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Changes in the Global Carbon Cycle and the Biosphere

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CHANGES IN THE GLOBAL CARBON CYCLE AND THE BIOSPHERE

Jerry S. Olson
Environmental Sciences Division

Helen A. Pfuderer
Ecological Sciences Information Center
Information Center Complex

Yip-Hoi Chan
Graduate Program in Ecology
The University of Tennessee, Knoxville

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OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37830
operated by
UNION CARBIDE CORPORATION
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PREFACE AND ACKNOWLEDGMENTS

This document is a progress report of Oak Ridge National Laboratory's continuing assessment entitled Global Carbon Cycles and Climatic Risks and is also one part of a progress report for the Department of Energy's National Coal Utilization Assessment. Previous phases of the ORNL studies of carbon cycles (Olson, 1963a, 1963b, 1970, 1974, 1975; Sollins et al., 1973; Reichle et al., 1973a, 1973b; Baes et al., 1976, 1977; Killough, 1977) evaluated the needs for combining new findings on the carbon cycle, the influence of CO_2 on climate, and the impact of climate change on the biosphere and on man. The present report emphasizes the interdependence of the biosphere and the physical pools of carbon in the global cycle. Initial mathematical simulations relating the changes of atmospheric CO_2 to forest clearing verify the importance of examining the impact of expanding human populations on the carbon cycle. Coping with the resulting feedback loop (carbon cycle → climate → ecosystems → society → carbon cycle...) constitutes one of the main scientific challenges of carbon/climate research.

The first draft of this report was a working paper for the Biological Effects Panel at the Conference on Global Effects of Increased Carbon Dioxide held in Miami Beach, Florida, March 7-11, 1977. The main conclusions of this report have been endorsed and elaborated on by that panel. Many individuals and groups have since been diagnosing the problem and concurring on the research which is still urgently needed to reduce some of the uncertainties about human impacts on the biosphere, CO_2, and climate change (e.g., Loomis, in press).

It is important that scientific research on all these aspects of the carbon/climate problem be integrated and that the strengths and weaknesses of data and models at all stages of investigation be evaluated as part of practical assessments of energy and environmental policies.

A few historic comments are necessary to relate the present study to other research efforts. The Terrestrial Production Section of the International Biological Program (the National Science Foundation's Ecosystem Analysis program) was partly devised as a start toward gaining preliminary ecosystem budgets and models so that a suitably aggregated biospheric model of carbon and mineral cycles could be developed (Olson, 1970a,b). The references just cited were the main basis for the SCEP (1970) Tables 2A1 and 2A2 that were used by Olson, Machta, Keeling, and others in their studies of CO_2 risk as a major concern for man's impact on the global environment and later by the Stockholm United Nations Conference on the Environment. The same analysis, with relatively minor adjustments and reiterated questions, was summarized with a growing sense of urgency by Reiners et al. (1973).

Much of the current literature besides that cited in the present report and by Baes et al. (1976, 1977) has been brought together in a bibliography by Olson, Allison, and Collier (1977). This bibliography was also used as a working document for the Miami Beach conference, and was used as well at subsequent workshops related to CO_2 and climatic change. The bibliography (with its computerized information file) and the present document summarize the literature used in our assessments. Continuing companion studies on radiocarbon and CO_2 are those of Killough (1977) and Olson and Killough (1977).

We particularly appreciate the encouragement and comments of S. I. Auerbach, W. Frank Harris, and other members of the Environmental Sciences Division at Oak Ridge National Laboratory. We are especially grateful to Linda Allison and to many other staff members of the Ecological Sciences Information Center, Information Center Complex, Information Division, Oak Ridge National Laboratory for aiding in the preparation of this report. Work was funded by the Technology Overview Division and the Environmental Impact Division of the Department of Energy, under contract with Union Carbide Corporation.

ABSTRACT

OLSON, J. S., H. A. PFUDERER, and Y.-H. CHAN. 1978. Changes in the global carbon cycle and the biosphere. ORNL/EIS-109. Oak Ridge National Laboratory, Oak Ridge, Tennessee. 169 pp.

Increases in atmospheric CO_2, risks of climatic change, and impacts from such change are reviewed. Needs for closer scrutiny of changes in organic carbon and in the patterns of the biosphere are explained. The organic carbon pool is considered here as a moderate source of CO_2, perhaps 1 to 3 Gtons/yr in recent years. The biosphere could become a net sink for CO_2 if it were managed optimally to minimize the future peak of atmospheric CO_2 and to maximize storage as well as production rates of organic carbon. However, this would require unequal shifts in rates of (a) net primary production, (b) return of organic carbon to CO_2, and (c) plant respiration. Global rates of a, b, and c, each estimated near 56 Gtons/yr, are much greater than ± net shifts of carbon to or from the atmosphere. These rates are much smaller than the 933 to 488 Gtons for the live pool in "woods" (forests, open woodlands, and thickets) that we estimate for times respectively before and after prehistoric and historic clearing. Live carbon in nonwooded landscapes has been a smaller pool than "woods", but could have increased historically (e.g., from 63 to 69 Gtons). Estimates of dead carbon are larger than those of live carbon (> 1000 Gtons in active circulation), but are even less certain. A review of human population trends, food production, and actual or possible biological production rates shows the pressures toward increasing usable biological products. However, doing this may enhance turnover rates, thereby decreasing the storage of organic carbon. A preliminary global computer model explores the implications of tropical and subtropical forest clearing as a nonfossil source of CO_2 as well as some limits on the biosphere's role as a potential sink. Because of these limits and the oceanic factors of carbonate buffering, slow physical circulation, and limited net sedimentation of carbon, models confirm that 4- to 7-fold increases of CO_2 could occur if projections of high fossil energy consumption were to materialize. Review of climatic changes does not support beliefs that cooling would become great enough to counteract the mean surface temperature rise of 2-9° C in 100 years. Changes in climate pattern, temperature, drought, and waterlevel, and in their varied biological effects, would interact to change success of crops, other ecosystems, and many social institutions. Unless the several uncertainties are resolved on the optimistic side, man will have to make profound economic and ecological adjustments, including contingency plans for energy and many natural resources.

INTRODUCTION AND PREVIEW

1.1 Introduction

The global carbon dioxide problem has resulted from input to the atmosphere of increasing amounts of carbon dioxide released by fossil fuel combustion and by the significantly increased oxidation of organic matter currently being produced by forests, soils, and other sources (Baes et al., 1976, 1977). These releases of CO_2 occur simultaneously with, and probably enhance, the photosynthetic absorption of atmospheric CO_2 by some terrestrial plants.

The possibility that trees and humus have been either net sources or net sinks for atmospheric carbon dioxide has thus become an increasingly important and controversial issue. The present assessment attempts to place this issue in historic perspective and to identify work that is needed to project future changes. Our data and simulation models, even at a preliminary stage, suggest that different parts of the biosphere may simultaneously be sources and sinks for CO_2. However, it is not yet clear just how these parts will respond either to the enhanced CO_2 itself or to climatic shifts.

It is now expected that changes in the earth's carbon cycle and in CO_2 concentrations will have a very high probability of significantly changing the climate. The ecological impacts resulting from altered climate may in turn affect man's life-support system. To further complicate the situation, ecological changes such as those outlined in this report would modify the carbon cycle in ways that further increase the release of CO_2.

The extent, intensity, and uncertainties about the effects of increased CO_2 therefore call for caution regarding the future policies on coal and other fossil fuels (Rotty and Weinberg, 1977). Coal use may have to expand temporarily to replace some uses of oil and natural gas. However, Niehaus (1976) and other analysts are prudent in cautioning about scenarios which assume protracted expansion of fossil fuel use with a slow decrease in rates only as the large geologic reserves of coal become significantly depleted.

Our much lower limiting scenario, which assumes a decrease in global CO_2 release within 50 years (Baes et al., 1976), would call for profound human adjustments if this scenario should prove necessary or even possible. Man will presumably seek an intermediate course between very high and very low bounds on the limits for future releases of CO_2. We shall want to become better prepared to anticipate and cope with the main implications of this choice.

The use of biomass could become a significant energy resource, especially if it were truly effective in moderating the use of fossil fuels. However, the increased use of biomass could also shorten the residence time of biospheric carbon. This in turn could have many impacts on nutrient cycles and on the integrity of ecosystems. Perhaps catastrophic repercussions of man's direct action on the biosphere could further complicate the indirect, fluctuating, and causally obscure impacts of the effects of CO_2 and climate on the biosphere.

If technological and agricultural releases of CO_2 continue their rapid increases, studies using several different carbon cycle models agree in suggesting the occurrence of a severalfold increase followed by a slow decrease in atmospheric CO_2. Under these conditions, experts anticipate a warming trend of several degrees C *despite the presence of various causes for cooling*. Such cooling influences would apparently be either much smaller or slower than the warming caused by increased CO_2. The warming trend might also be accompanied by less effective or less reliable precipitation over wide areas, even though some other areas may get wetter.

Models can be developed to examine the influence of these natural changes on feedback interactions among the atmosphere, biosphere, hydrosphere, and lithosphere. Figure 1-1 presents a world model which will be restated with equations and data in Chapters 2 through 4. Eventually, the improved individual models for each of the "spheres" will be dependent on one another, with the outputs from one unit being the essential inputs for the next.

Whatever combinations of climatic trends and fluctuations finally occur, their probable impacts on the biosphere and on man must be anticipated by new research and assessments. Linking specialized studies will require a better overall systems analysis of the problem (Young et al., 1972; Gowdy et al., 1975), explicit objective functions of operations research, and better data and more accurate functional relations for improving the models.

1.2. Preview

1.2.1 Objectives

It is too late to forestall the prospect of higher future concentrations of atmospheric CO_2. Clear increases are already being monitored around the world (see Fig. 2-1). Therefore, minimizing the future *excess*

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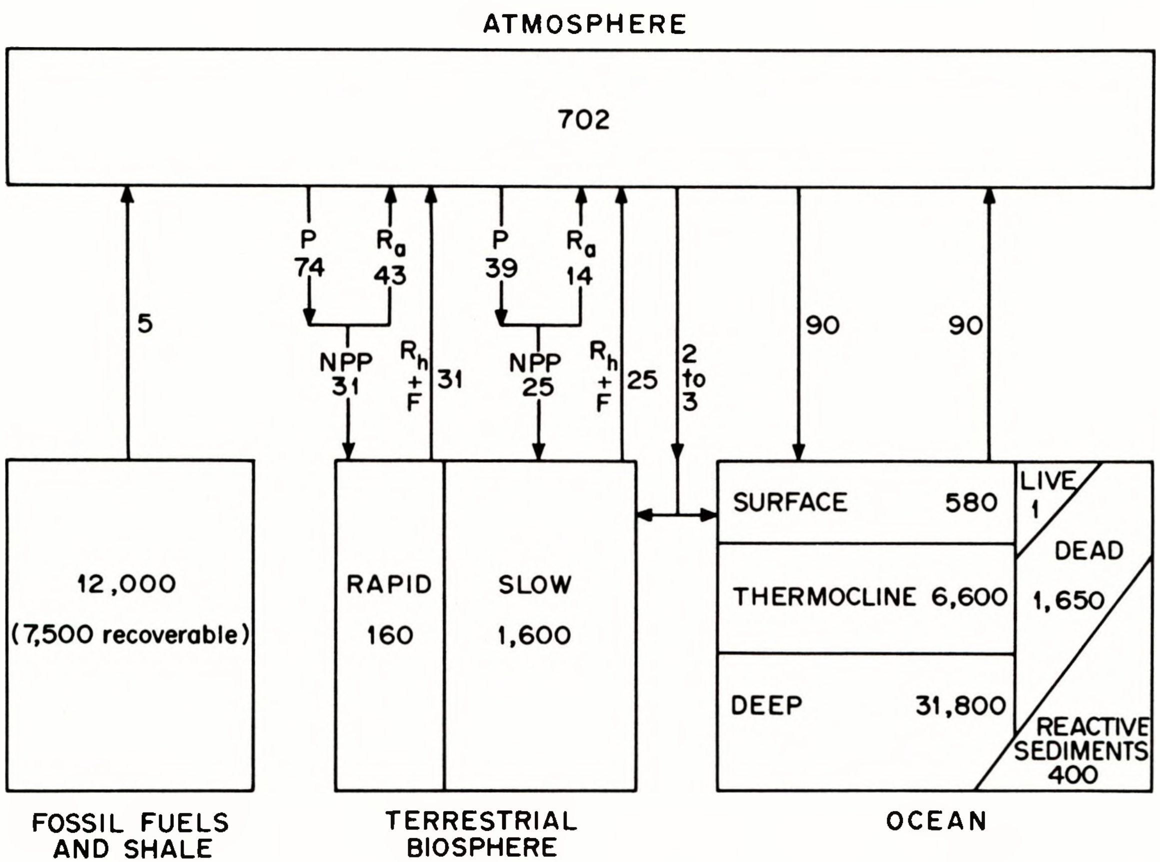

Fig. 1-1. Main pools of the earth's active carbon cycle (after Baes et al., 1976). Preliminary estimates in boxes are in gigatons (10^9 metric tons = 10^{15} g) of elemental carbon. Fluxes in Gtons/yr average rate are adapted from the Study of Critical Environmental Problems (1970).

CO_2 might conceivably become objective one of a concerted effort to preserve humanity's options for energy and natural resources. Maximizing biological production could become objective two for global management of the biosphere. However, if the biosphere is to help significantly as a mode of "waste disposal" of the excess CO_2 that will continue to be released while fossil fuels last, high *rate* of income (objective 2a) will have to be coupled with notably increased *storage* of the carbon fixed by plants in order to delay release back to CO_2 (objective 2b).

1.2.2 Global Models

Even under optimum conditions, the capacity of forests and soils may not be nearly sufficient to store the CO_2 released from the burning of fossil fuels at rates commonly extrapolated from past trends. Oceans have a greater storage capacity than land, but their response will be delayed by factors of chemistry (the buffer factor in carbonate systems), physics (slow diffusion and ocean circulation), and perhaps geobiology (constraints on carbonate and organic sedimentation).

Results from models combining terrestrial and oceanic subsystems with the atmosphere, driven by inputs of CO_2 from fossil fuels and from trees and humus, are generally consistent in suggesting that CO_2 will increase far above present levels.

1.2.3 Ecosystem Exchanges of Carbon

Increase instead of decrease or stabilization of rates of CO_2 release will follow from expanded human populations, despite disagreements of estimates of between 6 and 16 billion people or more by 2075. Clearing of forest lands for agricultural use has already taken most of the best land. Further clearing--of the more or less wild marginal lands--may soon pass points of diminishing economic return. Intensive agriculture for the purposes of higher net assimilation rates, higher leaf area index, and efficient conversion of net primary production to more usable products per unit area may even add to the growing commitment of fossil energy in agriculture for a while. However, we must also anticipate how to manage the biosphere when petroleum, gas, and even coal will be unavailable (too rare and/or costly) for as much mechanization in normal farming as is now used or is expected for the near future. Land areas now offering food and forest products will furthermore face competing demands for producing renewable biomass sources of energy. Thus, to judge the options available for both nonfossil and fossil energy, a better knowledge of ecosystems' carbon exchange (from all the methods of study to be discussed in Chapter 3) is clearly a high priority requirement for future study.

Recent assessments of existing biomass and of the organic carbon contained in plants, residues, and humus differ considerably. Estimates of area covered by ecosystem types and maturity classes, of amounts of carbon per unit area, and of exchange rates per unit time also require closer review and systematic refinement. Global summaries of Rodin, Bazilevich, and Rozov (1970) may approximate the preagricultural conditions more closely than recent conditions (Olson, 1974, 1975). Their estimates for the tropical forest and the figures of Whittaker and Likens (1973) (Table 3.1) seem high to us--both in area covered by forest and in carbon per unit area. Our estimates of biomass, which attempt to allow for much prehistoric and historic clearing (Table 2.2), may have to be adjusted downward still further as a result of improving survey data on forests and soils.

Our estimates of ecosystem production *rates* (as distinct from inventories of dry matter and carbon) from the citations above and in Table 2.2 generally fall within the range of the more recent estimates reviewed in several chapters in Lieth and Whittaker (1975) and in the International Biological Program syntheses which are still appearing. The needs for better methodology and geographic coverage are recognized by investigators of carbon cycles. General conclusions about the magnitude of ecological fluxes of carbon (positive and negative) might change considerably. But the net shift--the difference between income and loss--could change relatively more because this is a fairly small difference between large quantities.

1.2.4 Lessons from Models

Even with our present limited data on carbon inventories and exchanges, trial box models suffice to show some important bounds on recent changes of the global system. Because our estimates of the amounts of rapidly and slowly exchanging carbon in active circulation are lower than some others, our estimate (Baes et al., 1976, p. 23) of approximately 1 percent clearing per year of forest *areas* south of 30° N latitude gives moderate values of 1.2 gigatons (1 gigaton = 10^9 metric tons = 10^{15}g) extra carbon released fairly promptly from land clearing and about 2 more Gtons potentially released after additional time required for decay.[1] Could clearing at these rates have continued for many decades? Apparently not. The very preliminary simulations in Chapter 4 suggest that a rate of

[1]As this report was in press, Bolin (1977, Table 3) published an estimate based on some common sources of approximately 1 Gton/year for net current carbon release from nonfossil carbon and 70 Gton cumulative release of carbon since the early 19th century.

clearing this great could not have been occurring since 1860. Either forests, especially in the tropics, would have been depleted even more than we estimate (Table 2.2), or the 1860 forests would have had to have been far more extensive than that table indicates. Under such rapid clearing conditions, the atmosphere might have approached 800 Gtons of carbon in 1975 instead of the 700 Gtons actually observed (Table 4.6).

However, Table 4.6 also shows model results which suggest that the 800-Gton level (380 ppm by volume) may be reached before the end of this century (under widely differing assumptions of ultimate fossil carbon reserves: 5000 to 10,000 Gtons of carbon). Hypotheses following the approach of Keeling (1973) and Keeling and Bacastow (1977) suggest a continuing increase of CO_2 to 5 to 6 times the present level by A.D. 2160, *if* anthropogenic releases were to continue rising toward a peak release rate of 60 Gtons per year (12 times the current rate) by A.D. 2100 (Fig. 4-1).

Results in Chapter 4 are conservative in their projections of CO_2 concentration, insofar as they still allow for a severalfold increase in the storage capacity of both the rapidly and slowly exchanging pools of organic carbon (Fig. 4-2). The slow pool includes both trees and humus. Neither of these components is expected to increase as drastically as the initial model studies suggest. A major factor limiting storage of CO_2 as biomass is the human pressure for the growing and rapid harvest of food and of some biomass for energy (discussed in Chapter 3). Further examination would probably show that some carbon storage in nonforested systems is conceivable, *if* optimized worldwide management (e.g., humus-building agricultural practices for all crops, pastures, and rangelands;

desert irrigation; and protection of tundra and bogs) could be assumed. In the boreal and north temperate forests (hereafter called Northern Woods and defined as including forests, open woodland, and low thickets), bog forests may still be accumulating peat, yet forest clearing and reforestation (or natural succession) are sometimes assumed to be roughly in balance (Rostlund, 1956). However, in tropical, subtropical, and south temperate forests (hereafter called Southern Woods), clearing definitely prevails over forest establishment (Persson, 1974; Sommer, 1976). Thus, the estimate cited above (Baes et al., 1976, p. 23) for the nonfossil carbon release resulting from forest clearing and the simulation of clearing presented in Fig. 4-3 agree in suggesting that a rate of clearing as rapid as 1 percent per year could not have been continuing since 1860. However, if such a high clearing rate should occur in the near future, the reductions in carbon storage could have numerous substantial impacts on the biosphere's future productivity. The resulting trend would also decrease the capacity of trees and humus to maintain the storage and cycling of nitrogen and mineral nutrients. Such changes would grossly undermine the long-range recuperative capability of the important tropical and subtropical regions, even if the stress on their ecosystems was later reduced.

Figures 4-1 through 4-3 come from models in which we assume only a moderate positive response of organic carbon (β = 0.1 to 0.3 percent increase of net primary production of organic carbon for a 1 percent increase of CO_2) out of the broader range of values for β (0.0 to 0.4) which various authors have considered (see Table 4.5). The conservative estimate of β = 0.1 leads to limiting values for most organic pools near

1.5 x the initial values we assumed for 1860. A limit near a 1.5- or 2-fold increase in organic carbon storage also seems likely to be imposed by nutrients, water, and other environmental constraints (even if β could take on higher values such as 0.2 or 0.3).

1.2.5 Climatic, Ecological, and Social Consequences

The calculations in Chapter 4 imply an increase in atmospheric CO_2 and a high probability of warming the surface temperature, along with many other regional climatic changes. The changes emerging above the background of natural fluctuations by early in the 21st century or before can be projected only within broad bounds (Figs. 5-1, 5-2). The many ecological and social impacts that may follow can only be partly predicted now (Baes et al., 1976, pp. 43-49). Such impacts are very likely to include surprising interactions from such varied partial effects as the following:

(1) changes in biological products (both positive and negative) as production rates and respiration increase differently [Equations (2-3) through (2-6)];
(2) loss of effective moisture related to enhanced evaporation and perhaps to changed storm trajectories (and hence moisture input);
(3) hydrologic and shoreline changes (e.g., Fig. 5-3);
(4) many indirect biological changes; possibly including
(5) different effects on humans in the major global zones;
(6) controversial sociopolitical and moral issues which may arise (despite present complacency) long before the ultimate balance of benefits and costs or risks can be calculated by experience and system models due to the differences among social sectors, regions, and nations which will incur the risks (or benefits).

1.2.6 Conclusions and Recommendations

Responding to the questions posed at the beginning of Chapter 2, we say: oxidation of nonfossil carbon (e.g., by land clearing) could indeed have been significant, perhaps by a few tenths of 1 Gton per year in various centuries of human history, and possibly now exceeds 1 to 3 Gtons per year. But if these high rates apply, they could do so only for a *few very recent years* at most. The surviving ecosystems and the new agricultural systems have probably already helped to reduce part of the net excess CO_2 arising from this oxidation and from the burning of fossil fuel as well. The simultaneous net shifts in both directions, in different places, seem quite possible, adding to recent confusion on what the total net shift was or is. The likely short-term fluctuations from such terrestrial exchanges could add to the oceanographic fluctuations in shifting the fine structure of the global CO_2 records.

Having thus emphasized the essential needs for finer discrimination for future biospheric models, we must then concede that the present or probable future biosphere does not seem likely to have the capacity for storing the large amounts of CO_2 from the fossil carbon use which high-burning scenarios suggest. Constraints of the buffer factor affect net CO_2 uptake in the mixed layer. Diffusive and convective mixing through the thermocline or intermediate layers slow the removal to the deep ocean and sediments. Still, we must look to the ocean for the main (though lagging) storage following the atmospheric peak release shown in our models. Organic and carbonate sediments have storage capacities that are ultimately large, but apparently deposition rates will not help dispose of much of the man-made excess in the few centuries that are of most concern--when people still have large fossil carbon resources to exploit.

Quantitatively, however, we are not yet ready to set very narrow limits for either the biospheric exchanges or the partitioning of atmospheric loss between biosphere and ocean. The airborne fraction for fossil *plus nonfossil* CO_2 excesses may be nearer 0.4 or 0.35 than the often-cited value of 0.5, but it is not likely to become much lower for a very long time. Ocean changes are instead likely to drive this fraction upward from the present value.

Relating the biosphere to atmospheric CO_2 is therefore among the highest priorities now seen in carbon cycling research. Specific needs to be explained in the rest of this report include:

- an integrated model of, and data on, the organic production and turnover of carbon (living and dead) for a full range of turnover times;
- clearer insight, data, and quantitative models relating carbon budgets to temperature, moisture, nutrients, and other variables;
- carefully revised tables of ecosystem areas;
- carbon, nitrogen, and other nutrient inventories per unit area and their turnover rates for the main life zones of the earth;
- carefully coordinated use of remote sensing data to record the actual changes in ecosytem extent and process;
- integration of all of the above with carbon and radiocarbon budgets on a global basis;
- prompt integration of revised carbon models with climate models.

Both carbon and climate models will be needed as links between updated inputs (from fuels and society) and the ecological and socioeconomic effects. Only with lead-time research on credible impacts can the future assessments of alternative energy policies be made and updated on a timely basis.

It seems likely that mankind will continue in a high burning scenario until the importance, cost, and inequity of these changes become obvious to all. Increases of 3 to 5 degrees C might already be incurred or committed before society and technology at last start shifting toward a schedule of lowered burning of fossil fuels. A linear (not exponential) increase in release rate of 1 Gton of carbon per decade could possibly be tolerated until A.D. 2000 or perhaps 2025. By then, the scientific questions and the choices of alternative energy systems should be clarified enough to show whether continued expansion is permissible (or desirable) or whether CO_2 release should be kept constant or decreased.

Reflection on mankind's future options suggests the prudence of diminishing the total fossil carbon allocated for fuel use to well below the 5000- to 10,000-Gton level considered here (e.g., to 3000 Gtons or less)--even if the difficulty and cost of extraction do not force such a conservation of future chemical feedstocks. The above-mentioned linear increase of 1 Gton/decade implies a reduction in the *percentage* growth rate of CO_2 from the present 4 percent to 3 and 2 percent (by A.D. 2000 and 2025 respectively). This reduction could be helpful in preserving options until we understand carbon and climate well enough to judge the penalty affecting many regions from the possible climatic changes. Continued availability of fossil carbon is summarized by the shape parameter expressed in the exponent of the two schematic curves that summarize the time course of future carbon burning. In Equation (2-1) (below) after Rotty (1976, 1977b), the values of A preferably approach 4 or more. In Equation (2-2) after Keeling, values of n might preferably be decreased from 1 or 0.5 (Fig. 2-2) in the simulations in Chapter 4 to 0.1 or less (Fig. 6-1).

Either expression for future carbon use would combine a gradually lowered growth rate with the prolonged availability of fossil carbon reserves for many later generations. While this would diminish the climatic and ecological risks, we need to be assured that such lowered use of fuel would not entail intolerable economic and political penalties.

BIOSPHERIC OPERATIONS RESEARCH AND THE CARBON CYCLE

Over geologic history, the photosynthetic production of organic carbon compounds by green plants (autotrophic organisms) has been greater than the release of organic carbon by animals and microorganisms (heterotrophic organisms). If this had not occurred, the world would not have its present reserve of fossil fuels. For eons, however, the global average annual photosynthetic rates must have almost balanced rates of return to the carbon cycle by respiration and fires (Baes et al., 1976, pp. 8-10; Garrels et al., 1976).

Although animal energy, wood, and peat have supported technology for most of human history, the agricultural and industrial revolutions began releasing more CO_2 than the vegetation could fix. Since 1860, the accelerating release of ancient photosynthate by the combustion of fossil fuel has increased atmospheric CO_2. Its annual increases measured since 1958 approximate one-half the CO_2 released each year by fossil fuel combustion. However, the airborne fraction has varied in individual years, raising the questions: Could the biosphere account for a significant fraction of the CO_2 released *to* the atmosphere? Of the total uptake of excess carbon *from* the atmosphere? For the variations in either flux among individual years?

Marine chemists sometimes doubt whether the oceans could have accommodated the amount of the excess CO_2 not remaining in the atmosphere (Keeling, 1973a; Oeschger et al., 1975; Broecker et al., 1977; Revelle, personal communication). Geophysicists emphasize that physical circulation as well as chemical buffering may make the oceans even less effective in absorbing excess CO_2 in the future than they were during the past century (Baes et al., 1976). It is thus important to answer the question: What possible limits of biospheric exchanges and net shifts of atmospheric carbon can be inferred for the past and for the future?

This chapter outlines possible formulations of the carbon cycle and its main parts as a step toward an operations research model of the biosphere (Section 2.1). The observed changes in the atmosphere are reviewed in Section 2.2 as one reason for society to seek control over the excess atmospheric CO_2. Section 2.3 discusses the probability that future inputs of CO_2 to the atmosphere could make concentrations become far greater in the future than they were in the past. In Section 2.4, a closer look is taken at the terrestrial biosphere both as a source and as a potential net consumer (and regulator) of CO_2. Finally, the question is raised: What are the possibilities of coupling improved ocean models with models of the atmosphere and biosphere as steps toward a balanced global model of moderate detail--a benchmark model--useful for explaining the consequences of various assumptions about the earth's future?

2.1 Objectives and Objective Functions

The questions posed above can be restated in terms of a mathematical expression whose value will be altered (perhaps minimized or maximized) by decisions on energy policy, climate, food, and resource use. One objective of operations research of biospheric problems is to formalize these expressions as objective functions (i.e., as quantities that might ideally be optimized within certain constraints which nature and society place upon the earth).

However, a broader objective of biospheric management must be to maintain the orderly operation and flexibility of the system. As the availability of fossil fuels decreases, we shall need more, not fewer, renewable energy resources for packaging dilute solar energy in organic form to take the place of the fossil fuels. Future generations should be able to rely on a robust biosphere whose species and ecosystems can adapt to mankind's total impact. This will require at least as much diversity and local adaptability as already exist. If resilient ecosystems are not allowed to maintain themselves, many of the benefits received by mankind will become expensive or nonexistent (SCEP, 1970, pp. 113-166).

Thus, the biological survival of mankind and of balanced ecosystems is accepted as a prerequisite or constraint. But what specific objective functions should be singled out as the variables to be controlled by a strategy for management of the earth?

The first possible class of objective functions focuses on the atmosphere itself. Yet it is difficult to define an optimal world climate pattern. The controversies over weather modification (Hess, 1974) are reminders of the social and political resistance to establishing benefits for one segment of society at a cost or risk to another. Scientists must therefore examine possible consequences of global weather modification with a better systems analysis than is currently available.

It is already too late to maintain the atmospheric CO_2 at its pre-industrial level. Some continued increase in global CO_2 must be accepted, but how much? Other causes of minor climatic fluctuations, mostly beyond our control, also have to be accepted. However, the risks resulting from the severalfold increase of CO_2 that is now forseen seem to rise steeply as shifts of CO_2 and climate reach beyond all of mankind's experience.

One viable objective function for guiding an energy policy would be the predicted future peak value of CO_2. An objective of management could then be to minimize this peak, which is also likely to delay the time of peak level of atmospheric CO_2. Some use of fossil fuels will nevertheless continue until their depletion (or high cost) eventually results in lowering of the emission rates. Phasing in nonfossil energy supplies would include increased use of biomass, although evidently on a rather modest scale.

A second group of objective functions could shift the emphasis more directly to the biosphere itself and to its use by man. An optimal biological pattern may be even harder to define than an optimal climatic pattern. However, there is a theoretical and practical basis for using the rate of organic production of the biosphere as one possible objective function (i.e., as a rate variable to be maximized within the real world's constraints). Gross and net primary production (see Section 2.3) represent two measures of the potentially usable solar energy that is fixed by green plants. These upper limits might theoretically be increased some, but probably not very much. Actual production of various commodities (food, forest products, fibers, energy sources) involves only a fraction of the total net primary production. This fraction can be increased substantially--but only with expenditure of energy and money and with some possible risks of the biosphere's long-range integrity.

The *cumulative* storage of solar energy and CO_2 in organic matter and the total carbon accumulation in certain organic pools are still more pertinent variables to be maximized. These variables will be examined more closely below. However, before exploring what land and marine systems can do with CO_2, let us review the atmospheric changes already taking place and the inputs of CO_2 to the atmosphere.

2.2 Atmospheric Changes

The measured increase of atmospheric CO_2 averaged about 0.76 to 0.72 parts per million (by volume) per year from 1959 through 1968 at Mauna Loa, Hawaii, and at the South Pole, respectively, and over 1 ppm by 1974 (Figure 2-1). The nearly continuous record maintained since 1958 at Mauna Loa (19° N, well within the northern tradewind belt, and 3,400-m altitude) shows a regular annual variation in atmospheric CO_2 content of approximately 6 ppm (Ekdahl and Keeling, 1973; Pales and Keeling, 1965). Remarkably smooth and consistent data were obtained with a continuously recording gas analyzer, after correcting for local effects as described by Machta (1972), Miller (1974a, 1974b, 1975), and Keeling et al. (1976b). Data unavailable for certain days and months of this record were estimated from the least square fit of the data to a function of time which includes oscillatory and five polynomial terms.

South Pole data, obtained mostly from flask samples collected since 1957 (Keeling et al., 1976a), lagged behind the Mauna Loa trend by 0.5 ppm in 1960 to at least 1.6 ppm in the early 1970's. This fits interpretations by these authors and by Revelle and Suess (1957) that the observed increase is a part of the excess of CO_2 injected into the atmosphere from the combustion of petroleum, gas, and coal, mostly in the industrialized nations of the northern hemisphere. Extreme seasonal variations of 1.6 ppm (November high vs March low) were resolved into two harmonics with amplitudes of only 0.46 and 0.09 ppm.

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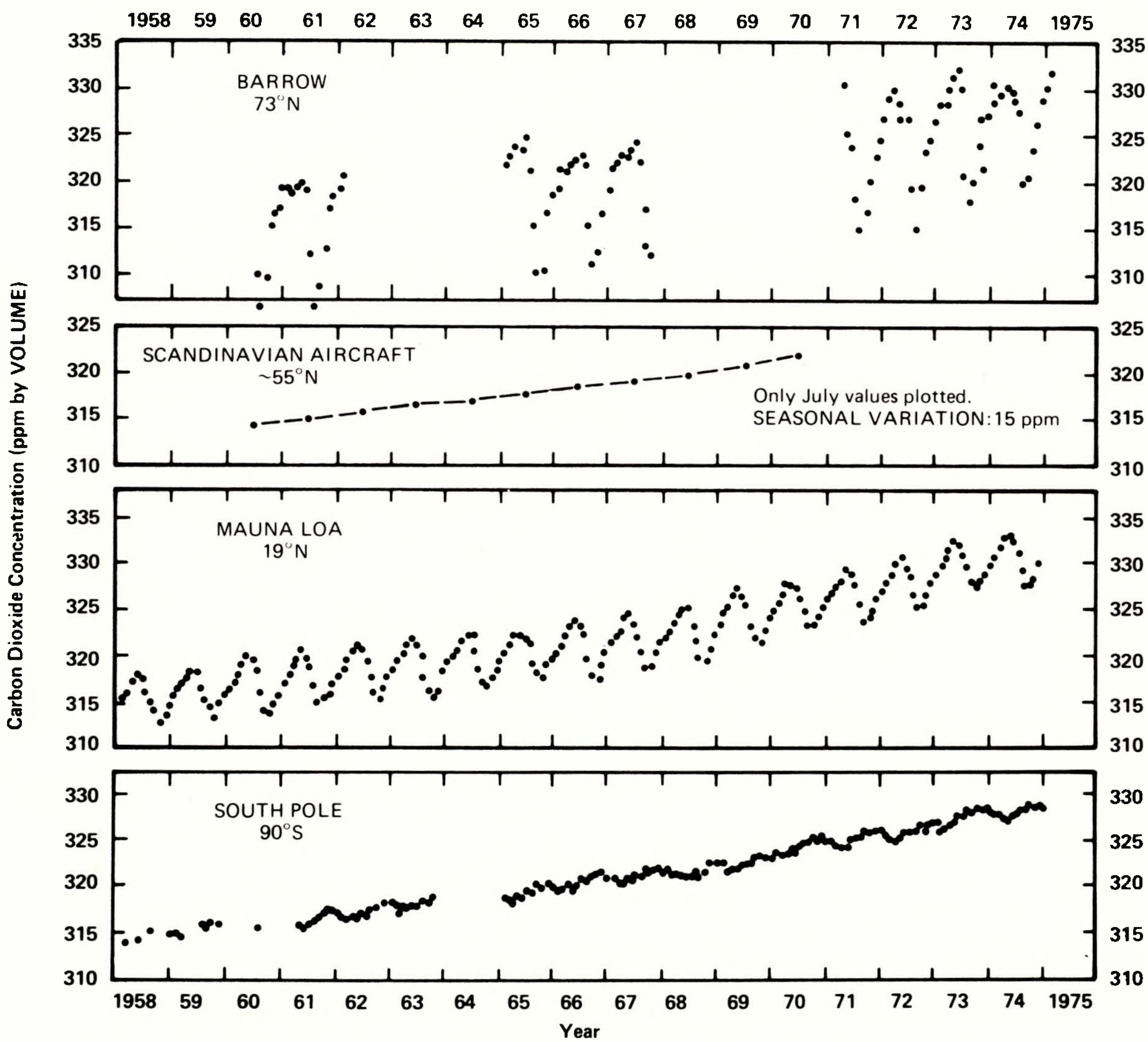

Fig. 2-1. Atmospheric monitoring for carbon dioxide (from Machta, Hanson, and Keeling, 1977).

