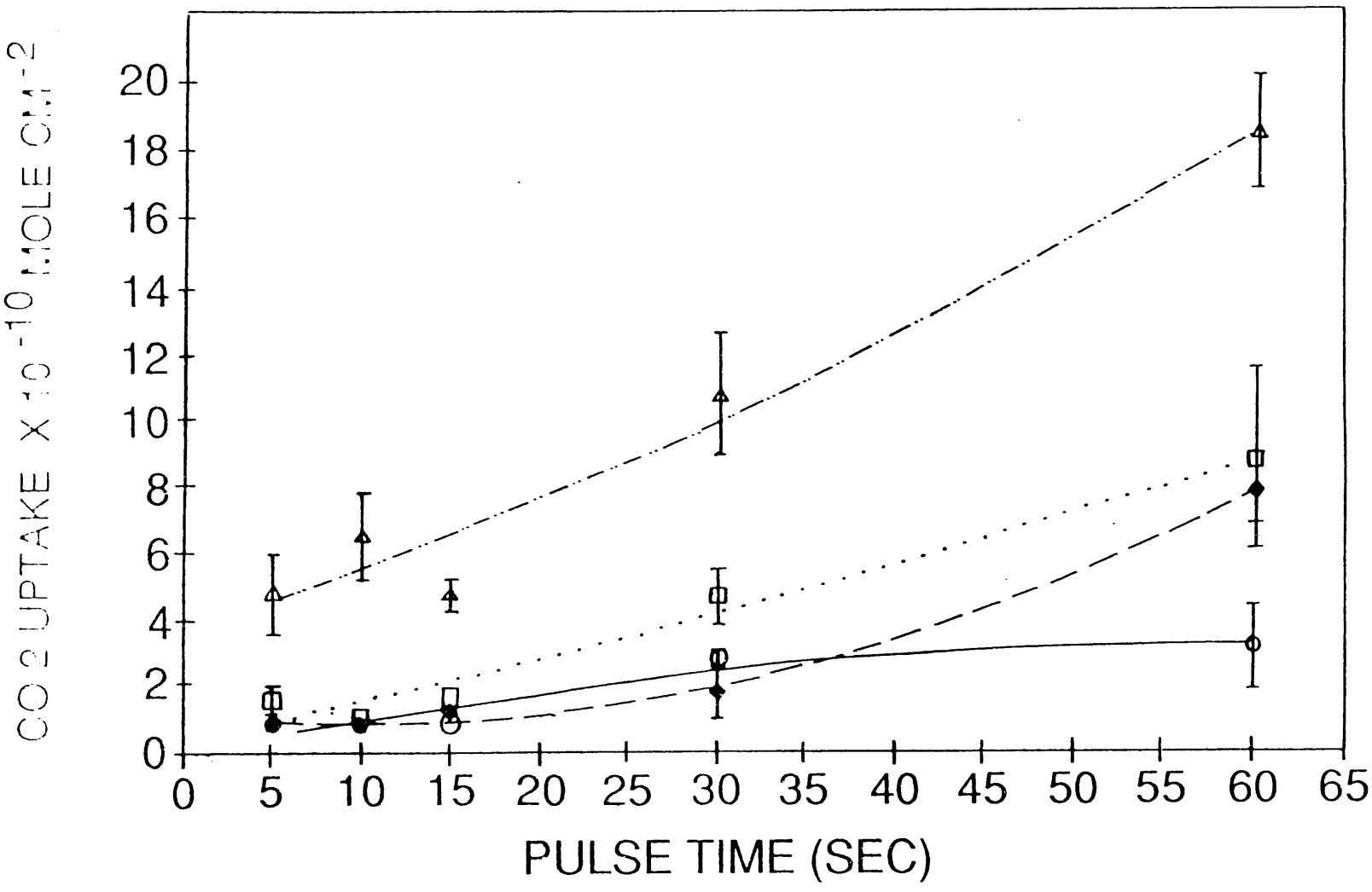
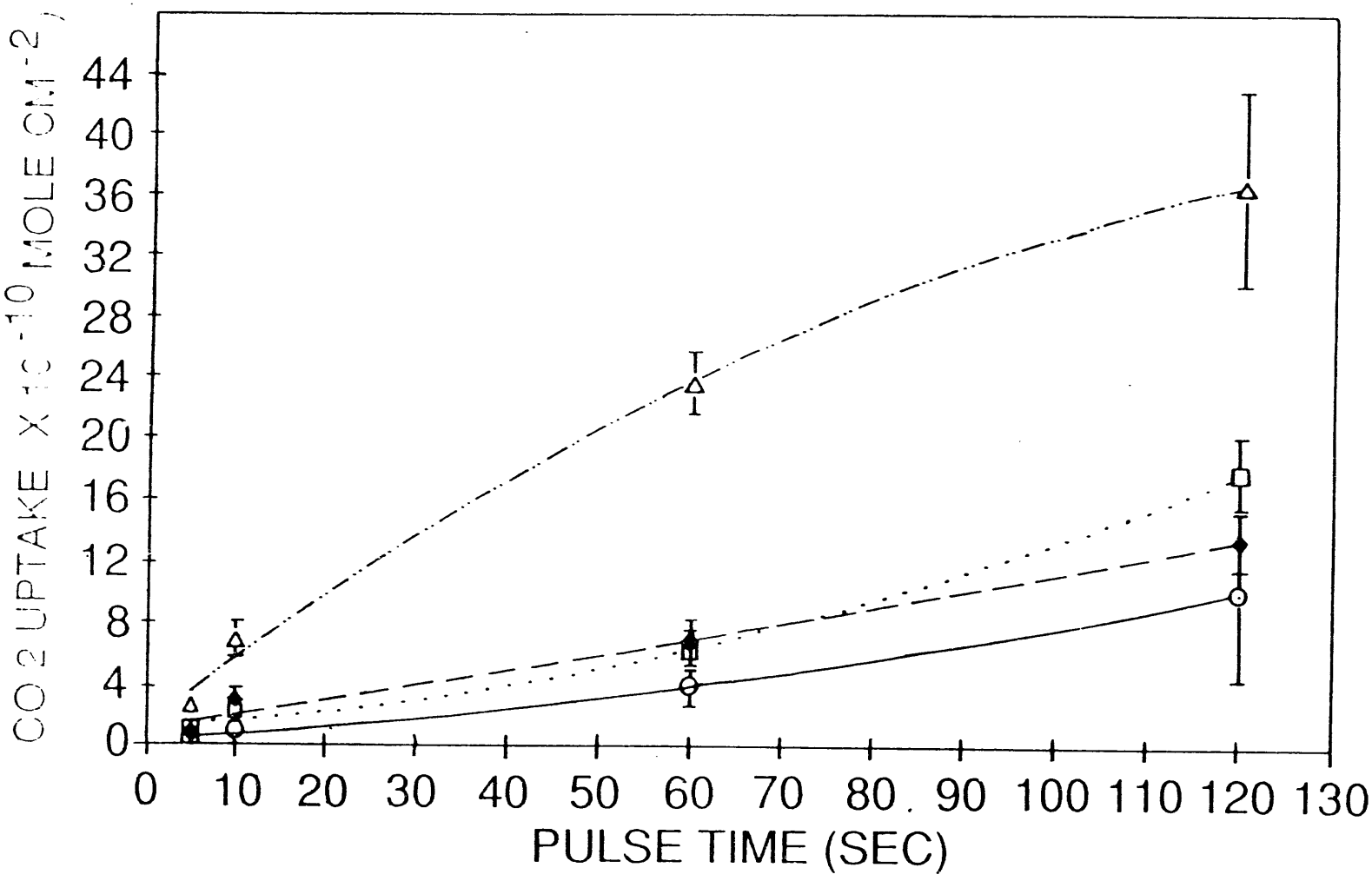
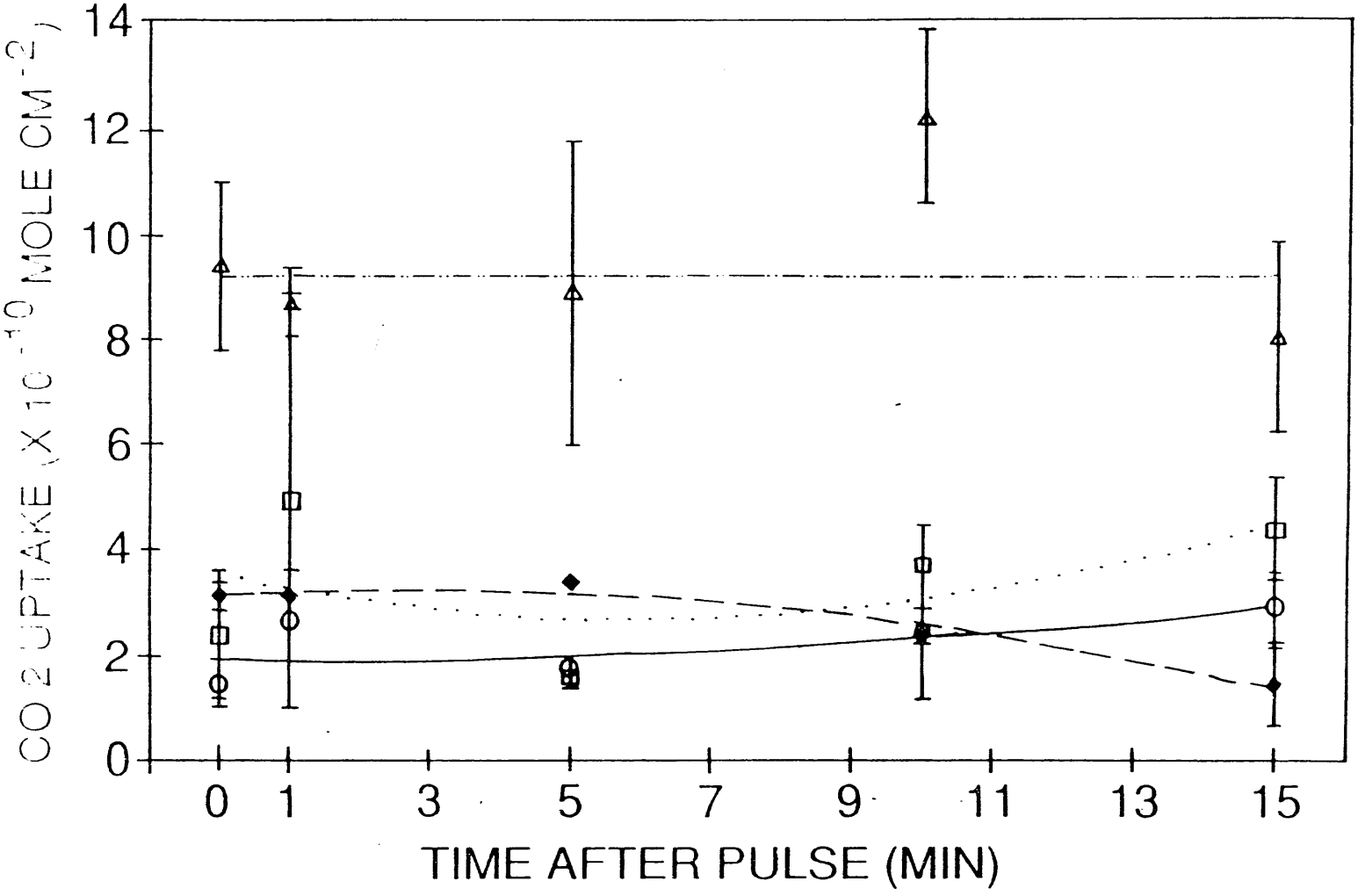
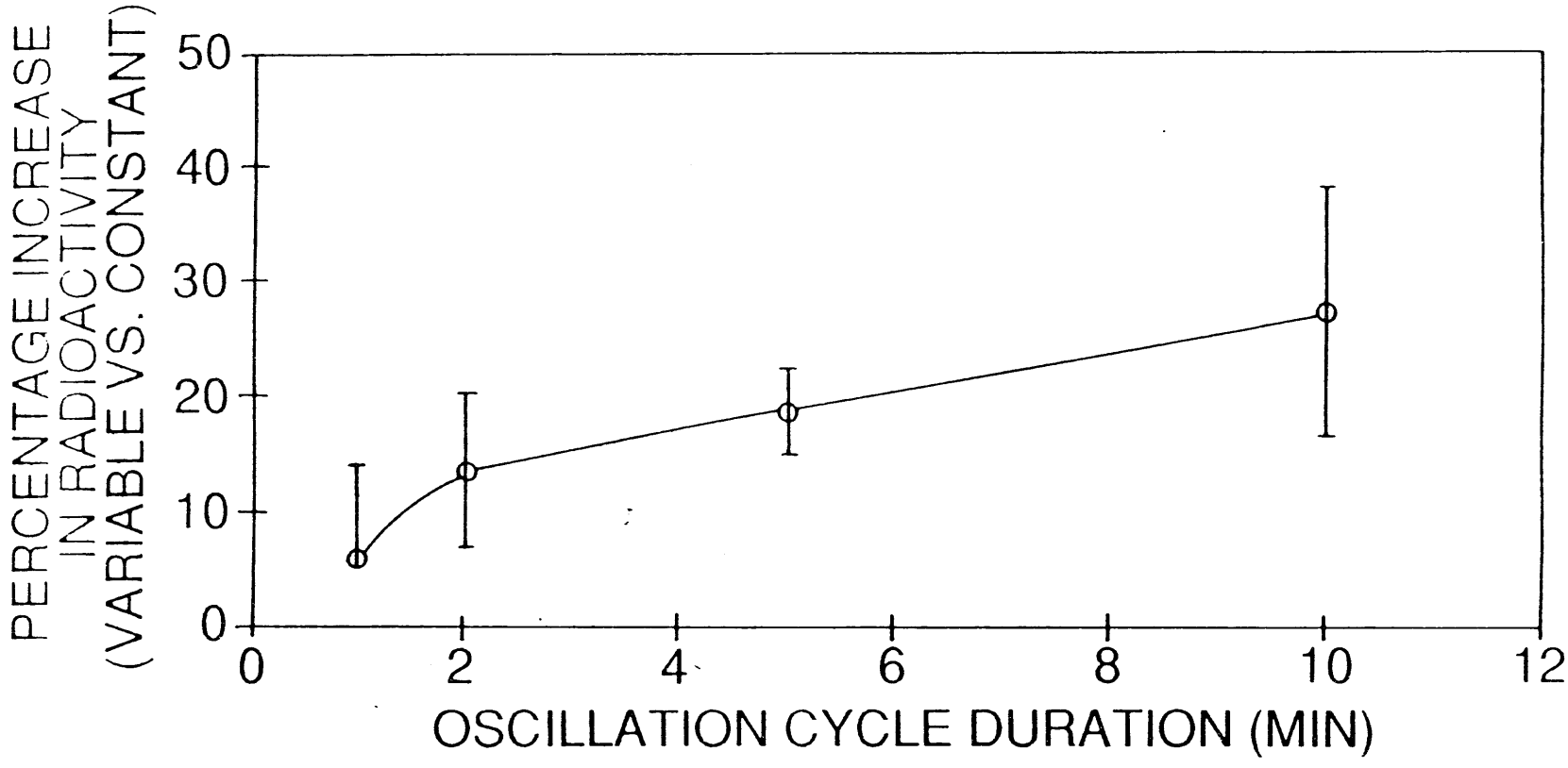
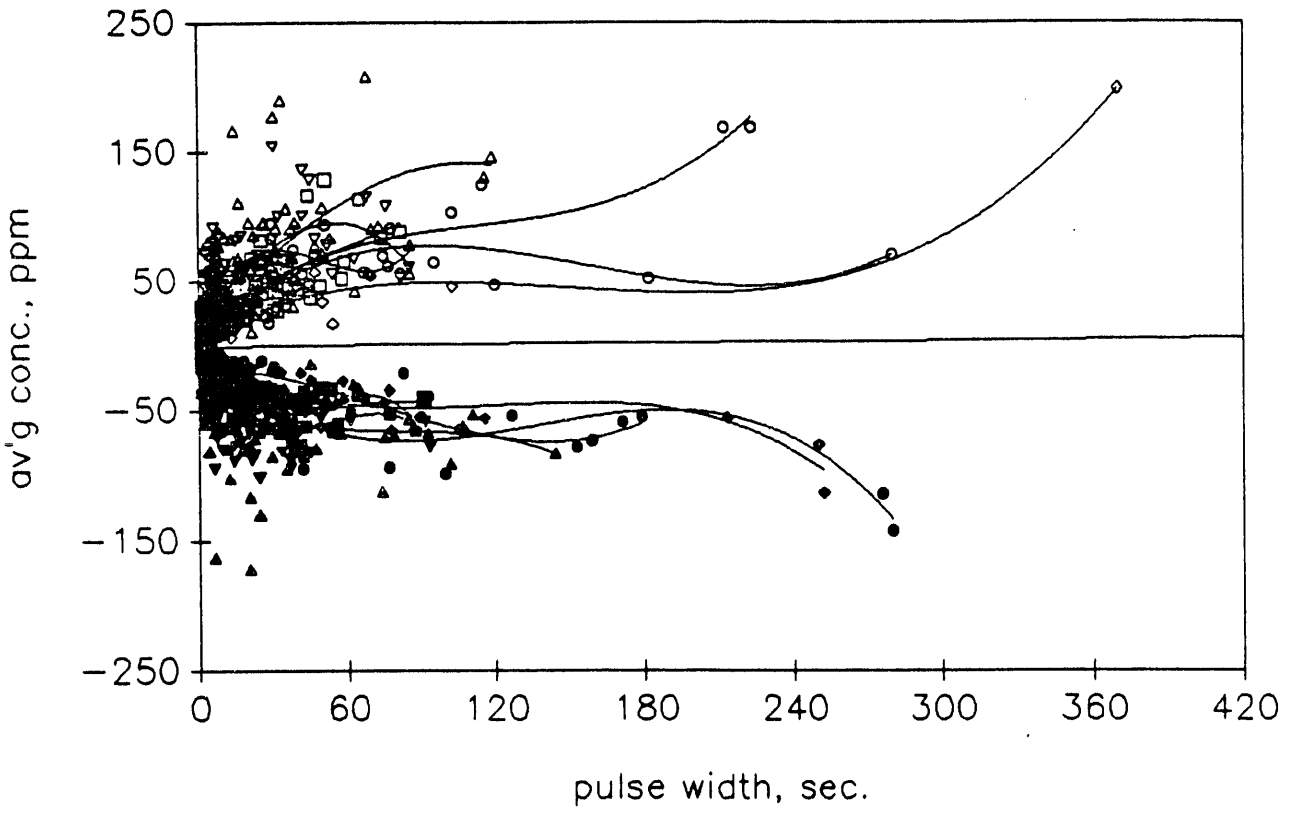

CO2 UPTAKE X 10 -10 MOLE CM-2
20
18
16
14
12
10
8
6
4
2
0
0
5
10
15
20
25
30
35
40
45
50
55
60
65
PULSE TIME (SEC)

Fig 2


CO 2 UPTAKE X 10 -10 MOLE CM-2
44
40
36
32
28
24
20
16
12
8
4
0
0 10 20 30 40 50 60 70 80 90 100 110 120 130
PULSE TIME (SEC)


CO 2 UPTAKE (X 10 -10 MOLE CM -2)
14
12
10
8
6
4
2
0
0 1 3 5 7 9 11 13 15
TIME AFTER PULSE (MIN)


PERCENTAGE INCREASE
IN RADIOACTIVITY
(VARIABLE VS. CONSTANT)
50
40
30
20
10
0
0
2
4
6
8
10
12
OSCILLATION CYCLE DURATION (MIN)


250
150
50
−50
−150
−250
0
60
120
180
240
300
360
420
av'g conc., ppm
pulse width, sec.

GROWTH AND YIELD OF COTTON EXPOSED TO FREE-AIR CO_2 ENRICHMENT (FACE)

Jack R. Mauney
Western Cotton Research Laboratory
4135 E. Broadway
Phoenix, Arizona 85040

Keith F. Lewin and George W. Hendrey
Department of Applied Science
Brookhaven National Laboratory
Upton, New York 11973

Bruce A. Kimball
U. S. Water Conservation Laboratory
4331 E. Broadway
Phoenix, Arizona 85040

I. INTRODUCTION

Most crops respond positively to an increase in CO_2 concentration, based on experiments in glasshouses, growth chambers and open-topped CO_2 enrichment enclosures. For example, Kimball (1983) examined 480 citations and found an average response of 30% increase in yield with doubling of CO_2. Such previous experiments with cotton (*Gossypium hirsutum* L.) have shown it to be one of the most responsive species observed, with yield increases of 60 to 100% when CO_2 is doubled (Mauney *et al.* 1978; Kimball *et al.* 1983).

However, all previous, long time exposures of cotton to elevated CO_2 have been in enclosures of some kind. The driving question was whether such responses would also occur under natural field conditions. The FACE project was initiated, in part, to determine whether such is the case. It is the objective of this chapter to present the growth and yield responses of cotton to free-air CO_2 enrichment in 1989.

II. EXPERIMENTAL PROTOCOL

The magnitude of the response of cotton and other crops to CO_2 enrichment depends heavily on the cultural practices of the experiment. For that reason, a protocol for crop management was developed to guide day-to-day decisions in the field. The protocol called for the use of an adapted cultivar of cotton, irrigations using underground drip tubing, fertility to be monitored by tissue analysis, and use of chemical herbicides, insecticides, and plant growth regulators according to accepted local guidelines for cotton culture.

The FACE plots were enriched for 12 hours, 0600 to 1800, to a level of 550 μmol mol^{-1} CO_2 (see Lewin *et al.* Chapter 5). This CO_2 level and enrichment duration were based on considerations of limiting the expense of CO_2 gas while

providing a sufficiently severe treatment of the crop that statistically meaningful data would be generated. Enrichment to 550 μmol mol^{-1} was chosen because the previous glasshouse and open-topped chamber experiments (Mauney *et al.* 1978; Kimball and Mauney, 1992) suggested that growth would probably increase at least 30% with enrichment to this level. With four replications in a uniform field location, we have found that the crop performance is statistically significant at the 5% level when treatment differences are of the order of 20 percent. Thus the 550 μmol mol^{-1} enrichment was expected to create differences well within an acceptable level of statistical significance.

The consequences of using less than a full-day exposure are more difficult to assess. In creating the GOSSYM model, Baker *et al.* (1983) used a linear function for the crop response to sunlight intensity. Thus, the low angle and low intensity of dawn and dusk lighting indicate that these hours do not play an important role in daily photosynthesis. Cotton does not have a pronounced burst of photosynthetic activity when first illuminated (unpublished personal observation) as do other species (notably soybean). Radin and Ackerson (1981) found stomatal resistance to be high during early morning hours. Hendrix and Huber (1986) found starch concentration in leaves to be minimal at 0600 h. In addition, Hendrix (personal communication, 1991) has found no effect of CO_2 on dark respiration of cotton.

These observations indicate that the early morning hours contribute no more than equivalent photosynthetic activity, when compared to other hours of the day. Measurements of specific leaf weight changes, which are primarily due to changes in starch accumulation, have shown that all time frames up until mid-afternoon are essentially equal in photosynthetic activity (Mauney, 1975). After 1600 h starch accumulation decreases (Mauney, 1975: Hendrix and Huber, 1986) and measurements of carbon dioxide exchange rate have been found variable but decreasing. Thus terminating the enrichment at 1800 h should have little effect on the daily carbohydrate budget of the crop.

III. CROP MANAGEMENT

The FACE 1989 experiment was conducted in a field at the University of Arizona Maricopa Agricultural Center (MAC). Elevation of the site is 358 m. The field had been fallow in the previous crop year. Rows run east-west with a spacing of 1.016 m (40 in.). The soil is classified as a Trix clay loam (see Kimball *et al.*, Appendix II-B). Irrigation water was applied using drip tubes buried 18 cm below the crop rows with emitters spaced at 40 cm intervals.

The crop was planted on April 18, 1989 with cultivar DPL-77 following the plot plan in Figure 11-1. After emergence, the crop within the FACE and control plots was thinned to approximately 10 plants per meter. Planting, thinning, fertilization, insect attacks, and insecticide applications are listed in Table 11-1. Figure 11-2 shows the timing an accumulation of irrigation and rainfall volume compared to the evapotranspiration (ET) as estimated by AZMET (Brown, 1987) and to Erie (1983) estimates of consumptive use by cotton in Arizona. Volume of water delivered to each block of the field was measured by volume gauges on the delivery pipes at the head of each block. Though the irrigation protocol for the experiment called for full replacement of ET by frequent irrigations, these comparisons show that from DOY165 to DOY185 ET withdrawal exceeded irrigation replacement.

Several management decisions had a direct impact on the performance of the crop and may have influenced the responses to CO_2 enrichment.

1) A lack of uniformity of the drip tube placement with relation to the planted seed resulted in poor germination in portions of the experimental plots. This was corrected by hand seeding, and in some cases transplanting of seedlings, into those areas. However, time of emergence varied somewhat due to this delay. Because cotton is an indeterminate long-season crop, this delay probably had minimum impact on final yield.

2) A lack of uniformity of irrigation volume was evident in some portions of the plots during the season. This caused unscheduled water stress to those areas. To correct the deficiency, all the tubes for the experimental areas were replaced. The early stress resulted in greater variability in crop performance than had been expected.

3) A general water stress occurred in mid-June (DOY160 to DOY180). The irrigation system volume was managed to maximize water use efficiency and yield. The fact that the control areas achieved a yield which is 50% greater than the average for the state attests to the accuracy of this strategy for the untreated crop. However, this stress probably had an impact on the productivity of the FACE treatments by contributing to the long cessation of growth after DOY232.

4) Leaves became slightly zinc deficient, which is common in this area. Zinc was applied in the irrigation water to try to prevent the deficiency. After symptoms were evident, foliar nutrient sprays were applied. The Zn deficiency may also have contributed to a cessation of growth.

IV. EXPERIMENTAL DESIGN

Plots were arranged within the experimental field as shown in Figure 11-1. There was over 100 m distance between all replications and between controls and FACE treatments in order to minimize cross contamination from one plot to another (see Lipfert *et al.* Chapter 6). The controls and treatments for each replication were offset for greater diagonal separation.

The area within the FACE and control plots was subdivided into subplots for particular experimental measurements as shown in Figure 11-3. The center circle 12 m in diameter in each array was considered to be the area of greatest uniformity of CO_2 concentration and constituted the sampling area for all crop performance and yield data.

Three types of yield data were obtained: periodic destructive harvests, daily flower tagging and subsequent recapitulation of the boll loading for the season, and final harvest from the "NO TRAFFIC" area (Figure 11-3). The latter was an area within each plot which personnel were restricted from entry except for cultural practices such as thinning, weeding, insecticide and foliar nutrient applications.

In order to reduce the impact of destructive harvests on the canopy, the periodic harvests were made by pulling every third plant out of three separate meter-lengths of row. The weight of major roots which remained attached was taken as the root weight, realizing that the total root biomass was not obtained. The three meters chosen for harvest on a given harvest date were in different rows. For analytical purposes the one-third of three meters sample was considered to constitute 1.016 square meters of crop.

On each harvest day the plants were dissected into leaves, stems, roots and fruits (bolls). Prior to attaining a crop leaf area index (LAI) of 1.0 all leaves from each plot were passed through an electronic area meter (LiCor 4000) and the sum recorded as the LAI of the plot. Subsequently, to speed processing, the area of leaves from one plant was measured with the area meter. The ratio of the wet weight of the leaves of that plant and the wet weight of the leaves from the entire plot was used to calculate the LAI for the plot. All mainstem nodes and the total nodes on each plant were counted and summed for each plot. Total fruiting positions, flowers buds (squares), immature and mature bolls, and abscised fruiting positions were recorded. The separated portions of each harvest were placed in an unventilated glasshouse (which heated to 70 C on bright days) until dry, at which time dry weights were recorded.

The flower tagging area consisted of six contiguous meters of row. Flowers were tagged with a dated tag each day that entry was possible. On weekends and on days of insecticide sprays, no tags were applied. At the end of the season all bolls with tags were assigned to the date of flowering. Bolls that had no tags were assigned to the open dates on a proportional basis.

The final yield area consisted of 6 six meter rows within each plot (Figure 11-3). From that area, a total of 26 meters of crop were harvested for yield and dry matter accumulation.

V. RESULTS

Development of the crop as measured by crop height, leaf area index, biomass accumulations and boll loading of the FACE and control crops are shown in Figures 11-4, 11-5, 11-6, and 11-7, respectively. There was rapid growth in height and LAI (Figures 11-4 and 11-5) of the FACE plots in early season resulting in a 34% increase over the biomass (Figure 11-6) of the controls by DOY208. This rapid growth rate ceased by DOY230. The subsequent continued growth of the controls resulted in narrowing the divergence induced by CO_2 enrichment.

The boll-loading data (Figure 11-7) from the flower tagging area of the plots also showed a pattern of early divergence of the FACE plots. These data indicate a pronounced cessation of flowering and boll retention in the FACE plots beginning about DOY200. This hiatus in flowering, called cutout, is commonly observed in cotton fields in early to mid-August. However, the cutout observed in the FACE plots began sooner and persisted longer than in the control plots. The continuation of boll-loading in the controls, at a lower rate than was initially observed in the FACE plots, resulted in there being no statistically significant difference in marketable yield in that portion of the plots at the end of the season.

In the final harvest area of the plots (NO TRAFFIC), the final yield increase due to FACE was 22% (Table 11-2). Projected yields similar to those that growers would obtain were calculated assuming that the crop would be harvested after the average date of frost for this location, which is November 15 (DOY318). However, in 1989 the farm manager for MAC terminated the crop by defoliating on October 18 (DOY290). For this reason, the actual yield differential between FACE and control plots remained greater than the projected yield differential.

The yield trends in each of the three yield-study areas within the plots show similar patterns. The FACE treatment produced a rapid buildup of boll-load early in the season followed by the hiatus in flowering which allowed the controls,

which continued to flower, to narrow the differential. This narrowing of differential was most evident in the flower tagging area. That was not surprising, since it has been observed by many workers doing research with cotton that the handling of the plants to place tags on flowers results in shorter plants which retain a greater boll-load early in the season and cutout sooner and for a longer duration than undisturbed plants.

Irrigation management of the field apparently was more favorable to the controls than to the FACE plots. In Arizona, the cotton crop is always subject to very negative midday leaf water potentials, due to high temperature, very high sun load, and low humidity. Mid-afternoon loss of leaf turgor is frequently used as an indicator of timing of additional irrigation. Although the irrigation management for this drip irrigated field followed the Arizona Meteorological Network, AZMET, (Brown, 1987) calculation of evapotranspiration, there was some midafternoon leaf water stress observed prior to DOY200. Fangmeier and Yitayew (1989) used resistance blocks to monitor soil moisture in untreated areas of the field immediately adjacent to the FACE plots. They found that from DOY205 to DOY215 the soil moisture was depleted to stress levels at both the 15 cm and 45 cm depths. Irrigations subsequent to DOY215 replenished the moisture at both depths by DOY236. They observed crop water stress indices (CWSI) that indicated plant water stress during the period of DOY210 to DOY220. Although mid-to late-morning crop CWSI values measured by Kimball *et al.* (Chapter 14) suggest that water stress levels were minimal for both controls and FACE, there was some mid-afternoon loss of turgor indicating water stress prior to DOY200.

One feature of the cutout phenomenon in cotton is that allocation of carbohydrate to root and stems is reduced compared with allocation to fruiting structures (Taylor and Klepper, 1974; Kerby *et al.* 1987). Using the data from the destructive harvests, Figure 11-8 shows the change in the fraction of dry weight (D.W.) accumulations going to bolls and to roots in the FACE and control plots between successive samplings.

The ratios were calculated by the following formula:

$$\frac{\text{Organ D.W. at DOY2 - Organ D.W. at DOY1}}{\text{Total Biomass D.W. at DOY2 - Total Biomass D.W. at DOY1}} \times 100$$

From this calculation a percentage greater than 100 indicates that the bolls gained more weight than the total biomass during that time period. A negative ratio indicates that the root D.W. decreased during that time period.

Both FACE and controls plots had negative accumulation of dry weight in the roots during the time of greatest demand by the fruit. However, the longer hiatus of flowering in FACE cannot be explained by this observation, since the controls experienced a more negative allocation to roots than FACE. This analysis implies that the FACE crop continued to allocate carbohydrates to the root systems at a higher rate throughout the season.

Table 11-3 shows the "harvest index", the ratio of boll dry weight to the total dry weight of the crop biomass (including roots), and the root-shoot ratio, the dry weight of roots divided by the dry weight of the stems and leaves. The harvest index shows that the FACE crop did not allocate as great a percentage of its weight to bolls as the controls. The root-shoot ratio shows that a

greater fraction of the vegetative structure of the crop was in roots. While it is possible that these percentages could change with other management regimes, it is also likely that the cultivars presently in use are not adapted to maximize the allocation of carbohydrate resources of a crop under CO_2 enrichment.

Assuming that the woody taproot which remained attached to the stem when the destructive samples were pulled from the moist soil was a constant fraction of the total root mass in all plots, the change in root mass due to CO_2 enrichment was greater than for other organs (Table 11-4). Rogers *et al.* (Chapter 16) also measured the total root mass on DOY270 and found that the percentage increase in dry weight of roots in the FACE plots was greater than other organs.

On DOY291 the crop within the FACE array but outside the interior 12-m diameter experimental area was harvested to determine the uniformity of the crop response. Boll weights (including carpels) from 2 m of row were compared. Three replications, 1, 2, and 4, were used for this comparison. The question to be answered was whether the area of crop uniformity was larger than the 12 m used in this study.

The results (Table 11-5) show that the crop within the plots was very uniform to within 2 m of the release array. Except for insect damage and excessive water stress in specific locations within the plots, the crop was uniform in height and in yield within an area of about 20-m in diameter. A slightly higher yield was observed in that portion of the crop which was within 2 m of the release array, but all other areas were statistically similar.

VI. DISCUSSION

The vertical vent-pipe array used to control CO_2 concentration experiment was a successful means of exposing an open field crop ecosystem to CO_2 enrichment. The high degree of uniformity of the growth responses within the plots means that the short-duration fluctuations in CO_2 concentration which were observed (Lewin *et al.* Chapter 5) did not change plant responses in a measurable way. This implies that the crop integrated any effects of short-term variations that occurred when wind shifts produced different gradients of CO_2 across the space. It also suggests that the diameter of the area in the FACE plots suitable for experimental use is at least 18 m, and perhaps 20 m.

The uniformity of response between plots was sufficient that four replications gave statistically significant data when the differences in growth measurements were 25 to 30%. In future experiments, if the area in which measurements is taken can be expanded, the economic value of the FACE technique will increase. This greater area will permit more sampling to occur within the plots, thus improving statistical accuracy.

The FACE plots grew faster and were significantly different in all growth characteristics for a major portion of the season. Though the difference in final yield was not statistically significant, the FACE plots attained an economic yield five weeks sooner then the controls. This indicates that improved cultural practices and cultivars which will be available in the future would be able to take better advantage of CO_2 enriched atmosphere by earlier maturing and higher yielding crops.

The growth characteristics which were enhanced in the FACE treatment are identical to those observed in glasshouse and open-topped chambers. Early in the season, leaf area, height, and vegetative dry weight were increased dramatically.

Subsequently, as the canopy reached maximum LAI, the shift toward fruit retention and maturation was increased in the FACE plots. Changes of this kind and magnitude have been reported for cotton plants in glasshouse (Mauney *et al.* 1978) and open-topped chambers (Kimball and Mauney, 1992). The fact that the qualitative and quantitative changes previously reported from glasshouse and open-topped chambers have also been observed in the open field enrichment broadens the data-base available for creating mathematical models of plant growth under CO_2 enrichment.

The observation that this woody crop allocated a relatively greater portion of carbohydrates to the roots than to the above ground organs has implications for carbon storage by the earth's biota under the CO_2-enriched atmosphere of the future. Should this phenomenon prove to be general for all species, the deposition of carbon as humus could alter the storage of carbon below ground, resulting in a net increase of carbon in that storage category. Additional studies are needed to confirm if this storage can account for an important fraction of the buffering effect of the biota on atmospheric CO_2.

VII. SUMMARY

This experiment successfully grew a cotton crop from germination to maturity with controlled CO_2 enrichment to 550 μmol mol^{-1} using a vertical vent pipe array to control the CO_2 concentration. Four replications were sufficient to obtain statistically significant results.

On DOY220, 112 days after planting, the FACE plots had 45% greater dry weight than the controls. Thereafter, the FACE plots added weight at a slower rate than the controls, so that at the final harvest the difference was only 20%. The crop allocated a greater proportion of its dry weight to roots in the FACE plots than in the controls. On DOY235 when the total dry weight increase was 39%, the root dry weight increase in the FACE plots was 85%.

The uniformity of the crop response within the plots and between replications will allow a greater area to be used in future experiments. The area for sampling crop responses can be enlarged from the 12 m used in this experiment. It appears that 18 and perhaps 20 m of the 22-m diameter of the plots can be used for sampling crop responses.

REFERENCES

1. Baker DN, Lambert JR, McKinion JM (1983) GOSSYM: A simulator of cotton crop growth and yield. Tech Bull 1089, South Carolina Agri. Exp. Station, Clemson.

2. Brown PW (1987) Users guide to the Arizona Meteorological Network. Arizona Cooperative Extension Service, Tucson.

3. Erie LJ, French OF, Bucks DA, Harris K (1983) Consumptive use of water by major crops in the Southwestern United States. Agr. Res. Serv. Conservation Res. Report No. 29.

4. Fangmeier DD, Yitayew M (1989) Sensor systems for irrigation management. Proceedings of Am. Soc. of Agri. Eng. 12/12/89 New Orleans.

5. Hendrix DL, Huber SC (1986) Diurnal fluctuations in cotton leaf carbon export, carbohydrate content, and sucrose synthesizing enzymes. Plant Physiol. 81: 584-586.

6. Kerby TA, Keeley M, Johnson S (1987) Growth and development of Acala cotton. Bull. 1921, Univ. of California Agric. Exper. Station, Davis.

7. Kimball BA (1983) Carbon dioxide and agricultural yield: An assemblage and analysis of 430 prior observations. Agron J 75: 779-788.

8. Kimball BA, Mauney JR (1992) Responses of cotton to varying CO_2, irrigation, and nitrogen: Yield and growth. Crop Sci. (in press).

8. Mauney JR (1975) Specific leaf weight changes as a measure of photosynthesis in cotton leaves. Proc. 1975 Beltwide Cotton Physiology Conf., National Cotton Council, Memphis. p56.

9. Mauney JR, Fry, KE, Guinn G (1978) Relationship of photosynthetic rate to growth and fruiting of cotton, soybean, sorghum, and sunflower. Crop Sci. 18:259-263.

10. Radin JW, Ackerson RC (1981) Water relations of cotton plants under nitrogen deficiency. III. Stomatal conductance, photosynthesis, and abscisic acid accumulation. Plant Physiol. 67: 115-119.

11. Taylor HM, Klepper B (1974) Water relations of cotton. I. Root growth and water use as related to top growth and soil water content. Agron J 66: 584-588.

FIGURE LEGENDS

Figure 11-1. Diagram of the FACE Facility showing the arrangement of the treatment (T-1 - T-4) and control (C1 - C4) plots in the 44 ha drip irrigated field.

Figure 11-2. Cumulative irrigation volume for the MAC-FACE experiment in 1989 compared to the AZMET (Brown, 1987) estimates of evapotranspiration and Erie *et al.* (1983) estimates of consumptive water use by cotton in Arizona. Irrigation was delivered by subsurface drip tubing.

Figure 11-3. Arrangement of experimental areas within each replication of the FACE and control treatments. The area shown is the 12-m circle at the center of each plot. The depiction is the arrangement for replications 2 and 3. Replications 1 and 4 were mirror images of this.

Figure 11-4. Mean crop height of FACE and control plots. Measurements were made from the soil surface to the growing tip along the main stem. Vertical bars indicate 1 standard error from the mean value. Plants measured were in the flower tagging area of the plots.

Figure 11-5. Leaf area index (LAI) of the FACE and control plots. Data were taken from the "Destructive Harvest" area of the plots.

Figure 11-6. Dry weight of the biomass from the FACE and control plots. Data are from the "Destructive Harvest" areas.

Figure 11-7. Cumulative boll load of the FACE and control plots. Data are the average number of bolls per meter of row harvested at the end of the season which were present on the dates listed. Data are from the "Tagged Flowers" area of the plots.

Figure 11-8. Fraction of the weight gain between successive destructive harvests which accumulated in roots or bolls in the FACE and control plots.

Table 11-1

Significant cultural events for the crop year 1990

Date	DOY	Event
4/10	100	Preplanting-irrigation with 100 mm water
		67.3 kg ha^{-1} of N applied as urea-ammonium nitrate solution
4/18	108	Planting - Cultivar: DPL-77
4/21	111	Emergence of 50% of seedlings
4/24	114	Irrigations began on approximately 5-day schedule.
5/1	121	Thinning to 10 plants per meter of row.
5/19	139	22.4 kg ha^{-1} of N applied as urea-ammonium nitrate solution
5/30	150	Destructive harvests began
		Application of Orthene insecticide
6/1	152	Application of Penncap insecticide
6/8	156	Application of Penncap insecticide
6/18	166	22.4 kg ha^{-1} of N applied as urea-ammonium nitrate solution
6/22	170	First flowers observed
6/25	173	Application of PIX plant growth regulator
6/27	175	Application of Orthene insecticide
7/10	191	Mites observed on leaves
7/11	192	Application of Curacron insecticide
		Application of Pix plant growth regulator
7/13	194	Application of Keltane miticide
7/18	200	Application of Karate insecticide
		22.4 kg ha^{-1} of N applied as urea-ammonium nitrate solution
7/24	206	Application of Keltane miticide
7/27	209	Application of Keltane miticide and Bolstar insecticide
8/4	215	Application of Capture insecticide
8/10	221	Application of Foliar nutrients
8/11	222	Application of Karate and Orthene insecticides
8/21	232	Application of Karate and Orthene insecticides
9/10	253	Application of Guthion insecticide
9/18	261	Final harvest began

Table 11-2

Cumulative weight of open bolls (calculated as kg ha^{-1}) on several harvest dates. Potential yield was calculated by assuming that the green bolls would mature before November 15 and contain 0.8 the weight of mid-season bolls. Because the crop was terminated on 10/18, the actual harvested yield was less.

Harvest			Yield of Open Bolls (kg ha^{-1})		
Date	DOY		Control	FACE	% Increase
8/7	219		28	56	103
8/15	227		206	439	113
8/25	237		685	1214	77
9/5	248		104	1568	50
9/22	265		1308	1793	37
10/16	283		1679	1961	17
		+ Green bolls	613	374	
Potential Yield (Tagged Rows)			2292	2335	2
Potential Yield (No Traffic area)			2280	2410	6
10/16	320	(Actual Yield)	2000	2436	22

Table 11-3

Harvest index and root-shoot ratios for the FACE (F) and control (C) plots in 1989. Harvest index was calculated from the destructive harvests on the ratio of boll dry weight to total biomass (including roots). Root-shoot ratio is the ratio of root dry weight to the sum of stem and leaf dry weight of the destructive harvests. No roots were taken in the 9/20 harvest.

		Harvest Index		Root-shoot Ratio	
		F	C	F	C
Date	DOY	gm gm^{-1}	gm gm^{-1}	gm gm^{-1}	gm gm^{-1}
6/14	165			.089	.119
6/28	179			.164	.124
7/11	192	.173	.140	.160	.161
7/27	208	.387	.300	.158	.135
8/9	221	.514	.469	.172	.112
8/23	235	.499	.477	.275	.188
9/20	263	.634*	.671*		

* Ratio did not include root weight on DOY263

Table 11-4

Dry weight of subdivisions of the destructive harvest on August 23, 1989 (DOY235).

	FACE	Control	% Increase
	gm m^{-2}	gm m^{-2}	
Leaves	289	242	19
Stems	384	301	28
Roots	185	100	85
Mature Bolls	471	270	74
Immature Bolls	382	316	21
Total	1711	1229	39

Table 11-5

Yield of 2 m row segments from the area inside the FACE arrays within 8 m of the CO_2 release vents. Data are dry weights of open bolls (including carpels) harvested on DOY291, 10/19/89. Averages are of the number of row segments shown from three replications.

Distance from vents m	Average yield gm m^{-1}	Number of segments	Standard Deviation gm m^{-1}
0-2	1963	13	210
2-4	1813	9	78
4-6	1751	4	38
6-8	1824	3	81
+8	1838	3	112

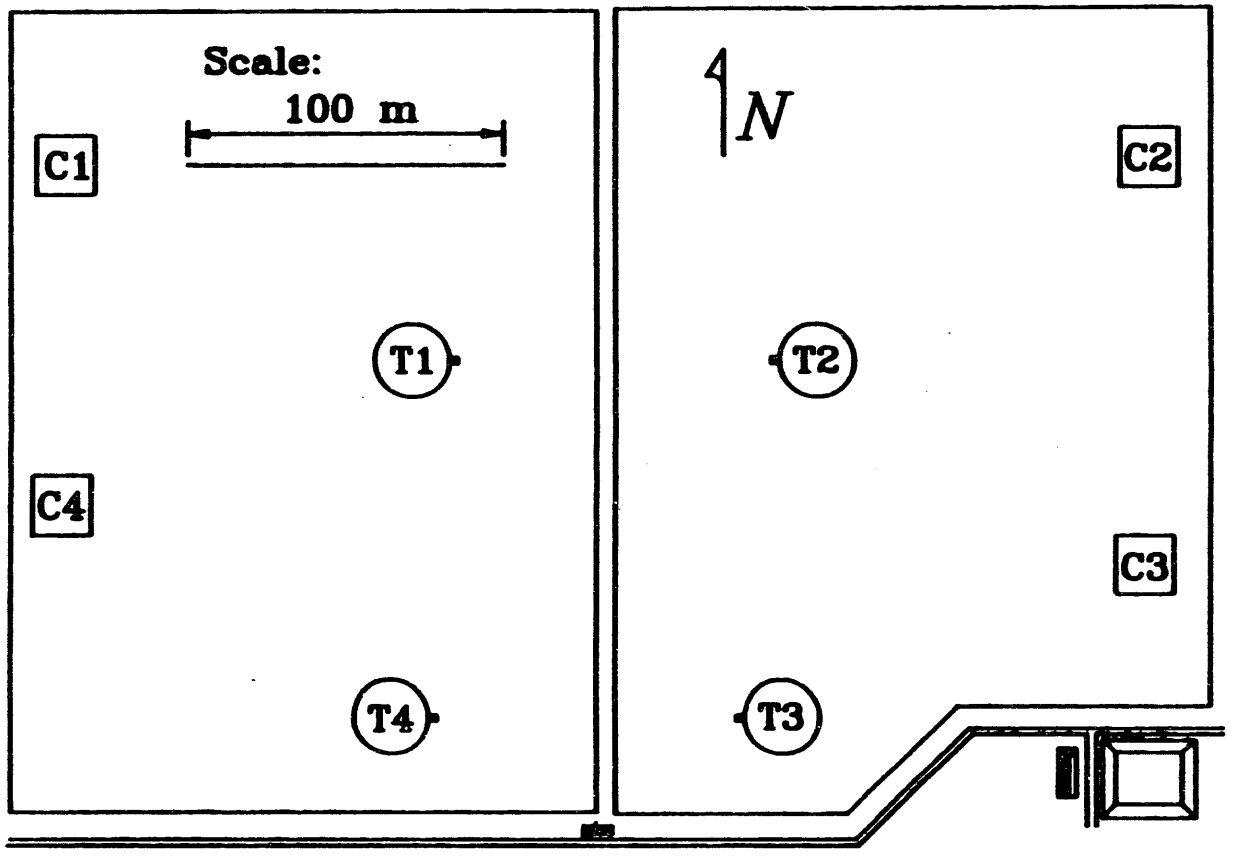


Fig 11-1

Fig. 11-3

IRRIGATION COMPARISONS

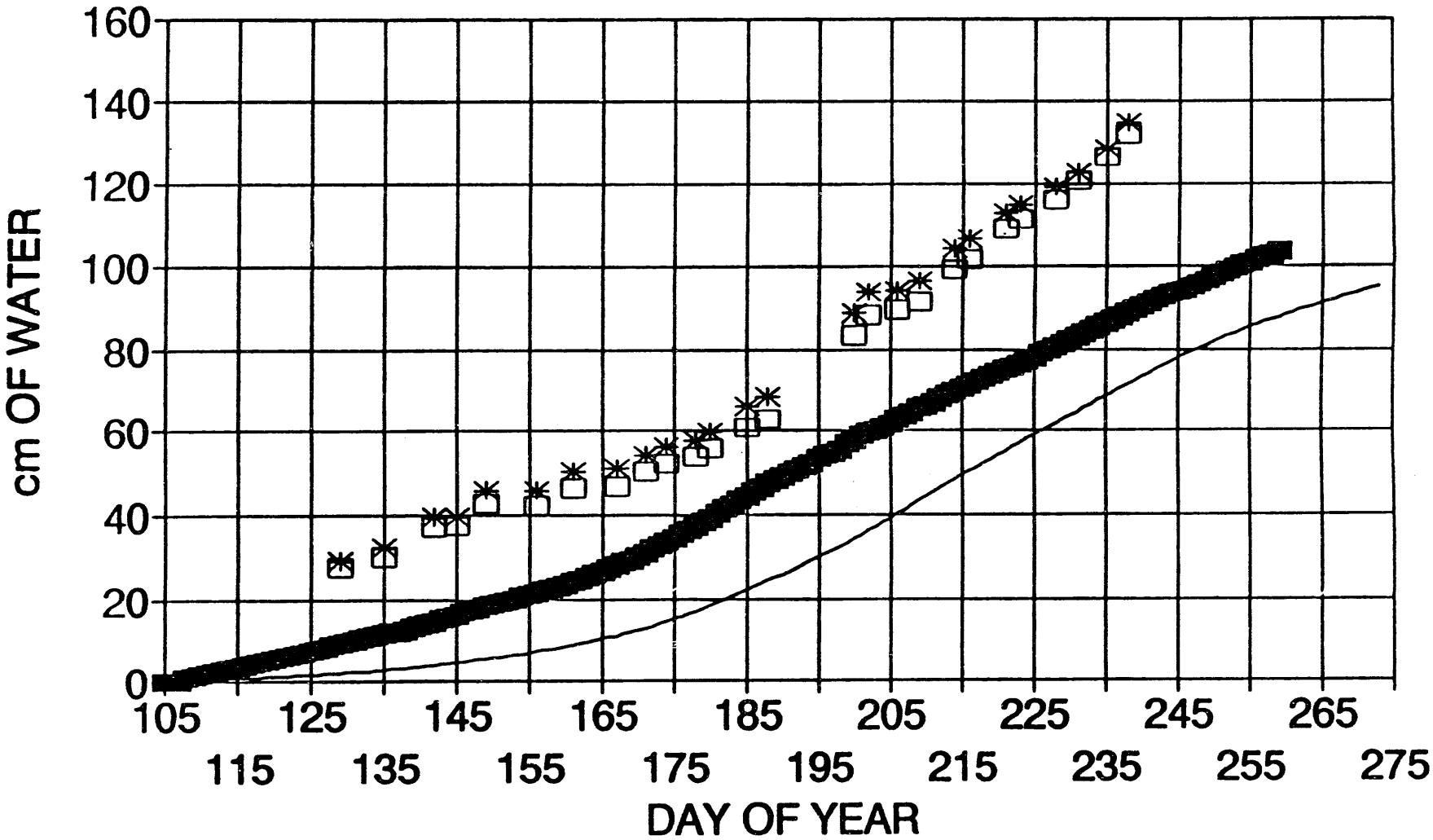
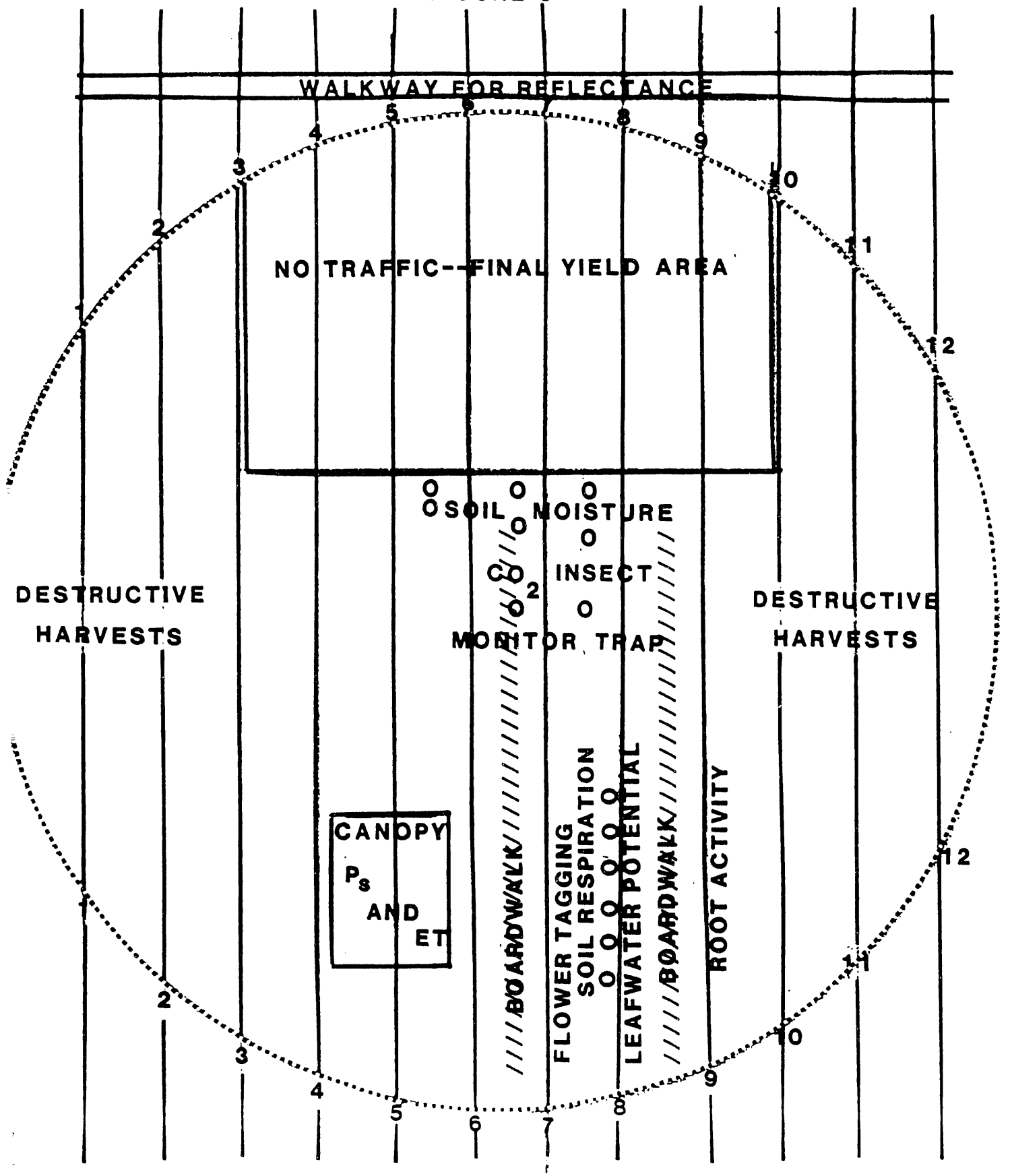
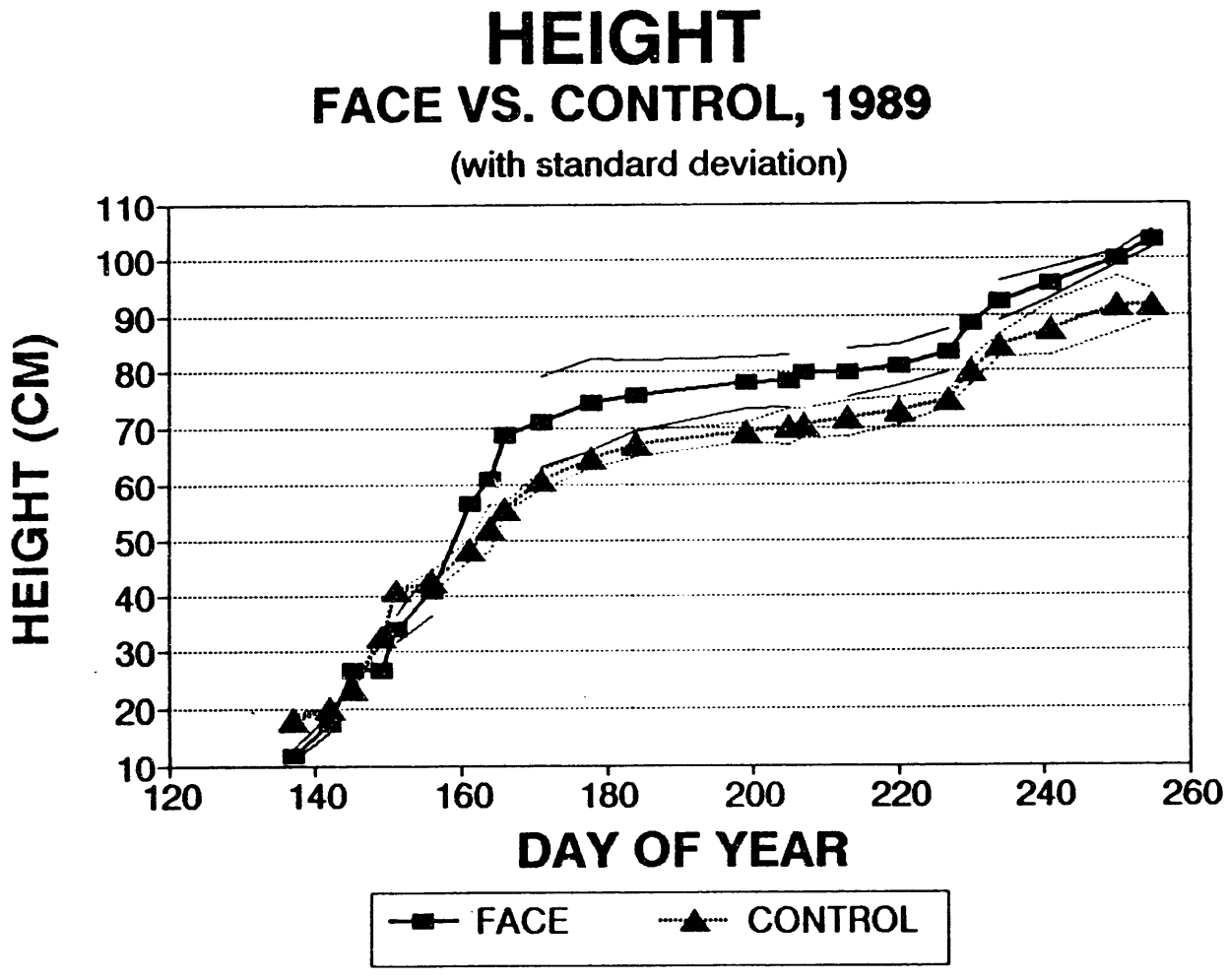


FIGURE 3

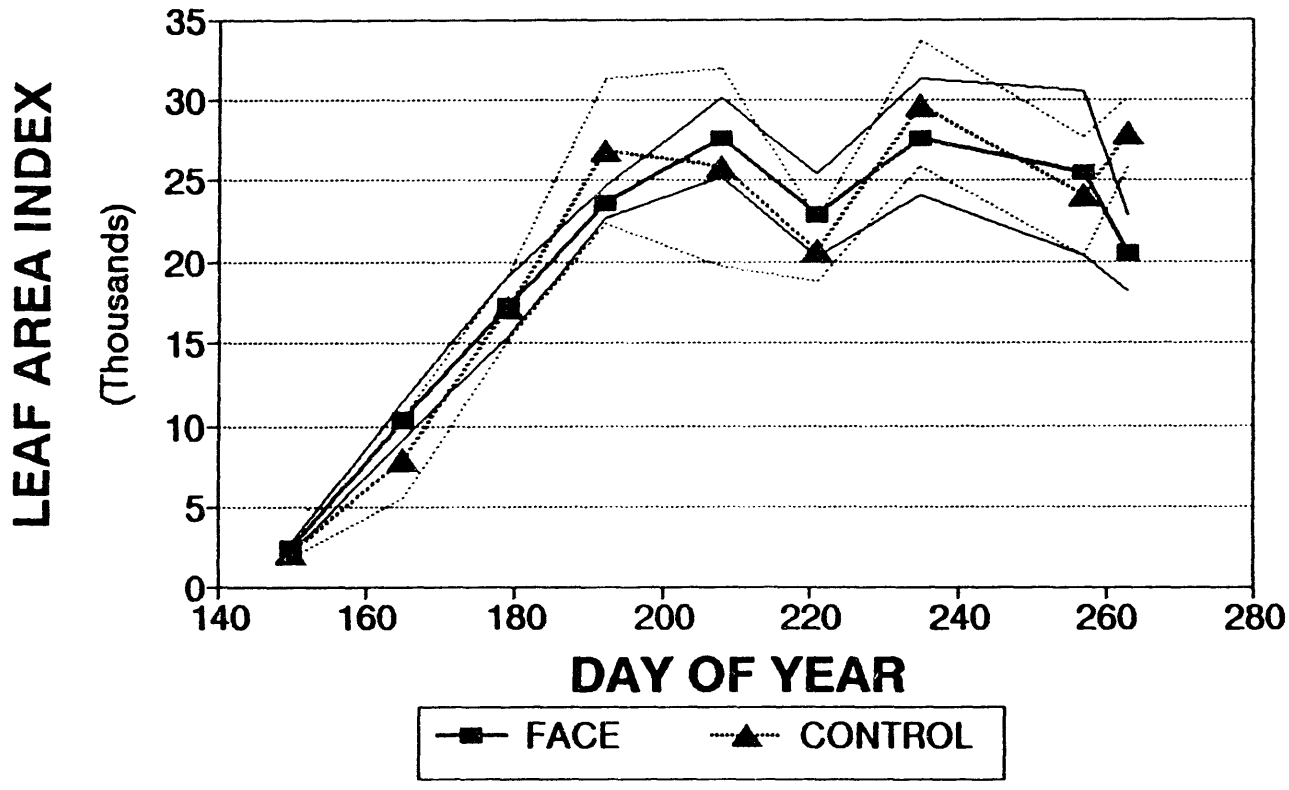

WALKWAY FOR REFLECTANCE
NO TRAFFIC--FINAL YIELD AREA
SOIL MOISTURE
INSECT
MONITOR TRAP
DESTRUCTIVE
HARVESTS
DESTRUCTIVE
HARVESTS
CANOPY
Ps
AND
ET
BOARDWALK
FLOWER TAGGING
SOIL RESPIRATION
LEAFWATER POTENTIAL
BOARDWALK
ROOT ACTIVITY

