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FUNCTIONAL COMPLEXITY AND ECOSYSTEM STABILITY: AN EXPERIMENTAL APPROACH[1,2]

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[2]Submitted as a thesis by Peter Van Voris to the Graduate Council of the University of Tennessee in partial fulfillment of the requirements for the degree of Doctor of Philosophy

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ABSTRACT

VAN VORIS, PETER, R. V. O'NEILL, H. H. SHUGART, and W. R. EMANUEL. 1978. Functional complexity and ecosystem stability: An experimental approach. ORNL/TM-5004. Oak Ridge National Laboratory, Oak Ridge, Tennessee. 136 pp.

The complexity-stability hypothesis was experimentally tested using intact terrestrial microcosms. "Functional complexity" was defined as the number and significance of component interactions (i.e., population interactions, physical-chemical reactions, and biological turnover rates) influenced by nonlinearities, feedbacks, and time delays. It was postulated that functional complexity could be non-destructively measured through analysis of a signal generated from the system. Power spectral analysis of hourly CO_2 efflux, from eleven old-field microcosms, was analyzed for the number of low frequency peaks and used to rank the functional complexity of each system. Ranking of ecosystem stability was based on the capacity of the system to retain essential nutrients and was measured by net loss of Ca after the system was stressed. Rank correlation supported the hypothesis that increasing ecosystem functional complexity leads to increasing ecosystem stability. The results indicated that complex functional dynamics can serve to stabilize the system. The results also demonstrated that microcosms are useful tools for system-level investigations.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER I

INTRODUCTION

The complexity-stability hypothesis has long been of interest to ecologists (Marsh 1885, Clements 1916, Gause 1934, Nicholson and Bailey 1935, MacArthur 1955). The hypothesis states that in ecological systems, an increase in complexity leads to a corresponding increase in stability. This hypothesis has great intuitive appeal and has almost become conventional wisdom without rigorous definition of either stability or complexity. Nor is it clear at what level of organization (i.e., population, community or ecosystem) the hypothesis applies (Van Voris 1976). The large number of alternative terms for stability (e.g., constancy, elasticity, sensitivity, fragility, ...) and the development of the hypothesis from intuitive understanding through theory and experimentation to mathematical treatment have added to the confusion (Lewontin 1969, May 1973, Orians 1974, Botkin and Sobel 1975, Innis 1975). As a result, the hypothesis has yet to be experimentally tested at the ecosystem level of organization.

Two approaches to ecosystem complexity and stability have emerged over the past quarter century: static and dynamic. Static methods identify an index of complexity (e.g., species diversity, trophic connectance or energy balance) which may be measured at a single point in time. A corresponding measure of stability is designated at the population or community level such as persistence of all species in the assemblage (Odum 1953, MacArthur 1955, Odum 1957, Margalef 1969).

Dynamic approaches utilize mathematical theory to examine the stability properties of models (Gardner and Ashby 1970, May 1971, Holling 1973, May 1973, Thorton and Mulholland 1974, DeAngelis 1975, O'Neill 1976).

Both dynamic and static methods of testing the hypothesis are limited where total ecosystems are concerned. Static approaches consider properties of populations or communities and make inferences about total ecosystems without directly measuring any ecosystem characteristics. Dynamic techniques, although rather elegant and impressive, are applied to models of ecosystems rather than to ecosystems. Both approaches have produced an interesting body of somewhat speculative ecological theory, but neither technique suggests an experimental approach that would allow testing the complexity-stability hypothesis at the ecosystem level (Van Voris 1976).

Stability is a dynamic property of ecosystems, and as such depends on functional response of the system to perturbation (Lewontin 1969, McNaughton 1977, Evans 1977). Ability to respond depends upon component interactions or "functional complexity" which determines the number (i.e., richness) of alternate methods of reacting to stress. The emphasis here on perturbation is important, because some ecosystems may seem to be stable only because they seldom experience perturbations rather than being more complex (Levin 1975). Ecosystem stability is used in the Webster et al. (1975) sense of resistance and resilience. Resistance is the capacity of the system to withstand stress and resilience is the ability of the system to return to a reference state or new equilibrium once displaced. Stability can be calculated by the

"perturbation integral," or the change in trajectory of a system property after perturbation (O'Neill 1976).