Shorter records from Point Barrow, Alaska (73° N) and from Scandinavian aircraft (Kelley, 1969; Bolin and Bischof, 1970; Bolin, 1975) show similar mean trends. Ground-level seasonal ranges are higher--commonly 15 ppm (Northern hemisphere: maximum in spring and minimum in late summer). Oscillations damp out with a monthly lag at an altitude of 10 km and a much longer lag at 11 km (average stratosphere altitude), with only 0.7 ppm average seasonal amplitude.

The seasonal variation in atmospheric CO_2 has been attributed principally to seasonal changes in net photosynthesis and respiration of the biosphere (Bolin and Keeling, 1963; Olson, 1970; Lieth, 1970; Junge and Czeplak, 1968; Machta, 1972). Purely physical and chemical processes, altered by winds and by annual variations in sea surface temperature and heat storage, may contribute to the seasonal oscillations and to the total flux from the atmosphere in all latitudes. Useful bounds can be put on net fluxes to the land and to the ocean by having both coupled with an atmospheric model.

2.3 Anthropogenic Inputs of CO_2 to the Atmosphere

Keeling, Rotty, and others have given relatively close attention to revising the United Nations statistics on the release of CO_2 from fossil fuels and carbonate minerals. Only preliminary estimates are available on increased anthropogenic releases of CO_2 from contemporary (nonfossil) energy (e.g., from wood burning and from the accelerated oxidation of other recently fixed organic matter).

2.3.1 CO_2 Releases from Fossil Fuels and Cement

Estimates of the President's Science Advisory Committee (Revelle et al., 1965) were updated by the Work Group on Energy (SCEP, 1970, Table

7.1) and by Keeling (1973b). Refined oil fuels were used instead of crude oil which contains asphalt and petrochemicals which do not all return CO_2 to the atmosphere. Rotty (1973, 1977a) and Baes et al. (1976) made several refinements and included the flaring of gas from petroleum fields as well as later data from the United Nations (1975), which included 1973 data and 1974 estimates. Rotty (1977b) extended estimates through 1976.

The burning of limestone ($CaCO_3$) to make quicklime (CaO) and cement was included by Rotty as a minor (2 percent) adjustment to the fossil fuel figures. However, Niehaus (1975) suggested that this refinement be omitted because the action is quickly reversed as soon as cement and mortar are used.

Extrapolations to the future are recognized by all as hazardous. Our SCEP (1970, Table 7.A.2) projections reached only to 1980: 26.0 Gtons/yr of CO_2 produced. Multiplying by 12/44 gives 7.09 Gtons/yr of carbon released as CO_2.

In January 1976, Rotty cautiously compared several complementary CO_2 estimates for A.D. 2000. Fuel use trends suggested that 14.4 Gtons/yr of carbon would be released as CO_2. Energy use projections, with and without fast expansion of nuclear power, suggested 8.2 to 11.2 Gtons/yr. Life style projections separately treated (1) United States (a conservative 100×10^{15} British thermal units); (2) "centrally controlled economies" (249×10^{15} Btu); (3) other industrialized nations--mostly north of 30° N latitude (135×10^{15} Btu); and (4) developing countries--mostly south of 30° N latitude (206×10^{15} Btu). Together, these imply a carbon release of 13.3 Gtons/yr. A slightly finer subdivision of these large geopolitical units is now being suggested by Rotty (1977b), with very tentative extension to 2025 A.D. (Table 2.1).

In order to project peak consumption of CO_2 and the pattern of decline as the resource is depleted, Rotty (1976, 1977b) used the expression for rate of change of CO_2 as

$$\frac{dN}{dt}\frac{1}{N} = R\left(1 - \frac{N}{N_\infty}\right)^A , \qquad (2\text{-}1)$$

where

N = cumulative release by time t,

N_∞ = hypothetical limit for all recoverable fossil fuel,

R = early percentage growth rate (0.043),

A = a parameter which can be *increased* to make early use slow and to allow long-term supplies to taper off more slowly.

A related formula used by Keeling and Bacastow (1977) and others in the National Academy of Sciences (1977) review of energy and climate gives

$$\frac{dN}{dt}\frac{1}{N} = R\left(\frac{N_\infty^n - N^n}{N_\infty^n}\right) \qquad (2\text{-}2)$$

$$= R\left(1 - \frac{N^n}{N_\infty^n}\right) ,$$

where n = a parameter which can be *decreased* to make early use slow and to allow long-term supplies to taper off more slowly. In Baes et al. (1976, Figs. 8 and 9), the Keeling formula [Equation (2-2)] was illustrated but α was used instead of n. Equation 11 of that report is the classic logistic case encompassed by both Equations (2-1) and (2-2) when their respective exponents are 1. The policy implications of switching from a high growth scenario of past trends to a lower growth scenario will be discussed briefly in Chapter 6.

TABLE 2.1. Estimated Emission of Carbon as CO_2 by Segments of the World (Gigatons C per year, after Rotty, 1977).

GEOGRAPHIC AREA	1974 Percent	1974 Gtons		2025 EXTRAPOLATION Percent	2025 EXTRAPOLATION Gtons
USA	27	1.32	1.42	8	2.08
Canada	2	0.10			
USSR	16	0.78	1.22	27	7.04
Europe, planned econ.	9	0.44			
Asia, planned economies	8	0.39		19	4.95
Western Europe	18	0.88		7	1.82
Japan	6	0.29	0.34	3	0.78
Australia, New Zealand	1	0.05			
Developing					
Asia	4	0.20	0.65	36	9.35
Mid East	3	0.15			
Africa	2	0.10			
America	4	0.20			
TOTAL	100	4.87		100	26

A companion report by Killough (1977, sec. 3.2 and Table 5.1-1) discusses the Keeling formula [Equation (2-2)] and its coupling with historic carbon fuel production data (his Table 3.1-1), and also retains the exponent n = 1 in sample calculations. Killough's purpose was to provide a conservative estimate of the dilution of radiocarbon by inert CO_2. Thus, a relatively low assumption was made--3080 Gtons carbon for N_∞, which he labeled P_∞--for the ultimate cumulative release of fossil-fuel carbon. The results below consider a credible upper boundary (10^4 Gtons carbon) and more plausible intermediate values. However, we use values of n = 0.5 in Chapter 4 and suggest n = 0.1 in Chapter 6 to characterize a fossil fuel policy that would not force mankind's use of this unique resource to drop as abruptly as it has risen (Fig. 2-2). Nonfossil carbon is clearly more important relative to the lower estimate of ultimate fossil carbon resources and especially for slow exploitation rates for energy than it would be relative to high reserves exploited at the highest conceivable rates.

2.3.2 CO_2 Releases from Land Clearing

Based on hypotheses discussed in Baes et al. (1976, pp. 21-24) and further explained in Chapter 3, we suggest that at least one extra Gton/yr of carbon may be undergoing release as CO_2 relatively quickly by fire and by rapid decay due to the accelerated clearing of certain forests to pasture and cropland. Furthermore, the clearing process puts some of the organic material originally having relatively slow turnover rates (e.g., living trees and stable humus) into a category more susceptible to rapid decay. The estimate of 2 additional Gtons/yr in this category adds an extra *commitment* each year of carbon to be released at an accelerated

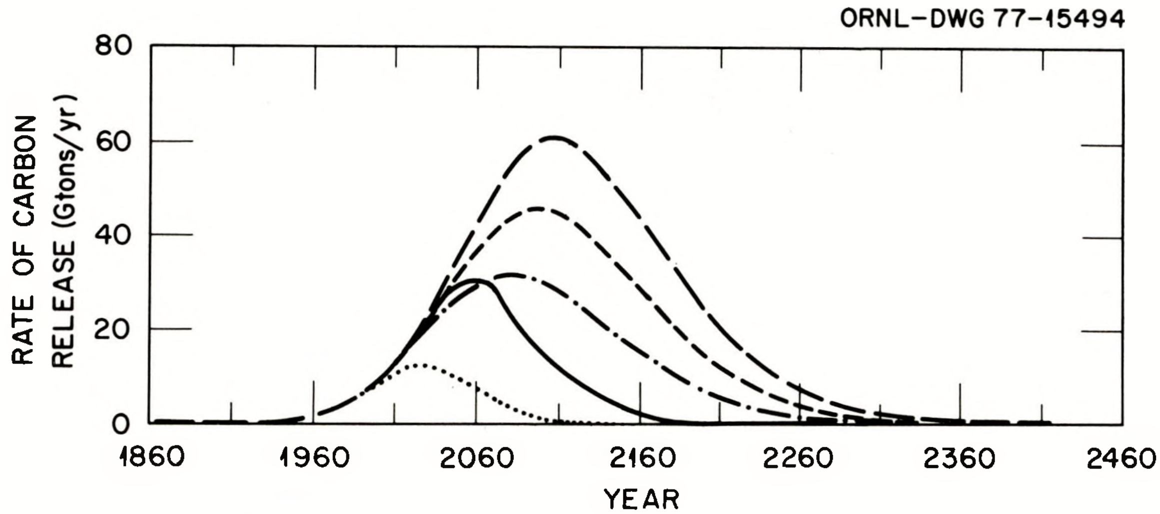

Fig. 2-2. Scenario hypotheses about rate of carbon release from burning fossil fuels, assuming very high (10,000 Gtons), high (7,500 Gtons), or medium (5,000 Gtons) consumption before depletion and cost bring energy use of fossil fuel back to low levels [n = 0.5 in Equation (2-2)] for upper broken curves; solid curve is for a low ultimate release (3,080 Gtons) but a relatively more abrupt rise and fall (n = 1), after Killough, 1977; dotted curve is for a very low maximum release at A.D. 2025 (ultimate release near 520 Gtons, n near 1, after the low scenario of Baes et al., Figs. 10, 11).

rate over the next few years. If these estimates are correct, their sum implies that 3 Gtons/yr of carbon will eventually have been added to the atmosphere as CO_2, even though the delayed part may not yet have had time to show the result of each year's most recent forest clearings.

Compared with fossil fuel releases of approximately 5 Gtons/yr in the mid 1970's, the addition of 1, 2, or 3 Gtons per year seems significant. Specifically, it affects our concept of the "airborne fraction," which was expressed as slightly over 50 percent in terms of the *fossil* fuel release of carbon *alone*:

$$\frac{\text{observed atmospheric increase}}{\text{fossil fuel (and lime) release}} = \frac{2.6}{5} = 0.52.$$

If we are still near the beginning of accelerated forest clearing, an appropriate denominator is at least nearer 6 than 5, and the airborne fraction[2] of promptly released carbon in a given year is no higher than

$$\frac{\text{observed atmospheric increase}}{\text{fossil, lime, and early forest release}} = \frac{2.6}{6} = 0.43.$$

If the accelerated forest clearing is confirmed to have been underway for several years, and if the estimate of 2 *additional* Gtons/yr for delayed release is anywhere near correct, then the concept of the airborne fraction will have to be revised to be nearer one-third than one-half:

$$\frac{\text{observed atmospheric increase}}{\text{fossil, lime, and total new forest release}} = \frac{2.6}{8} = 0.33.$$

If net release of nonfossil carbon from part of the land has a value >0, then the oceans and the rest of the lands together have already been

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[2]Since this report was prepared, Bolin (1977) reviewed some of the uncertainties about the actual releases of CO_2 due to expanded kindling use, forest land clearing, and soil humus oxidation and concluded independently that the airborne fraction may fall in the range of 40 ± 5 percent of the combined fossil and nonfossil releases.

taking up more of the total anthropogenic carbon than was thought possible, even when practically all of this input was considered to represent fossil fuels alone!

2.4 Terrestrial Organic Pools and Exchanges

How has the excess of CO_2 which is not still airborne been disposed of? Closer examination of the normal unperturbed cycle of carbon and its isotopes is necessary to answer this question. Scientific viewpoints have changed from an assumption of geophysical (ocean) dominance of world exchange to assumptions (perhaps exaggerated) of major roles of terrestrial vegetation.

Probably both processes will eventually be judged to be significant. Marine processes seem to dominate reactions having time scales of millenia and stability over millions of years (Garrels et al., 1976). Terrestrial pools may be as important as the oceans for exchanges and net trends over decades and centuries. Attention to these time scales is most urgent for our proposed energy policy on fossil fuel burning. This conclusion is suggested by inferences about pool size, fluxes, and turnover fractions which are summarized briefly (and tentatively in Baes et al., 1976, 1977) and in the following sections.

2.4.1 Terrestrial Pools

Recent estimates of the amount of organic carbon *circulating actively* in terrestrial ecosystems range from 1530 to 2420 Gtons. The higher figures in this range are from Russian sources (Bazilevich, 1974a, 1974b) and are based on ecosystem patterns that omit changes brought about by agriculture. The Russian figures were modified by Olson (1970b, 1974) to approximate conditions existing during the period following natural revegetation of previously glaciated territory but before clearing of forest for agricultural use during the Neolithic, Bronze, and Iron ages (Olson et al., 1974). Lower estimates of 1760 Gtons (Baes et al., 1976, Table 1) or 1580 Gtons (a minimum from SCEP, 1970, Table 2.A.1) are preferred for the mid-20th century. The difference, 800 to 900 Gtons, is one estimate (one-third of the preagricultural pool) for possible releases made by mankind over several thousand years. This *rate* represents a small fraction of the 1-plus Gton/yr net release estimated in Section 2.3.2 for current or near-future land clearing.

The estimate of 1760 Gtons of organic carbon includes approximately 1600 Gtons of carbon with a relatively slow turnover rate (averaging decades before it is returned to the atmosphere as CO_2)[3] and approximately 160 Gtons with a rapid turnover rate (a few years or less before return). Both estimates are revised upward from SCEP (1970, Tables 2.a.1, 2.a.2), but the relative increase is greater for the rapid pool (labeled "short" turnover in SCEP) than for the slow pool (labeled "long"). These and other estimates are discussed below and in Chapter 3 (see also Baes et al., 1976, pp. 12-25).

Table 2.2 elaborates slightly on the breakdown of wooded and non-wooded ecosystems by Olson (1970a, Table 3). This breakdown was used by the Carbon Work Group of SCEP (1970, pp. 160-166) and by Keeling (1973, Table 7). Rodin et al. (1970, 1975) and Russian maps of the world (Senderova et al., 1964; Olson, 1970b) provide a tentative basis for estimating the preagricultural extent of major ecosystem groups. We still

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[3]Total organic pools may be substantially higher, if they include carbon that is relatively slow in its circulation (e.g., residence time of ~1000 years or longer).

Table 2.2. Estimated Partitioning of Terrestrial Ecosystem Area Trends, Organic Carbon Pools, and Production Rates

Reservoir	Estimated Area (10^6 km^2)			Estimated Carbon Pool								Net Primary Production (Gtons yr^{-1}) 1970 estimate[h]		
	Preagri-cultural[a]	1860[b]	1970[c]	Live				Dead[e] Gtons	Total Gtons	Rapid[f] Gtons	Slow[g] Gtons			
				Preagri-cultural[a]	1860[b]	1970[c]	ktons[d]/km^2					Rapid[f]	Slow[g]	Total
1. WOODS COMPLEXES														
A. Boreal + Temperate														
Boreal(taiga)	10.10	9.5	9	101	88	81	9							
Semiboreal	6.91	5.6	5	64	48	40	8							
Cordilleran	3.77	3.5	3	68	61	45	15							
Other cool temperate	3.76	3	2	68	33	20	10							
Warm temperate	5.76	4.2	3.8	108	57	38	10							
Semiarid	3.83	2.5	2	25	15	10	5							
Arid moistland	1.07	0.4	0.2	13	2	1	5							
TOTAL	35.2	28.7	25.0	447	304	235	(9.4)							
SUBTOTAL N of 30° N			24		284	226		384	610	70	540	10	8	18
(excluding S of 30° N: add below)			∼1		20	(∼9)								
B. Tropical + Subtropical														
Wet site, rainforest	4.56	4.3	3.3	84	68	60	18							
Other tropical moist	8.83	7	5.3	216	126	90	17							
Montane, seasonal	1.18	1	0.5	38	16	6	12							
Montane, humid	2.42	2.2	2	60	26	20	10							
Arid moistland	0.32	0.2	0.1	3	2	1	10							
Woody savanna, scrub	14.05	13	11	139	91	77	7							
TOTAL	31.36	27.7	22.2	540	329	254	(11.4)							
SUBTOTAL S of 30° N			∼23.2		349	263		307	570	50	520	11	9	20
WOODS TOTAL			∼47.2	987	633	489		691	1180	120	1060	21	17	38
2. NONWOODS COMPLEXES														
Agro-urban[i]														
Crops	0	5	12		4	12	1							
Fringe area,[j]	1	3	7	2	6	14	2							
Buildings, etc.[k]	0	1	3		0	0	0							
		9	22		10	26	(1.2)							

Table 2.2. (Continued)

Reservoir	Estimated Area (10^6 km^2) Preagri-cultural[a]	1860[b]	1970[c]	Estimated Carbon Pool: Live Preagri-cultural[a]	Live 1860[b]	Live 1970[c]	Live ktons[d]/km^2	Dead[e] Gtons	Total Gtons	Rapid[f] Gtons	Slow[g] Gtons	Net Primary Production (Gtons yr^{-1}) 1970 estimate[h] Rapid[f]	Slow[g]	Total
Other Land														
Tundra-like, bogs	13.53	13	12	21	17	12	1.0							
Grasslands	22.96	21	20	31	21	14	0.7							
Desert, semidesert	29.35	30	29	9	15	17	0.6							
	65.84	64	61	61	53	43	(0.7)							
NONWOODS TOTAL	67	73	83	63	63	69		511	580	40	540	10	8	18
EARTH minus water, ice			130.2			557		1203	1760	160	1600	31	25	56
3. LAKES, RIVERS (including reservoirs)	3		3.1			0.03		60?	60?		60			
4. GLACIERS	15+		∿15			0.0								
EARTH minus oceans			148.3											
5. OCEANS	350+		361.8			1		1650	1651	2	1649			
						558		2913	3471	162	3309			
EARTH TOTAL			510.1											

[a]After Rodin, Bazilevich and Rozov (1970), and Olson (1974, 1975).

[b]Very preliminary judgement of forest clearing before and after 1860 (subject to revision).

[c]After Olson (1970a, and new estimates).

[d]1970 estimate only; previous values higher; parenthetical averages are weighted.

[e]Dead of relatively active dead pool, probably excluding significant amounts of peat (histosols) and other resistant humus (estimated as having residence time near or greater than 1000 years).

[f]Includes materials with a probability distribution of fairly short residence times (such as living and dead stages of leaves, flowers, fruits, small roots, most animals, and their unstable residues.

[g]Most woody parts of live plants and dead residues having residence times averaging many years.

[h]From SCEP, 1970; includes photosynthesis minus respirations of all live plant parts; subject to revision.

[i]After Ryabchikoff (1975).

[j]Fringe areas include decorative and wild vegetation, abandoned fields, roadsides, and other more or less vegetated areas around towns or other settlements.

[k]Relatively unvegetated areas in towns or industrial areas, mines, quarries, highways, and other disturbed areas besides agricultural fields.

have only rough approximations of each system's extent in 1970 after part of the area had been eliminated by agriculture, building, etc. Estimates of Whittaker and Likens (1973; see Table 3.1) for 1970 are generally higher than ours and may substantially approximate conditions *earlier in the historic clearing of the tropics.*

Grouping of boreal and temperate zones (which the cited Russian authors call "subboreal" and "subtropical") vs tropical and subtropical zones (in the ecologist's sense) was adjusted slightly in Table 2.2 to approximate the wooded areas north of 30° N ("Northern Woods" of Baes et al., 1976, pp. 13-15; Table 1) and south of this arbitrary line ("Southern Woods"). The term "Woods" should be interpreted as including not only closed and tall forests, but also open woodlands, secondary (immature) forests, and some tall scrub which may have scattered trees (Olson, 1970c). A patchwork of these and of the nonwoody types which may be interspersed with larger stands represents the "typical" vegetation of a forest region. Such sparser, shorter, and immature stands should be included in the average representing the extended and varied area of a whole region. This average would always represent a lesser pool than if the fully matured stands of a given ecosystem type extended over the totality of the region characterized by that type. Allowances for such "dilution" of forests and for the advanced stage of clearing already reached are reasons why Olson's estimates of living carbon are lower than most others.

The areas estimated for 1970, the amounts of carbon in live organisms per unit area (kilotons/km^2 = kg/m^2), and their products (Gtons of carbon) are still preliminary estimates and need to be updated on a national or continental basis. Estimates of dead carbon, and hence, of total carbon, are presented only for the broadest pools of the biosphere until a more systematic review of carbon (and nitrogen) in the world soil types can be made (e.g., Bohn, 1976).

Efforts to divide the total organic pool between materials with rapid recycling to CO_2 [what SCEP (1970, Table 2.A.2) and Keeling (1973, Table 6) called "short" residence time, as organic carbon in live *or* dead form] and slow recycling ("long" residence time before return to CO_2) are still in a preliminary stage. Our estimates reflect the dominance of trees as a delay stage in both of the Woods pools and of the more resistant organic humus compounds in all three pools (Nonwoods and 2 Woods). Residence times up to 1000 years (turnover $k < 10^{-3}$ yr^{-1}) were suggested as an arbitrary delimitation of the land's *mobile* carbon pool. The soil part is $\sim 10^3$ Gtons. It seems likely that an additional pool of immobile carbon (i.e., with slower turnover) in soils plus incipient fossil carbon in buried soil profiles, deep peats, and certain other sediments might be one to three times as large (Bohn, 1976). Mean residence time of this carbon exceeds 1000 years, but may nevertheless be much less than that for most organic matter in geologic sediments.[4]

2.4.2 Production

Until better data are available, the SCEP (1970) estimates of annual photosynthetic production will be retained. These slightly augmented estimates by Olson (1970) were used by Machta (1972), Keeling (1973), and Reiners et al. (1973, Tables 1 and 2). Slightly different estimates reviewed in Chapter 3 seem to reflect some convergence toward substantially

[4]W. H. Schlesinger (1977) estimated a soil pool near 1.5×10^3 Gtons, but agreed that part of this may belong in the relatively immobile pool.

higher rates than those cited in early geochemistry textbooks (e.g., Goldschmidt, 1958).

Total photosynthetic fixation of carbon converts quanta of solar energy to more organic matter than is necessary to grow plants and support animal life (Monsi and Saeki, 1953; Olson, 1964, 1975). More rigorous studies of the biophysical ecology of different habitats (along lines illustrated in Gates and Schmerl, 1975) are required to determine why the quantum efficiency of vegetation is of the order of only 1 percent, and why such a large fraction of captured solar energy and CO_2 is returned to the air by respiration of the various parts of green plants (Loomis and Williams, 1963). The return is an inescapable tax on production, either immediate, as in the photorespiration of some species (Zelitch, 1971), or delayed for a fairly short fraction of the organic matter's total duration (Olson, 1964, Equations 1 to 6). Various expressions (e.g., Olson, 1975, Equations 1 to 3) are still concerned with the *difference* between photosynthesis and the various forms of respiration of green plants, defined as

Net Primary Production = gross primary production - respiration of green plants,

or simply $$NPP = P - R_a \quad , \qquad (2\text{-}3)$$

where

P = gross primary production (often labeled GPP), or photosynthetic fixation of carbon per unit area of ground, integrated over time, and

R_a = respiration of green parts of plants + respiration of other parts of green plants per unit area over time $[(t - t_o) = \Delta t]$.

Equation (2-3) is one objective function which may have to become maximized (within certain genetic and environmental constraints) in the process of natural selection among competing species of populations. For example, communities of compatible species may have been sorted out to increase the net production over a year's time (e.g., by seasonal time phasing or other divisions of the limited resources in a given unit area or habitat type).

Growth analysis, initially for crops and then for other simple communities, has focused on the rate of change of Equation (2-3) during the growing season. The term "net assimilation rate" (NAR) involves this *rate* concept and is conventionally expressed as a rate *per unit area of leaves* (or of other photosynthetic tissue). Hence, NAR must be multiplied by the appropriate photosynthetic area per unit of *ground* area for an alternative expression for the derivative of Equation (2-3):

$$\text{NPP rate} = \frac{d(\text{NPP})}{dt} = \text{NAR} \times \text{LAI} \quad , \qquad (2\text{-}4)$$

where

NAR = rate of net primary production of whole plants per unit of photosynthetic area, and

LAI = Leaf Area Index, or ratio of foliage (or other photosynthetic tissue) area to ground area, a dimensionless quantity.[5]

In terms of natural or crop selection, NPP and its current rate can be optimized by enhanced efficiency of the photosynthetic machinery (NAR) or by a structure of the vegetation allowing more layers, and perhaps more light, to be effective over a longer part of the total annual cycle.

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[5]Total photosynthetic surface is divided by approximately 2 for flat leaves to give one-sided leaf area and by ∿2.2 for conifer forest canopies to give horizontally projected photosynthetic area of all canopy layers (J. Franklin, personal communication).

One advantage of forests in regions where carbon in plant tissue (Cp) can be carried from one favorable growing season to the next is that carbon dissolved in the sap of plants (Cs) can be deployed into (and then stored from) the photosynthetic leaves over a deep canopy column. Thus, the carbon dioxide in the air (Ca) in close proximity to these leaves is greater than that for a low crop or grass cover (Baumgartner, 1969). Baumgartner's illustrative calculations of these quantities for high forest, in terms of CO_2 equivalent per m^2, were:

	Cp	Cs	Ca	
High Forest	30,000	2×10^{-2}	0.2	gCO_2/m^2
Grass	200	5×10^{-3}	3×10^{-3}	gCO_2/m^2

Greenhouse experiments might lead us to expect some enhanced photosynthetic response as the CO_2 concentration increases in the world atmosphere in those habitats where limiting factors like water and nutrients allow. Lemon (1977) explained why the magnitude of such response is likely to vary greatly among species, circumstances, etc. Other findings (see Chapter 3) convince us that the percent response in growth will not be as great as the percent increase in atmospheric CO_2 (see 4.2.3). But the ratio β between these quantities is likely to vary between 0.1 and 0.4. Thus, closer attention to this ratio is required in order to estimate the effectiveness of plants in absorbing excess CO_2. Fspecially, the problem of applying experimental findings to extended areas in the field seems crucial for better modeling of this response.

2.4.3 Return of CO_2 to the Atmosphere

The first paragraph of this chapter noted that net primary production from green plants [Equations (2-3), (2-4)] tends to be regulated so that there is a near balance with the opposing processes of heterotrophic respiration and fire, integrating over a suitable period:

$$NPP \;\tilde{=}\; R_h + F \quad , \qquad (2\text{-}5)$$

where

R_h = Heterotrophic respiration (by fungi, bacteria, and animals), and

F ≡ fires from natural processes (lightning), deliberate use of wood and charcoal, and other deliberate or accidental burning by man.

Each species' secondary production (via food chains that depend on plants), and ultimately R_h, which expresses that species' respiration, could be considered as objective functions to be optimized from the standpoint of consumers of food. For these consumers, fire is merely a wasteful short-cut in the return of CO_2 to the atmosphere, and as such, competes with consumers and decomposers for each year's photosynthetic raw material.

For particular human consumer groups, foods and fuels [parts of both terms on the right of Expression (2-5)] are among the fluxes which each group tries to maximize--by minimizing flows along competing pathways (e.g., food to pest animals, disease, decay, and nonuseful burning). The foods and fuels favored vary according to the society in question.

Expression (2-5) is not precisely an equality when there is an accumulation or a net loss of some particular components, C_i, in an area. The expression for rate of change of C_i is

$$\frac{dCi}{dt} = \dot{P} - \dot{R}_a - \dot{R}_h - \dot{F} \; . \qquad (2\text{-}6)$$

Here, the dots indicate that appropriate income and loss terms for the area are expressed as instantaneous changes [the derivatives of Equation (2-3) and Expression (2-5) when these are expressed as cumulative functions of time, as by Olson, 1964].

The solid arrows in the global models shown in Fig. 1-1 and 2-3 represent a nearly balanced flow system. Net primary production [Equation (2-3)] is first assumed to be balanced by losses [Expression (2-5)] over a year or for a several-year period, even though there are fluctuations within and between years. For example, it is the temporary storage of terrestrial organic matter in Northern Woods, crops, other grasslands, and tundra (mostly north of 30° N) which draws down the atmospheric carbon pool each summer: that is, Equation (2-6) is positive for three to four months each summer in very high latitudes (tundra, taiga) and perhaps up to approximately six months at intermediate (temperate) latitudes. To compensate, Equation (2-6) gives a negative net rate of CO_2 exchange when photosynthesis drops below the average level of respiration plus fire which continues the remainder of the year. At low latitudes, the alternation of wet and dry seasons along with minor temperature fluctuations may also allow certain organic components (C_i) to accumulate seasonally, but the income and loss terms are both large throughout the year, and their difference is comparatively small.

Mankind seeks to maximize income and to shift the fluxes to his favored products. He also stores commodities and delays the return of their carbon to carbon dioxide (e.g., by burning or rotting of waste after the period of commodity use and disposal). Food products typically have rapid turnover in both primitive and industrial societies (Fig. 2-3). Forest products also include many commodities with rapid turnover (like paper) and wastes, but some fraction of lumber and chemical feedstocks can be deliberately added to the storage pool with slow turnover (e.g., in buildings). The latter pool actively counteracts the buildup of CO_2

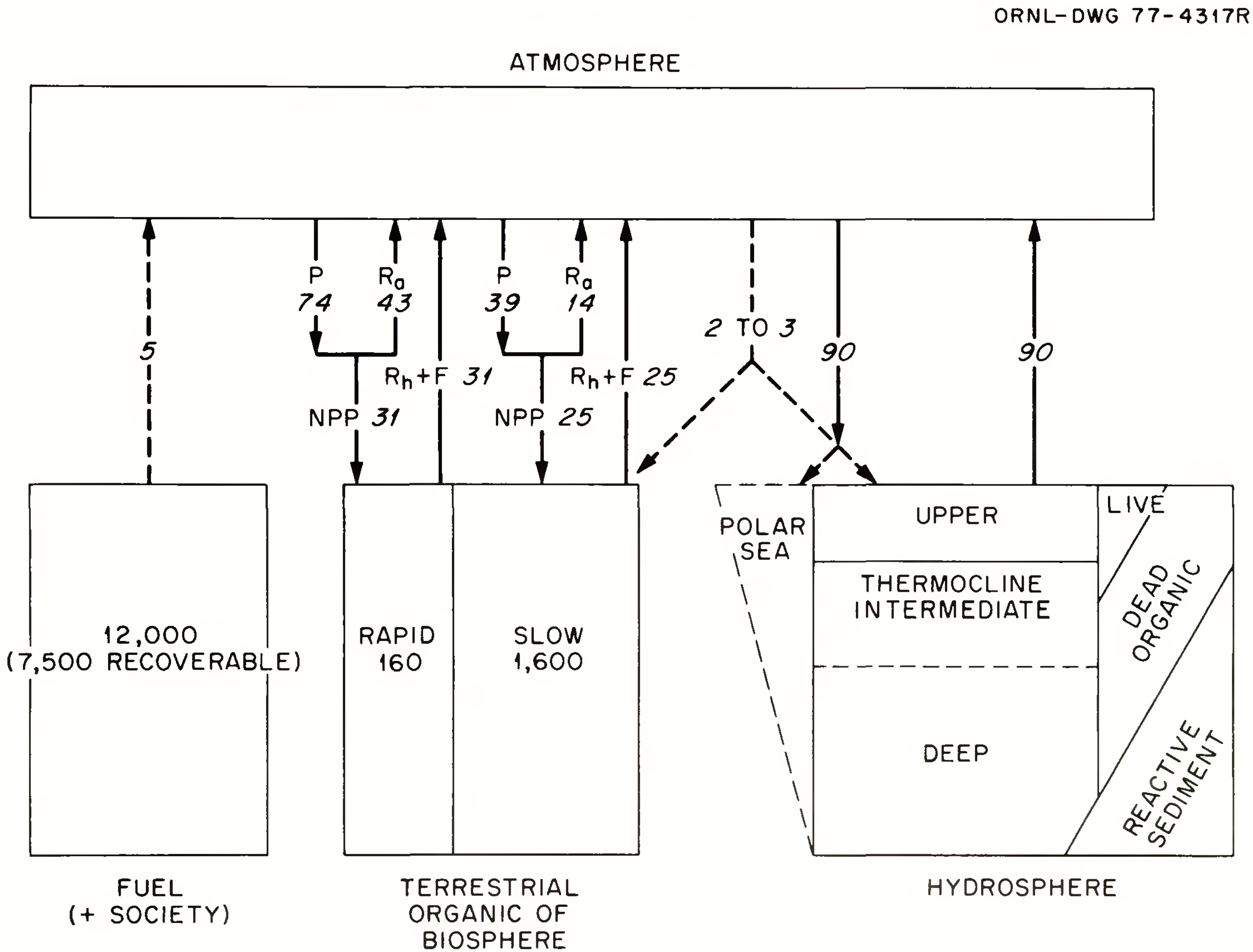

Fig. 2-3. Conceptual model of global carbon cycling: elaboration of the ocean to include a separate polar sea from which water flows to deep and intermediate layers.

in the atmosphere. Energy products with short residence time may be passively helpful, but only if they really decrease the consumption rate of equivalent fossil fuel and thereby stretch out the total duration for use of fossil fuel reserves. They do not add significantly to storage.

Some prospects for buildup (long-term storage) of organic matter in at least part of the world will be explored in a schematic way in Chapter 4. These allow for varying hypotheses about the shift in net intake of organic carbon, possibly stimulated by the "CO_2 fertilization" that is discussed in Chapter 3. Before turning attention to those topics, however, it is necessary to round out the schematic global model shown in Fig. 2-3.

2.5 Ocean Models

In order to complete a benchmark model for global carbon cycling, the atmosphere must be coupled with the hydrosphere as well as with the organic pools of the biosphere. The hydrosphere and its sediments evidently have a greater ultimate capacity than the land for storing excess atmospheric CO_2. However, there are several reasons why this capacity may not be effective soon enough to avoid a large peak in excess atmospheric CO_2.

2.5.1 Box Models of World Oceans

Early models of Revelle and Suess (1957), Craig (1957, 1958), and others summarized by Stuiver (1973) made a first approximation that divided the ocean into an upper and lower layer. The upper layer, called the mixed layer because the turbulent and other exchanges here tend to average out the carbon and radiocarbon content, approaches a fairly close approximation to a balance with the atmospheric CO_2. The so-called "deep" layer exchanges carbon after a lag (Broecker and Olson, 1960; Broecker et al., 1971), because mixing across the intervening gradient of temperature (thermocline) and salinity (pycnocline) is inhibited in the warm areas of the ocean. Bolin and Eriksson (1959) and Keeling and Bolin (1968) treated the mathematics of the two-layer ocean in contact with the atmosphere. (The atmosphere is mixed promptly in comparison with the lags inherent in the ocean, and may be treated as one or more pools.) All these authors emphasized the importance of the buffering of the carbonate system in seawater. This system limits the amount of excess atmospheric CO_2 which can come to equilibrium with the ocean. Keeling (1973) and Bacastow and Keeling (1973) present lengthy reviews and development of mathematical approaches to the problems of oceanic exchange. Broecker et al. (1971) and Baes et al. (1976, pp. 25-28) provide briefer summaries of the chemistry involved. Killough (1977) incorporated a time-varying buffer factor in model equations adapted from Keeling:

$$\text{flux air to mixed layer} = F_{am} - k_{am} N_a \qquad (2\text{-}7)$$

when

$k_{am} = 1/\tau_{am}$, and

τ = value of mean residence time that would hold if the ocean were the only (or main) means of uptake.