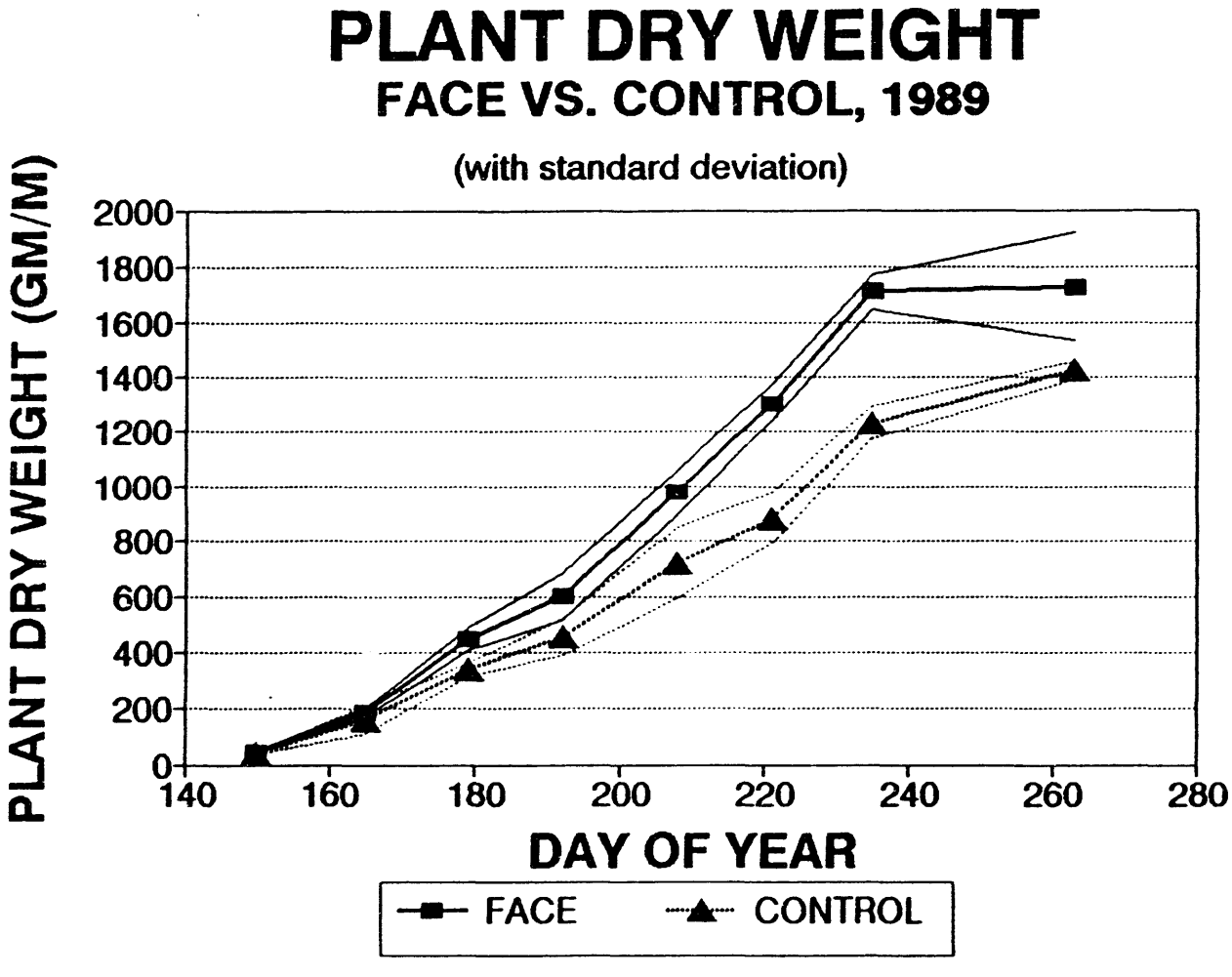

HEIGHT
FACE VS. CONTROL, 1989
(with standard deviation)
HEIGHT (CM)
110
100
90
80
70
60
50
40
30
20
10
120
140
160
180
200
220
240
260
DAY OF YEAR
FACE
CONTROL

LEAF AREA INDEX

FACE VS. CONTROL, 1989

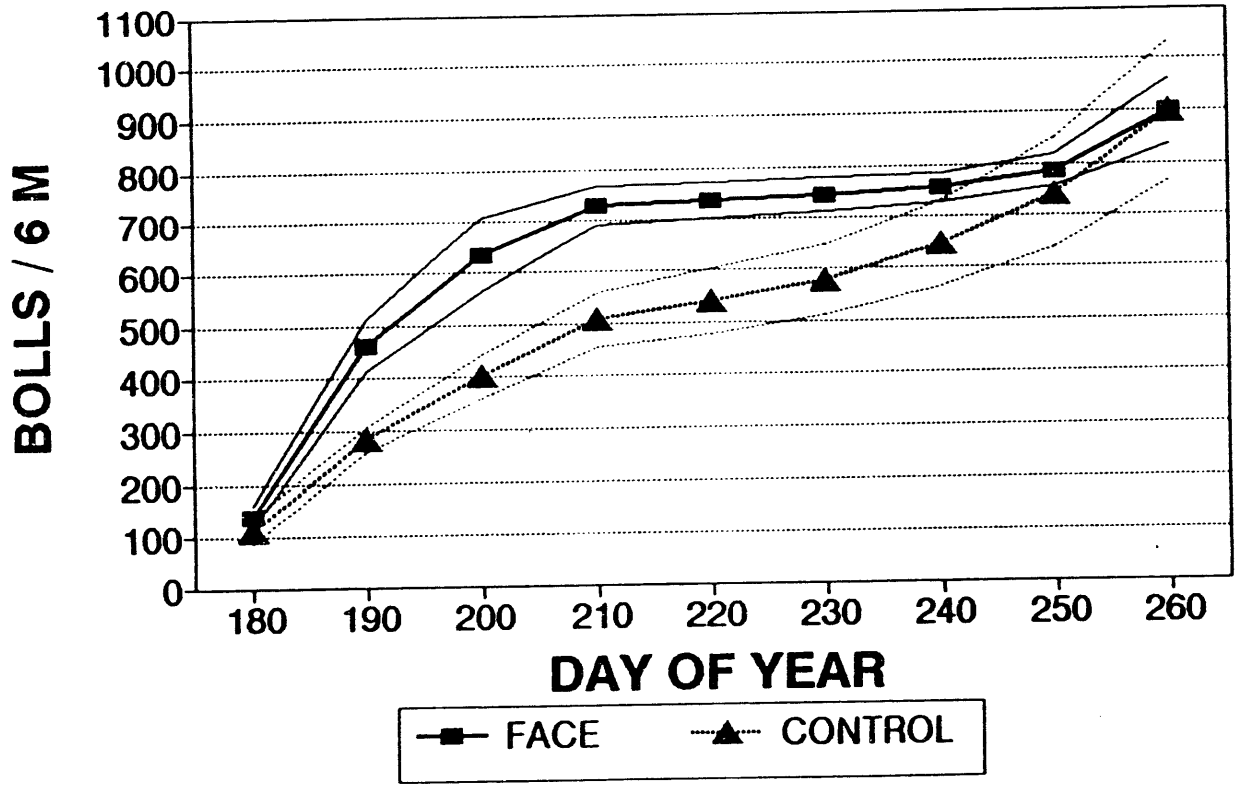
(with standard deviation)




PLANT DRY WEIGHT
FACE VS. CONTROL, 1989
(with standard deviation)
PLANT DRY WEIGHT (GM/M)
2000
1800
1600
1400
1200
1000
800
600
400
200
0
140
160
180
200
220
240
260
280
DAY OF YEAR
FACE
CONTROL

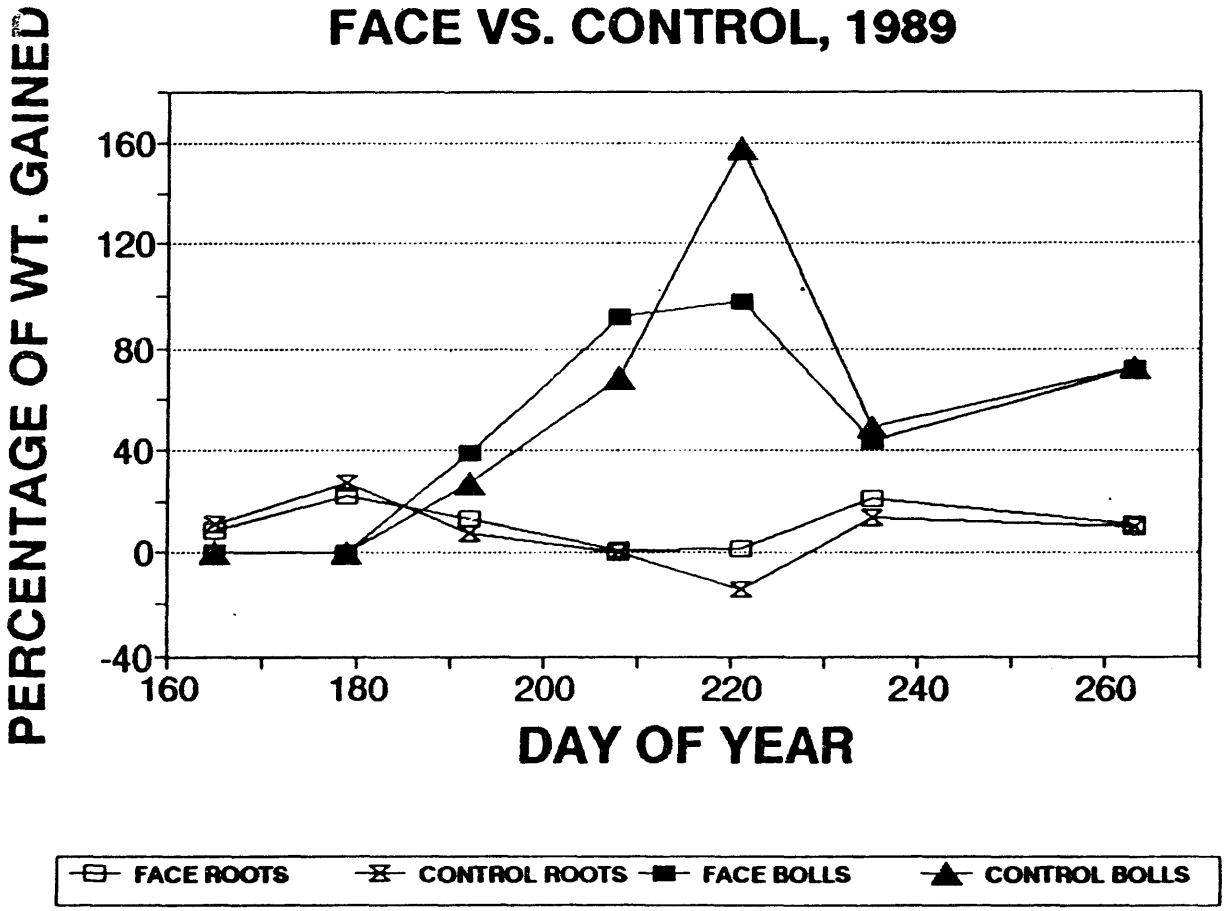
NUMBER OF BOLLS
FACE VS. CONTROL, 1989

(with standard deviation)



FRACTION OF WEIGHT GAINED

FACE VS. CONTROL, 1989



INFLUENCE OF ELEVATED CO_2 ON LEAF STARCH OF FIELD-GROWN COTTON[1]

Donald L. Hendrix
Western Cotton Research Laboratory
4135 East Broadway Road
Phoenix, AZ 85040

I. INTRODUCTION

Experiments were conducted to determine the effects of free-air carbon dioxide enrichment (FACE) upon cotton grown in fields near Yazoo City, MS and Maricopa, AZ. Among the measured responses was the starch content of cotton leaves. Leaf starch is an important carbon pool in cotton, since its degradation during the night and subsequent translocation of the products from the leaf is the major process supplying substrates for energy necessary for nocturnal growth and metabolism in this species (Hendrix and Huber 1986; Hendrix and Grange 1991). The nocturnal carbon supply is of particular importance in cotton as it provides the energy for a number of significant growth events which occur during dark periods, including flowering, fruit set and leaf growth. Earlier work (Hendrix and Huber 1986) has shown that the magnitude of cotton leaf carbon export during dark periods could be established by comparing the starch content in leaf samples collected from the same leaf at dusk and dawn. The difference between evening and morning leaf starch content equals the nocturnal contribution of carbon from that particular leaf to the growth and respiration of the plant (Hendrix and Grange 1991). Moreover, the cotton growth model COTCO2 (Amthor and Kimball 1990) accounts for such diurnal changes in the starch pool and observations of actual leaf starch content can provide data with which to validate this aspect of the model.

Cotton leaf starch has been found to increase substantially when cotton plants were raised in elevated CO_2 (Mauney *et al.* 1979). Since this is a plant response to chronic CO_2 exposure which can easily be quantified, the sampling protocol for leaf starch in the FACE experiments was also designed to test the uniformity of carbon dioxide exposure of plants across a 23-m diameter CO_2 FACE array placed in a field of cotton. In the first of these experiments, conducted in 1988, leaf samples were taken in a grid pattern across a FACE plot, with the objective of determining how the elevated starch in leaf samples changed with position across the array. The objective of experiments conducted during 1989 was to determine the starch dynamics in cotton leaves (i.e., PM vs. AM starch content) at various times during the season and to also provide more detail about the uniformity of the leaf starch response across the CO_2 release ring.

II. MATERIALS AND METHODS

Small discs (six, each 0.42 cm^2) were punched from the youngest fully expanded leaf near the top of the plant with a cork boring tool at dawn. These samples were removed from locations near the edge of cotton leaves (avoiding major veins) and placed into ice-cold 80% ethanol for transport to the laboratory. In the laboratory, tubes containing the leaf discs were tightly stoppered and stored at -80°C until extracted for starch.

In the 1988 grid sampling protocol in Yazoo City, MS, a single leaf was sampled at each location on the evening of 2 August (DOY214). At monthly intervals during the 1989 growing season in Arizona, leaf samples were taken from the FACE array at dawn; the same leaves were again sampled in this manner at dusk. The second set of punches was removed from locations on the leaf immediately adjacent to those in the first sampling. Unlike the Mississippi experiment, in the Arizona array three leaves were sampled per row in a 1-m wide path across the center of the release ring. This transect was oriented in a north-south direction, at right angles to the direction of the cotton rows. The first three samplings were done in the southwest ring (replicate 4). However, since toward the end of the season the appearance of plants in this ring was not as uniform as other plots, the final sampling was done in the northeast ring (replicate 2).

Cotton leaf discs were analyzed for starch by a novel technique which avoided disc homogenization. The tubes containing the discs in ethanol were heated to 80°C for 15 min and the alcohol discarded. This was repeated three times until all soluble sugars were extracted from the discs. After the last rinse, 0.2 N KOH was added to the tubes and the tubes were placed in a boiling water bath for 30 min. The tubes were next cooled to room temperature and the KOH neutralized with acetic acid. Starch in the discs was then digested enzymatically (Brown and Huber 1988; Hendrix and Peelen 1987). Glucose solubilized by this treatment was detected colorimetrically with a commercial glucose-6-phosphate dehydrogenase-iodonitrotetrazolium coupled assay (Sigma Chemical Co., St. Louis, MO) using a microplate reader.

III. RESULTS

The increased CO_2 within the center of the release ring caused a dramatic increase in leaf starch content in 1988, and the FACE array is clearly visible in the resulting three dimensional plot of the data from Yazoo City, MS (Figure 12-1). The maximal starch levels recorded in this experiment (up to 18 g m^{-2} leaf area) were substantially higher than those collected in August in Arizona (cf. Figure 12-3). The seasonal pattern of starch found in the meter-wide transects during the 1989 season is shown in Figures 12-2 and 12-3. Cotton leaf starch was relatively high at the beginning of the season and was significantly less when plant boll load increased (compare the data of 26 June [DOY177] to that of 17 July [DOY198] in Figure 12-2). Not only were starch levels relatively high at the beginning of the season, the pronounced daily cycling of leaf starch content was not observed in samples collected in June. A significant decrease in leaf starch content and an increase in the amplitude of the diurnal cycling of leaf starch content became evident after the first month of the growing season. The diurnal cycling was especially pronounced during July, suggesting

that the greatest contribution of elevated carbon dioxide to nocturnal plant metabolism (Hendrix and Grange 1991) occurred during this part of the cotton growing season. As in the Mississippi experiment (Figure 12-1), the pattern of elevated leaf starch content from samples taken within the area of CO_2 release, corresponded to the location of the FACE array, particularly in the PM samples (Figures 12-2 and 12-3).

IV. SUMMARY AND CONCLUSIONS

The fact that higher leaf starch was found in leaf samples obtained in Mississippi than those obtained in Arizona during the same month (August) may be partly due to the fact that the Mississippi release ring maintained a 600 μmol mol^{-1} CO_2 concentration inside the FACE array, whereas in the Arizona experiment the CO_2 concentration inside the array was only 550 μmol mol^{-1}. However, this difference in leaf starch is more likely due to the differences in climate between the two locations, which are known to alter cotton leaf carbohydrate content (Hendrix and Oosterhuis unpublished). In addition, there are seasonal differences in cotton development in the two locations. Cotton is planted considerably earlier in Arizona and develops relatively faster, since the crop receives higher temperatures in Phoenix than in the eastern part of the United States.

Although photosynthesis and starch accumulation is relatively uniform across a cotton leaf which is held in a plane perpendicular to a light source (Hendrix and Grange unpublished), starch is not uniformly distributed across cotton leaves grown in the field (Hendrix and Fink unpublished). Cotton leaf starch content also changes during the time of year. It typically decreases in the early summer as fruit load increases. A cessation in the diurnal cycling of leaf starch content such as that observed in figure one has been noted in other experiments (Hendrix and Mauney in preparation). Since this cycling usually supplies the energy for nocturnal metabolism in this species (Hendrix and Grange 1991), the nocturnal metabolic processes are either slowed during such episodes or they obtain carbon from other locations within the plant. The cessation of diurnal leaf starch cycling observed in Figure 12-1 does not seem to be related to the high starch content within the leaves induced by their CO_2 exposure, since it has also been observed in leaves not exposed to CO_2 which contained significantly lower starch content (Hendrix and Mauney in preparation).

Leaf starch in cotton plants is not only dependent upon photosynthesis, it is also strongly dependent upon plant water status and nutrition which can vary significantly within a single field. In light of these facts, the degree of uniformity of leaf starch across the release ring (Figure 12-1) is somewhat surprising. This result suggests that the CO_2 concentration and other variables inside the ring were controlled relatively uniformly prior to this sampling period since the starch content of a cotton leaf is largely a product of its photosynthetic history which, in turn, is related to the CO_2 in its environment (Mauney *et al.* 1979). Cotton leaf starch content appears to be an integral of the CO_2 exposure fluctuations it receives. If the field water and nutritional parameters are sufficiently uniform, leaf starch content can be employed to validate the uniformity of the biological response of starch accumulating plants within FACE array systems.

V. ACKNOWLEDGEMENTS

The author would like to thank Dr. J. R. Mauney for collecting the leaf samples for figure one and to acknowledge the excellent technical assistance of Dwayne Fink and Patsy Geimsoe.

REFERENCES

1. Brown CS, Huber SC (1988) Reserve mobilization and starch formation in soybean (Glycine max) cotyledons in relation to seedling growth. Physiol. Plant. 72:518-524.

2. Hendrix DL, Huber SC (1986) Diurnal fluctuations in cotton leaf carbon export, carbohydrate content, and sucrose synthesizing enzymes. Plant Physiol. 81:584-586.

3. Hendrix DL, Grange RI (1991) Carbon partitioning and export from mature cotton leaves. Plant Physiol. 95:228-233.

4. Hendrix DL, Peelen, KK (1987) Artifacts in the analysis of plant tissues for soluble carbohydrates. Crop Sci. 27:710-715.

5. Mauney JR, Guinn G, Fry KE, Hesketh JD (1979) Correlation of photosynthetic carbon dioxide uptake and carbohydrate accumulation in cotton, soybean, sunflower and sorghum. Photosynthetica 13:260-266.

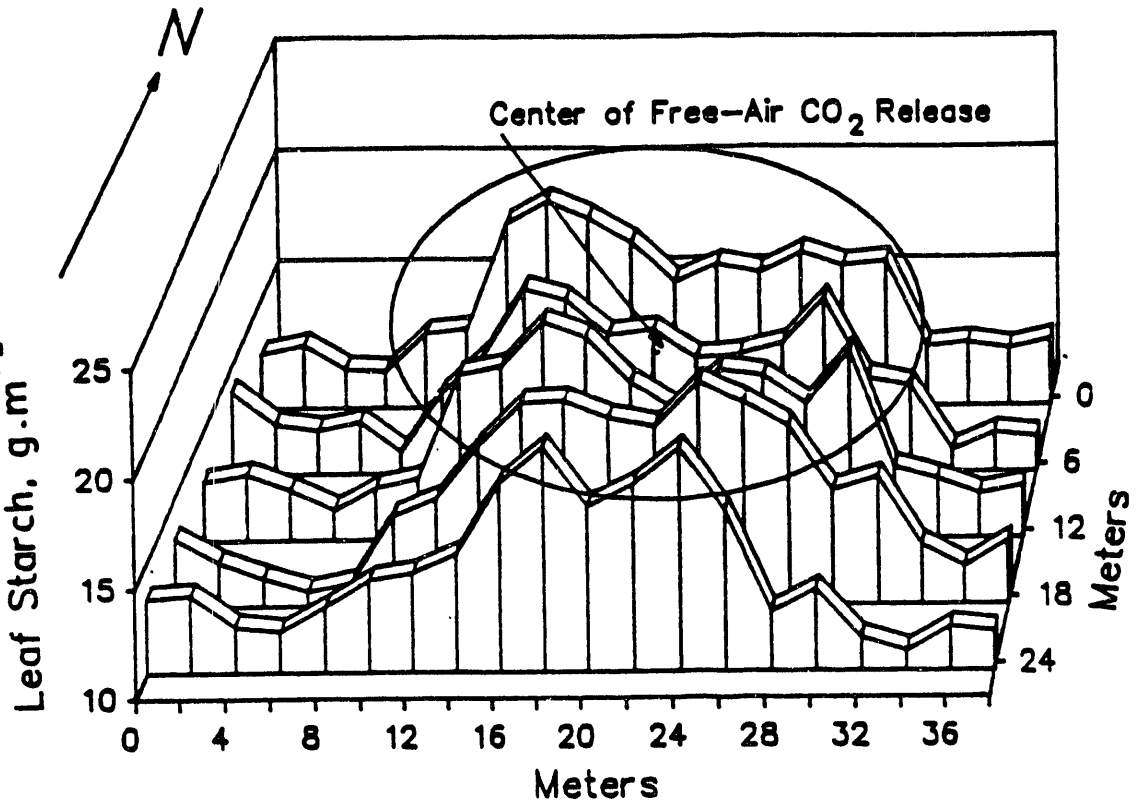
6. Amthor, JS, Kimball BA (1990) Predicting the growth and productivity of cotton in a future "greenhouse world": Development of a physiological model. Proc. Beltwide Cotton Prod. Res. Conf. 724.

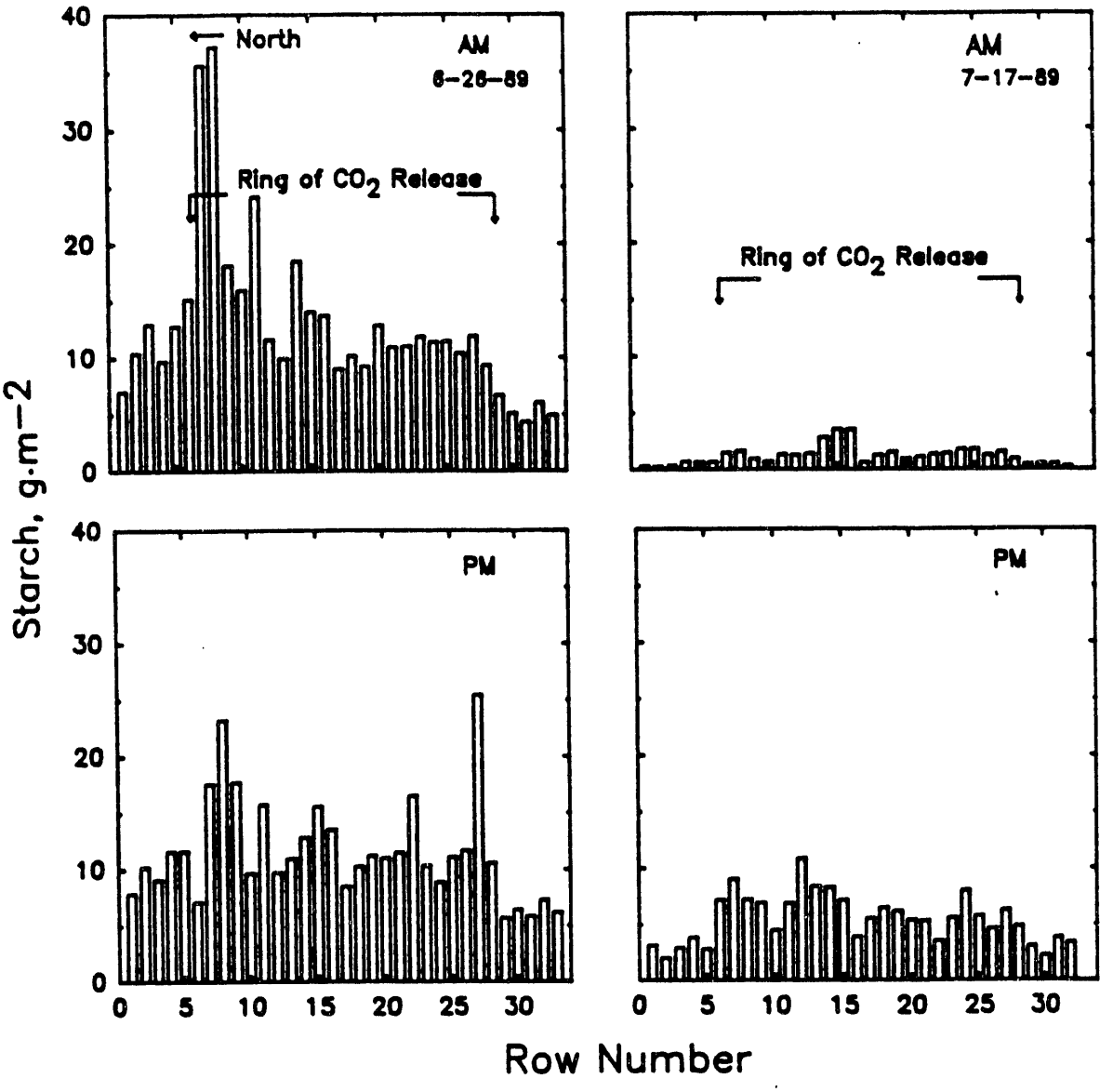
FIGURE LEGENDS

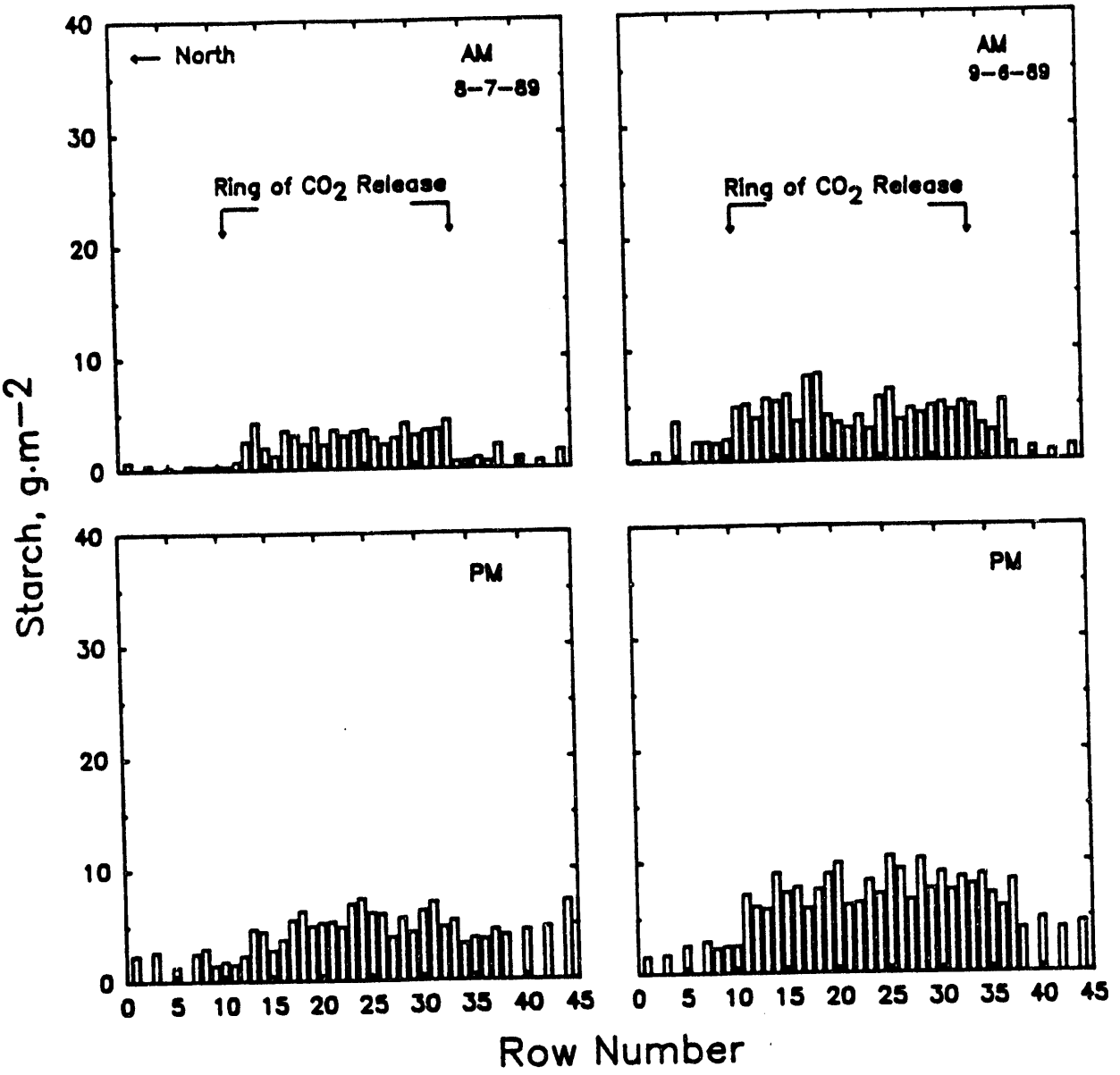
Figure 12-1. Pattern of cotton leaf starch across a FACE array (600 μmol mol^{-1}) in a field near Yazoo City, MS. The cotton was planted in rows oriented north to south which were 1-m apart. The FACE plot was 2-m in diameter. Leaves were sampled in the evening of August 2, 1988 (DOY214). Starch values in this and subsequent figures are expressed as g m^{-2} of leaf area of a single leaf at each location sampled. The values plotted in this figure were "smoothed" prior to plotting by applying a three term running average to the values in the five transects.

Figure 12-2. Cotton leaf starch on 26 June (DOY177) and 17 July, 1989 (198) in a 1-m wide transect through the north-south diameter of a FACE array (23 meters across, enriched within the array to 500 μmol mol^{-1} CO_2) placed in a field near Maricopa, AZ. Samples were removed from the same leaves at dawn (AM) and dusk (PM) on the dates shown in the upper panels. Each bar represents the mean of three leaf samples taken from that particular row.

Figure 12-3. Cotton leaf starch on 7 August (DOY219) and 6 September (DOY 249), 1989 in a 1-m wide transect through the north-south diameter of a FACE plot placed in a field near Maricopa, AZ. Sampling identical to that in Figure 12-2.


N
Center of Free–Air CO_2 Release
Leaf Starch, $g.m^{-2}$
25
20
15
10
0
4
8
12
16
20
24
28
32
36
Meters
0
6
12
18
24
Meters


North
AM
6-26-89
Ring of CO_2 Release
AM
7-17-89
Ring of CO_2 Release
PM
PM
Starch, g·m−2
Row Number
0
10
20
30
40
0
5
10
15
20
25
30


← North
AM
8-7-89
Ring of CO_2 Release
AM
9-6-89
Ring of CO_2 Release
PM
PM
Starch, g·m⁻²
Row Number
0
10
20
30
40
0 5 10 15 20 25 30 35 40 45

RESPONSES OF PHOTOSYNTHESIS AND STOMATAL CONDUCTANCE TO ELEVATED CARBON DIOXIDE IN FIELD-GROWN COTTON

D.R. Hileman[1], *N.C. Bhattacharya*[2*], *P.P. Ghosh*[2] *and P.K. Biswas*[2]
[1]Department of Biology and [2]Department of Plant and Soil Science
Tuskegee University
Tuskegee, AL 36088
*Present address: USDA-ARS
Western Cotton Research Laboratory
4135 E. Broadway
Phoenix, AZ 85040

K.F. Lewin and G.R. Hendrey
Department of Applied Science
Brookhaven National Laboratory
Upton, NY 11973

I. INTRODUCTION

Atmospheric CO_2 enrichment usually leads to increases in the growth and yield of crop plants (Kimball 1983, Cure and Acock 1986). These increases are direct results of enhanced photosynthetic CO_2 uptake rates. Under conditions of adequate light, water and nutrients, photosynthesis in C_3 plants is limited by CO_2 concentration. Therefore, knowledge of how photosynthesis responds to elevated CO_2 is central to the understanding of how the entire plant responds to elevated CO_2.

Plants exposed to CO_2 enrichment usually show a marked enhancement of photosynthesis, relative to plants grown at ambient CO_2 (Cure and Acock 1986). However, many of these data are based on plants raised in controlled-climate chambers or greenhouses under conditions of optimal nutrients and water, and in the case of controlled-climate chambers, low light as well. Under conditions of high light and ambient CO_2, well-watered soybeans grown in the field in open-top chambers had photosynthetic rates nearly double those of plants grown in pots in open-top chambers (Sionit *et al.* 1984). This difference was reduced at lower light levels or at elevated CO_2 concentrations. Results from controlled-climate studies must be applied to field situations with caution.

A few studies have demonstrated enhanced photosynthetic rates at elevated CO_2 in plants grown in the field in open-top chambers (Huber 1984a, 1984b, Radin *et al.* 1987). However, the microclimate inside an open-top chamber is clearly different from the microclimate in the open field, and some authors report significant differences in growth between plants grown in open-top chambers at

ambient CO_2 and plants grown in the open field (Drake *et al.* 1985).

The development of the Free-Air Carbon dioxide Enrichment (FACE) system provides a unique opportunity to monitor photosynthesis in field-grown plants in a CO_2-enriched atmosphere without an enclosure system. We measured photosynthetic rates and stomatal conductance in cotton plants both before and after three and one-half weeks of exposure to a CO_2-enriched atmosphere in an agricultural field.

II. METHODS

Cotton plants (*Gossypium hirsutum* L.) growing in an agricultural field in Yazoo City, MS in 1988 were exposed to a CO_2-enriched atmosphere using the FACE system described in Chapter 5. The field was laid out with four FACE plots and three control plots. The plots were 12 m in diameter and were at least 100 m from each other. The FACE plots were located in the center of 23 m diameter FACE rings. FACE plots were maintained at a CO_2 concentration of 550 μmol mol^{-1}, from 18-26 July and at 600 μmol mol^{-1} from 27 July until 31 August. The concentration of CO_2 in the control plots was approximately 350 μmol mol^{-1}.

Net photosynthetic CO_2 uptake rates of leaves were measured with a Li-Cor LI-6000 portable photosynthesis system. This system consists of a clamp-on leaf cuvette attached to an infra-red gas analyzer (IRGA) and a console that records and stores the data. During measurements, gas flows through a closed loop that also contains a desiccant to control the rise in water vapor. Photosynthetic rate was calculated from the decrease in carbon dioxide. Stomatal conductance was calculated from the rate of water vapor change and the flow rate through the desiccant.

Measurements were made on 13-16 July, just before CO_2 treatment began, and on 11-15 August, after 3-1/2 weeks of CO_2 treatment. The leaves measured in August were produced under CO_2 enrichment. The July measurements were made with a 4 ℓ cuvette. The August measurements were made with a 1 ℓ cuvette, which gave better results, but which was not available in July. Measurements were made on 3-6 plots per day. The selection and order of the plots was varied from day to day.

In each plot, measurements were made on 12 plants from the middle two rows, using the fifth leaf down from the tip of the main stem. Only unshaded and undamaged leaves were selected, and leaves were orientated in approximately the same direction as they were prior to insertion into the leaf cuvette. Measurements were made between 0900 and 1500 hours Central Standard Time when the sun was not obscured by clouds. Photosynthetically active radiation (PAR) incident on the leaves was measured with a quantum sensor; any measurements made at PAR levels less than 1200 μmol m^{-2} s^{-1} were discarded. To reduce vibration, the IRGA and control unit were placed on a wooden stand during measurements.

Despite the use of the desiccant, the relative humidity within the leaf cuvette frequently exceeded 80%, causing a decrease in the accuracy of the stomatal conductance values obtained by the LI-6000 system. Therefore, simultaneous stomatal conductance measurements were made with a Li-Cor LI-1600 steady state porometer. Porometer measurements were made using the same leaf-selection criteria as for photosynthesis, but different plants.

The data were analyzed by analysis of covariance. The measurements made before the CO_2 treatment began were used as the covariate in the analyses of the measurements made after CO_2 treatment.

III. RESULTS AND DISCUSSION

Before CO_2 treatment began, both leaf photosynthetic CO_2 uptake rate and stomatal conductance were identical in the FACE and control plots (Tables 13-1 and 13-2). After three and one-half weeks of exposure to elevated CO_2, leaf photosynthetic rates were 33% higher in FACE plots than in control plots, but the increase was not significant ($p=.09$), due to the large variation among the plots. After exposure to elevated CO_2, stomatal conductance remained identical in leaves from FACE and control plots.

When exposed to elevated CO_2, many plants respond by partly closing their stomata (Morison 1985). The greater diffusion gradient of CO_2 through the stomata usually leads to enhanced photosynthetic rates despite the greater stomatal diffusion resistance (Cure and Acock 1986). Most plants respond to elevated CO_2 with both an increase in photosynthetic rate and a decrease in transpiration rate, on a leaf-area basis.

In our experiment, mid-day stomatal conductance of cotton was not affected by CO_2 treatment. Radin *et al.* (1987) found similar results in cotton grown in open-top field chambers. However, Inoue *et al.* (1990) reported a decrease in stomatal conductance at elevated CO_2 in field-grown cotton.

Stomatal conductance in cotton is relatively insensitive to soil moisture and plant water potential (Ackerson and Krieg 1977, Ackerson *et al.* 1977, Hutmacher and Krieg 1983). Nitrogen deficiency and cool temperatures both increase the sensitivity of stomata to water stress (Radin and Parker 1979) and nitrogen deficiency increases the sensitivity of stomata to elevated CO_2 under water stress (Radin and Ackerson 1981). While stomata of cotton may respond to CO_2 enrichment under certain conditions, it appears that under field conditions, with adequate nutrients, cotton tends to maximize its photosynthetic rate rather than conserve water when grown under CO_2 enrichment. This may explain why cotton shows an unusually strong yield response to CO_2 elevation (Mauney *et al.* 1978). However, large increases in growth under elevated CO_2 combined with little change in stomatal conductance means that water loss on a whole-plant or ground area basis may actually increase.

In our experiment, the moisture content of the soil was not low at the time of the measurements. There had been 38 mm of precipitation in the 8 days prior to the July measurements and 12 mm of precipitation in the 4 days prior to the August measurements. In addition, the high clay content of the soil helped maintain soil moisture between rain events. Measurements of stomatal conductance made during periods of drought may be more strongly affected by the level of atmospheric CO_2 (Radin *et al.* 1987). Stomatal response to CO_2 has been shown to vary, depending on other environmental conditions, in a variety of plants (Louwerse 1980, Sionit *et al.* 1984).

Total water use by a plant is a function of both the leaf transpiration rate and plant size. The plants in the FACE plots were clearly larger than the plants in the control plots. Given the similarities in stomatal conductance, the total water use may have been higher in the FACE plots than in the control plots. In future experiments, attempts should be made to estimate total canopy water use.

Variation in both photosynthetic rate and stomatal conductance among plots was greater in August than in July, especially in FACE plots. Much of this variation may have related to a potassium deficiency that developed between the July and August measurements. Three of the four plots on the south side of the field (FACE 3 and 4, control 7) showed a distinct yellowing of the leaves. Leaf

samples confirmed that the chlorotic plants were deficient in potassium (J. Mauney, personal communication). Chlorosis was clearly more severe in the FACE plots than in the control plot or in the rest of the south side of the field. Apparently, treatment with elevated CO_2 exacerbated the deficiency symptoms, possibly due to greater demand caused by enhanced growth. Chlorosis was most obvious in FACE plot 3, which among all FACE plots showed the lowest photosynthetic response to CO_2 treatment and the greatest reduction in stomatal conductance between July and August. Experiments on the interaction of nitrogen supply and CO_2 enrichment in cotton have shown that a decrease in nitrogen leads to a decrease in the enhancement of photosynthetic rates by CO_2 (Wong 1979).

The apparent effect of nutrient supply on the photosynthetic response to CO_2 reinforces the need to conduct experiments involving atmospheric contaminants and plants in a field setting. Studies in controlled environment chambers and greenhouses can not duplicate field conditions such as soil moisture and fertility. The enhanced growth and yield often shown in controlled-environment CO_2 studies (Kimball 1983, Cure and Acock 1986) may not occur to the same degree in agricultural fields, where nutrients and water are often limiting. The FACE system provides the means for investigating plant responses to CO_2 in a field setting with a minimum of disturbance.

III. ACKNOWLEDGEMENTS

We thank L. H. Allen, Jr. for arranging the loan of the LI-6000 photosynthesis system. We also thank Clay McConnell and the Mississippi Chemical Company for their assistance and for permission to conduct this experiment in their field. This research was supported in part by the Department of Energy (contract no. DE-FG05-86ER-60498) and the Tuskegee University George Washington Carver Agricultural Experiment Station.

REFERENCES

1. Ackerson RC, Krieg DR (1977) Stomatal and nonstomatal regulation of water use in cotton, corn, and sorghum. Plant Physiol 60:850-853.

2. Ackerson RC, Krieg DR, Haring CL, Chang N (1977) Effects of plant water status on stomatal activity, photosynthesis, and nitrate reductase activity of field grown cotton. Crop Sci 17:81:84.

3. Cure JD, Acock B (1986) Crop responses to carbon dioxide doubling: a literature survey. Agric For Meteorol 38:127-145.

4. Drake BG, Rogers HH, Allen LH Jr (1985) Methods of exposing plants to elevated carbon dioxide. In Strain BR, Cure JD (eds) Direct Effects of Increasing Carbon Dioxide on Vegetation (DOE/ER-0238), US Department of Energy, Washington, DC, (available from NTIS, Springfield VA), pp 11-31.

5. Huber SC, Rogers H, Israel DW (1984a) Effects of CO_2 enrichment on photosynthesis and photosynthate partitioning in soybean (Glycine max) leaves. Physiol Plant 62:95-101.

6. Huber SC, Rogers HH, Mowry FL (1984b) Effects of water stress on photosynthesis and carbon partitioning in soybean (Glycine max [L.] Merr.) plants grown in the field at different CO_2 levels. Plant Physiol 76:244-249.

7. Hutmacher RB, Krieg DR (1983) Photosynthetic rate control in cotton: stomatal and nonstomatal factors. Plant Physiol 73:658-661.

8. Inoue Y, Kimball BA, Mauney JR, Jackson RD, Pinter PJ Jr, Reginato RJ (1990) Stomatal behavior and relationship between photosynthesis and transpiration in field-grown cotton as affected by CO_2 enrichment. Jpn J Crop Sci 59:510-517.

9. Kimball BA (1983) Carbon dioxide and agricultural yield: an assemblage and analysis of 430 prior observations. Agron J 75:779-788.

10. Louwerse W (1980) Effect of CO_2 concentration and irradiance on stomatal behavior of maize, barley and sunflower plants in the field. Plant Cell Environ 3:391-198.

11. Mauney JR, Fry KE, Guinn G (1978) Relationship of photosynthetic rate to growth and fruiting of cotton, soybean, sorghum, and sunflower. Crop Sci 18:259-263.

12. Morison JIL (1985) Sensitivity of stomata and water use efficiency to high CO_2. Plant Cell Environ 8:467-474.

13. Radin JW, Ackerson RC (1981) Water relations of cotton plants under nitrogen deficiency. III. Stomatal conductance, photosynthesis, and abscisic acid accumulation. Plant Physiol 67:115-119.

14. Radin JW, Parker LL (1979) Water relations of cotton plants under nitrogen deficiency. II. Environmental interactions on stomata. Plant Physiol 64:499-501.

15. Radin JW, Kimball BA, Hendrix DL, Mauney JR (1987) Photosynthesis of cotton plants exposed to elevated levels of carbon dioxide in the field. Photosynth Res 12:191-203.

16. Sionit N, Rogers HH, Bingham GE, Strain BR (1984) Photosynthesis and stomatal conductance with CO_2-enrichment of container- and field-grown soybeans. Agron J 76:447-451.

17. Wong SC (1979) Elevated atmospheric partial pressure of CO_2 and plant growth. I. Interactions of nitrogen nutrition and photosynthetic capacity in C_3 and C_4 plants. Oecologia 44:68-74.

Table 13-1

Midday net photosynthetic rates (± S.E.) of field-grown cotton leaves before (13-16 July) and after (11-15 August) 3 1/2 weeks of exposure to elevated CO_2. FACE plots were exposed to 550-600 μmol mol^{-1} CO_2 starting on 18 July. Control plots were exposed to ambient CO_2 (approximately 350 μmol mol^{-1}). The July measurements were made with a 4 ℓ cuvette. The August measurements were made with a 1 ℓ cuvette.

	13-16 July		11-15 August	
Plot	Days (n)	Photosynthetic Rate (μmol m^{-2} s^{-1})	Days (n)	Photosynthetic Rate (μmol m^{-2} s^{-1})
		FACE Plots		
1	1	18.7	3	35.7 ± 6.5
2	2	19.3 ± 2.3	2	45.5 ± 1.8
3	2	23.3 ± 1.7	4	21.5 ± 3.5
4	2	20.4 ± 1.4	1	27.4
Mean		20.4		32.5
		Control Plots		
5	2	19.8 ± 0.4	3	23.5 ± 2.5
6	2	19.0 ± 0.9	3	29.0 ± 2.2
7	2	21.6 ± 2.2	3	20.9 ± 0.7
Mean		20.1		24.5

Table 13-2

Midday stomatal conductance (± S.E.) of field-grown cotton leaves before (13-16 July) and after (11-15 August) 3 1/2 weeks of exposure to elevated CO_2. FACE plots were exposed to 550-600 μmol mol^{-1} CO_2 starting on 18 July. Control plots were exposed to ambient CO_2 (approximately 350 μmol mol^{-1}).

	13-16 July		11-15 August	
Plot	Days (n)	Stomatal Conductance (cm s^{-1})	Days (n)	Stomatal Conductance (cm s^{-1})
		FACE Plots		
1	1	1.83	3	1.96 ± 0.17
2	2	2.53 ± 0.23	2	2.16 ± 0.25
3	2	2.19 ± 0.04	4	0.72 ± 0.14
4	2	2.09 ± 0.02	1	1.58
Mean		2.16		1.60
		Control Plots		
5	2	2.27 ± 0.14	3	1.10 ± 0.23
6	2	2.31 ± 0.09	2	2.07 ± 0.04
7	2	1.87 ± 0.18	2	1.69 ± 0.11
Mean		2.15		1.62

COTTON LEAF AND BOLL TEMPERATURES IN THE 1989 FACE EXPERIMENT[1]

Bruce A. Kimball and Paul J. Pinter, Jr.
U. S. Water Conservation Laboratory
4331 East Broadway
Phoenix, AZ 85040

Jack R. Mauney
Western Cotton Research Laboratory
4135 East Broadway
Phoenix, AZ 85040

I. INTRODUCTION

Other chapters have described the 1989 Free-Air CO_2 Enrichment (FACE) experiment, which involved enriching the atmosphere to 550 μmol mol^{-1} of CO_2 over cotton in an open field at the University of Arizona Maricopa Agricultural Center (MAC). The prior work of Idso *et al.* (1987) showed that such enrichment in open-top chambers elevated the foliage temperatures of well-watered cotton by about 0.6 C (with a 95% confidence interval of about $\pm$ 0.3 C). Thus, one objective of the 1989 FACE experiment was to determine experimentally under open-field conditions how CO_2 concentrations like those expected in the future would affect cotton foliage temperatures.

The cotton growth model COTCO2 (J. S. Amthor and B. A. Kimball, 1990) is based on simulating physiological processes whose rates are dependent on the temperatures of the individual plant organs. Using actual plant temperatures contrasts with most previous plant models wherein plant temperatures are assumed to be at air temperature. Such an approach should enable COTCO2 to account for some of the interactive effects between CO_2 concentration and temperature. COTCO2 calculates the temperatures of specific organs by dynamically solving the energy balance of each organ for the microenvironmental conditions within the plant canopy at the sites of the organs. Therefore, validating leaf temperatures computed by the model is important for developing confidence in its predictive capabilities, and leads to another reason for measuring foliage temperatures.

---

[1]Contribution from the U. S. Department of Agriculture, Agricultural Research Service. Supported in part by the U. S. Department of Energy.

Under today's conditions, routine measurement of foliage temperatures can be used to estimate cotton plant water status, photosynthesis, and yield (Pinter and Reginato, 1982; Idso *et al.* 1982; Pinter *et al.*, 1983). The 1989 FACE experiment was planned to be well-watered, and the drip irrigation system was untested. Thus, a third reason to measure foliage temperature was that the information was deemed important from a day-to-day management standpoint in order to be sure that the equipment and strategy for scheduling irrigations did not introduce any water stress.

As mentioned above, the rates of processes in COTCO2 are driven by the temperatures of the organs in which they occur. Of course, some of the most important processes in a cotton plant are those involved with the growth of the bolls. Unlike leaves, however, which have stomata and are evaporatively cooled by transpiration, bolls have far fewer stomata (Elmore, 1973). Elmore (1973) has shown that the contribution of the capsule or boll wall is insignificant for CO_2 exchange. Yet, when they are small, the bolls are enclosed by a calyx that is composed of modified leaves or bracts, which have stomatal densities close to those of leaves and which take up CO_2 about 28% as efficiently as leaves (Elmore, 1973). Presumably the calyx could cool small developing bolls. Consequently, during the course of model development, the question arose as to how best to predict boll temperatures. Were they close to leaf temperatures when the bolls were small and deviated as the bolls grew? Did the degree of shading or exposure to solar radiation affect their temperature? To find the answer to these questions, an ancillary one-day experiment was conducted to measure temperatures of bolls and leaves in close proximity for bolls of various sizes and degrees of exposure to direct solar radiation.

II. METHODS

The measurements described in this chapter were obtained during the 1989 FACE experiment at the University of Arizona Maricopa Agricultural Center. Specific details are contained in other chapters, but briefly the cotton (*Gossypium hirsutum* L. cv Delta Pine 77) was planted on 17 April (day-of-year, DOY107) in east-west rows spaced 1.02 m (40 in) apart. Most of the plants emerged on 22 April (DOY112), and the population was thinned to approximately 100,000 plants ha^{-1} (10 plants m^{-1} of row) on 1 May (DOY121). Erection of the CO_2 dispensing apparatus began immediately after planting, and enrichment commenced on 20 May (DOY140) in FACE rings 1, 2, and 4. Enrichment of FACE ring 3, the so-called "engineering" ring for testing of alternative CO_2 dispensing strategies, started on June 10 (DOY161).

The field was irrigated with a subsurface drip irrigation system buried at 25 cm depth beneath each row. The system was operated by farm personnel who intended to provide ample water to the whole field with minimal water stress to the cotton. However, at the outset there were numerous skips in the field caused either by the planter or by inadequate wetting of the seed by the irrigation system. The FACE experimental plots were positioned away from larger skips, and additional plantings were done to fill minor gaps in the FACE plots. Through the course of the season, the plants in various areas in the field appeared to be water-stressed. Some of these areas were within the FACE plots. However, as will be shown later, the leaf temperature data suggest that the portions of the plots used for final harvest were generally well-watered.

A. Foliage temperature

The foliage temperatures were measured 2 to 4 times each week with an Everest Interscience[2] Model 112 infrared thermometer (IRT) with a 4° field-of-view. The data were automatically recorded with a portable Omnidata Polycorder computer and transmitted to IBM PC-AT type computers for later analysis. Before and after each set of field measurements were taken each day, readings were taken of the temperature of a black-body (BB) calibration source (Everest Interscience). Because the IRT generally agreed within about 1 °C of the BB temperature, and because before and after IRT-BB differences were generally within about 0.2 °C of each other, all the data on a particular day were adjusted by this average IRT-BB difference.

We measured foliage temperatures in both the enriched and ambient treatments on 35 days during the season beginning on 24 May (DOY144). The IRT operator walked a south to north transect that crossed 12 adjacent plant rows along the edge of an undisturbed section of canopy that was reserved for final harvest information and multispectral reflectance measurements (see Pinter *et al.*, chapter 15). Measurements of two, fully expanded, sunlit leaves were taken per row; twenty four observations were averaged for each replicate. All measurements were taken in the morning between 0930 h and 1130 h, approximately 30 min after reflectance measurements were completed. Data were averaged by treatments; observations obtained from the engineering array (replicate 3) before CO_2 enrichment had begun were excluded from the analysis. The operator made qualitative notes on weather and sky conditions during the measurement sequence. Dry (T_a) and wet bulb (T_w) air temperatures were obtained before and after IRT measurements using an aspirated Bendix psychrometer positioned in the field adjacent to the access road separating replicates 1 and 4 from replicates 2 and 3. Solar radiation (R_s) was measured by the University of Arizona's AZMET station approximately 2 km from our field site.

In addition to comparing the temperatures of the CO_2 enriched plots to those of the ambient control plots, the foliage temperatures were also analyzed within the context of a "crop water stress index" or "IJ" index (Idso *et al.*, 1987). The IJ index is measure of the rise of the foliage temperature above air temperature for a particular crop relative to the temperature rise of well-watered and non-transpiring water-stressed crops. Letting $\Delta T = T_f - T_a$ be the difference in temperature between the foliage, T_f, and air, T_a, the IJ index is defined:

$$IJ = (\Delta T - \Delta T_L)/(\Delta T_U - \Delta T_L) \qquad [1]$$

where ΔT_L is the foliage minus air temperature difference of a well-watered freely transpiring crop, and ΔT_U is the foliage minus air temperature difference of a non-transpiring very water-stressed crop. When a crop is well-watered, ΔT will be close to ΔT_L, so IJ will be close to zero, but as the soil dries and the

---

[2]Trade names and company names are included for the benefit of the reader and do not constitute an endorsement by the U. S. Departments of Agriculture or Energy.

crop becomes water stressed, ΔT increases closer to ΔT_U, and IJ tends toward a value of 1.0.

The lower temperature difference, ΔT_L, was computed using the following equation from Idso *et al.* (1987).

$$\Delta T_L = (r_a R_n)/(\rho c_p) - (e_f^* - e_a)/\{\gamma[1 + (r_c/r_a)]\} \quad [2]$$

where r_a and r_c are the aerodynamic and canopy resistances, respectively, R_n is the net radiation, ρ is the air density, c_p is the air heat capacity (1020 J kg^{-1} $°C^{-1}$), e_f^* is the saturation vapor pressure at the foliage temperature, e_a is the actual vapor pressure of the air, and γ is the psychrometric constant (0.067 kPa/°C). Using a barometric pressure of 95.0 kPa for Maricopa (elevation of 358 m), ρ = (95 kPa)(0.029 kg/mole)/[0.0083144 kPa m^3 $mole^{-1}$ °K (T_a + 273.16)]. The Tetens equation was used to calculate saturation vapor pressure from temperature: e (kPa) = 0.61078exp[17.1694T/(T+237.3)]. Following Idso *et al.*, values of 15 and 25 s m^{-1} were used for r_a and r_c, respectively, which had been obtained by fitting Eq. [2] to data for well-watered cotton at ambient CO_2. Net radiation was computed from the hourly AZMET solar radiation (Brown, 1987) using R_n = 0.738R_s - 70 W m^{-2}, an expression obtained by Fritschen (1967) over cotton.

B. Boll surface temperatures

The ancillary experiment to measure boll temperatures was conducted on 12 September on cotton in the same field but outside any of the FACE experiment plots. All of the bolls (68 total) from 15 selected plants were tagged from the top of plants down to and including the first open boll. The plants were selected by starting at a random spot in the row and then taking every 10th plant. There was a large range in the size of the plants with one of the plants having 20 bolls and 4 plants having only 1 boll each.

The measurements were taken using a "spot" infrared thermometer (Everest Interscience Model 112) whose optics were focused on a small spot about 20 cm from the end of the thermometer. A cone-shaped wire frame mounted on the front of the IRT enabled the operator to target individual bolls without other foliage or bolls getting in the field of view. The operator generally positioned himself so that the sun shown over his shoulder in the direction of target. Thus the boll temperature measurements were of the boll surface facing toward the sun. The thermometer data were automatically recorded on an Omnidata Polycorder portable computer. Concurrent manual notations were made as to whether the bolls were shaded, partly shaded, partly sunlit, or sunlit. Immediately after each boll temperature measurement, a second temperature measurement was made on a leaf as close as possible to that boll, which was about the same elevation in the canopy and which had about the same illumination.

The data were taken at hourly intervals from about 9:15 through 15:45 for 7 hours' worth of data or 476 sets of readings. Each measurement sequence required about 30 min to complete. Of course, as the sun angle changed during the day, some bolls that were sunlit in the morning became shaded and vice versa depending on their position with respect to other bolls and foliage. While the boll temperature study was underway, a data logger recorded 5-min-average air dry bulb temperatures from psychrometers mounted at the top of the crop (120 cm above

soil), with the air temperature closest to actual time of boll temperature observation being used for some of the data analyses. At the end of the day, the heights of bolls in the canopy above the soil surface were measured, and the percentage of the boll covered by the calyx was estimated. Then the plants were harvested. Then mainstem node number of each boll was recorded, and the bolls were cut from the plants, dried, and weighed.

III. RESULTS

A. Foliage temperatures

The foliage temperatures are plotted in Figure 14-1 against day of year for the FACE (550 μmol mol^{-1}) and ambient CO_2 treatments. Each point is the average of 24 observations per plot and of 4 reps (3 reps for the first 5 days). The standard errors of the means of each plot for each day averaged over reps and days of year were 0.22 and 0.21 for the FACE and ambient treatments, respectively. From late May until mid-September mid-morning foliage temperatures ranged from about 26 to 32 °C.

The temperature difference between the FACE and ambient CO_2 plots is plotted in Figure 14-2 against day of year. Before DOY200, the differences were striking; the enriched plots were consistently about 1 °C warmer than the ambient plots. After DOY200 the differences became rather scattered. Yet, the enriched plots were usually somewhat warmer than the ambient. Averaged over the 35 observation days, the enriched plots were 0.80 °C warmer with a 95% confidence interval from 0.58 to 1.02 °C. These free-air enrichment data are consistent with those of Idso *et al.* (1987) from open-top chambers. Their regression curve gives a value of 0.59 for the temperature difference at 550 μmol mol^{-1}, which is within the confidence interval for these data.

The foliage minus air temperature differences are plotted against the vapor pressure deficit (VPD) of the air in Figure 14-3. It is apparent that the temperature difference between foliage and air decreases strongly with increasing VPD (dryness of the air). The upper limit was calculated using a near-infinite value of 25,000 s m^{-1} for r_c. The lower baseline was computed (iteratively) from Eq. [2] following Idso *et al.* using R_n = 525 W m^{-2}, r_a = 15 s m^{-1}, and r_c = 25 s m^{-1}. A typical August value of 2.5 kPa was used for the actual vapor pressure and air temperature was varied to generate the curve. The lower baseline curve gives a good fit to the ambient CO_2 data, as well it should being developed originally by fitting to data from well-watered cotton at ambient CO_2. Because the ambient-CO_2 data are close to the lower baseline, apparently there was little water stress in those portions of the field where the foliage temperature observations were taken.

The FACE (550 μmol mol^{-1} CO_2) data are above those of the ambient plots in Figure 14-3. We interpret this to mean that the elevated CO_2 caused partial stomatal closure (Morison, 1987; Radin *et al*, 1988), thereby reducing transpiration and increasing leaf temperatures. Therefore, a baseline computed with a larger value of r_c would be more appropriate. In fact, such baselines for cotton enriched to 500 and 650 μmol mol^{-1} CO_2 were fitted by Idso *et al.* (1987) with r_c = 29.6 and 35.8 s m^{-1}, respectively (compared to 25 s m for ambient CO_2 conditions).

The lower baseline and upper limit curves in Figure 14-3 were computed using typical values for R_s and e_a. However, to account for day-to-day variations in R_s, solar radiation from the AZMET station was used to compute values of R_s for each measurement day with the expression of Fritschen (1967). The wet and dry bulb air temperature measurements from the psychrometer were used to compute e_a and ρ for each day. These daily lower baseline and upper limit values are plotted in Figure 14-4 against day of year, along with the actual measured foliage minus air temperature differences.

Graphically, the IJ index [Eq. 1] may be defined as the distance of the data points in Figure 14-4 above the lower baseline with respect to the total distance between the lower baseline and the upper limit. Accordingly, the IJ index was computed for each data point in Figure 14-4, and these indices are plotted against day of year in Figure 14-5. For most of the season, the IJ indices remained close to zero, indicating very little water stress for the ambient CO_2 plots. Early in the season when the plants were small, the indices were slightly elevated (0.2), but during this time, the thermometer easily could have viewed some warm soil, which would introduce a bias. Starting from DOY255 there appears to be slight water stress. However, the last irrigation was on DOY255 (12 September), so only on the very last observation day (DOY263) would the cotton be expected to exhibit some stress. Perhaps cooler temperatures (Figure 14-1) were causing some other stomatal effects at this time.

B. Boll surface temperatures

The relationships between boll surface and nearby leaf temperatures are summarized in Table 14-1. Sunlit bolls averaged 2.5 °C warmer than sunlit leaves (95% CL 1.65 to 3.33 °C). This result is lower than the 4 °C observed in a similar study recently completed by Chu and Henneberry (Chang-chi Chu, Personal Communication, 1991). Under shaded conditions, we found bolls were warmer than nearby leaves by an average 1.61 °C (1.39 to 1.83 °C), whereas Chu and Henneberry found shaded boll and leaf temperatures to be equivalent. Overall, the average increase of boll surface temperature in our study was 1.92 °C (1.70 to 2.14 °C). Suspecting that boll size may have played a role in our findings, we plotted the differences between boll surface and leaf temperatures versus boll size for both the sunlit and shaded conditions in Figures 14-6 and 14-7, respectively. No relationship was noted in either case. The boll-leaf temperatures were also plotted against solar radiation, against boll height above soil, and against the percentage of boll covered by calyx (data not shown). No relationship was found between leaf-boll temperature and any of these other variables. Thus it appears from our data that, during the daytime at least, boll temperature can be simulated from leaf temperature by simply assuming that the bolls are about 1.9 °C warmer than the leaves.

The foliage temperature can be simulated using Eq. [2] from measurements of air temperature and humidity and solar radiation, as was done in the previous section. However, the question remained as to whether there was any systematic variation of leaf temperature with height through the canopy. Therefore the air temperatures measured at the top of canopy with the weather mast psychrometer were subtracted from the leaf temperatures measured with the "spot" infrared thermometer, and these temperature differences are plotted against the height of the leaves above the soil in Figure 14-8 for the 1300-1400 h time period. No

relationship is apparent. There does appear to be a grouping or mode at about -3 °C. The mean at this time was -1.5 °C with a standard error of 0.3 °C (Table 14-2). Plots of leaf-air temperature against height in the canopy for the other time periods were similar to Figure 14-8, with no obvious effect of height in the canopy. The mean results from all the time periods are presented in Table 14-2, with the leaves averaging about 1.4 °C below air temperature through the day. Thus, these data suggest that an equation such as Eq. [2] can be used to predict foliage or leaf temperatures, and that no systematic adjustment of these temperatures needs to be made for the lower leaves in the canopy.

IV. SUMMARY AND CONCLUSIONS

Increasing CO_2 is known to cause partial stomatal closure, which can reduce transpirational cooling and raise leaf temperatures. To determine the degree of this effect with cotton under free-air CO_2 enrichment (FACE) conditions, measurements of foliage temperature were made with an infrared thermometer on cotton at 550 μmol mol^{-1} and ambient CO_2 concentrations on 35 days during the season. The results showed that this level of enrichment increased foliage temperatures by an average 0.80 °C (0.6 - 1.0 C = 95% confidence interval) above the ambient CO_2 plots.

The foliage temperature data were also analyzed within the context of the IJ index to test for any effects of water stress. Little or no water stress was apparent for most of the season for the portions of the ambient CO_2 plots where these measurements were taken. The IJ indices for the enriched plots were slightly higher. Rather than indicating that the CO_2-enriched plots were water-stressed, however, we interpret these higher IJ indices to mean that the baselines obtained under today's ambient CO_2 concentrations need to be adjusted upward for use under future higher CO_2 conditions.

Intensive measurements of boll surface temperatures were taken with a "spot" infrared thermometer on a single day late in the season. The bolls tended to be about 1.9 °C warmer than nearby leaves at comparable positions and illumination levels in the canopy. No correlations of boll-minus-leaf temperature with boll mass, with height above the soil, with solar radiation, or with percent of boll covered by calyx were found. Thus, boll temperatures apparently can be simulated from leaf temperatures by simply assuming the bolls are 1.9 °C warmer (1.7 - 2.1 C = 95% confidence interval).

V. ACKNOWLEDGEMENT

We gratefully acknowledge the technical assistance of R. Anderson and G. Peresta in collection and analysis of the data.

REFERENCES

1. Amthor JS, Kimball BA (1990) Predicting the growth and productivity of cotton in a future "greenhouse world": Development of a physiological model. Proc. Beltwide Cotton Production Research Conference, 9-14 January. Las Vegas NV, National Cotton Council of America, Memphis TN. 724.

2. Brown PW (1987) User's guide to the Arizona Meteorological Network. City of Phoenix, Water Conservation and Resource Div. and Arizona Cooperative Extension, Phoenix, AZ. 44 pp.

3. Elmore CD (1973) Contributions of the capsule wall and bracts to the developing cotton fruit. Crop Sci. 13:751-752.

4. Fritschen LJ (1967) Net and solar radiation relations over irrigated field crops. Agric. Meteorol. 4:55-62.

5. Idso SB, Kimball BA, Mauney JR (1987) Atmospheric carbon dioxide enrichment effects on cotton midday foliage temperature: Implications for plant water use and crop yield. Agronomy J. 79:667-672.

6. Idso SB, Reginato RJ, Radin JW (1982) Leaf diffusion resistance and photosynthesis in cotton related to a foliage temperature based plant water stress index. Agric. Meteorol. 27:27-34.

7. Morison JIL (1987) Intercellular CO_2 concentration and stomatal response to CO_2. In Zeiger E, Farquhar GD, and Cowan IR (eds) Stomatal Function, Stanford University Press, Stanford, California, pp 229-251.

8. Pinter PJ Jr, Reginato RJ (1982) A thermal infrared technique for monitoring cotton water stress and scheduling irrigations. Trans of the ASAE 25:1651-1655.

9. Pinter PJ Jr, Fry KE, Guinn G, Mauney JR (1983) Infrared thermometry: a remote sensing technique for predicting yield in water-stressed cotton. Agric. Water Management 6:385-395.

10. Radin JW, Hartung W, Kimball BA, Mauney JR (1988) Correlation of stomatal conductance with photosynthetic capacity of cotton only in a CO_2-enriched atmosphere: Mediation by abscisic acid. Plant Physiol. 88:1058-1062

FIGURE LEGENDS

Figure 14-1. Foliage temperatures from the 550 μmol mol^{-1} and ambient CO_2 plots versus day of the year, as measured by an infrared thermometer in the 1989 Free-Air CO_2 Enrichment (FACE) experiment. Each point is the mean of 2 observations per row (viewed from opposite sides), 12 rows per plot, and 4 replicate plots (3 plots for the first 5 observation days when Rep. 3 was not enriched) for a total of 96 observations per data point. The standard errors of the means (as computed each day for each plot and averaged over the 4 replicates and 35 observation days) were 0.22 and 0.21 C for the 550 and ambient CO_2 plots, respectively.

Figure 14-2. Foliage temperature difference between the 550 μmol mol^{-1} and ambient CO_2 plots of Figure 14-1 plotted against day of the year.

Figure 14-3. Foliage temperature minus air temperature plotted against vapor pressure deficit of the corresponding day for the 550 μmol mol^{-1} and ambient CO_2 plots for the data of Figure 14-1. The vapor pressure deficit was calculated from observations of dry and wet bulb air temperature taken at the start of the infrared thermometer readings. The lower baseline was computed following Idso *et al.* (1987) using 95 kPa for barometric pressure, 525 W m^{-2} for net radiation, 15 s m^{-1} for aerodynamic resistance, and 25 s m^{-1} for the canopy resistance. A typical August value of 2.5 kPa was used for the actual vapor pressure and air temperature was varied to generate the varying vapor pressure deficit of the baseline. The upper limit was computed using the same values but with a near-infinite canopy resistance.

Figure 14-4. Foliage temperature minus air temperature plotted against day of year for the 550 μmol mol^{-1} and ambient CO_2 plots for the data of Figure 14-1. As in Figure 14-3, the lower baseline was computed following Idso *et al.* (1987), using the same values for barometric pressure, and aerodynamic and canopy resistance. Unlike Figure 14-3, actual air temperature, vapor pressure, and net radiation were used. The net radiation was estimated from solar radiation data taken at the AZMET station 1 km from the field and converted to net with the equation, $R_n = 0.738R_s - 70$ W m^{-2} (for cotton from Fritschen, 1967). The upper limit was calculated from the same values as the lower baseline but with near-infinite canopy resistance.

Figure 14-5. IJ index calculated for the foliage minus air temperature differences in Figure 14-4. The IJ index is the ratio of the distance above the lower baseline to the total distance between the lower baseline and the upper limit.

Figure 14-6. Difference in temperature between sunlit boll surfaces and sunlit leaves at the same position in the canopy versus mass of the boll. Data taken with "spot" infrared thermometer on 12 September 1989 on ambient CO_2 cotton.

Figure 14-7. Difference in temperature between shaded boll surfaces and shaded leaves at the same position in the canopy versus mass of the boll. Data taken with "spot" infrared thermometer on 12 September 1989 on ambient CO_2 cotton.

Figure 14-8. Difference in temperature between cotton leaves and the air at the top of the canopy (120 cm height) at the same time versus height of the boll above the soil. Data taken with "spot" infrared thermometer on 12 September 1989 on ambient CO_2 cotton.

Table 14-1

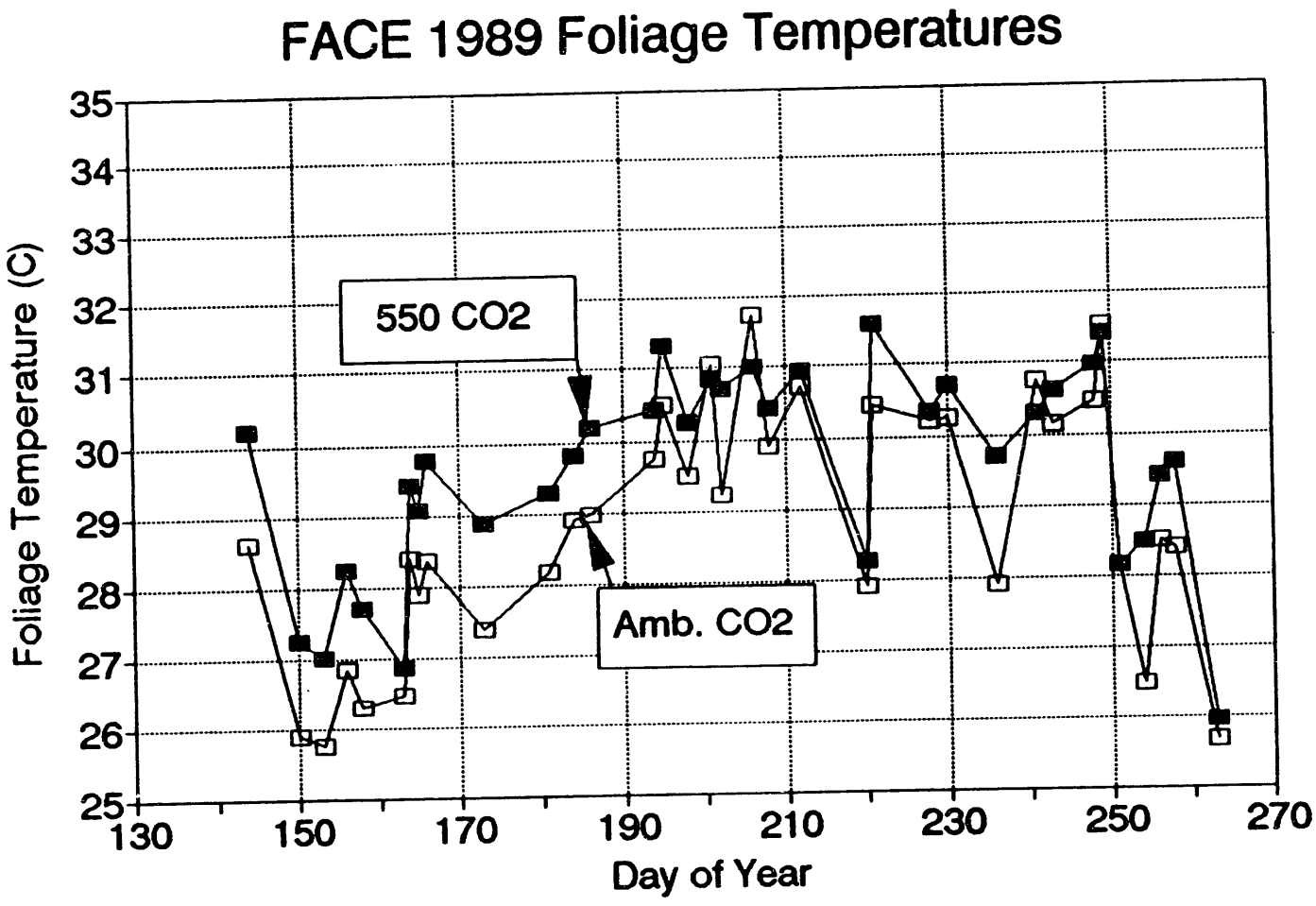
Elevation of cotton boll temperature above leaf temperature at same position in canopy on 12 September 1989 for various degrees of shading.

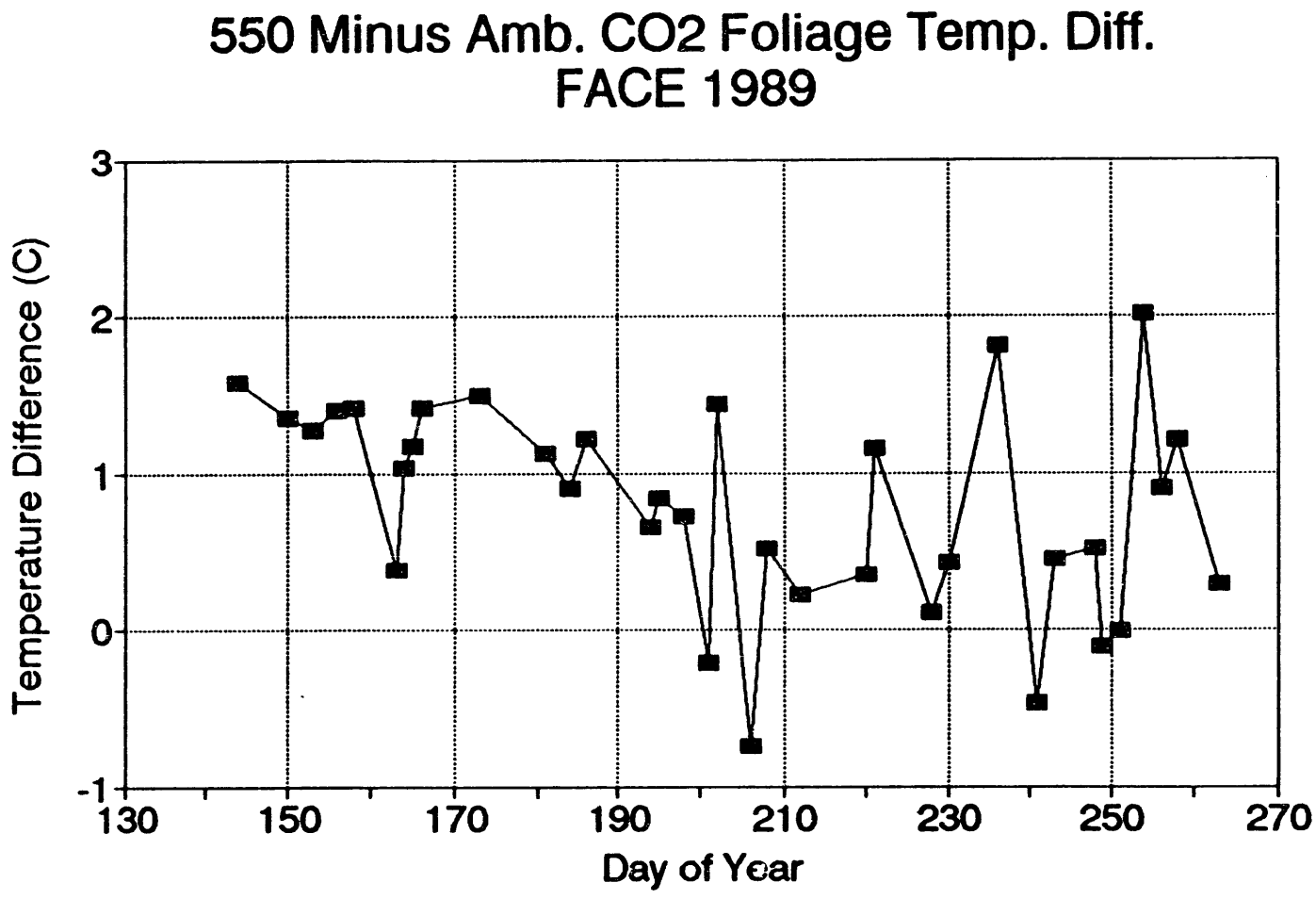
Shade Class	Number of Boll-Leaf Observations	Mean Boll Minus Leaf Temperature	Standard Error of Mean
		C	C
Shaded	190	1.61	0.11
Mostly shaded	139	2.50	0.15
Mostly sunlit	89	1.30	0.37
Sunlit	55	2.49	0.43
Overall	473	1.92	0.11

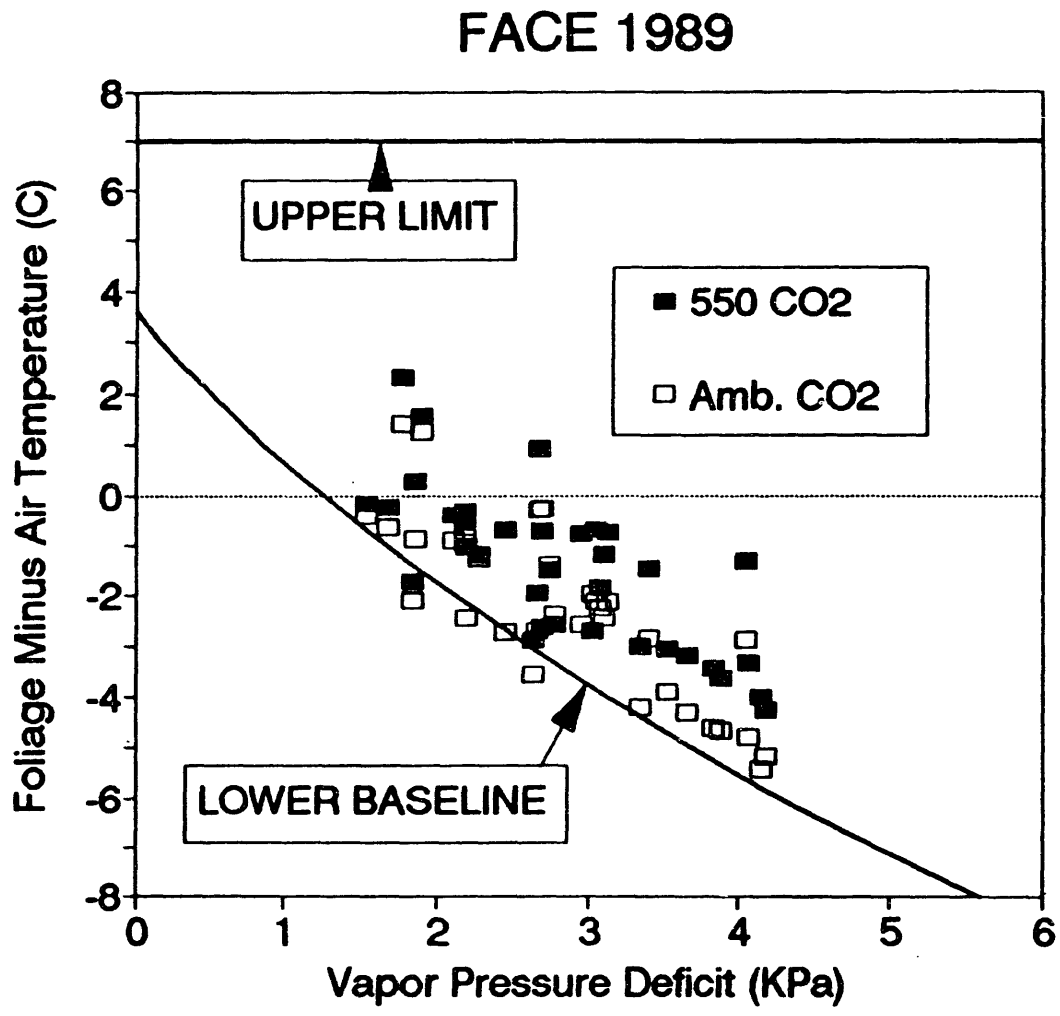
Table 14-2

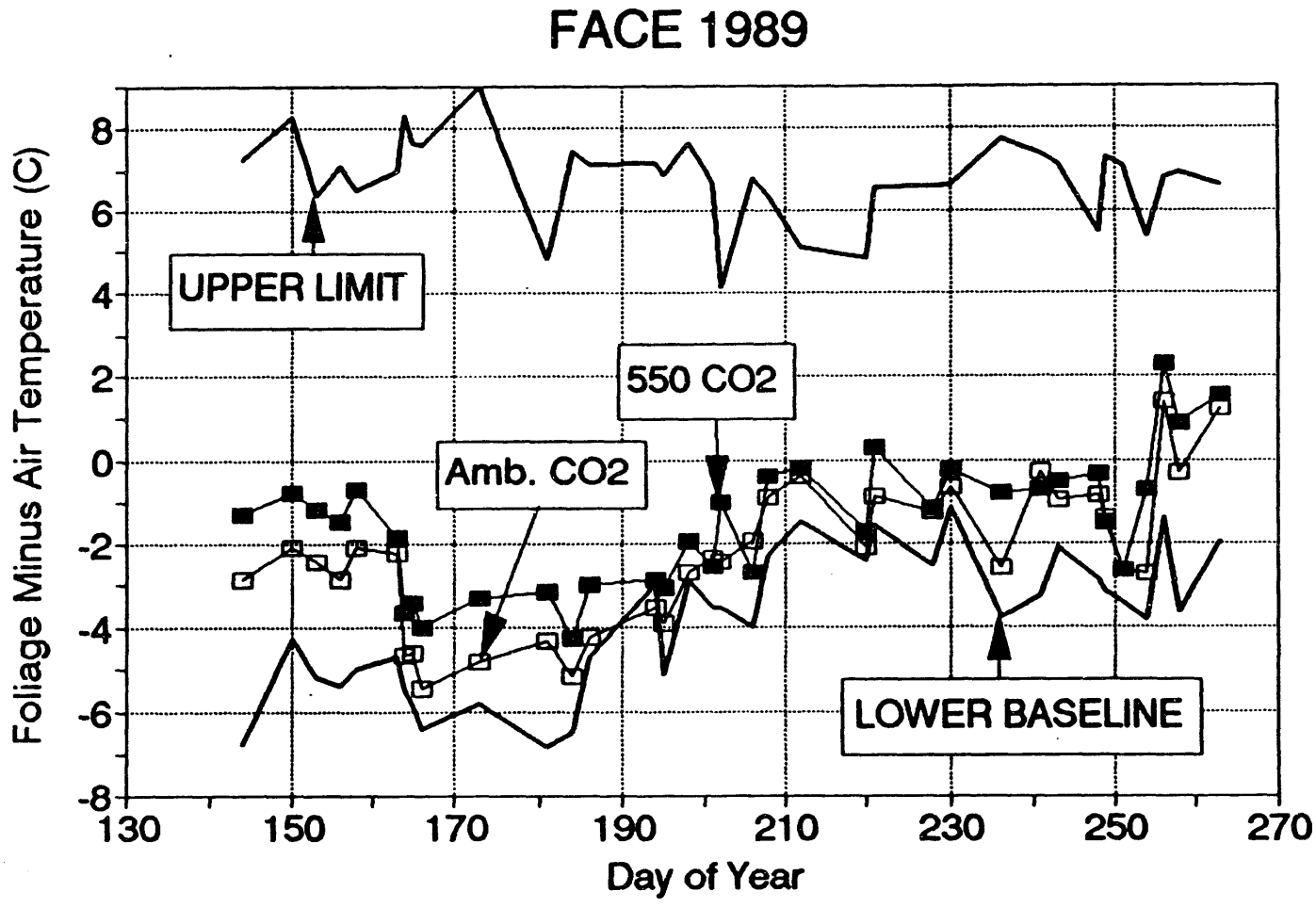
Mean cotton leaf temperatures at ambient CO_2 minus air temperature at the top of the canopy averaged over all canopy heights for several hours on 12 September 1989.

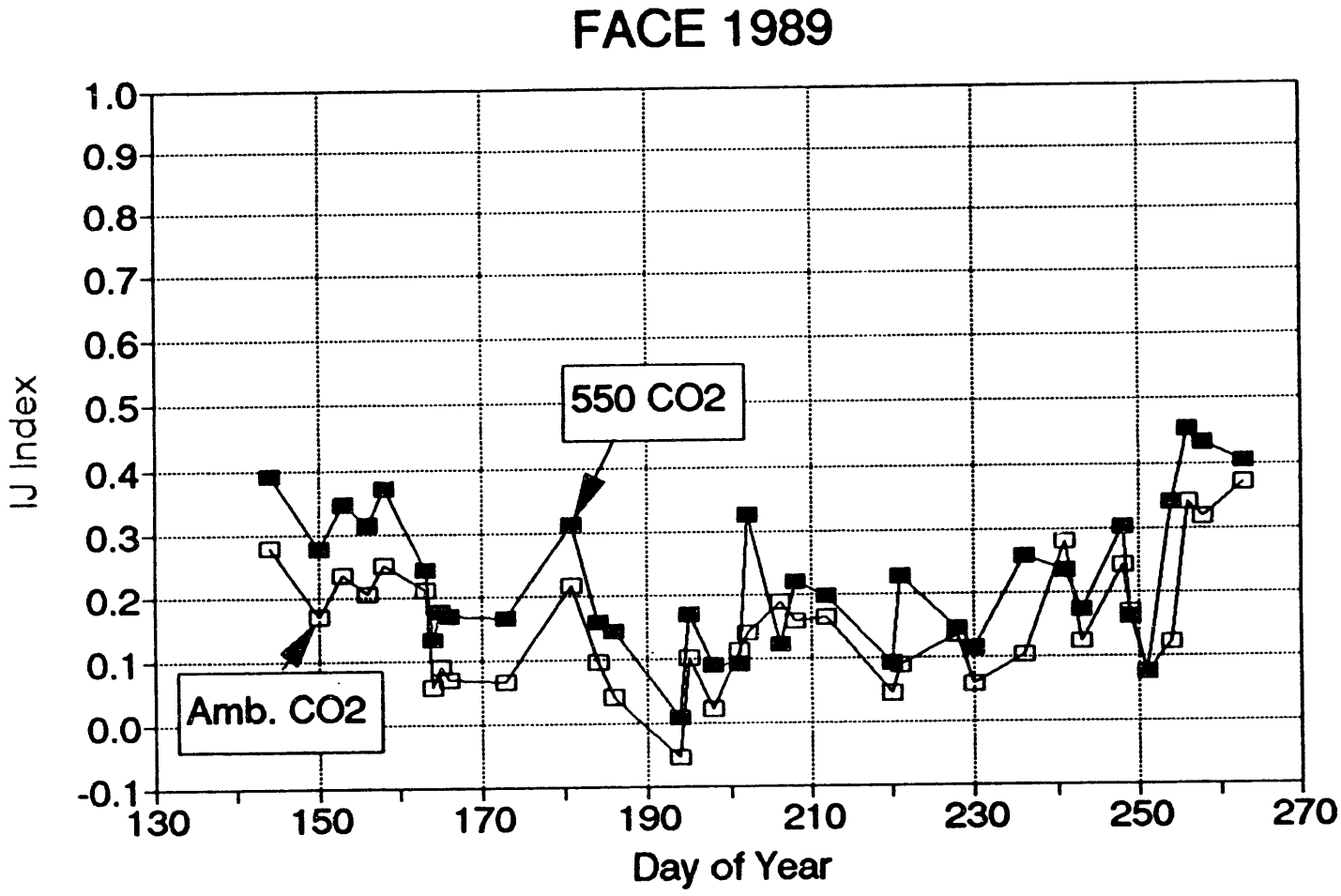
Time	Solar Rad	Air Temp. at Top of Canopy	Vap. Pres. Deficit at Top of Canopy	Mean Leaf Temp. Minus Air Temp.	Standard Error of Mean
MST	W m^{-2}	C	kPa	C	C
9-10	585	23.2	1.54	-0.4	0.4
10-11	769	28.8	2.03	-1.7	0.3
11-12	857	30.0	2.14	-1.3	0.4
12-13	885	30.4	2.16	-0.6	0.4
13-14	842	30.9	2.23	-1.5	0.3
14-15	711	30.5	2.10	-2.1	0.3
15-16	518	30.6	2.05	-2.3	0.2


FACE 1989 Foliage Temperatures
Foliage Temperature (C)
35
34
33
32
31
30
29
28
27
26
25
550 CO2
Amb. CO2
130
150
170
190
210
230
250
270
Day of Year


550 Minus Amb. CO2 Foliage Temp. Diff.
FACE 1989
Temperature Difference (C)
3
2
1
0
-1
130
150
170
190
210
230
250
270
Day of Year

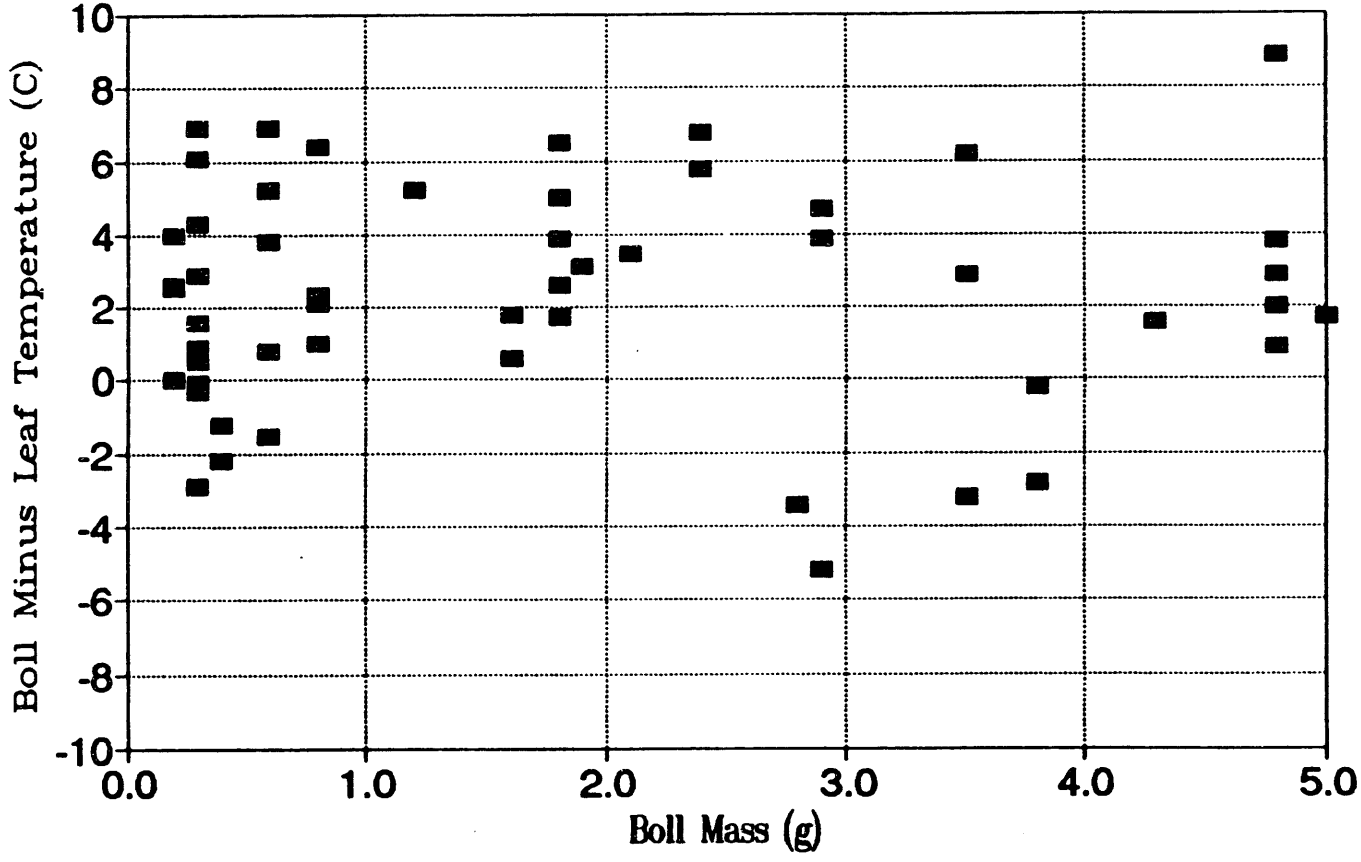

FACE 1989
UPPER LIMIT
LOWER BASELINE
550 CO2
Amb. CO2
Foliage Minus Air Temperature (C)
Vapor Pressure Deficit (KPa)
8
6
4
2
0
-2
-4
-6
-8
0
1
2
3
4
5
6


FACE 1989
Foliage Minus Air Temperature (C)
8
6
4
2
0
-2
-4
-6
-8
130
150
170
190
210
230
250
270
Day of Year
UPPER LIMIT
550 CO2
Amb. CO2
LOWER BASELINE


FACE 1989
IJ Index
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
-0.1
550 CO2
Amb. CO2
130
150
170
190
210
230
250
270
Day of Year

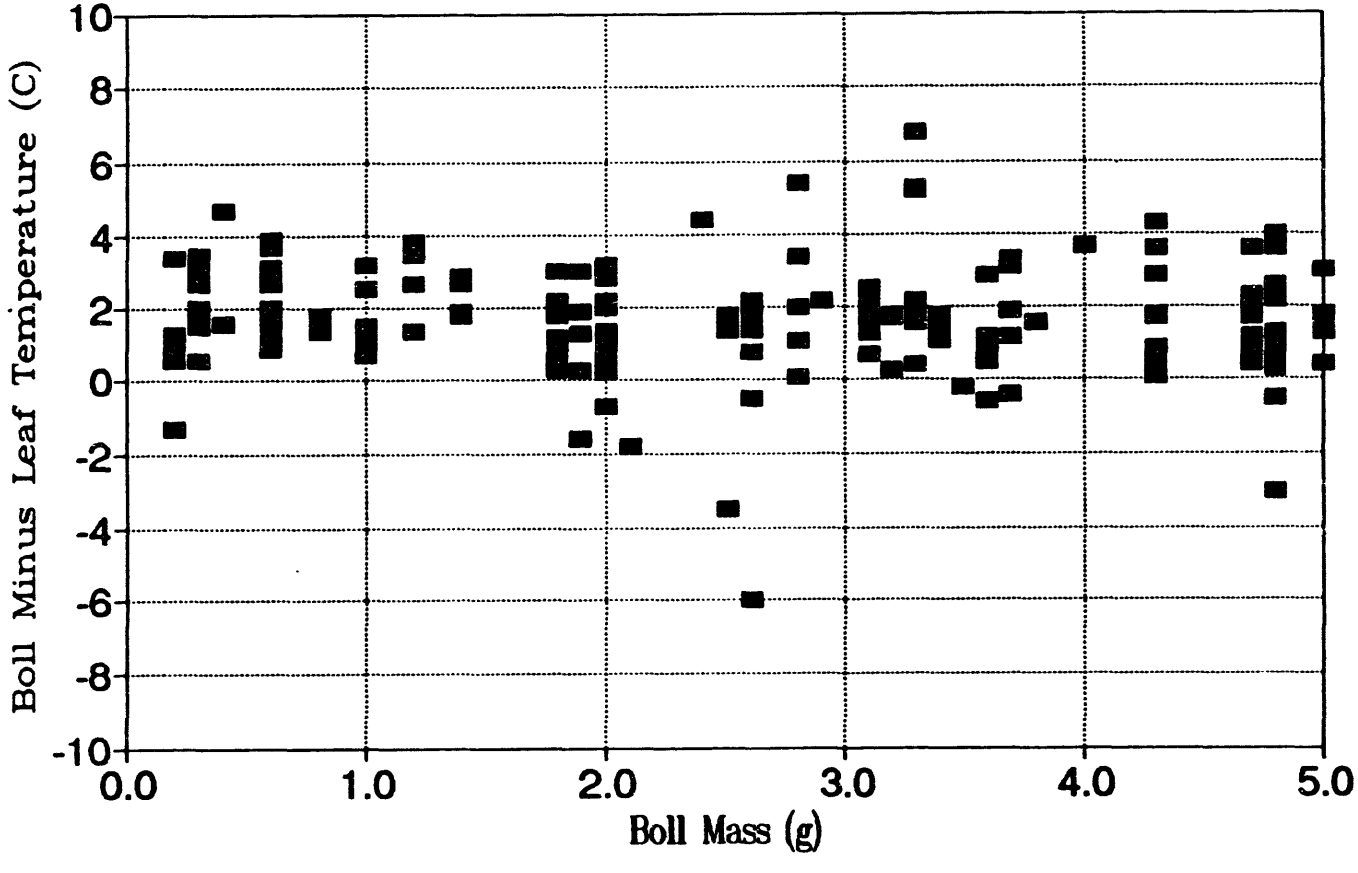
Sunlit Boll – Sunlit Leaf Temperatures

12 September 1989



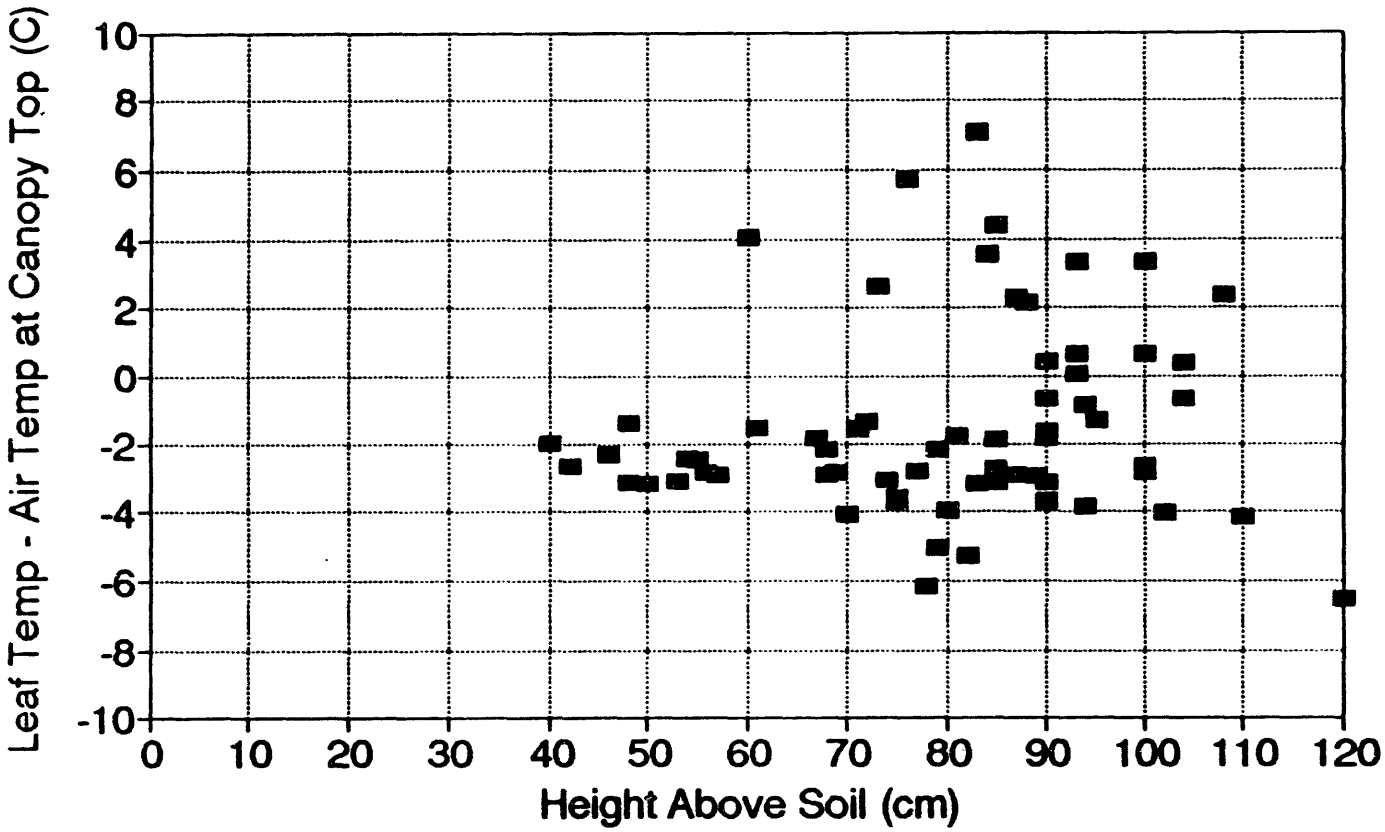
Shaded Boll – Shaded Leaf Temperature

12 September 1989



Leaf Temperature Profile

13:00-14:00 12 September 1989



EVALUATING COTTON RESPONSE TO FREE AIR CARBON DIOXIDE ENRICHMENT WITH CANOPY REFLECTANCE OBSERVATIONS

Paul J. Pinter, Jr., Robert J. Anderson, Bruce A. Kimball
USDA/ARS U.S. Water Conservation Laboratory
4331 East Broadway
Phoenix, AZ 85040

Jack R. Mauney
USDA/ARS Western Cotton Research Laboratory
4331 East Broadway
Phoenix, AZ 85040

I. INTRODUCTION

Most approaches for monitoring plant growth and development have serious drawbacks which limit their use in agricultural research programs. First of all, traditional methods for measuring above-ground green leaf area index (LAI) and biomass are very labor intensive, tedious and time consuming to execute. The size, number and frequency of samples required to characterize the plant canopy and detect statistically significant differences between treatments are usually large and often not practicable because of constraints on labor and space for cold storage and oven drying. Destructive sampling techniques are usually not appropriate in small research plots because the removal of some individuals from the population alters the response of remaining plants. Furthermore, the time required for physically separating leaves from stems and measuring them with a leaf area meter or waiting for tissues to dry in an oven precludes the use of these data in real-time decision making processes. Thus, important information that has immediate utility for assessing the efficacy of different treatments, identifying incipient problems, or guiding future sampling efforts is typically not available until several days or weeks after the samples have been collected.

Non-invasive, remote sensing techniques which use plant canopy reflectance to monitor changes in canopy condition avoid these problems while providing scientists with an efficient tool for research and management of their projects. The physical basis for this approach derives from the contrasting spectral reflectance properties of plant canopies and the underlying soil. Healthy green plant foliage typically has a very low reflectance (2-5%) in the visible portion of the electromagnetic spectrum and high reflectance (50-60%) in the near-infrared (NIR). By contrast reflectance of visible light from many soils may be an order of magnitude greater than that from green plants, while in the NIR it might be only half that of the plants.

Differences in reflectance characteristics of plants and soils can be enhanced by computing spectral vegetation indices (VIs) which are combinations of reflectances in two or more waveband intervals. VIs can assume the form of

simple band ratios, normalized differences between bands or linear combinations of bands which have been optimized to yield specific information about a plant canopy (Tucker 1979, Richardson and Wiegand 1977, Jackson 1983). The ratio of NIR/Red reflectances or a normalized difference between these bands [(NIR-Red)/(NIR+Red)] are common examples of VIs that are responsive to canopy LAI. Although band ratio VIs are particularly sensitive to changes in the angle of solar irradiance and view angle of the sensor (Pinter *et al.* 1990), they retain much of their information about the plant canopy under conditions of varying surface soil moisture, topography, illumination intensity, and intermittent cloud cover (Jackson *et al.* 1980, Pinter *et al.* 1987). These advantages are particularly important if remote measurements of canopy reflectance are to be used routinely as reliable estimates of plant response throughout the growing season.

Several spectrophotometric studies have examined the relationship between reflectance in visible and NIR wavelengths and the water relations, chloride concentration and pigment content of individual detached, cotton leaves (Thomas *et al.* 1967, 1971; Thomas and Gausman, 1977; Bowman, 1989.) Significant correlations were usually found when extreme conditions were included in the analysis. These authors point out that natural variation caused by other factors such as leaf age, interactions of light with multiple leaves within a canopy, etc. will prevent the use of detailed single leaf reflectance *per se* for detecting stress under more moderate and physiologically meaningful conditions..

Subtle differences in daily plant water status however, are ultimately expressed as relatively large differences in plant growth, ground cover, canopy architecture and development of leaf area. Thus at the level of the entire canopy, agronomic parameters are more amenable to detection by remote means. Thomas *et al.* (1967) for example, successfully used aerial infrared photography to estimate the yield of cotton subjected to varying levels of moisture stress during growth. Henneberry *et al.* (1979) demonstrated that aerial color infrared photography could detect effects of growth regulators, fertilizer treatment and disease in cotton. In 1984, Kimes *et al.*, characterized the directional reflectance characteristics of a long staple cotton canopy, *Gossypium barbadense* L., showing the importance of solar illumination angles and viewing direction on measured values. Jackson and Ezra (1985) made frequent reflectance measurements over a cotton canopy which was abruptly deprived of water. They attributed the significant changes in spectral response to changes in canopy architecture caused by severe wilting of the leaves. Huete (1985) then examined the reflectance of a developing upland cotton canopy (*G. hirsutum* L.) and related it to the spectral response of background soil conditions. Results of these investigations form the basis for using canopy reflectance for non-destructive monitoring of cotton growth and development during the season.

The experiment we describe here was designed to evaluate multispectral reflectance techniques for monitoring season-long cotton plant response to ambient and enriched carbon dioxide concentrations during 1989. Observations were made using a handheld radiometer configured to measure canopy reflectances in three visible and one NIR wavelength interval. Our objectives were: 1) to determine the feasibility of using a ground-based, handheld system for measuring spectral reflectance factors of a moderately tall, row crop; 2) establish relationships between plant characteristics and VIs calculated from canopy

reflectances of CO_2 enriched and ambient cotton; and 3) to monitor the temporal response of cotton to CO_2 enrichment via multispectral VIs.

II. METHODS

The reflectance measurements were carried out within the experimental framework provided by the 1989 large scale FACE Experiment (Free Air Carbon dioxide Enrichment). The experiment was conducted on upland cotton (*G. hirsutum* L. cv Delta Pine 77) grown in a 37 ha field on the demonstration farm at the University of Arizona's Maricopa Agricultural Center (MAC) located approximately 40 km south of Phoenix, AZ (33.075°N 111.983°W). The surface soils were classified as a reclaimed Trix clay-loam (fine-loamy, mixed (calcareous), hyperthermic Typic Torrifluvents). The field had been fallow for the previous 3 years and was in cotton production for approximately 10 years prior to that. Seeds were planted on 17 April 1989 in east/west oriented rows spaced at 1-m intervals. Plants within measured areas were thinned to approximately 100,000 ha^{-1} on 1 May. Water application to the entire field was by subsurface micro-irrigation (drip irrigation). Other cultural operations and agrichemical treatments [including aerial application of Pix (a commercial growth regulator), insecticides and defoliants] were applied according to local practices by farm personnel. Reflectance observations and plant samples were taken from within 20 m-diameter, open field, circular arrays (enriched during daylight hours with 550 $\mu mol\ mol^{-1}$ CO_2) and paired, open field, control canopy areas (with ambient CO_2 levels). Additional details on experimental design, CO_2 delivery system and actual CO_2 levels during the season are provided by Lipfert *et al.* (1991) and in companion chapters in this book.

A. Destructive Plant Sampling

Agronomic characteristics were estimated from 7 sets of destructive plant samples, beginning 30 May 89 and subsequently obtained at biweekly intervals until 23 August 89. The sampling routine consisted of removing every third cotton plant from a 3-m section of row in a predetermined location within the 550 $\mu mol\ mol^{-1}$ treated arrays and ambient controls. This was equivalent to sampling all the plants in 1.0 m^2 area, but did not leave exaggerated bare spots that would seriously impact aerodynamics of CO_2 flow in the canopy. This procedure usually yielded 9 or 10 plants per sample on each sampling date. The number of fruiting structures and the dry biomass of leaves, stems, fruit and roots were determined on all plants. Before drying, a subsample, consisting of all the green leaves from one of the plants, was measured using an optical leaf area meter. The total leaf area of the entire sample was then estimated using the area from the single plant subsample, it's associated wet biomass, and the wet biomass of the other plants in the sample. LAI was computed as the total leaf area of the sample (m^2) divided by the ground surface area (m^2) subtended by the sample.

B. Reflectance Measurements

Canopy reflectances were measured using an Exotech Model 100A[1] portable radiometer equipped with 15° field-of-view optics and spectral bandpass filters spanning 3 visible and one NIR wavelength intervals. Spectral filters were similar to the blue channel (0.45 to 0.52μm) on LANDSAT 5 and the green (0.50 to 0.59μm), red (0.61 to 0.68μm), and NIR (0.79 to 0.89μm) channels on SPOT satellite platforms. The radiometer was deployed along a permanent north-south transect which crossed 12 cotton rows in four replicate plots having the 550 μmol mol^{-1} treatment and 4 replicates of the ambient CO_2 control. The radiometer was extended at arm's length towards the east and held approximately 1.5 m above the soil surface. Data were collected at a rate of four, evenly-spaced measurements per row of plants. The sensor was always pointed in a nadir direction. Thus each lense viewed an area that was approximately 0.26 m in diameter when the plants were 0.5 m in height.

Multispectral observations were made 2 to 4 times each week from 17 May until 20 September 89 (40 data sets). Forty eight measurements in each wavelength interval were combined to yield an average reflectance for each transect. The entire measurement sequence over 8 transects (4-550 μmol mol^{-1} arrays and 4-ambient controls) required approximately 25-35 minutes to complete. To minimize the effects of changing solar zenith angle as the season progressed, observations were centered on a morning time period corresponding to a solar zenith angle of 45°. The solar azimuth during measurements varied from a minimum of 87° in June to a maximum of 134° in September; the mean azimuth was 100°. Qualitative observations of weather, sky conditions and canopy appearance were recorded at time of data collection.

Analog signals from the radiometer were recorded on a portable data acquisition system (Polycorder[1], Omnidata International, Inc.) which also registered the time when measurements were taken. Single band reflectance factors were calculated as the ratio of radiant exitance measured over each cotton target to irradiance inferred from a time-based linear interpolation of data collected at 15-minute intervals over a 0.6 by 0.6 m, horizontally positioned, calibrated, painted $BaSO_4$ reference panel. Correction factors were applied to the $BaSO_4$ data to compensate for its non-lambertian reflectance properties at a solar zenith of 45° (Jackson *et al.* 1987). The NIR/Red spectral vegetation index was computed as the NIR reflectance divided by red reflectance. The normalized difference (ND) was computed as the difference of NIR and red reflectances divided by their sum.

---

[1] Trade names and company names are included for the benefit of the reader and do not constitute an endorsement by the U. S. Department of Agriculture.

B. Reflectance Measurements

Canopy reflectances were measured using an Exotech Model 100A[1] portable radiometer equipped with 15° field-of-view optics and spectral bandpass filters spanning 3 visible and one NIR wavelength intervals. Spectral filters were similar to the blue channel (0.45 to 0.52μm) on LANDSAT 5 and the green (0.50 to 0.59μm), red (0.61 to 0.68μm), and NIR (0.79 to 0.89μm) channels on SPOT satellite platforms. The radiometer was deployed along a permanent north-south transect which crossed 12 cotton rows in four replicate plots having the 550 μmol mol^{-1} treatment and 4 replicates of the ambient CO_2 control. The radiometer was extended at arm's length towards the east and held approximately 1.5 m above the soil surface. Data were collected at a rate of four, evenly-spaced measurements per row of plants. The sensor was always pointed in a nadir direction. Thus each lense viewed an area that was approximately 0.26 m in diameter when the plants were 0.5 m in height.

Multispectral observations were made 2 to 4 times each week from 17 May until 20 September 89 (40 data sets). Forty eight measurements in each wavelength interval were combined to yield an average reflectance for each transect. The entire measurement sequence over 8 transects (4-550 μmol mol^{-1} arrays and 4-ambient controls) required approximately 25-35 minutes to complete. To minimize the effects of changing solar zenith angle as the season progressed, observations were centered on a morning time period corresponding to a solar zenith angle of 45°. The solar azimuth during measurements varied from a minimum of 87° in June to a maximum of 134° in September; the mean azimuth was 100°. Qualitative observations of weather, sky conditions and canopy appearance were recorded at time of data collection.

Analog signals from the radiometer were recorded on a portable data acquisition system (Polycorder[1], Omnidata International, Inc.) which also registered the time when measurements were taken. Single band reflectance factors were calculated as the ratio of radiant excitance measured over each cotton target to irradiance inferred from a time-based linear interpolation of data collected at 15-minute intervals over a 0.6 by 0.6 m, horizontally positioned, calibrated, painted $BaSO_4$ reference panel. Correction factors were applied to the $BaSO_4$ data to compensate for its non-lambertian reflectance properties at a solar zenith of 45° (Jackson *et al.* 1987). The NIR/Red spectral vegetation index was computed as the NIR reflectance divided by red reflectance. The normalized difference (ND) was computed as the difference of NIR and red reflectances divided by their sum.

---

[1] Trade names and company names are included for the benefit of the reader and do not constitute an endorsement by the U. S. Department of Agriculture.

III. RESULTS AND DISCUSSION

A. Agronomic Characteristics

Above-ground, dry biomass accumulated in a fairly linear fashion from 30 May (DOY150) until 23 August (DOY235; Figure 15-1), increasing more rapidly in the 550 μmol mol^{-1} CO_2 treated cotton than the ambient controls. Most of this difference was caused by larger boll numbers and heavier bolls and stems in the CO_2 enriched treatment (data not shown). Green LAI increased in a typical manner during the first part of the season. In direct conflict with destructive samples however, our visual observations from mid-July until late-August suggested that there were large differences between LAI of enriched and ambient cotton. During this period, spider mite populations (*Tetranychus sp.*) built to economically damaging levels in the higher CO_2 treatment (see chapter by Akey in this book). We believe this caused the extensive, atypical leaf shedding and slowing of new growth which appears in LAI data shown in Figure 15-1. Spider mites did not reach damaging levels in the ambient controls. Indeed, our visual assessment of the controls revealed those plants were still growing rapidly and leaf area continued to increase on DOY208 and 221 instead of declining as the data in Figure 15-1 indicate. The discrepancy between visual observations and destructive samples in the ambient CO_2 treatment may have been caused by the relatively small number of plants in each sample and the fact that they may not have been representative of the control area as a whole.

B. Soil Reflectance

Bare soil reflectances were measured routinely in the experimental field on a 1 by 1 m patch of sunlit soil adjacent to the cotton canopy. Reflectances for each waveband are shown in Figures 15-2, 15-3, 15-4, and 15-5 for 23 mostly clear days when cloud cover was less than 20% and not present within 20-30° of the sun. Reflectance factors of the clay loam soil increased with wavelength, averaging about 7-8% in the blue, 10-11% in the green, 15-16% in the red and 20-25% in the NIR. The day-to-day variation displayed in each waveband was caused principally by differences in surface moisture conditions. In the red, for example, reflectances dropped abruptly to 12% on DOY181 (Figure 15-4) when capillary action moistened the soil surface above the subsurface drip line. Reflectances in all wavelengths increased gradually after DOY212 as the surface soils became progressively drier.

C. Canopy Reflectance

Reflectance factors for 550 μmol mol^{-1} and ambient CO_2 cotton are also shown in Figures 15-2, 15-3, 15-4, and 15-5 for clear days. Data in these and subsequent figures represent mean values from the three replicate treatments having similar CO_2 enrichment regimes and means from three matched ambient CO_2 controls. Reflectances from replicate 4 were not included because the CO_2 in that array was not turned on until several weeks after measurements had begun. Initially, reflectances from the treated and ambient cotton were very similar to the bare soil. Then as the canopy developed and covered more of the soil, the spectral characteristics of the soil were dominated by reflectances typical of

vigorous green foliage. By early August, reflectance in the visible portion of the spectrum decreased to between 2 and 5%, while in the NIR it increased to more than 50%.

CO_2 treatment differences were apparent in each wavelength interval. In the three visible wavebands (Figures 15-2 to 15-4), cotton in the enriched treatment displayed slightly higher reflectances until the second week of June (DOY160). From then until mid-July (DOY200), visible reflectances from the enriched cotton were consistently lower but the differences were relatively small. Rather large differences between CO_2 treatments became evident in green wavelengths during September (Figure 15-3, after DOY248). This may have been caused by late season changes in pigments of individual leaves. During that time, large numbers of adult whiteflies, *Bemisia sp.*, were also present in the upper portions of the canopy; the shiny honeydew they deposited on the upper surfaces of leaves may have caused a specular increase in visible reflectance.

In the NIR (Figure 15-5), differences between CO_2 treatments were more conspicuous and opposite from those observed in the visible wavelengths (Figures 15-2 to 15-4). NIR reflectances from the enriched plants were several percent higher than ambient controls during three weeks in June (DOY153 until DOY175). These data were consistent with larger and more vigorous plants in the enriched treatment during that period. For several weeks, NIR reflectances of both treatments were similar. Then, after mid-July (DOY193) enriched plants displayed lower NIR reflectance factors. By mid-August (DOY226), NIR measured in the enriched canopy was fully 7% lower than the ambient controls, supporting the visual impression of substantial canopy decline in the 550 $\mu mol\ mol^{-1}$ treatment.

C. Spectral Vegetation Indices

The season long trajectories of the NIR/Red and ND are shown in Figures 15-6 and 15-7 for the bare soil, enriched and ambient cotton targets. These data are smoother than the reflectance factor data (Figures 15-2 to 15-5) because band ratioing techniques suppress variation in single band reflectances caused by day-to-day changes in illumination intensity and cloudy skies (Pinter *et al.* 1987). As a result all 40 days of spectral data are shown in Figures 15-6 and 15-7. While both VIs enhanced the contrast between bare soil and the cotton canopy, the NIR/Red ratio was particularly effective at minimizing variation in soil reflectance caused by changes in surface moisture content on DOY181.

The NIR/Red and ND differed in their ability to portray changes in canopy density at various times of the season. The NIR/Red (Figure 15-6) increased slowly with the gradual increase of ground cover by the developing canopy. By the beginning of July, the NIR/Red in the ambient CO_2 canopy was between 5 and 6 units, only one third of the maximum value of 17 units observed six weeks later in mid-August (DOY228). The ND however, increased more rapidly at the beginning of the season (Figure 15-7). By early July, the ND had already attained approximately 75% of its maximum value. The asymptotic nature of ND relationship with canopy development was evident in data collected after the last week in July (DOY210). The ND did not change much from that time until measurements were terminated in mid-September. The NIR/Red however, showed distinct differences between CO_2 treatments from DOY210 to 248 and then declined sharply after DOY249. We suspect that this late-season decline was caused by increases in red

reflectance due to pigment changes associated with leaf senescence or the shiny honeydew residue mentioned earlier.