The flow of CO_2 from the atmosphere to the ocean is very nearly proportional to the mass of carbon in the air. The return flow from the ocean to the air is modified by the chemistry of the inorganic-organic carbon reactions (and also by some other solutes like boron) in a way that limits the partial pressure and the ultimate amounts of uptake by the sea. Values near 10 for the buffer factor ζ introduce one lag in the uptake in the mixed layer. Additional lags arise from the time for redistribution of excess CO_2 to deeper layers where it could be stored or perhaps (in part) precipitated.

Keeling (1973) and Bacastow and Keeling (1973) inferred that the terrestrial organic pools may already have a significant share in storing part of the excess CO_2 that is not still in the atmosphere. These authors further suggested that one alternative to the difficult task of monitoring biomass change directly would be to first use physical grounds to estimate the transfer coefficient k_{am}, the Suess effect (dilution of radiocarbon by excess CO_2 from fossil fuel whose ^{14}C has decayed away), and other parameters of the model. Then, if the resulting model values were appropriate (e.g., τ_{am} = 7 years; τ_{md}= 1500 years for effective exchange time between mixed and deep ocean; effective size of mixed layer N_m/N_{ab} = 2), preferred values of the Suess effect would suggest that terrestrial organic carbon had a net increase of β = 0.3 percent per 1 percent increase in atmospheric CO_2 (Keeling, 1973, p. 321). The following discussion suggests a number of improvements in the ocean model which should accompany further exploration of the terrestrial biosphere.

2.5.2 Discrete or Diffusive Thermocline

Broecker et al. (1971), Broecker and Li (1970), Baes et al. (1976), and others have reviewed some of the reasons for including the thermocline as a distinct part of the ocean model. Oeschger et al. (1975) provided the most detailed discussion and analytical solution for doing this by treating vertical diffusion as a continuous process. They also approximated the gradient of the thermocline by a sequence of many thin (25-meter) boxes between depths of minus 75 m and minus 1000 m. A computer program combining their approach and Keeling's treatment of the terrestrial organic compartments is explained by Killough (1977).

A compromise in detail, allowing for five layers of the thermocline (each 185-m thick), provides almost the same behavior as the 37 layers of 25 m each. The true deep ocean (below 1000 m, instead of below the mixed layer) is retained essentially as Oeschger et al. provide: 560 m in each of five layers of deep ocean.

For simplicity, the computer simulations in Chapter 4 still retain the box model without this treatment of diffusion. A hybrid approach combining the latter with more detailed treatment of the terrestrial biosphere seems to be the next step.

2.5.3 Marine Biosphere

The foregoing discussion acknowledges the complication of carbon moving from the mixed layer into marine plants by photosynthesis [Equation (2-3)] and then into animals, microorganisms, and particles which may settle by gravity into deeper waters. The extended discussion of organic and carbonate settling (Broecker, 1974; Craig, 1970) was reviewed briefly in Baes et al. (1976) and is beyond the scope of the present summary.

An estimate of 1.5 Gtons carbon for live organic matter in the world ocean (larger than 1 Gton carbon in Baes et al., 1976, but much smaller than the values of Bolin, 1970) is accepted in Chapter 4. The dead organic matter could be divided into various categories according to digestibility and particle size (and settling). An optional breakdown by the ocean layers (mixed, perhaps thermocline, deep) is suggested in Fig. 2-4.

2.5.4 Polar and Intermediate Water

Stuiver (1973) and Broecker (1974) have reviewed the long series of attempts to make models reflect the "shortcut" which radiocarbon (and tritium) seem to follow in certain ocean areas of high latitude. For example, the "outcrop" model (Craig, 1958, et seq; Broecker et al., 1971, Fig. 11.3) allowed direct atmospheric contact with a part of the cold ocean which comes to the surface in some winters in places like the Greenland Sea. This contact provides an opportunity for either CO_2 or ^{14}C to mix not only with surface waters but with much deeper waters as well, that is, when winter chilling and ice freezing at the upper surface weaken the gradients of temperature and salinity so that the whole water column can "overturn" or get stirred deeply by strong storm winds.

Broecker (1974) explains and illustrates how such water acts as a source for solutes moving horizontally southward through the deep Atlantic waters, then around Africa (primarily) to Pacific and Indian Deep Waters (PIDW). The latter waters show the greatest radiocarbon age because of the delay in horizontal transport and the inhibition of vertical mixing across the thermocline.

Bolin (1975a) provides only a preliminary formulation of time lags in schematically reflecting this water mass movement. His scheme starts with a distinct "Polar Ocean," either limited to the small areas of overturn, or representing a larger geographic center of the world. Broecker and Olson (1960) also treated the Arctic and Antarctic oceans separately, before seeking to simplify the total number of pools and fluxes (Broecker and Li, 1970).

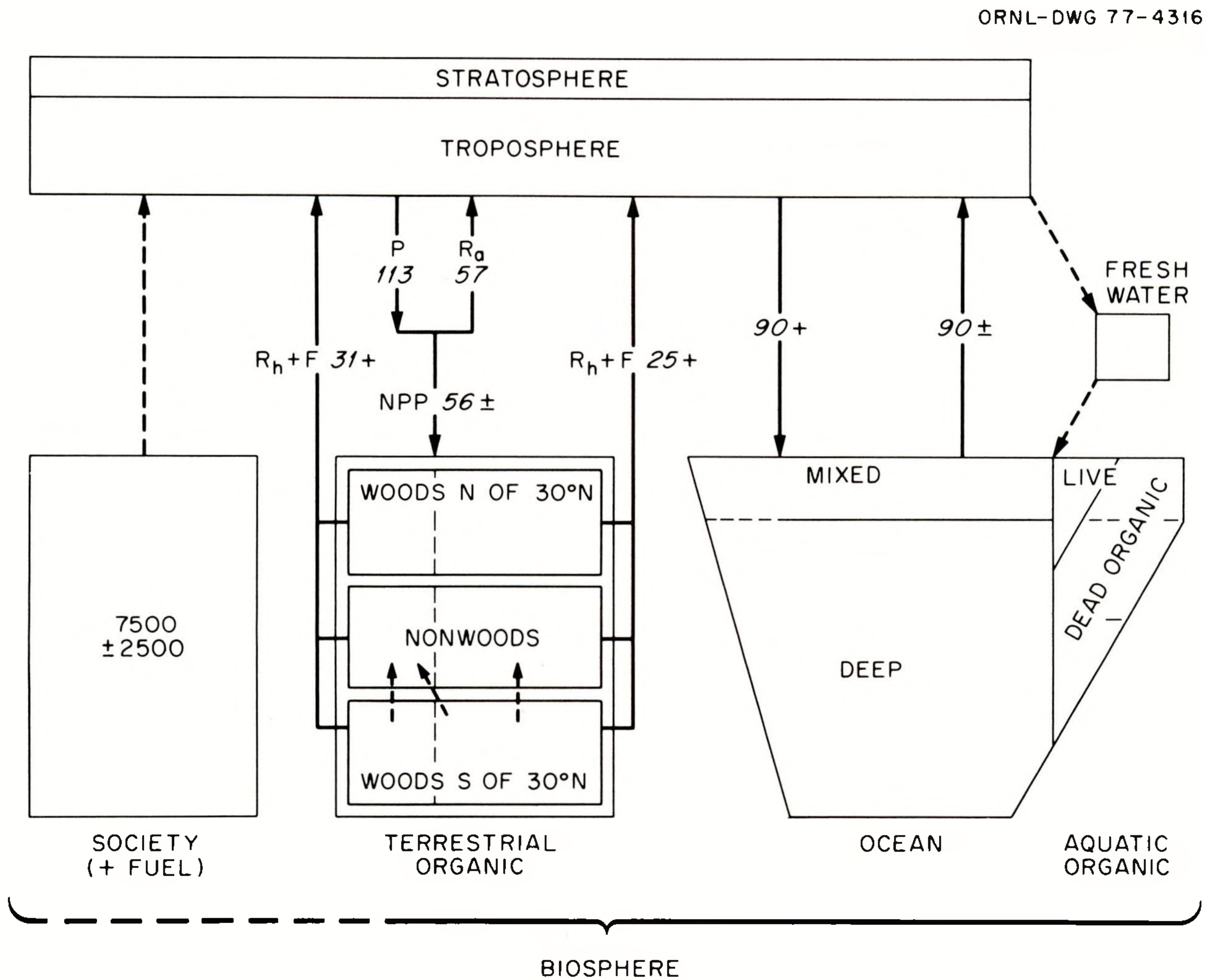

Fig. 2-4. Conceptual model of global carbon cycling: elaboration of terrestrial organic pools to show areas of wooded and nonwooded ecosystems and (diagonal arrow) transfer of trees and some humus from slowly exchanging pool (right side of terrestrial organic) to rapidly exchanging pool (left side).

Bolin (1977b) reviews the complexities of physical circulation in the real ocean and of general mathematical expressions for the physical and biological processes which are to be combined in modeling the transfer of carbon through the ocean. He builds on contributions of Keeling and Bolin (1967, 1968) for very tentative estimates of carbon and phosphorus fluxes between warm and cold surface waters and deep sea water, and suggests that phosphorus enrichment due to human pollution of coastal waters may enhance the capabilities of marine organic matter and sediment for removing some of the excess carbon reaching the surface waters from the atmosphere.

2.5.5 Sediments and CO_2 Disposition

Many of the references cited above and in Chapter 4 consider some sedimentation of inorganic or organic carbon as a part of the larger global geologic cycle. Additional chapters in Andersen and Malahoff (1977) examine many technical points regarding this cycle in general, carbonate dissolution, and the obvious importance of sediments in the long-term cycling (e.g., Pytkowicz and Small, 1977; Broecker and Takahashi, 1977; Berger, 1977). Disposition of the transient excess CO_2 produced from accelerated human burning of fossil and nonfossil carbon is also discussed. Recommendations edited by the above authors on behalf of their respective working groups at the January 1976 Honolulu meeting on *The Fate of Fossil Fuel CO_2 in the Oceans* should assure continuing support for these topics from the National Science Foundation and Office of Naval Research (sponsors of the meeting). Most investigators estimate the sedimentary deposition as less than 1 Gton/yr, but the possibility of higher rates deserves closer scrutiny.

The chemistry of carbonates and seawater implies that the first effect of marine uptake of CO_2 will be an accelerating acidification of seawater. This will result in a *diminished* capacity for later absorption of CO_2 from the atmosphere, until the slow process of dissolving existing carbonate sediments brings substantial amounts of carbonate ion to the mixed layer. Unfortunately, the general conclusion from the works cited tends to confirm our impression (Baes et al., 1976, 1977) that the physical lags in ocean circulation and the chemical rates of exchange are not necessarily capable of disposing of the substantial pulse of excess atmospheric CO_2 rapidly enough to prevent its reaching several times the present atmospheric concentration. Some quantitative aspects of this conclusion are examined further in our simple models in Chapter 4 and in further developments that have continued since the present report was drafted for the Conference on Global Effects of Increased Carbon Dioxide, Miami Beach, March 1977.

The oceanographers' panel of the Miami Beach meeting, and a workshop on Biogeochemical Cycling of Carbon arranged by SCOPE (the Scientific Committee on Problems of the Environment) in Hamburg/Ratzeburg, Germany, (March, 1977) also provided a further review emphasizing the physical aspects of the carbon cycle (i.e., cosmic abundance, rock cycle, freshwater and ocean cycles, monitoring). In addition, SCOPE working papers on biological production in the aquatic and terrestrial ecosystems gave increasing attention to our concern for the biosphere as a source and/or a sink for CO_2. The oceanographers' own dissatisfaction with the hydrosphere's potential for prompt absorption of the excess CO_2 from fossil and nonfossil sources emphasizes the importance of closer attention to the carbon budgets of ecosystems. Future work must examine more closely the historic trends of terrestrial pools (Table 2.2) and Equations (2-2) - (2-6) and (4-1) - (4-9) for organic production. Some of the problems of predicting biomass changes will be discussed further in the next two chapters.

FOOD PRODUCTION, LAND CLEARING, AND CARBON DIOXIDE

Terrestrial organic pools could be important either as additional sources of atmospheric CO_2 or as sinks for some of the excess CO_2 released from organic pools and fossil fuels. There will be pressures to convert more forests to farmland and to seek maximum production per unit area because of the increasing demands for limited food supplies. This chapter discusses the past and future of these pressures, the ecosystem areas available, the intensity and kind of production per unit area, and the prospects for net shift (which will be modeled in Chapter 4).

3.1 Past Trends and Future Choices

A brief review of past agricultural and population trends is necessary in order to gain an insight into what future choices are available for mankind.

3.1.1 Historical View

The slow, early prehistoric changes resulting from man's influences have been discussed briefly elsewhere (Olson, 1974; Olson et al., 1974). The evolution and advancement of crop production and animal husbandry techniques resulted in an expansion of the earth's food producing capacity, permitting increases in man's numbers. Population growth in turn exerted pressure on food supply, compelling man to further alter the biosphere in order to meet his food needs. Population growth and advances in crop production have thus used about 12 million km--approximately 8 percent of the earth's total land surface (Table 2.2). However, a considerably larger fraction of the land (i.e., the area excluding most deserts, polar regions, and higher elevations) is capable of supporting vegetation products.

3.1.2 Projections of Populations and Demands

Statistics show unprecedented rates of population growth in recent decades. Although experts disagree about how rapidly and to what extent planned intervention can reduce birth rates, both optimists and pessimists agree that a population increase of close to 2 billion between 1975 and 2000 (or shortly thereafter) is almost inevitable, even if family planning programs are highly successful (National Research Council Study on World Food and Nutrition, 1975). Echols (1976) considered several population scenarios that level off near 6 to 8 billion people before 2075 and reviewed the alternatives of life shortening or a belated lowering of birth rates. He stressed that without enough of one or both kinds of population constraint (the demographic transition for the populous nations), these scenarios would be much higher, and the problems of food and energy per capita would be much more severe. Killough's (1977) version of the "medium variant" projection of the United Nations (1974) rises by segments resembling a logistic curve to 12.2 billion people by 2075. The United Nations' "Low" and "High" variants for those years are about 9.5 and 15.9 billion people. Kahn et al. (1976) are more optimistic than most analysts about society's ability to accommodate these or higher populations.

Per capita food supply and energy use have also increased in most countries--even in the many developing countries where the population has been growing at a rate of 2 to 3 percent and where the increase in production was very slow prior to World War II. But it has become difficult to expand food production to keep far enough ahead of population growth to substantially reduce risks of hunger. The Food and Agriculture Organization of the United Nations (FAO) estimates that the number of malnourished people may even increase in the next decade unless there is a strong upward trend in food production (and energy use) in the developing countries.

Paradoxically, part of the solution to the hunger problem is also part of the problem. Rising per capita incomes permit individuals to consume more food and energy. Unfortunately, modern society is oriented toward consumption, and unless present attitudes about food and energy change, people will continue to increase production of both even after the population stabilizes. Rising incomes also increase the problems that result from rapid population growth. As per capita incomes increase, competing claims rise on the limited supplies of available food, energy, and other resources. People less able to compete for scarce supplies on the basis of income are thus jeopardized.

Like population, the rate of rise of per capita income since World War II, both worldwide and in the developing countries, has been unprecedented. From 1960 to 1973, per capita income in real terms rose 53 percent in the developing countries and 66 percent in the developed countries. This rise of income is inextricably bound up with the increase in agricultural production (National Research Council Study on World Food and Nutrition, 1975).

If expansion of the gross national product in the developing countries resumes the 5 to 6 percent growth rate that preceded the financial and other disruptions of the 1970's, rising incomes may cause average per capita food demands to rise by well over one percent. Where current population growth rates average about 2.5 percent, the annual increase of food supply would need to be 3.5 to 4 percent to reconcile the pull on food supplies by people in medium- and high-income brackets with the need for significantly improved access to food by the poor. Cultivated land is unlikely to increase by more than one percent per year--roughly the present level--and will increase less in nations which have little or no suitable unused land (SCEP, 1970). Cost and other difficulties of bringing new land into production, coupled with the geographic separation of most of the arable unfarmed land from the centers of population, strongly inhibit the opening of new areas. In general, there is a higher return from investment in methods of increasing yield per unit area.

Tropical agriculture has unique advantages, primarily longer growing seasons and greater total solar energy per year. Efforts to control problems of tropical agriculture, such as special soil conditions, diseases, and pests, and to identify more productive biological inputs and farming systems have been inconsistent in precolonial, colonial, and recent times and still have far to go. The open woodlands and humid savannas are heavily used by village cultures, but commonly have socioeconomic barriers to maximum production and storage. Tropical seasonal and rain forests have long been used in shifting cultivation (swidden agriculture), but now seem the most likely to be cut to clear land for more persistent agricultural use. The returns on effort, as well as energy and money, will not always be rewarding. Less intensive use, as by grazing, may precede or follow row crops or tree crops. In any case, the high biomass of native forests will continue to be reduced over wide areas.

Burning of fossil fuel for energy is likely to continue at an increased rate unless extraordinary efforts for replacement with such renewable energy resources as wood, charcoal, alcohol, and other organic products are taken very soon. Energy-intensive agriculture will continue to grow and expand in developing countries, with human and animal labor being replaced as energy and distribution systems become developed. Eventually, effective controls of energy-related pollutants will be found, but in the meantime, the CO_2-fixing capacity of the vegetation may be hindered by atmospheric pollution from increased fossil fuel combustion.

3.2 Problems of Biomass and Production

There are serious questions about the *adequacy* of data for estimates of present world plant production and biomass. The magnitude of the world's production rates and biomass can be estimated in three ways: (1) by stratifying the biosphere into ecosystem types, estimating areas and mean amount per unit area, and then multiplying to calculate total values for each type; (2) by modeling the effects of environmental factors on production and biomass and integrating the results of the model for the earth's surface as values for productivity of various regions and environmental conditions become available; and (3) on a global scale (see Chapter 4), normalizing the month-to-month CO_2 data (Section 2.2) by subtracting industrially derived CO_2 (Hall et al., 1975).

3.2.1 Estimations of Ecosystem Areas and Changes

There is much *disparity* in the information available on ecosystems. Whittaker and Likens (1973) and Olson (1970, 1975) considered that their estimates for temperate forests are "not bad," that data for other temperate, boreal, and arctic communities are reasonable, but that data for tropical communities are very meager. Whittaker and Likens' estimates of world production and biomass are given in Table 3.1 for comparison with our preferred estimates in Table 2.2 and Fig. 3-1.

Defining the recent changes in area of the different ecosystem types is part of the problem of estimating present world plant production and biomass. Man is now using over 40 percent of the total land surface (Table 3.2). More than half of the remainder is not usable because it is too cold, frozen, or mountainous. The President's Science Advisory Committee (PSAC) Report of 1967, the most optimistic report on land use that has appeared in recent times, estimates that as much as two-thirds of the total land surface is usable. These figures can be taken as the upper limit. If an estimate is weighted for the different land uses, we appear to be using about half of the earth's land resources at the present time (Table 3.2).

Table 3.2. Present and Potential Uses of the Land Surface of the Planet (approximate percent of total area).[a]

Use	Present	Potential
Croplands (and fringe)[b]	11	24
Rangelands	20	28
Managed forests	10	15
Buildings, roads, mines	2	?
Reserves (80% forest)	26	0
Not usable	33	33

[a]Modified from the President's Science Advisory Committee (PSAC) Report, 1967.

[b]After Ryabchikov, 1975; includes wild and domesticated vegetation around farms, towns, and miscellaneous areas.

The Food and Agriculture Organization of the United Nations (FAO) projected very little exploitation of the remaining potential (Table 3.3). The land already in use tends to be the best for such use, and intensi-

Table 3.1 Alternative Estimates of Primary Production and Biomass for the Biosphere (from Whittaker and Likens, 1973).

1	2	3	4	5	6	7	8
Ecosystem type	Area, 10^6 km^2 = 10^{12} m^2	Mean net primary productivity, g C/m^2/year	Total net primary production, 10^9 metric tons C/year	Combustion value, kcal/g C	Net energy fixed, 10^{15} kcal/year	Mean plant biomass, kg C/m^2	Total plant mass, 10^9 metric tons C
Tropical rain forest	17.0	900	15.3	9.1	139	20	340
Tropical seasonal forest	7.5	675	5.1	9.2	47	16	120
Temperate evergreen forest	5.0	585	2.9	10.6	31	16	80
Temperate deciduous forest	7.0	540	3.8	10.2	39	13.5	95
Boreal forest	12.0	360	4.3	10.6	46	9.0	108
Woodland and shrubland	8.0	270	2.2	10.4	23	2.7	22
Savanna	15.0	315	4.7	8.8	42	1.8	27
Temperate grassland	9.0	225	2.0	8.8	18	0.7	6.3
Tundra and alpine meadow	8.0	65	0.5	10.0	5	0.3	2.4
Desert scrub	18.0	32	0.6	10.0	6	0.3	5.4
Rock, ice, and sand	24.0	1.5	0.04	10.0	0.3	0.01	0.2
Cultivated land	14.0	290	4.1	9.0	37	0.5	7.0
Swamp and marsh	2.0	1125	2.2	9.2	20	6.8	13.6
Lake and stream	2.5	225	0.6	10.0	6	0.01	0.02
Total continental	149	324	48.3	9.5	459	5.55	827
Open ocean	332.0	57	18.9	10.8	204	0.0014	0.46
Upwelling zones	0.4	225	0.1	10.8	1	0.01	0.004
Continental shelf	26.6	162	4.3	10.0	43	0.005	0.13
Algal bed and reef	0.6	900	0.5	10.0	5	0.9	0.54
Estuaries	1.4	810	1.1	9.7	11	0.45	0.63
Total marine	361	69	24.9	10.6	264	0.0049	1.76
Full total	510	144	73.2	9.9	723	1.63	829

*All values in columns 3 to 8 expressed as carbon on the assumption that carbon content approximates dry matter x 0.45.

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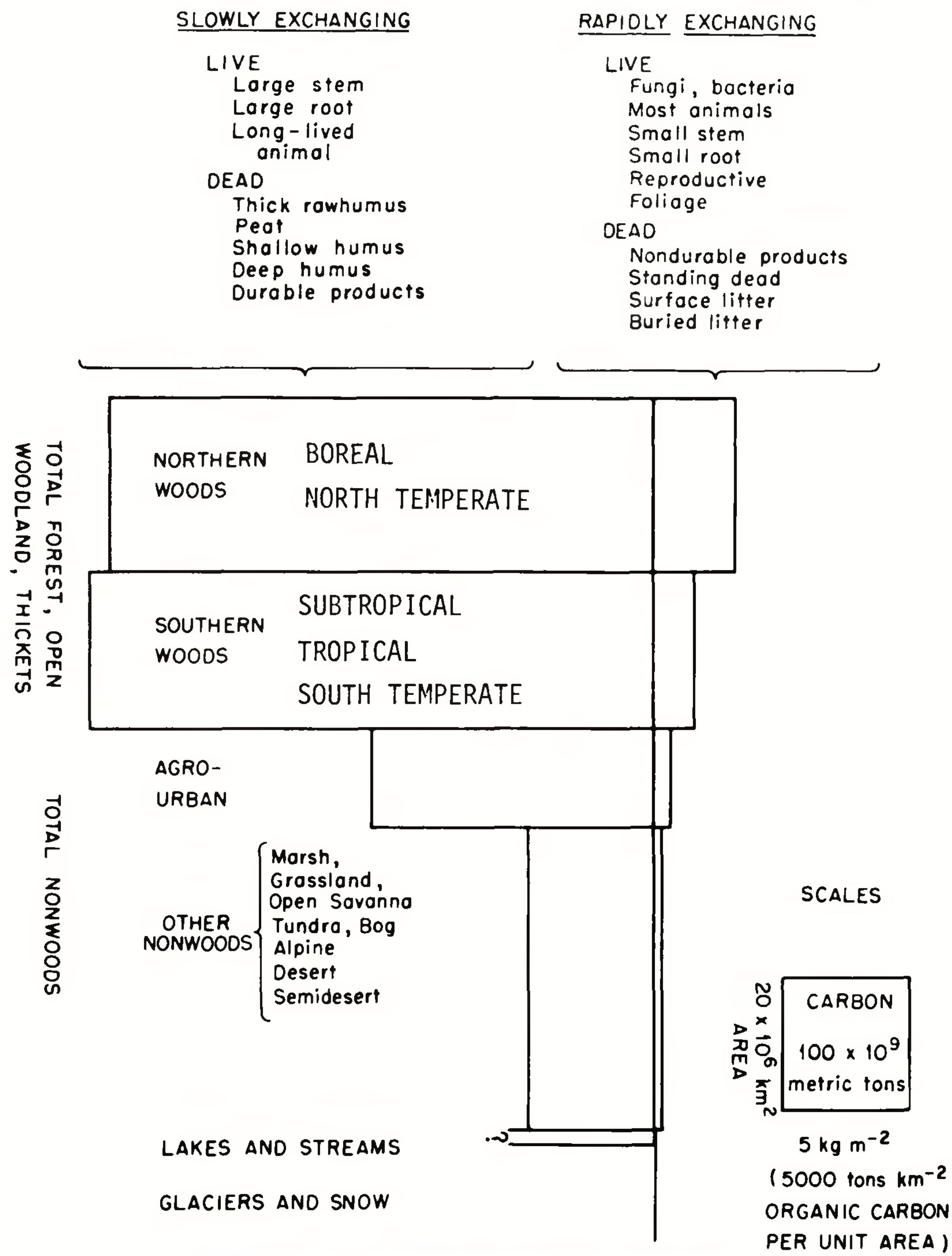

Fig. 3-1. Relative amounts of carbon in various ecosystems. Total = area in each category x amount per unit area.

fication of management will probably be chosen rather than an expansion into marginal lands. Expansion has ended in the developed nations, and by 1985 is expected to end in most of the world. Thus, *except for an expansion in the utilization of forest land,* land use is expected to become stabilized. The difference between the FAO projections and the potential estimated in the PSAC Report is only a factor of two. This is not large in comparison with differences in projections of human population growth over the next century. Yet we certainly need to improve on such estimates.

Table 3.3. Past and Projected World Land Use Changes (percent of total land area).

Use	1950-1968	1968-2000
Cropland	+1.5	+0.4
Rangeland	+5.2	-1.3
Total forest	-0.2	-1.3

Sources: Food and Agriculture Organization (FAO), 1951, 1958, 1969.

3.2.2 Biomass and Production Rates per Unit Area

At the same time that forest areas seem to be decreasing, the biomass and its organic carbon per unit area would seem likely to be decreasing as well. This hypothesis needs to be tested quantitatively, but seems credible on several grounds. The same population growth which increases the number of mouths to feed also increases the amount of fuel wood which many nations still use for cooking, heating, and supplying many technologies.[6] In India many tree branches are routinely lopped for animal fodder.

[6]Adams et al. (1977) estimated maximum cutting of 1 ton of carbon per capita per year, or 2.1 Gtons/year of carbon for ∿2.1 billion people living south of 30° N latitude. This estimate deserves refinement by systematic study.

Throughout much of the Middle East and North Africa, goats and other livestock open up the stands that remain and interfere with the regeneration that could replace some of the harvested materials. Our observations in Southeast Asia and Central America show numerous other cases of the opening up of forests, woodlands, or brush that are not cleared outright.

Sommer (1976) and Persson (1974, 1977) documented the general decrease in forest volume, and hence in carbon, which follows from a combination of decreasing forest area and decreasing carbon per unit area. In the zones between ±30° latitude there is little doubt that the decrease is substantial. Our previous estimate of over 1 Gton/year for prompt release of excess CO_2 (Baes et al., 1976, p. 23) from *accelerated* cutting did not include the component of faster net removals of material from forests that are not being cleared. Even where forest management is being designed to increase the forest production (or at least the usable part of production), such management is very often tied to earlier harvest of the crop produced (short rotation forestry). Where there is no premium on the dimension of the logs removed, the tendency of intensive management is to shorten the rotation further by harvesting at smaller sizes, even though more stems are thereby allowed to grow through the rotation instead of being thinned by death or by preharvest cuttings. Because stands would be spending relatively more of each rotation in the youngest age classes (when biomass and carbon are very small), it seems likely that many of the forests managed for pulp or pole-sized stock would be found to average lower in carbon mass per unit area than those forests that are allowed to age into the sawtimber size classes that support a high carbon inventory for much of their lifetime.

A systematic review of such data, suitable for translation into total carbon budgets, is highly desirable for the many geographic regions which may turn out to differ markedly in their trends. Such a review would have to use the data collected for total biomass and biological production in order to allow for the carbon which is not included in the merchantable parts of the ecosystem.

To estimate the total production required to build and support a certain biomass and the turnover of carbon that takes place during that growth, closer attention must be given to the terms in the equations of Section 2.4.2. Below ground parts are commonly left out of production estimates or else are introduced as adjustments at the end of any detailed procedure for above ground parts. Harvest methods are based mainly on the net changes in mass (or carbon) per unit area between successive increments of time; therefore, they are subject to statistical uncertainties from the use of different sample plots if destructive sampling is scheduled or from indirect estimates of biomass by regression from nondestructive measurements like plant height, diameter, or cover. More serious uncertainties arise from failures to estimate the amounts of biomass produced and simultaneously lost by death, shedding, and grazing. Although the harvest method is quite feasible and allows for computation of the CO_2 exchange for vegetation periods or for one year, many methodological problems must still be solved. For example, in many ecosystems, problems arise in underestimating "root" production.

The annual carbon exchange can be estimated by the annual production of dry plant matter on the basis that the ratio of the atomic weights of CO_2 to carbon is 44/12 and that the dry matter contains 40 to 50 percent carbon. To produce 1 g of woody "dry matter of plants" (DMP), it is necessary to assimilate 0.5 x 44/12 = 1.83 g CO_2. An old estimate of Filzer (1951) for the production of organic matter in an area of Europe receiving 1000 mm rainfall was as follows:

	DMP (g/m^2)	NAR ($mg/cm^2/yr$)
Grass, clover	395-505	80
Cereals	380-545	85
Potatoes, beets	490-625	105

To account for an annual volume increase in forests of about 5 m^3/ha, a net assimilation rate of at least 100 mg CO_2/cm^2/year is a minimal estimate. Net primary production must actually be greater than estimates of biomass increment in all these cases to allow for plant losses during the year (Olson, 1964, 1971). Lieth and Whittaker (1975) included additional contributions on many of the particular environments, along with further reviews of the methods which are most commonly used by them.

Detailed studies on the total production budgets of specific ecosystem types are included in the literature of the International Biological Program's Terrestrial, Freshwater, and Marine Productivity Sections. This literature, still in various stages of synthesis, should significantly improve on the results to date for those areas where interdisciplinary efforts could be mounted.

Fairly detailed work is forthcoming from many European countries, Japan, Australia, and North America. However, results are very sparsely distributed over most of Asia, Africa, and South America. Ecosystem studies are thus badly needed to represent large areas of the earth.

Even if intensive research sites become better distributed for representing the main bioclimatic zones of the earth, there will always be problems of interpolating between them and extrapolating to various extreme or special conditions which could not be adequately studied from a statistical or experimental standpoint. Thus, filling in the gaps in the global picture will require close attention to the environmental factors explaining global or local variations.

3.3 Variables Controlling Productivity

One method of estimating world plant productivity and biomass is to determine the productivity of various regions, to model the effects of environmental factors on productivity and biomass, and to integrate the results with the model of the earth's surface. This report will not attempt to model these results for an accurate answer, but will note some elaboration of Equation (2-3) in assessing photosynthetic productivity.

Before investigating the problems involved with the measurement of dry matter production, it is necessary to relate several terms concerning production processes in plants and plant communities. Increments of biomass (ΔB) or of carbon (ΔC) depend on the following relations:

(a) The specific photosynthetic capacity of the individual plants comprising the plant cover. For woody plants, the photosynthetic capacity varies between CO_2 uptake rates of 10-20 mg CO_2 per dm^2 (single face) per hour for deciduous trees, 8-15 mg CO_2 per dm^2 per hour for evergreen broadleaf trees, and 5-8 mg CO_2 per dm^2 per hour for conifers (Rabinowitch, 1951; Larcher, 1963, 1969). Biochemical pathways (photorespiration) and genetic control (C_3 and C_4 pathways) are also important for maximum production and for adaptation to extreme environments (Zelitch, 1971; Gates and Schmerl, 1975).

(b) <u>The effects of internal and environmental variables during the production period</u>. Photosynthetic production rates of plants vary depending on development, aging, water supply, nutrition, and favorable or unfavorable climatic conditions. Average rates may be lower because lower leaves are shaded where leaf area index is high.

(c) <u>The leaf area index (LAI) of the plant cover and the morphological characteristics of the individual plants</u>. The net ΔB of a plant or of a plant community depends largely on the total leaf area compared to the amount of nonphotosynthetic tissue in the plant (the ratio of foliage to the total mass of twigs, stems, roots, and reproductive organs), as part of the assimilates will be consumed by the respiration of the nonphotosynthetic organs [Equations (2-3), (2-4)].

Since mutual shading of leaves in tree crowns and in dense plant stands reduces the intensity of photosynthesis in lower canopy layers, the specific shape of the crown and the characteristic density and 3-dimensonal distribution of foliage in the canopy must also be considered.

(d) <u>Duration of periods of conditions favorable for photosynthesis</u>. Plants require a certain level of irradiance, a sufficient water supply, and favorable temperatures for efficient photosynthetic activity. Consequently, the day-length and the duration of the productivity period each year determine to a great extent the amount of photosynthetic dry matter accumulation. Those tropical trees which are photosynthetically active throughout the year could therefore reach higher yields than do trees in the temperate zones where the productivity period is limited by a relatively short growing season (generally from May to September) and is occasionally interrupted by summer drought. Evergreen trees in the temperate zones utilize the autumn or spring for production; in winter, their photosynthetic activity is depressed, except in maritime climates.

(e) Translocation and storage of carbohydrates in plants and losses of plant material. An analysis of the productivity of the plant cover requires that the translocation processes and the characteristic distribution patterns of carbohydrates in different plants be known, since considerable differences among species have been demonstrated (Kozlowski and Keller, 1966). The respiration rates in the roots and the stem organs and the losses of organic material to the rhizosphere by litter fall, stem death, spread of fruits, animal consumption, etc. should also be determined (Mar-Møller et al., 1954; Yoda, 1967).

3.3.1 Geographic Regressions of Environmental Variables

A refinement of production estimates uses quantitative relationships with environmental variables on a geographic or a microenvironmental scale. For terrestrial communities, the principal variables controlling broad geographic patterns are moisture availability and temperature. Additional important variables between sites of a region are sunlight intensity (on different topography), nutrient availability (on different substrates), and seasonal changes in the climatic factors.

A number of scientists have suggested relationships between productivity and one or several of the above variables. Walter (1962) showed that in grasslands of fairly dry climates, the aboveground production increased in a nearly linear manner of 1 gm^2 per year per millimeter of precipitation. Paterson (1961, 1962) employed formulas using several climatic variables: mean temperature of the warmest month, range between warmest and coldest months, precipitation amount, length of growing season, and insolation. Rosenzweig (1968) demonstrated the existence of an effective logarithmic relation between net primary production and actual evapotranspiration: $\log NAAP = (1.66 \pm 0.27) \log AE - (1.66 \pm 0.07)$, where NAAP is net annual aboveground productivity in grams per square meter per year, AE is annual actual evapotranspiration in millimeters, and 5 percent confidence limits are given. Russian work has related production to the amount of heat needed to evaporate the annual precipitation. It is thus not difficult to establish a variety of correlations between productivity and environmental variables.

To make an estimation of world production easier, Lieth (1973) reduced the environmental variables to the two that seem most critical and are most widely available in climatic data: mean annual temperature and mean annual precipitation. Production data were plotted in relation to these variables, and curves were fitted to the data (Figures 3-2 and 3-3). The equations for these curves were then applied to climatic data to give two production estimates for each station. Of the estimates from the two curves, Lieth preferred the lower estimate for any station--in accord with the Liebig principle of limiting factors. Lieth used this technique to prepare maps of the net annual primary production of the land surface (e.g., Fig. 3-4). These maps imply production values for the land that are close to the totals of Tables 2.2 and 3.1. The two approaches should agree because they are averaging some of the same production estimates. The approach of using regressions fitted to dispersed data to account for more of the many factors that affect productivity is feasible, but has yet to be fully tested for worldwide prediction.