The NIR/Red VI appeared more useful than the ND when related to experimental variables during mid- and late-season. To further emphasize the effect of CO_2 treatment, the NIR/Red measured over the ambient cotton was subtracted from the NIR/Red from the enriched cotton and graphed versus day of the year (Figure 15-8). Large positive values were apparent during June and early July (DOY165 to 185), when the 550 μmol mol^{-1} CO_2 treatment was enhancing growth. Later, during most of July and August when leaf drop and spider mite infestations precipitated a dramatic decline in the visual appearance of the enriched cotton, large negative values were observed.

The NIR/Red difference (Figure 15-8) was also very responsive to canopy regrowth following various management procedures applied to the cotton (see chapter by Mauney *et al.* in this book). As an example, foliar nutrients were sprayed on both the enriched and ambient cotton on 9 August (DOY221) after tissue sampling confirmed plants in the enriched treatment had suboptimum nutrient status. At about the same time, the micro irrigation system was changed from subsurface to surface lines capable of delivering a more reliable supply of water to the plants. The plants in the enriched treatment responded almost immediately. The sharp reversal in the NIR/Red difference after 14 August (DOY226) was associated with observations of marked regrowth in the canopy.

By the first week in September (DOY249) both the enriched and ambient cotton canopies were similar from a spectral VI standpoint, then they began to diverge again. Assuming that the general decrease in NIR/Red during this time was caused either by pigment changes or honeydew deposits, then the faster decrease in the NIR/Red suggests that these changes or damage were greater in the enriched treatment. More research is needed to clarify these late season spectral phenomena.

Finally, there appears to be a correlation between daily changes in VIs and spraying of Pix, a commercial growth regulator intended to suppress vegetative canopy development and enhance reproductive development. Close inspection of Figures 15-6 and 15-7 reveals two transient plateaus in the overall increase of NIR/Red and ND during the early and middle portion of the season. The first, between DOY174 and DOY186 is most conspicuous. It follows the aerial application of Pix (1,1-dimethyl-piperidinium chloride; 0.58 l ha^{-1}) to the entire field on DOY173. The second plateau is just a momentary blip (DOY195 to 198) which can only be detected in the enriched cotton, but it also follows a second application of Pix on DOY192. The timing of the two Pix applications and subsequent changes in VIs may be coincidental. However, if a growth regulator acts as intended, spectral vegetation indices should be capable of monitoring its effect.

D. Predicting Biomass and LAI from VIs

Biweekly samples of cotton plants from enriched and ambient CO_2 treatments provided an opportunity to test the hypothesis that spectral vegetation indices were a function of agronomic characteristics of the canopy. Average biomass and LAI data for cotton within each array and ambient control were paired with spectral VIs measured in the same replicate on the same day. Spectral data were interpolated linearly for two plant sampling dates when reflectance data were not taken. Results for the NIR/Red versus biomass are shown in Figure 15. They

suggest that the relationship between NIR/Red and biomass was dependent upon CO_2 treatment during the 1989 FACE experiment. This is because the ratio of leaf area to total biomass was different in the two treatments, especially during the middle portion of the growing season when the larger plant samples were obtained (Figure 15-1, DOY208 to 235). A nadir viewing radiometer viewed mostly leaves in the ambient canopy during this time and a higher vegetation index was obtained. In the enriched cotton however, many of the leaves had been shed and the index was more strongly influenced by the spectral characteristics of the stems and bolls. A similar phenomena was observed in alfalfa, where selective grazing by sheep stripped leaves from plant stems and decreased the NIR/Red index without appreciably reducing biomass (Mitchell *et al.*, 1990).

The relationship between green LAI and NIR/Red measured during the experiment yielded results that were much more variable than those for biomass (Figure 15-10). They imply that similar relationships exist for both CO_2 enriched and ambient cotton plants. Because of the discrepancy between visual observations of the canopy and the destructive plant samples discussed earlier in this chapter, the data of both Figures 15-9 and 15-10 should be viewed as preliminary until verified with additional measurements.

IV. CONCLUDING REMARKS AND NEEDS FOR ADDITIONAL RESEARCH

Canopy level observations of single band reflectance factors and multispectral vegetation indices were used to monitor the response of cotton to elevated CO_2 concentrations during the 1989 FACE experiment. These data were sensitive to the amount and condition of green plant material viewed by the radiometer, revealing foliage response to mite and insect pressure, growth regulating chemicals and nutrient conditions. Differences in plant growth, leaf area and biomass between cotton in enriched and ambient CO_2 treatments were evident in season-long vegetation indices. This information was not degraded appreciably when measurements were taken under cloudy sky conditions. Because of the speed and facility with which measurements could be taken and processed, we found them useful for augmenting less frequent destructive plant sampling procedures and very practical for monitoring and supervising the experiment in a near-real time capacity.

Faced with the prospect of rising levels of atmospheric CO_2, additional research is needed to verify relationships between spectral data and agronomic parameters of CO_2 enriched plants. We found significant correlations between the NIR/Red index and cotton biomass; its relation with leaf area index was weaker but still significant. Our preliminary data suggest that the relationship between biomass and spectral vegetation indices is a function of CO_2 concentration in the plant environment. Such findings will affect interpretation of VIs acquired via satellite sensors and used to estimate carbon balance on a global scale in the future (*eg.* see Tucker, *et al.* 1986). Upcoming research in FACE experiments will address the relationship between spectral VIs and photosynthetically active radiation absorbed by the canopy and examine the effect of CO_2 on high resolution reflectance and absorption spectra of single leaves.

REFERENCES

1. Bowman WD (1989) The relationship between leaf water status, gas exchange and spectral reflectance in cotton leaves. Remote Sens. Environ. 30:249-255.

2. Henneberry TJ, Hart WG, Bariola LA, Kittock DL, Arle HF, Davis MR, Ingle SJ (1979) Parameters of cotton cultivation from infrared aerial photography. Photogrammetric Engineering and Remote Sens. 45:1129-1133.

3. Huete AR, Jackson RD, Post DF (1985) Spectral response of a plant canopy with different soil backgrounds. Remote Sens. Environ. 17:37-53.

4. Jackson RD (1983) Spectral indices in n-space. Remote Sens. Environ. 13:409-421.

5. Jackson RD, Ezra CE (1985) Spectral response of cotton to suddenly induced water stress. International J. Remote Sens. 6:177-185.

6. Jackson RD, Jones CA, Uehara G, Santo LT (1980) Remote detection of nutrient and water deficiencies in sugarcane under variable cloudiness. Remote Sens. Environ. 11:327-331.

7. Jackson RD, Moran MS, Slater PN, Biggar SF (1987) Field calibration of reference reflectance panels. Remote Sens. Environ. 22:145-158.

8. Kimes DS, Newcomb WW, Schutt JB, Pinter PJ Jr, Jackson RD (1984) Directional reflectance factor distributions of a cotton row crop. Int. J. Remote Sens. 5:263-277.

9. Lipfert F, Alexander Y, Lewin K, Hendrey G, Nagy J (1991) A turbulence-driven air fumigation facility for studying air pollution effects on vegetation. Pages J199-202 in Seventh Symposium on Meteorological Observations and Instrumentation and Special Sessions on Laser Atmospheric Studies, 14-18 January, 1991, New Orleans, LA.

10. Mitchell AR, Pinter PJ Jr, Guerrero JN, Hernandez CB (1990) Spectral reflectance measurements of alfalfa under sheep grazing. Agronomy Journal 82:1098-1103.

11. Pinter PJ Jr, Kelly HL Jr, Schnell S (1987) Spectral estimation of alfalfa biomass under conditions of variable cloud cover. Pages 83-86 in 18th Conference on Agricultural and Forest Meteorology, 15-18 Sept. 1987, West Lafayette, IN.

12. Pinter PJ Jr, Jackson RD, Moran MS (1990) Bidirectional reflectance factors of agricultural targets: A comparison of ground-, aircraft-, and satellite-based observations. Remote Sens. Environ. 32:215-228.

13. Pinter PJ Jr, Zipoli G, Maracchi G, Reginato RJ (1987) Influence of topography and sensor view angles on NIR/red ratio and greenness vegetation indices of wheat. International Journal of Remote Sensing 8:953-957.

14. Richardson AJ, Wiegand CL (1977) Distinguishing vegetation from soil background information. Photogrammetric Engineering and Remote Sensing 43:1541-1552.

15. Thomas JR, Wiegand CL, Myers VI (1967) Reflectance of cotton leaves and its relation to yield. Agronomy Journal 59:551-554.

16. Thomas JR, Namken LN, Oerther GF, Brown RG (1971) Estimating leaf water content by reflectance measurements. Agronomy Journal 63:845-847.

17. Thomas JR, Gausman HW (1977) Leaf reflectance vs. leaf chlorophyll and carotenoid concentrations for eight crops. Agronomy Journal 69:799-802.

18. Tucker CJ (1979) Red and photographic linear combinations for monitoring vegetation. Remote Sensing of Environment 8:127-150.

19. Tucker CJ, Fung IY, Keeling CD, Gammon RH (1986) Relationship between atmospheric CO_2 concentrations and a satellite-derived vegetation index. Nature 319:195-199.

FIGURE LEGENDS

Figure 15-1. Agronomic data from destructive cotton samples in the 1989 FACE experiment.

Figure 15-2. Reflectance factors from soil and cotton in the blue (0.45 to 0.52 μm) wavelength interval. Data are for clear days only.

Figure 15-3. Reflectance factors from soil and cotton in the green (0.50 to 0.59 μm) wavelength interval. Data are for clear days only.

Figure 15-4. Reflectance factors from soil and cotton in the red (0.61 to 0.68 μm) wavelength interval. Data are for clear days only.

Figure 15-5. Reflectance factors from soil and cotton in the NIR (0.79 to 0.89 μm) wavelength interval. Data are for clear days only.

Figure 15-6. Season-long NIR/Red vegetation index measured during the 1989 FACE experiment. This figure also includes data collected on cloudy days.

Figure 15-7. Season-long normalized difference vegetation index measured during the 1989 FACE experiment. This figure also includes data collected on cloudy days.

Figure 15-8. The difference between the NIR/Red vegetation index measured in the FACE (550 μmol mol^{-1} CO_2) treatment and the ambient CO_2 controls versus day of the year. This figure also includes data collected on cloudy days.

Figure 15-9. Least squares linear regression between NIR/Red vegetation index and biomass of FACE (550 μmol mol^{-1} CO_2) and ambient CO_2 controls.

Figure 15-10. Least squares regression between NIR/Red vegetation index and green leaf area index of FACE (550 μmol mol^{-1} CO_2) and ambient CO_2 controls.

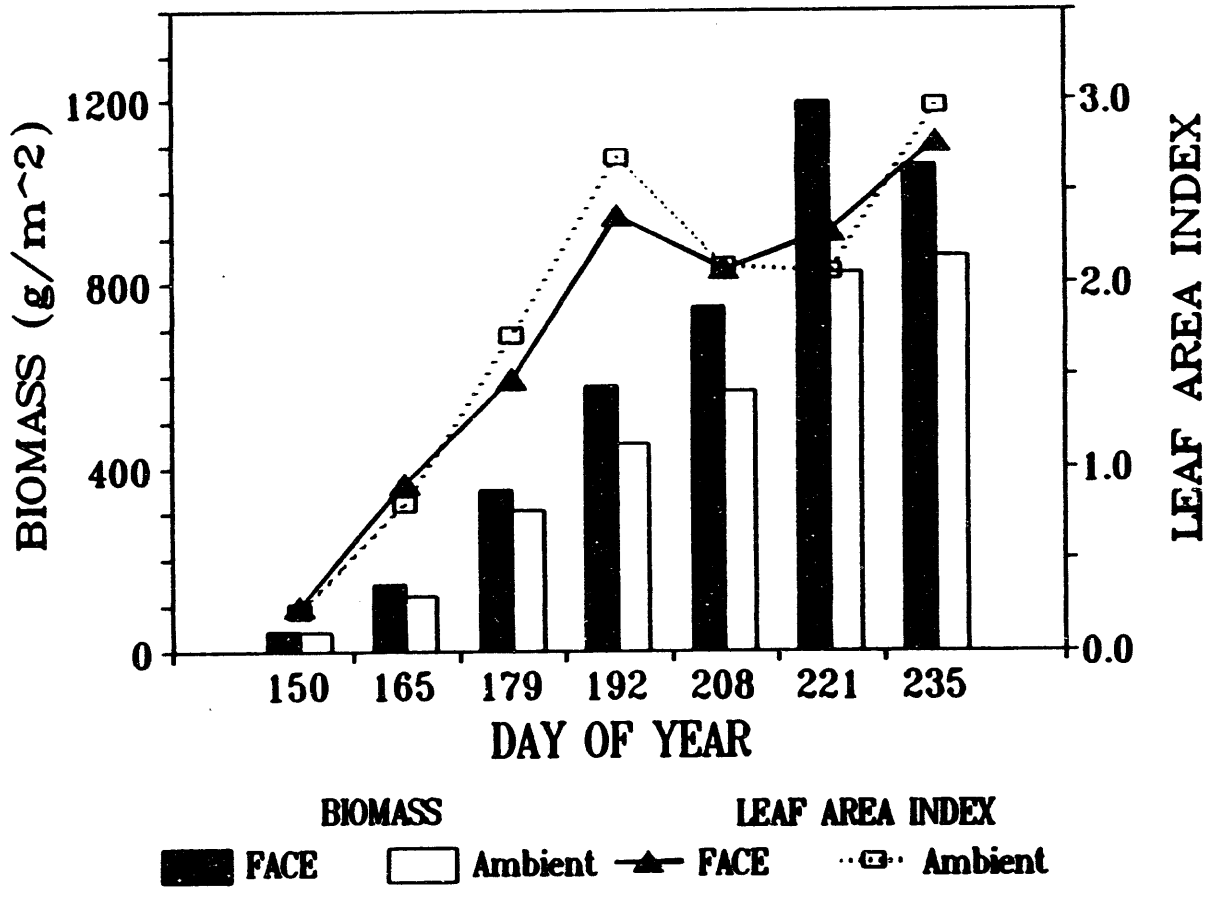


Figure 15-1. Agronomic data from destructive cotton samples in the 1989 FACE experiment.

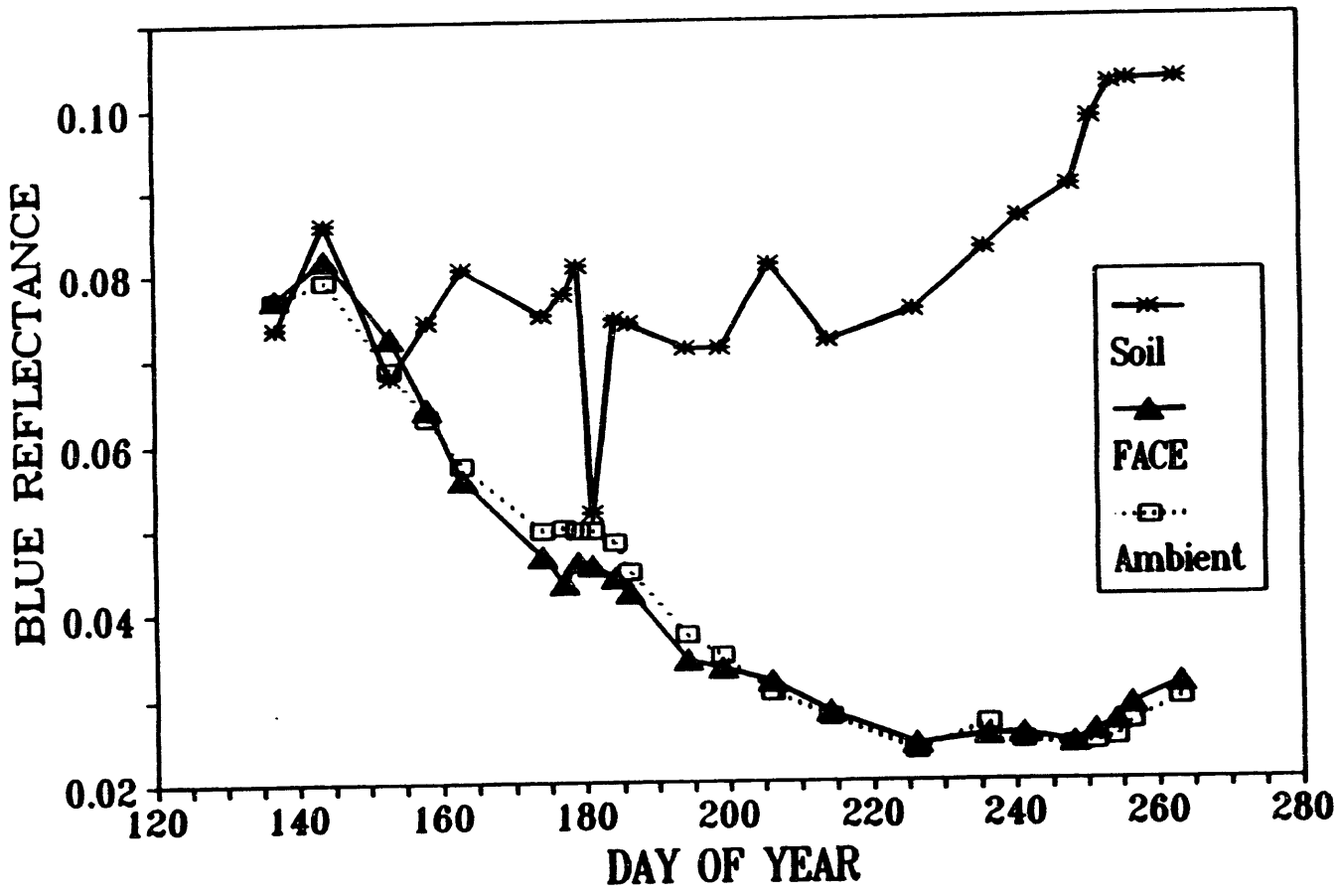


Figure 15-2. Reflectance factors from soil and cotton in the blue (0.45 to 0.52 μm) wavelength interval. Data are for clear days only.

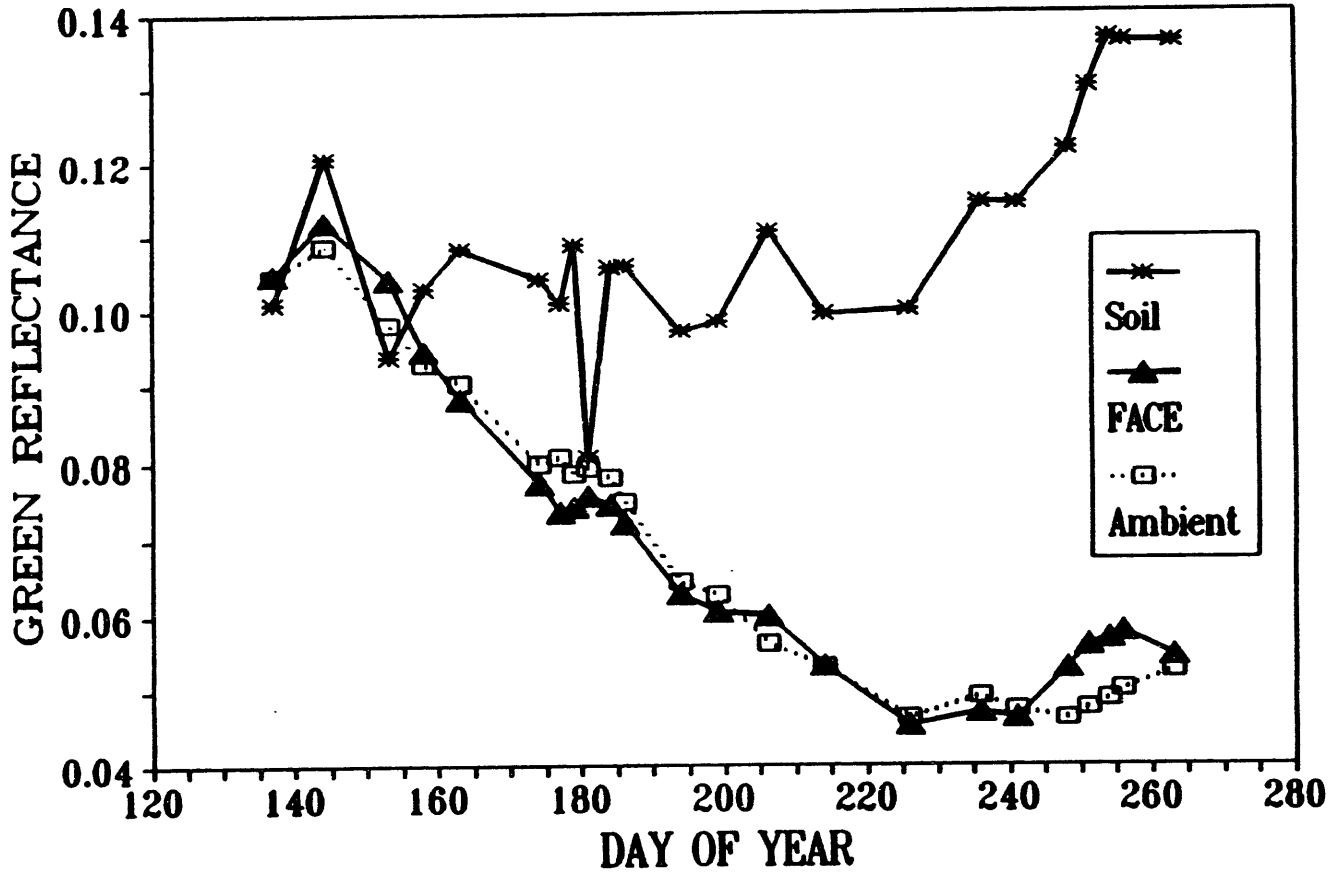


Figure 15-3. Reflectance factors from soil and cotton in the green (0.50 to 0.59 μm) wavelength interval. Data are for clear days only.

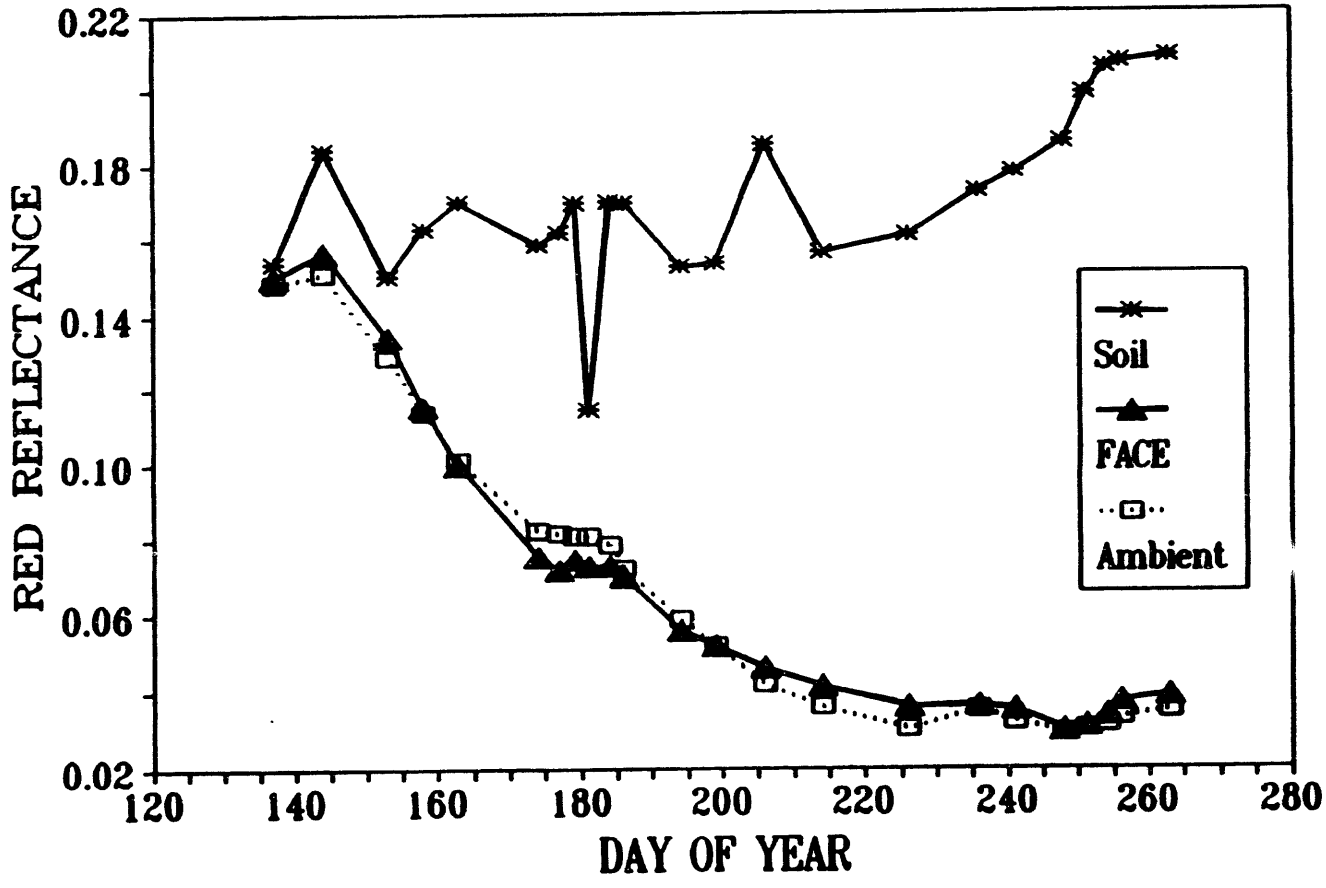


Figure 15-4. Reflectance factors from soil and cotton in the red (0.61 to 0.68 μm) wavelength interval. Data are for clear days only.

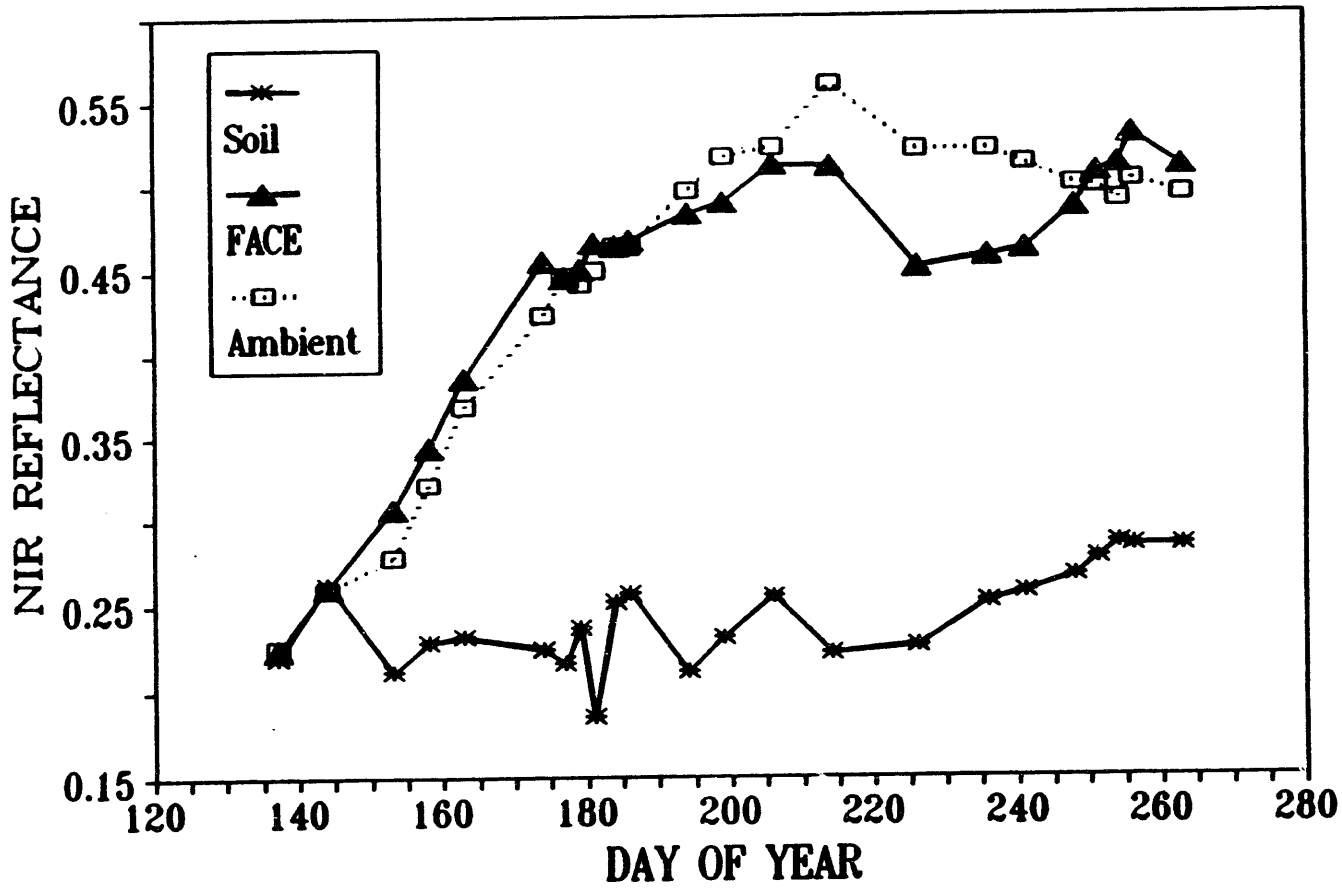


Figure 15-5. Reflectance factors from soil and cotton in the NIR (0.79 to 0.89 μm) wavelength interval. Data are for clear days only.

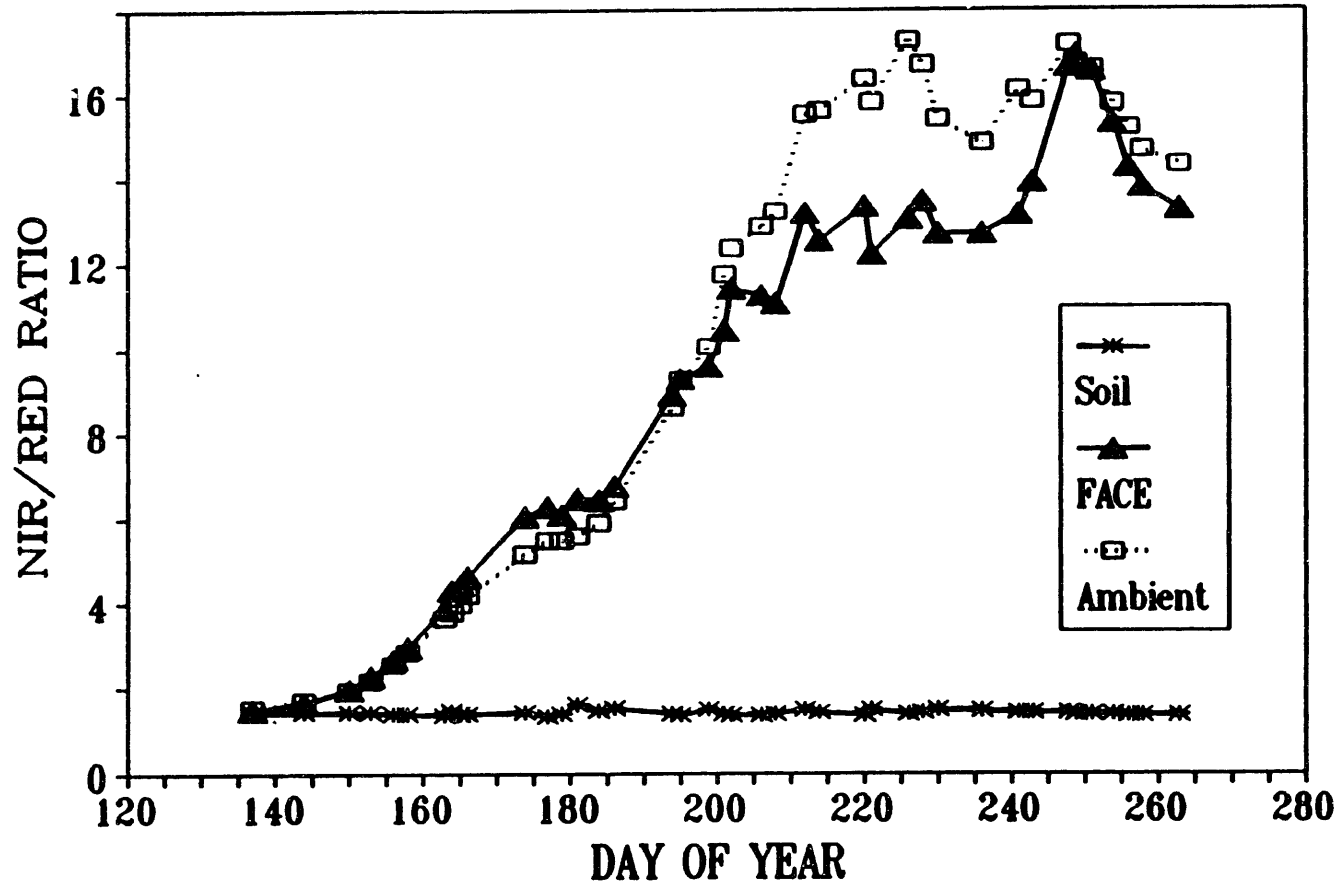


Figure 15-6. Season-long NIR/Red vegetation index measured during the 1989 FACE experiment. This figure also includes data collected on cloudy days.

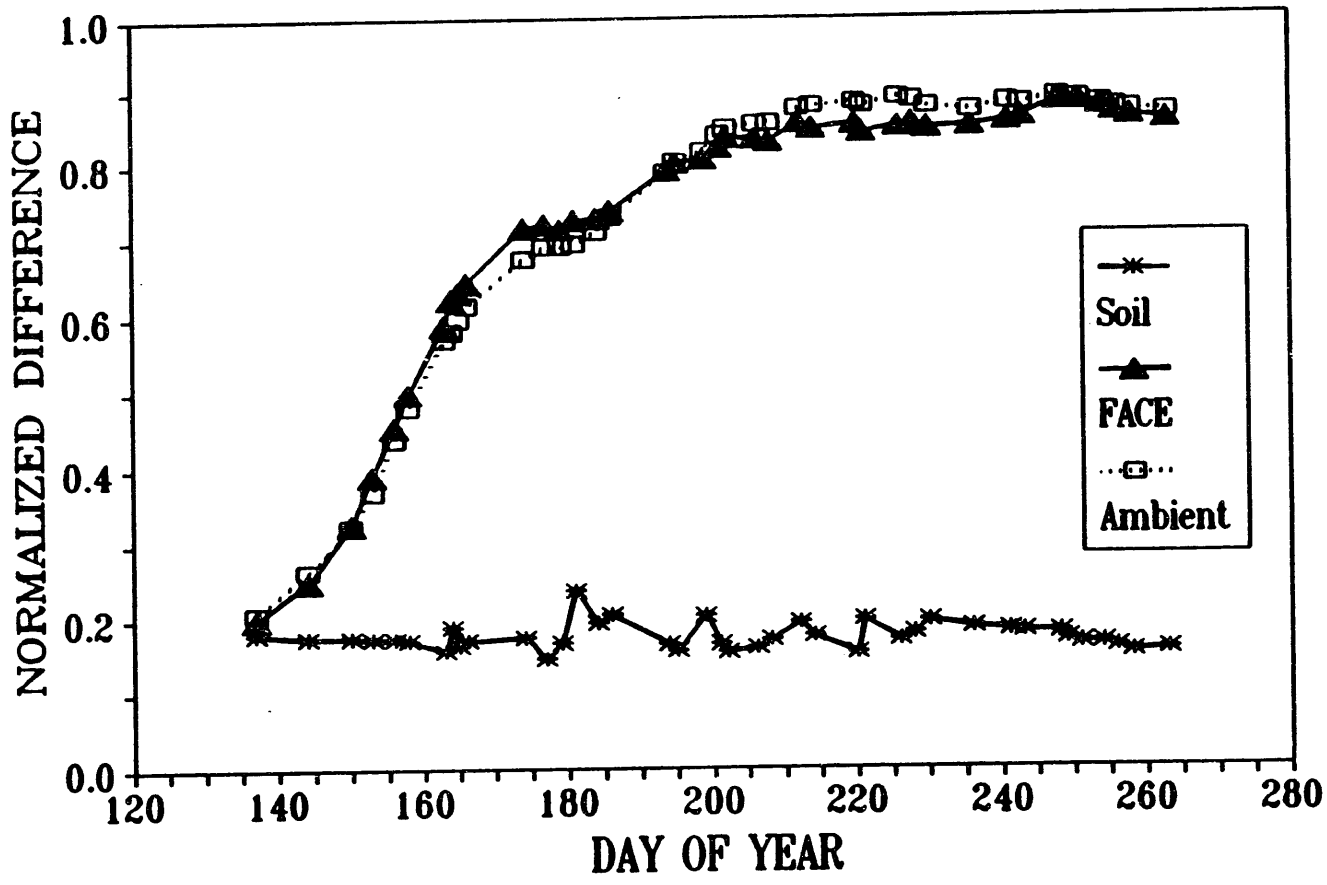


Figure 15-7. Season-long normalized difference vegetation index measured during the 1989 FACE experiment. This figure also includes data collected on cloudy days.

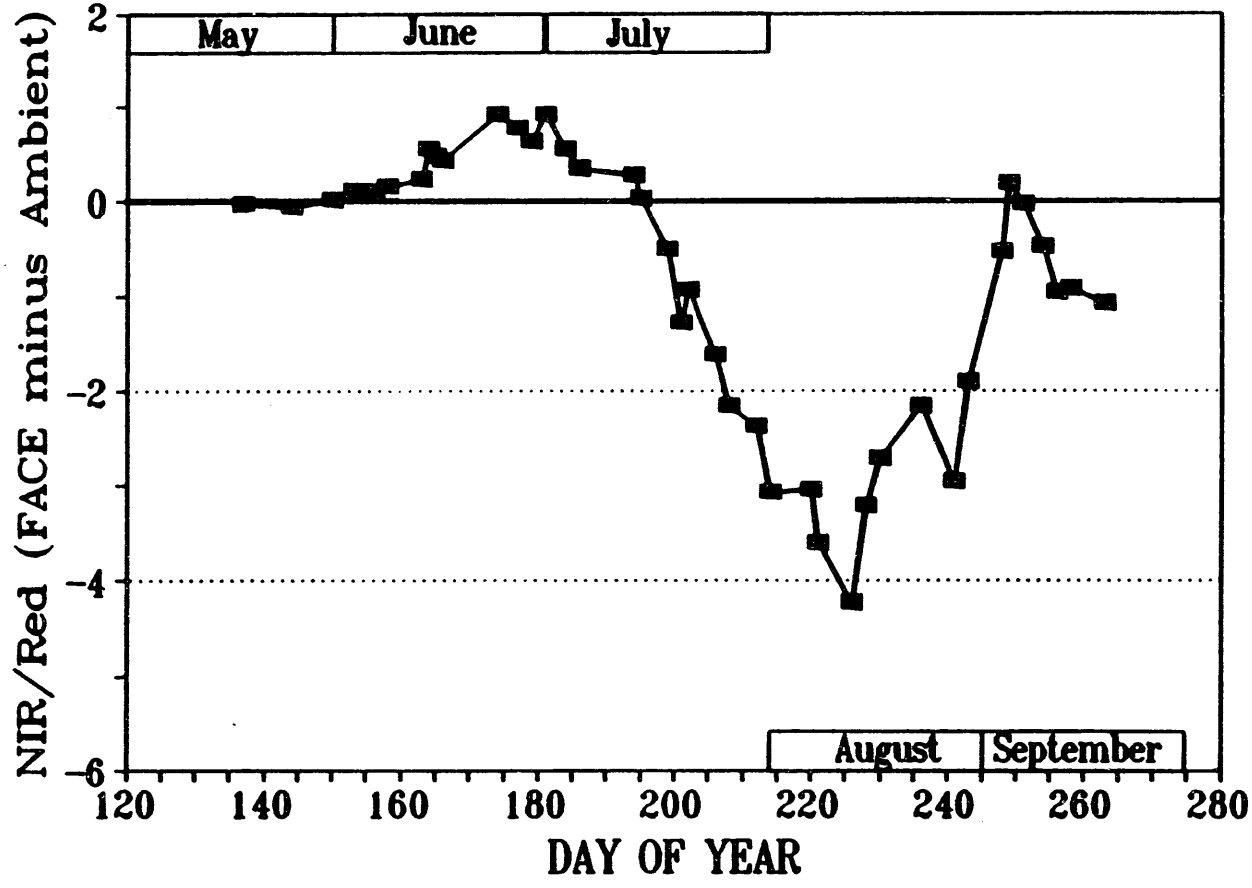


Figure 15-8. The difference between the NIR/Red vegetation index measured in the FACE (550 μmol mol^{-1} CO_2) treatment and the ambient CO_2 controls versus day of the year. This figure also includes data collected on cloudy days.

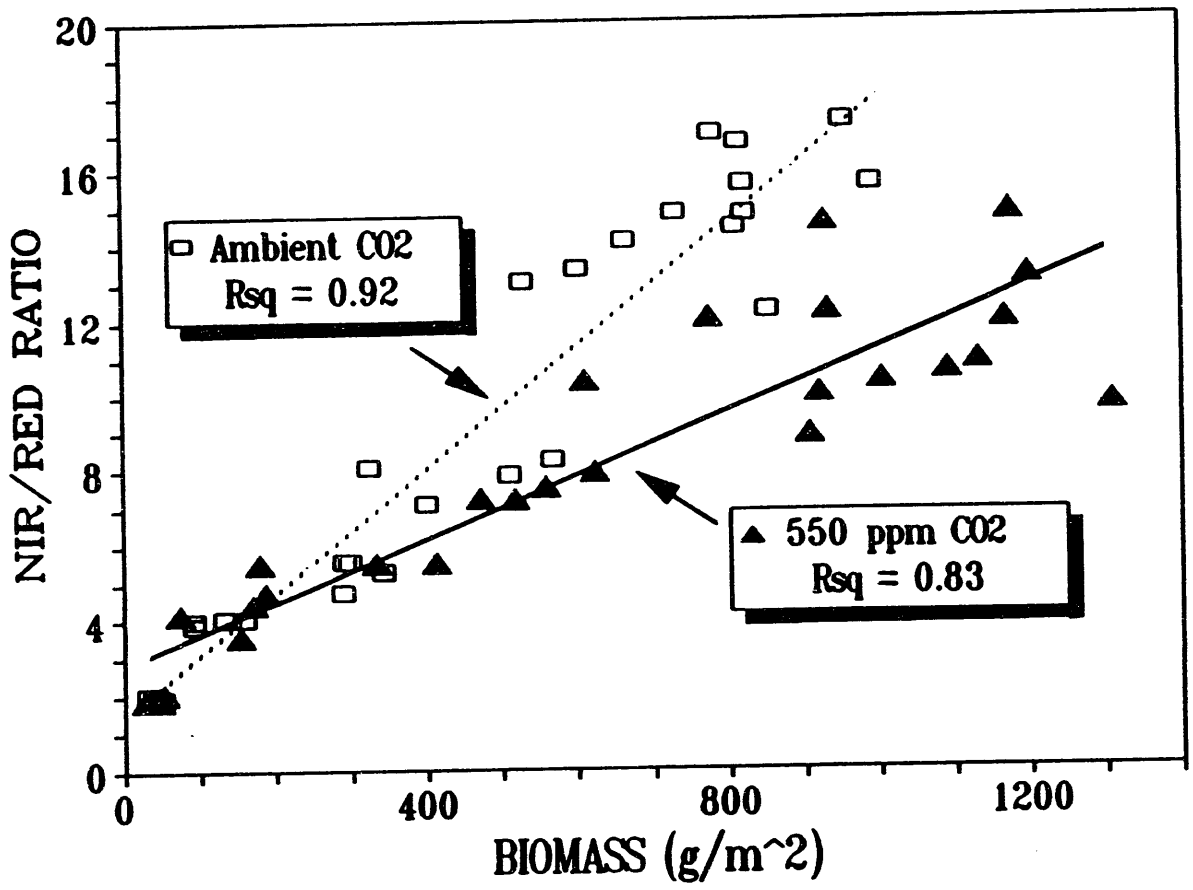


Figure 15-9. Least squares linear regression between NIR/Red vegetation index and biomass of FACE (550 μmol mol^{-1} CO_2) and ambient CO_2 controls.

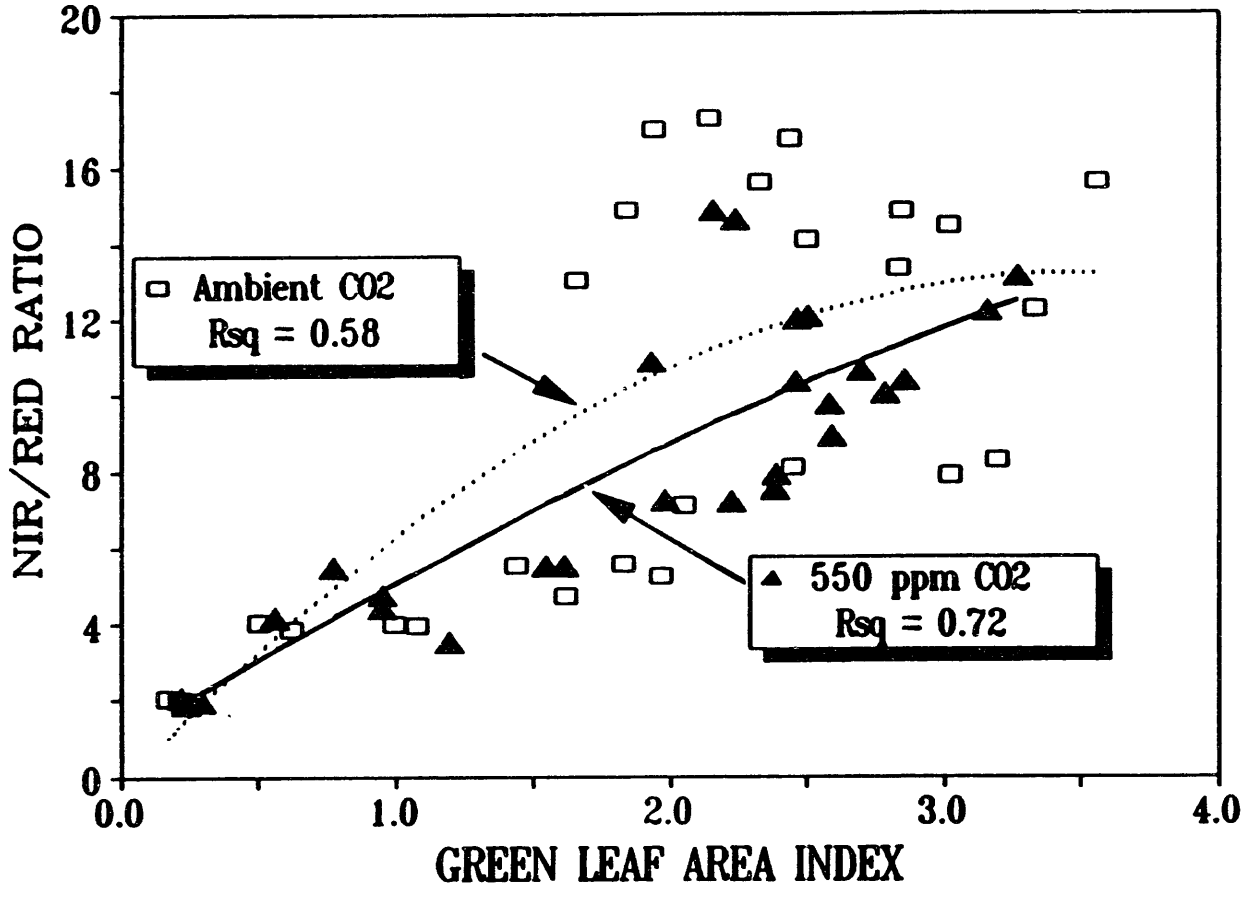


Figure 15-10. **Least squares regression between NIR/Red vegetation index and green leaf area index of FACE (550 μmol mol^{-1} CO_2) and ambient CO_2 controls.**

COTTON ROOT AND RHIZOSPHERE RESPONSES TO FREE-AIR CO_2 ENRICHMENT

Hugo H. Rogers and Stephen A. Prior
National Soil Dynamics Laboratory
and Auburn University
Agricultural Research Service
U. S. Department of Agriculture
P. O. Box 792
Auburn, AL 36831

Elizabeth G. O'Neill
Environmental Sciences Division
Oak Ridge National Laboratory
P. O. Box 2008
Oak Ridge, TN 37831

I. INTRODUCTION

Plant responses to above-ambient levels of CO_2 have been summarized in several excellent reviews of recent origin, each with its own special intent. Lemon (1983), Waggoner (1984), and Wittwer (1985) offer a solid background. Good syntheses of this topic have also be given by Allen (1989), Curry *et al.* (1988), Enoch and Zieslin (1988), Gifford (1988), Morison (1988), and Strain (1987). Kimball (1983a, 1983b) provides a comprehensive statistical synthesis of previous research. Strain and Cure (1985) give in-depth coverage to recent findings. Krupa and Kickert (1989) have summarized the greenhouse effect in terms of ultraviolet-B radiation, CO_2, and ozone. They underscore the need for multi-factor studies. Smith and Tirpak have also provided good coverage of climate (1989a) and CO_2 (1989b) relationships to agriculture as have Adams *et al.* (1990) in a more condensed fashion using model output. In their very recent ASA Special Publication, Kimball *et al.* (1990) offer a state-of-the-art report on the impact of CO_2 on global agriculture (including a look at the greenhouse effect, trace gases, and possible influence on soils). Primary productivity in agro-ecosystems has been covered in a recent book (Goudriaan *et al.*, 1990). Especially germane to our current effort is the past research on elevated atmospheric CO_2 responses of root systems and their rhizospheres, and experimental systems used to expose test plants to CO_2. A brief discussion of these topics follows.

In their state-of-the-art report which reviewed 184 research papers, Acock and Allen (1985) reported that for agricultural species "virtually nothing is known about root growth response to high CO_2 concentrations, other than that the root-to-shoot ratio generally increases." They recommended that since "mechanistic information on several organ-level responses to CO_2 is particularly missing, work should be initiated on the following areas: root growth, leaf net

photosynthesis rates of plants grown from seed at various CO_2 concentrations, and carbon allocation relationships between photosynthetic leaves and nonphotosynthetic growing points." Since that report, some very limited experiments within a few laboratories including our own have shown that elevated atmospheric CO_2 can cause significant changes in plant root morphology (Rogers *et al.*, 1987) and physiology (Masle *et al.*, 1990), and the root system's capacity to explore soil volumes (Chaudhuri *et al.*, 1990; Chaudhuri *et al.*, 1986; Del Castillo *et al.*, 1989; Rogers *et al.*, 1987). More specifically, substantial increases in root dry weight of winter wheat [*Triticum aestivum* (L.); Chaudhuri *et al.*, 1990], sorghum [*Sorghum bicolor* (L.) Moench.; Chaudhuri *et al.*, 1986], and soybean [*Glycine max* (L.) Merr.; Del Castillo *et al.*, 1989 and Rogers *et al.*, 1987] have been reported when these crops were grown under higher-than-normal CO_2. Chaudhuri *et al.* (1990) reported that roots of wheat plants grown under CO_2 enrichment achieved maximum rooting depth ahead of plants grown under ambient conditions. Carbon dioxide enrichment was found to increase the number of actively growing soybean roots rather than increase root elongation rate, thus implying that high CO_2-grown plants do not increase the volume of soil explored but rather explore a given volume more thoroughly (Del Castillo *et al.*, 1989). Sorghum plants grown under added CO_2 were reported to have higher root numbers and dry weights at all soil profile depths relative to the ambient CO_2 concentration (Chaudhuri *et al.*, 1986). Rogers *et al.* (1987) demonstrated that CO_2 enrichment increased root diameter in the root hair zone, length of unbranched first order laterals, and total root length and volume. A theoretical framework of the growth and carbon economy of wheat seedlings as affected by soil resistance to penetration and CO_2 level has been developed (Masle *et al.*, 1990). Idso *et al.* (1988) reported that root:shoot ratio response to CO_2 level can vary with plant species.

The next logical extension of belowground effects induced by plant response to CO_2 is the rhizosphere, the zone of microbial activity near root surfaces where root/soil interaction takes place. Perhaps attention was first focused on this topic in a 1983 statement-of-the-art by Lamborg *et al.* Elevated CO_2 may have indirect yet significant effects on microorganisms in the plant rhizosphere that are involved in nutrient transformations. Of particular interest are nitrifiers (*Nitrosomonas, Nitrobacter*) and phosphorus-solubilizing bacteria (*Pseudomonas, Bacillus*, many other genera). These bacterial groups, although not dependent upon the host plant for carbon supply, do exist in greater numbers in plant rhizospheres where they would be likely to benefit from increased root exudation should it occur under CO_2 enrichment (Norby *et al.*, 1987). Increased activity or biomass of these bacteria could ultimately enhance plant growth. Populations of nitrifying and phosphorus-solubilizing bacteria were increased in rhizospheres of yellow poplar (*Liriodendron tulipifera* L.) seedlings grown at 692 $\mu mol\ mol^{-1}$, although high variability precluded statistical significance (O'Neill *et al.*, 1987b). Increased availability of nutrients could thus be an indirect benefit of elevated CO_2.

Mycorrhizae may also be stimulated by increased availability of translocated photosynthate. Colonization by ectomycorrhizae (short root tips per cm fine root and total mycorrhizal short roots per plant) was increased in seedlings of white oak (*Quercus alba* L.) and shortleaf pine (*Pinus echinata* Mill.) grown under twice ambient CO_2 (O'Neill *et al.*, 1987a). Seedlings of yellow poplar grown with CO_2 enrichment, had greater total colonization per seedling,

although infection per cm of root length did not differ (O'Neill and Norby, 1988). Growth, particularly of roots, was increased in all three tree species when provided additional CO_2.

In the studies mentioned above, experimental work was conducted in environmental chambers, on first year seedlings grown in pots, or in large containers grown in outdoor chambers. Therefore, many of the responses documented above must be qualified by knowledge of the many restrictions imposed by pot culture.

With respect to belowground studies of agro-ecosystems, the free-air carbon dioxide exposure system (FACE) which is the subject of this book, provides an excellent opportunity. First, because of the inherent high variability of crop roots, large numbers of samples are needed which require the larger sampling areas afforded by FACE systems (300-400 m^2). The bigger test areas available also allow access by sampling machines such as farm tractors equipped with coring devices. The FACE experiments offer enough test material to permit multiple investigations of biological systems, thus providing a more comprehensive understanding. And unlike chamber systems, there is virtually no modification of meteorological conditions nor of the soil profile available to plant roots.

Very little is known of how root and rhizosphere processes are affected by additional CO_2. To help fill this gap in our knowledge base we have begun work in this area. Herein, we describe the early results of a first ever study of cotton growing in an open field enriched with CO_2. An important purpose of the entire study of which we are a part was to determine and to model the response of field-grown cotton to elevated atmospheric CO_2. The specific goal of the research summarized here was to assess belowground responses. Our efforts focus on responses of the plant root system, rhizosphere, and associated edaphic factors under free-air CO_2 enrichment.

II. MATERIALS AND METHODS

A. Yazoo City, MS, 1988

In the preliminary field trials of the FACE system, cotton [*Gossypium hirsutum* (L.) 'Stoneville 506'] was planted in 1-meter rows on a 7 hectare site. Located north of Yazoo City, MS, the field was bordered on the north by the South Levee of the Yazoo River and on the east by U.S. Highway 49E. The site was on the premises of the Mississippi Chemical Corporation, across from their manufacturing facilities. The Yazoo City site was originally chosen because of its proximity to an inexpensive source of CO_2.

The soil series was Morganfield silt loam: coarse-silty, mixed, nonacid, thermic Typic Udifluvents. The cotton crop and soil were managed according to recommended practices for that area. No supplemental irrigation was used. Eight study plots were established, four at nominal CO_2 concentrations of 550 μmol mol^{-1} (surrounded by 22-m FACE arrays) and four (controls) at ambient (360 μmol mol^{-1}). Plots were spaced so as to maximize distance between them, thus minimizing the chances of enriched air blowing into control plots. Free-air controlled enrichment was maintained for a period of just over 6 weeks, ending on August 31. The system, which was in its initial stages of development, supplied CO_2 during approximately 80% of daylight hours.

On September 10, prior to final harvest on October 13, fourteen replicate

soil core samples were taken. Three were for soil water content, bulk density (gravimetric, oven-dry weight basis, 105° C), and nutrient content determinations; three for rhizosphere microbiology; and eight for root density measurements. Each sample was taken from a continuous 60-cm core cut into four sections of 15 cm each. A Giddings slotted sample tube (3.8 cm I.D. with a #123 bit; Giddings Machine Co., 1985) was driven below the 60-cm depth with a 20-kg custom-made, sleeve-type post driver to obtain a core that was transferred to a stationary tray and divided in the field. Each core was carefully inspected for uniformity and retaken if a problem occurred. Core sections were cut and raked into 530 ml pre-labeled Whirl-Pak plastic bags with a putty knife, the tip of which was modified to fit the tray shape. The tray was constructed from a 1-m section of 5-cm PVC pipe split in half lengthwise and attached to a wood base. Length calibration marks made core separation easier. The tray was nailed to a portable wooden table at a slight incline with one end over the table edge to facilitate raking soil samples into bags. A car whisk broom was used to clean the tray between successive samplings. Penetrometer readings were taken for the four plots (two treated and two controls) on the south side of the field (Anderson *et al.*, 1980). Eight plants from all study plots were pulled up with the taproots and accompanying lateral roots. All samples were immediately transported by truck to our laboratory in Auburn, AL, and placed in cold storage until processed. Roots were washed from cores using a Gillison's hydropneumatic elutriation system (Smucker *et al.*, 1982; Gillison's, 1990) and refrigerated in 20% ethanol at 5° C (Bohm, 1979). Samples were placed in a shallow white-bottomed pans and roots were separated from organic debris with tweezers and suction pipettes. Lengths were measured with a Comair root length scanner (Hawker de Havilland, 1985). The various parts of the whole plant samples were measured for geometric size and/or volume and dry weights (55° C) ascertained.

For rhizosphere microbiological assays, cores were placed in plastic bags, covered with ice, and shipped in an ice-chest to Oak Ridge National Laboratory by overnight mail. Upon arrival, they were refrigerated intact at 4° C until processed. Three replicates of each CO_2 x Plot x Depth core were composited for microbial assays for a total of 21 samples (cores from plot #5 were saturated with water and impossible to sieve, so were eliminated from further analysis). Soil was sieved (2 mm) and roots recovered while sieving were placed in Formalin:Ethanol:Acetic Acid (FAA) fixative for subsequent vesicular-arbuscular (VA) mycorrhizal assessment. Dehydrogenase activity was assessed for three depth increments: 0-15 cm, 15-30 cm, and 30-45 cm. Bacterial biomass was determined for the 0-15 cm increment only.

For total bacterial biomass, one g (fresh weight) from each sieved soil sample was placed in 99 ml 60 mM Phosphate buffer (pH 7.6) and macerated in a blender at low speed for 2 min. Additional 1 g samples were also taken at this time and placed in a 75° C oven to allow later expression of data on a dry weight basis. Nineteen ml of bacterial suspension was removed from the blender, fixed with 1 ml of filtered (0.22 μm) formalin and refrigerated at 4° C. Soil suspension smears were stained with fluorescein isothiocyanate (Babiuk and Paul, 1970) and counted with an epifluorescence microscope within 1 wk of fixation. Twenty fields on each of two soil smears were counted per sample.

For total microbial activity (dehydrogenase assay), three replicate 1 g samples were removed from sieved soil as above (with additional samples taken for dry weight conversion) and analyzed for dehydrogenase activity using the

triphenyltetrazolium chloride (TTC) reduction method (Ingham *et al.*, 1985). Soil was mixed with 0.7 g freshly prepared TTC solution and incubated at room temperature in the dark for 48 h. Formazan resulting from TTC reduction was extracted with 9.3 ml methanol and solution absorbance read at 430 nm using a spectrophotometer.

For VA mycorrhizal quantification, roots fixed in FAA were stained using trypan blue stain (Phillips and Hayman, 1970) and examined for mycorrhizal infection using the grid intersect method (Giovannetti and Mosse, 1980). Intersections were scored as mycorrhizal only if internal fungal structures (arbuscules, vesicles, spores, or penetration points with internal hyphae) were present.

B. Maricopa, AZ, 1989

The 1988 site at Yazoo City, MS, was relocated to Maricopa Agricultural Center (MAC) of the University of Arizona at Maricopa, AZ, 25 miles south of Phoenix, in 1989. Cotton [*G. hirsutum* (L.) 'Delta Pine 77'] was planted April 17, 1989. Rows were on 1-meter centers with plants being thinned to 10 per meter after full emergence. The soil series was Trix clay loam: fine, loamy, mixed (calcareous), hyperthermic Typic Torrifluvents. The field was well-watered throughout the growing season by a subsurface drip irrigation system whose tubes were buried about 25 cm below each row. Recommended farming practices of the area were followed. Again, as in 1988, eight experimental plots were established, four at nominal CO_2 concentrations of 550 μmol mol^{-1} and four at ambient, 360 μmol mol^{-1}. Free-air CO_2 enrichment (FACE) was supplied over the 1989 season using four 22-m diameter circular standpipe arrays. Complexities of new installation prevented all arrays from commencing operation on the same date; three arrays began running on May 20 and one on June 10. CO_2 enrichment stopped on September 22 (with final harvest on October 16).

On 27-29 September, eight replicate sets of 15 soil sample cores were taken from the study plots, four for soil water content, bulk density (gravimetric, oven-dry weight basis, 105° C), and nutrient content determinations; and eight for root length density and root weight density measurements at crop row center and three from the interrow zone (at 0.17, 0.33, and 0.50 m from row center). Each sample was taken from a continuous 90-cm core cut into six sections of 15 cm each. Samples were taken with a Giddings sample tube (described above) pushed into the ground with a hydraulic sampler mounted on a custom-made frame (carried and powered by a 2700 kg, 55 HP farm tractor). The sampling unit was designed to allow lateral precision positioning of the probe over a two meter distance with hydraulically driven threaded rods. Once obtained, handling of soil cores and retrieval of roots was the same as in 1988. Eight plants, with taproots and attached lateral roots, from each study plot were pulled up after loosening with a drain spade. After sampling was completed, all materials were flown to our Auburn, AL, laboratory and placed in cold storage. Geometric size and dry weights (55° C) of the various plant parts were ascertained.

Statistical analyses, which were the same in both years, were based on a randomized complete block design with four blocks and two treatments (ambient air at 360 μmol mol^{-1} CO_2 and elevated CO_2 at 540 μmol mol^{-1}). All analyses were performed using the general linear models procedure (Proc GLM) of the Statistical Analysis System (SAS Institute, Inc., 1985). Single degree of freedom t tests

were used to determine the significance of differences in cotton growth variables between the two [CO_2], with block X [CO_2] used as a measure of error variance when it was significant ($P < 0.20$). In all analyses, CO_2 treatment means were considered significantly different if they differed at the $P < 0.10$ level. Probabilities were presented in tables to allow for discussion of trends.

All data from soil cores (i.e., root densities) were analyzed for differences between [CO_2] for each core segment (=soil depth) individually in the same manner described previously. The response to soil depth was not determined for any variables in either year of the experiment.

In 1989, soil cores were taken at various distances away from the center of a row of cotton plants. These data represent repeated observations in space and were analyzed using the repeated statement under GLM. Again, these data were analyzed for differences between [CO_2] for each core segment and the response to soil depth was not determined.

III. RESULTS AND DISCUSSION

A. Yazoo City, MA, 1988

Summaries for 1988 Mississippi data are presented in Tables 16-1 through 16-5. Nutritionally, the soil (Morganfield silt loam) appeared to be well-managed with respect to pH, P, K, Mg, and Ca (Table 16-1). However, a K problem with respect to plant tissue was noted during the season. Soil water content (data not shown) was similar under both the elevated CO_2 treatments (0.194 g g^{-1}) and ambient conditions (0.178 g g^{-1}). Bulk densities, as expected, were about the same for both treatments. They were quite low for the field at large (ca 1.35 g cm^{-3}) but a tillage pan was observed to occur at approximately plow depth. This was verified by penetrometer readings (Figure 16-1) which shows a soil strength (cone resistance) increase between 20 and 30 cm. The rise in strength with increasing depth probably reflects tillage practice.

Plant measurands (Tables 16-2 through 16-4) were generally not significant, however, at the 550 μmol mol^{-1} CO_2 concentration, numerous variables exhibited a tendency to increase. For aboveground measurements (Table 16-2), a statistically significant (0.05 level) increase was seen only for height, plants being 17% taller. At the elevated CO_2 level, trends of increase were observed for stem diameter ($P=0.21$) and stem dry weight ($P=0.15$).

Table 16-3 displays geometric values and counts for taproots and their associated lateral roots. Mean values for taproot length, top diameter, dry weight, and volume were numerically higher at 550 μmol mol^{-1} than at ambient ($P=0.26$, $P=0.21$, $P=0.28$, and $P=0.18$, respectively). The number of attached laterals was 20% higher with significance at 0.05 for the elevated CO_2 treatment. The decrease in bottom diameter ($P=0.15$) of taproots was associated with a shape change where the taproot thinned as it lengthened; nevertheless, overall mass and volume rose. Table 16-4 shows root length density (root length/soil core volume) and root weight density (root dry weight/soil core volume) at each depth increment. Root length density for the entire profile tended to be higher at the 550 μmol mol^{-1} treatment level ($P=0.25$). And root dry weight density rose 33% (0.10 level). We have observed a doubling of total root length in a growth chamber study of soybean seedlings when a CO_2 level of 350 μmol mol^{-1} was compared to one of 700 μmol mol^{-1} (Rogers *et al.*, 1987); an increase of 143% was seen for

root dry weight. At least in the early stages of soybean development, roots responded to a greater degree than shoots. Referring to Table 16-4, significance ($P < 0.10$) was noted at two of the depths for both root length density and root dry weight density. Viewed collectively, very clear trends of increased root growth at elevated CO_2 were observed. Root length density tended to be higher at all depths for the 550 μmol mol^{-1} treatments and particularly increased in the 0-45 cm soil depth. Similarly, Chaudhuri *et al.* (1986) reported that root length increases were usually greater in the upper soil profile for sorghum grown in glass-sided boxes under CO_2 enrichment. The relationship between rooting and crop yields has not been fully elucidated and therefore the implications of enhanced rooting are still open to question. For this experiment a final yield increase of 30-45% of both lint and yield has been reported elsewhere (Evans, 1990).

Most rhizosphere microbial parameters, were not significantly different due to CO_2 enrichment (Table 16-5). However, there were consistent trends for both bacterial biomass and dehydrogenase activity. Bacterial populations (numbers per g dry weight of soil) were 58% greater in cores taken from the first 15 cm in the elevated CO_2 plots ($P=0.17$). Dehydrogenase activity (an estimator of aerobic respiration) decreased significantly ($P=0.0017$) with depth for both CO_2 treatments. Activity tended to be higher in soils from the elevated CO_2 samples in both the 0-15 cm and 15-30 cm increments.

Mycorrhizal infection rates were virtually identical for both treatments. The overall mean for all samples was 36.2% of root length infected. This magnitude of infection is reasonable for plants sampled towards the end of the growing season.

B. Maricopa, AZ, 1989

The 1989 Arizona data are given in Tables 16-6 through 16-9. The soil (Trix clay loam) appeared to be nutritionally well-managed with respect to pH, P, K, Mg, and Ca; no treatment differences were observed (Table 16-6). Soil water (data not shown) was nearly the same under both regimes (0.126 g g^{-1} for CO_2 plots and 0.132 g g^{-1} for ambient), as were bulk densities with a plow layer mean of 1.3 g cm^{-3}. A trend toward less organic matter in the high CO_2 regimes is seen (Table 16-6). No final conclusion can be drawn from this single sampling but it is interesting to note that in a new paper on the carbon economy of a planted soil as affected by elevated atmospheric CO_2, Lekkerkerk *et al.* (1990) concluded that microorganisms utilize easily decomposable root-derived material as their energy source, which was higher when plants were exposed to 700 μmol mol^{-1} CO_2. This reduced the turnover of the more resistive native soil organic matter at 700 μmol mol^{-1}. Non-soluble carbon residue increased with CO_2. Perhaps such microbial phenomena relate to our data suggesting less organic matter.

Aboveground plant data showed significant increases or strong trends with CO_2 enrichment (Table 16-77). Leaf and boll numbers were both around 40% higher ($P=0.13$, $P=0.07$), and stem diameter approximately 20% higher ($P=0.02$) for the 550 μmol mol^{-1} plots compared to controls, but height and node number was essentially unchanged. A significant difference near the 0.05 level was noted for stem dry weight. Boll and top dry weights rose 32 and 36% ($P= 0.18$, $P=0.15$) with elevated CO_2.

Most taproot and lateral root variables increased at 550 μmol mol^{-1} compared

to 360 μmol mol^{-1}. Taproot volume and dry weight increases were 73% and 82%, respectively. All root diameter measurements were greater at 550 μmol mol^{-1} treatment level. The total number of lateral roots was up 35% under CO_2 enrichment. In addition, CO_2 enrichment increased both lateral root length and dry weight by 100 and 157%. Appreciable differences (significant at four depths) in root length density (Table 16-9) were seen in the upper layers of the soil profile, with an average increase of 18% for the whole profile. We have no clear explanation of the reduction at greater depths, but it could be related to the onset of end-of-season senescence phenomenon. Experimental protocol did not allow us to enter the field earlier because the root and soil sampling techniques were highly intrusive and destructive.

Root dry weight density for the whole profile showed a 100% increase due to CO_2 enrichment (Table 16-9); significance occurred at the first three depths ($P < 0.01$) and was near the 0.1 level for the next two. The sparseness of roots deeper in the soil could increase sampling variability. In general, vertical distribution patterns are similar, but densities have a tendency to be increased by added CO_2. To provide some idea of root patterns across rows, one set of core samples was pulled from each plot at a right angle to row direction. Figure 16-2 shows this horizontal distribution of roots at four positions from row center (0.00 m) to the middle of the interrow space (0.50 m). Patterns are very much alike without appreciable differences; the overlap of roots from adjacent rows may account for the similarity. The low sample number prohibited statistical separation, but a snapshot of the across-row profile is provided.

Whole-field root:shoot ratios are given in Table 16-10 for both 1988 and 1989. Ratios were very close for both 360 and 550 μmol mol^{-1} CO_2 at the Mississippi site where conditions were mild with high rainfall and humidity. For the desert site in Arizona, a marked increase in root:shoot ratio was observed for the high CO_2 treatment. While it should be noted that the 1988 exposure was shorter than that for 1989, the higher percentage of total biomass allocated to roots in the arid climate suggest a possible stress amelioration by elevated CO_2. Such a strategy could reduce overall root resistance to soil water uptake.

IV. CONCLUSION

Data from the field presented here clearly suggest that elevated atmospheric CO_2 stimulates cotton root proliferation. It may be inferred that other belowground processes impacted by root proliferation could also shift. Both root length density and root weight density appear to increase, especially in the upper layers of the soil profile. Enhanced growth of cotton roots resulted in a more thorough exploration of the soil volume occupied, possibly increasing water and nutrient availability. Increased rooting induced by CO_2 enrichment could become very important for seedling establishment, especially for a crop under stress. For agronomic conditions where water and nutrients are essentially unlimited, denser root patterns may have less significance than under the limiting circumstances of more primitive or sustainable agricultural systems, or in natural ecosystems. A more thorough understanding of the implications of CO_2-enhanced root growth must await further experimentation.

Even 6 weeks of exposure to CO_2 enrichment can affect belowground structure and function. Although the rhizosphere *per se* was not sampled, increased bacterial populations and microbial activity are indicative of a trend toward

plant-mediated stimulatory effect of elevated CO_2. Mycorrhizae (per unit root length) were not significantly increased. However, greater root length density suggests that total plant mycorrhization and thus the ability to exploit soil resources were increased. Both rhizosphere and plant responses to CO_2 enrichment are heavily dependent upon seasonality, upon plant developmental stages, and upon cultural practices. A thorough understanding of the responses of the belowground system will require sampling over an extended period of time. These data clearly indicate the need for further investigation of the belowground system of plants exposed to elevated CO_2 at FACE facilities.

V. ACKNOWLEDGEMENTS

Partial support of this effort by the Environmental Sciences Research Division, U. S. Department of Energy through Interagency No. ER60001 to the USDA, and by the Alabama Agricultural Experiment Station, Auburn University, under AAES Research Grant 2-33130 is gratefully acknowledged. We thank Drs. B. A. Kimball, J. R. Mauney, G. R. Hendrey, and G. B. Runion for invaluable input. We thank Mr. Bernard E. McLean for assistance in preparing this paper.

REFERENCES

1. Acock B, Allen LHJr (1985) Crop responses to elevated carbon dioxide concentrations. p. 53-98. In: B. R. Strain and J. D. Cure (eds.). Direct effects of increasing carbon dioxide on vegetation. Dept. of Energy, Washington, D.C.

2. Adams RM, Rosenzweig C, Peart RM, Ritchie JT, McCarl BA, Glyyer JD, Curry RB, Jones JW, Boote KJ, Allen LHJr (1990) Global climate change and US agriculture. Nature 345:219-224.

3. Allen LHJr (1989) Global climate change and its impact on plant growth and development. Proc. Plant Growth Regul. Soc. Am. p. 1-13.

4. Anderson G, Pidgeon JD, Spencer HB, Parks R (1980) A new hand-held recording penetrometer for soil studies. J. Soil Sci. 31:279-296.

5. Babiuk LA, Paul EA (1970) The use of fluorescein isothiocyanate in the determination of the bacterial biomass of grassland soil. Can. J. Microbiol. 16:57-62.

6. Bohm W (1979) Methods of studying root systems. Springer-Verlag, NY. 188 p.

7. Chaudhuri UN, Kirkham MB, Kanemasu ET (1990) Root growth of winter wheat under elevated carbon dioxide and drought. Crop Sci. 30:853-857.

8. Chauduri UN, Burnett RB, Kirkham MB, Kanemasu ET (1986) Effect of carbon dioxide on sorghum yield, root growth, and water use. Agric. For. Meteorol., 37:109-122.

9. Curry RB, Peart RM, Jones JW, Boote KJ, Allen LHJr (1988) Simulation as a tool for analyzing crop response to climate change. Paper 88-7512. Winter Mtg. ASAE. 29 p.

10. Del Castillo D, Acock B, Reddy VR, Acock MC (1989) Elongation and branching of roots on soybean plants in a carbon dioxide-enriched aerial environment. Agron. J. 81:692-695.

11. Enoch HZ, Zieslin N (1988) Growth and development of plants in response to carbon dioxide concentrations. App. Agric. Res. 3:248-256.

12. Evans LS (1990) Relationships between carbon dioxide enrichment and reproductive yield. p. 716. Proceedings of the 1990 Beltwide Cotton Production Research Conferences. National Cotton Council of America, Nashville, TN.

13. Giddings Machine Company (1985) Operating Instructions. 401 Pine Street, Fort Collins, CO 80522.

14. Gifford RM (1988) Direct effect of higher carbon dioxide concentrations

on vegetation. p. 506-519. In Pearman, G. I. (ed.), Greenhouse: Planning for climate change. E.J. Brill Publishing Co., NY.

15. Gillison's Variety Fabrication, Inc. (1990) Basic operation of the hydropneumatic root washer. 3033 Benzie Hwy., Benzonia, MI 49616.

16. Giovannetti M, Mosse B. (1980) An evaluation of techniques for measuring vesicular-arbuscular mycorrhizal infection in roots. New Phytol. 84:489-500.

17. Goudriaan J, van Keulen H, van Laar HH (eds.) (1990) The greenhouse effect and primary productivity in european agro-ecosystems. Pudoc, Wageningen. 90 p.

18. Hawker de Havilland (1985) Users manual. 304 Lorimer Street, Port Melbourne, Victoria, 3207, Australia.

19. Idso SB, Kimball BA, Mauney JR (1988) Effects of atmospheric CO_2 enrichment on root:shoot ratios of carrot, radish, cotton and soybean. Agric. Ecosystems Environ. 21:293-299.

20. Ingham ER, Klein DA, Trlica MJ (1985) Responses of microbial components of the rhizosphere to plant management strategies in a semiarid rangeland. Plant and Soil 85:65-76.

21. Kimball BA, Rosenberg NJ, Allen LHJr. (ed.) (1990) Impact of CO_2, trace gases, and climate change on global agriculture. ASA Special Publication No. 53, Am. Soc. Agron., Madison, WI. 133 p.

22. Kimball BA (1983a) Carbon dioxide and agricultural yield: an assemblage and analysis of 430 prior observations. Agron. J. 75:779-788.

23. Kimball BA (1983b) Carbon dioxide and agricultural yield: an assemblage and analysis of 770 prior observations. WCL Report 14, U. S. Dept. of Agric., Agric. Res. Serv., 71 p.

24. Krupa SV, Kickert RN (1989) The greenhouse effect: impacts of ultraviolet-B (UV-B) radiation, carbon dioxide (CO_2), and ozone (O_3) on vegetation. In Demkpster, J. P. and W. J. Manning (ed.) Environmental Pollution, Vol. 61, Elsevier Publishers.

25. Lamborg MR, Hardy RWF, Paul EA (1983) Microbial effects. p. 131-176. In Lemon, E. R. (ed.). CO_2 and plants: the response of plants to rising levels of atmospheric carbon dioxide. AAAS Selected Symposium 84. Westview Press, Boulder, CO.

26. Lekkerkerk LJA, Van De Geijn SC, Van Veen JA (1990) Effects of elevated atmospheric CO_2-levels on the carbon economy of a soil planted with wheat. p. 423-429. In Bouwman, A. F. (ed.). Soils and the greenhouse effect. John Wiley & Sons, NY.

27. Lemon ER (ed.) (1983) CO_2 and plants: the response of plants to rising

levels of atmospheric carbon dioxide. AAAS Selected Symposium 84. Westview Press, Boulder, CO. 280 p.

28. Masle J, Farquhar GD, Gifford RM (1990) Growth and carbon economy of wheat seedlings as affected by soil resistance to penetration and ambient partial pressure of CO_2. Aust. J. Plant Physiol. 17:465-487.

29. Morison JIL (1988) Effect of increasing atmospheric CO_2 on plants and their responses to other pollutants, climatic and soil factors. Aspects App. Biol. 17:113-122.

30. Norby RJ, O'Neill EG, Hood WG, Luxmoore RJ (1987) Carbon allocation, root exudation, and mycorrhizal colonization of *Pinus echinata* seedlings under CO_2 enrichment. Tree Physiol. 3:203-210.

31. O'Neill EG, Norby RJ (1988) Differential Responses of ecto- and endomycorrhizae to elevated atmospheric CO_2. Bull. Ecol. Soc. Amer. 69(2):248. (abstract)

32. O'Neill EG, Luxmoore RJ, Norby RJ (1987a) Increases in mycorrhizal colonization and seedling growth in *Pinus echinata* and *Quercus alba* in an enriched CO_2 atmosphere. Can. J. For. Res. 17:878-883.

33. O'Neill EG, Luxmoore RJ, Norby RJ (1987b) Elevated atmospheric CO_2 effects on seedling growth, nutrient uptake, and rhizosphere bacterial populations of *Liriodendron tulipifera* L. Plant and Soil 101:3-11.

34. Phillips JM, Hayman DS (1970) Improved procedures for clearing roots and staining parasitic and vesicular arbuscular mycorrhizal fungi for rapid assessment of infection. Trans. Br. Mycol. Soc. 55:158-161.

35. Rogers HH, Peterson CM, McCrimmon JM, Cure JD (1987) Response of soybean roots to elevated atmospheric carbon dioxide. Agron. Abst., p. 100.

36. Statistical Analysis System (SAS) Institute, Inc., SAS Institute, Inc. 1985. User's guide: statistics. Box 8000, Cary, NC. 956 p.

37. Smith JB, Tirpak DA (ed.) (1989a) The potential effects of global climate change on the United States. Report to Congress. EPA, Office of Policy, Planning and Evaluation, Washington, DC.

38. Smith JB, Tirpak DA (ed.) (1989b) The potential effects of global climate change on the United States. Appendix C - Agriculture Vols. I & II. EPA, Office of Policy, Planning and Evaluation, Washington, DC.

39. Smucker AJM, McBurney SL, Srivastava AK (1982) Quantitative separation of roots from compacted soil profiles by the hydropneumatic elutriation system. Agron. J. 74:500-503.

40. Strain BR, Cure, JD (ed.) (1985) Direct effects of increasing carbon

dioxide on vegetation. DOE/ER-0238. The Office of Energy Research. U. S. Dept. of Energy, Washington, DC.

41. Strain BR (1987) Direct effects of increasing atmospheric CO_2 on plants and ecosystems. Trend. Ecol. Evol. 2:18-21.

42. Waggoner PE (1984) Agriculture and carbon dioxide. Amer. Sci. 72:179-184.

43. Wittwer SH (1985) Carbon dioxide levels in the biosphere: effects on plant productivity. CRC Press 2:171-198.

Figure 16-1. Penetration resistance (cone resistance; MPa) at various depths in plots with cotton grown under 350 and 550 μmol mol^{-1} CO_2 at Yazoo City, MS, 1988. N=24.

Figure 16-2. Mean root length density (km m^{-3}) of cotton grown under 350 and 550 μmol mol^{-1} CO_2 different soil profile depths and four positions from row center to the middle of the interrow space at Maricopa, AZ, in 1989.

Table 16-1

Soil properties at different profile depths from which cotton was grown under ambient conditions and CO_2 enrichment at Yazoo City, MS, in 1988. Mean values for bulk density, pH and four macronutrients are shown. N = 12.

	CO_2 Concentration											
	350 μmol mol^{-1}						50 μmol mol^{-1}					
Depth	Db[1]	pH	P	K	Mg	Ca	Db[1]	pH	P	K	Mg	Ca
(cm)	(g cm^{-3})	(kg ha^{-1})					(g cm^{-3})	(kg ha^{-1})				
0-15	1.28	6.2	99	151	539	3077	1.26	6.1	99	162	457	2643
15-30	1.40	6.0	89	144	679	2702	1.46	5.9	93	130	608	2620
30-45	1.34	6.3	87	133	717	2777	1.33	6.5	101	133	748	2870
45-60	1.33	6.4	99	128	858	3327	1.35	7.0	99	124	821	2912

[1] Db = Bulk Density

Table 16-2

Aboveground growth parameters of cotton at Yazoo City, MS, in 1988: height, diameter, node number, leaf number, boll number, leaf dry weight, stem dry weight, boll dry weight and top dry weight under ambient conditions and CO_2 enrichment. Means, standard errors, probabilities and percent differences are shown. N = 4.

Variable	CO_2 Concentration		Probability[1]	% Difference
	350 μmol mol^{-1}	550 μmol mol^{-1}		
Height (cm)	129.2 ± 1.2	151.6 ± 6.0	0.0381	17
Diameter (mm)	14.5 ± 0.4	16.3 ± 0.9	0.2115	12
Node no.	22.1 ± 1.0	23.1 ± 0.5	0.3224	5
Leaf no.	32.0 ± 9.1	40.1 ± 14.4	0.5188	25
Boll no.	15.1 ± 1.0	16.5 ± 4.1	0.7549	9
Leaf dry wt. (g)	14.7 ± 4.7	15.8 ± 6.2	0.7637	7
Stem dry wt. (g)	44.8 ± 3.2	60.5 ± 8.1	0.1522	35
Boll dry wt. (g)	63.7 ± 6.0	63.5 ± 15.9	0.9912	-0.3
Top dry wt. (g)	123.2 ± 11.1	139.8 ± 29.9	0.5835	13

[1] Probability of greater F by chance.

Table 16-3

Taproot parameters of cotton at Yazoo City, MS, in 1988: length, top diameter, middle diameter, bottom diameter, total dry weight, volume and number of attached lateral roots under ambient conditions and CO_2 enrichment. Means, standard errors, probabilities and percent differences are shown. N = 4.

Variable	CO_2 Concentration		Probability[1]	% Difference
	350 μmol mol^{-1}	550 μmol mol^{-1}		
Taproot				
Length (cm)	19.4 ± 1.6	22.2 ± 1.4	0.2640	14
Top diameter (mm)	14.5 ± 0.4	16.3 ± 0.9	0.2115	12
Mid diameter (mm)	7.9 ± 0.6	7.4 ± 0.6	0.6868	-6
Bottom diameter (mm)	3.4 ± 0.7	2.2 ± 0.2	0.1460	-35
Dry weight (g)[1]	4.8 ± 0.4	5.5 ± 0.7	0.2852	15
Volume (cm^3)	15.3 ± 1.0	18.4 ± 2.0	0.1845	20
Laterals				
No. attached	21.6 ± 0.8	25.9 ± 0.7	0.0370	20

[1] Probability of greater F value by chance.

[1] Taproot weight includes attached laterals.

Table 16-4

Root length density (km m^{-3}) and root dry weight density (kg m^{-3}) of cotton grown under ambient conditions and CO_2 enrichment at different soil profile depths at Yazoo City, MS, in 1988. Means, standard errors, probabilities and percent differences are shown. N = 8.

Root Length Density (km m^{-3})

Depth (cm)	CO_2 Concentration 350 μmol mol^{-1}	550 μmol mol^{-1}	Probability[1]	% Difference
0-15	45.7 ± 6.2	58.5 ± 8.9	0.0266	28
15-30	9.5 ± 0.8	28.2 ± 13.9	0.3807	197
30-45	6.5 ± 0.7	14.2 ± 3.3	0.0209	118
45-60	4.9 ± 0.8	5.8 ± 0.6	0.6059	18
Overall mean	16.7 ± 1.7	26.7 ± 6.4	0.2550	60

Root Dry Weight Density (kg m^{-3})

Depth (cm)	CO_2 Concentration 350 μmol mol^{-1}	550 μmol mol^{-1}	Probability[1]	% Difference
0-15	0.42 ± 0.08	0.44 ± 0.08	0.8071	5
15-30	0.09 ± 0.01	0.19 ± 0.06	0.2915	111
30-45	0.06 ± 0.01	0.09 ± 0.02	0.0819	50
45-60	0.03 ± 0.005	0.09 ± 0.02	0.0538	200
Overall mean	0.15 ± 0.02	0.20 ± 0.04	0.0803	33

[1] Probability of greater F by chance.

Table 16-5

Microbial populations of soil taken from rooting zone of cotton plants grown within FACE array at Yazoo City, MS, 1988. N = 3 for 350 μmol mol^{-1}; N = 4 for 550 μmol mol^{-1}.

Assay	Depth (cm)	CO_2 Concentration 350 μmol mol^{-1}	CO_2 Concentration 550 μmol mol^{-1}	Probability[1]	%Difference
# Bacteria g^{-1} soil (x 10^{12})	0-15	1.89 ± 0.38	2.98 ± 0.75	0.17	58
μg Formazan g^{-1} soil	0-15	50.7 ± 17.7	84.7 ± 23.2	0.24	67
	15-30	3.4 ± 2.1	15.3 ± 12.2	>>0.20	350
	30-45	9.3 ± 8.4	10.9 ± 4.3	>>0.20	17
% Mycorrhizal root length	0-45	33.0 ± 9.9	39.4 ± 2.2	>>0.20	19

[1] Probability of greater F value by chance.

Table 16-6

Soil properties at different profile depths from which cotton was grown under ambient conditions and CO_2 enrichment at Maricopa, AZ, in 1989. Mean values for bulk density, percent organic matter, pH and four macronutrients are shown. N = 16.

	CO_2 Concentration													
	350 μmol mol^{-1}							550 μmol mol^{-1}						
Depth	Db[1]	OM[1]	pH	P	K	Mg	Ca	Db[1]	OM[1]	pH	P	K	Mg	Ca
(cm)	(g cm^{-3})	(%)		(kg ha^{-1})				(g cm^{-3})	%		(kg ha^{-1})			
0-15	1.27	1.10	8.6	38	926	1120	11,199	1.34	0.95	8.5	37	898	1120	11,199
15-30	1.24	0.93	8.6	32	910	1120	11,199	1.29	0.40	8.5	30	904	1120	11,199
30-45	1.27	0.68	8.6	27	911	1120	11,199	1.33	0.52	8.6	29	885	1120	11,199
45-60	1.46	0.55	8.6	21	849	1085	11,199	1.48	0.28	8.6	17	740	1028	11,199
60-75	1.55	0.45	8.6	14	751	982	10,972	1.60	0.35	8.6	11	586	756	9,999
75-90	1.52	0.73	8.6	9	616	934	10,381	1.61	0.78	8.6	11	485	614	7,942

[1] Db = Bulk Density
[1] OM = % Organic Matter

Table 16-7

Aboveground growth parameters of cotton at Maricopa, AZ, in 1989: height, diameter, node number, leaf number, boll number, leaf dry weight, stem dry weight, boll dry weight and top dry weight under ambient conditions and CO_2 enrichment. Means, standard errors, probabilities and percent differences are shown. N = 32.

Variable	CO_2 Concentration		Probability[1]	% Difference
	350 μmol mol^{-1}	550 μmol mol^{-1}		
Height (cm)	143.7 ± 2.6	152.6 ± 3.2	0.3091	6
Diameter (mm)	14.3 ± 0.3	17.0 ± 0.2	0.0244	19
Node no.	31.8 ± 0.6	32.1 ± 0.6	0.9293	1
Leaf no.	91.1 ± 5.7	127.5 ± 8.8	0.1305	40
Boll no.	38.4 ± 2.3	52.5 ± 2.9	0.0676	37
Leaf dry wt. (g)	27.7 ± 1.5	33.6 ± 2.3	0.4668	21
Stem dry wt. (g)	62.1 ± 3.0	92.0 ± 4.0	0.0638	48
Boll dry wt. (g)	95.8 ± 7.4	126.6 ± 9.3	0.1825	32
Top dry wt. (g)	185.6 ± 11.0	252.2 ± 13.9	0.1458	36

[1] Probability of greater F value by chance.

Table 16-8

Taproot parameters of cotton at Maricopa, AZ, in 1989: length, top diameter, middle diameter, bottom diameter, total dry weight, volume, number of attached lateral roots, total number of laterals, attached lateral root length and attached lateral root dry weight under ambient conditions and CO_2 enrichment. Means, standard errors, probabilities and percent differences are shown. N = 32.

Variable	CO_2 Concentration 350 μmol mol^{-1}	CO_2 Concentration 550 μmol mol^{-1}	Probability[1]	% Difference
Taproot				
Length (cm)	36.4 ± 1.2	37.6 ± 1.1	0.4402	3
Top diameter (mm)	15.5 ± 0.3	19.5 ± 0.3	0.0200	26
Mid diameter (mm)	5.7 ± 0.2	7.4 ± 0.3	0.0540	30
Bottom diameter (mm)	2.6 ± 0.1	3.4 ± 0.1	0.0001	31
Dry weight (g) [1]	7.1 ± 0.3	12.9 ± 0.6	0.0140	82
Volume (cm^3)	17.6 ± 0.7	30.4 ± 1.3	0.0171	73
Laterals				
No. attached	21.9 ± 1.2	31.7 ± 1.3	0.0001	45
No. unattached	17.6 ± 1.0	21.7 ± 1.4	0.0166	23
No. total	39.5 ± 1.5	53.3 ± 2.0	0.0001	35
Attached length (cm)	1.6 ± 0.1	3.2 ± 0.2	0.0479	100
Attached dry wt. (g)	0.51 ± 0.08	1.31 ± 0.12	0.0434	157

[1] Probability of greater F value by chance.

[1] Taproot weight includes laterals.

Table 16-9

Root length density (km m^{-3}) and root dry weight density (kg m^{-3}) at different soil profile depths for cotton grown under ambient and CO_2 enriched conditions at Maricopa, AZ, in 1989. Means, standard errors, probabilities and percent differences are shown. N = 32.

Root Length Density (km m^{-3})

Depth (cm)	CO_2 Concentration 350 μmol mol^{-1}	550 μmol mol^{-1}	Probability[1]	% Difference
0-15	38.0 ± 2.3	49.6 ± 2.3	0.0006	31
15-30	29.4 ± 1.8	35.5 ± 2.0	0.0334	21
30-45	15.1 ± 1.2	19.9 ± 1.2	0.0049	32
45-60	12.3 ± 1.0	11.6 ± 0.8	0.5434	-6
60-75	7.2 ± 0.5	5.8 ± 0.4	0.0179	-19
75-90	5.2 ± 0.5	4.1 ± 0.4	0.1009	-21
Mean	17.9 ± 0.8	21.1 ± 0.7	0.0033	18

Root Dry Weight Density (kg m^{-3})

Depth (cm) %Difference	CO_2 Concentration 350 μmol mol^{-1}	550 μmol mol^{-1}	Probability[1]	
0-15	0.31 ± 0.02	0.74 ± 0.13	0.0017	139
15-30	0.28 ± 0.04	0.48 ± 0.05	0.0032	71
30-45	0.15 ± 0.03	0.37 ± 0.08	0.0089	147
45-60	0.10 ± 0.01	0.22 ± 0.08	0.1460	120
60-75	0.06 ± 0.01	0.08 ± 0.01	0.1573	33
75-90	0.04 ± 0.01	0.06 ± 0.01	0.3970	50
Mean	0.16 ± 0.01	0.32 ± 0.03	0.0001	100

[1] Probability of greater F by chance.

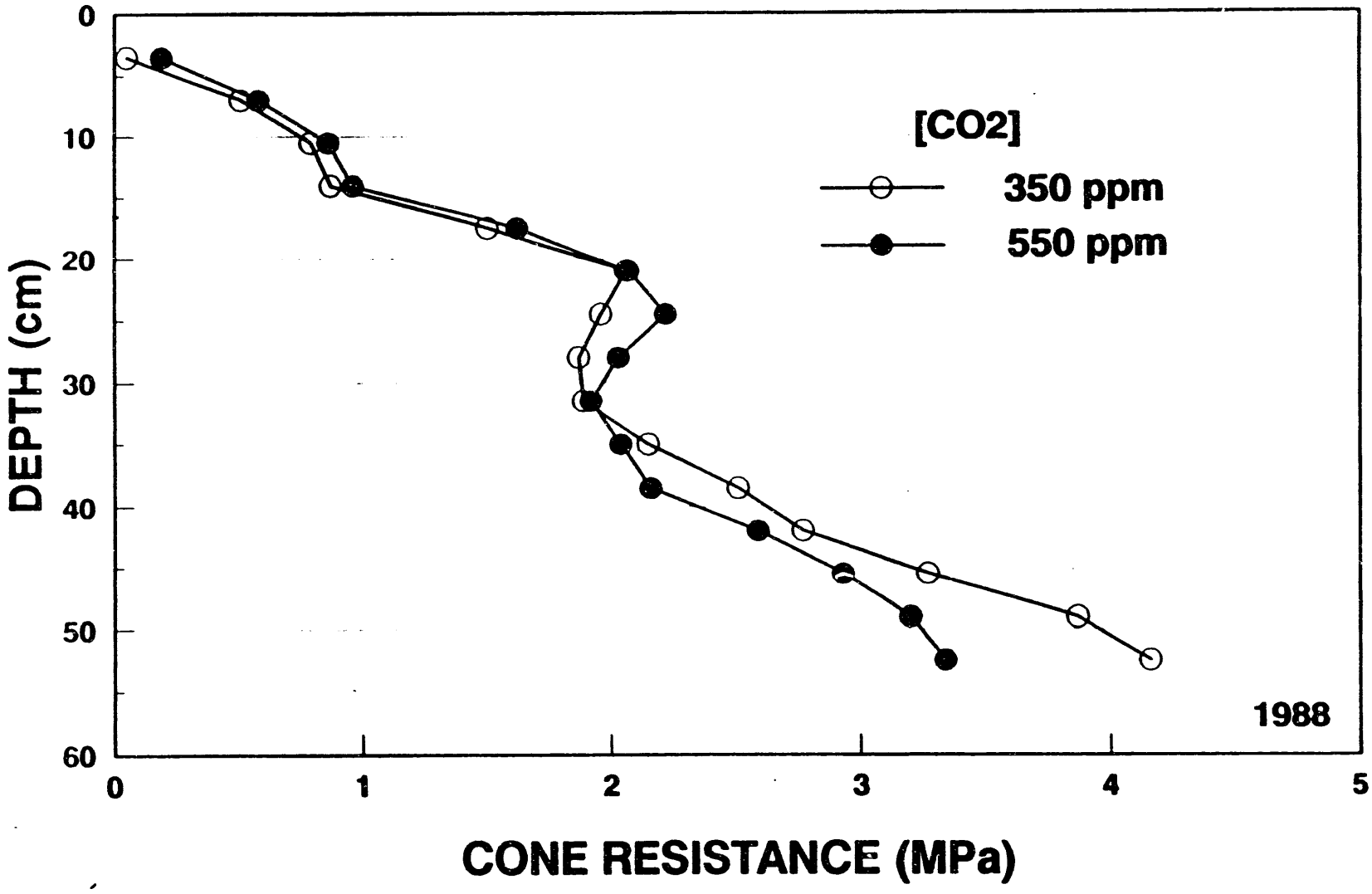
Table 16-10

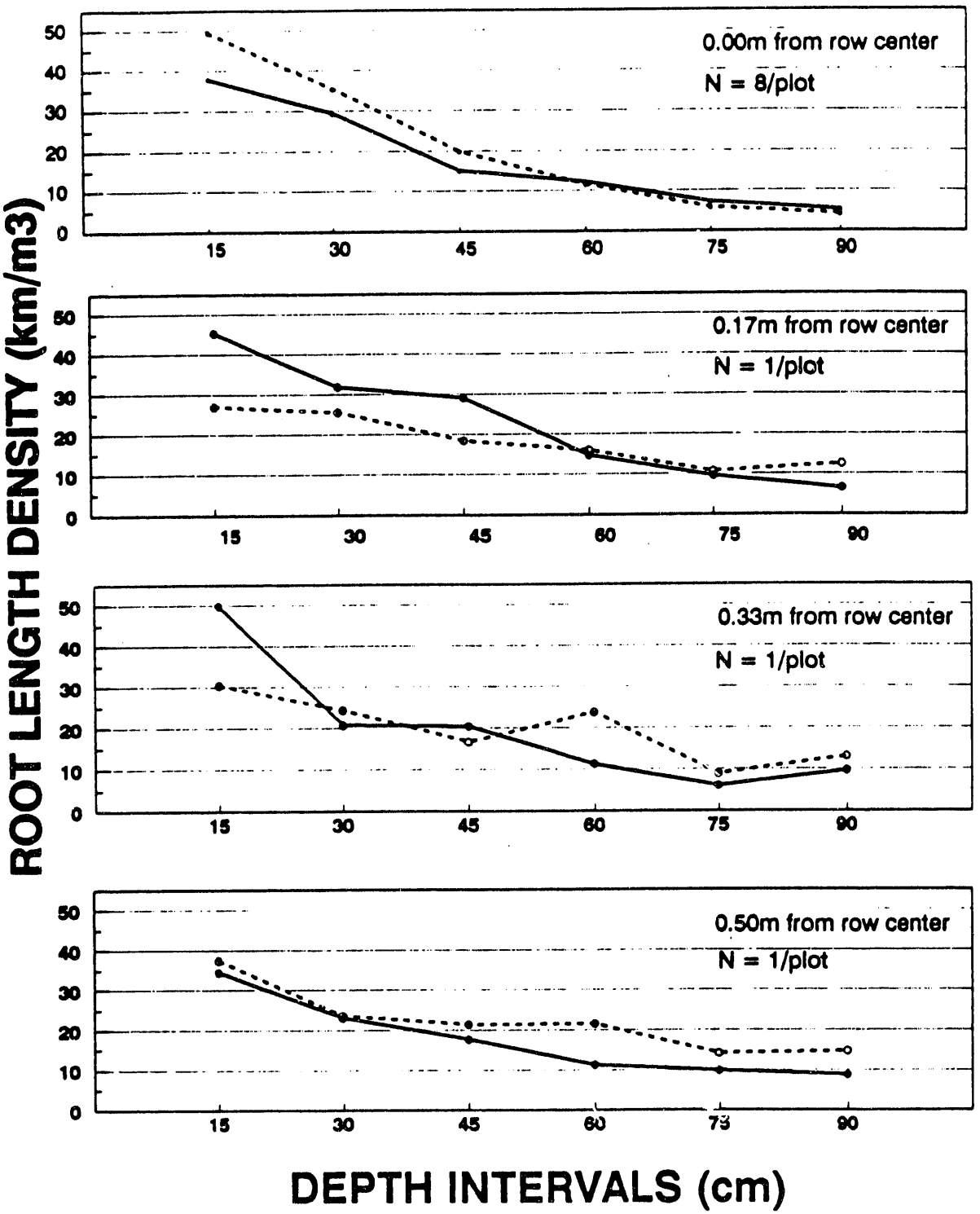
Mean root:shoot ratios of cotton grown under ambient conditions and CO_2 enrichment at Yazoo City, MS, 1988, and at Maricopa, AZ, 1989. Means and percent differences are shown. N = 4.

Date	Location	CO_2 Concentration		% Difference
		350 μmol mol^{-1}	550 μmol mol^{-1}	
1988	Yazoo City, MS	0.112	0.127	13
1989	Maricopa, AZ	0.114	0.168	47

Figure 16-1. Penetration resistance (cone resistance; MPa) at various depths in plots with cotton grown under 350 and 550 μmol mol^{-1} CO_2 at Yazoo City, MS, 1988. N=24.

Figure 16-2. Mean root length density (km m^{-3}) of cotton grown under 350 and 550 μmol mol^{-1} CO_2 different soil profile depths and four positions from row center to the middle of the interrow space at Maricopa, AZ, in 1989.


DEPTH (cm)
0
10
20
30
40
50
60
0
1
2
3
4
5
CONE RESISTANCE (MPa)
[CO2]
350 ppm
550 ppm
1988


ROOT LENGTH DENSITY (km/m3)
0.00m from row center
N = 8/plot
0.17m from row center
N = 1/plot
0.33m from row center
N = 1/plot
0.50m from row center
N = 1/plot
0
10
20
30
40
50
15
30
45
60
75
90
DEPTH INTERVALS (cm)
[ppm CO2]
350
550

SECTION III: COST

COST COMPARISONS AMONG FREE-AIR CO_2 ENRICHMENT, OPEN-TOP CHAMBER, AND SUNLIT CONTROLLED-ENVIRONMENT CHAMBER METHODS OF CO_2 EXPOSURE

Bruce A. Kimball
U. S. Water Conservation Laboratory
USDA, Agricultural Research Service
Phoenix, AZ 85040

I. INTRODUCTION

Several techniques for exposing plants and ecosystems to elevated CO_2 were presented by Allen *et al.* (Chapter 3), and the experimental characteristics of each were discussed in detail. However, one important factor which was not addressed by them is cost, which can easily dictate use of less than ideal methods. The purpose of the this chapter is to evaluate and compare the approximate costs of the free-air CO_2 enrichment (FACE) method with two other popular techniques -- open-top chambers (OTC) and sunlit controlled-environment chambers (Soil, Plant, Atmosphere Research chambers, SPAR).

The primary comparison among the SPAR, OTC, and FACE techniques is a consideration of the relative costs incurred in the production of plants grown in an elevated CO_2. However, measurements of plant response must also be made, which requires scientific personnel and instruments, so the plant production costs will also be compared to the overall costs of conducting CO_2-enrichment experiments.

II. COSTS ASSOCIATED WITH PRODUCING PLANTS IN AN ELEVATED CO_2 ATMOSPHERE

A. Assumptions and value estimates

The assumptions and the values used in the cost analysis are listed in Table 17-1. Estimation of the CO_2, power, land, and other experimental requirements necessitates a decision about the plot areas to be treated, which are very different for the FACE, OTC, and SPAR methods, as used by various laboratories. The plot sizes and equipment estimates used in this comparison are based on (1) the Brookhaven FACE apparatus described by Lewin and Hendrey (Chapter 5), the OTC units of Kimball *et al.* (1992), and the SPAR units of Jones *et al.* (1984). All three are for vegetation with a height on the order of 1 m, such as cotton and soybean. Each type of facility is assumed to have 16 plots, of which 8 are enriched with CO_2. To achieve this number, 4 circular FACE rings and 4 corresponding ambient-CO_2 control rings are assumed to have an 18-m-dia. useable space that is split into 2 sub-plots with a 2-m-wide border between them, resulting in semi-circular plots of 109 m^2 each. The OTC and SPAR facilities have 16 chambers each, with square OTC chambers 3-m on a side for 9 m^2 each, and with

rectangular SPAR units 1 by 2 m for 2 m^2 each.

The overall land requirement for the FACE facility is about 10 ha in order to space the 22-m-dia. rings about 100 m apart so that they will not interfere with one another. OTC's and SPAR can be packed much closer together with prevention of mutual shading and convenience for personnel to walk between them being considerations.

I arbitrarily selected a 6 month growing season, which is slightly longer than the season for cotton and considerably longer than many agricultural crops in high latitudes. However, it is only half the "season" required for natural vegetation, pastures, etc. in warmer climates that grow all year long. The selection of a 300 μmol mol^{-1} enrichment above ambient follows from the commonly-used doubling or near-doubling of present atmospheric CO_2 concentrations, and 300 μmol mol^{-1} was the amount of enrichment used by Kimball *et al.* (1992) in a series of open-top chamber experiments on cotton. The decision to enrich for 24 hours per day rather than just during the daytime comes from recent reports of effect of elevated CO_2 on dark respiration.

The FACE CO_2 usage estimate is based on the total actual use at Maricopa, AZ, in 1989 (800 ton, Nagy *et al.*, Chapter 7) scaled proportionally for 300 rather than 200 μmol mol^{-1} of enrichment, for 24 h rather than 12 h/day of enrichment, and for 6 months rather than 4 months of operation. The OTC CO_2 usage is based on records from 1986 in Phoenix, AZ, from the experiments reported by Kimball *et al.* (1992). The relatively tiny CO_2 requirement for SPAR units is based on supplying the CO_2 needed for photosynthesis of an actively growing crop (average of 25 μmol m^{-2} s^{-1}).

The power requirements for FACE are primarily those associated with 2 hp (3000 W, assuming 50% efficiency) fans at each of the 4 FACE rings, with none used for the ambient plots. Similarly for OTC, the power requirements are those of 1/2 hp (750 W, assuming 50% efficiency) fans for every chamber, enriched and ambient. The SPAR power requirements were calculated from the air conditioning load associated with 1000 W/m^2 solar input and maintaining up to a 40 C temperature difference between inside and out for about 1/4 of the time.

For labor requirements, I assumed that the complexity of the FACE and SPAR systems required one skilled person to be on site every day, which necessitates hiring two such persons who can alternate. OTC's are somewhat simpler, and therefore at least 1 skilled person is needed but does not have to be present every day. One assistant was assumed to be needed for all three types of facilities.

The land, farming operation, and office space costs are based on the 1991 fee schedule used by the University of Arizona, Maricopa Agricultural Center, accounting for the overall amount of land needed for each system.

All of the above assumptions and values pertain to estimation of the operating costs. Of course, the initial purchase and installation costs are also an important consideration. The cost of a FACE facility is based on a cost of $50,000 per FACE ring from Hendrey (G. R. Hendrey, personal communication, 1990) plus another $100,000 to cover utility hookups and other installation costs. The initial cost of a OTC facility is about $200,000 based my own records (Kimball et al, 1992). I have estimated the cost of a single SPAR unit to be about $10,000, and then I doubled this to allow for labor and other installation costs to arrive at a figure of $350,000 for the initial SPAR facility cost. This estimate was confirmed by Allen (L. H. Allen, personal communication, 1990).

B. Results and discussion of plant production expenses

The results of the plant production cost calculations are shown in Figure 17-1. Starting with the initial costs in Figure 17-1a, a SPAR facility with its equipment for control of temperature and humidity in addition to CO_2 is estimated to be most expensive at about $350,000 followed by FACE at $300,000 and then OTC at $200,000.

The annual operating costs are also illustrated in Figure 17-1a, where a FACE facility is seen to cost about three times as much as SPAR and OTC. For the example shown, CO_2 expense dominates the FACE operating costs at about $300,000/yr. For the SPAR facility, CO_2 cost is so tiny, it can not even be seen in Figure 17-1a.

The assumptions for all three enrichment factors -- growing season length, concentration above ambient, diurnal duration -- greatly affect the amount of CO_2 required by the FACE system and its resultant cost. If a lower set point concentration or a shorter duration of enrichment can be justified, then these CO_2 costs can be cut. Nagy *et al.* (Chapter 7) enriched to only 200 rather than 300 μmol mol^{-1}, and they shorted the enrichment duration to 12 h^{-1} day for a 4 month growing season, yet statistically significant crop responses were observed (e.g. Mauney *et al.*, Chapter 11). The CO_2 requirement of Nagy *et al.* was 800 rather than 3,600 tons, thereby cutting their seasonal CO_2 expense from $300,000 to about $65,000.

Electrical power costs are relatively small for all three facilities. Labor appears to be an important component for all three facilities, and it is the largest single cost for operating a SPAR facility. Land cost is larger for a FACE facility than for the other CO_2 exposure techniques, but it is a relatively small component after CO_2, labor, and supplies. Costs for supplies (including other miscellaneous expenses) are estimated to be about $35,000 per year for all three types of facilities, which is about 1/4 of the total operating expense for SPAR and OTC facilities.

The total enriched area for each type of facility is plotted in Figure 17-1b, which illustrates that more than 100 times as much treated plant material can be produced from a FACE facility than from SPAR units and 12 times as much as from a OTC facility. When the total annual operating cost is divided by the total enriched area, a huge economy of scale in favor of a FACE facility becomes obvious, as also is shown in Figure 17-1b. The cost per enriched area of a FACE facility is only 5% of that for SPAR and 26% of that for OTC.

To some extent, I am comparing apples and oranges with these cost comparisons among SPAR, OTC, and FACE facilities. Each has advantages and disadvantages (Allen *et al.*, Chapter 3), and each has a role to play in global change, air pollution, and other plant research. SPAR units can produce controlled environments over ranges that do not now exist for convenient field experiments. On the other hand, the limited amount of plant material available from the small plots restricts destructive harvesting, and of course, their walls isolate them almost completely from the "real world". OTC's offer an intermediate step between isolation and the field. They produce conditions just slightly more humid and warmer than outside, but with greatly altered windflow. Both SPAR and OTC can produce atmospheres in which a component is removed from the air (e.g. CO_2, ozone), and both can operate at temperatures different from outside, although apparently such use has not be made of OTC's yet. Considering that CO_2 expense is relatively smaller for SPAR and OTC, these techniques also gain advantage over FACE as the degree of enrichment increases higher than the 300

μmol mol^{-1} considered here.

FACE has as its forte the production of plants under true field conditions. However, as illustrated in Figure 17-1b, FACE also has a big advantage in plot size. The huge economy of scale produces an incentive for large FACE experiments with many cooperating scientists, and there is enough plant material available for many different tests and measurements.

Another consideration related to the amount of plant produced is that with a FACE facility there is less need to use the same plants for many measurements. It is a common observation that handling of plants by humans can affect their growth (cotton tends to become shorter). Even if no intermediate destructive harvesting is done before the final harvest in SPAR or OTC units, the plants frequently have suffered inadvertent damage from many prior organ count, height, leaf punch, etc. measurements.

III. CONSIDERATION OF PLANT PRODUCTION COST RELATIVE TO OVERALL EXPERIMENT COSTS

Thus far, only the cost of producing high-CO_2-grown plants has been considered in this comparison between SPAR, OTC, and FACE facilities. The major costs of CO_2 enrichment experiments have not been considered -- the labor cost of scientific personnel and the cost of scientific instruments -- both of which are necessary if we are to learn anything useful from producing the treated plants.

The number of scientists to assign to each of the techniques is somewhat arbitrary (Table 17-2). Referring to other chapters of this book, about 20 scientists and an equivalent number of technicians participated in the FACE experiment in 1989 in Maricopa, AZ. The percentage of each one's time devoted to the FACE project varied from about 90 to 10%, so let us assume there were about 8 full-time-equivalents (FTE). Although the number of FTE scientists was about 8, the 1989 FACE experiment probably could have accommodated several more if additional funding had been available.

The number of FTE scientists ascribed to the OTC facility is 4 (Table 17-2) based on my records from Phoenix (Kimball *et al.*, 1992). The number assigned to SPAR is 3 based solely on a lesser amount of plant material available.

The salaries plus benefits are assumed to be about $70,000 and $35,000 for scientists and technicians, respectively (Table 17-2). The total salary plus benefits cost amounts to $315,000, $420,000, and $840,000, for SPAR, OTC, and FACE, respectively, which shows that scientific labor is the largest research expense.

The annual cost of instrumentation is more difficult to estimate because most instruments last for several years and because they are often shared among several experiments. However, a figure of $50,000 would be reasonable. Temporary labor, travel, publication expenses, and the overhead costs of the laboratories for every scientist add to the totals, so that $160,000 is a reasonable number for the instrument etc. cost of the FACE experiment (Table 17-2). The values for the SPAR and OTC are scaled with the number of scientists. Thus, the cost of scientific measurements on the plants from a FACE experiment is on the order of $1,000,000, with OTC and SPAR scaled to about $500,000 and $375,000, respectively.

Adding the scientific measurement cost to the plant production costs, the overall experiment costs are about $516,000, $636,650, and $1,451,500 for SPAR, OTC, and FACE, respectively. The plant production costs amount to 27, 22, and 31% of the total expense for SPAR, OTC, and FACE, respectively. Therefore, while the

cost of producing treated plants is a major expense, it is less than one third of the overall cost of conducting the scientific research.

Lastly, the cost of CO_2 for a FACE experiment should be put in perspective. While a CO_2 cost of $300,000 per year for 300 μmol mol^{-1} enrichment all season long (Figure 17-1a) is a huge expense for most research budgets, nevertheless, this cost is only about 20% of the annual cost of a FACE project (Table 17-2).

IV. SUMMARY

The costs associated with producing high-CO_2-grown plants were compared for three experimental techniques -- free-air CO_2 enrichment (FACE), open-top chambers (OTC), and sunlit controlled-environment chambers (Soil, Plant, Atmosphere Research units, SPAR). The annual operating costs were estimated to be about $140,000/yr for SPAR and OTC. For FACE they were about $450,000/yr, with the CO_2 cost amounting to about $300,000/yr for continuous enrichment by 300 μmol mol^{-1} above ambient for a 6 month growing season. Substantial savings in FACE CO_2 expense can be realized where lower concentrations or shorter enrichment duration can be used. Nevertheless, the FACE plots are much larger so there is a huge economy of scale. The cost per enriched area for plant growth was about $500 m^{-2} yr^{-1} for FACE compared to about $9000 and $2000 m^{-2} yr^{-1} for SPAR and OTC, respectively. When the additional costs of making scientific measurements was addressed, the cost of scientific labor was seen to be the largest expense of conducting research, and the costs of producing treated plants were seen to be only about 27, 22, and 31% of the total costs of SPAR, OTC, and FACE projects, respectively.

V. REFERENCES

1. Jones P, Jones JW, Allen LH Jr., Mishoe JW (1984) Dynamic computer control of closed environmental plant growth chambers. Design and verification. Trans ASAE 27:879-888.

2. Kimball BA, Mauney JR, La Morte RL, Guinn G, Nakayama FS, Radin JW, Lakatos EA, Mitchell ST, Parker LL, Peresta GJ, Nixon PE, Savoy B, Harris SM, MacDonald R, Pros H, and Martinez J (1992) Carbon dioxide enrichment: Data on the response of cotton to varying CO_2, irrigation, and nitrogen. Report ORNL/CDIAC-44 NDP-037, Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U. S. Dept. of Energy, Oak Ridge, TN.

Table 17-1

Assumptions and values used in the cost comparisons among free-air CO_2 enrichment (FACE), open-top chamber (OTC), and sunlit controlled-environment (soil, plant, atmosphere research or SPAR) chamber facilities.

	CO_2 EXPOSURE TECHNIQUE		
ITEM	SPAR	OTC	FACE
Areal scale:			
Total number of plots	16	16	16
Number of enriched plots	8	8	8
Total enriched area (m^2)	8	72	874
Area per plot (m^2)	2	9	109
Overall land requirement (ha)	0.5	1	10
CO_2 enrichment assumptions:			
Growing season (months/year)	6	6	6
Enrichment (μmol mol^{-1} above ambient)	300	300	300
Diurnal duration (hours/day)	24	24	24
Annual CO_2 requirement (Tons)	0.6	134	3,600
price ($/Ton)	200	185	80
Power, labor, land, and supply assumptions:			
Annual electrical requirement (kW-h)	78,000	52,000	52,000
price ($/kW-h)	0.08	0.08	0.08
Skilled labor (persons)	2	1	2
price ($/year)	35,000	35,000	35,000
Unskilled labor (persons)	1	1	1
price ($/year)	20,000	20,000	20,000
Land, farming operations, office ($/yr)	10,000	12,000	24,400
Supplies ($/yr)	35,000	35,000	35,000

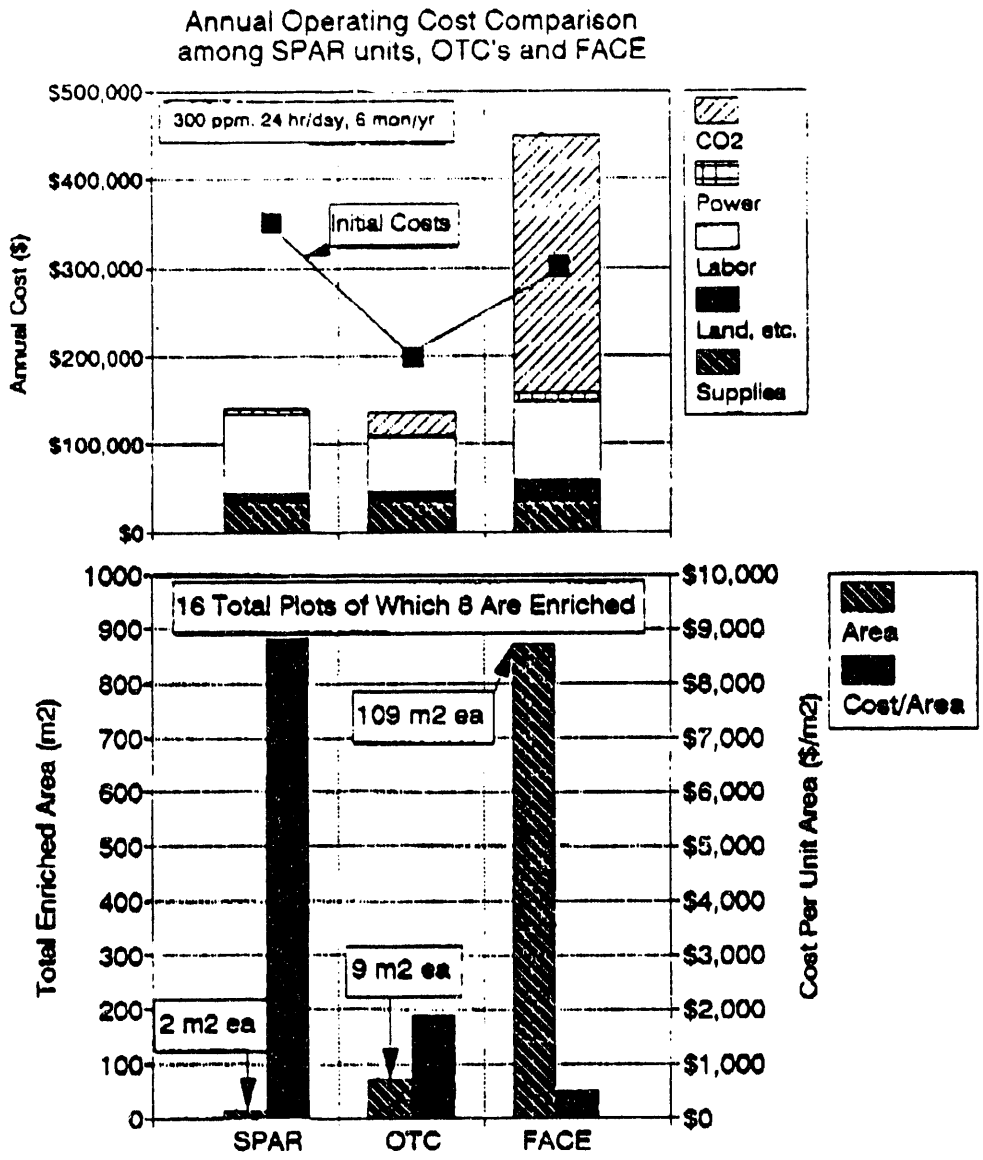
Table 17-2

Overall experimental cost comparisons among free-air CO_2 enrichment (FACE), open-top chamber (OTC), and sunlit controlled-environment (soil, plant, atmosphere research or SPAR) chamber facilities.

	CO_2 EXPOSURE TECHNIQUE		
ITEM	SPAR	OTC	FACE
Cost of producing high-CO_2-grown plants:			
Annual facility operating cost ($/yr)	141,000	136,650	451,500
Cost of making scientific measurement on the high-CO_2-grown plants:			
Number of scientists (FTE)	3	4	8
single scientist salary ($/yr)	70,000	70,000	70,000
single technician salary ($/yr)	35,000	35,000	35,000
Total scientific personnel cost ($/yr)	315,000	420,000	840,000
Approx. instrument etc. cost ($/yr)	60,000	80,000	160,000
Cost of scientific measurements ($/yr)	375,000	500,000	1,000,000
Overall comparisons:			
Total experiment cost ($/yr)	516,000	636,650	1,451,500
Plant production portion (%)	27	22	31
CO_2 cost portion (%)	0	4	20

VI. FIGURE LEGEND

Figure 17-1. Comparison of areas and estimated costs for exposing plants to elevated CO_2 among three types of facilities -- free-air CO_2 enrichment (FACE), open-top chambers (OTC), and sunlit controlled-environment chambers (Soil, Plant, Atmosphere Research units, SPAR).