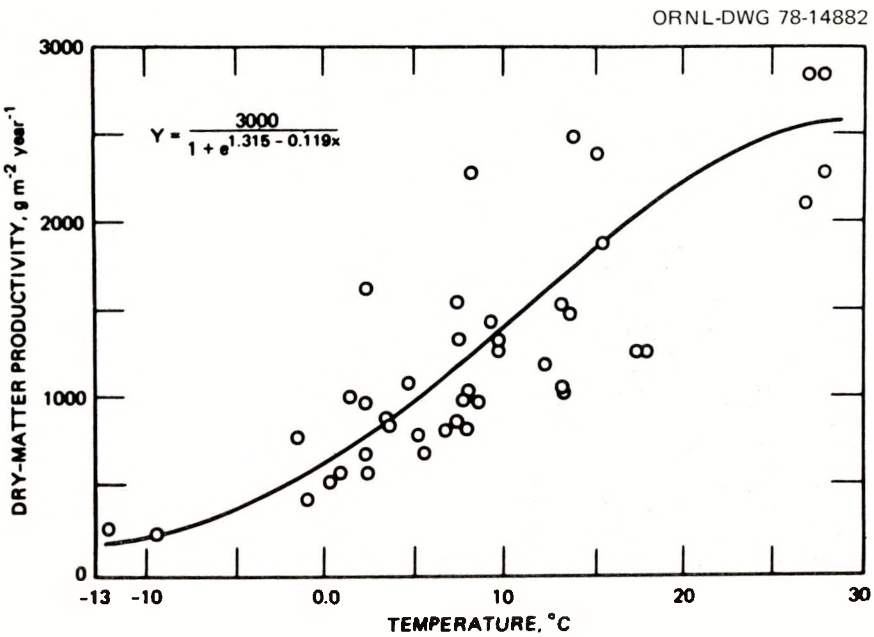

Fig. 3-2. Annual dry-matter productivity vs mean annual temperature.
Source: Lieth, 1975, Table 12-3a, p. 243.

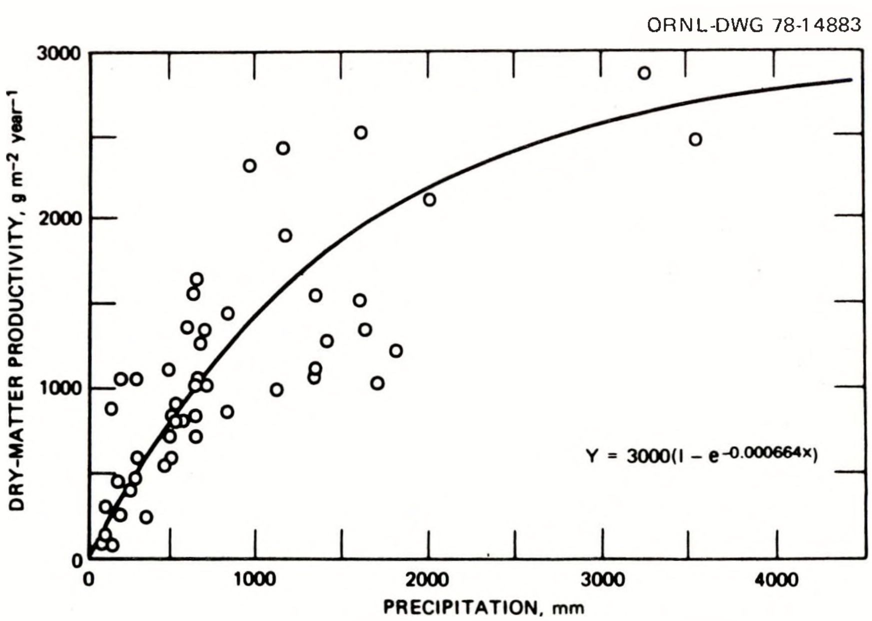

Fig. 3-3. Annual dry-matter productivity vs mean annual precipitation.
Source: Lieth, 1975, Table 12-4a, p. 244.

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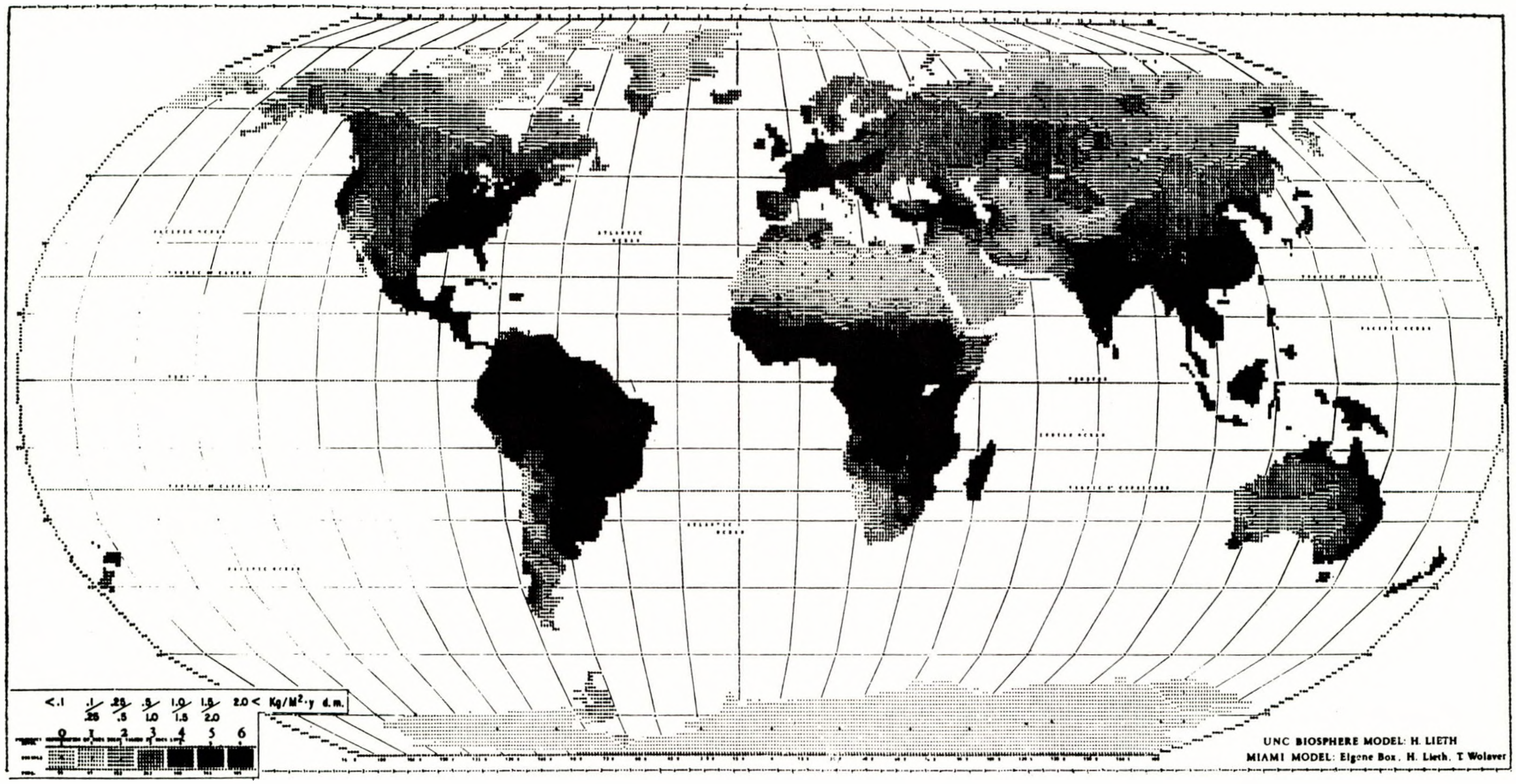

Fig. 3-4. An example of preliminary estimates and geographic interpolations of organic dry matter production rates inferred from temperature and precipitation (Box, Lieth, and Wolaver's "Miami Model," discussed by Lieth, 1973, 1974, 1975).

However, the use of regression formulation does not yet provide much basis for predicting variations in production rate and especially in biomass under the altered climatic conditions to be considered in Chapter 5. For example, increased temperature would not necessarily increase production rate unless there were sufficient extra moisture to compensate for enhanced evaporation. Even then, respiration may increase faster than photosynthesis in locally adapted genetic types. Unless there were species or varieties already available to take advantage of a different response of NPP (photosynthesis minus respiration) to temperature, it is quite possible that total and usable production will decrease with rising temperature.

3.3.2 Biophysical Ecology of Production

An approach complementary to that treating broad geographic trends is one which treats the physical and physiological constraints within or immediately surrounding the plant (or animal) parts which affect production, survival, or adaptation to changing climate. The relationships listed at the beginning of Section 3.3 provide a basis for modeling the processes of carbon exchange that link the underlying biochemistry to the current (and quite localized) surrounding conditions. This modeling involves needed areas of active research, as illustrated by the many contributions to Gates and Schmerl (1975). (Presently, there is a wide gap between research at that level of refinement and the improved modeling at the level of whole ecosystems or geographic complexes of ecosystems.)

Lemon (1977) reviewed some of the intermediate steps between the chemical reactions and the whole stand (crop), with particular reference to the response to increased atmospheric CO_2 concentration. He linked the steps of a hierarchy of yield responses on different levels of organization: from the chemical reactions to the mesophyll cell, to the intact leaf, to the (crop) stand's daytime response, to crop growth over a number of days at different phenologic stages of growth, and finally to yield over the full cycle of the annual crop.

Lemon (1977) also examined the difference between two biochemically distinct groups of species. The C_4 plants, so-called because of a 4-carbon carboxylation intermediase, had a 2- to 3-fold advantage in affinity for CO_2 over the C_3 plants, which contained other enzymes. This hypothetical advantage is damped to around 1.5 by other factors which limit growth at the stand level and to nearer 1 for the whole crop yield. Lemon hypothesized that responsiveness to *excess* CO_2 would likewise be moderated as one moved from greenhouse conditions with controlled factors into field conditions where many factors other than CO_2 would limit the photosynthetic response to CO_2 fertilization.

Thus, it is not surprising in Chapter 4 to find a relatively low responsiveness to enhanced CO_2. Values of β = 0.1 or a few tenths of a percent for each percent of increase in CO_2 are suggested for global models of atmospheric and biospheric change. Hopefully, physiological studies will provide more refined models and parameter values.

3.3.3 Other Factors Controlling Carbon Exchange of Ecosystems

Between the broad, heterogeneous system of the continents and the local, homogeneous system of a crop and its parts lies an intermediate level representing the size and complexity of most real ecosystems or local complexes of ecosystems (e.g., drainage basins or other tracts with stands in various stages of composition or maturity and regeneration).

Research and modeling on this scale should help provide a link between both the global and internal systems. Phenomena of importance at this scale would add steps to the chain of considerations listed above from Lemon (1976). For example, foresters would have to include distinctions among stages of stand establishment (years before crown closure), a period of main stand growth, and perhaps later stages when R_a and R_h [Equations (2-3) and (2-5)] both become relatively higher as more living and dead organic material undergoes respiration. Ecologists might envision the first (pioneer or planted) forest stage as a transient condition leading up to an ecosystem with sufficient stability to perpetuate itself with or without significant modification by human influences.

The idealized concept of an ecological "climax" envisions a mature ecosystem as one where the living parts of the system have attained a balance between the production rates (income) and the losses of carbon both back to the atmosphere and as input to the large pool of humus. Over long periods--centuries or millenia--the soil pool may also approximate an equilibrium between the fairly small fraction of produced material which provides its income of organic carbon and the CO_2 or CH_4 loss (via microbes) from that soil pool. An improved understanding of the rates of turnover through both the living and dead pools is one of the central needs for a better understanding of the future changes in the organic carbon pool. Such findings are expected to emerge from the relatively few but intensive studies of ecosystems. Ideally, these studies, with insights on the stages of carbon transformation and the residence times at each stage, should be coupled with research on the overall flux of CO_2 into and out of the whole system.

3.4 CO_2 Data and Modeling on a Field Scale

Another complex topic mentioned here to round out the discussion of the problem of overall carbon balance is the measurement and interpretation of CO_2 fluxes.

3.4.1 Soil-Atmosphere Carbon Dioxide Flux

The carbon dioxide assimilated by crops is provided by a downward transfer from the atmosphere and an upward transfer from the soil. Gross photosynthetic rates may be estimated from the diurnal variation of the atmospheric flux alone (Monteith, 1962), but determination of a complete carbon dioxide budget requires that the flux from the soil be calculated separately. Lundegardh (1927) and Misra (1950) measured carbon dioxide concentrations within the crop foliage and suggested that assimilation rates are closely related to the rate at which carbon dioxide is evolved from the soil. However, Moss et al. (1961) found that the rate of soil respiration beneath maize was much smaller than the net above ground assimilation rate in bright sunshine.

3.4.2 Measurements of Gas Exchange of Plant Communities

Gas exchange of plant communities is measured by two methods: physiological gasometric methods and meteorological approaches. The gasometric methods determine the CO_2 concentration of the air before and after the air flows at a constant rate over a given amount of plant material. The difference between the CO_2 concentrations of the two air samples represents a measure of the intensity of the gas exchange between the plants and the atmosphere. Reduction of the CO_2 concentration in the air after it has passed over the leaves is an indication of photosynthetic CO_2 uptake (net or apparent photosynthesis).

An increase of CO_2 in the air samples indicates respiratory CO_2 release.

It is also possible to measure photosynthesis and respiration by measuring the O_2 exchange. However, this method is applied only when special problems (i.e., respiration quotients) have to be solved. The time scale of measurements is in minutes; values for longer periods--hours or days--are computed by calculations or determined by automatic summation of short-term data (Olson, 1964).

There are several advantages of the physiological gasometric methods. The influence of various environmental factors on photosynthesis can be measured without disturbing the plant. Gasometric methods may be used in the laboratory as well as in the open field. Laboratory research is important for the measurement of the specific photosynthetic capacity of different species, varieties, or ecotypes, while gas exchange measurements under field conditions provide information on responses to optimal and suboptimal environmental conditions and to diurnal and seasonal changes of photosynthetic activity of plants.

There are also several disadvantages of the gasometric methods. The plants, or portions of them, must be put into enclosures which impose a somewhat artificial environment. The samples are usually rather small (leaves or branches, with only occasional full-grown specimens). The results are used to calculate the CO_2-fixation rates of entire trees and forest stands, but this requires extrapolation and simplifying assumptions. Gas exchange measurements also require a team of closely integrated scientists and expensive equipment (see Specht, 1967.).

In meteorological approaches, the CO_2 budget of plant communities is calculated from measurements of the vertical gradients of CO_2 concentration in the air and from determinations of the vertical changes in microclimatological variables in the plant cover. Meteorological approaches require a large upwind fetch and, therefore, a large area of homogeneous vegetation for the experimental plot. However, it is possible to determine the net CO_2 exchange of the plant community, including the CO_2 budget of the soil, without extrapolation from small plant parts and without disturbing the plant by enclosures (for further information see Monteith, 1963; Baumgartner, 1969; Ordway, 1969).

Vertical distributions of CO_2 fluctuations in a cornfield in the 4- to 0.25-cycle/minute frequency range were studied by Lemon et al. (1969). These investigators proposed that the CO_2 fluctuations were generated in the cornfield by variable sources and sinks associated with photosynthesis and respiration. They observed that eddies contributing to the fluctuations could originate either inside or outside the field or both, but to be detected, they had to be moving across the field at a much slower velocity than the mean wind speed.

Verma and Rosenberg (1976) observed the CO_2 concentration and flux in an area of typical agricultural land use in the east Central Great Plains of North America (Mead, Nebraska). Their observations were made at heights sufficient to represent an integration of CO_2 fixation and release due to all types of land use in the region (pasture, alfalfa, annual crops). Minimum daytime CO_2 concentrations were 295-300 ppm in late July to early August and 328-332 ppm in winter. Peak daytime fluxes from the atmosphere to the ground varied from about 0.5 mg m^{-2} sec^{-1} in early June to 1.5-2.0 mg m^{-2} sec^{-1} in July and August to 0.5 mg m^{-2} sec^{-1} in late September. The net daily CO_2 flux, calculated from the downward daytime and upward nocturnal fluxes, is about 10-12 g m^{-2} day^{-1} in early June, 18-20 g m^{-2} day^{-1} in early August, 6-10 g m^{-2} day^{-1} in September, and 1-5 g m^{-2} day^{-1} in early October.

The annual cycle of CO_2 observed at Mead, Nebraska is compared with that at Barrow, Alaska, and Mauna Loa, Hawaii. The minimum CO_2 at Mead is relatively sharp and intense compared with the minimum at the other locations. The minimum CO_2 at Mauna Loa lags behind that at Barrow and Mead by about one to two months. Presumably, the autumn shift from net assimilation to net respiration in the North is delayed as air mixes southward and is diluted by tropical air which has much less seasonal contrast.

Denmead (1969) studied the comparative micrometeorology of a field of wheat and a forest of *Pinus radiata*. The studies were made in the spring, when both communities grew under natural rainfall in similar aerial environments. At a given short-wave solar radiation intensity, large differences were observed between the two communities in net radiation, evaporation, photosynthesis, and soil heat flux. The first three were greater for the forest, while the last was smaller. Apparent photosynthesis by the forest was approximately twice as high as that of wheat. Productivity, in the sense of greater photosynthetic gain per unit of evaporation, was also greater in the forest. Nevertheless, the forest used more water.

The data suggested that not only was absorption of net radiation higher for the forest, but also that more of the available energy was partitioned into latent heat. Approximate calculations of mean foliage temperatures, made from the radiation balance of both communities, indicated that foliage temperatures of the forest were generally close to, or less than, air temperatures, while those of the wheat field were several degrees higher. These calculations also provided evidence for greater proportional evaporation from the forest than from the wheat field. Eddy diffusivities were generally almost an order of magnitude greater over the forest than over the wheat field due to differences in surface roughness.

Sestak et al. (1971) summarized many of the techniques used in gas exchange studies and related them to growth analysis equations [Equations (2-3) and (2-4)].

This review cannot summarize all the contributions from the many countries of the International Biological Program. Research on production processes in many biome regions was summarized by Cooper (1975). Reichle (1970, in press) brings together information on many aspects of forest ecosystems which store much of the earth's total biomass. Each of the biome studies on primary production of total ecosystems addresses the special problems of its own life forms and life zones. Reichle et al. (1975) brought together one early synthesis of this work, but more syntheses are forthcoming which can be applied to the respective ecosystem areas outlined in Tables 2.2 and 3.1.

TERRESTRIAL AND GLOBAL SIMULATIONS

This chapter represents one step toward elaborating the terrestrial part of the global model outlined in Fig. 1-1 and especially in Fig. 2-4. It includes an explicit treatment of the clearing of tropical forest--most of the "Southern Woods"--to Nonwoods (mostly crops and pasture) as a result of the human population growth and food requirements that were reviewed in Chapter 3.

The model formulations and results presented in this chapter constitute a report of progress to the time of the March 1977 Miami Beach meeting on the global CO_2 problem. A report from the Department of Energy on that meeting is expected to include slightly later results (Chan and Olson, in preparation) which build upon the background presented in more detail here. Both of these reports prepared for a future volume on modeling the consequences of land clearing for the atmosphere and biosphere. Our models, along with most others, are subject to much improvement.

4.1 Partitions and Shifts of Terrestrial Pools

The present model has much in common with that of the SCEP (1970) group, and hence with those of Keeling (1973a) and Keeling and Bacastow (1977), in distinguishing the rapidly and slowly exchanging pools of carbon, either in live or dead organic matter. However, we treat both pools separately (Table 4.1) for the broad geographic categories of Baes et al. (1976, 1977) and of Table 2.2--namely, wooded lands both north and south of 30° N latitude and nonwooded lands of any latitude. A general aim is to use these distinctions of the biosphere within a global compartment model of the carbon cycle to help explore major human impacts over several centuries.

Table 4.1. Carbon Mass of Various Reservoirs at Steady-State (1860 A.D.).

Compartment	Reservoir	Symbol	Initial Value[a] (in Gtons)
C1	Atmosphere	XIC1	616
C3	Living aquatic organisms	XIC3	1.5[b]
C4	Dead organisms and organic matter in mixed surface layer	XIC4	29
C7	Mixed surface layer (inorganic C)	XIC7	580
C8	Thermocline and deep ocean (inorganic C)	XIC8	38,420
C10	Nonwoods (rapidly exchanging C)	XIC10	40
C11	Nonwoods (slowly exchanging C)	XIC11	540
C12	Northern Woods (rapidly exchanging C)	XIC12	75
C13	Northern Woods (slowly exchanging C)	XIC13	540
C14	Northern Woods (rapidly exchanging C)	XIC14	47
C15	Southern Woods (slowly exchanging C)	XIC15	520
C16	Dead organisms and organic matter in thermocline and deep ocean	XIC16	1,620
C17	Inorganic sedimentary deposits	XIC17	30,000,000
C18	Organic sedimentary deposits (Recoverable fossil fuels)	XIC18	6,600,000 (10,000)

a: values taken from Baes et al. (1976) except as indicated;
b: revised according to Reiners et al. (1973).

The quantitative projections, especially beyond A.D. 2000, could of course be changed in important ways as the model structure and choice of parameter values are refined. With this caveat, it is nevertheless possible--indeed it is essential for our purposes--to examine a number of very hypothetical scenarios for future centuries which would follow *if* our working premises were to become fair approximations of the real world. Our main conclusions about drastic change in the atmosphere and biosphere now seem very likely to hold, even though the quantitative estimates and the details about the ocean-sediment part of the model will be revised.

A specific aim of certain simulations is to indicate whether forest clearing (i.e., net release of *nonfossil* carbon to the atmosphere) could have been going on for as long as a century at rates equivalent to the removal of 1 percent of the forest area. This rate was suggested by Baes et al. (1976, p. 23) as a credible estimate for recent years, without necessarily implying that such a high rate had been in effect for a century or more.

Some of the release of carbon in an average unit area would occur more quickly with an increase in rates of burning (F) of wood as fuel, to dispose of slash from land clearing, or from other fires, either intentional or accidental. Some extra release of CO_2 represents enhanced respiration by heterotrophic organisms (R_h). The latter speedup is expected as the organic and mineral layers of soil are exposed to the sun and then mixed and moistened in the processes of cultivation or grazing.

4.2 Working Hypotheses

The long-term geologic cycling of carbon and the relation of this cycling to carbonate and organic sediments are not discussed in detail here, but these large, very slowly changing compartments are recognized (compartments C16 and C17 in Table 4.1). Our general hypothesis is that the release of CO_2 from recoverable fossil fuels (part of C18 in Table 4.1) and the nonfossil CO_2 released from tropical ecosystems (compartments C14 and C15) both contribute to changes in atmospheric CO_2 (compartment C1).

4.2.1 Assumption of Steady-State Before Large-Scale Industrialization

Over the last half-billion years, the ratio of isotopic carbons in marine carbonates has varied within a relatively narrow range (Broecker, 1970). This fact tends to support the postulate that the global carbon cycle has maintained a dynamic steady state for a long time (Garrels et al., 1976). Man has inadvertently perturbed this equilibrium by hastening the release of carbon dioxide through deforestation and the combustion of fossil fuels. Since the beginning of agriculture, forests have been cleared to provide land for the growing of crops (Chapters 2 and 3). Coal and oil shale were used locally for several centuries. However, fossil fuels were not used extensively until a much later date, probably after the last half of the 19th century (Putnam, 1953). At present, there are no compiled data giving the amounts of anthropogenic carbon dioxide released before 1860.

In this report (Section 2.3), the year 1860 is arbitrarily taken as the onset of the large-scale perturbation. Hence, all simulation runs start with t_0 = 1860. Much of the colonial clearing of tropical forest to be simulated in the present study also accelerated around that time. Similar treatment of earlier land clearing will require longer simulations.

4.2.2 Primary Production of Marine Organisms

The growth of marine microphytes is known to be limited by the availabilities of nitrogen, phosphorus, and silicon in the ocean (Stengel and Soeder, 1975). These microphytes may thus not be able to fully utilize the predicted addition of carbon dioxide to the ocean. Seaweeds and other aquatic plants growing along the coastal regions may get sufficient nutrients from river runoff. However, the contributions of these organisms to the total marine organic carbon are probably small. Some concern also exists about the eutrophication of lakes and oceans by human activities. However, we still do not totally understand the effect of eutrophication combined with marine pollution from toxic chemicals (Odum, 1971). It is probably valid to assume that the change in net primary production of aquatic organisms would remain small within the time span of this simulation, or at least in the early decades before drastic change of ocean circulation and climate occur. For this simulation, net primary production of marine organisms is kept at the same rate: NPP (23 Gtons/yr) = 46 Gtons/yr of photosynthesis minus 23 Gtons/yr of plant respiration.

4.2.3 Primary Production of Terrestrial Biota

As in Keeling (1973a), the flux of carbon from the atmosphere to the land biota at a high concentration of atmospheric carbon dioxide is expressed by the formula

$$F_{ab} = F_{ab,0}[1 + \beta \ln (C_a/C_{a,0})] (C_b/C_{b,0}), \qquad (4\text{-}1)$$

where:

C_a = total carbon in the atmosphere,

C_b = total carbon in the biota,

$C_{a,0}$ = initial carbon in the atmosphere (coded as XIC1 in Table 4.1),

$C_{b,0}$ = initial carbon in the biota,

β = biological growth factor,

and the last factor in parentheses allows for a rough proportionality of the changing mass of the biota with its initial value $C_{b,0}$. The above equation implies that the flux of carbon from the atmosphere to the biota is proportional to the logarithm of the relative increase of atmospheric carbon. Moreover, carbon in the rapidly exchanging reservoir is also assumed to depend on the relative increase of the slowly exchanging reservoir. The biological growth factor, β, accounts for the availabilities of limiting resources for photosynthesis and for the genetic variation of the individual tree species in utilizing carbon dioxide. Values for β may range from 0 to 0.4 (Keeling, 1973a). In this study, β is set equal to a fixed value of 0.0, 0.1, 0.2, 0.3, or 0.4, but different values may subsequently be considered for various ecosystems exhibiting a wide spectrum of potential in their primary productions.

4.2.4 Ocean Buffering Factor for Excess Carbon Dioxide

Carbon dioxide is in a dissociative equilibrium with the inorganic carbon species HCO_3^- and CO_3^{--} in the ocean water (Broecker et al., 1971). If the atmospheric carbon dioxide concentration increases by x percent, the resulting relative increase of oceanic carbon dioxide and inorganic carbon ions in equilibrium will be approximately x/ζ percent (Keeling, 1973a). This buffering action of the ocean water is taken into account by multiplying the additional carbon mass by ζ in the expression for the flux from the mixed surface layer of the ocean to the atmosphere. Theoretically, ζ increases with increasing temperature and increasing inorganic carbon in the ocean (Jorgensen and Mejer, 1976). This means that more carbon dioxide will be released to the atmosphere as the oceanic carbon increases. In this study, however, ζ is assumed to be constant within each simulation. Models are run with ζ equal to 9, 10, or 11. Killough (1977) has recently coded one procedure for treating the variations of this factor. Baes et al. (1976a) have explained the chemical relations controlling the buffer factor and the reasons why it severely delays the ocean uptake of atmospheric CO_2.

4.2.5 Other Fluxes Between Adjacent Reservoirs

All exchanges of carbon other than the fluxes mentioned above are considered to be linear finite-rate processes. Consequently, the flux of carbon from one compartment to the other is directly proportional to the carbon mass of the donor compartment, or inversely proportional to the residence time of the carbon molecules in the donor compartment. The relation implies a time response equivalent to that of a well-mixed carbon reservoir. This assumption can probably be justified in the present model, because the reservoirs involved have either a fast residence time (e.g., the atmosphere) or a very large pool size (e.g., organic and inorganic sediments). Refinements based on work by others can be introduced later if necessary for certain evaluations.

4.3 Elaboration of a Terrestrial Model

The 14 reservoirs, their symbols, and their initial values at year 1860 are given in Table 4.1. Except for C3 (living aquatic organisms), all values are taken from Baes et al. (1976). C3 is revised upward from the original 1.0 Gton to 1.5 Gtons (Whittaker, 1975). Initial values for the six biospheric reservoirs represent the conditions which existed in the middle of the 19th century. The values are less than the amounts given by Whittaker and Likens (1975) for the period around 1950 and those of Rodin et al. (1975) for potential carbon masses at the precultivated or prelogging state.

The ocean was divided into two compartments: the mixed surface layer and the combined thermocline and deep ocean reservoir. This is a highly simplified view of the physical nature of the ocean. However, such simplification allows a larger initial effort to be put on the elucidation of the interrelationships of the terrestrial reservoirs. Other models emphasizing the diffusion processes of inorganic carbon in the sea and the further subdivision into polar and warm oceans are being developed by Killough (1977) and Olson and Munro.

Table 4.2 gives the definition of the fluxes and their values at steady-state. Most of the fluxes are given in Baes et al. (1976). Several of the remaining fluxes are taken from various sources and a few are calculated by mass-balancing the total influx and outflux of each reservoir.

The rate of change of carbon mass in any one reservoir is defined as the total influx minus the total outflux. Basically, the model can

Table 4.2. Carbon Fluxes of Various Reservoirs at Steady-State (1860 A.D.).

Flux	Value (Gtons/yr)	Note	Process
F0107	90	a	Mass transfer across air-ocean interface
F0701	90	a	Mass transfer across air-ocean interface
F0110	10	a	NPP of Nonwoods (rapidly exchanging C)
F0111	8	a	NPP of Nonwoods (slowly exchanging C)
F0112	10	a	NPP of Northern Woods (rapidly exchanging C)
F0113	8	a	NPP of Northern Woods (slowly exchanging C)
F0114	11	a	NPP of Southern Woods (rapidly exchanging C)
F0115	9	a	NPP of Southern Woods (slowly exchanging C)
F0304	16	b	Death of aquatic organisms
F0307	7	c	Respiration of aquatic animals
F0407	10.62	b	Oxidation decay in mixed surface layer
F0408	3.9	d	Oxidative decay and formation of calcareous shells of aquatic organisms in thermocline and deep ocean
F0416	1.7	a	Gravitational sinking of organic detritus
F0703	23	a	NPP of aquatic plants and phytoplanktons
F0708	40	e	Mass transfer of inorganic C from mixed surface layer to thermocline and deep ocean
F0807	45	e	Mass transfer of inorganic C from deep ocean to surface layer
F0817	0.44	b	Sedimentation of inorganic C
F1001	10	a	Oxidative decay of rapidly exchanging C in Nonwoods
F1101	7.98	b	Oxidative decay of slowly exchanging C in Nonwoods
F1201	10	a	Oxidative decay of rapidly exchanging C in Northern Woods
F1301	7.97	b	Oxidative decay of slowly exchanging C in Northern Woods
F1401	11	a	Oxidative decay of rapidly exchanging C in Southern Woods
F1501	8.98	b	Oxidative decay of slowly exchanging C in Southern Woods
F1118	0.02	f	Deposition of organic sediments from Nonwoods
F1318	0.03	f	Deposition of organic sediments from Northern Woods
F1518	0.02	f	Deposition of organic sediments from Southern Woods
F1608	1.54	b	Oxidative decay in deep ocean
F1618	0.16	b	Deposition of organic sediments from marine organic matters
F1701	0.04	a	Outgassing from Earth's interior
F1707	0.34	a	Dissolved carbonates transferred by streams
F1801	0.03	g	Oxidation of old organics
F1804	0.2	g	Organic matters in streams

Notes:

a -- from Baes et al. (1976).

b -- by mass balancing the influxes and outfluxes of the particular reservoir.

c -- calculated as 75 percent of the marine animal consumption of 9.2 Gtons of carbon (Whittaker, 1975).

d -- 0.9 Gtons/yr is from calcareous shells (Baes et al., 1976) and the balance of 2.98 Gtons/yr is assumed to come from oxidative decay.

e -- Plass (1972); Bolin (1975).

f -- 0.07 Gtons of terrestrial organic humus is deposited as organic sediment annually (Garrels et al., 1976); this amount is arbitrarily divided among the three reservoirs.

g -- Garrels et al. (1975).

be described by a set of ordinary differential equations. Atmospheric carbon can be described by the equation:

$$\frac{d}{dt}(C1) = U + FL0701 + A1001 * C10 + A1101 * C11 + A1201 * C12 + A1301 * C13 + A1401 * C14 + A1501 * C15 + F1701 + A1801 * C18 - A0107 * C1 - FL0110 - FL0111 - FL0112 - FL0113 - FL0114 - FL0115. \quad (4\text{-}2)$$

where

$$FL0701 = A0701 * \zeta * (C7 - XIC7) + A0701 * XIC7, \quad (4\text{-}3)$$

$$FL0110 = F0110 * [1 + \beta * \ln(C1/XIC1)] (C11/XIC11), \quad (4\text{-}4)$$

$$FL0111 = F0111 * [1 + \beta * \ln(C1/XIC1)] (C11/XIC11), \quad (4\text{-}5)$$

$$FL0112 = F0112 * [1 + \beta * \ln(C1/XIC1)] (C13/XIC13), \quad (4\text{-}6)$$

$$FL0113 = F0113 * [1 + \beta * \ln(C1/XIC1)] (C13/XIC13), \quad (4\text{-}7)$$

$$FL0114 = F0114 * [1 + \beta * \ln(C1/XICI)] (C15/XIC15), \quad (4\text{-}8)$$

$$FL0115 = F0115 * [1 + \beta * \ln(C1/XICI)] (C15/XIC15), \quad (4\text{-}9)$$

A_{ij} = the rate constant defined as F_{ij}/XIC_i for $i \neq j$, and

U = the carbon input function from combustion of fossil fuels and kilning of limestone (Section 2.3).

(Other symbols are defined in Tables 4.1 and 4.2).

The changes with time of organic matter in the ocean are defined by the following three equations:

$$\frac{d}{dt}(C3) = F0703 - (A0304 + A0307) * C3, \quad (4\text{-}10)$$

$$\frac{d}{dt}(C4) = A0304 * C3 + A1804 * C18 - (A0407 + A0408 + A0416) * C4, \quad (4\text{-}11)$$

$$\frac{d}{dt}(C16) = A0416 * C4 - (A1608 + A1618) * C16. \quad (4\text{-}12)$$

Only two equations are used to describe the rate of change of inorganic carbon in the ocean:

$$\frac{d}{dt}(C7) = A0107 * C1 + A0307 * C3 + A0407 * C4 + A0807 * C8 + A1707 * C17 - FL0701 - F0703 - A0708 * C7, \quad (4\text{-}13)$$

$$\frac{d}{dt}(C8) = A0408 * C4 + A0708 * C7 + A1608 * C16 - (A0807 + A0817) * C8. \quad (4\text{-}14)$$

It is desirable to divide the organic matter in the terrestrial biota into two categories according to the carbon residence time: the rapidly exchanging carbon and the slowly exchanging carbon. Net primary productivities and respiration of the rapidly exchanging carbon in the three terrestrial reservoirs are assumed to be at equilibrium. These three equations are:

$$\frac{d}{dt}(C10) = FL0110 - A1001 * C10, \qquad (4\text{-}15)$$

$$\frac{d}{dt}(C12) = FL0112 - A1201 * C12, \qquad (4\text{-}16)$$

$$\frac{d}{dt}(C14) = FL0114 - A1401 * C14. \qquad (4\text{-}17)$$

Besides respiration, a small fraction of the slowly exchanging carbon is deposited as organic sediment. Additional fluxes are thereby incorporated into the equations for the slowly exchanging carbon of the terrestrial reservoirs:

$$\frac{d}{dt}(C11) = FL0111 - (A1101 + A1118) * C11, \qquad (4\text{-}18)$$

$$\frac{d}{dt}(C13) = FL0113 - (A1301 + A1318) * C13, \qquad (4\text{-}19)$$

$$\frac{d}{dt}(C15) = FL0115 - (A1501 + A1518) * C15. \qquad (4\text{-}20)$$

The last two equations describe the kinetics of the organic and inorganic sediments:

$$\frac{d}{dt}(C17) = A0817 * C8 - F1701 - A1707 * C17 \qquad (4\text{-}21)$$

$$\frac{d}{dt}(C18) = A1118 * C11 + A1318 * C13 + A1518 * C15 + A1618 * C16 - (A1801 + A1804) * C18 - U. \qquad (4\text{-}22)$$

4.4 Global Simulation

Using the reference model and assuming no effect from deforestation, simulation runs were performed by taking different combinations of the three factors: (i) promptness of CO_2 source peak ($n = 0.5, 1.0$), (ii) responsiveness of *net* primary production to CO_2 enrichment ($\beta = 0.0$ to 0.4), and (iii) the Revelle (buffer) factor ($\zeta = 9, 10, 11$). Not all combinations of these values were used in the study.