Annual Operating Cost Comparison
among SPAR units, OTC's and FACE
$500,000
$400,000
$300,000
$200,000
$100,000
$0
Annual Cost ($)
300 ppm, 24 hr/day, 6 mon/yr
Initial Costs
CO2
Power
Labor
Land, etc.
Supplies
1000
900
800
700
600
500
400
300
200
100
0
Total Enriched Area (m2)
16 Total Plots of Which 8 Are Enriched
109 m2 ea
9 m2 ea
2 m2 ea
SPAR
OTC
FACE
$10,000
$9,000
$8,000
$7,000
$6,000
$5,000
$4,000
$3,000
$2,000
$1,000
$0
Cost Per Unit Area ($/m2)
Area
Cost/Area

Appendices

Appendix I: Weather, Soils, Cultural Practices, and Cotton Growth Data from the 1989 FACE Experiment in IBSNAT Format[1]

B. A. Kimball, R. L. La Morte, and G. J. Peresta

U.S. Water Conservation Laboratory, 4331 East Broadway, Phoenix, AZ 85040

J. R. Mauney

Western Cotton Research Laboratory, 4331 East Broadway, Phoenix, AZ 85040

K. F. Lewin and G. R. Hendrey

Department of Applied Science, Brookhaven National Laboratory, Upton, NY 11973

A major objective of the free-air CO_2 enrichment (FACE) project is to provide data suitable for validation of plant growth models. These models are intended to have the capability to predict the effects of the increasing atmospheric CO_2 concentration and its interactions with climate variables on future plant growth, yield, and water use. And indeed one such model called COTCO2 has been written for cotton in cooperation with the FACE project (Amthor and Kimball, 1990). Therefore, it is important that the data from the project be assembled for convenient use by modelers seeking to validate COTCO2 or other cotton growth models. The objective of this Appendix is to present these data in a standard format used by many plant growth models (the data are also available on diskette by request).

In 1986 a group of plant growth modelers collaborated in an effort to standardize crop model input and output file structures (IBSNAT, 1986, 1988). Operating under the auspices of the International Benchmark Sites of Agrotechnology Transfer (IBSNAT) Project, they published IBSNAT Technical Report 5, Decision Support System for Agrotechnology Transfer (DSSAT), Documentation for IBSNAT Crop Model Input and Output Files, Version 1.0. Such standardization should facilitate cooperation and exchange of data among different groups of workers and thus aid plant model development because adhering to the standard would minimize the need to continually reformat the data files.

As is the case with all attempts to standardize, however, the individuals doing the standardizing were working from within the confines of their collective experience, and they could not foretell all future needs. In this case, the IBSNAT standard 1.0 was authored primarily by individuals involved with the development of the CERES-Maize (Jones and Kiniry, 1986), CERES-Wheat (Ritchie and Otter, 1985), and SOYGRO (Wilkerson *et al.*, 1985) models, which, for example, do not use humidity information nor do they consider CO_2 concentration to be a weather or climate variable. These models also use different parameters to characterize soil hydraulic properties than do the more complex GOSSYM (Baker *et al.*, 1983), GLYCIM (Acock *et al.*, 1982), or COTCO2 (Amthor and Kimball, 1990) models.

Another important (to us) aspect not considered by IBSNAT (1986) was the inclusion of cotton as one of the original crops. However,

[1] Contribution from the U. S. Department of Agriculture, Agricultural Research Service. Supported in part by the U. S. Department of Energy.

Kimball *et al.* (1992) addressed this problem with the recent publication of cotton growth data from their CO_2 enrichment experiments using open-top chambers. Following the IBSNAT 1.0 standard as closely as possible and also a proposal by Acock (B. Acock, personal communication, 1988), they prepared tentative modifications to the standard. The dialogue is continuing, and therefore any format used in this book is destined for obsolescence. However, in order that these data be useful for validating models for as many users as possible, the parameters required to meet the IBSNAT (1986) standard are provided as fully as possible. The IBSNAT parameters are then followed by those proposed by Acock and by Kimball *et al.* and then by any additional parameters required by GOSSYM. The resultant format is identical to that used by Kimball *et al.* (1992).

REFERENCES

1. Acock B, Reddy VR, Whisler FD, Baker DN, McKinion JM, Hodges HF, and Boote KJ (1982) The soybean crop simulator GLYCIM: Model documentation. USDA-ARS Crop Simulation Research Unit and Department of Agronomy, Mississippi State University, Mississippi State, MS. 316 pp.
2. Amthor JS and Kimball, BA (1990) Predicting the growth and productivity of cotton in a future "greenhouse world": Development of a physiological model. Proc. Beltwide Cotton Production Research Conference, 9–14 January, Las Vegas, NV, National Cotton Council of America, Memphis, TN 724.
3. Baker DN, Lambert JR, and McKinion JM (1983) GOSSYM: A Simulator of Cotton Crop Growth and Yield. Tech. Bull. 1089, S. Carolina Agric. Expt. Sta., Clemson, SC. 134 pp.
4. Bouwer H (1966) Rapid field measurements of air-entry value and hydraulic conductivity of soil as significant parameters in flow system analysis. Water Resources Res. 2:729–738.
5. Brooks RH and Corey AT (1964) Hydraulic properties of porous media. Hydrology Papers, Colorado State University, Ft. Collins, CO. 3: 1–27.
6. Brown PW (1987) User's guide to the Arizona Meteorological Network. City of Phoenix, Water Conservation and Resource Div. and Arizona Cooperative Extension, Phoenix, AZ. 44 pp.
7. Erie LJ, French OF, Bucks DA, and Harris K (1982) Consumptive use of water by major crops in the southwestern United States. Conservation Res. Rept. No. 29, U. S. Dept. of Agric., Agric. Res. Ser., Wash. DC. 40 pp.
8. Fink DH, and Jackson RD (1973) An equation for describing water vapor adsorption isotherms of soils. Soil Sci. 116: 256–261.
9. Gardner WR and Mayhugh MS (1958) Solutions and tests of the diffusion equation for the movement of water in soil. Soil Sci. Soc. Amer. Proc. 22: 197–201.
10. Idso SB, Jackson RD, Reginato RJ, Kimball BA, and Nakayama FS. 1975. The dependence of bare soil albedo on soil water content. J. Appl. Meteorol. 14: 109–113.
11. IBSNAT, the International Benchmark Sites Network for Agrotechnology Transfer (1986) IBSNAT Technical Report 5, Decision Support System for Agrotechnology Transfer (DSSAT), Documentation for IBSNAT Crop Model Input and Output Files, Version 1.0. Department of Agronomy and Soil Science, University of Hawaii, Honolulu, HA. 53 pp.
12. IBSNAT, the International Benchmark Sites Network for Agrotechnology Transfer (1988) IBSNAT Technical Report 1, Experimental Design and Data Collection Procedures for IBSNAT, Third Edition, Department of Agronomy and Soil Science, University of Hawaii, Honolulu, HA. 73 pp.
13. Jackson RD, Reginato RJ, Kimball BA, and Nakayama FS (1974) Diurnal soil water evaporation: Comparison of measured and calculated soil-water fluxes. Soil Sci. Soc. Amer. Proc. 38:861–866.
14. Jones CA, and Kiniry JR (eds.) (1986) CERES-Maize: A simulation model of maize growth and development. Texas A & M University Press, College Station, TX. 194 pp.
15. Kimball BA, Mauney JR, La Morte RL, Guinn G, Nakayama FS, Radin JW, Lakatos EA, Wall G, Mitchell ST, Parker LL, Peresta GJ, Nixon PE II, Savoy B, Harris SM, MacDonald R, Pros H, Martinez J, and Reaves M. (1992) Response of cotton to varying CO_2, irrigation, and nitrogen: data for growth model validation. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, Oak Ridge, TN (In press).
16. Klute A (ed.) (1986) Methods of soil analysis, Part 1, Physical and mineralogical methods, 2nd ed., Ch. 26, 635–662.
17. Mualem Y (1976) A new model for predicting the hydraulic conductivity of unsaturated porous media. Water Resour. Res. 12:513–522.
18. Post DF, Mack C, Camp PD, and Suliman AS (1988) Mapping and characterization of the soils on the University of Arizona Maricopa Agricultural Center. Proc. of Hydrology and Water Resources in the Southwest, Arizona-Nevada Academy of Science 18:49–60.
19. Reginato RJ and van Bavel CHM (1962) Pressure cell for soil cores. Soil Sci. Soc. Amer. Proc. 26:1–3.
20. Ritchie JT (1972) Model for predicting evaporation from a row crop with incomplete cover. Water Resources Research 8: 1204–1213.
21. Ritchie, J. T. 1985. A user-orientated model of the soil water balance. In W. Day and R. K. Arkin (eds.), Wheat growth and modeling, Plenum Publishing Corp. 293–305.

22. Ritchie JT, and Otter S (1985) Description and performance of CERES-Wheat: A user-oriented wheat yield model. USDA-ARS. ARS–38. 159–175.
23. Ritchie JT, Kiniry JR, Jones CA, and Dyke PT (1986) Model inputs. In Jones CA and Kiniry JR (eds), CERES-Maize: A simulation model of maize growth and development, Texas A&M University Press, College Station, TX. 37–48.
24. Schmidli RJ (1986) Climate of Phoenix, Arizona. NOAA Technical Memorandum NWS WR–177, National Weather Service, National Oceanic and Atmospheric Administration, U. S. Dept. of Commerce, Salt Lake City, UT. 126 pp.
25. Soil Improvement Committee, California Fertilizer Association (1985) Western fertilizer handbook. Interstate Printers and Publishers, Inc., Danville, IL.
26. Van Genuchten MTh (1980) A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. Soil Sci. Soc. Amer. J. 44: 892–898.
27. Van Genuchten MTh and Nielsen DR (1985) On describing and predicting the hydraulic properties of unsaturated soils. Annales Geophysicae 3:615–628.
28. Van Genuchten MTh, Leij FJ, and Yates SR (1992) The RETC Code for quantifying the hydraulic functions of unsaturated soils. EPA Report, Robert S. Kerr Environmental Res. Lab., U.S. Environmental Protection Agency, Ada, OK. (In press).
29. Whisler FD (1976) Calculating the unsaturated hydraulic conductivity and diffusivity. Soil Sci. Soc. Amer. J. 40: 150–151.
30. Whisler FD (1982) Soil data preparation for crop growth models. Agronomic Series No. 1, Mississippi State University, Mississippi State, MS. 9 pp.
31. Wilkerson GG, Jones JW, Boote KJ, Ingram KT, and Mishoe JW (1983) Modeling soybean growth for management. Trans. of the ASAE 26:63–73.

APPENDIX II-A: GLOSSARY

This glossary defines all the terms and their units that are used in the headings of the data tables (Appendix II-D). Additional information about some of terms can be found in Jones and Kiniry (1986), IBSNAT (1986, 1988), Baker *et al.* (1983), Acock *et al.* (1982), Whisler (1976, 1982), van Genuchten (1980), van Genuchten and Nielsen (1985), van Genuchten *et al.* (1992), and especially Kimball *et al.* (1992).

ALPHA(L) - parameter in the van Genuchten soil water retention curve (van Genuchten, 1980; van Genuchten and Nielsen, 1985; van Genuchten *et al.*, 1992) (m^{-1}).

AFERT - amount of nitrogen fertilizer added on JFDAY(J) (kg N ha^{-1}) (same as FERTN).

AIRDR - volumetric water content of air dry soil in soil layer L (m^3 m^{-3}).

AMP - annual amplitude (maximum minus minimum) in mean monthly temperature (°C).

AMTIRR - amount of irrigation added on JDIRR(J) (mm).

AOO - character representation of day of year.

BD(L) - moist bulk density of the soil in soil layer L (Mg m^{-3}).

BDRATO - ratio of initial to final volumetric water content of the bottom soil layer.

BDSLOP - rate of change of water content in bottom soil layer after day of first bloom ((m^3 m^{-3})/day).

BEGDATE - beginning date in weather file (8 characters).

BETA(L) - slope of graph of log (hydraulic diffusivity) vs. volumetric water content for soil layer L (Gardner and Mayhugh 1958).

CATEXC(L) - cation exchange capacity in soil layer L, (meq kg^{-1}).

CLAY(L) - percentage of clay in soil layer L (%).

CN2 - SCS curve number used to calculate daily runoff.

COND - soil hydraulic conductivity (m s^{-1}).

CO2 - mean daily carbon dioxide concentration (μmol mol^{-1}).

CO2DAT - switch to indicate if daily carbon dioxide concentration data

are available (Yes=1,No=0).

CO2YR - mean seasonal CO_2 concentration (μmol mol^{-1}).

DATAID - soil classification.

DEWDAT - switch to indicate if dew point temperature data are available (Yes=1,No=0).

DEWPT - dew point temperature (°C).

DFERT - depth of incorporation of fertilizer application (cm).

DIFF - soil water diffusivity (m^2 s^{-1}).

DIFFO - diffusivity of soil layer L at a low reference water content for Gardner and Mayhugh (1958) equation (m^2 s^{-1}).

DLAYR(L) - thickness of soil layer L (cm).

DMOD - zero-to-unity factor which reduces the rate constant for mineralization of humus pool of soil for which organic matter is chemically or physically protected (default =1).

DNH4(L) - default soil ammonium in soil layer L (mg of N kg^{-1} of soil).

DNO3(L) - default soil nitrate in soil layer L (mg of N kg^{-1} of soil).

DPH(L) - default pH of soil layer L.

DSOIL - irrigation management depth (cm).

DSW(L) - default water content of soil layer L (m^3 m^{-3}).

DUL(L) - drained upper limit soil water content for soil layer L (m^3 m^{-3}).

EFFIRR - irrigation system efficiency (fraction).

ENDDATE - ending date in weather file (8 characters).

ETA(L) - soil characteristic parameter (Brooks & Corey, 1964) relating volumetric water content to soil water potential (matric) for soil in layer L.

EXPDES - experiment description (40 characters).

EXPID - experiment identifier (8 characters) with in institute code, site code, year of the experiment, and experiment number.

EXPTNO - experiment number.

FC(L) - "field capacity" defined as the volumetric water content at a soil water potential (matric) of -33 kPa or other appropriate value, as specified in PSISFC (m^3 m^{-3}).

FERCOD - code for placement of fertilizer application, as defined by IBSNAT (1988) where:
01 - broadcast, not incorporated
02 - broadcast, incorporated
03 - banded on surface
04 - banded beneath surface
05 - applied in irrigation water
06 - foliar spray
07 - bottom of hole
08 - on the seed
99 - other.

FERTIN - effective amount of inoculants and amendments (kg ha^{-1}).

FERTK - effective amount of potassium in fertilizer added (kg ha^{-1}).

FERTN - effective amount of nitrogen in fertilizer added (kg ha^{-1}).

FERTP - effective amount of phosphorus in fertilizer added (kg ha^{-1}).

FILE1 to FILE9 FILEA FILEB - names of the data files as defined in the 'File Structures and Data Formats' section.

GBD(L) - bulk density of soil layer L (g cm^{-3}).

GH2OC( ) - gravimetric water content of a particular bulk density-root impedance curve (kg kg^{-1}).

GLAYR(L) - thickness of soil layer L (cm).

HISTRY - brief description of previous cropping history for site.

ID - is a combination of codes for institute, site, year (last two digits), and experiment number.

IDUMSL - number assigned to a soil type.

IFTYPE - code number for the type of fertilizer added on JDFERT.

IITYPE - code number for the type of inoculants and amendments added on JDFERT.

IIRR - switch describing irrigation (default = 1).
1: no irrigation

2: irrigation applied using field schedule
3: automatically irrigated at threshold soil water
4: assume no water stress, water balance not used

IKTYPE - code number for the type of potassium fertilizer.

IMERGE - emergence date, Day of the year.

INRIM( ) - number of pairs of bulk density / root impedance values defining a curve at a particular water content.

INSTE - code for institute ID in files FILE6, FILE7, FILE8, FILEA, FILEB, and weather files.

INSTS - code for institute ID in soil files FILE4 and FILE5.

INSTW - code for institute ID in weather files FILE1.

INTYPE - code number for the type of nitrogen fertilizer, as defined by IBSNAT (1988), where:
05 - urea
08 - calcium nitrate
10 - urea ammonium nitrate solution.

IPTYPE - code number for the type of potassium fertilizer.

IRRCOD - type of irrigation system, as defined by IBSNAT (1988) where:
01 - furrow
02 - alternating furrows
03 - flood
04 - sprinkler
05 - drip or trickle
99 - other.

ISIM - Day of year simulation begins.

ISOILT - soil number for this treatment.

ISOW - sowing date, Day of the year.

ISWDIS - switch to indicate if disease data are available (Yes=1,No=0).

ISWEED - switch to indicate if weed data are available (Yes=1,No=0).

ISWINS - switch to indicate if insect data are available (Yes=1,No=0).

ISWNEM - switch to indicate if nematode data are available (Yes=1,No=0).

ISWNIT - switch to indicate if nitrogen routines are used (default=0)

0: nitrogen subroutines are not used, assumes adequate nitrogen.
1: nitrogen subroutines are used.

IVARTY - cultivar number for this treatment.

IYR - year for which weather data is being read.

JDFERT - Day of the year of fertilizer application (same as JFDAY).

JDIRR - Day of the year of irrigation event J.

JDOY - Day of year.

JEMRGD - day of emergence, which is the day of year that 50% of the plants emerge from the soil (day of year).

JFDAY - Day of the year of fertilizer application.

JFLRJD - day of first flower, which is the day of year that 50% of the plants display their first flower (day of year).

JNABSM - measured number of abscised sites per m^2.

JNFLWM - measured number of flowers per m^2.

JNGBLM - measured number of green bolls per m^2.

JNMBLM - measured number of mature bolls per m^2.

JNNODM - measured number of nodes per m^2.

JNSQRM - measured number of squares per m^2.

JSQRJD - day of first square, which is the day of year that 50% of the plants display their first square (day of year.)

JUL - Day of year of weather record in data file.

L - soil layer index.

LL(L) - lower limit of plant-extractable soil water for soil layer L, (m^3 m^{-3}).

LYRSOL - number of soil layers.

NCURVE - number of bulk density / root impedance curves, one for each water content.

NLAYR - number of soil layers.

NH4(L) - soil ammonium in soil layer L (mg N kg^{-1} soil).

NOVAR - number of "state" variables for which there are intermediate growth data in FILEB.

NO3(L) - soil nitrate in soil layer L (mg N kg^{-1} soil).

NPATH - number of characters in path given by PTODAT.

NV( ) - array of pointers to indicate which "state" variables for which there are data in FILEB.

OC(L) - organic carbon concentration in soil layer L (%).

OUT1 to OUT4 - output file names.

PARDAT - switch to indicate if PAR data are available (Yes=1,No=0).

PARFAC - factor to convert MJ m^{-2} to mol m^{-2} (2.30 if unknown).

PEDON - SCS pedon number.

PH(L) - pH of soil in soil layer L in a 1:1 soil water slurry.

PHFAC3 - variable to reduce apparent photosynthesis attributed to soil fertility (for grain legume models, default = 1.00).

PHOSPH - soil phosphorus in soil layer L (mg P kg^{-1} soil).

PLANTS - plant population (plants m^{-2})

POTASS - soil phosphorus in soil layer L (mg K kg^{-1} soil).

PROCK - procedure used to determine soil K.

PROCN - procedure used to determine soil N.

PROCP - procedure used to determine soil P.

PSIBUB(L) - soil water potential (matric) near saturation taken to be bubbling pressure at which air starts to enter the soil as it dries (kPa, positive number).

PSISFC - soil water potential (matric) used to define field capacity (kPa, positive number).

PSIR - reference low (dry) soil water potential (matric) in Marani equation corresponding to THETAR (kPa).

RHOS - density of solid soil particles (Mg m^{-3}).

RHOW - density of water (Mg m^{-3}).

ROCK(L) - coarse rock fragments in soil layer L (%).

ROOT - dry weight of root residue of previous crop (kg ha^{-1}, default=500).

ROWSPC - row spacing (m).

RSAT - relative saturation as defined by Eq. 14.

RWUMX - maximum daily root water uptake per unit root length (cm^3 cm^{-1} root-day, default = 0.03).

SALB - bare soil albedo.

SAND(L) - sand in soil layer L (%).

SAT(L) - saturated water content for soil layer L (m^3 m^{-3}).

SCN - C:N ratio of surface residue of previous crop (kg C kg^{-1} N, default = 75.).

SCOND(L) - saturated hydraulic conductivity (m s^{-1}, or μm s^{-1} in the data files).

SDEP - depth of surface residue incorporation (cm).

SDEPTH - sowing depth L (cm).

SILT(L) - silt in soil layer L (%).

SITEE - code for site ID in files FILE6, FILE7, FILE8, FILEA, and FILEB.

SITES - code for site ID in soil files FILE4 and FILE5.

SNAME - description of soil for root impedance data.

SOLRAD - daily total solar radiation (MJ m^{-2}).

STATW - code for weather station ID (2 characters).

STDAT - switch to indicate if soil temperature data are available (Yes=1,No=0).

STMAX - daily value of maximum temperature at 10 cm depth in bare soil (°C).

STMIN - daily value of minimum temperature at 10 cm depth in bare soil (°C).

STRAW - weight of organic residue of previous crop and/or added green manure (kg ha^{-1}).

SW(L) - soil water content for soil layer L (m^3 m^{-3}).

SWCON - soil water drainage constant, (fraction drained/day).

SWCON1 - coefficient in the steady-state solution of the radial-flow root uptake equation (cm^3 cm^{-1} root-day, default=0.00267).

SWCON2 - coefficient in the steady-state solution of the radial-flow root uptake equation (cm^3 cm^{-1} root-day, default=58.0).

SWCON3 - coefficient in the steady-state solution of the radial-flow root uptake equation (cm^3 cm^{-1} root-day, default=6.68).

TAV - annual average ambient air temperature (°C).

TAXON - soil classification.

TD - number of days after first bloom that water content of the bottom soil layer begins to change (days).

THETA - volumetric soil water content (m^3 m^{-3}).

THETAC - percent available water which triggers irrigation (%).

THETAI - initial water content of bottom layer in soil profile for some sites and data sets where this is known (m^3 m^{-3}).

THETAR(L) - "residual" soil water content of Brooks and Corey (1964) or "reference" soil water content near the wilting point for the Marani equation, taken as THETA0 slightly reduced (typically by 0.001) (m^3 m^{-3}).

THETAS(L) - volumetric water content of soil in layer L at "saturation". Assumed to be the same as the water content at which air starts to enter the soil as it dries (i.e. at the bubbling pressure) (m^3 m^{-3}).

THETA0(L) - reference volumetric water content of soil in layer L for Gardner and Mayhugh (1958) equation, generally at a low (wilting point) soil water potential of -1500 kPa (m^3 m^{-3}).

TITLET - title of treatment.

TSTBD(,) - bulk density at a point on bulk density / root impedance curve (Mg m^{-3}).

TRTNO - treatment number.

TSTIMP(,) - root impedance at a point on the bulk density / root impedance curve (kg cm^{-2}).

U - upper limit of stage 1 soil evaporation (mm).

VGTHR(L) - "residual" soil water content fitted to the extrapolated dry end of the retention curve for the van Genuchten equation. (van Genuchten, 1980; van Genuchten and Nielsen, 1985; van Genuchten *et al.*, 1992) (m^3 m^{-3}).

VGTHS(L) - "saturated" soil water content fitted to the extrapolated wet end of the retention curve for the van Genuchten equation. (van Genuchten, 1980; van Genuchten and Nielsen, 1985; van Genuchten *et al.*, 1992) (m^3 m^{-3}).

WIND - daily total wind run (km).

WINDYR - long-term average daily total wind run for the experimental site (km).

WNDDAT - switch to indicate if daily wind data are available (Yes=1, No=0).

WR(L) - weighting factor for soil depth L to determine new root growth distribution.

WTHES - weather station description (40 characters).

WTHID - weather station identifier (4 characters).

XAPTNP - measured nitrogen content of stems plus burrs plus lint at maturity (kg ha^{-1}).

XBIOM - field-measured above-ground biomass at maturity (kg ha^{-1}).

XBLSM - field-measured mature boll number (bolls m^{-2}).

XLAI - measured leaf area index (m^2 m^{-2}).

XLAIMX - maximum leaf area index during season (m^2 m^{-2}).

XLAT - latitude of station (degrees).

XLONG - longitude of station (degrees).

XLTYLD - final dry lint yield attainable by hand harvesting (kg ha^{-1}).

XM(L) - parameter in the van Genuchten soil water retention curve. (van Genuchten, 1980; van Genuchten and Nielsen, 1985; van Genuchten *et al.*, 1992)

XN(L) - parameter in the van Genuchten soil water retention curve. (van Genuchten, 1980; van Genuchten and Nielsen, 1985; van Genuchten *et al.*, 1992)

XPAR - daily total PAR (mol m^{-2}).

XPLTHT - measured plant height (cm).

XRAIN - daily total precipitation (mm day^{-1}).

XSDN - measured nitrogen content of seed at maturity (kg ha^{-1}).

XSDTN - measured nitrogen concentration in seed at maturity (%).

XSDWT - measured seed dry weight (g $seed^{-1}$).

XSDYLD - final dry seed yield (kg ha^{-1}).

XSPB - measured number of seeds per boll (seeds/boll).

XSTBR - field-measured stem plus burr weight at maturity (kg ha^{-1}).

XTMAX - daily value of maximum air temperature (°C).

XTMIN - daily value of minimum air temperature (°C).

XTOTNP - measured total crop nitrogen content at maturity (kg ha^{-1}).

XWBURR - measured dry weight of burrs (kg ha^{-1}).

XWGBLH - measured dry weight of green bolls (kg ha^{-1}).

XWLEFH - measured dry weight of leaves (kg ha^{-1}).

XWLINT - measured dry weight of lint (kg ha^{-1}).

XWMBLH - measured dry weight of mature bolls (kg ha^{-1}).

XWROTH - measured dry weight of roots (kg ha^{-1}).

XWSEED - measured dry weight of seed (kg ha^{-1}).

XWSTMH - measured dry weight of stems (k ha^{-1}).

X1FERT - distance from plant row to closest edge of fertilizer application area (cm).

X1IRR - distance from plant row to closest edge of water application area (cm).

X2FERT - distance from plant row to furthest edge of fertilizer application area (cm).

X2IRR - distance from plant row to furthest edge of water application area (cm).

YEAR - year, last 2 digits

Z - depth or length variable (m).

Z1FERT - topmost depth in soil where fertilizer is applied (cm).

Z1IRR - topmost depth in soil where water is applied (cm). For flood, sprinkler, or furrow irrigation, the appropriate entry would be zero.

Z2FERT - lowest depth in soil where fertilizer is applied (cm).

Z2IRR - lowest depth in soil where water is applied (cm).

APPENDIX II-B: SOILS DATA SOURCES

Much of information about the culture of the cotton crop and its response to the FACE treatment is discussed in previous chapters of this book (particularly Mauney *et al.*, Chapter 11, this book). The weather data are from the University of Arizona's AZMET weather station located about 2 km north of the FACE field site (Brown, 1987), but with the FACE CO_2 concentrations observed by us (see Lewin *et al.*, Chapter 7, this book) and the ambient CO_2 concentration assumed to have been 350 μmol mol^{-1}. Irrigation was accomplished with a subsurface drip irrigation system at a depth of about 20 cm beneath the rows, and all fertilizer was applied in the irrigation water through the drip system. There were some problems with blockages in the drip system, as mentioned by Mauney *et al.* (Chapter 11, this book), and on about 9-11 August, new drip tubes were installed on the soil surface in the experimental plots along the rows. A value of 0.95 has been supplied in the data tables for the efficiency of irrigation, EFFIRR, but this may be too high for the time period of about a month before the surface tubes were installed.

However, soil properties strongly influence plant growth, and although they are not expected to change much due to changing atmospheric CO_2 concentration in the short term, nevertheless, they are needed for modeling the growth of the crop. This Appendix lists each one included in the soils file TRIX.CT2 (Appendix II-C, this book) and either gives the reference for its source or justifies the value used.

Classification: Trix clay loam [fine-loamy, mixed (calcareous) hyperthermic Typic Torrifluvents]. The land used by the FACE experiment (east end of field 27, Maricopa Agricultural Center, MAC) is near the center of an area of Trix clay loam, as mapped intensively by Post *et al.* (1988).

Particle density, RHOS: The particle density for Avondale loam in Phoenix is 2.72 Mg m^{-3} (Kimball *et al.*, 1992), yet a value common to many soils is about 2.65. Therefore, we assume the particle density must be close to 2.70 Mg m^{-3}.

Albedo, SALB: Ritchie *et al.* (1986) list 0.13 as a typical value for the albedo of a clay loam. However, albedo can change rather drastically with water content as shown by Idso *et al.* (1975) who found a value of 0.12 for wet roughened Avondale loam which increased to about 0.25 as the field dried. In our case, the field had been fallow for 3 years prior to the start of the FACE experiment, so it was relatively free of trash. The field was pre-plant irrigated with 10 cm of water on 10 April 1989 and had received sporadic amounts of water before that as the new sub-surface drip irrigation system was tested. Fortunately, Jackson and colleagues (RD Jackson, personal communication, 1991) flew over the FACE field on 9 and 15 April and measured reflectances in red, green, and near-infrared bands. After making corrections to account for the proportion of the total solar spectrum represented by these bands, Jackson calculated that the albedo for Trix clay loam on those days was 0.17 and 0.22, respectively. Considering that the surface moisture content on those days was probably somewhere between wet and dry, an average value of 0.20 is very reasonable.

Upper limit of stage 1 soil evaporation, U: Assuming Trix clay loam is similar to Avondale loam (whose texture is on the clay loam border) studied previously in Phoenix, AZ (Kimball et al, 1992), a value of 12 mm was taken from Ritchie (1972).

Soil water drainage constant, SWCON: Following Ritchie *et al.* (1986, p.39), SWCON was calculated for each soil layer from the porosity and "drained upper limit" for each soil layer, and then the minimum value among all the layers was taken as the profile value of 0.286.

SCS curve number for calculating runoff, CN2: According to local SCS personnel (Mr. Harry Millsaps, personal communication, 1991), Trix clay loam is in the "B" class, and therefore, for cotton planted in straight rows which were leveled originally for furrow irrigation, the curve number would be about 70.

Annual average air temperature, TAV, and range or amplitude, AMP: The elevation of the MAC farm is 358 m (Post et al, 1988), which is close to that of Sky Harbor International Airport in Phoenix AZ (Schmidli, 1986). Therefore, the long term weather data recorded in Phoenix should also be appropriate for MAC. The annual average air temperature recorded by the National Weather Service at Sky Harbor was 21.8°C with a maximum of 33.5 °C for the month of July and a minimum of 11.3 °C for January (Schmidli, 1986) for a range of 22.2 °C.

Annual average deep soil temperature and range: Average annual deep soil temperature would be expected to exceed average annual air temperature slightly. For about 2 1/2 years Kimball *et al.* [Kimball BA, Mitchell ST, and Brooks G (1981) Annual Report, U. S. Water Conservation Laboratory, Phoenix, AZ] measured soil temperature at a depth of 2.5 m in Phoenix, AZ. The average maximum was 27.3 in October and the average minimum was 19.8 in March for a range of 7.5. The annual average at the 2.5 m depth was about 23.6 °C.

Mineralization rate reducer, DMOD; Coefficients for the radial-flow root uptake equation, SWCON1, SWCON2, and SWCON3; Maximum daily root water uptake per unit root length, RWUMX; and Variable to reduce apparent photosynthesis attributed to soil fertility, PHFAC3: Lacking any better information, the values supplied for these parameters are the IBSNAT (1986) default values: 1.0, 0.00267, 58, 6.68, 0.03, and 1.0, respectively.

Thickness of each soil layer, DLAYR(L): The soil layer thicknesses were chosen following Ritchie *et al.* (1986) and the horizon descriptions of Post *et al.* (1988). The layers above the 30 cm depth are in the Ap horizon. Just under this ploughed surface Ap horizon at depths from about 30 to 70 cm is a C1 horizon with texture and properties similar to those of the Ap. Below the C1 is a C2, which is coarser (more sand) with properties like the subsoil of a Casa Grande soil. Trix is alluvial and presumed to overlie Casa Grande.

Lower limit of plant extractable water, LL(L): LL was calculated from the algorithm of Ritchie *et al.* (1986, p. 43) from the clay content, bulk density, and organic matter content. The calculated values of about 0.20 for the upper 30 cm are in agreement with the -1500 kPa water retention values measured by USWCL

personnel, Post *et al.* (1988), and Post (DF Post, 1990, personal communication) (Fig. 1). However, the values of about 0.12 for the deeper depths are considerably lower than a value of 0.21 measured by Post (DF Post, 1990, personal communication).

Drained upper limit of soil water content, DUL(L): DUL was similarly calculated from Ritchie *et al.* (1986, p. 43) using LL(L) and clay content, bulk density, and organic matter content. The calculated value of 0.32 for the surface soil is near midrange of the -33 kPa water contents determined by USWCL and University of Arizona personnel (Fig. 1).

Saturated water content, SAT(L): The saturated water content values were computed following Ritchie *et al.* (1986) as the drained upper limit plus 0.5 times the difference between total porosity and drained upper limit.

Default soil water content, DSW(L): The DUL values were used because probably there would have been a pre-irrigation before the start of a simulation.

Weighting factor for soil layer to determine new root growth distribution, WR(L): Following Ritchie *et al.* (1986), the top soil layer was set to 1.0, and then their exponential decay function was used to compute the values for the other depths. This distribution appears to be in agreement with the rooting profiles measured by Rogers *et al.* (Chapter 16, this book).

Bulk density, BD(L): The bulk density data are those measured by Rogers *et al.* (Chapter 16, this book) within the plots of the experiment. The values near the surface of about 1.3 Mg m^{-3} are slightly lower than those reported by Post *et al.* (1988), whereas the value of 1.57 for the deeper depths is somewhat higher. No measurements of the effects of tillage or wheel tracks were available.

Organic carbon concentration, OC(L): Rogers *et al.* (Chapter 16, this book) present organic matter content data, so the organic carbon concentrations were computed from them by assuming the organic matter was predominantly similar to carbohydrate (CH_2O) and therefore 40% carbon. The values of about 0.4% are slightly lower than the 0.48 to 0.6% given by Post *et al.* (1988).

Default and initial soil ammonium nitrogen, DNH4(L), NH4(L): Zero. Experience from many samples has shown that NH_4^+-N contents of Arizona soils are very low (P. Eberhart, IAS Laboratories, Phoenix, Arizona, Personal communication, 1990), presumably because nitrification is rapid at our temperatures (Soil Improvement Committee, 1985).

Default and initial soil nitrate nitrogen, DNO3(L), NO3(L): The default and initial soil nitrate nitrogen content were set to low values after 3 years of fallow, as estimated from surface measurements made by Lakatos (Lakatos EA, personal communication, 1989) in April, 1989.

Default and initial pH, DPH(L), PH(L): The default and initial pH of 8.6 are from Rogers *et al.* (Chapter 16, this book). This is slightly higher than a value

of 8.0 reported by Lakatos (Lakatos EA, personal communication, 1989) and as stated as typical of the Trix series by the Soil Survey.

Coarse fragments, ROCK(L); sand, SAND(L); silt, SILT(L); and clay, CLAY(L): The amount of coarse fragments was taken as 0%, based on measurements by Warrick (A. W. Warrick, personal communication, 1990), which showed gravel content to be generally less than 1%. Post *et al.* (1988) list the sand and clay percentages as 25-45 and 27-40%, respectively, for both the 0-30 and 30-70 cm depths. Averaging, the sand, silt, and clay percentages were taken as 35, 31, and 34%. At the deeper depths, higher sand contents were found by Warrick in the field immediately to the north of our FACE site, which was also mapped as Trix clay loam (Post *et al.*, 1988). The higher sand content at the deeper depths is consistent with the belief that Trix overlies Casa Grande soil (Post *et al.*, 1988).

Saturated hydraulic conductivity, SCOND(L): Because apparently no measurements had been made previously the site of the FACE experiment of saturated hydraulic conductivity, and because it is one of the most important parameters that characterizes soil water movement, we made 14 determinations of it in January 1990 using the air-entry permeameter method (Bouwer, 1966). The measurement locations were just outside the 1989 FACE plot areas as listed in Table II-B-1. The measurements were taken both in and between rows. Briefly, a 24.6-cm-diameter steel cylinder was driven into the soil surface to a depth of 10 cm. Then an upper water reservoir with connecting standpipe was clamped to the cylinder. Water was poured into the reservoir and allowed to infiltrate the soil to a depth of about 8-10 cm. Toward the end of the infiltration period, the rate of fall of water in the reservoir was measured. Then at the end of the infiltration time, the standpipe was closed and the bubbling pressure was measured. This was accomplished using a gauge to measure the maximum amount of vacuum that developed in the space above the soil just before air started to bubble up through the soil. After the bubbling pressure was measured, the reservoir was removed from the cylinder, and the depth to the wetted front was measured by inserting a 6-mm-diameter rod into the soil in several places and noting how far it could be pushed easily. Because the soil was initially very dry, the wetting front was very abrupt, and the depth to the hard dry soil could easily be measured to within 0.5 cm. Finally, using the heights to the water level in the reservoir, to the vacuum gauge, etc., the saturated hydraulic conductivity was calculated following Bouwer (1966).

The results are presented in Table II-B-1. The number of data points is small and the scatter is high, typical of saturated hydraulic conductivity data. There was no obvious effect of site on the field (Rep) or of row, so the data were pooled. Assuming a log-normal distribution, the mean conductivity was 4.3 $\mu m\ s^{-1}$.

In October 1991, Whisler (FD Whisler, personal communication, 1992) obtained 8 76-mm-dia. undisturbed soil cores close to the FACE plots. Three sections 76 mm long were taken to be representative of 0-28, 28-52, and 52-200 cm horizons. These were taken to the laboratory for determination of hydraulic conductivity. The mean values obtained were 6.4, 2.1, and 4.7 $\mu m\ s^{-1}$, respectively, for the three horizons. Because the number of our samples was larger, and because our field apparatus was wider in diameter, we regard the 4.3 $\mu m\ s^{-1}$ figure (Table 1) to be more representative, and it is presented in the data

Table II-B-1. Saturated hydraulic conductivity and bubbling pressure for Trix clay loam measured just outside the plots of the 1989 FACE experiment in Field 27, Maricopa Agricultural Center, Maricopa, AZ. The means and confidence limits were calculated assuming a log-normal distribution for conductivity and normal for pressure.

SITE				SATURATED HYDRAULIC CONDUCTIVITY	BUBBLING PRESSURE
Rep	Treat-ment	Quad-rant	Row		
				$\mu m\ s^{-1}$	kPa
1	Amb.	NW	between	4.6	8.4
1	Amb.	NW	row	7.5	8.4
1	FACE	NW	between	14.8	6.4
1	FACE	NW	row	6.6	7.6
1	FACE	SE	between	9.1	8.4
1	FACE	SE	row	2.4	9.3
2	Amb.	SE	row	1.8	8.4
2	FACE	SE	between	9.3	8.4
2	FACE	NW	row	1.3	9.8
3	Amb.	SE	row	1.6	8.4
3	FACE	NW	between	7.3	5.9
3	FACE	NW	row	3.3	8.4
4	FACE	SE	between	3.7	8.4
4	FACE	SE	row	3.5	9.5
			Lower 95% confidence limit	2.9	7.7
			Mean	4.3	8.3
			Upper 95% confidence limit	6.4	8.8

table (ITRIX.CT2). The Whisler data suggest the conductivity becomes smaller and then larger with depth. Considering the large variability in this parameter, however, we have entered a constant 4.3 $\mu m\ s^{-1}$ for all depths in TRIX.CT2.

The conductivity data in Table II-B-1 are also lower than those reported by Warrick (A. W. Warrick, personal communication, 1990) for Field 28 immediately to the north of the FACE site on soil also mapped as Trix clay loam (Post et al., 1988). He took duplicate undisturbed cores from the 5-20 cm depth to the laboratory, and found values of 27, 11, 21, 28, 21, and 2.3 $\mu m\ s^{-1}$ for a geometric mean of 14 $\mu m\ s^{-1}$. The latter 2 values were from areas closest to the FACE site.

Thus, while we have entered a value of 4.3 $\mu m\ s^{-1}$ into the soils file, there is some evidence to suggest this value might be somewhat low.

Cation exchange capacity, CATEXC(L): The cation exchange capacity was reported by Post *et al.* (1988) to be 240-270 and 220-260 meq kg^{-1} for the 0-30 and 30-70 cm layers, respectively, and we have estimated the profile to 70 cm from these data and adjusted in proportion to clay content for the deeper depths.

Air dry water content, AIRDR: The "air dry" water content is needed for some models. However, it is not precisely defined unless the temperature and relative humidity conditions are specified. For Avondale loam at 27 °C, Fink and Jackson (1973) showed that the water content increased roughly linearly from about 0.02 at a relative humidity of 10% to about 0.06 at a relative humidity of 80%. Considering that the average annual relative humidity is about 40% for Phoenix (Schmidli, 1986), a figure of 0.03 for the air dry volumetric water content is reasonable.

Soil water retention curve and soil water potential: Probably the most important function governing soil water flow and plant water uptake is the soil moisture characteristic or soil water retention curve that relates soil water potential (matric) to soil water content. Extensive discussion of the parameters for alternative methods of describing this curve are given in Kimball *et al.* (1992) and in van Genuchten *et al.* (1992) and will not be repeated here.

We were not aware of any published retention curves for Trix clay loam, so a measurement program was initiated. Undisturbed core samples were collected using a sampler of a type similar to Soilmoisture Equipment Corp. Model 200-A during the winter, 1990. A pair of 3-cm-deep by 5.51-cm-diameter cores were taken from the 0-3 and 3-6 cm layers and another pair from the 20-23 and 23-26 cm layers from locations just outside the 1989 FACE plots. The "surface" pair of cores were taken by driving the sampler into the soil surface. Then a shovel was used to dig down to the 20-cm depth and smooth an area where the "deep" pair of cores were taken. After removal of the cores from the sampler, they were sealed in individual cans for transport back to the laboratory in Phoenix, where they were stored at 4°C until their turn for measurement.

The intact cores were placed in reweighable "Tempe" cells (Reginato and van Bavel, 1962) and saturated with distilled water from below. Then pressures of 1, 10, 25, 50, 75, and 100 kPa were successively imposed, weighing every day or so to obtain the drainage curve. After the last weighing of the whole cell for the 100 kPa reading, the cores were removed from the cells and dried in an oven at 105 °C. After oven-dry weighing, the soil from the cores was removed and crumbled. This loose soil was then brought to a water content of ≈5% in a plastic bag by adding a known volume of water from a syringe, mixing the soil by kneading the bag, and allowing the soil to equilibrate about 7 days. Next, the soil was brought to almost exactly 7% by weighing the bag with soil and adding the appropriate amount of water from a syringe. More mixing by kneading was followed by another equilibration of about 2 days, and then portions of it were packed to original bulk density in 1-cm-deep by 5.55-cm-diameter retaining rings in Soil Moisture Equipment Corp. Model 1700 pressure membrane extractors. Using the techniques described by Klute (1986), data were obtained for higher pressures at 100, 250, 600, and 1500 kPa.

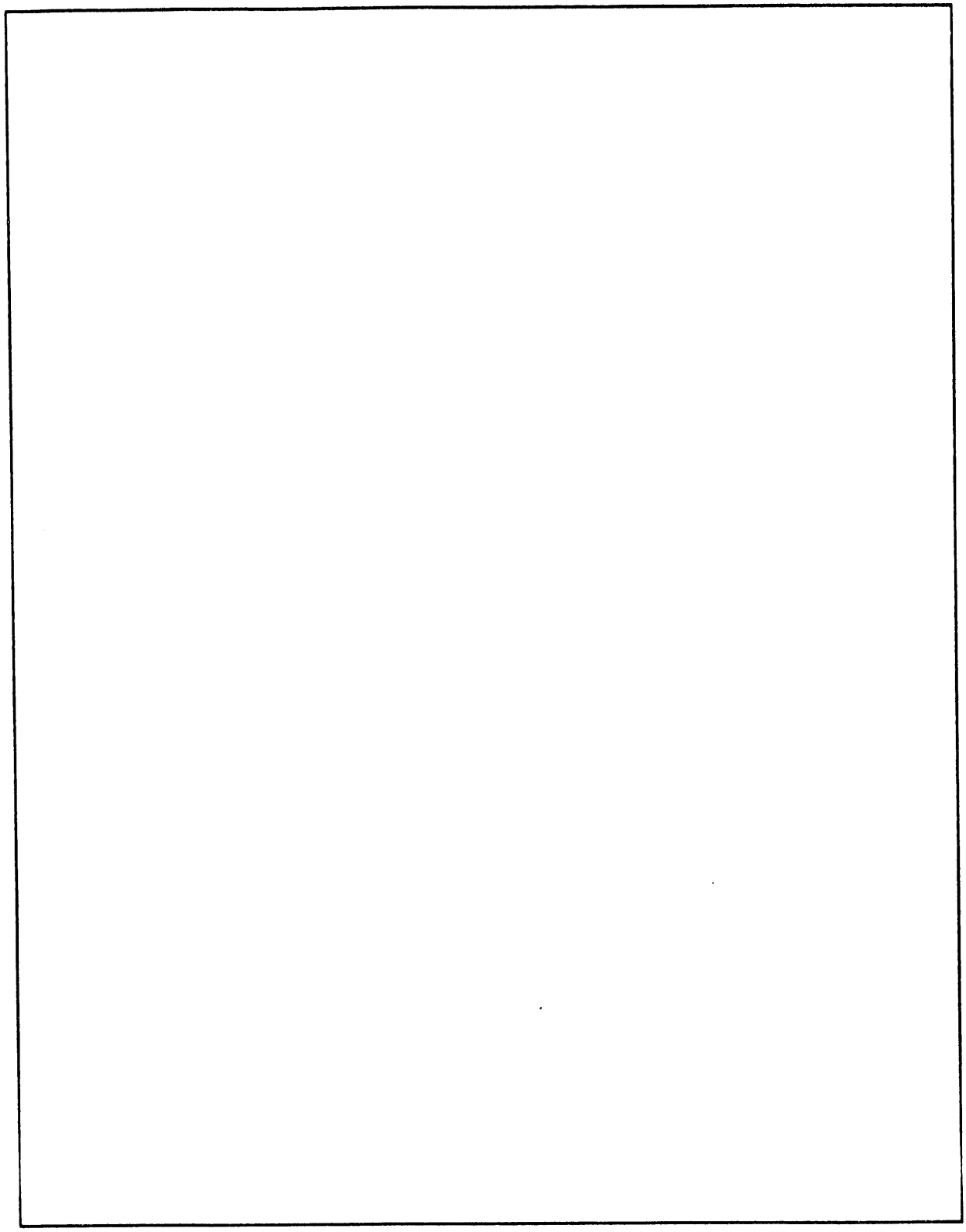
In October 1991, Whisler (FD Whisler, personal communication, 1992) obtained 8 76-mm-dia. undisturbed soil cores close to the FACE plots. Three sections 10 mm long were taken to be representative of 0-28, 28-52, and 52-200 cm horizons. They were placed on cheese cloth in pressure membrane apparatus, as described by Klute (1986). After saturation with a salt solution to minimize swelling, pressure was applied in increments. At each pressure increment, the cores with cheese cloth were lifted to a balance for weighing and then placed back on the pressure membrane.

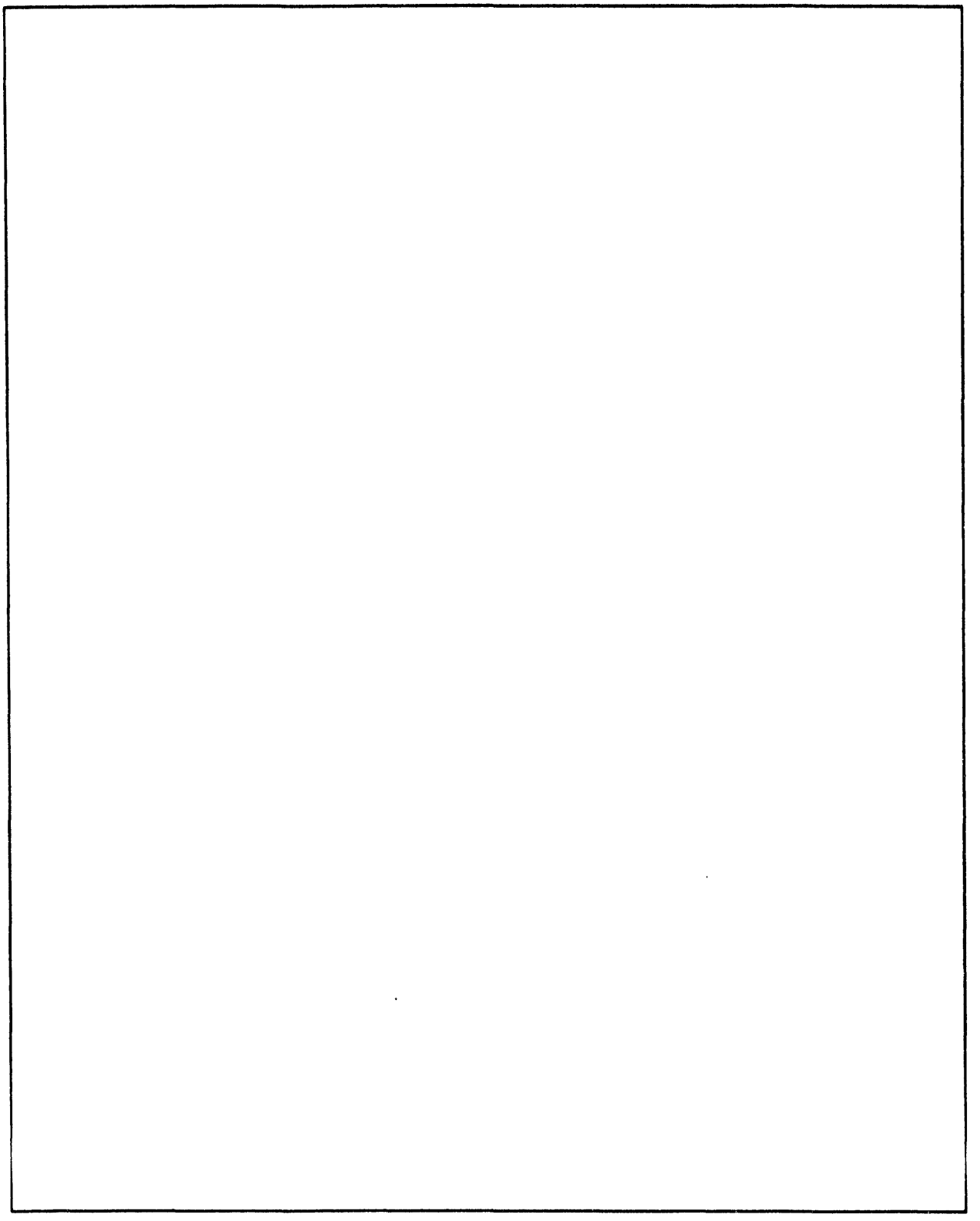
The soil water retention data are presented in Fig. II-B-1 for the surface 0-30 cm horizon. The scatter among the data obtained by USWCL personnel is higher than expected or desired. However, the ranges for Trix clay loam reported by Post *et al.* (1988) are also fairly broad. The points obtained by Post (1990, personal communication) near the FACE field are also in excellent agreement. The points obtained by Whisler are also in fairly good agreement, except for the wettest point at 1 kPa water potential. Two reasons Whisler's point is wetter than ours could be that he minimized swelling with a salt solution and that he used thinner samples. Therefore, his point may be more accurate, but we still regarded soil inhomogeneity to be important, so we gave all points equal weight in curve fitting procedures.

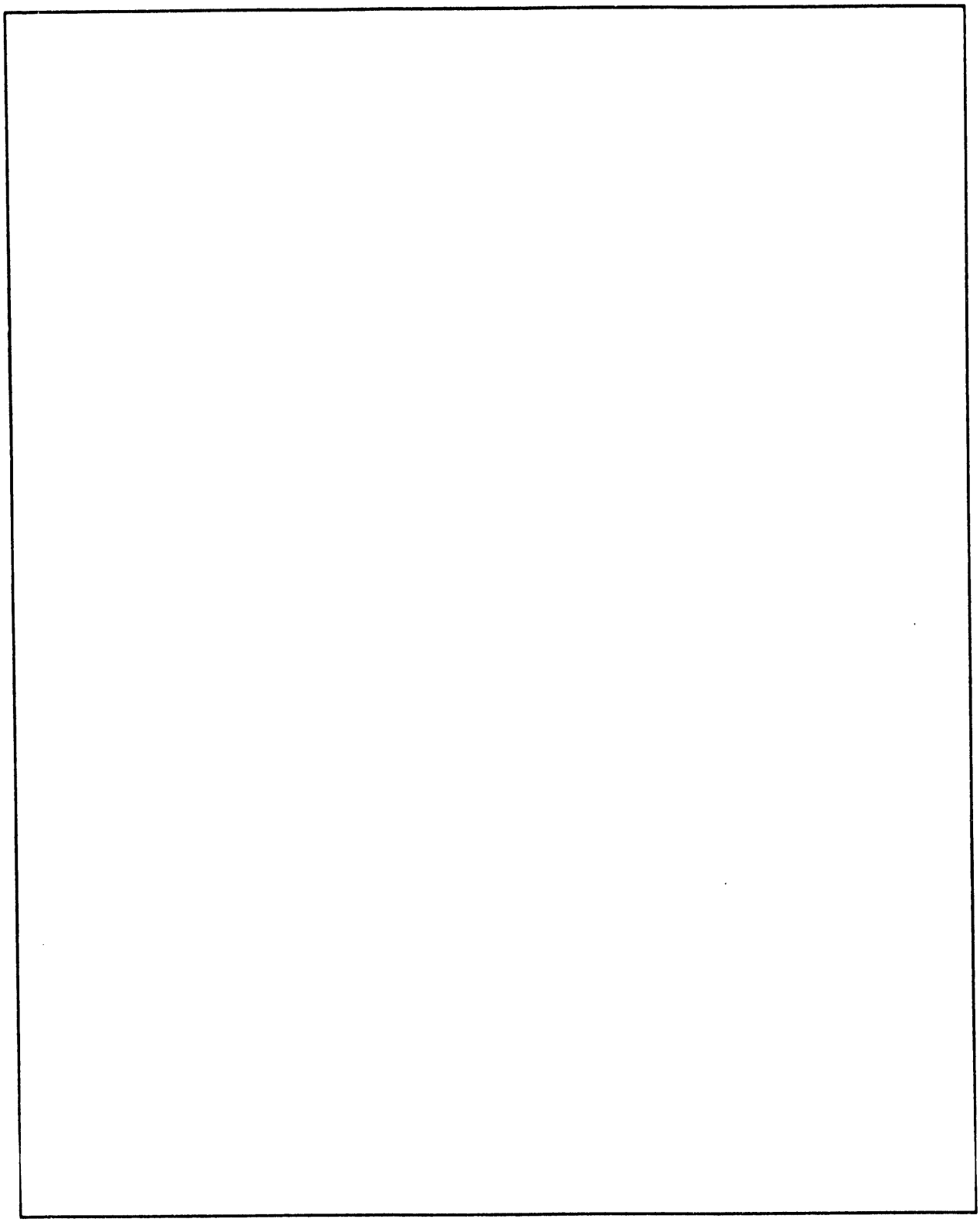
The RETC code of van Genuchten *et al.* (1992) was used to fit the curve through the data points. Solving for ALPHA, XN, the saturated water content, VGTHS, and the so-called residual water content, VGTHR, a parabolic-appearing curve was obtained with values of 0.103, 0.609, 93.93 m^{-1}, and 1.162 for VGTHR, VGTHS, ALPHA, and XN, respectively, and an r^2 of 0.95. Considering that curves fit to this Trix clay loam before inclusion of Whisler data were sigmoid, that the curve for the similar Avondale loam (Kimball *et al.*, 1992) is sigmoid, and that van Genuchten *et al.* (1992) list a value for ALPHA of about 3 m^{-1} for clay loams, the RETC code was run again with a fixed value for ALPHA of 2.9 m^{-1}. The resultant curve is presented in Fig. II-B-1 with values of VGTHR, VGTHS, and XN of 0.187, 0.454, and XN of 1.369, respectively, and the r^2 of 0.94 is almost as good as the best-fit parabolic curve. Once the curve was obtained, field capacity (FC, at 33 kPa) and the wilting point (THETA0, at 1500 kPa) were read from the curve.

The RETC code was also run specifying the Brooks and Corey option, from which a bubbling pressure value of 6.9 kPa was taken as 1 $ALPHA^{-1}$, in good agreement with the air-entry permeameter values (Table II-B-1). The N from the RETC run was taken as the Brooks and Corey lambda, from which ETA = 2 + 3*lambda was calculated.

Because the texture becomes coarser for the deeper horizons, separate curves are appropriate. For the 30-70 cm layer, the range for Trix at three matric potentials was available from Post *et al.* (1988), seven individual data points from near the FACE plots were available from Post (DF Post, personal communication, 1990), and seven mean data points were available from Whisler (FD Whisler, personal communication, 1992), obtained as described previously. The Whisler points appear somewhat drier than the Post data for the same matric potential (Fig. II-B-2). For the 70-200 cm layer, only five individual points from Post (DF Post, personal communication, 1990), and seven mean data points from Whisler (FD Whisler, personal communication, 1992) were available. Again the Whisler points are drier than the Post data for the same matric potential (Fig. II-B-3). The RETC code was run with the data in Figs. II-B-2 and II-B-3, fitting







VGTHR, VGTHS, ALPHA, and XN. The resultant curves have sigmoid shapes.

The RETC code was also run with these two sets of deeper data (Figs. II-B-2 and II-B-3) with the Brooks and Corey option to obtain ETA, as described in the previously for the 0-30 cm data.

Soil water diffusivity: No soil water diffusivity data were available. However, the RETC code from van Genuchten *et al.* (1992) also calculates hydraulic conductivity and diffusivity from the retention curve using the model of Mualem (1976). These diffusivity curves for the surface and the deeper depths were plotted on semilog paper, and then straight lines were fitted by eye that passed through the wilting point water contents, THETA0. The diffusivity at THETA0 was taken as the reference diffusivity for each, DIFF0, and then the Gardner and Mayhugh (1958) BETA was determined from the slope of the line.

Deep or lower boundary soil water content, THETAI: In GOSSYM (Baker *et al.*, 1983), the water content at the bottom of the lowest layer of the soil profile at the beginning of the season must be given as THETAI. Then at a given time, TD (days), after the appearance of the first bloom, the water content is modeled to decline at a rate given by BDSLOP (m^3 m^{-3} day^{-1}) until it reaches some final low water content defined at a given ratio, BDRATO, which is the ratio of the initial to the final water content. To some extent, this empirical approach requires that an experiment be performed to obtain TD, BDSLOP, and BDRATO. The soil profiles have been defined to a depth of 190 cm in the files for these experiments. Because soil water content at 190 cm apparently did not change significantly during our previous experiments (Kimball *et al.*, 1992), it was assumed that probably the water content at 190 cm did not change much during the growing season. The "consumptive use" studies of Erie *et al.* (1982) also suggested that a cotton crop uses little water from below 180 cm in this area. Therefore, TD was taken as 47 (typically used in Mississippi for GOSSYM), BDSLOP as zero, and BDRATO as 1.0.

Initial soil water content, SW: The initial soil water content profile was estimated from neutron scattering measurements by Lakatos (Lakatos EA, personal communication, 1989) at mid-April 1989 from several locations in the same field as the FACE experiment.

ACKNOWLEDGEMENT

We thank R. D. Jackson, E. A. Lakatos, A. W. Warrick, D. F. Post, and F. D. Whisler for sharing data with us. Special thanks go to P. W. Brown for providing the AZMET weather data. The cooperation of R. Rauschkolb, P. Murphee, and other staff of the Maricopa Agricultural Center is appreciated. We also thank K. McClellan and L. Reeves for their technical assistance in acquiring the data.

APPENDIX II-C: LIST OF DATA FILE NAMES

1989 FACE EXPERIMENT, MARICOPA, ARIZONA

The convention for naming the data files follows IBSNAT (1986) but with some changes to suit our particular experimental circumstances. Some notes that may be helpful for remembrance are as follows.

CT - stands for cotton in the experiment file directory and in the extensions of the names of other files.

MC - stands for Maricopa where it appears as the first two characters in any of the files.

12345678.123 - character position
MCAC0406.W89 - name for weather file where:
characters 1 and 2 are the MC for Maricopa;
character 3 is A for AZMET station
or M for our own micrometeorological station;
character 4 is C for control plots (ambient CO_2)
or 1, 2, 3, or 4 for Replicate number of the FACE plots with elevated CO_2;
characters 5 and 6 are the starting month (04 for April);
characters 7 and 8 are the number of months of data in the file (06 for 6 months from April through September);
extension character 1 is W for weather;
extension characters 2 and 3 are 89 for the year, 1989.

MCMC8901.CT4
characters 1 and 2 are MC for Maricopa;
character 3 is M for the actual field site (coming from M for the micrometeorological mast);
character 4 is C for control plots,
or 1, 2, 3, or 4 for the FACE replicate numbers;
characters 5 and 6 are 89 for the year 1989;
characters 7 and 8 are 01, 02, 03, or 04 for the replicate numbers of the plots were the data were collected.
extension characters 1 and 2 are CT for cotton;
extension character 3 is:
2 for soils data,
4 for soil organic residue,
5 for soil profile initial conditions,
6 for irrigation management,
7 for fertilizer management,
8 for treatment management data,
A for harvest summary data, or
B for intermediate growth data for graphing.

An exception is the soils file named TRIX.CT2, where the TRIX comes from the classification of Trix clay loam.

The presentation sequence follows treatment - replicate order, with replication cycling fastest and CO_2 the slowest, as done by Kimball *et al.* (1992). The lowest level of treatment is presented first. The data for some of the files were common to all plots. To save space and needless duplication, therefore, in such cases the data for all plots are in the file named for the plot with the lowest level treatment and replicate numbers. For example, all plots had the same organic residue history for 1989, so these data are in the file for the lowest CO_2 level (ambient controls) and replicate 1, MCMC8901.CT4. The master experiment file directory, CTEXP89.DIR, lists the particular sets of files that are to be used for each one of the eight plots for the 1989 FACE experiment.

Some additional clarification is appropriate for the weather files, which contain the CO_2 concentration data. The weather data for the four ambient CO_2 control plots are in MCAC0406.W89. The weather data for Replicates 1, 2, and 4 FACE plots are in MCA10406.W89. However, because the so-called "engineering ring" in Replicate 3 was started later and was "down" a few days near midseason (see Lewin *et al.*, Chapter 5, this book), it has its own weather file, MCA30406.W89.

Item	File Name
Experiment file directory	CTEXP89.DIR
Weather file directory	WTH89.DIR
Daily weather data	
Control plots (AZMET, amb. CO_2)	MCAC0406.W89
FACE (AZMET, 550 CO_2, Rep 1) (use also for Reps 2 and 4)	MCA10406.W89
FACE (AZMET, 550 CO_2, Rep 3)	MCA30406.W89
Soil profile properties	
Trix clay loam	TRIX.CT2
Soil organic residue	MCMC8901.CT4
Soil profile initial conditions	MCMC8901.CT5
Irrigation management data	
For Reps 1 and 4	MCMC8901.CT6
For Reps 2 and 3	MCMC8902.CT6
Fertilizer management data	MCMC8901.CT7
Treatment management data	
Control, Rep 1	MCMC8901.CT8
Control, Rep 2	MCMC8902.CT8
Control, Rep 3	MCMC8903.CT8
Control, Rep 4	MCMC8904.CT8
FACE, Rep 1	MCM18901.CT8
FACE, Rep 2	MCM28902.CT8
FACE, Rep 3	MCM38903.CT8
FACE, Rep 4	MCM48904.CT8
Harvest summary data	
Control, Rep 1	MCMC8901.CTA
Control, Rep 2	MCMC8902.CTA
Control, Rep 3	MCMC8903.CTA
Control, Rep 4	MCMC8904.CTA
FACE, Rep 1	MCM18901.CTA

FACE, Rep 2	MCM28902.CTA
FACE, Rep 3	MCM38903.CTA
FACE, Rep 4	MCM48904.CTA
Intermediate growth data for graphics	
Control, Rep 1	MCMC8901.CTB
Control, Rep 2	MCMC8902.CTB
Control, Rep 3	MCMC8903.CTB
Control, Rep 4	MCMC8904.CTB
FACE, Rep 1	MCM18901.CTB
FACE, Rep 2	MCM28902.CTB
FACE, Rep 3	MCM38903.CTB
FACE, Rep 4	MCM48904.CTB

APPENDIX II-D: THE 1989 FACE DATA FILES IN IBSNAT FORMAT

FILENAME: CTEXP89.DIR EXPERIMENT FILE DIRECTORY FOR 1989
FACE EXPERIMENT AT MARICOPA, AZ

EXPID , EXPERIMENT DESCRIPTION, WEATHER FILE, SOIL FILE,
SOIL NITR., INITIAL SOIL, IRRIGATION, NITR. FERT, CROP MANAGMENT, GENETICS,
FINAL HARVEST, INTER GROWTH, OUTPUT 1, OUTPUT 2, OUTPUT 3, OUTPUT 4

MCMC8901 1989, CO2=AMBIENT CONTROL, REP 1 MCAC0406.W89 TRIX.CT2
MCMC8901.CT4 MCMC8901.CT5 MCMC8901.CT6 MCMC8901.CT7 MCMC8901.CT8 GENETICS.CT9
MCMC8901.CTA MCMC8901.CTB OUT1.CT OUT2.CT OUT3.CT OUT4.CT

MCMC8902 1989, CO2=AMBIENT CONTROL, REP 2 MCAC0406.W89 TRIX.CT2
MCMC8901.CT4 MCMC8901.CT5 MCMC8902.CT6 MCMC8901.CT7 MCMC8902.CT8 GENETICS.CT9
MCMC8902.CTA MCMC8902.CTB OUT1.CT OUT2.CT OUT3.CT OUT4.CT

MCMC8903 1989, CO2=AMBIENT CONTROL, REP 3 MCAC0406.W89 TRIX.CT2
MCMC8901.CT4 MCMC8901.CT5 MCMC8902.CT6 MCMC8901.CT7 MCMC8903.CT8 GENETICS.CT9
MCMC8903.CTA MCMC8903.CTB OUT1.CT OUT2.CT OUT3.CT OUT4.CT

MCMC8904 1989, CO2=AMBIENT CONTROL, REP 4 MCAC0406.W89 TRIX.CT2
MCMC8901.CT4 MCMC8901.CT5 MCMC8901.CT6 MCMC8901.CT7 MCMC8904.CT8 GENETICS.CT9
MCMC8904.CTA MCMC8904.CTB OUT1.CT OUT2.CT OUT3.CT OUT4.CT

MCM18901 1989, CO2=550 FACE, REP 1 MCA10406.W89 TRIX.CT2
MCMC8901.CT4 MCMC8901.CT5 MCMC8901.CT6 MCMC8901.CT7 MCM18901.CT8 GENETICS.CT9
MCM18901.CTA MCM18901.CTB OUT1.CT OUT2.CT OUT3.CT OUT4.CT

MCM28902 1989, CO2=550 FACE, REP 2 MCA10406.W89 TRIX.CT2
MCMC8901.CT4 MCMC8901.CT5 MCMC8902.CT6 MCMC8901.CT7 MCM28902.CT8 GENETICS.CT9
MCM28902.CTA MCM28902.CTB OUT1.CT OUT2.CT OUT3.CT OUT4.CT

MCM38903 1989, CO2=550 FACE, REP 3 MCA30406.W89 TRIX.CT2
MCMC8901.CT4 MCMC8901.CT5 MCMC8902.CT6 MCMC8901.CT7 MCM38903.CT8 GENETICS.CT9
MCM38903.CTA MCM38903.CTB OUT1.CT OUT2.CT OUT3.CT OUT4.CT

MCM48904 1989, CO2=550 FACE, REP 4 MCA10406.W89 TRIX.CT2
MCMC8901.CT4 MCMC8901.CT5 MCMC8901.CT6 MCMC8901.CT7 MCM48904.CT8 GENETICS.CT9
MCM48904.CTA MCM48904.CTB OUT1.CT OUT2.CT OUT3.CT OUT4.CT

FILENAME: WTH89.DIR WEATHER FILE DIRECTORY FOR 1989

WTHID	WEATHER STATION DESCRIPTION	BEGDATE	ENDDATE	WEATHER FILE
MCAC AZMET	MARICOPA,AZ CO2=AMB. REPS 1,2,3,4	04/01/89	09/30/89	MCMC0406.W89
MCA1 AZMET	MARICOPA,AZ CO2=FACE REPS 1,2,4	04/01/89	09/30/89	MCM10406.W89
MCA3 AZMET	MARICOPA,AZ CO2=FACE REP 3	04/01/89	09/30/89	MCM30406.W89

FILENAME: MCAC0406.W89 WEATHER DATA FOR MARICOPA AGRICULTURAL CENTER, AZMET STATION, AMBIENT CO2

options (for PAR, WIND, DEWPT, STDAT & CO2)

INSTW	XLAT	XLONG	PARFAC	↓	CO2YR	WINDYR
MCAC	33.05	112.00	2.30	0 1 1 1 1	350	0.0

INSTW	IYR	JUL	SOLRAD	XTMAX	XTMIN	XRAIN	XPAR	WIND	DEWPT	STMAX	STMIN	CO2	AOO
MCAC	89	91	23.46	30.7	14.2	0.0	0.00	345.6	3.0	24.9	17.7	350	01-Apr
MCAC	89	92	25.33	30.7	11.6	0.0	0.00	198.7	1.0	28.6	16.7	350	02-Apr
MCAC	89	93	25.95	31.9	12.9	0.0	0.00	181.4	2.9	29.8	18.3	350	03-Apr
MCAC	89	94	26.89	33.8	11.1	0.0	0.00	155.5	7.9	30.7	18.7	350	04-Apr
MCAC	89	95	27.66	35.5	11.7	0.0	0.00	224.6	4.6	31.0	19.1	350	05-Apr
MCAC	89	96	27.99	37.6	10.2	0.0	0.00	155.5	3.2	31.8	19.2	350	06-Apr
MCAC	89	97	27.77	38.6	11.1	0.0	0.00	164.2	1.6	29.4	19.1	350	07-Apr
MCAC	89	98	27.83	38.1	12.5	0.0	0.00	172.8	0.7	31.7	18.8	350	08-Apr
MCAC	89	99	27.79	37.0	17.2	0.0	0.00	293.8	-6.7	32.1	20.5	350	09-Apr
MCAC	89	100	27.94	36.3	12.6	0.0	0.00	164.2	-2.5	32.8	20.3	350	10-Apr
MCAC	89	101	25.12	34.3	13.1	0.0	0.00	224.6	-5.0	31.3	21.0	350	11-Apr
MCAC	89	102	27.17	32.7	14.1	0.0	0.00	285.1	-5.7	31.6	20.4	350	12-Apr
MCAC	89	103	27.13	32.2	15.0	0.0	0.00	164.2	3.5	31.4	21.9	350	13-Apr
MCAC	89	104	27.73	33.8	12.6	0.0	0.00	155.5	2.4	29.4	20.1	350	14-Apr
MCAC	89	105	24.07	33.7	13.3	0.0	0.00	198.7	2.1	29.7	19.4	350	15-Apr
MCAC	89	106	27.96	35.0	13.9	0.0	0.00	241.9	-1.1	31.8	20.1	350	16-Apr
MCAC	89	107	27.23	35.1	12.1	0.0	0.00	181.4	0.3	29.2	20.7	350	17-Apr
MCAC	89	108	28.75	36.8	12.2	0.0	0.00	155.5	-0.1	30.5	19.1	350	18-Apr
MCAC	89	109	27.86	38.8	12.9	0.0	0.00	164.2	1.4	32.8	19.8	350	19-Apr
MCAC	89	110	26.77	40.4	13.7	0.0	0.00	155.5	1.9	33.2	21.2	350	20-Apr
MCAC	89	111	25.01	38.8	17.5	0.0	0.00	216.0	-2.3	34.0	22.8	350	21-Apr
MCAC	89	112	22.78	33.7	15.7	0.0	0.00	207.4	-8.7	27.5	21.4	350	22-Apr
MCAC	89	113	29.70	32.2	11.4	0.0	0.00	233.3	-9.4	30.7	18.8	350	23-Apr
MCAC	89	114	27.94	27.8	11.5	0.0	0.00	285.1	-6.7	27.3	20.3	350	24-Apr
MCAC	89	115	28.87	26.4	8.3	0.0	0.00	267.8	-2.9	26.9	17.4	350	25-Apr
MCAC	89	116	30.29	21.8	10.0	0.0	0.00	293.8	-5.3	27.6	17.7	350	26-Apr
MCAC	89	117	30.04	26.3	5.5	0.0	0.00	164.2	-5.5	31.7	17.3	350	27-Apr
MCAC	89	118	29.99	28.7	7.2	0.0	0.00	190.1	-8.1	28.1	18.2	350	28-Apr
MCAC	89	119	29.82	30.4	9.6	0.0	0.00	190.1	-9.0	29.5	17.8	350	29-Apr
MCAC	89	120	28.89	32.7	12.1	0.0	0.00	181.4	-8.6	31.6	19.7	350	30-Apr
MCAC	89	121	28.67	34.7	13.5	0.0	0.00	181.4	-6.8	31.3	21.5	350	01-May
MCAC	89	122	28.73	35.3	13.1	0.0	0.00	216.0	-6.1	30.6	20.3	350	02-May
MCAC	89	123	30.37	36.9	16.6	0.0	0.00	216.0	-1.3	33.4	20.9	350	03-May
MCAC	89	124	28.79	37.7	14.2	0.0	0.00	198.7	-0.5	33.4	23.2	350	04-May
MCAC	89	125	29.70	39.8	16.8	0.0	0.00	172.8	-0.5	31.4	21.5	350	05-May
MCAC	89	126	23.04	37.9	16.6	0.0	0.00	198.7	0.0	31.6	21.9	350	06-May
MCAC	89	127	30.55	40.8	13.8	0.0	0.00	172.8	1.3	35.6	22.2	350	07-May
MCAC	89	128	30.12	42.6	17.7	0.0	0.00	198.7	-0.8	32.7	24.6	350	08-May
MCAC	89	129	25.85	38.7	21.9	0.0	0.00	432.0	-2.3	32.2	23.2	350	09-May
MCAC	89	130	27.01	30.4	14.8	0.0	0.00	259.2	1.5	33.0	22.7	350	10-May
MCAC	89	131	27.14	24.1	12.1	0.0	0.00	388.8	-2.1	27.5	20.4	350	11-May

INSTW	IYR	JUL	SOLRAD	XTMAX	XTMIN	XRAIN	XPAR	WIND	DEWPT	STMAX	STMIN	CO2	AOO
MCAC	89	132	27.16	26.9	9.1	0.0	0.00	207.4	-1.1	27.2	17.7	350	12-May
MCAC	89	133	27.71	29.7	11.5	0.0	0.00	293.8	-0.3	30.8	18.9	350	13-May
MCAC	89	134	29.78	29.3	11.2	0.0	0.00	233.3	0.1	31.6	20.9	350	14-May
MCAC	89	135	24.29	26.6	13.5	0.0	0.00	293.8	-0.2	29.6	22.2	350	15-May
MCAC	89	136	18.57	23.2	12.6	0.0	0.00	259.2	5.0	24.9	19.8	350	16-May
MCAC	89	137	30.24	29.9	10.3	0.0	0.00	198.7	6.8	29.8	18.6	350	17-May
MCAC	89	138	30.79	35.5	15.6	0.0	0.00	198.7	5.5	31.2	21.4	350	18-May
MCAC	89	139	31.51	36.7	15.3	0.0	0.00	198.7	1.2	31.6	20.6	350	19-May
MCAC	89	140	31.89	37.7	14.0	0.0	0.00	181.4	0.3	34.9	21.7	350	20-May
MCAC	89	141	29.20	38.3	16.6	0.0	0.00	285.1	-1.8	34.2	23.6	350	21-May
MCAC	89	142	28.69	38.6	15.7	0.0	0.00	259.2	-1.4	34.3	23.9	350	22-May
MCAC	89	143	32.42	39.5	15.4	0.0	0.00	276.5	-5.8	31.4	24.0	350	23-May
MCAC	89	144	32.57	36.0	21.4	0.0	0.00	388.8	-6.5	33.4	22.5	350	24-May
MCAC	89	145	32.23	34.8	13.5	0.0	0.00	276.5	-4.4	30.3	23.1	350	25-May
MCAC	89	146	32.23	36.7	15.0	0.0	0.00	172.8	1.3	33.3	20.5	350	26-May
MCAC	89	147	31.85	38.2	15.9	0.0	0.00	267.8	2.2	35.5	22.9	350	27-May
MCAC	89	148	31.52	37.9	16.9	0.0	0.00	337.0	3.5	35.8	24.6	350	28-May
MCAC	89	149	31.23	36.0	17.6	0.0	0.00	319.7	6.0	35.3	24.9	350	29-May
MCAC	89	150	31.86	30.9	13.1	0.0	0.00	250.6	-0.1	33.7	23.8	350	30-May
MCAC	89	151	32.64	34.2	10.4	0.0	0.00	164.2	-2.2	35.0	22.7	350	31-May
MCAC	89	152	32.50	36.0	14.0	0.0	0.00	216.0	-1.2	33.9	22.1	350	01-Jun
MCAC	89	153	32.60	36.0	14.0	0.0	0.00	224.6	-3.7	32.0	20.0	350	02-Jun
MCAC	89	154	31.80	35.0	17.0	0.0	0.00	250.6	-3.7	32.9	23.1	350	03-Jun
MCAC	89	155	31.40	37.0	16.0	0.0	0.00	276.5	1.7	34.1	23.9	350	04-Jun
MCAC	89	156	32.20	37.0	18.0	0.0	0.00	302.4	-0.8	36.3	23.8	350	05-Jun
MCAC	89	157	32.30	35.0	16.0	0.0	0.00	224.6	-2.5	35.1	24.9	350	06-Jun
MCAC	89	158	32.10	38.0	16.0	0.0	0.00	216.0	-0.7	35.0	25.1	350	07-Jun
MCAC	89	159	32.10	36.0	16.0	0.0	0.00	224.6	-2.0	33.9	24.1	350	08-Jun
MCAC	89	160	32.60	37.0	17.0	0.0	0.00	241.9	-1.1	34.7	21.3	350	09-Jun
MCAC	89	161	31.80	37.0	17.0	0.0	0.00	259.2	4.3	34.0	25.9	350	10-Jun
MCAC	89	162	32.30	38.0	18.0	0.0	0.00	198.7	3.1	35.5	26.5	350	11-Jun
MCAC	89	163	31.90	37.0	18.0	0.0	0.00	216.0	1.5	36.1	25.9	350	12-Jun
MCAC	89	164	29.10	41.0	20.0	0.0	0.00	259.2	2.8	35.5	28.4	350	13-Jun
MCAC	89	165	31.30	42.0	22.0	0.0	0.00	241.9	2.2	37.8	28.3	350	14-Jun
MCAC	89	166	31.00	42.0	20.0	0.0	0.00	250.6	3.3	37.0	25.1	350	15-Jun
MCAC	89	167	31.10	42.0	20.0	0.0	0.00	233.3	7.7	35.4	24.6	350	16-Jun
MCAC	89	168	31.80	43.0	21.0	0.0	0.00	198.7	6.9	36.7	29.3	350	17-Jun
MCAC	89	169	32.30	44.0	19.0	0.0	0.00	164.2	4.4	35.5	30.5	350	18-Jun
MCAC	89	170	17.60	42.0	22.0	0.0	0.00	224.6	5.9	37.6	26.4	350	19-Jun
MCAC	89	171	27.50	42.0	21.0	0.0	0.00	198.7	6.1	37.9	28.1	350	20-Jun
MCAC	89	172	30.50	41.0	24.0	0.0	0.00	354.2	10.3	39.5	28.5	350	21-Jun
MCAC	89	173	32.40	39.0	18.0	0.0	0.00	207.4	2.3	37.6	24.4	350	22-Jun
MCAC	89	174	32.40	40.0	19.0	0.0	0.00	328.3	2.4	33.3	22.7	350	23-Jun
MCAC	89	175	31.80	39.0	19.0	0.0	0.00	250.6	2.4	36.2	25.8	350	24-Jun
MCAC	89	176	31.70	38.0	18.0	0.0	0.00	267.8	0.2	34.7	27.3	350	25-Jun
MCAC	89	177	31.60	40.0	16.0	0.0	0.00	172.8	2.1	37.5	26.6	350	26-Jun
MCAC	89	178	28.00	41.0	19.0	0.0	0.00	172.8	4.0	35.6	28.4	350	27-Jun
MCAC	89	179	28.00	40.0	22.0	0.0	0.00	250.6	11.1	39.4	26.6	350	28-Jun

INSTW	IYR	JUL	SOLRAD	XTMAX	XTMIN	XRAIN	XPAR	WIND	DEWPT	STMAX	STMIN	CO2	A00
MCAC	89	180	31.20	42.0	21.0	0.0	0.00	181.4	14.2	38.3	25.7	350	29-Jun
MCAC	89	181	32.10	42.0	19.0	0.0	0.00	190.1	10.0	36.6	25.4	350	30-Jun
MCAC	89	182	30.82	42.2	18.6	0.0	0.00	216.0	7.7	38.3	26.3	350	01-Jul
MCAC	89	183	32.11	42.2	19.9	0.0	0.00	181.4	7.6	39.3	27.3	350	02-Jul
MCAC	89	184	31.64	43.7	19.2	0.0	0.00	181.4	8.9	39.0	28.0	350	03-Jul
MCAC	89	185	30.80	45.8	19.4	0.0	0.00	207.4	8.4	38.7	27.6	350	04-Jul
MCAC	89	186	30.83	42.8	23.4	0.0	0.00	241.9	11.2	39.1	29.0	350	05-Jul
MCAC	89	187	27.45	42.8	24.4	0.0	0.00	224.6	12.1	34.9	29.3	350	06-Jul
MCAC	89	188	30.13	43.6	25.5	0.0	0.00	216.0	11.8	36.0	26.6	350	07-Jul
MCAC	89	189	25.82	40.8	25.7	0.0	0.00	259.2	12.4	37.4	28.3	350	08-Jul
MCAC	89	190	29.51	40.0	23.6	0.0	0.00	267.8	11.8	38.7	28.5	350	09-Jul
MCAC	89	191	19.08	38.5	23.2	0.0	0.00	276.5	17.1	36.9	28.8	350	10-Jul
MCAC	89	192	29.59	36.6	22.1	0.0	0.00	164.2	19.2	37.8	27.5	350	11-Jul
MCAC	89	193	30.50	40.4	21.3	0.0	0.00	138.2	17.2	38.6	28.0	350	12-Jul
MCAC	89	194	31.00	42.7	19.7	0.0	0.00	181.4	14.0	34.5	28.0	350	13-Jul
MCAC	89	195	30.17	43.4	21.2	0.0	0.00	224.6	11.8	35.1	25.2	350	14-Jul
MCAC	89	196	28.85	41.0	23.9	0.0	0.00	198.7	15.4	38.4	27.4	350	15-Jul
MCAC	89	197	19.64	39.2	26.1	0.0	0.00	190.1	17.0	36.7	29.4	350	16-Jul
MCAC	89	198	28.27	41.1	24.3	0.0	0.00	181.4	16.4	39.4	28.7	350	17-Jul
MCAC	89	199	30.29	43.6	23.0	0.0	0.00	216.0	10.8	39.7	28.8	350	18-Jul
MCAC	89	200	29.67	43.9	26.3	0.0	0.00	276.5	11.3	40.0	29.6	350	19-Jul
MCAC	89	201	29.67	42.7	27.3	0.0	0.00	267.8	12.4	35.4	28.9	350	20-Jul
MCAC	89	202	21.28	41.1	24.3	0.0	0.00	250.6	21.7	34.1	27.0	350	21-Jul
MCAC	89	203	23.31	38.0	23.7	0.0	0.00	198.7	22.4	36.9	27.5	350	22-Jul
MCAC	89	204	27.36	40.1	24.5	0.0	0.00	233.3	20.5	38.1	28.3	350	23-Jul
MCAC	89	205	28.61	41.5	25.2	0.0	0.00	216.0	18.1	38.8	29.0	350	24-Jul
MCAC	89	206	29.61	41.2	24.8	0.0	0.00	250.6	16.7	39.4	29.5	350	25-Jul
MCAC	89	207	29.17	40.1	25.5	0.0	0.00	285.1	14.1	39.8	29.5	350	26-Jul
MCAC	89	208	25.23	38.4	21.3	5.0	0.00	224.6	20.9	35.9	29.1	350	27-Jul
MCAC	89	209	24.92	34.7	21.2	2.0	0.00	155.5	20.7	34.1	27.1	350	28-Jul
MCAC	89	210	26.68	37.3	23.3	0.0	0.00	164.2	22.2	35.6	27.2	350	29-Jul
MCAC	89	211	29.06	38.9	22.9	0.0	0.00	216.0	21.5	38.5	27.5	350	30-Jul
MCAC	89	212	26.56	39.7	26.1	1.0	0.00	216.0	21.1	39.0	29.8	350	31-Jul
MCAC	89	213	27.97	41.4	23.1	0.0	0.00	198.7	22.0	38.4	27.0	350	01-Aug
MCAC	89	214	29.55	39.9	22.0	0.0	0.00	207.4	16.3	38.3	28.6	350	02-Aug
MCAC	89	215	25.02	37.9	23.9	2.0	0.00	233.3	22.7	37.9	30.3	350	03-Aug
MCAC	89	216	26.42	37.4	22.8	0.0	0.00	216.0	21.9	37.5	28.6	350	04-Aug
MCAC	89	217	28.03	38.5	23.9	0.0	0.00	233.3	20.7	37.8	29.3	350	05-Aug
MCAC	89	218	25.08	40.4	24.1	0.0	0.00	267.8	19.4	37.3	29.9	350	06-Aug
MCAC	89	219	27.47	38.8	24.2	0.0	0.00	285.1	19.9	38.2	29.9	350	07-Aug
MCAC	89	220	27.58	39.3	24.3	0.0	0.00	250.6	18.0	37.6	29.9	350	08-Aug
MCAC	89	221	25.31	37.8	23.5	0.0	0.00	259.2	17.4	37.3	29.1	350	09-Aug
MCAC	89	222	18.77	34.7	23.8	0.0	0.00	216.0	20.7	37.2	29.4	350	10-Aug
MCAC	89	223	23.38	37.6	22.2	0.0	0.00	181.4	21.3	34.1	28.5	350	11-Aug
MCAC	89	224	26.65	39.0	26.4	0.0	0.00	207.4	19.1	33.7	27.4	350	12-Aug
MCAC	89	225	28.23	41.7	25.2	0.0	0.00	267.8	19.1	36.1	26.9	350	13-Aug
MCAC	89	226	27.94	41.6	27.3	0.0	0.00	259.2	16.6	37.9	28.9	350	14-Aug
MCAC	89	227	27.77	41.4	25.2	0.0	0.00	216.0	17.1	39.0	29.5	350	15-Aug

INSTW	IYR	JUL	SOLRAD	XTMAX	XTMIN	XRAIN	XPAR	WIND	DEWPT	STMAX	STMIN	CO2	AOO
MCAC	89	228	24.52	40.1	23.8	0.0	0.00	276.5	20.1	38.1	29.7	350	16-Aug
MCAC	89	229	27.34	38.6	22.0	0.0	0.00	267.8	18.7	39.0	29.0	350	17-Aug
MCAC	89	230	24.24	37.6	24.5	0.0	0.00	224.6	21.2	37.3	29.6	350	18-Aug
MCAC	89	231	27.31	39.1	22.0	0.0	0.00	172.8	18.1	37.8	28.9	350	19-Aug
MCAC	89	232	27.71	38.5	21.3	0.0	0.00	267.8	14.3	37.1	28.5	350	20-Aug
MCAC	89	233	27.03	37.4	19.9	0.0	0.00	224.6	10.2	36.2	27.3	350	21-Aug
MCAC	89	234	28.22	38.5	15.1	0.0	0.00	190.1	7.6	36.1	25.9	350	22-Aug
MCAC	89	235	28.49	39.4	15.2	0.0	0.00	190.1	10.5	36.1	25.9	350	23-Aug
MCAC	89	236	28.48	38.0	18.0	0.0	0.00	190.1	8.1	36.0	26.2	350	24-Aug
MCAC	89	237	28.36	38.3	17.7	0.0	0.00	233.3	9.9	35.6	25.9	350	25-Aug
MCAC	89	238	28.38	38.3	14.9	0.0	0.00	181.4	6.7	35.7	25.4	350	26-Aug
MCAC	89	239	27.64	38.2	17.7	0.0	0.00	155.5	10.2	36.0	26.0	350	27-Aug
MCAC	89	240	27.25	39.2	18.0	0.0	0.00	155.5	13.9	36.4	26.3	350	28-Aug
MCAC	89	241	26.78	41.0	17.7	0.0	0.00	164.2	12.1	36.3	26.3	350	29-Aug
MCAC	89	242	26.12	40.0	21.0	0.0	0.00	198.7	13.9	36.4	27.2	350	30-Aug
MCAC	89	243	25.77	38.7	21.9	0.0	0.00	164.2	14.5	34.7	27.7	350	31-Aug
MCAC	89	244	25.89	40.1	20.8	0.0	0.00	155.5	16.9	33.0	26.5	350	01-Sep
MCAC	89	245	15.52	35.0	22.8	0.0	0.00	172.8	20.1	30.5	26.2	350	02-Sep
MCAC	89	246	16.85	32.2	20.7	12.0	0.00	216.0	20.2	30.9	26.2	350	03-Sep
MCAC	89	247	24.90	38.2	21.0	0.0	0.00	121.0	20.4	33.2	26.0	350	04-Sep
MCAC	89	248	25.81	41.1	21.2	0.0	0.00	129.6	20.2	34.4	26.0	350	05-Sep
MCAC	89	249	24.87	40.7	22.8	0.0	0.00	164.2	19.2	35.3	26.6	350	06-Sep
MCAC	89	250	25.72	40.0	22.0	0.0	0.00	224.6	18.3	33.6	27.0	350	07-Sep
MCAC	89	251	26.13	36.8	20.7	0.0	0.00	233.3	12.3	30.2	25.1	350	08-Sep
MCAC	89	252	26.28	37.7	13.9	0.0	0.00	155.5	6.8	32.0	22.7	350	09-Sep
MCAC	89	253	26.25	37.9	15.1	0.0	0.00	172.8	9.4	32.2	23.1	350	10-Sep
MCAC	89	254	26.00	37.2	15.5	0.0	0.00	224.6	9.7	32.0	23.9	350	11-Sep
MCAC	89	255	25.33	36.9	14.8	0.0	0.00	190.1	7.2	32.1	23.6	350	12-Sep
MCAC	89	256	24.81	36.0	13.6	0.0	0.00	146.9	10.1	32.2	23.9	350	13-Sep
MCAC	89	257	24.89	38.2	13.0	0.0	0.00	138.2	10.6	31.4	23.6	350	14-Sep
MCAC	89	258	24.25	39.2	13.4	0.0	0.00	146.9	9.1	29.8	22.3	350	15-Sep
MCAC	89	259	22.64	40.7	19.4	0.0	0.00	155.5	12.2	30.5	23.7	350	16-Sep
MCAC	89	260	20.04	36.6	19.9	0.0	0.00	276.5	12.8	30.8	24.9	350	17-Sep
MCAC	89	261	24.20	36.1	16.4	0.0	0.00	233.3	14.6	31.3	23.7	350	18-Sep
MCAC	89	262	24.00	34.0	13.6	0.0	0.00	276.5	6.5	29.9	22.9	350	19-Sep
MCAC	89	263	24.34	31.0	10.3	0.0	0.00	155.5	7.0	29.6	22.0	350	20-Sep
MCAC	89	264	24.74	36.7	8.8	0.0	0.00	146.9	3.8	29.6	21.1	350	21-Sep
MCAC	89	265	23.86	41.8	10.9	0.0	0.00	146.9	4.1	28.5	20.3	350	22-Sep
MCAC	89	266	20.86	39.0	20.2	0.0	0.00	397.4	8.1	28.7	22.5	350	23-Sep
MCAC	89	267	22.43	39.8	18.0	0.0	0.00	155.5	10.5	30.9	22.9	350	24-Sep
MCAC	89	268	22.24	41.9	18.8	0.0	0.00	146.9	10.3	31.8	23.7	350	25-Sep
MCAC	89	269	21.99	41.3	21.8	0.0	0.00	276.5	9.3	31.4	24.4	350	26-Sep
MCAC	89	270	22.79	39.2	17.5	0.0	0.00	285.1	-1.7	30.8	23.4	350	27-Sep
MCAC	89	271	23.30	39.3	16.1	0.0	0.00	207.4	1.0	30.1	22.9	350	28-Sep
MCAC	89	272	23.26	40.3	11.4	0.0	0.00	155.5	1.9	27.8	20.7	350	29-Sep
MCAC	89	273	22.47	39.0	10.8	0.0	0.00	155.5	2.4	27.7	19.8	350	30-Sep

FILENAME: MCA10406.W89

WEATHER DATA FOR MARICOPA AGRICULTURAL CENTER, AZMET STATION, FACE PLOTS 1, 2, & 4

options (for PAR, WIND, DEWPT, STDAT & CO2)

INSTW	XLAT	XLONG	PARFAC	↓					CO2YR	WINDYR
MCAC	33.05	112.00	2.30	0	1	1	1	1	550	0.0

INSTW	IYR	JUL	SOLRAD	XTMAX	XTMIN	XRAIN	XPAR	WIND	DEWPT	STMAX	STMIN	CO2	AOO
MCAC	89	91	23.46	30.7	14.2	0.0	0.00	345.6	3.0	24.9	17.7	350	01-Apr
MCAC	89	92	25.33	30.7	11.6	0.0	0.00	198.7	1.0	28.6	16.7	350	02-Apr
MCAC	89	93	25.95	31.9	12.9	0.0	0.00	181.4	2.9	29.8	18.3	350	03-Apr
MCAC	89	94	26.89	33.8	11.1	0.0	0.00	155.5	7.9	30.7	18.7	350	04-Apr
MCAC	89	95	27.66	35.5	11.7	0.0	0.00	224.6	4.6	31.0	19.1	350	05-Apr
MCAC	89	96	27.99	37.6	10.2	0.0	0.00	155.5	3.2	31.8	19.2	350	06-Apr
MCAC	89	97	27.77	38.6	11.1	0.0	0.00	164.2	1.6	29.4	19.1	350	07-Apr
MCAC	89	98	27.83	38.1	12.5	0.0	0.00	172.8	0.7	31.7	18.8	350	08-Apr
MCAC	89	99	27.79	37.0	17.2	0.0	0.00	293.8	-6.7	32.1	20.5	350	09-Apr
MCAC	89	100	27.94	36.3	12.6	0.0	0.00	164.2	-2.5	32.8	20.3	350	10-Apr
MCAC	89	101	25.12	34.3	13.1	0.0	0.00	224.6	-5.0	31.3	21.0	350	11-Apr
MCAC	89	102	27.17	32.7	14.1	0.0	0.00	285.1	-5.7	31.6	20.4	350	12-Apr
MCAC	89	103	27.13	32.2	15.0	0.0	0.00	164.2	3.5	31.4	21.9	350	13-Apr
MCAC	89	104	27.73	33.8	12.6	0.0	0.00	155.5	2.4	29.4	20.1	350	14-Apr
MCAC	89	105	24.07	33.7	13.3	0.0	0.00	198.7	2.1	29.7	19.4	350	15-Apr
MCAC	89	106	27.96	35.0	13.9	0.0	0.00	241.9	-1.1	31.8	20.1	350	16-Apr
MCAC	89	107	27.23	35.1	12.1	0.0	0.00	181.4	0.3	29.2	20.7	350	17-Apr
MCAC	89	108	28.75	36.8	12.2	0.0	0.00	155.5	-0.1	30.5	19.1	350	18-Apr
MCAC	89	109	27.86	38.8	12.9	0.0	0.00	164.2	1.4	32.8	19.8	350	19-Apr
MCAC	89	110	26.77	40.4	13.7	0.0	0.00	155.5	1.9	33.2	21.2	350	20-Apr
MCAC	89	111	25.01	38.8	17.5	0.0	0.00	216.0	-2.3	34.0	22.8	350	21-Apr
MCAC	89	112	22.78	33.7	15.7	0.0	0.00	207.4	-8.7	27.5	21.4	350	22-Apr
MCAC	89	113	29.70	32.2	11.4	0.0	0.00	233.3	-9.4	30.7	18.8	350	23-Apr
MCAC	89	114	27.94	27.8	11.5	0.0	0.00	285.1	-6.7	27.3	20.3	350	24-Apr
MCAC	89	115	28.87	26.4	8.3	0.0	0.00	267.8	-2.9	26.9	17.4	350	25-Apr
MCAC	89	116	30.29	21.8	10.0	0.0	0.00	293.8	-5.3	27.6	17.7	350	26-Apr
MCAC	89	117	30.04	26.3	5.5	0.0	0.00	164.2	-5.5	31.7	17.3	350	27-Apr
MCAC	89	118	29.99	28.7	7.2	0.0	0.00	190.1	-8.1	28.1	18.2	350	28-Apr
MCAC	89	119	29.82	30.4	9.6	0.0	0.00	190.1	-9.0	29.5	17.8	350	29-Apr
MCAC	89	120	28.89	32.7	12.1	0.0	0.00	181.4	-8.6	31.6	19.7	350	30-Apr
MCAC	89	121	28.67	34.7	13.5	0.0	0.00	181.4	-6.8	31.3	21.5	350	01-May
MCAC	89	122	28.73	35.3	13.1	0.0	0.00	216.0	-6.1	30.6	20.3	350	02-May
MCAC	89	123	30.37	36.9	16.6	0.0	0.00	216.0	-1.3	33.4	20.9	350	03-May
MCAC	89	124	28.79	37.7	14.2	0.0	0.00	198.7	-0.5	33.4	23.2	350	04-May
MCAC	89	125	29.70	39.8	16.8	0.0	0.00	172.8	-0.5	31.4	21.5	350	05-May
MCAC	89	126	23.04	37.9	16.6	0.0	0.00	198.7	0.0	31.6	21.9	350	06-May
MCAC	89	127	30.55	40.8	13.8	0.0	0.00	172.8	1.3	35.6	22.2	350	07-May
MCAC	89	128	30.12	42.6	17.7	0.0	0.00	198.7	-0.8	32.7	24.6	350	08-May
MCAC	89	129	25.85	38.7	21.9	0.0	0.00	432.0	-2.3	32.2	23.2	350	09-May
MCAC	89	130	27.01	30.4	14.8	0.0	0.00	259.2	1.5	33.0	22.7	350	10-May
MCAC	89	131	27.14	24.1	12.1	0.0	0.00	388.8	-2.1	27.5	20.4	350	11-May

INSTW	IYR	JUL	SOLRAD	XTMAX	XTMIN	XRAIN	XPAR	WIND	DEWPT	STMAX	STMIN	CO2	AOO
MCAC	89	132	27.16	26.9	9.1	0.0	0.00	207.4	-1.1	27.2	17.7	350	12-May
MCAC	89	133	27.71	29.7	11.5	0.0	0.00	293.8	-0.3	30.8	18.9	350	13-May
MCAC	89	134	29.78	29.3	11.2	0.0	0.00	233.3	0.1	31.6	20.9	350	14-May
MCAC	89	135	24.29	26.6	13.5	0.0	0.00	293.8	-0.2	29.6	22.2	350	15-May
MCAC	89	136	18.57	23.2	12.6	0.0	0.00	259.2	5.0	24.9	19.8	350	16-May
MCAC	89	137	30.24	29.9	10.3	0.0	0.00	198.7	6.8	29.8	18.6	350	17-May
MCAC	89	138	30.79	35.5	15.6	0.0	0.00	198.7	5.5	31.2	21.4	350	18-May
MCAC	89	139	31.51	36.7	15.3	0.0	0.00	198.7	1.2	31.6	20.6	550	19-May
MCAC	89	140	31.89	37.7	14.0	0.0	0.00	181.4	0.3	34.9	21.7	550	20-May
MCAC	89	141	29.20	38.3	16.6	0.0	0.00	285.1	-1.8	34.2	23.6	550	21-May
MCAC	89	142	28.69	38.6	15.7	0.0	0.00	259.2	-1.4	34.3	23.9	550	22-May
MCAC	89	143	32.42	39.5	15.4	0.0	0.00	276.5	-5.8	31.4	24.0	550	23-May
MCAC	89	144	32.57	36.0	21.4	0.0	0.00	388.8	-6.5	33.4	22.5	550	24-May
MCAC	89	145	32.23	34.8	13.5	0.0	0.00	276.5	-4.4	30.3	23.1	550	25-May
MCAC	89	146	32.23	36.7	15.0	0.0	0.00	172.8	1.3	33.3	20.5	550	26-May
MCAC	89	147	31.85	38.2	15.9	0.0	0.00	267.8	2.2	35.5	22.9	550	27-May
MCAC	89	148	31.52	37.9	16.9	0.0	0.00	337.0	3.5	35.8	24.6	550	28-May
MCAC	89	149	31.23	36.0	17.6	0.0	0.00	319.7	6.0	35.3	24.9	550	29-May
MCAC	89	150	31.86	30.9	13.1	0.0	0.00	250.6	-0.1	33.7	23.8	550	30-May
MCAC	89	151	32.64	34.2	10.4	0.0	0.00	164.2	-2.2	35.0	22.7	550	31-May
MCAC	89	152	32.50	36.0	14.0	0.0	0.00	216.0	-1.2	33.9	22.1	550	01-Jun
MCAC	89	153	32.60	36.0	14.0	0.0	0.00	224.6	-3.7	32.0	20.0	550	02-Jun
MCAC	89	154	31.80	35.0	17.0	0.0	0.00	250.6	-3.7	32.9	23.1	550	03-Jun
MCAC	89	155	31.40	37.0	16.0	0.0	0.00	276.5	1.7	34.1	23.9	550	04-Jun
MCAC	89	156	32.20	37.0	18.0	0.0	0.00	302.4	-0.8	36.3	23.8	550	05-Jun
MCAC	89	157	32.30	35.0	16.0	0.0	0.00	224.6	-2.5	35.1	24.9	550	06-Jun
MCAC	89	158	32.10	38.0	16.0	0.0	0.00	216.0	-0.7	35.0	25.1	550	07-Jun
MCAC	89	159	32.10	36.0	16.0	0.0	0.00	224.6	-2.0	33.9	24.1	550	08-Jun
MCAC	89	160	32.60	37.0	17.0	0.0	0.00	241.9	-1.1	34.7	21.3	550	09-Jun
MCAC	89	161	31.80	37.0	17.0	0.0	0.00	259.2	4.3	34.0	25.9	550	10-Jun
MCAC	89	162	32.30	38.0	18.0	0.0	0.00	198.7	3.1	35.5	26.5	550	11-Jun
MCAC	89	163	31.90	37.0	18.0	0.0	0.00	216.0	1.5	36.1	25.9	550	12-Jun
MCAC	89	164	29.10	41.0	20.0	0.0	0.00	259.2	2.8	35.5	28.4	550	13-Jun
MCAC	89	165	31.30	42.0	22.0	0.0	0.00	241.9	2.2	37.8	28.3	550	14-Jun
MCAC	89	166	31.00	42.0	20.0	0.0	0.00	250.6	3.3	37.0	25.1	550	15-Jun
MCAC	89	167	31.10	42.0	20.0	0.0	0.00	233.3	7.7	35.4	24.6	550	16-Jun
MCAC	89	168	31.80	43.0	21.0	0.0	0.00	198.7	6.9	36.7	29.3	550	17-Jun
MCAC	89	169	32.30	44.0	19.0	0.0	0.00	164.2	4.4	35.5	30.5	550	18-Jun
MCAC	89	170	17.60	42.0	22.0	0.0	0.00	224.6	5.9	37.6	26.4	550	19-Jun
MCAC	89	171	27.50	42.0	21.0	0.0	0.00	198.7	6.1	37.9	28.1	550	20-Jun
MCAC	89	172	30.50	41.0	24.0	0.0	0.00	354.2	10.3	39.5	28.5	550	21-Jun
MCAC	89	173	32.40	39.0	18.0	0.0	0.00	207.4	2.3	37.6	24.4	550	22-Jun
MCAC	89	174	32.40	40.0	19.0	0.0	0.00	328.3	2.4	33.3	22.7	550	23-Jun
MCAC	89	175	31.80	39.0	19.0	0.0	0.00	250.6	2.4	36.2	25.8	550	24-Jun
MCAC	89	176	31.70	38.0	18.0	0.0	0.00	267.8	0.2	34.7	27.3	550	25-Jun
MCAC	89	177	31.60	40.0	16.0	0.0	0.00	172.8	2.1	37.5	26.6	550	26-Jun
MCAC	89	178	28.00	41.0	19.0	0.0	0.00	172.8	4.0	35.6	28.4	550	27-Jun
MCAC	89	179	28.00	40.0	22.0	0.0	0.00	250.6	11.1	39.4	26.6	550	28-Jun

INSTW	IYR	JUL	SOLRAD	XTMAX	XTMIN	XRAIN	XPAR	WIND	DEWPT	STMAX	STMIN	CO2	AOO
MCAC	89	180	31.20	42.0	21.0	0.0	0.00	181.4	14.2	38.3	25.7	550	29-Jun
MCAC	89	181	32.10	42.0	19.0	0.0	0.00	190.1	10.0	36.6	25.4	550	30-Jun
MCAC	89	182	30.82	42.2	18.6	0.0	0.00	216.0	7.7	38.3	26.3	550	01-Jul
MCAC	89	183	32.11	42.2	19.9	0.0	0.00	181.4	7.6	39.3	27.3	550	02-Jul
MCAC	89	184	31.64	43.7	19.2	0.0	0.00	181.4	8.9	39.0	28.0	550	03-Jul
MCAC	89	185	30.80	45.8	19.4	0.0	0.00	207.4	8.4	38.7	27.6	550	04-Jul
MCAC	89	186	30.83	42.8	23.4	0.0	0.00	241.9	11.2	39.1	29.0	550	05-Jul
MCAC	89	187	27.45	42.8	24.4	0.0	0.00	224.6	12.1	34.9	29.3	550	06-Jul
MCAC	89	188	30.13	43.6	25.5	0.0	0.00	216.0	11.8	36.0	26.6	550	07-Jul
MCAC	89	189	25.82	40.8	25.7	0.0	0.00	259.2	12.4	37.4	28.3	550	08-Jul
MCAC	89	190	29.51	40.0	23.6	0.0	0.00	267.8	11.8	38.7	28.5	550	09-Jul
MCAC	89	191	19.08	38.5	23.2	0.0	0.00	276.5	17.1	36.9	28.8	550	10-Jul
MCAC	89	192	29.59	36.6	22.1	0.0	0.00	164.2	19.2	37.8	27.5	550	11-Jul
MCAC	89	193	30.50	40.4	21.3	0.0	0.00	138.2	17.2	38.6	28.0	550	12-Jul
MCAC	89	194	31.00	42.7	19.7	0.0	0.00	181.4	14.0	34.5	28.0	550	13-Jul
MCAC	89	195	30.17	43.4	21.2	0.0	0.00	224.6	11.8	35.1	25.2	550	14-Jul
MCAC	89	196	28.85	41.0	23.9	0.0	0.00	198.7	15.4	38.4	27.4	550	15-Jul
MCAC	89	197	19.64	39.2	26.1	0.0	0.00	190.1	17.0	36.7	29.4	550	16-Jul
MCAC	89	198	28.27	41.1	24.3	0.0	0.00	181.4	16.4	39.4	28.7	550	17-Jul
MCAC	89	199	30.29	43.6	23.0	0.0	0.00	216.0	10.8	39.7	28.8	550	18-Jul
MCAC	89	200	29.67	43.9	26.3	0.0	0.00	276.5	11.3	40.0	29.6	550	19-Jul
MCAC	89	201	29.67	42.7	27.3	0.0	0.00	267.8	12.4	35.4	28.9	550	20-Jul
MCAC	89	202	21.28	41.1	24.3	0.0	0.00	250.6	21.7	34.1	27.0	550	21-Jul
MCAC	89	203	23.31	38.0	23.7	0.0	0.00	198.7	22.4	36.9	27.5	550	22-Jul
MCAC	89	204	27.36	40.1	24.5	0.0	0.00	233.3	20.5	38.1	28.3	550	23-Jul
MCAC	89	205	28.61	41.5	25.2	0.0	0.00	216.0	18.1	38.8	29.0	550	24-Jul
MCAC	89	206	29.61	41.2	24.8	0.0	0.00	250.6	16.7	39.4	29.5	550	25-Jul
MCAC	89	207	29.17	40.1	25.5	0.0	0.00	285.1	14.1	39.8	29.5	550	26-Jul
MCAC	89	208	25.23	38.4	21.3	5.0	0.00	224.6	20.9	35.9	29.1	550	27-Jul
MCAC	89	209	24.92	34.7	21.2	2.0	0.00	155.5	20.7	34.1	27.1	550	28-Jul
MCAC	89	210	26.68	37.3	23.3	0.0	0.00	164.2	22.2	35.6	27.2	550	29-Jul
MCAC	89	211	29.06	38.9	22.9	0.0	0.00	216.0	21.5	38.5	27.5	550	30-Jul
MCAC	89	212	26.56	39.7	26.1	1.0	0.00	216.0	21.1	39.0	29.8	550	31-Jul
MCAC	89	213	27.97	41.4	23.1	0.0	0.00	198.7	22.0	38.4	27.0	550	01-Aug
MCAC	89	214	29.55	39.9	22.0	0.0	0.00	207.4	16.3	38.3	28.6	550	02-Aug
MCAC	89	215	25.02	37.9	23.9	2.0	0.00	233.3	22.7	37.9	30.3	550	03-Aug
MCAC	89	216	26.42	37.4	22.8	0.0	0.00	216.0	21.9	37.5	28.6	550	04-Aug
MCAC	89	217	28.03	38.5	23.9	0.0	0.00	233.3	20.7	37.8	29.3	550	05-Aug
MCAC	89	218	25.08	40.4	24.1	0.0	0.00	267.8	19.4	37.3	29.9	550	06-Aug
MCAC	89	219	27.47	38.8	24.2	0.0	0.00	285.1	19.9	38.2	29.9	550	07-Aug
MCAC	89	220	27.58	39.3	24.3	0.0	0.00	250.6	18.0	37.6	29.9	550	08-Aug
MCAC	89	221	25.31	37.8	23.5	0.0	0.00	259.2	17.4	37.3	29.1	550	09-Aug
MCAC	89	222	18.77	34.7	23.8	0.0	0.00	216.0	20.7	37.2	29.4	550	10-Aug
MCAC	89	223	23.38	37.6	22.2	0.0	0.00	181.4	21.3	34.1	28.5	550	11-Aug
MCAC	89	224	26.65	39.0	26.4	0.0	0.00	207.4	19.1	33.7	27.4	550	12-Aug
MCAC	89	225	28.23	41.7	25.2	0.0	0.00	267.8	19.1	36.1	26.9	550	13-Aug
MCAC	89	226	27.94	41.6	27.3	0.0	0.00	259.2	16.6	37.9	28.9	550	14-Aug
MCAC	89	227	27.77	41.4	25.2	0.0	0.00	216.0	17.1	39.0	29.5	550	15-Aug

INSTW	IYR	JUL	SOLRAD	XTMAX	XTMIN	XRAIN	XPAR	WIND	DEWPT	STMAX	STMIN	CO2	AOO
MCAC	89	228	24.52	40.1	23.8	0.0	0.00	276.5	20.1	38.1	29.7	550	16-Aug
MCAC	89	229	27.34	38.6	22.0	0.0	0.00	267.8	18.7	39.0	29.0	550	17-Aug
MCAC	89	230	24.24	37.6	24.5	0.0	0.00	224.6	21.2	37.3	29.6	550	18-Aug
MCAC	89	231	27.31	39.1	22.0	0.0	0.00	172.8	18.1	37.8	28.9	550	19-Aug
MCAC	89	232	27.71	38.5	21.3	0.0	0.00	267.8	14.3	37.1	28.5	550	20-Aug
MCAC	89	233	27.03	37.4	19.9	0.0	0.00	224.6	10.2	36.2	27.3	550	21-Aug
MCAC	89	234	28.22	38.5	15.1	0.0	0.00	190.1	7.6	36.1	25.9	550	22-Aug
MCAC	89	235	28.49	39.4	15.2	0.0	0.00	190.1	10.5	36.1	25.9	550	23-Aug
MCAC	89	236	28.48	38.0	18.0	0.0	0.00	190.1	8.1	36.0	26.2	550	24-Aug
MCAC	89	237	28.36	38.3	17.7	0.0	0.00	233.3	9.9	35.6	25.9	550	25-Aug
MCAC	89	238	28.38	38.3	14.9	0.0	0.00	181.4	6.7	35.7	25.4	550	26-Aug
MCAC	89	239	27.64	38.2	17.7	0.0	0.00	155.5	10.2	36.0	26.0	550	27-Aug
MCAC	89	240	27.25	39.2	18.0	0.0	0.00	155.5	13.9	36.4	26.3	550	28-Aug
MCAC	89	241	26.78	41.0	17.7	0.0	0.00	164.2	12.1	36.3	26.3	550	29-Aug
MCAC	89	242	26.12	40.0	21.0	0.0	0.00	198.7	13.9	36.4	27.2	550	30-Aug
MCAC	89	243	25.77	38.7	21.9	0.0	0.00	164.2	14.5	34.7	27.7	550	31-Aug
MCAC	89	244	25.89	40.1	20.8	0.0	0.00	155.5	16.9	33.0	26.5	550	01-Sep
MCAC	89	245	15.52	35.0	22.8	0.0	0.00	172.8	20.1	30.5	26.2	550	02-Sep
MCAC	89	246	16.85	32.2	20.7	12.0	0.00	216.0	20.2	30.9	26.2	550	03-Sep
MCAC	89	247	24.90	38.2	21.0	0.0	0.00	121.0	20.4	33.2	26.0	550	04-Sep
MCAC	89	248	25.81	41.1	21.2	0.0	0.00	129.6	20.2	34.4	26.0	550	05-Sep
MCAC	89	249	24.87	40.7	22.8	0.0	0.00	164.2	19.2	35.3	26.6	550	06-Sep
MCAC	89	250	25.72	40.0	22.0	0.0	0.00	224.6	18.3	33.6	27.0	550	07-Sep
MCAC	89	251	26.13	36.8	20.7	0.0	0.00	233.3	12.3	30.2	25.1	550	08-Sep
MCAC	89	252	26.28	37.7	13.9	0.0	0.00	155.5	6.8	32.0	22.7	550	09-Sep
MCAC	89	253	26.25	37.9	15.1	0.0	0.00	172.8	9.4	32.2	23.1	550	10-Sep
MCAC	89	254	26.00	37.2	15.5	0.0	0.00	224.6	9.7	32.0	23.9	550	11-Sep
MCAC	89	255	25.33	36.9	14.8	0.0	0.00	190.1	7.2	32.1	23.6	550	12-Sep
MCAC	89	256	24.81	36.0	13.6	0.0	0.00	146.9	10.1	32.2	23.9	550	13-Sep
MCAC	89	257	24.89	38.2	13.0	0.0	0.00	138.2	10.6	31.4	23.6	550	14-Sep
MCAC	89	258	24.25	39.2	13.4	0.0	0.00	146.9	9.1	29.8	22.3	550	15-Sep
MCAC	89	259	22.64	40.7	19.4	0.0	0.00	155.5	12.2	30.5	23.7	550	16-Sep
MCAC	89	260	20.04	36.6	19.9	0.0	0.00	276.5	12.8	30.8	24.9	550	17-Sep
MCAC	89	261	24.20	36.1	16.4	0.0	0.00	233.3	14.6	31.3	23.7	350	18-Sep
MCAC	89	262	24.00	34.0	13.6	0.0	0.00	276.5	6.5	29.9	22.9	350	19-Sep
MCAC	89	263	24.34	31.0	10.3	0.0	0.00	155.5	7.0	29.6	22.0	350	20-Sep
MCAC	89	264	24.74	36.7	8.8	0.0	0.00	146.9	3.8	29.6	21.1	350	21-Sep
MCAC	89	265	23.86	41.8	10.9	0.0	0.00	146.9	4.1	28.5	20.3	350	22-Sep
MCAC	89	266	20.86	39.0	20.2	0.0	0.00	397.4	8.1	28.7	22.5	350	23-Sep
MCAC	89	267	22.43	39.8	18.0	0.0	0.00	155.5	10.5	30.9	22.9	350	24-Sep
MCAC	89	268	22.24	41.9	18.8	0.0	0.00	146.9	10.3	31.8	23.7	350	25-Sep
MCAC	89	269	21.99	41.3	21.8	0.0	0.00	276.5	9.3	31.4	24.4	350	26-Sep
MCAC	89	270	22.79	39.2	17.5	0.0	0.00	285.1	-1.7	30.8	23.4	350	27-Sep
MCAC	89	271	23.30	39.3	16.1	0.0	0.00	207.4	1.0	30.1	22.9	350	28-Sep
MCAC	89	272	23.26	40.3	11.4	0.0	0.00	155.5	1.9	27.8	20.7	350	29-Sep
MCAC	89	273	22.47	39.0	10.8	0.0	0.00	155.5	2.4	27.7	19.8	350	30-Sep

FILENAME: MCA30406.W89 WEATHER DATA FOR MARICOPA AGRICULTURAL CENTER, AZMET STATION, REP 3 FACE PLOTS

options (for PAR, WIND, DEWPT, STDAT & CO2)

INSTW	XLAT	XLONG	PARFAC	↓					CO2YR	WINDYR
MCAC	33.05	112.00	2.30	0	1	1	1	1	550	0.0

INSTW	IYR	JUL	SOLRAD	XTMAX	XTMIN	XRAIN	XPAR	WIND	DEWPT	STMAX	STMIN	CO2	AOO
MCAC	89	91	23.46	30.7	14.2	0.0	0.00	345.6	3.0	24.9	17.7	350	01-Apr
MCAC	89	92	25.33	30.7	11.6	0.0	0.00	198.7	1.0	28.6	16.7	350	02-Apr
MCAC	89	93	25.95	31.9	12.9	0.0	0.00	181.4	2.9	29.8	18.3	350	03-Apr
MCAC	89	94	26.89	33.8	11.1	0.0	0.00	155.5	7.9	30.7	18.7	350	04-Apr
MCAC	89	95	27.66	35.5	11.7	0.0	0.00	224.6	4.6	31.0	19.1	350	05-Apr
MCAC	89	96	27.99	37.6	10.2	0.0	0.00	155.5	3.2	31.8	19.2	350	06-Apr
MCAC	89	97	27.77	38.6	11.1	0.0	0.00	164.2	1.6	29.4	19.1	350	07-Apr
MCAC	89	98	27.83	38.1	12.5	0.0	0.00	172.8	0.7	31.7	18.8	350	08-Apr
MCAC	89	99	27.79	37.0	17.2	0.0	0.00	293.8	-6.7	32.1	20.5	350	09-Apr
MCAC	89	100	27.94	36.3	12.6	0.0	0.00	164.2	-2.5	32.8	20.3	350	10-Apr
MCAC	89	101	25.12	34.3	13.1	0.0	0.00	224.6	-5.0	31.3	21.0	350	11-Apr
MCAC	89	102	27.17	32.7	14.1	0.0	0.00	285.1	-5.7	31.6	20.4	350	12-Apr
MCAC	89	103	27.13	32.2	15.0	0.0	0.00	164.2	3.5	31.4	21.9	350	13-Apr
MCAC	89	104	27.73	33.8	12.6	0.0	0.00	155.5	2.4	29.4	20.1	350	14-Apr
MCAC	89	105	24.07	33.7	13.3	0.0	0.00	198.7	2.1	29.7	19.4	350	15-Apr
MCAC	89	106	27.96	35.0	13.9	0.0	0.00	241.9	-1.1	31.8	20.1	350	16-Apr
MCAC	89	107	27.23	35.1	12.1	0.0	0.00	181.4	0.3	29.2	20.7	350	17-Apr
MCAC	89	108	28.75	36.8	12.2	0.0	0.00	155.5	-0.1	30.5	19.1	350	18-Apr
MCAC	89	109	27.86	38.8	12.9	0.0	0.00	164.2	1.4	32.8	19.8	350	19-Apr
MCAC	89	110	26.77	40.4	13.7	0.0	0.00	155.5	1.9	33.2	21.2	350	20-Apr
MCAC	89	111	25.01	38.8	17.5	0.0	0.00	216.0	-2.3	34.0	22.8	350	21-Apr
MCAC	89	112	22.78	33.7	15.7	0.0	0.00	207.4	-8.7	27.5	21.4	350	22-Apr
MCAC	89	113	29.70	32.2	11.4	0.0	0.00	233.3	-9.4	30.7	18.8	350	23-Apr
MCAC	89	114	27.94	27.8	11.5	0.0	0.00	285.1	-6.7	27.3	20.3	350	24-Apr
MCAC	89	115	28.87	26.4	8.3	0.0	0.00	267.8	-2.9	26.9	17.4	350	25-Apr
MCAC	89	116	30.29	21.8	10.0	0.0	0.00	293.8	-5.3	27.6	17.7	350	26-Apr
MCAC	89	117	30.04	26.3	5.5	0.0	0.00	164.2	-5.5	31.7	17.3	350	27-Apr
MCAC	89	118	29.99	28.7	7.2	0.0	0.00	190.1	-8.1	28.1	18.2	350	28-Apr
MCAC	89	119	29.82	30.4	9.6	0.0	0.00	190.1	-9.0	29.5	17.8	350	29-Apr
MCAC	89	120	28.89	32.7	12.1	0.0	0.00	181.4	-8.6	31.6	19.7	350	30-Apr
MCAC	89	121	28.67	34.7	13.5	0.0	0.00	181.4	-6.8	31.3	21.5	350	01-May
MCAC	89	122	28.73	35.3	13.1	0.0	0.00	216.0	-6.1	30.6	20.3	350	02-May
MCAC	89	123	30.37	36.9	16.6	0.0	0.00	216.0	-1.3	33.4	20.9	350	03-May
MCAC	89	124	28.79	37.7	14.2	0.0	0.00	198.7	-0.5	33.4	23.2	350	04-May
MCAC	89	125	29.70	39.8	16.8	0.0	0.00	172.8	-0.5	31.4	21.5	350	05-May
MCAC	89	126	23.04	37.9	16.6	0.0	0.00	198.7	0.0	31.6	21.9	350	06-May
MCAC	89	127	30.55	40.8	13.8	0.0	0.00	172.8	1.3	35.6	22.2	350	07-May
MCAC	89	128	30.12	42.6	17.7	0.0	0.00	198.7	-0.8	32.7	24.6	350	08-May
MCAC	89	129	25.85	38.7	21.9	0.0	0.00	432.0	-2.3	32.2	23.2	350	09-May
MCAC	89	130	27.01	30.4	14.8	0.0	0.00	259.2	1.5	33.0	22.7	350	10-May
MCAC	89	131	27.14	24.1	12.1	0.0	0.00	388.8	-2.1	27.5	20.4	350	11-May