A similar simulation was carried out to explore possible aggravating effects of deforestation in the Southern Woods reservoirs. The values of the three factors chosen for this exploratory run were $n = (0.5, 1.0)$, $\beta = (0.2, 0.3)$, and $\zeta = 10$. Baes et al. (1976) have considered an annual cutting rate of 1 percent and have estimated that 0.2 Gtons/yr of carbon from C14 and 1.0 Gton/yr from C15 would be released to the atmosphere (C1). At the same time, 0.27 Gtons/yr from C14 and 2.0 Gtons/yr from C15 would transfer to compartment C10, and another 2.2 Gtons/yr from C15 would eventually go to compartment C11. The shifts into compartments with shorter residence times result in a prompt release of carbon to the atmosphere. Exploring this kind of accelerated impact was one of the original reasons for starting the present work.

Another simulation was run with different values for total fossil fuel reserve. Two low estimates were used in the present study in addition to the high estimate of 10×10^3 Gtons. One of the estimates, 7.5×10^3 Gtons, was about the same as the 7.3×10^3 Gtons given in Baes et al. (1976). The other estimate was 5×10^3 Gtons. The nominal values chosen for the three factors were $n = 0.5$, $\beta = 0.2$, and $\zeta = 10$.

4.5 Trial Results

Table 4.3 summarizes the estimates of atmospheric carbon obtained from the computer runs. After considering several scenarios of world energy consumption, Rotty (1976a) has estimated that 13 Gtons of carbon will be produced as carbon dioxide from fossil fuel combustion in 2000 A.D. This suggestion is adopted in the present simulation. The best fitting values for the three factors were $n = 0.5$, $\beta = (0.2 \text{ or } 0.3)$, and $\zeta = (9 \text{ or } 10)$.

Table 4.3. Estimates of Atmospheric Carbon Using Different Values of n, β, and ζ, Without Major Deforestation and with Very High Fossil Fuel Carbon Release ($N_\infty = 10^4$ Gtons, n = 0.5).

Factor			Values (in Gtons)				
β	ζ	n[a]	1960	1970	1975	2000	Approximate Maximum (Year)
0.4	10	0.5	658.1	676.4	689.8	798.1	2815.4 (2135)
	11		658.7	677.2	690.7	800.5	2857.4 (2135)
0.3	10	0.5[b]	662.2	681.9	696.3	814.0	3400.7 (2145)
	11		662.8	682.8	697.4	816.7	3469.5 (2150)
0.2	9	0.5[b]	666.1	687.3	702.6	828.7	4002.0 (2165)
		1.0				835.7	5039.5 (2135)
	10	0.5[b]	667.0	688.6	704.1	832.5	4126.8 (2165)
		1.0				839.6	4903.7 (2135)
	11	0.5	667.8	689.6	705.4	835.7	4236.0 (2165)
		1.0				842.8	5310.2 (2135)
0.1	9	0.5	671.7	695.0	711.6	849.7	4723.2 (2180)
		1.0				856.9	5675.3 (2145)
	10	0.5	672.8	696.5	713.5	854.2	4903.7 (2180)
		1.0				861.5	5866.2 (2145)
	11	0.5	673.8	697.9	715.1	858.1	5065.1 (2185)
		1.0				865.4	6033.2 (2145)
0.0	9	0.5	678.5	704.2	722.6	874.4	5330.9 (2190)
		1.0				881.8	6199.1 (2150)
	10	0.5	679.9	706.2	724.9	880.0	5561.6 (2195)
		1.0				887.4	6426.0 (2150)
	11	0.5	681.1	707.8	726.8	884.7	5770.4 (2195)
		1.0				892.2	6625.2 (2155)

Notes:

a--Carbon contents for both values of n are the same before 1974. They are slightly different after the first decimal place in 1975.

b--Parameter combinations leading to atmospheric carbon close to the 1975 Mauna Loa observation estimate of 702 Gtons.

Without deforestation, the concentration of atmospheric carbon shows an initial rapid increase in phase with the annual production curve and then a slow decline after a peak concentration is reached between 2135 and 2165 A.D. (Fig. 4-1). Values for 1960 to 1970 can be compared with the actual observations published elsewhere (Keeling, 1973b).

For A.D. 2000, estimates of atmospheric carbon soar to approximately 835 Gtons, which is equivalent to 135 percent of the preindustrial value. By A.D. 2165, the concentration of atmospheric carbon would peak between 3400 and 4200 Gtons. This represents 5.5 to 7 times the preindustrial value. However, the attainment of the various peak values depends on how the fuel consumption curve is stretched out (Keeling and Bacastow, 1977 and Baes et al., 1976, Figs. 8, 9). For $n = 1$, the peak values would be 1000 Gtons more than those for which $n = 0.5$, and they would arrive 35-40 years earlier.

When primary production of the land biota was kept constant ($\beta = 0$), atmospheric carbon levels were initially 10 percent greater than the values obtained using $\beta = 0.2$ and rose to approximately 20 percent at the peak values. The peaking time was also delayed by about 30 years.

The prediction of a 5- to 7-fold increase of atmospheric carbon in 190 years agrees with the findings of Keeling (1977) and Bacastow and Keeling (1973). This is more severe than the predictions given by other workers (Cramer and Myers, 1972; Zimen and Altenhein, 1973; Hoffert, 1974; Gowdy et al., 1975). Our Tables 4.3 through 4.5 first consider the limiting case of very high ultimate release of carbon from fossil fuels, $N_\infty = 10^4$ Gtons. Scaling back to $N_\infty = 0.75$ or 0.5×10^4 Gtons will be illustrated in Table 4.6 (see below).

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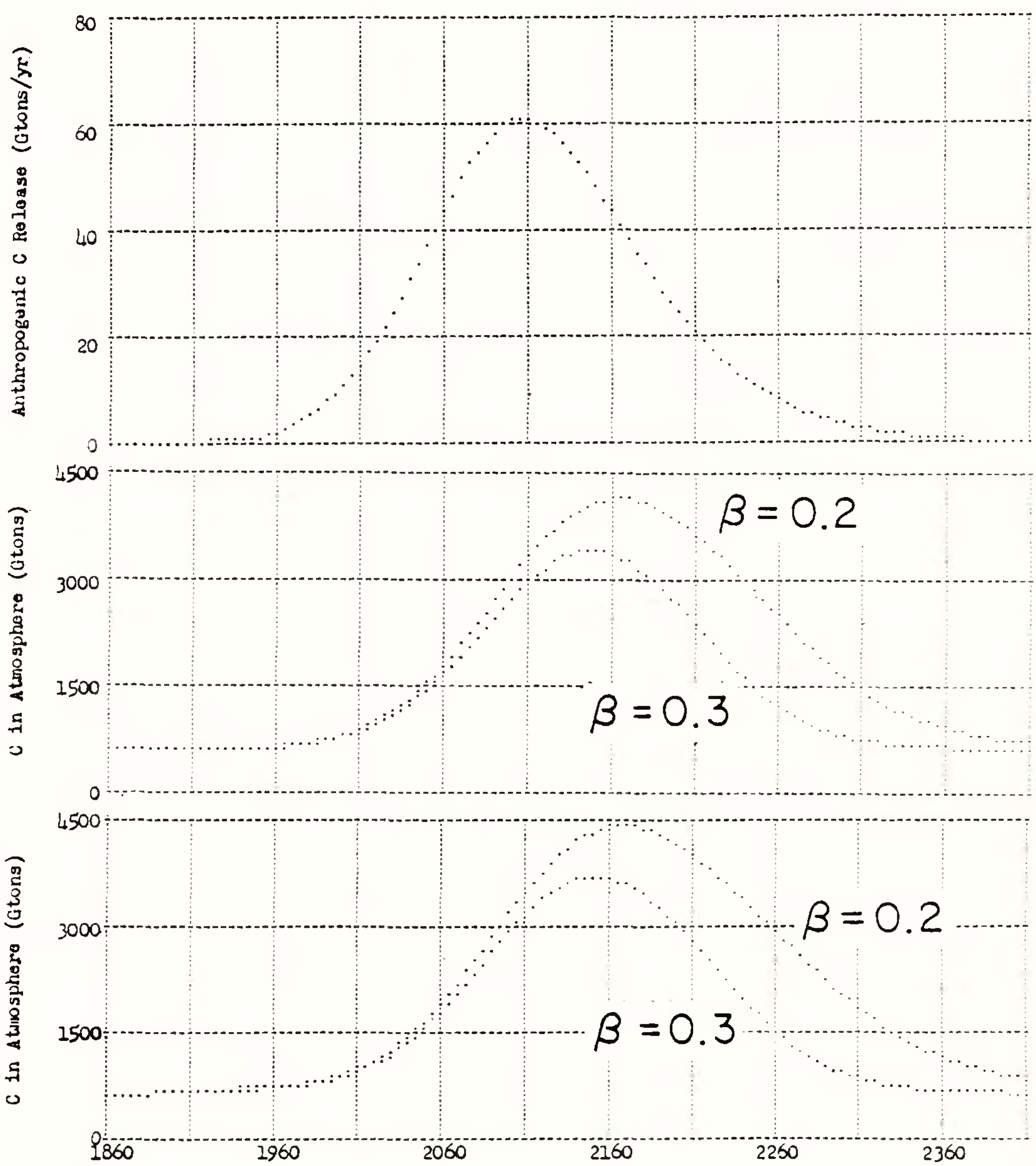

Fig. 4-1. Upper curve: Rate of production of anthropogenic CO_2 from fossil fuels and limestone plotted in units of gigatons of carbon per year. Middle curves: Change in atmospheric carbon from 1860 to 2410 as predicted by a model with different values of the biological growth factor, β. Lower curves: Same as the middle curves, but the model has incorporated an annual cutting rate of 1 percent in the Southern Woods. β denotes the fractional increase in the net primary productivity of plants relative to the increase in atmospheric CO_2. ($N_\infty = 10^4$ Gtons)

Table 4.4. Estimates of Carbon in the Various Reservoirs With Deforestation in the Southern Woods (n = 0.5).

Cpt.	β	ζ	Values (in Gtons)					
			1960	1970	1975	2000	2160	Approximate Maximum (Year)
C1	0.3	11	752.7	772.5	786.8	905.8		3766.9 (2150)
	0.3	10	750.0	769.4	783.5	900.7		3687.3 (2150)
	0.2	10	769.2	791.2	806.9	935.5		4399.8 (2170)
C7	0.3	11	591.2	592.8	594.0	603.6		840.2 (2155)
	0.3	10	592.0	593.7	595.0	605.4		857.9 (2155)
	0.2	10	593.8	595.7	597.1	608.4		922.7 (2170)
C8	0.3	11	38463	38471	38475	38504		41021 (2285)
	0.3	10	38466	38475	38479	38511		41207 (2285)
	0.2	10	38471	38481	38486	38522		42456 (2345)
C10	0.3	11	59.4	60.6	61.4	66.2	226.3	
	0.3	10	59.3	60.5	61.2	66.0	222.8	
	0.2	10	57.8	58.7	59.3	62.8	153.8	
C11	0.3	11	716.9	732.0	739.7	782.7	2031.3	
	0.3	10	716.3	731.3	738.9	781.5	2008.1	
	0.2	10	706.1	719.2	725.7	760.8	1517.0	
C12	0.3	11	83.1	84.3	85.0	90.5	294.5	
	0.3	10	83.0	84.1	84.9	90.2	290.2	
	0.2	10	80.8	81.7	82.2	86.0	201.7	
C13	0.3	11	569.8	575.2	578.2	598.3	1458.0	
	0.3	10	569.3	574.6	577.6	597.3	1441.4	
	0.2	10	561.3	565.2	567.4	581.7	1090.2	
C14	0.3	11	19.4	17.8	17.1	14.3	11.1	
	0.3	10	19.4	17.8	17.1	14.3	11.0	
	0.2	10	18.8	17.2	16.5	13.5	7.2	
C15	0.3	11	203.7	186.3	178.3	144.6	82.6	
	0.3	10	203.5	186.1	178.1	144.3	81.5	
	0.2	10	200.1	182.6	174.5	139.9	58.8	

Table 4.5. Estimates of Carbon in the Biospheric Reservoirs with n = 0.5, ζ = 10 (in Gtons).

Compartment	β	1960	1970	1975	2000	2160
C10	0.3	41.2	41.6	41.9	44.5	139.7
	0.2	40.8	41.2	41.4	43.2	100.7
	0.1	40.5	40.6	40.8	41.7	66.3
C11	0.3	545.6	547.7	549.1	561.0	1286.6
	0.2	544.1	545.6	546.6	555.1	1007.5
	0.1	542.2	543.1	543.6	548.2	752.5
C12	0.3	77.0	77.7	78.2	82.6	255.4
	0.2	76.4	77.0	77.3	80.4	185.0
	0.1	75.8	76.1	76.3	77.9	123.0
C13	0.3	545.6	547.7	549.1	561.0	1286.6
	0.2	544.1	545.6	546.6	555.1	1007.5
	0.1	542.2	543.6	543.6	548.2	752.5
C14	0.3	48.4	49.0	49.3	52.5	188.6
	0.2	48.0	48.4	48.7	50.9	130.7
	0.1	47.6	47.8	47.9	49.1	82.2
C15	0.3	526.4	528.7	530.2	543.7	1433.9
	0.2	524.6	526.3	527.4	537.0	1077.5
	0.1	522.5	523.5	524.1	529.3	766.3

Table 4.6. Atmospheric Carbon from Different Levels of Fossil Fuel Reserves ($n = 0.5$, $\beta = 0.2$, $\zeta = 10$).

Annual Deforestation Rate	N_∞ ($\times 10^3$ Gtons)	Value in Gtons 1960	1970	1975	2000	Approx. max. Value (Year)	% of preindustrial value
0%	5	667.0	688.6	704.1	828.1	2352.7 (2135)	382
	7.5	667.0	688.6	704.1	830.9	3232.0 (2155)	525
	10	667.0	688.6	704.1	832.5	4126.8 (2165)	670
1%	5	769.2	791.2	806.9	931.1	2527.1 (2140)	410
	7.5	769.2	791.2	806.9	933.9	3457.1 (2155)	561
	10	769.2	791.2	806.9	935.5	4399.8 (2170)	714

If the two Southern-Woods reservoirs had sustained a 1 percent cutting annually since 1860, even more CO_2 would have been released to the atmosphere (Table 4.4 and Fig. 4-1). The simulation predicted a 50 percent increase over the preindustrial value for the atmospheric reservoir by the year 2000 A.D. Moreover, a peak of 6 to 7 times the preindustrial level would be reached between 2150 and 2170. Peak estimates are 6-8 percent more than those from the cases without deforestation.

The present simulation showed a steady rise of carbon mass for each of the biospheric reservoirs (Table 4.5, Fig. 4-2A and 4-2B) except for the case where $\beta = 0$. Judging from the plots obtained, the simulation time was not long enough to eliminate all the transient responses. However, even under natural conditions (without deforestation), these extreme increases of biospheric storage would probably be unattainable for several reasons: first, as mentioned earlier, primary production of many natural ecosystems is limited by the availabilities of many resources; second, increasing atmospheric carbon dioxide is known to induce stomatal closure, thereby increasing the diffusion resistance of carbon dioxide to the mesophyll [e.g., stomatal closure was observed to begin at 400 to 500 ppm of ambient carbon dioxide for most plants with a C_4 metabolic pathway and at 1000 ppm for C_3 plants (Lister and Lemon, 1976)]; and finally, other atmospheric pollutants, such as ozone, acid rain, and heavy-metal aerosols, are known to have adverse effects on plant productivity (Tyler, 1972; Smith, 1974; Likens and Bormann, 1974). These and other inhibiting factors would together imply and control an upper limit on carbon production rates and storage. Killough (1977) and Chan and Olson (in press) therefore provide for such a limit in models simulating the interaction of atmospheric CO_2 and biospheric carbon.

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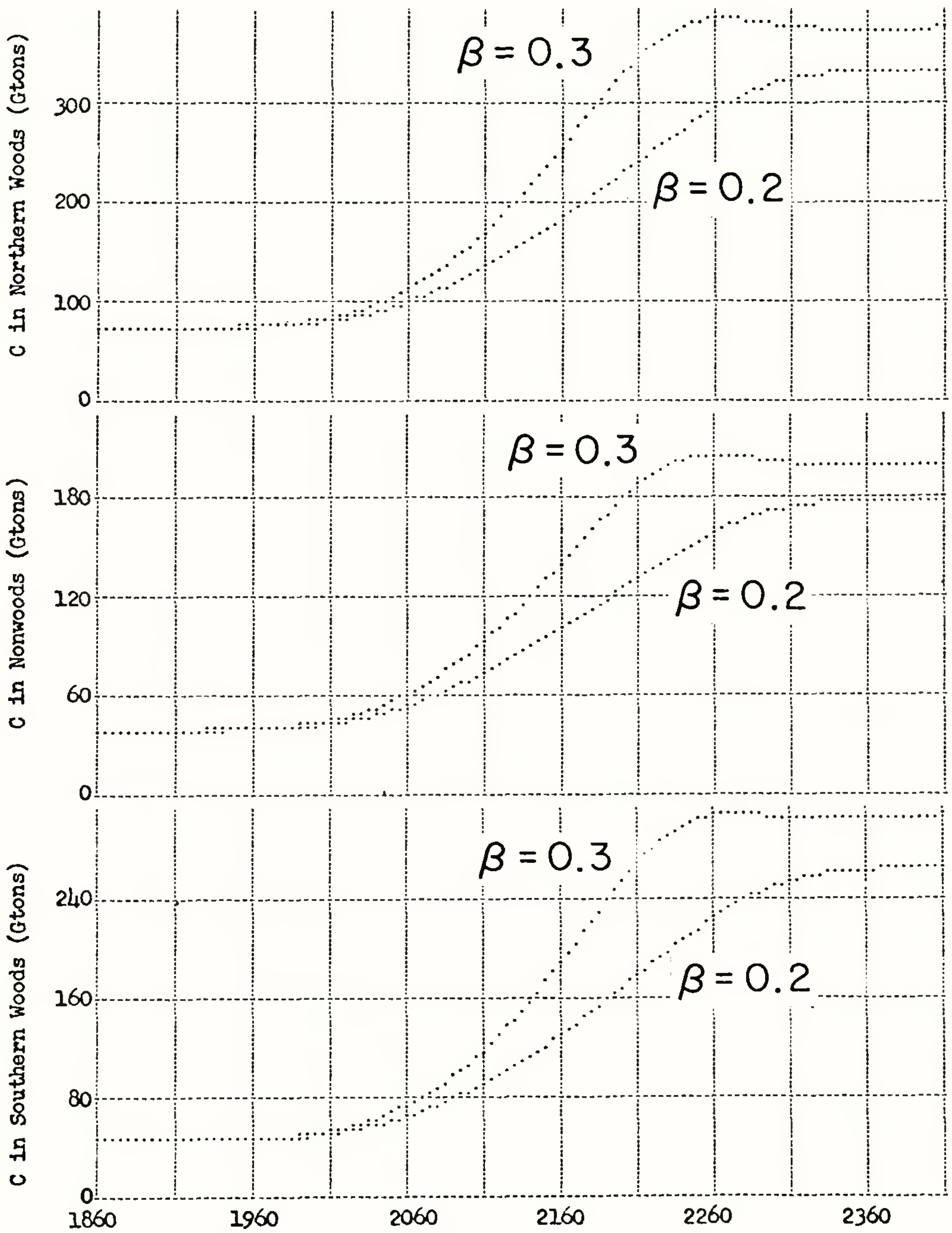

Fig. 4-2A. Increase of rapidly exchanging carbon in the terrestrial biota as predicted by a model with different values of β. Upper curves: Organic carbon in Northern Woods. Middle curves: Organic carbon in Nonwoods. Lower curves: Organic carbon in Southern Woods.

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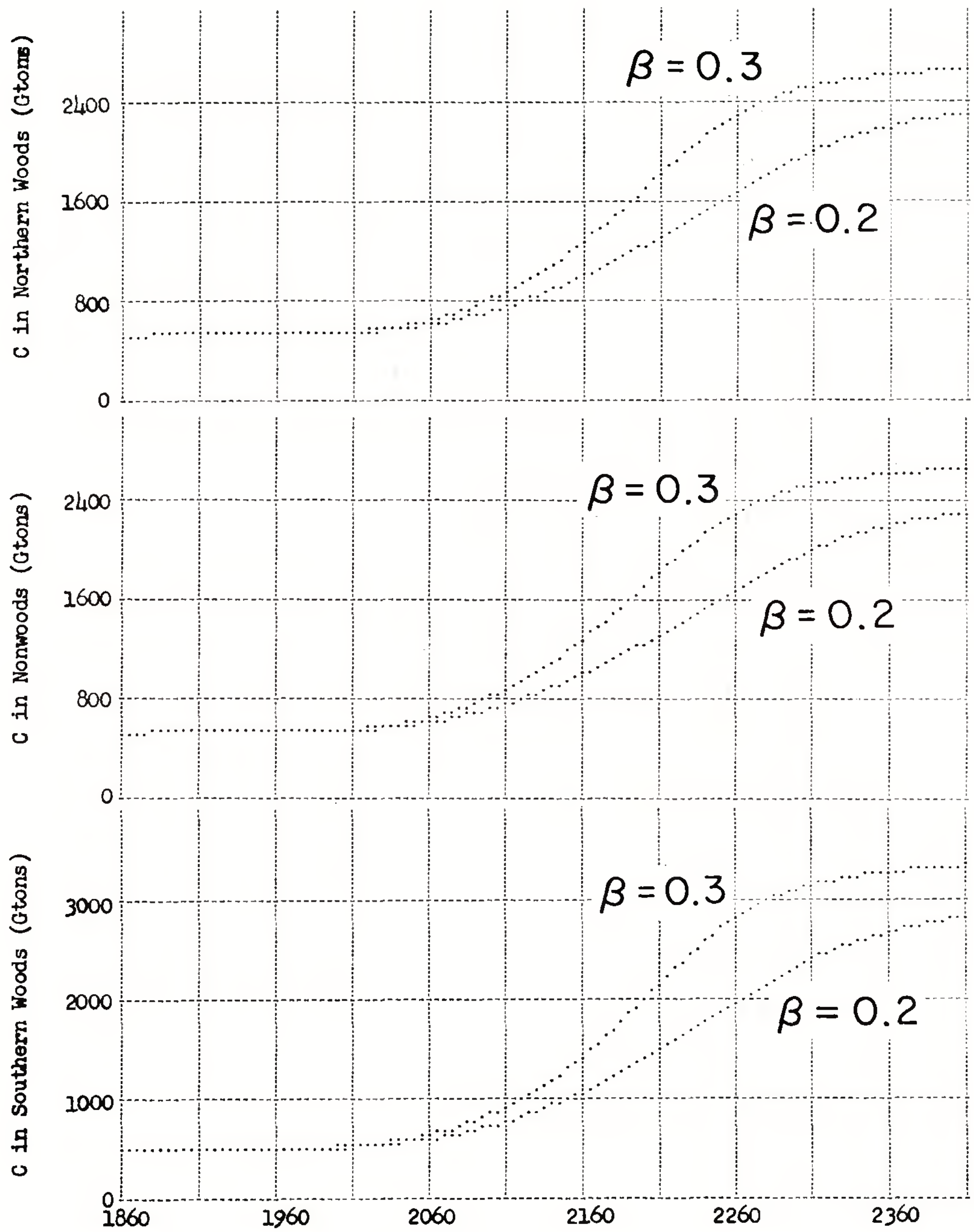

Fig. 4-2B. Increase of slowly exchanging carbon in the terrestrial biota as predicted by the same model as in Fig. 4-2A. Upper curves: Organic carbon in Northern Woods. Middle curves: Organic carbon in Nonwoods. Lower curves: Organic carbon in Southern Woods.

Obvious differences in the carbon content of the two Southern-Woods reservoirs were observed from a simulation incorporating a 1 percent annual cutting rate (Table 4.4 and Fig. 4-3A and 4-3B). As expected, the estimates for these two reservoirs declined rapidly, resembling negative exponential functions. The simulation gave an estimate of only 35 percent of the preindustrial values for the rapidly- and the slowly-exchanging carbon pools for 1975. However, these estimates are rather low in comparison to the estimated inventory of tropical moist forests given by Sommer (1976). Thus, a carefully compiled cutting rate from the land-use data is required to improve on the model's estimates.

Table 4.6 gives the estimates of atmospheric carbon from the simulation which used three levels of total fossil fuel reserves. It shows that if less fossil fuel were burned, there would eventually be less CO_2 added to the atmosphere. This difference would be comparatively small by A.D. 2000. However, it could be very large at the time of the predicted peak of CO_2 (the quantity proposed in Section 2.1 as the first objective function for optimizing an energy policy).

The range of eventual CO_2 release from fossil fuel reserves (N_∞ from 5-10 x 10^3 Gtons of carbon) spans the most credible geologic estimates of recoverable fossil carbon. Compared with the maximum value of 10^4 Gtons used in Table 4.4, the intermediate estimate in Table 4.6 is close to the total of 7.3 x 10^3 Gtons reviewed and explained by Baes et al. (1976, 1977). Contentions occasionally heard--that atmospheric CO_2 would not even double if all the fossil fuels were burned--are clearly not compatible with a carbon cycle operating like our model or like those of Keeling and Bacastow (1977), Revelle and Munk (1977), and others.

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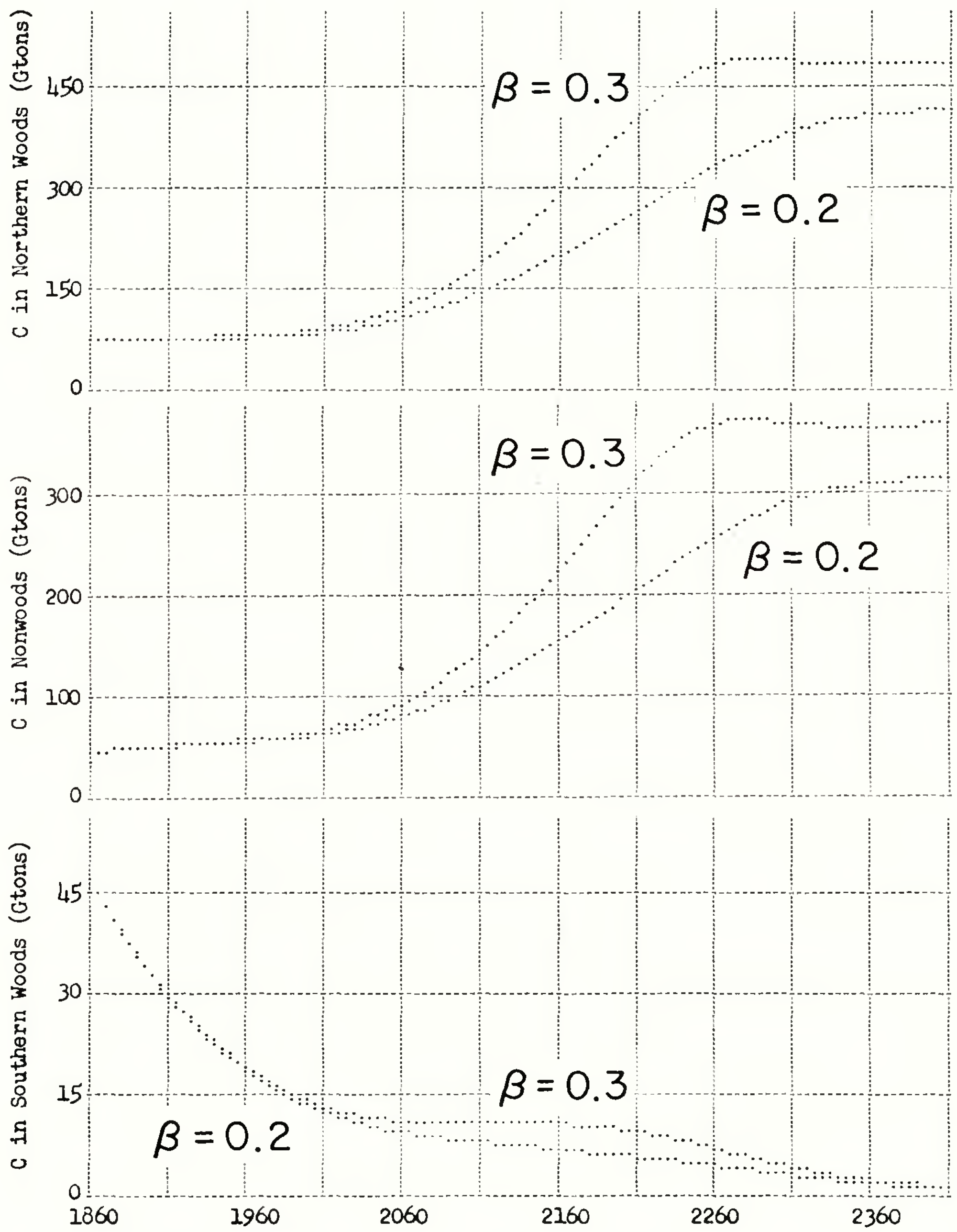

Fig. 4-3A. Increase of rapidly exchanging carbon in the terrestrial biota as predicted by a model incorporating an annual cutting rate of 1% in the Southern Woods. The curves show the results obtained by taking different values of β in the simulation. Upper curves: Organic carbon in Northern Woods. Middle curves: Organic carbon in Nonwoods. Lower curves: Organic carbon in Southern Woods.

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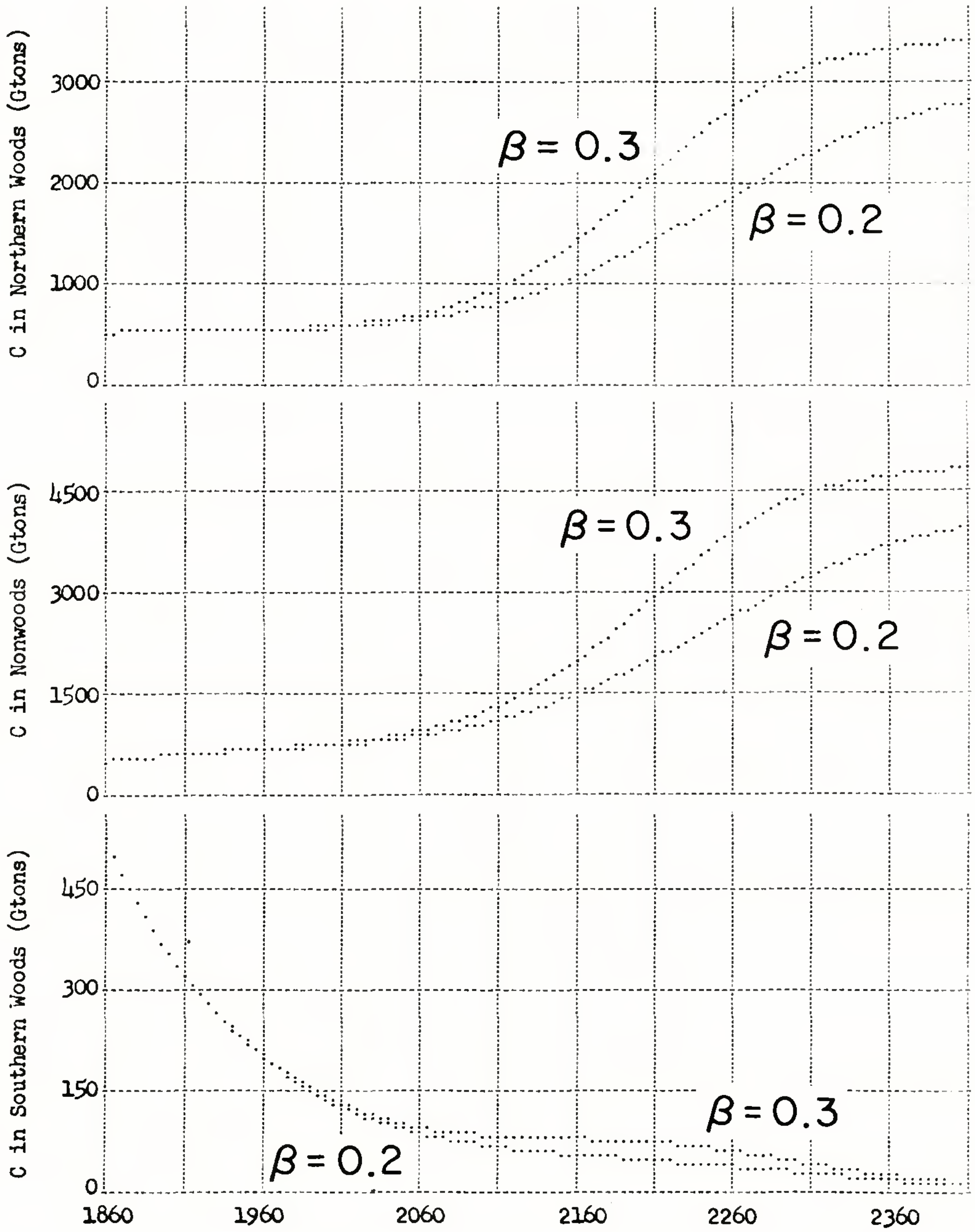

Fig. 4-3B. Increase of slowly exchanging carbon in the terrestrial biota as predicted by the same model as in Fig. 4-3A. Upper curves: Organic carbon in Northern Woods. Middle curves: Organic carbon in Nonwoods. Lower curves: Organic carbon in Southern Woods.

Even if the real reserves of fossil fuel fall within our estimated range of 5 to 10 thousand Gtons of carbon, it may become prudent policy to consider some lower fraction of this total to be used in the next few centuries for fuels and the remainder to be used for chemical feedstocks and/or for energy reserves for a very distant future. For example, the solid curve in Fig. 2-2 is Killough's (1977) projection of carbon release for a total value of $N_\infty = 3080$ (for $n = 1$). His early course of CO_2 release is close to the rising curve of release for $N_\infty = 5$, 7.5, and 10×10^3 Gtons (for $n = 0.5$). The later release rates, integrated releases, and the corresponding predicted atmospheric peaks of CO_2 given in Table 4.6 obviously depend on future constraints. It is not yet clear whether the economic costs of coal extraction, the social costs of the impacts of the CO_2 and climatic changes which we discuss in Chapter 5, or other environmental and health costs of fossil fuels will be weighed most heavily against the obvious benefits of fossil energy and of coal in particular.

It does seem clear, from our simulations and the reasons reviewed in Chapter 2, that the ocean layers are ultimately important absorbers of CO_2. They help keep maximum atmospheric concentrations from becoming even higher than the atmospheric predictions given above, even though the deeper parts of the ocean system respond sluggishly.

Carbon in the ocean's mixed surface layer closely followed the response of the atmospheric reservoir and showed the same transient behavior, arriving at the peak value at the same time. Compared with an assumed initial value of 580 Gtons, the simulation gave maxima of approximately 830 to 920 Gtons in the mixed layer, representing a 40 to 60 percent increase from the preindustrial value (Table 4.7 and Fig. 4-4). Whether

Table 4.7 Estimates of Carbon Mass in the Mixed Surface Layer with Different Values of n, β, and ζ.

Factor			Values (in Gtons)				
β	ζ	n[a]	1960	1970	1975	2000	Approximate Maximum (Year)
0.3	10	0.5[b]	584.1	585.1	587.1	597.5	832.0 (2150)
0.2	9	0.5[b]	584.9	586.9	588.4	600.8	919.2 (2165)
		1.0				601.4	1022.4 (2135)
	10	0.5[b]	584.5	586.4	587.8	599.1	897.8 (2165)
		1.0				599.7	993.0 (2135)
	11	0.5	584.2	585.9	587.2	597.7	878.9 (2165)
		1.0				598.3	967.4 (2140)
0.1	9	0.5	585.4	587.7	589.3	602.8	991.6 (2180)
		1.0				603.5	1086.4 (2145)
	10	0.5	585.0	587.1	588.6	601.1	968.3 (2180)
		1.0				601.7	1054.9 (2145)
	11	0.5	584.7	586.6	588.0	599.6	947.7 (2185)
		1.0				600.4	1027.0 (2145)
0.0	9	0.5	586.1	588.6	590.4	605.2	1052.6 (2190)
		1.0				605.9	1138.9 (2150)
	10	0.5	585.7	588.0	589.6	603.3	1028.1 (2195)
		1.0				604.0	1105.6 (2150)
	11	0.5	585.3	587.4	588.9	601.7	1006.0 (2195)
		0.1				602.3	1076.2 (2155)

Notes:

a -- Carbon contents for both values of n are the same before 1974. They are slightly different after the first decimal place in 1975.

b -- Most plausible values.

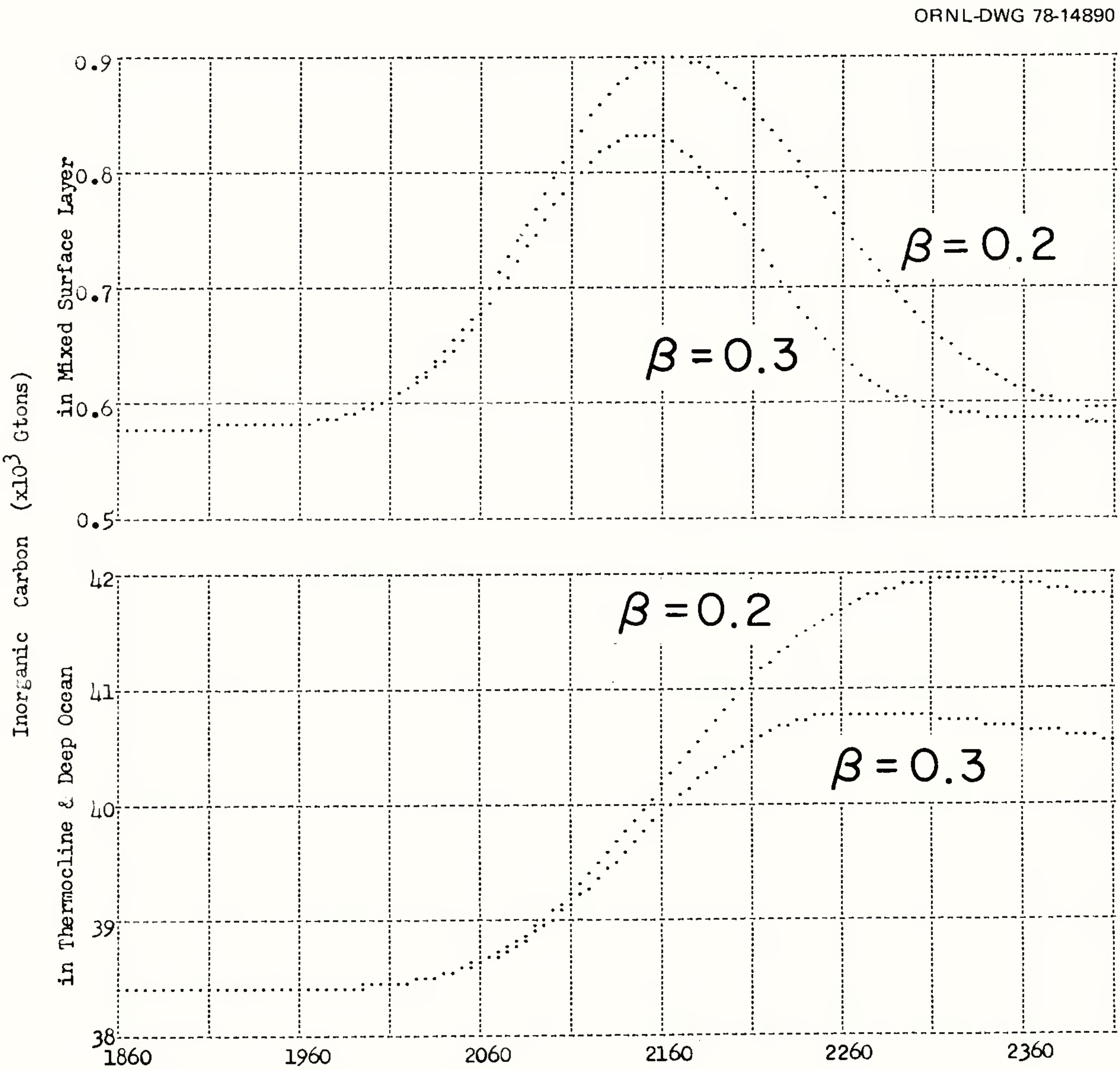

Fig. 4-4. Change in the masses of inorganic carbon in the ocean from 1860 to 2410 as predicted by a model with different values of β. Upper curves: Mass of carbon in the mixed surface layer. Lower curves: Mass of carbon in the combined thermocline and deep ocean reservoir.

the injection of this large quantity of carbon dioxide into the shallow seas would cause the dissolution of calcareous shells of marine organisms is still open to question (Fairhall, 1973; Whitfield, 1974; Moller and Parekh, 1975; Alexanderssen, 1976). These high quantities would probably not be attained, since the buffering action of sea water would lower its effectiveness for further uptake of CO_2 as sea temperature and total inorganic carbon increased. As a result, *even more carbon might be retained in the atmosphere than that projected in the present simulation.*

Projections for the combined thermocline and deep ocean reservoir (Fig. 4-4) reflected its slow residence time. Peak values showed a 6-10 percent increase over the preindustrial value, with a time-delay of ∿300-500 years. If the deep ocean were to be the ultimate sink for the excess carbon dioxide, it would take several hundred more years for the whole carbon cycle to reach another steady-state.[7]

Both the mixed layer and the combined thermocline and deep ocean would take up even more carbon if deforestation in the Southern Woods were incorporated into the model (Table 4.7 compared with Table 4.4). Comparisons of the peak values of both reservoirs with those from the no-cutting runs suggest that the mixed layer could absorb 3 percent more carbon and the combined thermocline and deep ocean 1 percent more. Comparisons of different combinations of β (biospheric response to CO_2 enrichment) and ζ (Revelle factor) suggest moderate influences on the ocean's eventual peak uptake of CO_2. However, as expected, there would be relatively little influence of these factors by A.D. 2000.

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[7]See Revelle and Munk (1977) for another formulation developed subsequently.

Further sensitivity analyses (Tomovic, 1964) of some of the parameters are now in progress to explore the validity of the model structure under parameter perturbation. Owing to the complexity and non-linearity of the model, only "brute force" calculation by computer is used at the present. In all the following sensitivity analyses, the nominal values for the three factors are taken to be $n = 0.5$, $\beta = 0.2$, and $\zeta = 10$. Only the analyses for β and ζ are given in this report.

The model was repeatedly run on the computer, varying the values of β and ζ by ± 10 percent. The responses of each reservoir were compared with the results obtained by using the nominal values. Figures 4-5 to 4-8 show the relative transient sensitivities of β and ζ as a function of time. The time courses of the coefficients given in the figures represent the percentage change of the atmospheric carbon relative to the nominal values when the perturbed parameter was increased or decreased by 1 percent.

All four figures revealed reasonably low sensitivities as the values of β and ζ were varied, although the uncertainty increased as the amount of atmospheric carbon reached the peak values. A 1 percent change in the biological growth factor incurred a maximum change of 5 percent in the carbon content of the atmosphere, whereas a 1 percent change in the buffering factor caused the atmospheric carbon to vary by a maximum of 2.5 percent.

4.6 Further Needs

Preliminary results from the present simulations reveal two major topics that require further refinement. The first topic relates to the carbon in the mixed surface layer of the ocean. As mentioned earlier, a constant buffering factor is not suitable in the long term prediction of

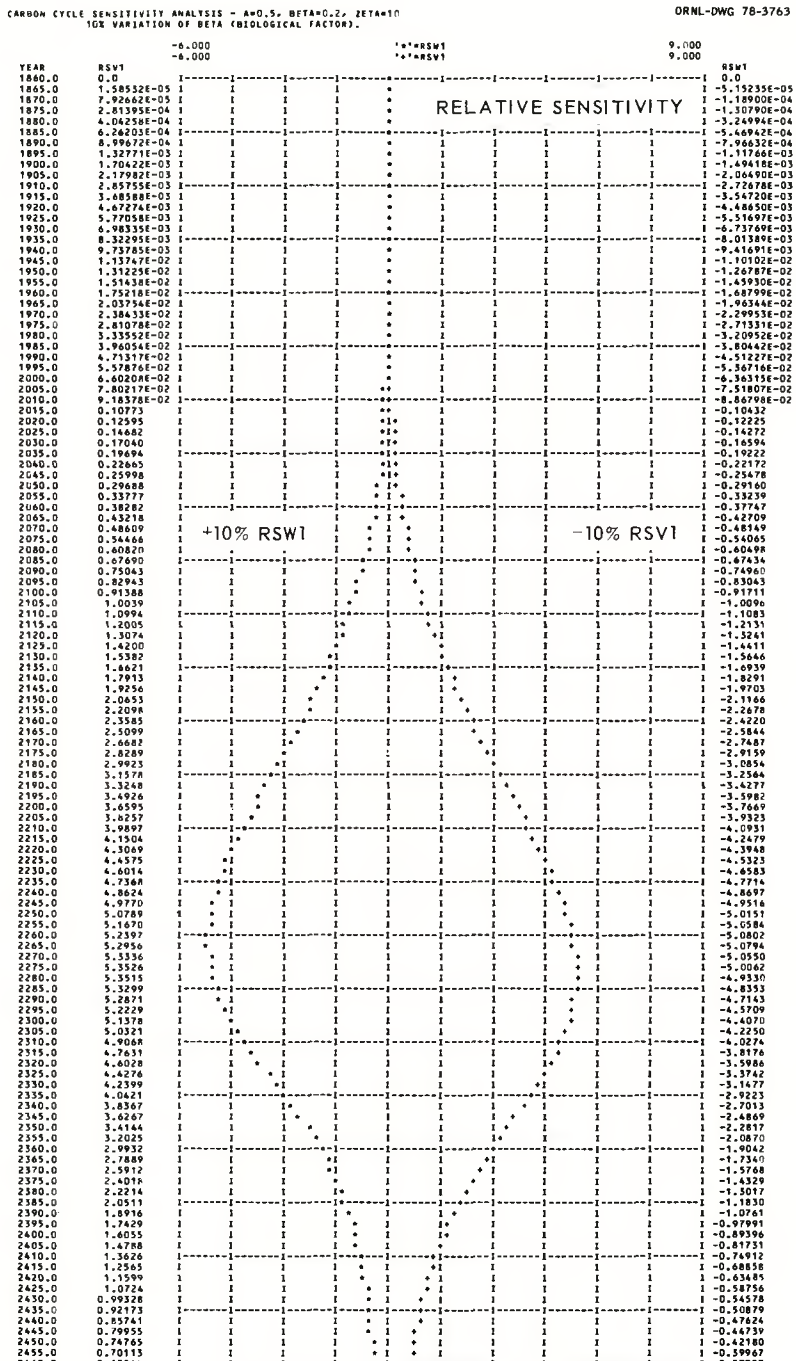

Fig. 4-5. Relative sensitivity of atmospheric carbon to changes in the biological growth factor, β. The model assumed no effects from deforestation, and used nominal values of $n = 0.5$, $\beta = 0.2$, and $\zeta = 10$. RSV1 (upper curve) = β - 10 percent; RSW1 (lower curve) = β + 10 percent.

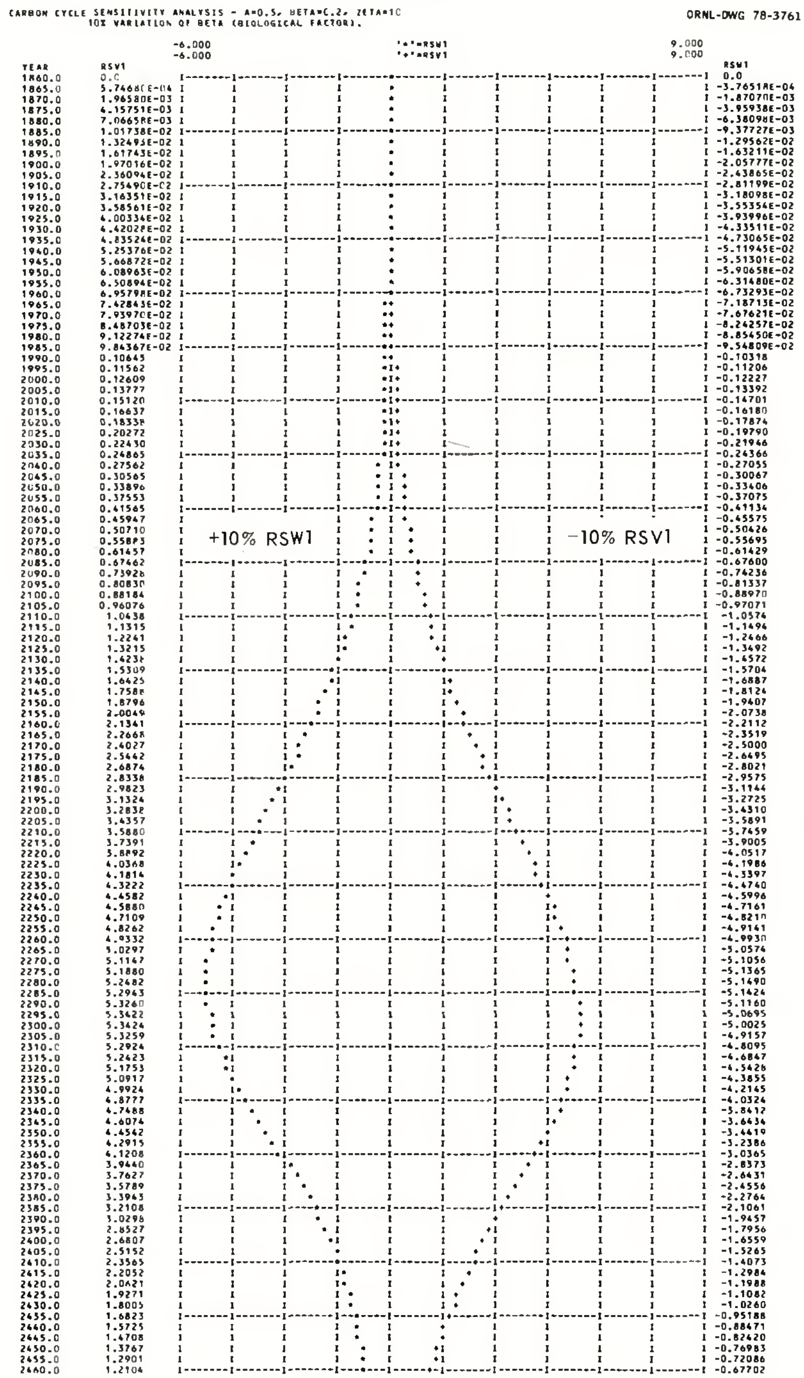

Fig. 4-6. Relative sensitivity of atmospheric carbon to changes in the biological growth factor, β. The model incorporated an annual cutting rate of 1 percent in the Southern Woods, and used the nominal values of n = 0.5, β = 0.2, and ζ = 10. RSV1 (upper curve): β - 10 percent; RSW1 (lower curve): β + 10 percent.

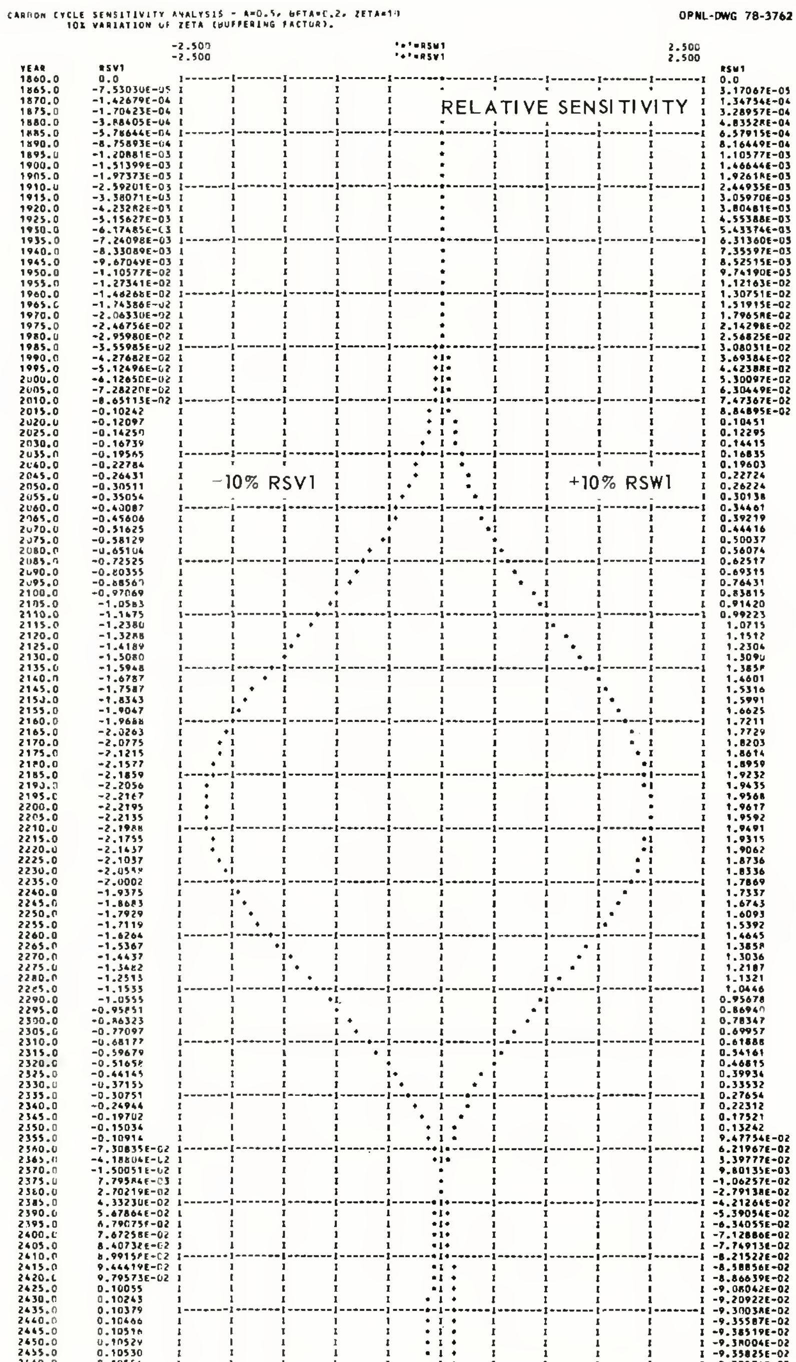

Fig. 4-7. Relative sensitivity of atmospheric carbon to changes in the buffering factor, ζ. The model assumed no effects from deforestation, and used nominal values of $n = 0.5$, $\beta = 0.2$, and $\zeta = 10$. RSV1 (lower curve): ζ - 10 percent; RSW1 (upper curve): ζ + 10 percent.

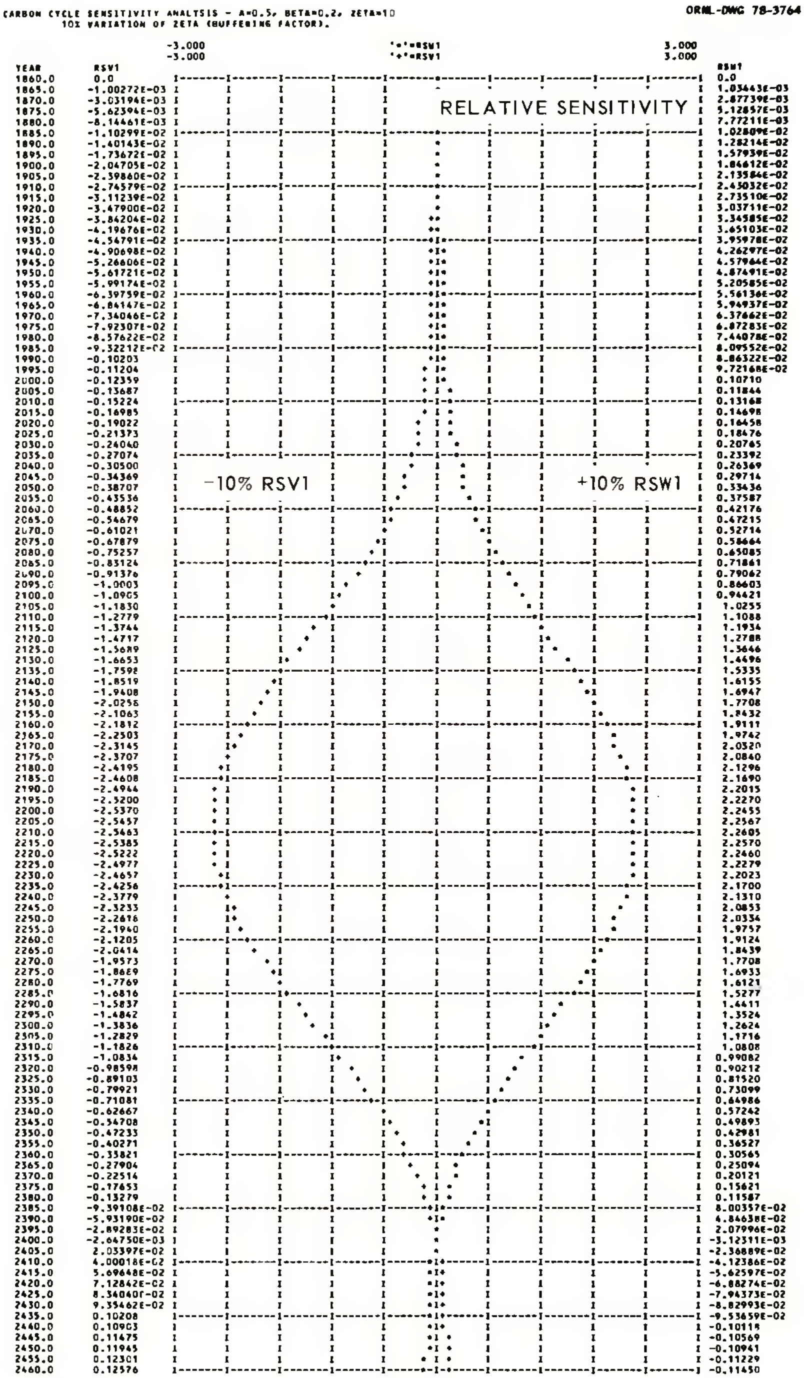

Fig. 4-8. Relative sensitivity of atmospheric carbon to changes in the buffering factor, ζ. The model incorporated an annual cutting rate of 1 percent in the Southern Woods, and used nominal values of n = 0.5, β = 0.2, and ζ = 10. RSV1 (lower curve): ζ - 10 percent; RSW1 (upper curve): ζ + 10 percent.

carbon masses in the ocean. It is obvious that more insight would be gained by adopting a varying ζ as Keeling has done (1973a).[8] Moreover, a recalculation of the transfer rates between the mixed layer and the deep ocean needs to be considered along with refinements of the ocean model currently being made by Killough and by Olson and Munro.

The second topic concerns the effects of land-use patterns on the carbon cycle. Results obtained thus far indicate that the model used in the present simulation is very sensitive to man's forestry practices. A similar observation was made by Young et al. (1973) on their own model. It is, therefore, necessary to recalculate the actual cutting rates of the Southern Woods reservoirs as accurately as possible. Even if we are correct in assuming much less recent clearing in temperate forests than in the tropics, a refined model should explore the possibility that gains and losses of forest area are not in balance (as we have assumed here for simplicity). Table 2.2 tentatively suggests significant clearing of live carbon in all regions between 1860 and 1970, even though the tropical forest may be subject to much more rapid clearing in recent decades and the near future.

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[8]Olson and Killough (1977) have presented a recent model which recognizes the dependence of ζ on temperature and which also provides for changes in photosynthetic input to woody and nonwoody biomass as atmospheric CO_2 changes. (Abstract in Eos 58:808.)

CLIMATIC CHANGE AND IMPACTS

More attention is currently being directed toward understanding and predicting climatic change than toward evaluating the consequences of such change once it occurs (Baes et al., 1976, pp. 39-66). Improved capability for predicting significant change in climatic averages and patterns is necessary for many reasons (e.g., transportation, effect of fluorocarbons, etc.) besides those of energy (CO_2, particles, excess heat) (Kellogg, 1975, 1977a, 1977b). It is also important to determine the ecological and social impacts of any such change, regardless of which human and natural perturbations are interacting.

5.1 Natural Variations in Climate

Recent developments suggest possible bases for predicting certain natural climate changes, but these changes are either much slower or smaller than those related to increased CO_2. The Milankovitch theory of glacial-interglacial climatic alternations correlates with some of the slow changes recorded in deep sea cores with their sedimented layers of foraminifera microfossils (Hays et al., 1976). The dominant period of about 100,000 years matches the length of the known cyclic change in the Earth's orbit from more nearly circular (at cold times) to more elongated (leaving the Earth nearer the sun for a longer fraction of the year in interglacial times, which include the present). A 42,000-year cyclic component matches changes in the tilt of the Earth's spin axis with respect to the plane of the solar orbit. A low tilt is followed by warmer summers and colder winters, with more ice melting during the summer than accumulates each winter. A 19,000 to 23,000-year fluctuation (not quite periodic) related to precession of the equinoxes adds to the complexity of the total record when these predictable but uncontrollable factors are superimposed. While inclusion of these factors could create more confidence in long-range climatic predictions, the onset of the next full glacial is so far beyond conventional projections of fossil fuel depletion (Fig. 2-2) that one can hardly contemplate CO_2 increases as being available as countermeasures against that glaciation.[9]

Astronomic causes related to the magnetism and energy of the sun itself (Eddy, 1976) suggest 11- and 20-22-year alternations in upper atmospheric energy relations and ultimately in climates on the Earth's surface. Repetitions of the dustbowl of the 1930's and 1950's had been expected around 1977 for midcontinental North America. However, the simultaneous occurrence of drought in the West and extreme cold in the East in the winter of 1977 illustrated the difficulty of coping with even minor fluctuations: those mentioned above are milder than changes resulting from glacial-interglacial astronomic causes, and are probably much milder than climatic changes related to the CO_2 increases predicted in Chapter 4. Even the historic cool periods of many decades (when solar activity was generally low) involved fluctuations of 1°C or less. Volcanic dust has less predictable effects, mostly in the direction of global cooling (SMIC, 1971), but unless future eruptions are clustered in a surprising way, this influence would be as brief as those related to the solar fluctuations.

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[9]A technocratic world which did not discount the options required 3000 years from now would save fossil fuel use for that time! The National Academy of Sciences (1977) urges that this policy of very long-range conservation of fossil fuels be considered more seriously for present energy policy.

5.2 Human Impacts from Energy on Climate

5.2.1 Heat Generated from Technology

We do not dismiss the ultimate importance or local impact of sources of intense waste heat (i.e., power "parks" or clusters). Yet, scientists analyzing thermal effluents find that global changes from these sources are probably further in the future than the impacts from particles and CO_2 (National Academy of Sciences, 1977).

5.2.2 Particles from Pollution

Palmer (1973) and others have emphasized that there are various indirect effects of aerosols (e.g., providing nuclei for precipitation) that affect clouds and heat budgets. The quantitative effects of clouds and particles may be quite variable, depending on the altitude of the particles and clouds and on their relation to underlying surfaces of high reflectivity (ice, desert) or low reflectivity (vegetation, ocean). Particles could either counteract or reinforce the net warming influence of increased CO_2 on the thermal balance of the Earth. The Energy panel of the November 1976 meeting on "Living with Climatic Change" (MITRE Corporation, 1977) reached a consensus that particles as well as waste heat probably constitute a risk of a lower order of magnitude than the risks related directly or indirectly to CO_2.

5.2.3 Carbon Dioxide and Climate

Effects of carbon dioxide on climate may already be present, but may be submerged in variations related to the preceding factors or in random fluctuations ("noise"). However, almost any of the carbon models discussed above will eventually have CO_2 increases so large that the mean warming can be expected to equal and then considerably exceed all the chilling factors put together.

Two scenarios of Baes et al. (1976, Fig. 10, no. 1 and 2) bracket a range of fossil fuel use that is generally more conservative than the range shown in Fig. 2-2. Both scenarios allow for the possibility of extra CO_2 release from forest clearing as well as the opposite possibility of substantial increase in fixation of excess CO_2 by enrichment of photosynthesis.

Fig. 5-1 (from Fig. 12 of Baes et al., 1976) also allows for the possibility of changing the airborne fraction over a range of 40 to 60 percent. In all cases, the high burning scenario increased the atmospheric CO_2 to four or more times the present level. The plausibility of such change was confirmed by Chapter 4 of the present report and also by Killough (1977).

A sudden reduction in the expansion rate of CO_2 release--from 4.6 percent per year to 2 percent--followed by a symmetrical *decrease* in fossil fuel burning after 2025 A.D. is taken to be a lower limiting scenario. However, even this level of combustion implies a 60 to 110 percent increase in atmospheric CO_2 over the late 19th century level by 2075 A.D., depending on assumptions about concurrent land-use changes and percent retention of the released CO_2 in the atmosphere.

The right axes of Fig. 5-1 illustrate the wide uncertainty climatologists have about the average surface temperature response (ΔT of 1 to 5°K, for a doubling of CO_2, depending on the importance of several positive and negative feedback processes). The temperature response is stated in a different way in Fig. 5-2, where cross-hatched area 1 shows the range of possibilities encompassed by these temperature uncertainties for the upper scenario line of Fig. 5-2 and represents the assembled

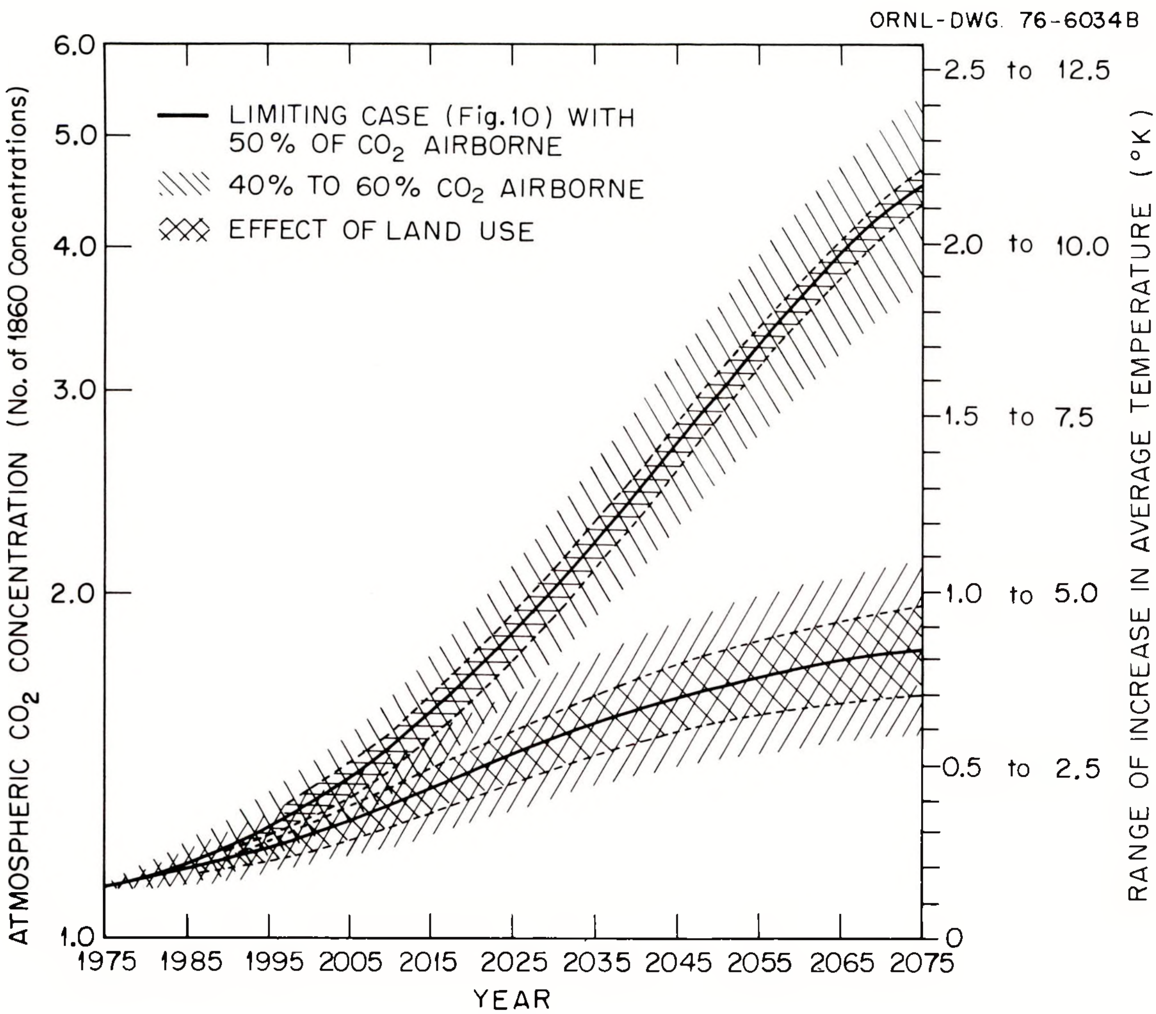

Fig. 5-1. Projected atmospheric CO_2 concentrations and possible changes in the average surface temperature, assuming either low sensitivity to CO_2 (1°C per doubling) or high sensitivity (5°C per doubling). An intermediate range (3° ± 1°C) seems a far more probable response than either of these extremes.

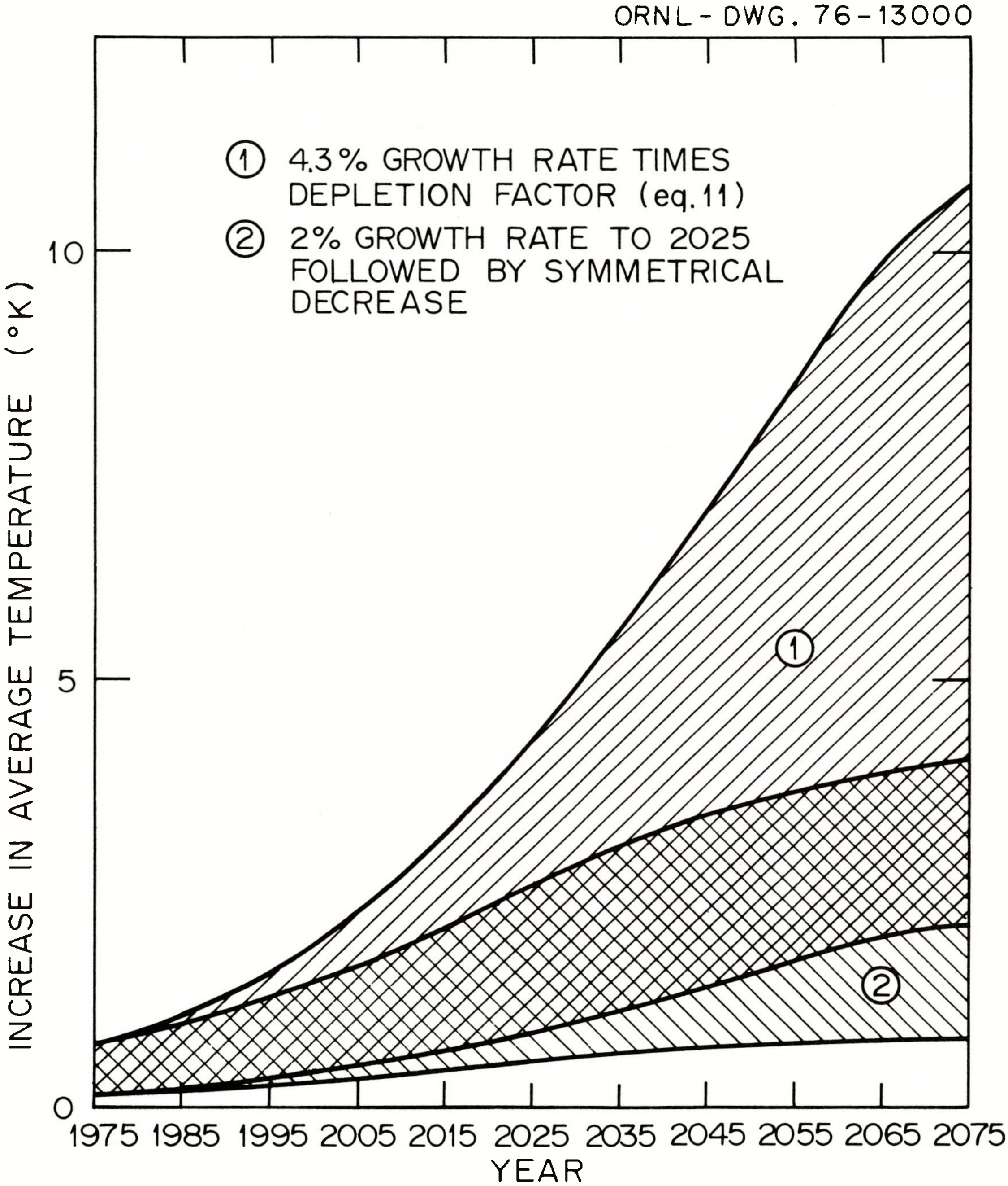

Fig. 5-2. Projected range of increase in average surface temperature for the limiting cases of fossil fuel use. ΔT = 1 to 5°K per doubling of CO_2 concentration (Baes et al., 1976, Fig. 13).

upper limiting case for the future. Cross-hatched area 2 shows the range for the lower limiting case and is probably unrealistically low. The double cross-hatched region represents an area of mean temperature trends that seem plausible for either the high scenario (in combination with a low temperature response) or the low scenario (in combination with high temperature response). *Many intermediate scenarios and net temperature responses that are inherently more probable than either extreme could lead to trends within the same double cross-hatched area.* This area thus deserves particular attention in future workshop explorations of biological impacts.