INSTW	IYR	JUL	SOLRAD	XTMAX	XTMIN	XRAIN	XPAR	WIND	DEWPT	STMAX	STMIN	CO2	AOO
MCAC	89	132	27.16	26.9	9.1	0.0	0.00	207.4	-1.1	27.2	17.7	350	12-May
MCAC	89	133	27.71	29.7	11.5	0.0	0.00	293.8	-0.3	30.8	18.9	350	13-May
MCAC	89	134	29.78	29.3	11.2	0.0	0.00	233.3	0.1	31.6	20.9	350	14-May
MCAC	89	135	24.29	26.6	13.5	0.0	0.00	293.8	-0.2	29.6	22.2	350	15-May
MCAC	89	136	18.57	23.2	12.6	0.0	0.00	259.2	5.0	24.9	19.8	350	16-May
MCAC	89	137	30.24	29.9	10.3	0.0	0.00	198.7	6.8	29.8	18.6	350	17-May
MCAC	89	138	30.79	35.5	15.6	0.0	0.00	198.7	5.5	31.2	21.4	350	18-May
MCAC	89	139	31.51	36.7	15.3	0.0	0.00	198.7	1.2	31.6	20.6	350	19-May
MCAC	89	140	31.89	37.7	14.0	0.0	0.00	181.4	0.3	34.9	21.7	350	20-May
MCAC	89	141	29.20	38.3	16.6	0.0	0.00	285.1	-1.8	34.2	23.6	350	21-May
MCAC	89	142	28.69	38.6	15.7	0.0	0.00	259.2	-1.4	34.3	23.9	350	22-May
MCAC	89	143	32.42	39.5	15.4	0.0	0.00	276.5	-5.8	31.4	24.0	350	23-May
MCAC	89	144	32.57	36.0	21.4	0.0	0.00	388.8	-6.5	33.4	22.5	350	24-May
MCAC	89	145	32.23	34.8	13.5	0.0	0.00	276.5	-4.4	30.3	23.1	350	25-May
MCAC	89	146	32.23	36.7	15.0	0.0	0.00	172.8	1.3	33.3	20.5	350	26-May
MCAC	89	147	31.85	38.2	15.9	0.0	0.00	267.8	2.2	35.5	22.9	350	27-May
MCAC	89	148	31.52	37.9	16.9	0.0	0.00	337.0	3.5	35.8	24.6	350	28-May
MCAC	89	149	31.23	36.0	17.6	0.0	0.00	319.7	6.0	35.3	24.9	350	29-May
MCAC	89	150	31.86	30.9	13.1	0.0	0.00	250.6	-0.1	33.7	23.8	350	30-May
MCAC	89	151	32.64	34.2	10.4	0.0	0.00	164.2	-2.2	35.0	22.7	350	31-May
MCAC	89	152	32.50	36.0	14.0	0.0	0.00	216.0	-1.2	33.9	22.1	350	01-Jun
MCAC	89	153	32.60	36.0	14.0	0.0	0.00	224.6	-3.7	32.0	20.0	350	02-Jun
MCAC	89	154	31.80	35.0	17.0	0.0	0.00	250.6	-3.7	32.9	23.1	350	03-Jun
MCAC	89	155	31.40	37.0	16.0	0.0	0.00	276.5	1.7	34.1	23.9	350	04-Jun
MCAC	89	156	32.20	37.0	18.0	0.0	0.00	302.4	-0.8	36.3	23.8	350	05-Jun
MCAC	89	157	32.30	35.0	16.0	0.0	0.00	224.6	-2.5	35.1	24.9	350	06-Jun
MCAC	89	158	32.10	38.0	16.0	0.0	0.00	216.0	-0.7	35.0	25.1	350	07-Jun
MCAC	89	159	32.10	36.0	16.0	0.0	0.00	224.6	-2.0	33.9	24.1	350	08-Jun
MCAC	89	160	32.60	37.0	17.0	0.0	0.00	241.9	-1.1	34.7	21.3	350	09-Jun
MCAC	89	161	31.80	37.0	17.0	0.0	0.00	259.2	4.3	34.0	25.9	350	10-Jun
MCAC	89	162	32.30	38.0	18.0	0.0	0.00	198.7	3.1	35.5	26.5	550	11-Jun
MCAC	89	163	31.90	37.0	18.0	0.0	0.00	216.0	1.5	36.1	25.9	550	12-Jun
MCAC	89	164	29.10	41.0	20.0	0.0	0.00	259.2	2.8	35.5	28.4	550	13-Jun
MCAC	89	165	31.30	42.0	22.0	0.0	0.00	241.9	2.2	37.8	28.3	550	14-Jun
MCAC	89	166	31.00	42.0	20.0	0.0	0.00	250.6	3.3	37.0	25.1	550	15-Jun
MCAC	89	167	31.10	42.0	20.0	0.0	0.00	233.3	7.7	35.4	24.6	550	16-Jun
MCAC	89	168	31.80	43.0	21.0	0.0	0.00	198.7	6.9	36.7	29.3	550	17-Jun
MCAC	89	169	32.30	44.0	19.0	0.0	0.00	164.2	4.4	35.5	30.5	550	18-Jun
MCAC	89	170	17.60	42.0	22.0	0.0	0.00	224.6	5.9	37.6	26.4	550	19-Jun
MCAC	89	171	27.50	42.0	21.0	0.0	0.00	198.7	6.1	37.9	28.1	550	20-Jun
MCAC	89	172	30.50	41.0	24.0	0.0	0.00	354.2	10.3	39.5	28.5	550	21-Jun
MCAC	89	173	32.40	39.0	18.0	0.0	0.00	207.4	2.3	37.6	24.4	550	22-Jun
MCAC	89	174	32.40	40.0	19.0	0.0	0.00	328.3	2.4	33.3	22.7	550	23-Jun
MCAC	89	175	31.80	39.0	19.0	0.0	0.00	250.6	2.4	36.2	25.8	550	24-Jun
MCAC	89	176	31.70	38.0	18.0	0.0	0.00	267.8	0.2	34.7	27.3	350	25-Jun
MCAC	89	177	31.60	40.0	16.0	0.0	0.00	172.8	2.1	37.5	26.6	350	26-Jun
MCAC	89	178	28.00	41.0	19.0	0.0	0.00	172.8	4.0	35.6	28.4	350	27-Jun
MCAC	89	179	28.00	40.0	22.0	0.0	0.00	250.6	11.1	39.4	26.6	350	28-Jun

INSTW	IYR	JUL	SOLRAD	XTMAX	XTMIN	XRAIN	XPAR	WIND	DEWPT	STMAX	STMIN	CO2	A00
MCAC	89	180	31.20	42.0	21.0	0.0	0.00	181.4	14.2	38.3	25.7	550	29-Jun
MCAC	89	181	32.10	42.0	19.0	0.0	0.00	190.1	10.0	36.6	25.4	550	30-Jun
MCAC	89	182	30.82	42.2	18.6	0.0	0.00	216.0	7.7	38.3	26.3	550	01-Jul
MCAC	89	183	32.11	42.2	19.9	0.0	0.00	181.4	7.6	39.3	27.3	550	02-Jul
MCAC	89	184	31.64	43.7	19.2	0.0	0.00	181.4	8.9	39.0	28.0	550	03-Jul
MCAC	89	185	30.80	45.8	19.4	0.0	0.00	207.4	8.4	38.7	27.6	550	04-Jul
MCAC	89	186	30.83	42.8	23.4	0.0	0.00	241.9	11.2	39.1	29.0	550	05-Jul
MCAC	89	187	27.45	42.8	24.4	0.0	0.00	224.6	12.1	34.9	29.3	550	06-Jul
MCAC	89	188	30.13	43.6	25.5	0.0	0.00	216.0	11.8	36.0	26.6	550	07-Jul
MCAC	89	189	25.82	40.8	25.7	0.0	0.00	259.2	12.4	37.4	28.3	550	08-Jul
MCAC	89	190	29.51	40.0	23.6	0.0	0.00	267.8	11.8	38.7	28.5	550	09-Jul
MCAC	89	191	19.08	38.5	23.2	0.0	0.00	276.5	17.1	36.9	28.8	550	10-Jul
MCAC	89	192	29.59	36.6	22.1	0.0	0.00	164.2	19.2	37.8	27.5	550	11-Jul
MCAC	89	193	30.50	40.4	21.3	0.0	0.00	138.2	17.2	38.6	28.0	550	12-Jul
MCAC	89	194	31.00	42.7	19.7	0.0	0.00	181.4	14.0	34.5	28.0	550	13-Jul
MCAC	89	195	30.17	43.4	21.2	0.0	0.00	224.6	11.8	35.1	25.2	550	14-Jul
MCAC	89	196	28.85	41.0	23.9	0.0	0.00	198.7	15.4	38.4	27.4	550	15-Jul
MCAC	89	197	19.64	39.2	26.1	0.0	0.00	190.1	17.0	36.7	29.4	550	16-Jul
MCAC	89	198	28.27	41.1	24.3	0.0	0.00	181.4	16.4	39.4	28.7	550	17-Jul
MCAC	89	199	30.29	43.6	23.0	0.0	0.00	216.0	10.8	39.7	28.8	550	18-Jul
MCAC	89	200	29.67	43.9	26.3	0.0	0.00	276.5	11.3	40.0	29.6	550	19-Jul
MCAC	89	201	29.67	42.7	27.3	0.0	0.00	267.8	12.4	35.4	28.9	550	20-Jul
MCAC	89	202	21.28	41.1	24.3	0.0	0.00	250.6	21.7	34.1	27.0	550	21-Jul
MCAC	89	203	23.31	38.0	23.7	0.0	0.00	198.7	22.4	36.9	27.5	550	22-Jul
MCAC	89	204	27.36	40.1	24.5	0.0	0.00	233.3	20.5	38.1	28.3	550	23-Jul
MCAC	89	205	28.61	41.5	25.2	0.0	0.00	216.0	18.1	38.8	29.0	550	24-Jul
MCAC	89	206	29.61	41.2	24.8	0.0	0.00	250.6	16.7	39.4	29.5	550	25-Jul
MCAC	89	207	29.17	40.1	25.5	0.0	0.00	285.1	14.1	39.8	29.5	550	26-Jul
MCAC	89	208	25.23	38.4	21.3	5.0	0.00	224.6	20.9	35.9	29.1	550	27-Jul
MCAC	89	209	24.92	34.7	21.2	2.0	0.00	155.5	20.7	34.1	27.1	550	28-Jul
MCAC	89	210	26.68	37.3	23.3	0.0	0.00	164.2	22.2	35.6	27.2	550	29-Jul
MCAC	89	211	29.06	38.9	22.9	0.0	0.00	216.0	21.5	38.5	27.5	550	30-Jul
MCAC	89	212	26.56	39.7	26.1	1.0	0.00	216.0	21.1	39.0	29.8	550	31-Jul
MCAC	89	213	27.97	41.4	23.1	0.0	0.00	198.7	22.0	38.4	27.0	550	01-Aug
MCAC	89	214	29.55	39.9	22.0	0.0	0.00	207.4	16.3	38.3	28.6	550	02-Aug
MCAC	89	215	25.02	37.9	23.9	2.0	0.00	233.3	22.7	37.9	30.3	550	03-Aug
MCAC	89	216	26.42	37.4	22.8	0.0	0.00	216.0	21.9	37.5	28.6	550	04-Aug
MCAC	89	217	28.03	38.5	23.9	0.0	0.00	233.3	20.7	37.8	29.3	550	05-Aug
MCAC	89	218	25.08	40.4	24.1	0.0	0.00	267.8	19.4	37.3	29.9	550	06-Aug
MCAC	89	219	27.47	38.8	24.2	0.0	0.00	285.1	19.9	38.2	29.9	550	07-Aug
MCAC	89	220	27.58	39.3	24.3	0.0	0.00	250.6	18.0	37.6	29.9	550	08-Aug
MCAC	89	221	25.31	37.8	23.5	0.0	0.00	259.2	17.4	37.3	29.1	550	09-Aug
MCAC	89	222	18.77	34.7	23.8	0.0	0.00	216.0	20.7	37.2	29.4	550	10-Aug
MCAC	89	223	23.38	37.6	22.2	0.0	0.00	181.4	21.3	34.1	28.5	550	11-Aug
MCAC	89	224	26.65	39.0	26.4	0.0	0.00	207.4	19.1	33.7	27.4	550	12-Aug
MCAC	89	225	28.23	41.7	25.2	0.0	0.00	267.8	19.1	36.1	26.9	550	13-Aug
MCAC	89	226	27.94	41.6	27.3	0.0	0.00	259.2	16.6	37.9	28.9	550	14-Aug
MCAC	89	227	27.77	41.4	25.2	0.0	0.00	216.0	17.1	39.0	29.5	550	15-Aug

INSTW	IYR	JUL	SOLRAD	XTMAX	XTMIN	XRAIN	XPAR	WIND	DEWPT	STMAX	STMIN	CO2	AOO
MCAC	89	228	24.52	40.1	23.8	0.0	0.00	276.5	20.1	38.1	29.7	550	16-Aug
MCAC	89	229	27.34	38.6	22.0	0.0	0.00	267.8	18.7	39.0	29.0	550	17-Aug
MCAC	89	230	24.24	37.6	24.5	0.0	0.00	224.6	21.2	37.3	29.6	550	18-Aug
MCAC	89	231	27.31	39.1	22.0	0.0	0.00	172.8	18.1	37.8	28.9	550	19-Aug
MCAC	89	232	27.71	38.5	21.3	0.0	0.00	267.8	14.3	37.1	28.5	550	20-Aug
MCAC	89	233	27.03	37.4	19.9	0.0	0.00	224.6	10.2	36.2	27.3	550	21-Aug
MCAC	89	234	28.22	38.5	15.1	0.0	0.00	190.1	7.6	36.1	25.9	550	22-Aug
MCAC	89	235	28.49	39.4	15.2	0.0	0.00	190.1	10.5	36.1	25.9	550	23-Aug
MCAC	89	236	28.48	38.0	18.0	0.0	0.00	190.1	8.1	36.0	26.2	550	24-Aug
MCAC	89	237	28.36	38.3	17.7	0.0	0.00	233.3	9.9	35.6	25.9	550	25-Aug
MCAC	89	238	28.38	38.3	14.9	0.0	0.00	181.4	6.7	35.7	25.4	550	26-Aug
MCAC	89	239	27.64	38.2	17.7	0.0	0.00	155.5	10.2	36.0	26.0	550	27-Aug
MCAC	89	240	27.25	39.2	18.0	0.0	0.00	155.5	13.9	36.4	26.3	550	28-Aug
MCAC	89	241	26.78	41.0	17.7	0.0	0.00	164.2	12.1	36.3	26.3	550	29-Aug
MCAC	89	242	26.12	40.0	21.0	0.0	0.00	198.7	13.9	36.4	27.2	550	30-Aug
MCAC	89	243	25.77	38.7	21.9	0.0	0.00	164.2	14.5	34.7	27.7	550	31-Aug
MCAC	89	244	25.89	40.1	20.8	0.0	0.00	155.5	16.9	33.0	26.5	550	01-Sep
MCAC	89	245	15.52	35.0	22.8	0.0	0.00	172.8	20.1	30.5	26.2	550	02-Sep
MCAC	89	246	16.85	32.2	20.7	12.0	0.00	216.0	20.2	30.9	26.2	550	03-Sep
MCAC	89	247	24.90	38.2	21.0	0.0	0.00	121.0	20.4	33.2	26.0	550	04-Sep
MCAC	89	248	25.81	41.1	21.2	0.0	0.00	129.6	20.2	34.4	26.0	550	05-Sep
MCAC	89	249	24.87	40.7	22.8	0.0	0.00	164.2	19.2	35.3	26.6	550	06-Sep
MCAC	89	250	25.72	40.0	22.0	0.0	0.00	224.6	18.3	33.6	27.0	550	07-Sep
MCAC	89	251	26.13	36.8	20.7	0.0	0.00	233.3	12.3	30.2	25.1	550	08-Sep
MCAC	89	252	26.28	37.7	13.9	0.0	0.00	155.5	6.8	32.0	22.7	550	09-Sep
MCAC	89	253	26.25	37.9	15.1	0.0	0.00	172.8	9.4	32.2	23.1	550	10-Sep
MCAC	89	254	26.00	37.2	15.5	0.0	0.00	224.6	9.7	32.0	23.9	550	11-Sep
MCAC	89	255	25.33	36.9	14.8	0.0	0.00	190.1	7.2	32.1	23.6	550	12-Sep
MCAC	89	256	24.81	36.0	13.6	0.0	0.00	146.9	10.1	32.2	23.9	550	13-Sep
MCAC	89	257	24.89	38.2	13.0	0.0	0.00	138.2	10.6	31.4	23.6	550	14-Sep
MCAC	89	258	24.25	39.2	13.4	0.0	0.00	146.9	9.1	29.8	22.3	550	15-Sep
MCAC	89	259	22.64	40.7	19.4	0.0	0.00	155.5	12.2	30.5	23.7	550	16-Sep
MCAC	89	260	20.04	36.6	19.9	0.0	0.00	276.5	12.8	30.8	24.9	550	17-Sep
MCAC	89	261	24.20	36.1	16.4	0.0	0.00	233.3	14.6	31.3	23.7	350	18-Sep
MCAC	89	262	24.00	34.0	13.6	0.0	0.00	276.5	6.5	29.9	22.9	350	19-Sep
MCAC	89	263	24.34	31.0	10.3	0.0	0.00	155.5	7.0	29.6	22.0	350	20-Sep
MCAC	89	264	24.74	36.7	8.8	0.0	0.00	146.9	3.8	29.6	21.1	350	21-Sep
MCAC	89	265	23.86	41.8	10.9	0.0	0.00	146.9	4.1	28.5	20.3	350	22-Sep
MCAC	89	266	20.86	39.0	20.2	0.0	0.00	397.4	8.1	28.7	22.5	350	23-Sep
MCAC	89	267	22.43	39.8	18.0	0.0	0.00	155.5	10.5	30.9	22.9	350	24-Sep
MCAC	89	268	22.24	41.9	18.8	0.0	0.00	146.9	10.3	31.8	23.7	350	25-Sep
MCAC	89	269	21.99	41.3	21.8	0.0	0.00	276.5	9.3	31.4	24.4	350	26-Sep
MCAC	89	270	22.79	39.2	17.5	0.0	0.00	285.1	-1.7	30.8	23.4	350	27-Sep
MCAC	89	271	23.30	39.3	16.1	0.0	0.00	207.4	1.0	30.1	22.9	350	28-Sep
MCAC	89	272	23.26	40.3	11.4	0.0	0.00	155.5	1.9	27.8	20.7	350	29-Sep
MCAC	89	273	22.47	39.0	10.8	0.0	0.00	155.5	2.4	27.7	19.8	350	30-Sep

FILENAME: TRIX.CT2 SOIL PROFILE PROPERTIES FOR TRIX CLAY LOAM

IDUMSL	PEDON	TAXON
01	-9	TRIX CLAY LOAM (FINE-LOAMY, MIXED (CALCAREOUS), HYPERTHERMIC.

SALB	U	SWCON	CN2	TAV	AMP	DMOD	SWCON1	SWCON2	SWCON3	RWUMX	PHFAC3
0.20	12.00	0.29	70.00	21.8	22.2	1.0	2.67E-03	58.0	6.68	0.03	1.00

DLAYR	LL	DUL	SAT	DSW	WR	BD	OC	DNH4	DNO3	DPH
5.	0.202	0.320	0.417	0.320	1.000	1.31	0.41	0.0	3.0	8.5
5.	0.202	0.320	0.417	0.320	0.861	1.31	0.41	0.0	3.0	8.5
10.	0.201	0.319	0.424	0.319	0.741	1.27	0.35	0.0	3.0	8.5
10.	0.199	0.319	0.424	0.319	0.607	1.27	0.27	0.0	3.0	8.5
20.	0.198	0.318	0.419	0.318	0.449	1.30	0.24	0.0	2.0	8.6
20.	0.198	0.318	0.387	0.318	0.301	1.47	0.16	0.0	1.0	8.6
30.	0.186	0.299	0.359	0.299	0.183	1.57	0.30	0.0	1.0	8.6
30.	0.159	0.275	0.347	0.275	0.100	1.57	0.10	0.0	0.5	8.6
30.	0.136	0.254	0.336	0.254	0.055	1.57	0.00	0.0	0.5	8.6
30.	0.128	0.244	0.331	0.244	0.030	1.57	0.00	0.0	0.5	8.6
-1.										

ROCK	SAND	SILT	CLAY	SCOND	CATEXC	ALPHA	XN	VGTHS	VGTHR
0.0	35.0	31.0	34.0	4.3	255.0	2.900	1.369	0.454	0.187
0.0	35.0	31.0	34.0	4.3	255.0	2.900	1.369	0.454	0.187
0.0	35.0	31.0	34.0	4.3	255.0	2.900	1.369	0.454	0.187
0.0	35.0	31.0	34.0	4.3	255.0	2.900	1.369	0.454	0.187
0.0	35.0	31.0	34.0	4.3	245.0	7.111	1.306	0.498	0.165
0.0	35.0	31.0	34.0	4.3	235.0	7.111	1.306	0.498	0.165
0.0	45.0	25.0	30.0	4.3	207.0	3.134	1.566	0.439	0.156
0.0	55.0	20.0	25.0	4.3	173.0	3.134	1.566	0.439	0.156
0.0	60.0	20.0	20.0	4.3	138.0	3.134	1.566	0.439	0.156
0.0	65.0	17.0	18.0	4.3	124.0	3.134	1.566	0.439	0.156

DATAID

TRIX CLAY LOAM (FINE-LOAMY, MIXED (CALCAREOUS), HYPERTHERMIC.

LYRSOL

3

DIFFO	THETAO	BETA	GLAYR	THETAS	FC	THETAR	AIRDR	ETA	GBD	PSIBUB
0.85E-10	0.215	49.9	0.30E+02	0.46	0.30	0.21	0.03	5.02	1.31	3.40
0.12E-10	0.205	43.9	0.40E+02	0.46	0.29	0.21	0.03	5.02	1.40	4.80
0.12E-10	0.164	69.8	0.80E+02	0.42	0.23	0.16	0.03	5.02	1.57	4.70
0.85E-10	0.215	49.9		0.46	0.30	0.21	0.03	5.02	1.31	3.40
0.85E-10	0.215	49.9		0.46	0.30	0.21	0.03	5.02	1.31	3.40

TD	THETAI	BDSLOP	BDRATO	PSISFC
47	0.150	0.00	1.00	33.0

SNAME
Norfolk silt loam

NCURVE
7

INRIM GH2OC
6 0.05

TSTBD	TSTIMP
0.9	0.1
1.1	5.4
1.3	16.2
1.5	36.0
1.7	62.0
1.9	93.0

INRIM GH2OC
6 0.07

TSTBD	TSTIMP
0.9	0.1
1.1	2.5
1.3	7.8
1.5	22.6
1.7	44.5
1.9	71.3

INRIM GH2OC
6 0.09

TSTBD	TSTIMP
0.9	0.1
1.1	1.0
1.3	2.3
1.5	12.8
1.7	30.4
1.9	52.6

INRIM GH2OC
6 0.11

TSTBD	TSTIMP
0.9	0.1
1.1	0.9
1.3	1.7
1.5	7.5

1.7	21.5
1.9	31.2

INRIM	GH2OC
6	0.13

TSTBD	TSTIMP
0.9	0.1
1.1	0.5
1.3	1.0
1.5	5.6
1.7	15.2
1.9	29.8

INRIM	GH2OC
6	0.15

TSTBD	TSTIMP
0.9	0.1
1.1	0.2
1.3	0.5
1.5	4.9
1.7	13.9
1.9	27.7

INRIM	GH2OC
6	0.30

TSTBD	TSTIMP
0.9	0.1
1.1	0.2
1.3	0.5
1.5	0.9
1.7	1.1
1.9	1.3

FILENAME: MCMC8901.CT4 SOIL ORGANIC RESIDUE (ALL PLOTS)

ID	TRTNO	STRAW	SDEP	SCN	ROOT
MCMC8901	01	0.	0.	80.	0.

FILENAME: MCMC8901.CT5 SOIL PROFILE INITIAL CONDITIONS (ALL PLOTS)

TRTNO	ID
01	MCMC8901

DLAYR	SW	NH4	NO3	PH
5.	0.250	0.0	3.0	8.5
5.	0.280	0.0	3.0	8.5
10.	0.310	0.0	3.0	8.5
10.	0.310	0.0	3.0	8.5
20.	0.280	0.0	2.0	8.6
20.	0.230	0.0	1.0	8.6
30.	0.200	0.0	1.0	8.6
30.	0.160	0.0	0.5	8.6
30.	0.150	0.0	0.5	8.6
30.	0.150	0.0	0.5	8.6
-1.				

FILENAME: MCMC8901.CT6 IRRIGATION FOR REPS 1 AND 4

TRTNO ID
01 MCMC8901

	AMTIRR		X1IRR		X2IRR	
JDIRR	IRR	COD	Z1IRR		Z2IRR	
114	43.	5	0.0	20.0	0.0	20.0
118	43.	5	0.0	20.0	0.0	20.0
121	34.	5	0.0	20.0	0.0	20.0
125	47.	5	0.0	20.0	0.0	20.0
129	43.	5	0.0	20.0	0.0	20.0
131	30.	5	0.0	20.0	0.0	20.0
139	73.	5	0.0	20.0	0.0	20.0
145	30.	5	0.0	20.0	0.0	20.0
156	52.	5	0.0	20.0	0.0	20.0
163	43.	5	0.0	20.0	0.0	20.0
178	60.	5	0.0	20.0	0.0	20.0
180	13.	5	0.0	20.0	0.0	20.0
182	47.	5	0.0	20.0	0.0	20.0
185	26.	5	0.0	20.0	0.0	20.0
188	26.	5	0.0	20.0	0.0	20.0
192	34.	5	0.0	20.0	0.0	20.0
196	60.	5	0.0	20.0	0.0	20.0
199	56.	5	0.0	20.0	0.0	20.0
200	13.	5	0.0	20.0	0.0	20.0
201	34.	5	0.0	20.0	0.0	20.0
208	26.	5	0.0	20.0	0.0	20.0
210	17.	5	0.0	20.0	0.0	20.0
212	34.	5	0.0	20.0	0.0	20.0
214	17.	5	0.0	20.0	0.0	20.0
216	30.	5	0.0	20.0	0.0	20.0
218	22.	5	0.0	20.0	0.0	20.0
220	17.	5	0.0	20.0	0.0	20.0
222	9.	5	0.0	20.0	0.0	20.0
224	22.	5	0.0	0.0	1.0	0.0
226	13.	5	0.0	0.0	1.0	0.0
228	22.	5	0.0	0.0	1.0	0.0
230	17.	5	0.0	0.0	1.0	0.0
232	30.	5	0.0	0.0	1.0	0.0
234	26.	5	0.0	0.0	1.0	0.0
-1						

FILENAME: MCMC8902.CT6 IRRIGATION FOR REPS 2 AND 3

TRTNO ID
MCMC8902 01

JDIRR	AMTIRR	IRRCOD	X1IRR	Z1IRR	X2IRR	Z2IRR
114	33.	5	0.0	20.0	0.0	20.0
118	43.	5	0.0	20.0	0.0	20.0
121	38.	5	0.0	20.0	0.0	20.0
125	47.	5	0.0	20.0	0.0	20.0
129	47.	5	0.0	20.0	0.0	20.0
131	28.	5	0.0	20.0	0.0	20.0
139	85.	5	0.0	20.0	0.0	20.0
145	38.	5	0.0	20.0	0.0	20.0
156	47.	5	0.0	20.0	0.0	20.0
163	38.	5	0.0	20.0	0.0	20.0
178	57.	5	0.0	20.0	0.0	20.0
180	28.	5	0.0	20.0	0.0	20.0
182	38.	5	0.0	20.0	0.0	20.0
185	19.	5	0.0	20.0	0.0	20.0
188	28.	5	0.0	20.0	0.0	20.0
192	57.	5	0.0	20.0	0.0	20.0
196	66.	5	0.0	20.0	0.0	20.0
199	52.	5	0.0	20.0	0.0	20.0
200	14.	5	0.0	20.0	0.0	20.0
201	28.	5	0.0	20.0	0.0	20.0
208	28.	5	0.0	20.0	0.0	20.0
210	28.	5	0.0	20.0	0.0	20.0
212	33.	5	0.0	20.0	0.0	20.0
214	24.	5	0.0	20.0	0.0	20.0
216	24.	5	0.0	20.0	0.0	20.0
218	24.	5	0.0	20.0	0.0	20.0
220	24.	5	0.0	20.0	0.0	20.0
222	33.	5	0.0	20.0	0.0	20.0
224	19.	5	0.0	0.0	1.0	0.0
226	19.	5	0.0	0.0	1.0	0.0
228	28.	5	0.0	0.0	1.0	0.0
230	19.	5	0.0	0.0	1.0	0.0
232	28.	5	0.0	0.0	1.0	0.0
234	28.	5	0.0	0.0	1.0	0.0
-1						

FILENAME: MCMC8901.CT7 FERTILIZER MANAGEMENT (ALL PLOTS)

TRTNO ID
01 MCMC8901

JDFERT	FERTN	DFERT	INTYPE	FERTP	IPTYPE	FERTK	IKTYPE	FERTIN	IITYPE	FERCOD	X1FERT	Z1FERT	X2FERT	Z2FERT
100	67.3	20.0	10	0.0	0	0.0	0	0.0	0	5	0.0	20.0	0.0	20.0
139	22.4	20.0	10	0.0	0	0.0	0	0.0	0	5	0.0	20.0	0.0	20.0
166	22.4	20.0	10	0.0	0	0.0	0	0.0	0	5	0.0	20.0	0.0	20.0
200	22.4	20.0	10	0.0	0	0.0	0	0.0	0	5	0.0	20.0	0.0	20.0
-1														

FILENAME: MCMC8901.CT8 TREATMENT MANAGEMENT FILE

ID	TRTNO	TITLET	ISOILT	IVARTY
MCMC8901	01	CO2 = 350 ppm, REP #1	1	77

(ISWEED, ISWINS, ISWNEM & ISWDIS) options

ISIM	ISOW PLANTS	ROWSPC	SDEPTH	IIRR ISWNIT	EFFIRR DSOIL	THETAC IMERGE				
111	107 10.00	1.016	5.00	2 1	0.95 0.00	0.0 111	0	0	0	0

HISTRY
FIELD WAS FALLOW FOR 3 YEARS

FILENAME: MCMC8902.CT8 TREATMENT MANAGEMENT FILE

ID	TRTNO	TITLET	ISOILT	IVARTY
MCMC8902	01	CO2 = 350 ppm, REP #2	1	77

(ISWEED, ISWINS, ISWNEM & ISWDIS) options

ISIM	ISOW PLANTS	ROWSPC	SDEPTH	IIRR ISWNIT	EFFIRR DSOIL	THETAC IMERGE				
111	107 10.00	1.016	5.00	2 1	0.95 0.00	0.0 111	0	0	0	0

HISTRY
FIELD WAS FALLOW FOR 3 YEARS

FILENAME: MCMC8903.CT8 TREATMENT MANAGEMENT FILE

ID	TRTNO	TITLET	ISOILT	IVARTY
MCMC8903	01	CO2 = 350 ppm, REP #3	1	77

(ISWEED, ISWINS, ISWNEM & ISWDIS) options

ISOW		ROWSPC		IIRR		EFFIRR		THETAC						
ISIM	PLANTS		SDEPTH	ISWNIT		DSOIL		IMERGE						
111	107	10.00	1.016	5.00	2	1	0.95	0.00	0.0	111	0	0	0	0

HISTRY

FIELD WAS FALLOW FOR 3 YEARS

FILENAME: MCMC8904.CT8 TREATMENT MANAGEMENT FILE

ID	TRTNO	TITLET	ISOILT	IVARTY
MCMC8904	01	CO2 = 350 ppm, REP#4	1	77

(ISWEED, ISWINS, ISWNEM & ISWDIS) options

ISOW		ROWSPC		IIRR		EFFIRR		THETAC						
ISIM	PLANTS		SDEPTH	ISWNIT		DSOIL		IMERGE						
111	107	10.00	1.016	5.00	2	1	0.95	0.00	0.0	111	0	0	0	0

HISTRY

FIELD WAS FALLOW FOR 3 YEARS

FILENAME: MCM18901.CT8 TREATMENT MANAGEMENT FILE

ID	TRTNO	TITLET	ISOILT	IVARTY
MCM18901	01	FACE CO2 = 550 ppm, REP#1	1	77

(ISWEED, ISWINS, ISWNEM & ISWDIS) options

ISOW		ROWSPC		IIRR		EFFIRR		THETAC						
ISIM	PLANTS		SDEPTH	ISWNIT		DSOIL		IMERGE						
111	107	10.00	1.106	5.00	2	1	0.95	0.00	0.0	111	0	0	0	0

HISTRY

FIELD WAS FALLOW FOR 3 YEARS

FILENAME: MCM28902.CT8 TREATMENT MANAGEMENT FILE

ID	TRTNO	TITLET	ISOILT	IVARTY
MCM28902	01	FACE CO2 = 550 ppm, REP#2	1	77

(ISWEED, ISWINS, ISWNEM & ISWDIS) options

ISIM	ISOW	PLANTS	ROWSPC	SDEPTH	IIRR	ISWNIT	EFFIRR	DSOIL	THETAC	IMERGE				
111	107	10.00	1.016	3.00	2	1	0.95	0.00	0.0	111	0	0	0	0

HISTRY
FIELD WAS FALLOW FOR 3 YEARS

FILENAME: MCM38903.CT8 TREATMENT MANAGEMENT FILE

ID	TRTNO	TITLET	ISOILT	IVARTY
MCM38903	01	FACE CO2 = 550 ppm, REP#3	1	77

(ISWEED, ISWINS, ISWNEM & ISWDIS) options

ISIM	ISOW	PLANTS	ROWSPC	SDEPTH	IIRR	ISWNIT	EFFIRR	DSOIL	THETAC	IMERGE				
111	107	10.00	1.016	5.00	2	1	0.95	0.00	0.0	111	0	0	0	0

HISTRY
FIELD WAS FALLOW FOR 3 YEARS

FILENAME: MCM48904.CT8 TREATMENT MANAGEMENT FILE

ID	TRTNO	TITLET	ISOILT	IVARTY
MCM48904	01	FACE CO2 = 550 ppm, REP#4	1	77

(ISWEED, ISWINS, ISWNEM & ISWDIS) options

ISIM	ISOW	PLANTS	ROWSPC	SDEPTH	IIRR	ISWNIT	EFFIRR	DSOIL	THETAC	IMERGE				
111	107	10.00	1.016	5.00	2	1	0.95	0.00	0.0	111	0	0	0	0

HISTRY
FIELD WAS FALLOW FOR 3 YEARS

FILENAME: MCMC8901.CTA FINAL HARVEST DATA FILE
AMBIENT CO2, REP 1

ID	TRTNO	XLTYLD	XSDYLD	XSDWT	XBLSM	XSPB	XLAIMX	XBIOM	XSTMBR
MCMC8901	01	2055.	3288.	-9.0000	144.	-9.	3.50	12591.	5927.

XSDTN	XTOTNP	XAPTNP	XSDN
-9.00	-9.0	-9.0	-9.0

FILENAME: MCMC8902.CTA FINAL HARVEST DATA FILE
AMBIENT CO2, REP 2

ID	TRTNO	XLTYLD	XSDYLD	XSDWT	XBLSM	XSPB	XLAIMX	XBIOM	XSTMBR
MCMC8902	01	1809.	2894.	-9.0000	132.	-9.	3.05	12226.	4939.

XSDTN	XTOTNP	XAPTNP	XSDN
-9.00	-9.0	-9.0	-9.0

FILENAME: MCMC8903.CTA FINAL HARVEST DATA FILE
AMBIENT CO2, REP 3

ID	TRTNO	XLTYLD	XSDYLD	XSDWT	XBLSM	XSPB	XLAIMX	XBIOM	XSTMBR
MCMC8903	01	1884.	3014.	-9.0000	156.	-9.	2.97	12533.	5479.

XSDTN	XTOTNP	XAPTNP	XSDN
-9.00	-9.0	-9.0	-9.0

FILENAME: MCMC8904.CTA FINAL HARVEST DATA FILE
AMBIENT CO2, REP 4

ID	TRTNO	XLTYLD	XSDYLD	XSDWT	XBLSM	XSPB	XLAIMX	XBIOM	XSTMBR
MCMC8904	01	2259.	3614.	-9.0000	147.	-9.	3.28	12684.	5721.

XSDTN	XTOTNP	XAPTNP	XSDN
-9.00	-9.0	-9.0	-9.0

FILENAME: MCM18901.CTA FINAL HARVEST DATA FILE
550 FACE CO2, REP 1

ID	TRTNO	XLTYLD	XSDYLD	XSDWT	XBLSM	XSPB	XLAIMX	XBIOM	XSTMBR
MCM18901	01	2664.	4262.	-9.0000	218.	-9.	3.21	14313.	7971.

XSDTN	XTOTNP	XAPTNP	XSDN
-9.00	-9.0	-9.0	-9.0

FILENAME: MCM28902.CTA FINAL HARVEST DATA FILE
550 FACE CO2, REP 2

ID	TRTNO	XLTYLD	XSDYLD	XSDWT	XBLSM	XSPB	XLAIMX	XBIOM	XSTMBR
MCM28902	01	2613.	4181.	-9.0000	224.	-9.	2.74	17900.	7356.

XSDTN	XTOTNP	XAPTNP	XSDN
-9.00	-9.0	-9.0	-9.0

FILENAME: MCM38903.CTA FINAL HARVEST DATA FILE
550 FACE CO2, REP 3

ID	TRTNO	XLTYLD	XSDYLD	XSDWT	XBLSM	XSPB	XLAIMX	XBIOM	XSTMBR
MCM38903	01	2190.	3504.	-9.0000	205.	-9.	3.19	13900.	6121.

XSDTN	XTOTNP	XAPTNP	XSDN
-9.00	-9.0	-9.0	-9.0

•

FILENAME: MCM48904.CTA FINAL HARVEST DATA FILE
550 FACE CO2, REP 4

ID	TRTNO	XLTYLD	XSDYLD	XSDWT	XBLSM	XSPB	XLAIMX	XBIOM	XSTMBR
MCM48904	01	2277.	3643.	-9.0000	198.	-9.	2.79	12808.	6554.

XSDTN	XTOTNP	XAPTNP	XSDN
-9.00	-9.0	-9.0	-9.0

FILENAME: MCMC8901.CTB

MEASURED INTERMEDIATE GROWTH DATA
AMBIENT CO_2, CONTROL REP 1

ID	TRTNO	JEMRGD	JSQRJD	JFLRJD
MCMC8901	01	111	140	166

NOVAR
13 1 2 3 4 5 6 7 8 9 10 11 12 13

JDOY	XPLTHT	XLAI	JNNODM	JNSQRM	JNFLWM	JNGBLM	JNMBLM	JNABSM	XWLEFH	XWSTMH	XWROTH	XWGBLH	XWMBLH
150	21.	0.25	62	0	0	0	0	0	260.8	189.9	-9.0	0.0	0.0
165	46.	0.50	79	0	0	0	0	0	736.4	589.7	142.5	0.0	0.0
179	60.	1.94	114	85	11	3	0	0	1451.7	1916.3	428.4	0.0	0.0
192	82.	3.15	127	128	31	99	0	56	1977.7	2892.4	573.7	712.5	0.0
208	73.	2.46	139	31	15	102	0	93	1933.3	2497.6	470.3	2109.2	0.0
221	76.	1.91	129	29	2	91	2	68	1907.5	1897.8	438.8	3335.9	0.0
235	77.	3.50	176	30	8	97	48	94	2633.0	3512.2	875.6	3601.0	2474.6
263	88.	2.41	149	43	7	75	85	59	1284.3	4419.6	1546.2	2165.4	4721.2

-1

FILENAME: MCMC8902.CTB

MEASURED INTERMEDIATE GROWTH DATA
AMBIENT CO_2, CONTROL REP 2

ID	TRTNO	JEMRGD	JSQRJD	JFLRJD
MCMC8902	01	111	140	166

NOVAR
13 1 2 3 4 5 6 7 8 9 10 11 12 13

JDOY	XPLTHT	XLAI	JNNODM	JNSQRM	JNFLWM	JNGBLM	JNMBLM	JNABSM	XWLEFH	XWSTMH	XWROTH	XWGBLH	XWMBLH
150	23.	0.17	63	0	0	0	0	0	187.9	129.8	-9.	0.0	0.0
165	45.	1.06	68	0	0	0	0	0	517.1	409.2	104.9	0.0	0.0
179	63.	1.59	134	1	8	7	0	0	1209.9	1646.9	352.8	0.0	0.0
192	78.	2.02	131	121	49	112	0	56	1212.9	1888.0	432.5	829.3	0.0
208	69.	1.63	129	34	10	94	0	64	1634.1	1457.4	485.1	2113.0	0.0
221	71.	2.11	154	14	1	121	2	110	2183.1	2218.2	435.4	4442.4	0.0
235	76.	2.40	147	25	2	79	56	92	2257.2	2822.6	1056.6	2946.2	3023.1
263	102.	3.05	151	46	7	57	91	41	2452.4	3612.2	1264.8	1991.5	4169.9

-1

FILENAME: MCMC8903.CTB

MEASURED INTERMEDIATE GROWTH DATA
AMBIENT CO_2, CONTROL REP 3

ID	TRTNO	JSQRJD JEMRGD	JFLRJD
MCMC8903	01	111	140	166

NOVAR
13 1 2 3 4 5 6 7 8 9 10 11 12 13

JDOY	XPLTHT	XLAI	JNNODM	JNSORM	JNFLWM	JNGBLM	JNMBLM	JNABSM	XWLEFH	XWSTMH	XWROTH	XWGBLH	XWMBLH
150	24.	0.21	64	0	0	0	0	0	231.0	161.4	-9.	0.0	0.0
165	50.	0.61	79	0	0	0	0	0	511.1	414.1	116.6	0.0	0.0
179	60.	1.80	137	105	10	4	0	0	1287.8	1641.9	365.4	0.0	0.0
192	77.	2.41	153	151	29	85	0	44	1554.8	1343.8	718.5	295.7	0.0
208	69.	2.79	135	67	28	81	0	90	2110.7	2313.1	646.8	1500.2	0.0
221	70.	1.81	157	22	3	95	6	44	1916.7	1183.1	392.2	3547.5	0.0
235	77.	2.97	173	31	0	90	48	50	2212.8	2517.4	1120.7	3230.8	2475.6
263	94.	2.63	199	55	6	62	86	70	2124.1	4097.3	1433.5	1546.2	4765.7

-1

FILENAME: MCMC8904.CTB

MEASURED INTERMEDIATE GROWTH DATA
AMBIENT CO_2, CONTROL REP 4

ID	TRTNO	JSQRJD JEMRGD	JFLRJD
MCMC8904	01	111	140	166

NOVAR
13 1 2 3 4 5 6 7 8 9 10 11 12 13

JDOY	XPLTHT	XLAI	JNNODM	JNSORM	JNFLWM	JNGBLM	JNMBLM	JNABSM	XWLEFH	XWSTMH	XWROTH	XWGBLH	XWMBLH
150	23.	0.22	64	0	0	0	0	0	297.1	204.6	-9.	0.0	0.0
165	45.	0.98	99	0	0	0	0	0	787.6	781.9	196.6	0.0	0.0
179	59.	1.42	123	91	12	6	0	0	1233.6	1627.4	343.6	0.0	0.0
192	79.	2.98	121	126	41	50	0	57	1729.8	2346.1	554.8	951.3	0.0
208	66.	3.28	154	56	13	138	0	124	2390.9	3225.2	722.8	2766.8	0.0
221	68.	2.29	138	28	0	1	4	83	2129.7	2162.1	453.3	3246.1	0.0
235	73.	2.80	203	37	0	64	45	94	2437.9	2995.0	896.1	2656.7	2660.1
263	89.	2.84	168	53	5	72	83	64	2163.8	4064.0	1422.4	1427.2	5029.2

-1

FILENAME: MCM18901.CTB MEASURED INTERMEDIATE GROWTH DATA
550 CO_2, FACE REP 1

ID	TRTNO	JEMRGD	JSQRJD	JFLRJD
MCM18901	01	111	140	166

NOVAR
13 1 2 3 4 5 6 7 8 9 10 11 12 13

JDOY	XPLTHT	XLAI	JNNODM	JNSQRM	JNFLWM	JNGBLM	JNMBLM	JNABSM	XWLEFH	XWSTMH	XWROTH	XWGBLH	XWMBLH
150	31.	0.22	69	0	0	0	0	0	306.8	211.8	-9.	0.0	0.0
165	59.	0.94	99	0	0	0	0	0	985.2	859.8	142.2	0.0	0.0
179	81.	1.95	108	96	11	5	0	0	1854.0	2791.9	176.9	0.0	0.0
192	86.	2.42	140	101	34	80	0	60	1925.9	3156.4	875.1	918.5	0.0
208	81.	3.11	170	49	22	147	0	86	2316.9	3099.8	855.8	3744.0	0.0
221	73.	2.12	137	21	5	140	4	65	2350.8	2615.3	752.8	6031.8	0.0
235	87.	2.21	146	12	0	48	97	60	2734.8	3833.8	1922.4	2561.9	5624.2
263	106.	1.80	174	60	9	35	107	111	1590.6	6017.3	2707.1	185.8	6519.7

-1

FILENAME: MCM28902.CTB MEASURED INTERMEDIATE GROWTH DATA
550 CO_2, FACE REP 2

ID	TRTNO	JEMRGD	JSQRJD	JFLRJD
MCM28902	01	111	140	166

NOVAR
13 1 2 3 4 5 6 7 8 9 10 11 12 13

JDOY	XPLTHT	XLAI	JNNODM	JNSQRM	JNFLWM	JNGBLM	JNMBLM	JNABSM	XWLEFH	XWSTMH	XWROTH	XWGBLH	XWMBLH
150	19.	0.23	67	0	0	0	0	0	282.0	175.4	-9.0	0.0	0.0
165	47.	1.17	102	0	0	0	0	0	804.4	705.5	104.6	0.0	0.0
179	72.	1.59	135	135	12	5	0	0	2274.3	1791.1	520.3	0.0	0.0
192	85.	2.35	116	80	13	76	0	86	1744.5	3159.1	755.1	1235.7	0.0
208	85.	2.74	160	23	13	171	0	88	1973.8	3059.6	830.3	4019.3	0.0
221	85.	1.90	127	7	1	130	3	75	2177.3	2676.0	838.7	5735.4	0.0
235	86.	2.71	170	11	0	109	68	59	2740.0	3671.9	1636.5	4316.4	4363.4
263	103.	2.23	206	27	3	62	140	84	3056.2	5440.1	2447.3	2058.6	7345.2

-1

FILENAME: MCM38903.CTB

MEASURED INTERMEDIATE GROWTH DATA
550 CO_2, FACE REP 3

ID	TRTNO	JEMRGD	JSQRJD	JFLRJD
MCM38903	01	111	140	166

NOVAR

13 1 2 3 4 5 6 7 8 9 10 11 12 13

JDOY	XPLTHT	XLAI	JNNODM	JNFLWM	JNMBLM	JNSORM	JNGBLM	JNABSM	XWLEFH	XWSTMH	XWROTH	XWGBLH	XWMBLH
150	19.	0.16	69	0	0	0	0	0	178.9	108.5	-9.	0.0	0.0
165	39.	0.55	60	0	0	0	0	0	415.3	327.8	86.1	0.0	0.0
179	59.	0.76	105	103	8	3	0	0	673.5	1098.0	629.4	0.0	0.0
192	80.	2.35	132	125	18	45	0	56	1898.9	2749.0	808.7	847.8	0.0
208	72.	2.47	157	33	23	121	0	55	1952.7	2579.3	665.4	3088.5	0.0
221	75.	2.43	182	12	3	151	2	65	2426.6	2240.4	991.5	6264.2	0.0
235	80.	3.19	176	82	2	116	69	82	3141.4	3802.9	1858.3	4837.0	4159.5
263	101.	1.77	209	50	4	42	111	94	2216.2	4514.9	2032.0	1314.5	5854.7

-1

FILENAME: MCM48904.CTB

MEASURED INTERMEDIATE GROWTH DATA
550 CO_2, FACE REP 4

ID	TRTNO	JEMRGD	JSQRJD	JFLRJD
MCM48904	01	111	140	166

NOVAR

13 1 2 3 4 5 6 7 8 9 10 11 12 13

JDOY	XPLTHT	XLAI	JNNODM	JNFLWM	JNMBLM	JNSORM	JNGBLM	JNABSM	XWLEFH	XWSTMH	XWROTH	XWGBLH	XWMBLH
150	23.	0.29	71	0	0	0	0	0	233.0	181.4	-9.	0.0	0.0
165	53.	0.94	112	0	0	0	0	0	892.2	782.7	177.4	0.0	0.0
179	67.	1.52	125	94	5	1	0	0	1380.9	1903.0	449.9	0.0	0.0
192	78.	2.19	138	111	33	80	0	49	1584.0	2725.2	610.1	796.2	0.0
208	76.	2.55	22	62	30	150	0	152	2242.0	2825.1	821.6	3867.1	0.0
221	77.	2.54	162	12	8	112	4	88	2494.4	3092.9	828.1	6737.8	0.0
235	79.	2.79	185	34	1	74	75	77	2771.3	3794.6	1854.1	3316.3	4402.3
263	102.	2.26	170	53	2	26	106	92	1820.9	4883.5	2198.2	480.6	5623.4

-1

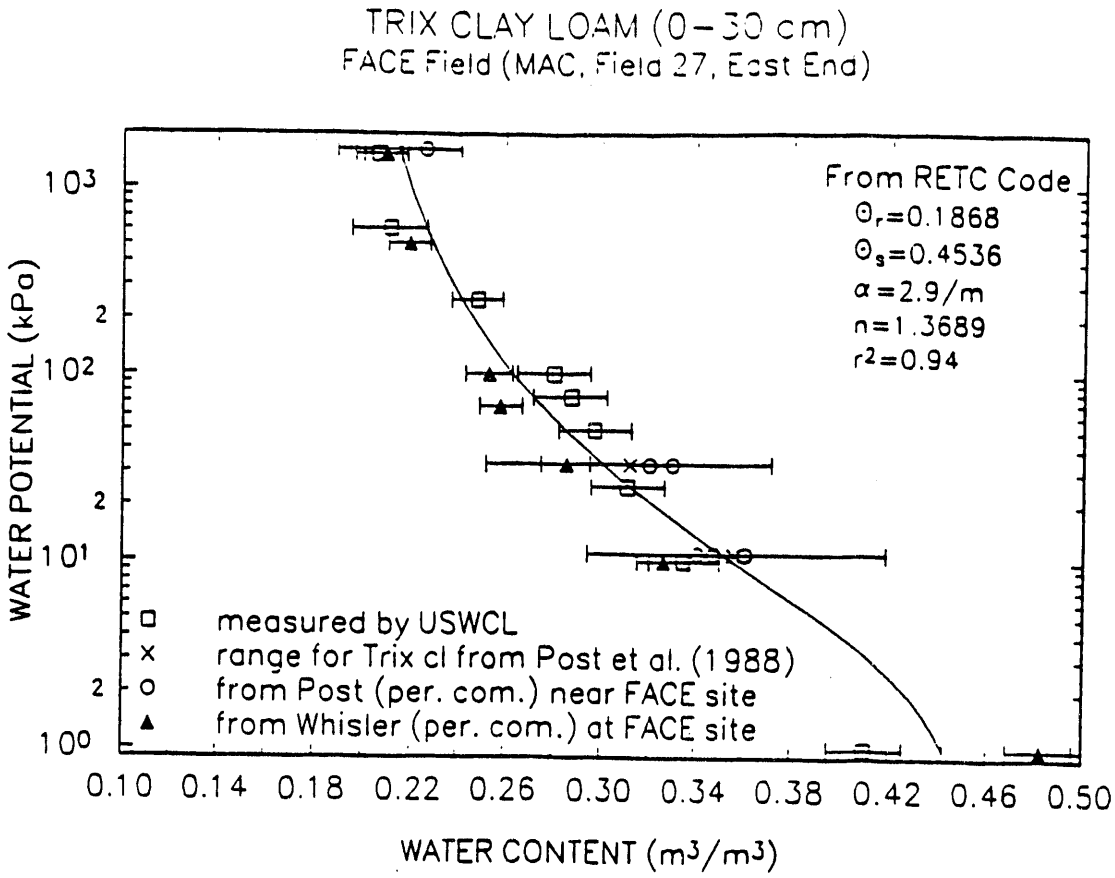


Figure II-B-1. Water retention curve for the surface 0 – 30 cm of Trix clay loam from the FACE field site at the University of Arizona, Maricopa Agricultural Center (east end, field 27). The curve was fitted using the RETC Code of van Genuchten *et al.* (1992). The main body of data were determined by USWCL personnel (160 points, about 18 per mean value, but with ALPHA fixed at 2.9/m). The indicated ranges for Trix clay loam are from Post (DF Post, 1990, personal communication) for sites close to the FACE field. Mean values of 8 points each were supplied by Whisler (FD Whisler, personal communication, 1992).

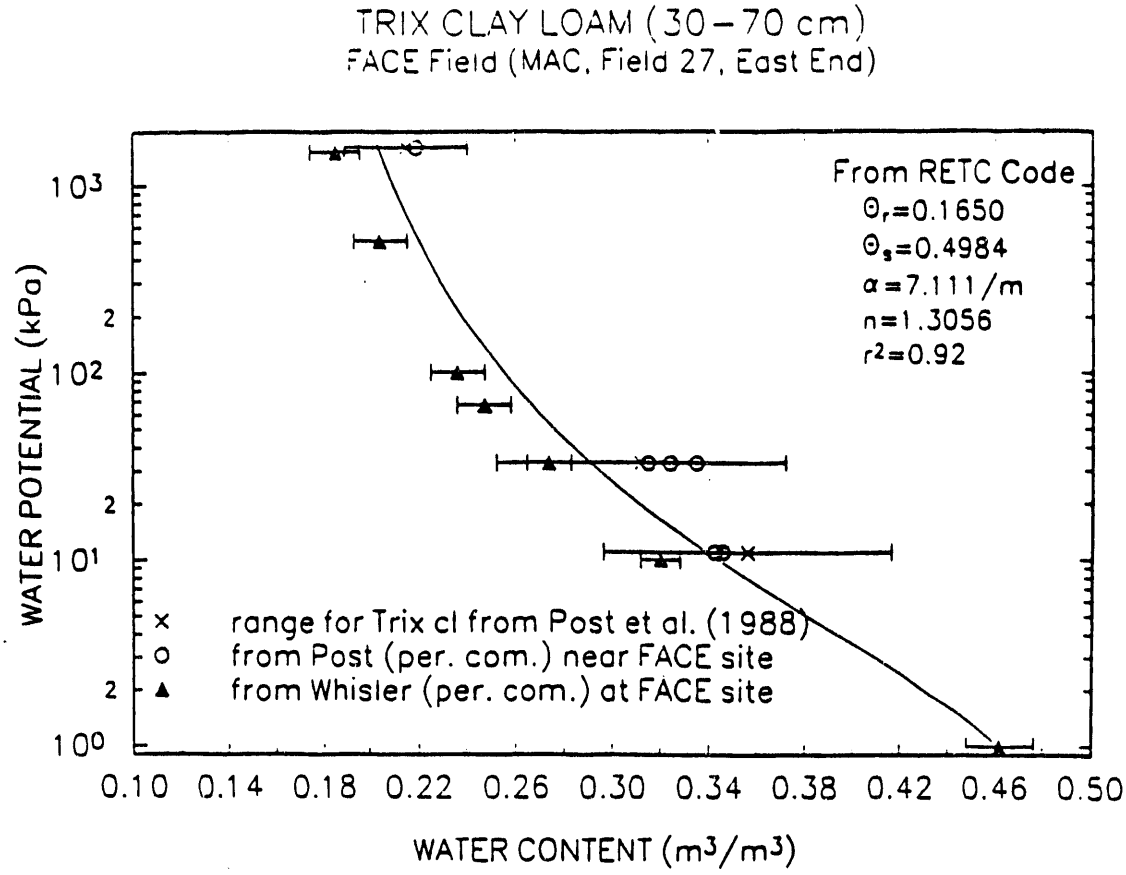


Figure II-B-2. Water retention curve for the 30 – 70 cm layer of Trix clay loam from the FACE field site at the University of Arizona, Maricopa Agricultural Center (east end, field 27). The curve was fitted using the RETC Code of van Genuchten *et al.* (1992). The indicated ranges for Trix clay loam are from Post *et al.* (1988), and the individual data points were supplied by Post (DF Post, 1990, personal communication) for sites close to the FACE field. Mean values of 8 points each were supplied by Whisler (FD Whisler, personal communication, 1992).

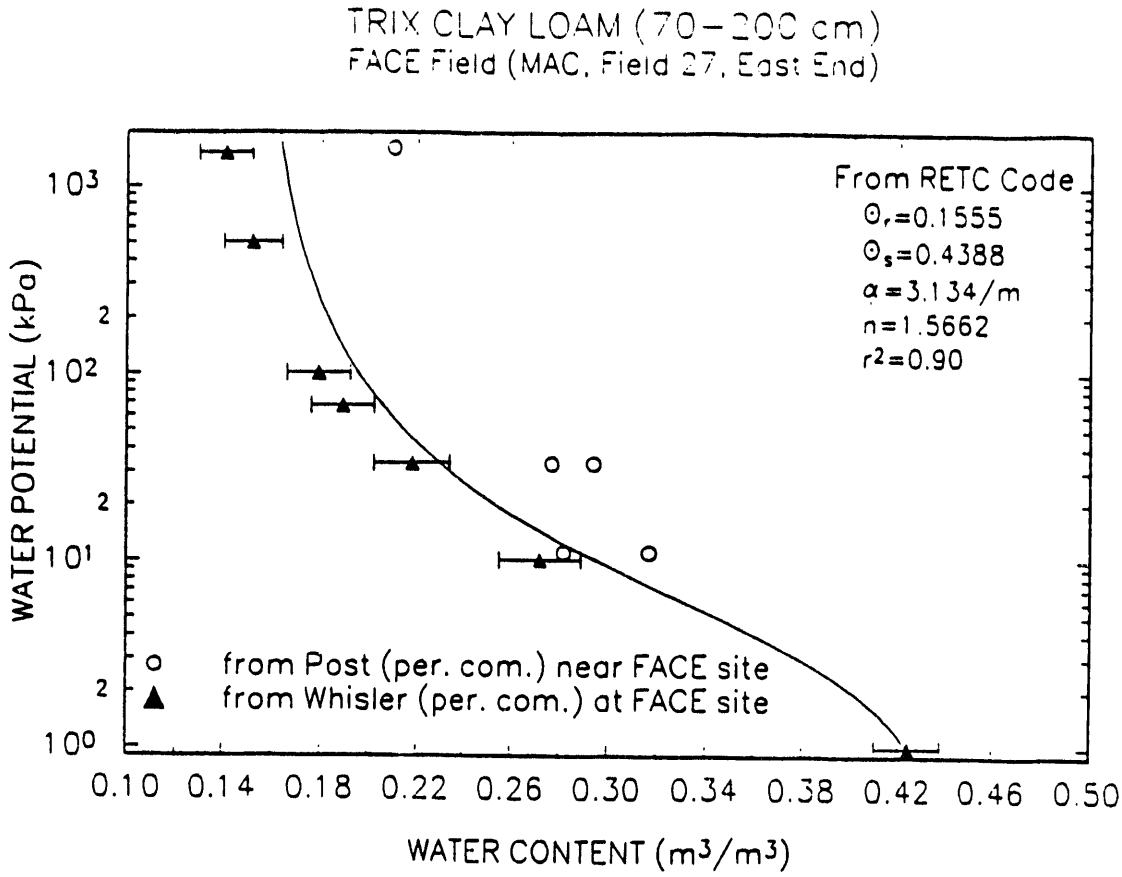


Figure II-B-3. Water retention curve for 70 – 200 cm layer of Trix clay loam from the FACE field site at the University of Arizona, Maricopa Agricultural Center (east end, field 27). The curve was fitted using the RETC Code of van Genuchten *et al.* (1992). The individual data points were supplied by Post (DF Post, 1990, personal communication) for sites close to the FACE field, and mean values (8 points each)came from Whisler (FD Whisler, personal communication, 1992).

END

DATE FILMED

4/6/93