5.3 Some Impacts on Man and His Environment

Acceptance of the theory that increased atmospheric CO_2 will result in global warming raises questions concerning the effects of such warming and of the related changes in climatic pattern.

5.3.1 Changes in Biological Productivity

In those subtropical and temperate regions having abundant and stable precipitation, a longer growing season with higher summer temperatures could significantly improve the harvestable yield of some crops. For other crops, however, the increase of respiration could exceed the increase of photosynthesis, and the net primary production and yield of these crops would decrease [Equation (2-3)]. Such decreases in yield also seem possible in the tropics where P and R are already high, even though temperature changes will be smallest there.

In the Boreal zone, podzolic soils (on formerly glaciated terrain) are generally poor, and a high input of care and fertilizers would be needed to take advantage of the longer growing seasons. The average climatic warming in this zone is expected to be greater at high latitudes than at low latitudes, possibly by several degrees C. A northward shift of crops would not necessarily be *consistently* rewarding for agriculture, since risks from frost would still make yields uncertain in many years as the new northern limits of growth were reached. In addition, costs of facilities and tillage may not all be recovered in new marginal areas, but instead may be invested more profitably in areas which are presently marginal, e.g., in southeastern Canada.

5.3.2 Possible Drought Increases

Warming automatically increases evapotranspiration and thus demands enhanced water supply if the water balance formerly achieved under cool conditions is to maintained. It may be premature to judge whether mid-continental warming would also be accompanied by drying and by an enhancement of the fluctuations in moisture supply that are typical of continental climate. If these did result, however, "dust-bowl" droughts could significantly increase the risks to agriculture in the semiarid regions for more years than has been usual in the Great Plains drought cycle. Wheat may have to replace maize on the tallgrass prairie soils, and the corn belt might be shifted to parts of the maritime climate belts where rainfall increased. Even more complex changes might occur if storm tracks shift. It seems improbable that many areas would get enough *increase* in rain to make up for the above-mentioned losses from evapotranspiration.

5.3.3 Changes in Regional Hydrology

Warming increases evaporation from people and other animals, from plants, and from soils. After replenishing the extra moisture lost by vegetation, soil moisture has less drainage to groundwater reserves.

By A.D. 2025, it seems credible that the shifts of climatic pattern could be broad enough to cause changes in the water balance of whole states and geographic regions. Many categories of fuel development (i.e., oil shale and western coal) might then be held back because of unreliable surface and underground water supplies. Thus, agricultural and public use of limited water reserves may put an upward boundary on the U.S.A.'s part of the rate of releasing CO_2 (Table 2.1).

5.3.4 Human Effects

Human health and behavioral patterns might be changed in many ways. In a crowded world, nutrition, for instance, would be affected by many agricultural changes. Some medical changes would occur in the tropics where most people are already accustomed to hot weather and where additional warming is expected to be less than in the midlatitudes. In areas outside the tropics (>30° latitude), warming would result in more comfortable winters, but would also increase risks of heat exhaustion, heat stroke, heat stress and debilitation of people with chronic illnesses during heat waves in the hotter summers, thereby increasing rates of premature death in some areas. In urban settings, irritability, aggression and intolerance of crowding are likely to increase under the anticipated warmer conditions. These physiological and emotional problems could be redressed by emigration poleward in an attempt to stay with accustomed climates and/or by expanded air conditioning. However, the latter would add to the demand for fuel consumption, and would thus hasten the rise of the high CO_2 scenario projected for the early 21st century. Perhaps society's decision makers would finally have to conclude that in a regime of increasingly expensive energy, with organic carbon too precious to use as an energy source, such luxuries as air conditioning could no longer be shared by all.

5.3.5 Far-reaching Indirect Biological Effects

The possibilities outlined above deserve scrutiny regardless of the exact extent or timing of their eventual occurrence. However, indirect biological effects could prove more damaging to man and society than the more obvious direct impacts.

Failures of wild species to complete their life cycles (for many physical and biological reasons) would be followed by life zone shifts in some cases, with species tracking the movement of climate to new geographic belts. "Weedy" species might thrive where balances of competition have been upset. Some native plant and animal populations would start the long course toward extinction. Usable resources might be upset because of pest and disease problems aggravated by the loss of former climatic and biological controls (e.g., southern pine bark beetle). Retreat of the spruce-fir zone northward or to the high mountain refugia would be hastened by other pests such as the balsam wooly aphid (Becking and Olson, in press).

Genetic changes of wild and domesticated species, and possibly of humans, would become accelerated as old adaptations became obsolete. The fittest people would be selected for toleration of high temperature, high social pressures, and possibly for abandonment of the individualistic initiatives which had been cherished before A.D. 1984.

5.3.6 Lowering of Lake Levels

Long before the rise of sea level from melting glaciers becomes obvious to society, we expect there would be noticeable changes of inland water levels because these levels are far more sensitive to either a wetter or a drier regional hydrologic balance (Section 5.3.3). Net warming and evaporation would probably mean a net lowering of many inland waters, with devastating results. Lowering of the Great Lakes would cause severe navigational and sewage disposal problems, such as those experienced by Chicago during the last natural low fluctuation of Lakes Michigan and Huron (1964). Economic analysis of this contingency would show many millions (perhaps billions) of dollars at stake, considering (a) the investment for replacing unusable facilities, (b) existing legal compacts that may have to be over-ridden at municipal, state, national, and international levels of government, and (c) the importance of the time element in completing the necessary adjustment if these changes should indeed turn out to be inevitable (Rockefeller Lake Superior Project, 1976, a, b, c,).

5.3.7 Acceleration of Sea-level Rises

Estimates of glacial ice volumes and their sealevel equivalents in Flint's (1971) Table 4-E suggest that it would require melting of only 10 percent of the Antarctic glacier plus 20 percent of all the other glaciers (mostly Greenland) to raise the sealevel 7.2 meters. Tangible records of the ocean reaching this level before the last (Wisconsin) glaciation, in perhaps Sangamon or Eem interglacial time, are evident in the so-called Pamlico shore features along most of the Atlantic and Gulf coasts of the United States (Fig. 5-3). Evidence derived from the biological indicators of that period for the Alps, Netherlands, Czechoslovakia, Southeastern Europe, and Toronto implies temperatures only 2 to 3° warmer than present climates (Flint, 1971, Table 16-D).

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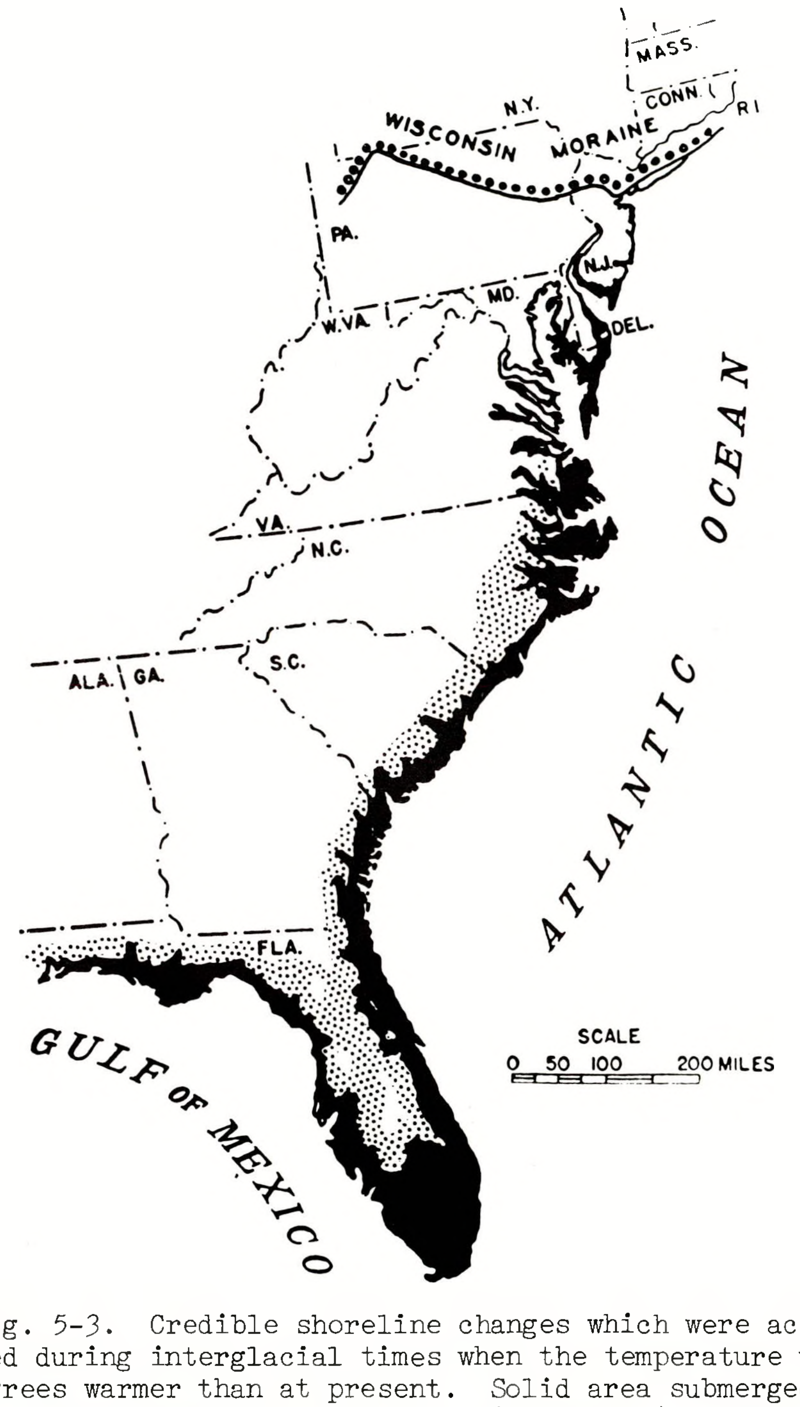

Fig. 5-3. Credible shoreline changes which were actually attained during interglacial times when the temperature was a few degrees warmer than at present. Solid area submerged by Pamlico or Princess Anne shore, ∿8 m (Sangamon?). Dotted area submerged by Wicomico shore, ∿30 m (Yarmouth?).

Many kinds of geologic and historical evidence confirm that moderate amplitudes of temperature oscillation in the tropical oceans (e.g., 5°C between typical glacial and interglacial times) are accompanied by larger oscillations (2- to 3-fold?) at high latitudes, especially in continental areas or in regions where the moderating influence of water has been masked by freezing. The most sophisticated global climatic modeling (Manabe and Wetherald, 1975) likewise suggests a warming of 8 to 10°C at the high latitudes that control glaciers, even if there is only an average rise of 3°C per doubling of atmospheric CO_2. With two or more doublings of CO_2 projected for a sustained period by most of the newer carbon models, commonplace conjectures about glacial melting and sealevel rise take on a credibility that is not usually examined or acknowledged.

According to Gribbin (1976), the possibility of surges in Antarctic ice melting could raise sea levels suddenly, perhaps by 5 meters in 300 years. This implies such a high economic and political risk that the whole question deserves closer scrutiny even though the probabilities for imminent change seem fairly low. Bolin (1975b) anticipated melting for sealevel rise on the order of mm per year, but even that adds up to decimeters per century. In essentially flat coastal areas, a few decimeters would imply submergence at mean sealevel or at high tide of vast areas of now valuable property.

Furthermore, the losses through property damage will not be as gradual as the creep of mean sealevel. Damage will be felt suddenly over wide areas during coastal storms which will reach meters above the rising mean sealevel and cause billions of dollars of damage in a few hours. Obviously, some of this kind of damage would be occurring sporadically anyway and has to be accepted by insurance companies, commercial firms, citizens, and the government, whether or not sea levels rise. But, if these parties continue to gamble on more and more intensive development of coastal areas, the cost of insurance premiums, bankruptcies, personal losses, disaster relief, and redevelopment expenses will be added to similar costs arising from agricultural catastrophes. Bolin's (1975b) map reminds us that the world's seaports, many of the largest cities, much of the richest farm land and a large fraction of the Earth's population are located within reach (50 to 70 m altitude) of glacial melt-water, should a sudden warming trigger major melting of the Antarctic glacier over a longer period of centuries.

5.3.8 Sociopolitical and Moral Impacts

The foregoing list may remind the reader of other possibilities of tangible or intangible loss. Some of these may be at least as important as the examples listed above and by Baes et al. (1976, 1977). Some effects will be anticipated, and perhaps even realized, as being beneficial for certain sectors of the national or world population. However, most effects will involve a disruption of existing adaptations by natural systems, of resources depending on these systems' stability, of economic systems which have already made their market adjustments, and of political systems which seek compromises to retain the familiar instead of facing the unfamiliar.

Just as random mutations almost always decrease the fitness of a finely tuned genetic system, sudden man-made environmental disruptions of ecosystems, agriculture, and society will probably outweigh particular benefits (lengthened growing seasons, diminished winter fuel bills, etc.). *Some repercussions and interactions will dawn upon their victims with far more surprise and force than the 1977 cold in the eastern states or the 1977 drought.*

Even if we become certain that panhandle dustbowls will become worse or that a significant fraction of Florida will be submerged, who is to decide that these risks outweigh the profit from using Wyoming's coal quickly or from expanding Quebec's agriculture far northward? Internationally, how would the submergence of much of the Netherlands be weighed against the benefits of having synthetic fuels available at rates equal to or greater than the current rates of use of natural gas and petroleum for a few generations after the latter energy sources are nearly gone?

One conventional moral principle is that humanity should forego those gambles that are so great and so sudden that they outweigh natural disasters which can be deplored and then patched up by charity. If the benefits of continued fossil fuel expansion are perceived as so overwhelming that they warrant taking comparable risks, then a minimal obligation would seem to include planning to cope with the uncertainties and with the worst possible set of outcomes, however disagreeably and sceptically the required analyses may be received in bureaucratic and legislative circles.

CONCLUSIONS

Specialists on the carbon cycle and climate are expressing deepening concern as global monitoring confirms their predictions that the atmospheric increase of CO_2 is real and will get much steeper and higher before it tapers off. Team assessments (SCEP, 1970; Reiners et al., 1973; Baes et al., 1976, 1977) have attempted to put the various aspects of the global problem in perspective and have made recommendations for firm action which is long overdue.

At present, actions on research and on filling specific gaps in the overall assessment are being emphasized. Scientists are reluctant to urge social actions each time an analysis raises new questions, but our findings and previous results (see citations in Olson, Allison, and Collier, 1977) suggest that the nation's contingency plan should already be scrutinizing the impact of drastic shifts in policy on fossil fuel and other energy sources and uses.

Technical support of such contingency planning will require a better systems analysis of how the carbon cycle, climate, ecosystems, and society operate, both separately and linked. Such support must examine the conditional probabilities that follow from the several quite different scenarios which humanity might choose, regardless of whether or not the real choices take any scientific view of the models. If the supporting data and analyses do build up enough confidence to invite attention to operations research, geophysics, and ecology, then the informed community will need all the lead time it can possibly get to take the next steps toward attempting to formulate and approach an optimum scenario.

6.1 Inputs to the System

It is natural for meteorologists to select the atmosphere as their main system of professional responsibility and to view the rest of the earth and the solar system as "environment" for it (WMO, 1974). From the viewpoint of the whole earth as a system, some of the inputs become flows inside the system. Thus, total analysis requires more holistic approaches.

6.1.1 Geologic Input

Reviews (Baes et al. 1976, pp. 8-10; Garrels, Lerman, and Mackenzie, 1976) of earlier work tend to suggest that the "exogenic cycle" involves volcanic releases as well as releases from the main lithosphere that were slow until man started exploiting fossil fuels. Refined estimates are of definite interest for past equilibria and for posterity's long-range prospects and might also be of interest for linking to atmospheric aerosol estimation.

6.1.2 Fossil Fuel Burning

The release of fossil fuel reserves to date has been such a small fraction of the total supply that many choices of release can still be made. For example, the inaccessible thinner (and more expensive) beds of coal and oil shale might be saved for much later generations than are assumed in Fig. 2-2. The release (for energy) of 3080 Gtons of carbon (assumed by Killough, 1977), or of even lower amounts, may be much nearer to a socially responsible use of fossil fuel resources than the 5000, 7500, or 10,000 Gtons/yr illustrated in that figure. Changes in coal use strategies [reflected in lower values for n in Equation (2-2) or higher values for A in (2-1)] would stretch out the choices left for posterity in addition to diminishing the whole suite of risks that will follow from an excess of CO_2 (e.g., Fig. 6-1, 6-2).

6.1.3 Biomass Oxidation

Detailed regional information on intentional burning of wood and organic debris needs closer scrutiny. Wood and charcoal burning is a fairly small fraction of the total burning estimated for various areas (Earl, 1975). Baes et al. estimated that burning released 7 Gtons per year (implicit in Figs. 2-3 and 2-4) and gave wide limits of uncertainty (±4 Gtons/yr) around that estimate. Refinement of their estimate is needed. Hutchinson (1954) and Robinson and Robbins (1970), on the other hand, assume considerably less burning. We expect that future estimates will be between the latter estimates and ours for the time preceding the recent accelerated clearing of land.

In the future, it would be ideal for humanity to derive more energy from the non-fossil organic material that would be burned or otherwise decayed without human use of fermentation products. A Man and Biosphere project (MAB-UNESCO) to evaluate this possibility for forests deserves immediate attention. The constraints of accessibility and the net energy balance (a comparison of fuel use and cost with derived value and energy) may keep this resource at a fairly modest level, more important in those nations which have low cost labor than in others. Earl's economic analysis offers a good step toward operations research for this industry, but the externalities (nonmarket costs to environment and society) could be high, and careful ecological assessment is required.

On nonforest lands, crops, such as cassava in Brazil, are already being expanded for alcohol fermentation for liquid fuel, supplementing

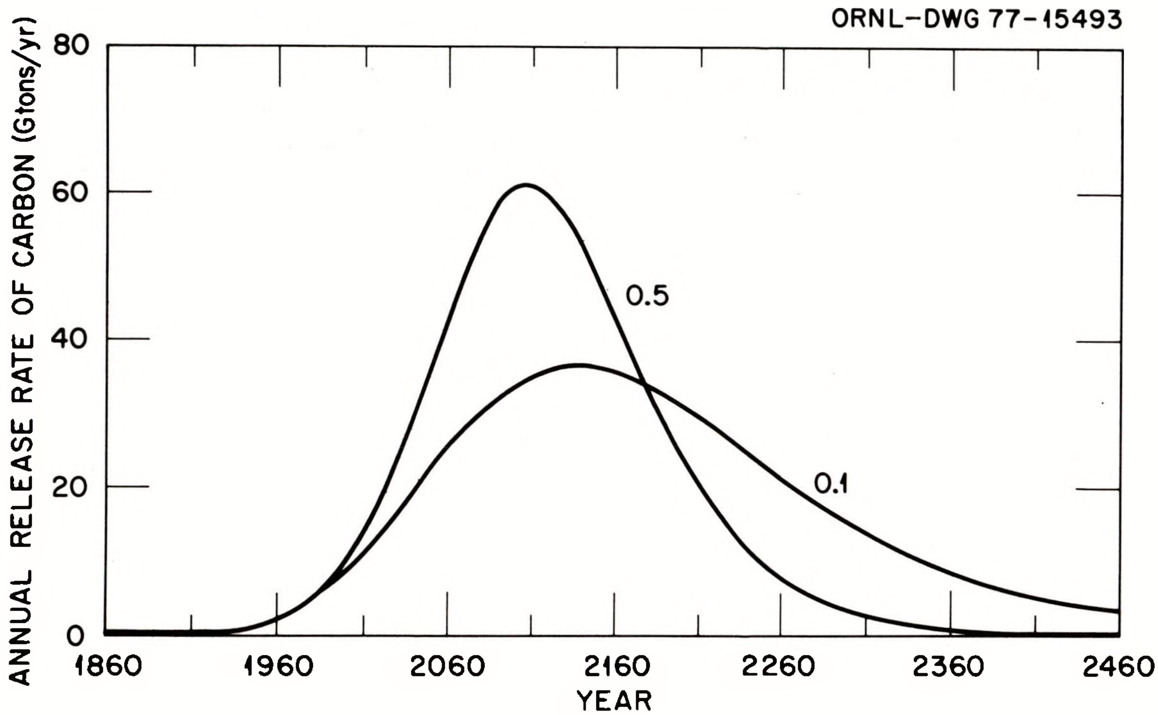

Fig. 6-1. Postponement of peak release rate of CO_2 represented by the Keeling formula with the shape parameter n changed from 0.5 to 0.1.

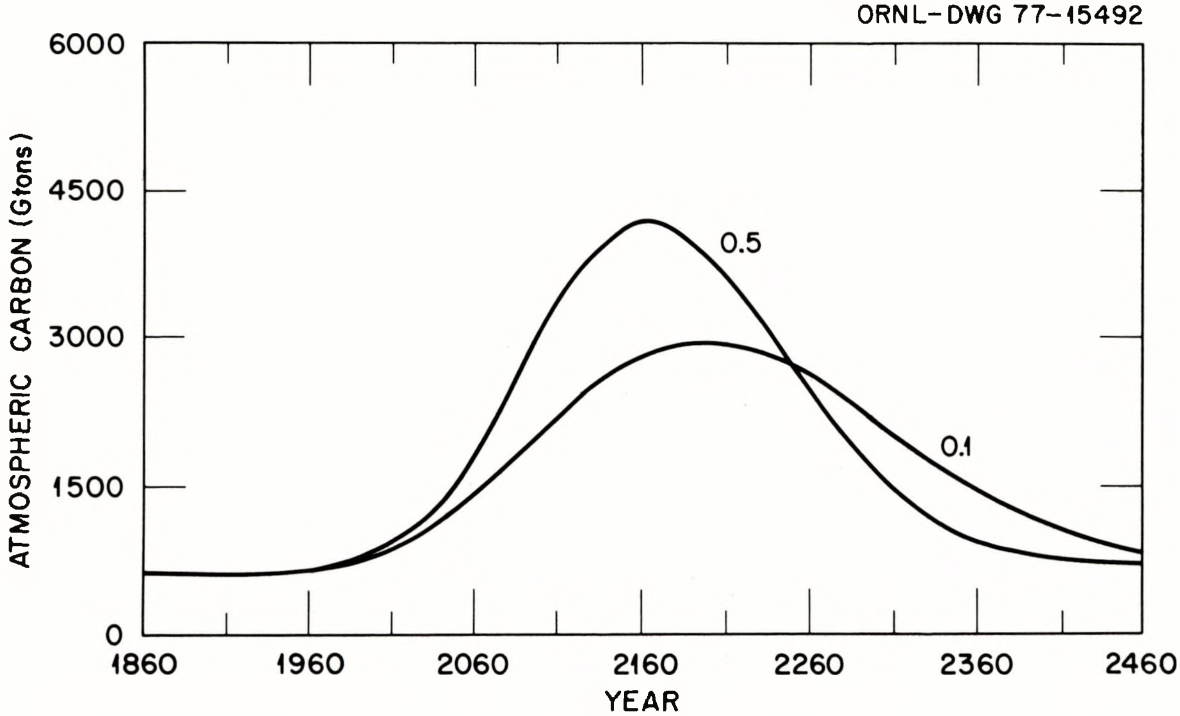

Fig. 6-2. Moderation of peak value of atmospheric CO_2, and delay in time of maximum, as shape factor for Keeling release function shifts from n = 0.5 to n = 0.1.

the use of sugarcane and other wastes. High retail prices of petroleum in these countries make this effort economically viable with government supervision. It is important to estimate when organic wastes and other sources of organic material can become competitive, given a variety of assumptions about the future supplies of gas, petroleum, and coal. Because of the food and land demands discussed in Chapter 3, there may be upper limits on the allocation of land to biomass. Thus, the latter may not be close to substituting for fossil fuel supplies nor to offering a continued exponential growth of the fuel burning. In Brazil and other tropical areas, extra agricultural land is being cleared for energy at the expense of the inventory of tropical forest. Close examination may reveal a net aggravation of the atmospheric CO_2 problem by premature oxidation of humus and wood rather than the net sparing of fossil fuel that could result from wiser use of the tropical forest.

There are pros and cons for the proposed expanded use of biomass. Biomass is a channel for solar energy (via chlorophyll), and its use could be expanded to exceed other solar energy sources (except hydropower) for some time to come. If biomass could replace fossil energy instead of adding one more kind of consumption to the consumption of fossil carbon--by burning or by its conversion to liquid or gaseous fuels--then the excess CO_2 production would be moderated. Essentially, the biomass would be storing and slowly recycling CO_2 waste products from previously used fossil fuel as well as from the normal metabolism of the earth. Biomass must be stored as such (as in trees) or in tree products for a long time if this storage is to help to even a moderate degree to keep excess carbon out of circulation, as natural forests and humus do without charge.

6.1.4 Scenarios for Exploration

The high scenarios of Figs. 2-2, 5-1, 5-2, and 6-3 may indeed be approximated for at least several decades until there is overwhelming evidence or public concern that the theoretical possibilities outlined in Chapter 5 are already underway. By then, of course, it will be too late to shift the earth to the lower scenarios of these diagrams.

There will be further delays because some nations cannot conceive of making the deliberate choice to take a smaller share than before of the earth's fossil energy (or of the technological and economic activities which now seem bound to such use). Furthermore, the options to use nuclear or solar energy on the vast scale envisioned by Niehaus (1976) and others may simply not be within reach, due to decisions to be made in the 1970's and 1980's.

A personal guess is that one doubling of CO_2 sometime in the second quarter of the 21st century will create so much hardship and controversy that a "shifting scenario" (moving from the high toward the low of Fig. 6-3) will at last get underway. Fossil fuel may become so expensive that the deeper, thinner beds of coal and oil shale will be saved for non-energy uses, although the energy cost of exploiting these sources may preclude their use almost indefinitely. In any case, the global mean surface temperature increase of 4° to 5°C will be committed for a century or longer (if an intermediate ΔT of 3° per doubling should prove appropriate). Temperature increases at the high latitudes will become two or three times as great (e.g., 8° to 15°C). Most, if not all, of the impacts in Section 5.3 will become apparent, and other more important impacts may appear.

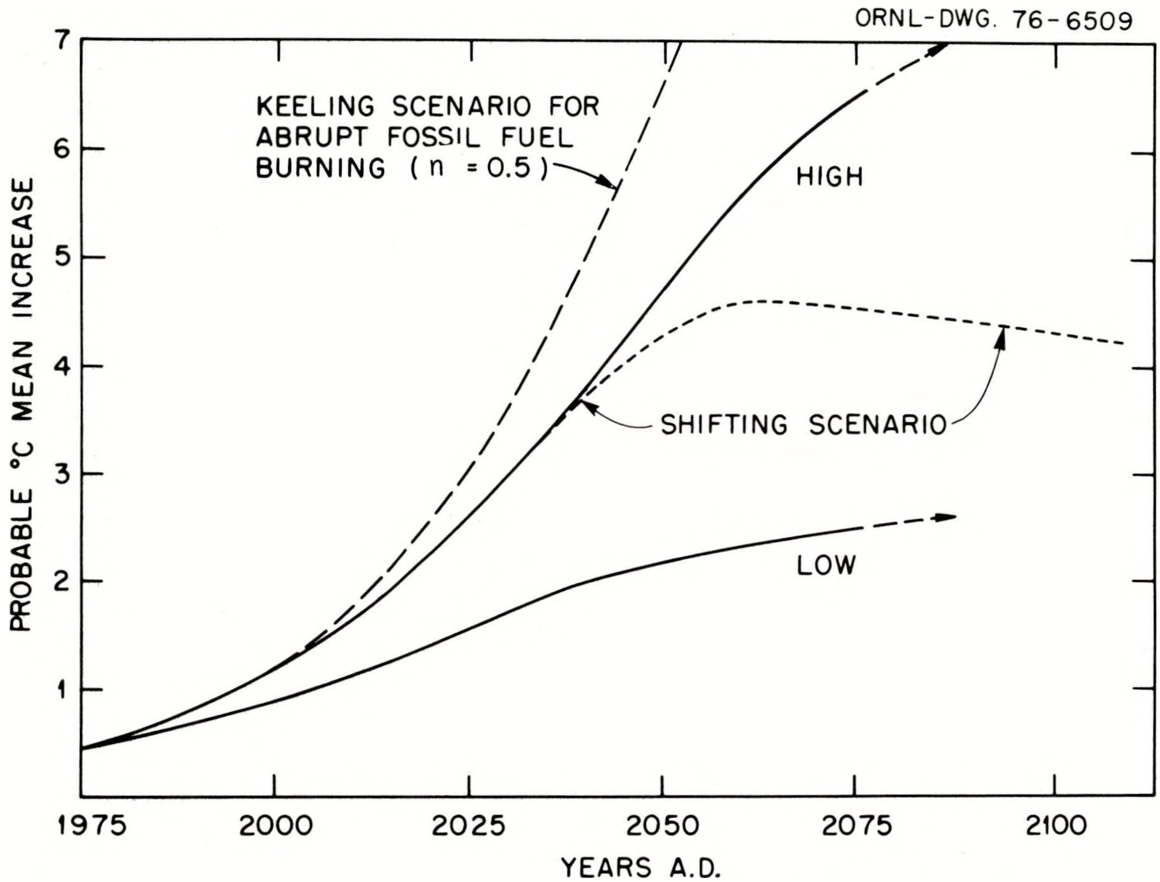

Fig. 6-3. Most plausible temperature changes for high, low, and shifting scenarios of CO_2 (assuming an average rise of 3°C per doubling of CO_2).

Relatively little has been said about how soon these impacts will be noticeable against the background of year-to-year weather fluctuations which are regretted but accepted as "normal". Examples in Sections 5.3.1 through 5.3.6 seem likely to appear in some extensive regions early in the 21st century under *almost any* growth scenario which emerges out of present trends of consumption and the determination to exploit coal. The sealevel rise would take a longer time and could involve international conflicts before the issue is resolved of who has the might (if not the right) to commit other nations to a flooding of their coasts at even a moderately accelerating rate. The sociopolitical and ethical issues will appear earlier, however, when the fate of one region or social sector is seen (or is suspected) to suffer, with or without concurrent benefit for another region or sector.

In order to answer questions about such possibilities before Congress, the public, and other nations, each American administration must improve upon its predecessors. Not only must the separate scientific parts of the problem (carbon cycle, climate, climatic impacts) be treated more completely than is possible in 1978, but a far better capability of fitting these parts into a total systems analysis must be developed, tested, and used.

The required systems analysis must relate the atmosphere simultaneously to society and its energy uses, to the terrestrial organic matter of the biosphere, to sediments, and to the hydrosphere. Objective functions for management of the atmospheric system should include: (1) the peak in concentration of atmospheric CO_2 (to be maximized), and (2) the storage as well as the production rates of organic materials (to be maximized, subject to constraints that must include preservation of the biosphere's adaptability to change).

Scenarios for conservative release rates of fossil fuel CO_2 (e.g., $dN/dt = NR(1-N^{0.1}/10^3)$ lead to a quadrupling of the atmospheric CO_2 after a delay reflecting constraint in the peak release rate and the time of burning: 36 gigatons/yr in A.D. 2135 (only 15 Gtons/yr by 2025, Fig. 6-1 and 6-2).

A computer simulation making this projection for the system assumes optimistically that the Revelle factor can remain near 10 for much of the ocean. A more realistic program suggests, however, that the Revelle factor will increase as CO_2 moves into the surface of the ocean and eventually through the thermocline and by polar currents into the deep ocean. Also optimistic is the assumption that net primary production of land plants can increase by 0.2 percent for each 1 percent of atmospheric CO_2, because ecological constraints are likely to make such response less than 0.2.

Simulation runs *can* reproduce present atmospheric and biospheric conditions, assuming no land clearing. They can also show that clearing of tropical forest at a rate of 1 percent per year since 1860 might generate unrealistically high atmospheric CO_2 (805 Gtons vs 711 Gtons actually released in 1975). The anomaly comes not so much from the prompt release of 1.2 Gtons/yr of carbon which such clearing implies (before depletion of the forest area), but from the "time bomb" effect: delayed release of CO_2 by shifting carbon from slowly exchanging pools.

While estimates can and must be improved, the present reconstruction of biosphere history suggests average releases of a few tenths of 1 Gton/yr over several thousand years since the beginning of Neolithic and especially of Iron Age technology. A working hypothesis is that Northern Woods (N of 30° N) already balance with Nonwoods. Rates of clearing of Southern Woods are tentatively suggested as having increased at rates between 0.2 and 2 percent per year by 1975, with a possibility of a distinct acceleration within this range around 1960. Future trends, related to human populations, food, and agriculture, will presumably enhance this clearing despite the law of diminishing returns and the very substantial energy costs.

Pending the outcome of such an analysis and the development of improved geophysical models of the carbon cycle and climate, energy policy planning would be prudent to include the possibility that all but the lowest peak of CO_2 releases from fossil fuel (Fig. 2-2) will prove too risky for national or international acceptance. Perhaps much of the accessible reserve can eventually be tapped safely, but only if a deliberate effort can *extend the time of exploitation* over more centuries than are usually included within planners' horizons.

6.2 Cycling Models and Data

The foregoing conclusions are not likely to change much with a refinement of the global model or its parts. However, the *timing* of carbon releases and delays is such a central problem that refinements of the general picture of Fig. 1-1 are essential. Linearized models, with flows represented as proportional to source compartments, may remain useful for short-term explorations. At least as many nonlinearities as are used in Chapter 4 seem desirable. These should show explicit response to changes in temperature, which reflect feedback from models of climatic change and climatic impact. Linking the cycles of nitrogen and phosphorus with that of carbon (Jorgensen and Mejer, 1976) could become increasingly important for both the terrestrial and aquatic submodels.

Refining the terrestrial submodel requires some data and model effort on distinctions already treated in this report:

- improving estimates of the allocation of biomass and production to rapid vs slow pools (short vs long residence times);
- estimating these residence times better, eventually as a continuum;
- using relatively intensive analyses of major ecosystem types to get functional relations between production and turnover rates and the biophysical and geographic factors controlling them;
- arranging global studies so that groups investigating all the ecosystem categories in Tables 2.1 and 3.1 are measuring and deriving parameters on a validly comparable basis;
- calibrating and extending satellite monitoring of terrestrial cover so that summaries (with bounds on uncertainty) can validly be extended across national and continental boundaries;
- combining ground and satellite data in better estimates of seasonal response of foliage mass and production;
- combining the above with ^{14}C studies and with measurement of atmospheric change in CO_2 in a model that treats broad and narrow bands of latitude as sinks and sources of carbon;
- using all of these results and those of climatic change and climatic impact to determine how the terrestrial carbon cycle might change.

Other refinements may be important for specialists on the aquatic carbon cycle. These scientists have a high priority for locating the sources of fresh carbon for the deep and intermediate layers of the world ocean, from overturn in the polar and subpolar oceans to complementary eddy exchanges and upwelling in many areas. In addition, sedimentation by marine food chains depends not only on nitrogen and phosphorus but on silica as well.

6.3 Climatic Predictions (and Reconstructions)

Readers are referred to Baes et al. (1976, pp. 6, 39-45 and 61-53), the Global Atmospheric Research Program (1975), the National Academy of Sciences (NAS, 1975), and the U.S. Interdepartmental Committee for Atmospheric Sciences (ICAS, 1974) for conclusions about climate modeling which will not be repeated here.

The output of the combined global carbon model is only one of several important inputs to improved models of climatic change. Nitrogen oxides (from a companion cycling model yet to be developed) may also prove important.

For large climatic models which grid out cells of longitude as well as latitude, additional ecological inputs are probably desirable to reflect the varied physical boundary conditions of different vegetated and non-vegetated lands. It is logical to include this information in the computerized data bases in connection with the varying inventories and exchange rates of carbon in different parts of the earth.

Other contributions to atmospheric science come from paleoclimatology. Tree rings, pollen records, fossil plants, and physical evidence of climate changes (lake shoreline fluctuations, dunes recording wind directions) all provide data for inferring and sometimes dating past atmospheric shifts. Shifts in air masses and storm tracks (Webb and Bryson, 1972) inferred from biological data need further attention. Consequently, a highly interdisciplinary climate study involving atmospheric and other physical scientists should be extended to include biologists and geographers in order that the needed quantitative data can be collected and organized.

Thus, we need ecological as well as atmospheric and ocean monitoring. All three are important for developing and testing climate models and for detecting and exploring the impacts of climatic change.

6.4 Consequences of Climatic Change

More space and time that we have here are required to explain all the needs concisely identified by Baes et al. (1976, pp. 6-7, 45-58, 63-66).

6.4.1 Organized Information

The data banks on ecosystems and surface conditions that are needed for estimating carbon budgets and for testing climate models should be developed immediately to help project how ecosystems and surfaces would shift as climate changes. Collection and compilation of maps and numbers, as well as methods for easing their use as inputs for models, would be important prerequisites for active research. Demonstrations of the consequences of simple climatic hypotheses, such as shifts of isotherms, would serve a valuable teaching function. The ultimate purpose of this information analysis would be to take the outputs of improved climatic models and to analyze their implications for biota, agriculture, other resources, and economics.

6.4.2 Models to Predict Effects of Climatic Change

The hierarchy of models must be extended from those on carbon, through models of climate, to models of impacts that may follow from climatic change. The impacts are viewed on different scales ranging from the components of organisms through ecosystems and regions to the biosphere as a whole. Projections for the future must ultimately build on experiences from the past. A basis for judgment must be developed to evaluate the effects of changes which have not yet occurred, and which we hope in some cases will not be allowed to occur.

Biophysical ecology of the energy and production balances of organisms and of their behavior tends to work with the smaller components (e.g., leaves) and with the simplified conditions (as in crops) which clarify laws and patterns. Hopefully, the principles gleaned can be extended deductively to more complex systems (Gates and Schmerl, 1975; Lemon, 1976). Analyses of communities (Shugart and West, 1977) and of ecosystems are necessary for treating the differential response of species and of processes, such as production and decomposition, to changed climatic conditions. A holistic view is needed, because nonclimatic factors (normal ecological development or succession, sporadic weather disturbances, or outbreaks of pests) could obscure the monitoring and interpretation of changes that indirectly reflect climate (Becking and Olson, in press).

Such varied and detailed studies tend to be located in small areas where unusually complete data or motivated investigators are already available. Additional effort will be required to make the transition to larger regions or to regions adjacent to those picked for early formulation and testing of models. Presently there is a strong temptation to generalize (as we had to for the carbon models) over the whole biosphere or major life zones (as on Table 2.2). Bridging the gap for intermediate scales of landscape and for regionally varying combinations of temperature, effective moisture, wind, and solar radiation will ultimately be essential for realistically estimating the impacts of climatic change. It will be mainly on the local and regional scale that validation tests can be made for reconstructions of past impact and for monitoring for early warning of future climatic and ecological change.

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369. R. Collis, Director, Atmospheric Science Laboratory, SRI International, Menlo Park, CA 94025
370. Barry Commoner, Washington University, St. Louis, MO 63130
371. M. J. Constantin, Comparative Animal Research Laboratory, Oak Ridge, TN 37830
372. Charles Cooper, Ecology Program, San Diego State University, San Diego, CA 92182
373-381. R. D. Cooper, Integrated Assessment, U.S. Department of Energy, Washington, DC 20545
382. H. Craig, Scripps Institute of Oceanography, La Jolla, CA 92037
383. Kermit Cromack, U.S. Forest Service Laboratory, Corvallis, OR 97330
384. Paul E. Damon, 2321 E. Hawthorne Street, Tucson, AZ 85719
385. W. Dansgaard, Geophysical Isotope Laboratory, University of Copenhagen, Copenhagen, Denmark
386. J. J. Davis, U.S. Nuclear Regulatory Commission, Washington, DC 20555

387. Kenneth W. Davis, Vice President, Bechtel Power Corporation, P.O. Box 3965, San Francisco, CA 94119
388. Stanley N. Davis, Chairman, Department of Hydrology, University of Arizona, Tucson, AZ 85721
389. Ted J. Davis, World Bank, 1818 H Street, N.W., Washington, DC 20433
390. E. S. Deevey, Jr., Florida State Museum, University of Florida, Gainesville, FL 32611
391. Wayne L. Decker, Department of Atmospheric Sciences, University of Missouri, Columbia, MO 65201
392. Egon T. Degens, Geologisch-Palaontologisches, Institut, University of Hamburg, Bundesstrabe 55, 2000 Hamburg 13, Federal Republic of Germany
393. C. C. Delwiche, Soils and Plant Nutrition, University of California, Davis, CA 95616
394. Thomas Denmead, C.S.I.R.O. Division of Environmental Mechanics, Black Mountain, Canberra A.C.T., Australia
395. H. R. Deselm, Department of Botany, University of Tennessee, Knoxville, TN 37916
396. C. T. deWit, Institute of Biological Sciences, University of Wageningen, Wageningen, Netherlands
397. Josephine Doherty, Division of Applied Research, National Sciences Foundation, Washington, DC 20555
398. Warren Doolittle, Associate Deputy Chief, Forest Service, USDA, Room 3007, South Building, 12th and Independence Avenue, S.W., Washington, DC 20250
399. Harold Dregne, Chairman, Department of International Center for Arid and Semi-Arid Studies, Texas Tech University, P.O. Box 4169, Lubbock, TX 79409
400. M. Drosdoff, Agronomy Department, Cornell University, Ithaca, NY 14853
401. P. Duvigneaud, Director, Laboratoire de Botanique Systematique et d'Ecologie, Universite Libre de Bruxelles, 28 Avenue Paul Heger, Bruxelles 5, Belgium
402. F. Dyson, Institute for Advanced Studies, Princeton, NJ 08540
403. C. W. Edington, Division of Biomedical and Environmental Research, U.S. Department of Energy, Washington, DC 20545
404. John Eddy, High Altitude Observatory, Box 1558, Boulder, CO 80302
405. A. E. J. Eggleton, EMS Division, Building 364, AERE, Harwell, Didcot, Oxford, United Kingdom
406. William P. Elliott, Division of Biomedical and Environmental Research, U.S. Department of Energy, Washington, DC 20545
407. C. Emiliani, Marine and Atmospheric Science, University of Miami, Coral Gables, FL 33124
408. A. H. Emmons, Vice President for Research, University of Missouri, Route 4, Box 210B, Columbia, MO 65201
409. E. Eriksson, University of Uppsala, Uppsala, Sweden
410. K. Ewel, Forestry Department, University of Florida, Gainesville, FL 32611
411. A. W. Fairhall, Department of Chemistry, University of Washington, Seattle, WA 98195
412. Anne Fege, Division of Solar Energy, U.S. Department of Energy, Washington, DC 20545
413. H. Flohn, Meteorological Institute, Bonn University, West Germany
414. J. A. C. Fortescue, Environmental Trace Substance Research Center, University of Missouri, Columbia, MO 65201
415. Frederic Fournier, SCOPE, ORSTOM, 24, Rue Bayard, F - 75008 Paris, France
416. J. Franklin, U.S. Forest Service Laboratory, Corvallis, OR 97330
417. R. E. Franklin, Division of Biomedical and Environmental Research, U.S. Department of Energy, Washington, DC 20545
418. P. Fraser, CSIRO, Division of Atmospheric Physics, Station Street, Aspendale Victoria, Australia
419. David Freeman, Tennessee Valley Authority, Knoxville, TN 37902
420. T. Frey, Academy of Science of Estonian SSSR, Tartu, Estonia
421. H. Fritts, Laboratory of Tree Ring Research, University of Arizona, Tucson, AZ 85721
422. J. C. Frye, Executive Secretary, Geological Society of America, 3300 Penrose Place, Boulder, CO 80301
423. Tzvi Gal-Chen, Department of Physics, University of Toronto, Toronto M5S 1A4, Canada

424. Richard R. Gardner, Deputy Assistant Administrator, Office of Coastal Zone Management, 3300 Whitehaven Street, N.W., Washington, DC 20235
425. R. M. Garrells, Department of Geology, Northwestern University, Evanston, IL 60201
426. J. R. Garrett, Commonwealth Scientific and Industrial Research Organization (CSIRO), Division of Atmospheric Physics, Aspendale, Victoria, Australia
427-430. William R. Gasser, National Defense University Research Directorate, Fort McNair, Washington, DC 20319
431. David M. Gates, Division of Biological Sciences, University of Michigan, Ann Arbor, MI 48109
432-434. W. L. Gates, Oregon State University, Corvallis, OR 97330
435. Stacja Geobotaniczna U. W., Bialowieza Woj., Bialystok, Poland
436. I. P. Gerasimov, Institute of Geography, USSR Academy of Science, Moscow State University, Moscow, USSR
437. J. H. Gibbons, Environmental Center, University of Tennessee, Knoxville, TN 37916
438. F. A. Gifford, ATDL, P.O. Box E, Oak Ridge, TN 37830
439. V. T. Gilbert, MAB Project 8 Coordinator, Division of Natural Resources, National Park Service, Department of the Interior, Washington, DC 20240
440. Robert A. Goldstein, Electric Power Research Institute, 3412 Hillview Ave., P.O. Box 10412, Palo Alto, CA 94304
441. Frank B. Golley, Jr., Institute of Ecology, Rockhouse, University of Georgia, Athens, GA 30601
442. David Goodall, Land Resources Management, C.S.I.R.O., Floreat Park, Perth, Australia
443. Alan G. Gordon, Ontario Ministry of Natural Resources, Forest Research Branch, P.O. Box 490, Sault Sainte Marie, Ontario, Canada
444. A. J. P. Gore, Monks Wood Experimental Station, Natural Resources Research Council, Abbots Ripton, Hunts, United Kingdom
445. T. K. Goryshina, Leningrad State University, Leningrad, USSR
446. J. Goudriaan, Department of Theoretical Production, Ecology, Agricultural University, De Dreijen 11, Wageningen, Netherlands
447. Carolyn Gowdy, E.S. 303, Oklahoma State University, Stillwater, OK 74074
448. Richard S. Greeley, Technical Director, Engineering Resources and Environment, the Mitre Corporation/Metrek Division, Westgate Research Park, McLean, VA 22101
449. John Gibbin, Science Policy Research Unit, University of Sussex, Sussex, United Kingdom
450. Charles C. Grier, School of Forestry, University of Washington, Seattle, WA 98195
451. L. A. Grishina, Department of Pedology, Moscow State University, Moscow, USSR
452. P. M. Grookes, Q.R.C. Johnson Hall 57, University of Washington, Seattle, WA 98195
453. Jurgen Hahn, Aeronomy Laboratory, NOAA-ERL, Boulder, CO 80302
454. C. Hall, Ecology and Systematics, Cornell University, Ithaca, NY 14850
455. Rolf Hallberg, Department of Geology, University of Stockholm, P.O. Box 6801, Kungstensgatan 25, 113 86 Stockholm, Sweden
456. Leonard Hamilton, Brookhaven National Laboratory, Upton, NY 11973
457. Ulrich Hampicke, Arbeitsgruppe Umwelt, Gesellschaft, Energie, Universitat Essen - Gesamthochschule, P.O. Box 6843, 4300 Essen 1, Federal Republic of Germany
458. Steven Hanna, National Oceanic and Atmospheric Administration, Atmospheric Turbulence and Diffusion Laboratory, Oak Ridge, TN 37830
459. Arthur G. Hansen, President, Purdue University, West Lafayette, IN 47907
460. Kirby Hanson, Environmental Research Laboratories, NOAA, Boulder, CO 80302
461. Wayne Hanson, Los Alamos Scientific Laboratory, Los Alamos, NM 87544
462. James D. Hays, Lamont-Doherty Geophysical Laboratory, Columbia University, New York, NY 10027
463. O. W. Heal, Institute of Terrestrial Ecology, Merlewood Research Station, Grange-over-Sands, Cumbria LA11 6JU, United Kingdom
464. Allen Hecht, Climate Dynamics, National Science Foundation, Washington, DC 20550
465. S. Hejny, Institut of Botany, Czechoslovakia Acadedemy of Sciences, Dukelska 145, 37982 Trebon, Czechoslovakia

466. Raymond Herrmann, Chief Scientist, Southeast Regional Office, National Park Service, 1895 Phoenix Boulevard, Atlanta, GA 30349
467. Wilmot Hess, Environmental Research Laboratories, National Oceanic and Atmospheric Administration, Boulder, CO 80302
468. Darryl Hessel, Pacific Northwest Laboratories, Box 999, Richland, WA 99352
469. Eigil Hesstvedt, Institute of Geophysics, P.O. Box 1022, Blindern, Oslo 3, Norway
470. Joan Hett, c/o College of Forestry, University of Washington, Seattle, WA 98195
471. H. R. Hickey, Environmental Planning, Tennessee Valley Authority, Chattanooga, TN 37401
472. J. B. Hilmon, Director, Southeastern Forest Experiment Station, Asheville, NC 28807
473. Charles J. Hitch, President, Resources for the Future, 1755 Massachusetts Avenue, NW, Washington, DC 20036
474. Martin I. Hoffert, Division of Applied Science, New York University, 26 Stuyvesant Street, New York, NY 10003
475. Gunter Hofmann, Institut fur Forstwissenschaft, DDR 13 Eberswalde, Finow 1, German Democratic Republic
476. J. P. Holdren, Energy and Resources Group, University of California 100 T-4, Berkeley, CA 94720
477. Crawford S. Holling, Institute of Animal Resource Ecology, the University of British Columbia, 2075 Wesbrook Place, Vancouver, British Columbia, V6T 1W5 Canada
478. H. Hollister, U.S. Department of Energy, Washington, DC 20545
479. Raymond P. Hosker, Jr., Atmospheric Turbulence and Diffusion Laboratory, National Oceanic and Atmospheric Administration, P.O. Box E, Oak Ridge, TN 37830
480. Peter House, U.S. Department of Energy, Washington, DC 20545
481. Wallace E. Howell, Assistant to the Chief, Division of Atmospheric Water Resources Management, Bureau of Reclamation, P.O. Box 25007, DFC, Denver, CO 80225
482. K. Hozumi, c/o Biology Department, Osaka City University, Osaka, Japan
483. T. Hughes, Department of Geology, University of Maine, Orono, ME 04473
484. J. Hung, Electrical Engineering, University of Tennessee, Knoxville, TN 37916
485. T. C. Hung, Institute of Oceanography, National Taiwan University, Taipei, Taiwan 115, Republic of China
486. J. B. Huntley, Savanna Ecosystem Project, CSIR, P.O. Box 395, Pretoria, 0001, South Africa
487. Boyd Hutchinson, Atmospheric Turbulence and Diffusion Laboratory, National Oceanic and Atmospheric Administration, P.O. Box E, Oak Ridge, TN 37830
488. G. E. Hutchinson, Yale University, New Haven, CT 06520
489. H. Hytteborn, Institute of Ecological Botany, P.O. Box 559, S-751 22, Uppsala, Sweden
490. S. Idso, U.S. Water Conservation Laboratory, Agricultural Research Service, Phoenix, AZ 85025
491. John Imbrie, Department of Geological Science, Brown University, Providence, RI 02912
492. Jack Ives, Director, Institute of Arctic and Alpine Research, University of Colorado, Boulder, CO 80302
493. Jay S. Jacobson, Environmental Programs, Division of Biomedical and Environmental Research, U.S. Department of Energy, Washington, DC 20545
494. J. N. R. Jeffers, Institute of Terrestrial Ecology, Merlewood Research Station, Grange-over-Sands, Cumbria LA11, United Kingdom
495. Han Jenny, Professor Emeritus of Soils, University of California, Berkeley, CA 97420
496. Albert W. Johnson, Dean, College of Sciences, San Diego State College, San Diego, CA 92115
497. W. C. Johnson, Biology Department, Virginia Polytechnic Institute, Blacksburg, VA 24061
498. Carl Jordan, c/o Institute of Ecology, University of Georgia, Athens, GA 30601
499-508. J. Jordan, Climate Dynamics, National Science Foundation, Washington, DC 20550
509. A. Jurko, Institute of Experimental Biology and Ecology, Slovak Academy of Sciences, Obrancov Miera 3, 88534 Bratislava, Czechoslovakia

510. V. G. Karpov, Laboratory of Experimental Phytocoenology, Geobotany Department, Komarov Botanical Institute, Leningrad, USSR
511. C. D. Keeling, Scripps Institute of Oceanography, La Jolla, CA 92037
512. W. W. Kellogg, National Center for Atmospheric Research, Boulder, CO 80303
513. T. Kerlin, Nuclear Engineering, University of Tennessee, Knoxville, TN 37916
514. B. H. Ketchum, Woods Hole Institute of Oceanography, Woods Hole, MA 02543
515. Donald King, Director, Office of Environmental Affairs, Department of State, Washington, DC 20520
516. Makoto Kimura, Department of Biology, Tokyo Metropolitan University, Fukazawa, Setagayaku, Tokyo, Japan
517. Tatuo Kira, Biology Department, Osaka City University, Osaka, Japan
518. Henry Kissman, Associate Director, Specialized Information Services, National Library of Medicine, 8600 Rockville Pike, Bethesda, MD 20014
519. H. Klinge, Max Planck Institute fuer Limnologie, Abteilung Tropenoekologie, D 232 Ploen, Postfach 165, Federal Republic of Germany
520. Kenneth R. Knoerr, School of Forestry and Environmental Studies, Duke University, Durham, NC 27706
521. Seppo E. Kolehmainen, Puerto Rico Nuclear Center, College Station, Mayaguez, PR 00708
522. Edward J. Kormondy, Division of Natural Science, The Evergreen State College, Olympia, WA 98505
523. V. Kovda, Moscow State University, Moscow, USSR
524. Sam Krammes, Forest Environment Research, USDA Forest Service, Washington, DC 20250
525. Stanley L. Krugman, U.S. Forest Service, Washington, DC 20250
526. T. L. Ku, Department of Geological Sciences, University of Southern California, Los Angeles, CA 90007
527. John E. Kutzbach, University of Wisconsin, Madison, WI 33706
528. G. Lambert, CFR-CNRS, 91190 Gif sur Yvette, France
529. Helmit Landsberg, University of Maryland, College Park, MD 20740
530. O. L. Lange, Botanical Institute II, University of Wuerzburg, Wuerzburg, Federal Republic of Germany
531. Nels Laulainen, Atmospheric Sciences, 622R, Battelle, Pacific Northwest Laboratories, P.O. Box 999, Richland, WA 99352
532. J. A. Laurmann, Division of Applied Mechanics, Stanford University, Stanford, CA 94305
533. Estella Leopold, Quaternary Center, University of Washington, Seattle, WA 98195
534. George Leppert, Argonne National Laboratory, Argonne, IL 60439
535. E. Lemon, U.S. Department of Agriculture, Bradfield Hall, Cornell University, Ithaca, NY 14850
536. Leona Libby, Engineering School, University of California, Los Angeles, CA 90024
537. Library, Rothamsted Experimental Station, Harpenden, Herts, England
538. Library, Tennessee Valley Authority, Knoxville, TN 37902
539. Library, Great Lakes Fishery Laboratory, U.S. Bureau of Sport Fisheries and Wildlife, Ann Arbor, MI 49904
540. Library, University of Michigan Biological Station, Ann Arbor, MI 48109
541. H. Lieth, Botany Department, University of Osnabruck, Postfach 4469, 4500 Osnabruck, Federal Republic of Germany
542. G. Likens, Ecology and Systematics, Cornell University, Ithaca, NY 14850
543. L. Lindgren, Ekologihuset, Helgonavaegen 5, S-223 62 Lund, Sweden
544. J. L. Liverman, Acting Deputy Secretary for Environment, U.S. Department of Energy, Washington, DC 20545
545. K. E. Lockridge, U.S. Department of Energy, Washington, DC 20545
546. Robert L. Loftness, Director, Washington Office, Electric Power Research Institute, 1750 New York Avenue, N.W., Suite 835, Washington, DC 20006
547. Ronald Lohrding, Los Alamos Scientific Laboratory, Los Alamos, NM 87544
548. Adam Lomnicki, Nature Conservation Research Center, Polish Academy of Sciences, Lubicz 46, 31-512 Cracow, Poland
549. R. S. Loomis, Agronomy and Range Science, University of California, Davis, CA 95616

550-559. Orie Loucks, The Institute of Ecology, Holcomb Institute, Butler University, Indianapolis, IN 46208

560. J. Lovell, Lawrence Livermore Laboratory, Box 808, Livermore, CA 94550
561. Ariel Lugo, Council on Environmental Quality, 722 Jackson Place, NW, Washington, DC 20006
562. MAB Program, State Department, Washington, DC 20521
563. Gordon MacDonald, the Mitre Corporation/Metrek Division, Westgate Research Park, McLean, VA 22101
564-566. L. Machta, Air Research Laboratory, NOAA, Silver Springs, MD 20910
567. H. A. I. Madgwick, Forest Research Institute, Rotorua, New Zealand
568. John J. Magnuson, Limnology Laboratory, University of Wisconsin, Madison, WI 53706
569. Jack Major, Department of Botany, University of California at Davis, Davis, CA 95616
570. Alexander Malahoff, National Ocean Survey, National Oceanic and Atmospheric Administration, Rockville, MD 20852
571-580. T. Malone, The Institute of Ecology, Holcomb Institute Research, Butler University, Indianapolis, IN 46208
581. S. Manabe, Geophysical Fluid Dynamics Laboratory, NOAA, Princeton, NJ 08540
582. Bryan Mar, Department of Civil Engineering, FX-10, University of Washington, Seattle, WA 98105
583. G. I. Marchuk, USSR Academy of Science, Leninskiy Prospect, Moscow, USSR
584. Alan F. Mark, Botany, University of Otag, Dunedin, New Zealand
585. G. Marland, Institute for Energy Analysis, Oak Ridge Associated Universities, Oak Ridge, TN 37830
586. William H. Matthews, Department of Urban and Regional Planning, Massachusetts Institute of Technology, Cambridge, MA 02139
587. Robert G. McAlpine, Southeastern Forest Experiment Station, Gainesville, FL 32601
588. F. McCormick, Ecology Program, University of Tennessee, Knoxville, TN 30916
589. William D. McElroy, Chancellor, University of California at San Diego, La Jolla, CA 92093
590. Samuel McKee, Office of the Foreign Secretary, National Academy of Sciences, 2101 Constitution Avenue, N.W., Washington, DC 20418
591. A. Medwecka-Kornas, Botanical Institute, Jagiellonian University, Cracow, Poland
592. D. H. Miller, Department of Geological Sciences, University of Wisconsin, Milwaukee, WI 53201
593. John Miller, P.O. Box 275, Hilo, HI 96720
594. Joseph Miller, Radiological and Environmental Research Division, Argonne National Laboratory, Argonne, IL 60439
595. Philip C. Miller, Department of Biology, San Diego State College Foundation for San Diego State University, San Diego, CA 92182
596. Kim Joon Min, Professor of Biology, Department of Biology, College of Education, Seoul National University, Kwanak-ku, Seoul, Korea
597. J. M. Mitchell, Environmental Data Service, NOAA, Silver Springs, MD 20910
598. A. A. Moghissi, Box 7166, Alexandria, VA 22307
599. Harold Mooney, Department of Biology, Stanford University, Palo Alto, CA 94305
600. Milton Moore, Australia Scientific Liaison Office, c/o Australian Embassy, London, United Kingdom
601. H. Moses, Division of Biomedical and Environmental Research, U.S. Department of Energy, Washington, DC 20545
602. Tom Moss, c/o George Brown, Rayburn Office Building, U.S. House of Representatives, Washington, DC 20515
603. Robert J. Mulholland, E.S. 303, Oklahoma State University, Stillwater, OK 74074
604. W. H. Munk, Institute of Geophysics and Planetary Sciences, University of California, La Jolla, CA 92093
605. Jerome Namias, Research Meteorologist, A-024, Room 2252, Sverdrup Hall, UCSD-Scripps Institute of Oceanography, La Jolla, CA 92093
606. J. Neuhold, Ecology Program, Utah State University, Logan, UT 84321
607. Reginald Newell, Department of Meteorology, Massachusetts Institute of Technology, Cambridge, MA 02139
608. B. C. Nguyen, Centre Des Faibles Radioactivities, C.N.R.S., 91190 Gif sur Yvette, France
609. A. M. Nicol, Lincoln College, Canterbury, New Zealand

610. William A. Nierenberg, Director, Scripps Institution of Oceanography, University of California at San Diego, P.O. Box 1529, La Jolla, CA 92037
611. Henry Nix, C.S.I.R.O., Division of Land Use Research, P.O. Box 1666, Canberra City A.C.T., Australia
612. R. Nydal, Physics Department, Technological Institute, Trondheim, Norway
613. E. P. Odum, Institute of Ecology, University of Georgia, Athens, GA 30601
614. H. T. Odum, Environmental Engineering, University of Florida, Gainesville, FL 32601
615. W. T. Odum, Environmental Sciences, University of Virginia, Charlottesville, VA 22903
616. H. Oeschger, Physics Institute, University of Bern, Bern, Switzerland
617. K. C. Oh, Biology Department, Solgang University, Seoul, Korea
618. C. I. Olaniyan, University of Lagos, Akoka, Lagos, Nigeria
619. I. U. Olsson, Institute of Physics, Uppsala University, Uppsala, Sweden
620. W. S. Osburn, Division of Biomedical and Environmental Research, U.S. Department of Energy, Washington, DC 20545
621. H. Gote Ostlund, School of Marine and Atmospheric Science, University of Miami, 4600 Rickenbacker Causeway, Miami, FL 33149
622. J. D. Ovington, Department of the Environment, Canberra A.C.T., Australia
623. Philip Palmedo, Brookhaven National Laboratory, Upton, NY 11973
624. John M. Palms, Dean, Emory College, Emory University, Atlanta, GA 30322
625. Anu Parnanen, The MAB National Committee of Finland, The Academy of Finland, Asemamiekenkatu 2, 00520 Helsinki 52, SF-Finland
626. G. I. Pearman, CSIRO, Division of Atmospheric Physics, Aspendale, Victoria, Australia
627. T. H. Peng, Lamont-Doherty Geological Observatory, Columbia University, Palisades, NY 10964
628. Ralph Perhac, Electric Power Research Institute, 3412 Hillview Avenue, P.O. Box 10412, Palo Alto, CA 94304
629. Hans Persson, Institute of Ecological Botany, University of Uppsala, Box 559, S-751-22, Uppsala 1, Sweden
630. Raoul Peterson, Director, Ecological Research Division, Food and Agricultural Organization of the United Nations, Via delle Terme di Caracalla, 00100 Rome, Italy
631. Robert Phares, Division of Timber Management Research, U.S. Forest Service, Department of Agriculture, Washington, DC 20250
632. Hugh Popenoe, 2001 McCarty Hall, University of Florida, Gainesville, FL 32611
633. J. Puigdefabregas, Centro Pirenaico de Biologia Experimental, AP., 64 Jaca (Huesca), Spain
634. Ricardo M. Pytkowicz, School of Oceanography, Oregon State University, Corvallis, OR 97331
635. Eric Charles Quaye, Botany Department, University of Cape Coast, Cape Coast, Ghana
636. R. Rabin, National Science Foundation, Washington, DC 20550
637. T. Rafter, Institute of Nuclear Studies, Lower Hutt, New Zealand
638. H. L. Ragsdale, Department of Biology, Emory University, Atlanta, GA 30322
639. V. Ramanathan, National Center for Atmospheric Research, Boulder, CO 80303
640. S. I. Rasool, 2880 Broadway, New York, NY 10025
641. Angela de Luca Rebello, Caiza Postal 3850/Gavea, 20.000 Rio de Janeiro, Brasil
642. William E. Reifsnyder, School of Forestry and Environmental Studies, Yale University, New Haven, CT 06511
643. W. A. Reiners, Biological Sciences, Dartmouth College, Hanover, NH 03755
644. Elmar Reiter, Department of Atmospheric Science, Colorado State University, Fort Collins, CO 80521
645. Gordon A. Riley, Institute of Oceanography, Dalhousie University, Halifax, Nova Scotia, Canada
646-648. M. Reilly, Fossil Fuels, U.S. Department of Energy, Washington, DC 20545
649. T. Ripley, Division of Forestry, Tennessee Valley Authority, Fisheries and Wildlife, Forestry Building, Norris, TN 37828
650. Paul Risser, University of Oklahoma, Norman, OK 73019
651. J. W. H. La Riviere, SCOPE Co-Chairman, IUBS, International Institute for Hydraulic and Environment Engineering, Oude Delft 95 Delft, Netherlands
652. Charles F. Roberts, Forest Fire and Atmospheric Sciences Research, U.S. Forestry Service, Washington, DC 20250

653. G. D. Robinson, Center for the Environment and Man, 275 Winsor Street, Hartford, CT 06120
654. L. R. Rodin, Botanical Institute, Ul. Prof. Popava 2, Leningrad 22, USSR
655. Wolfgang Roether, Zweites Physikalisches, Institut der Universitat Heidelberg, Philosophenweg 12, Heidelberg 1, Germany
656. Keith Ronnholm, Geophysics Program AK-50, University of Washington, Seattle, WA 98195
657. David Rose, Department of Urban and Regional Planning, Massachusetts Institute of Technology, Cambridge, MA 02139
658. Norman J. Rosenberg, Institute of Agriculture and Natural Resources, University of Nebraska, Lincoln, NE 68583
659. J. E. Ross, Department of Physics, University of Queensland, Brisbane, Queensland, Australia
660. Thomas Rosswall, Department of Microbiology, Agricultural College, 750 07 Uppsala, Sweden
661. A. J. Rutter, Botany Department, Imperial College, London, United Kingdom
662. R. Samaniego, University of the Philippines, College of Agriculture, Department of Agricultural Chemistry, Los Banos, Laguna, Philippines
663. Edouard Saouma, Director-General, Food and Agriculture Organization of the United Nations, Via delle Terme di Caracalla, 00100 Rome, Italy
664. Taisitiroo Satoo, Department of Forestry, University of Tokyo, Tokyo, Japan
665. Michael E. Schlesinger, Oregon State University, Corvallis, OR 97330
666. James Schlesinger, U.S. Department of Energy, Washington, DC 20545
667. William Schlesinger, Department of Biology, University of California, Santa Barbara, CA 93106
668. S. Schneider, National Center for Atmospheric Research, Boulder, CO 80303
669. R. C. Schnell, Mt. Kenya Project, Box 30218, Nairobi, Kenya
670. W. D. Sellers, University of Arizona, Tucson, AZ 85721
671. N. J. Shackleton, University of Cambridge, 5, Salisbury Villas, Station Road, Cambridge CB1 2JF, England
672. Hansford T. Shacklette, U.S. Geological Survey, Federal Center, Denver, CO 80225
673. David M. Sharpe, Department of Geography, Southern Illinois University, Carbondale, IL 62903
674. Peter Sharpe, Biosystems Group, Electrical Engineering Department, Texas A & M University, College Station, TX 77843
675. T. Shidei, Department of Forestry, Faculty of Agriculture, Kyoto University, Kyoto, Japan
676. Ray Siever, Hoffman Laboratory, Harvard University, Cambridge, MA 02138
677. S. Fred Singer, Professor of Environmental Sciences, University of Virginia, Clark Hall, Charlottesville, VA 22903
678. K. P. Singh, Department of Botany, Banaras Hindu University, Varanasi, Uttar Pradesh, India

679-700. D. Slade, Office of CO_2 Studies, U.S. Department of Energy, Washington, DC 20545

701. Ralph Slatyer, Research School of Biological Sciences, Australian National University, Canberra A.C.T. 2600, Australia
702. J. Smagorinsky, Geophysical Fluid Dynamics Laboratory, NOAA, Princeton, NJ 08540
703. Lawrence F. Small, School of Oceanography, Oregon State University, Corvallis, OR 97331
704. V. Smil, Geography, University of Manitoba, Winnipeg, Manitoba, Canada
705. Vassily Smirnyagin, SCOPE, 51, Boulevard de Montmorency, F 8 75016 Paris, France
706. Frederick E. Smith, Graduate School of Design, Harvard University, Cambridge, MA 02191
707. Samuel C. Snedaker, Associate Professor, School of Marine and Atmospheric Science, University of Miami, 4600 Rickenbacker, Causeway, Miami, FL 33149
708. R. E. Soeriaatmadja, Department of Biology, ITB, Jalan Ganesa 10, Bandung, Indonesia
709. A. I. Sors, Monitoring and Assessment Research Center, Chelsea College, University of London, The Octagon Building, 549a Fulham Road, London, SW10 0OX, England

710. Societe International Des Forestiers Tropicaux, 45 Bis, Avenue de la Belle Gabrielle, 94 130 Nogent Sur Marne, France
711. Philip Sollins, U.S. Forest Service Laboratory, Corvallis, OR 97330
712. Ray Specht, Botany Department, University of Queensland, Mill Road, St. Lucia, Brisbane, Australia
713. Walter O. Spofford, Jr., Director, Quality of the Environment Division, Resources for the Future, 1755 Massachusetts Ave., N.W., Washington, DC 20036
714. Douglas Sprugel, Argonne National Laboratory, Argonne, IL 60439
715. Gerald Stanhill, Director, Division of Agricultural Meteorology, Volcani Institute of Agricultural Research, P.O. Box 6, Rehovot, Israel
716. Forest Stearns, Department of Botany, The University of Wisconsin, Milwaukee, WI 53201
717. R. C. Steele, Natural Environment Research Council, Alhabra House, 27-33 Charing Cross Rd., London, WC2H OAY, England
718. Klaus Steinbeck, School of Forest Resources, University of Georgia, Athens, GA 30601
719. Earl L. Stone, Agronomy Department, Cornell University, Ithaca, NY 14850
720. J. D. Stout, Soils Bureau, Private Bag, Lower Hutt, New Zealand
721. Boyd R. Strain, Department of Botany, Duke University, Durham, NC 27706
722. M. Stuiver, University of Washington, Seattle, WA 98195
723. Hans Suess, Department of Chemistry, University of California at San Diego, La Jolla, CA 92093
724. Albert Swain, Center for Climatic Research, University of Wisconsin, Madison, WI 53706
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730. C. O. Tamm, Department of Forest Ecology, College of Forestry, S-104 05, Stockholm 50, Sweden
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