A direct approach to testing the complexity-stability hypothesis at the ecosystem level requires non-destructive monitoring of a dynamic property that integrates component interactions into an index of system complexity. A different integrative system parameter is required to assess the system's response to perturbation (i.e., its stability). Testing of the hypothesis can only be accomplished by monitoring two separate ecosystem parameters to provide separate indices of both complexity and stabilty at the ecosystem level of organization. Two different monitoring points are necessary even though the existence of a single index of total ecosystem dynamics has been questioned (Levin 1975, May 1975).

The objectives of the present study were to: (1) identify two ecosystem level parameters that could be non-destructively monitored; (2) relate these parameters to functional complexity and ecosystem stability; (3) identify an ecological system to test the complexity-stability hypothesis and; (4) test the complexity-stability hypothesis by monitoring the parameters. For this test to be convincing, certain constraints should be met: (1) the experimental systems must be isolated and replicable; (2) environmental conditions must be controllable and; (3) monitoring of both parameters must be non-destructive and accurate.

To avoid confounding effects and to show that the complexity-stability hypothesis can be applied more rigorously at the ecosystem level, the experiment must also measure population/community indices to

verify that; (1) experimental systems are replicates (or similar) in population/community measures; (2) system parameters are more sensitive than population/community measures and; (3) population/community measures are inadequate predictive indices of stability.

Ecosystem Parameters

Ecosystem analysis has identified a few properties of terrestrial ecosystems that can be non-destructively monitored (Odum 1969, O'Neill et al. 1975, Reichle 1975, Reichle and Auerbach 1972, Odum 1977). Ecosystem metabolism has been identified as a system parameter because it integrates physiological process in all living components as well as physical-chemical interactions in the soil. Experimental problems have limited measurement of ecosystem metabolism to a few experiments and to short time periods (Eckardt 1968, Monteith 1968, Woodwell and Botkin 1970, Odum 1970). However, ecosystem metabolism can be monitored non-destructively and is a sensitive measure of system response (Woodwell and Dykeman 1966, Woodwell and Botkin 1970).

During the past decade, numerous studies have focused on nutrient retention and recycling as an important property of terrestrial ecosystems (Likens et al. 1967, Jordan et al. 1972, Hannon 1973, Webster et al. 1975, O'Neill et al. 1977). At any given point in time, synchronized interactions of biotic components (e.g., producer-decomposer-mycorrhizae-roots) coupled with soil ion exchange capacity are responsible for recycling and retarding loss of nutrients. As a result, nutrient export has been suggested (O'Neill et al. 1977) as one

holistic parameter that is sensitive and responsive to changes in the interaction of components essential to nutrient retention.

Measuring Functional Complexity

The functional complexity of a system can be defined in terms of the number and intricacy of interactions and feedbacks among system components. Hutchinson (1948) postulated that complex interactions among system components should result in circular causal pathways. The greater the number of alternative causal pathways through the system, the greater the functional complexity. Cyclic or oscillatory behavior resulting from mutual causalities in such interactions should be measurable in a system parameter. May (1973) has shown that nonlinearities and Adams et al. (1976) has shown that time delays in ecosystem interactions also can lead to oscillations. Interactions that generate these oscillations could include feedbacks that can operate to stabilize the system (O'Neill 1976).

Eisner (1971) proposed a technique for investigating complex system oscillations. Oscillation frequencies can be estimated by spectral density analysis of a signal generated from the system (Blackman and Tukey 1958, Jensen and Ulrych 1973, Van Cauter 1974, Bloomfield 1976). The signal (i.e., monitored parameter) must have a sample interval that will allow the resolution of the shortest fluctuation with the limitation imposed by the Nyquist frequency taken into consideration (Nyquist 1928).

Signal analysis has had many applications in astrophysics and chronobiology (e.g., Solodovnikov 1960, McMahon 1965, Halberg 1969).

Analysis of population densities to uncover cycles are plentiful (e.g., Cole 1951, Moran 1953, Poole 1972, Steven and Glombitz 1972, Bigger 1973, Bulmer 1974) and demonstrate that low frequency cycles are the result of population interactions. Experimental work presented in the Cold Spring Harbor Symposia on Biological Clocks (1960) confirmed that high frequency cycles (frequencies > 0.0416 cy/hr) are mediated either by exogenous (e.g., day/night light or temperature) or endogenous agents (e.g., bio-chemical).

Use of spectral analysis to investigate interactions above the population level of organization has been limited (Platt and Denman 1975). Recent analyses of a forest community model (Emanuel et al. 1977a,b) have identified low frequency components in forest stand dynamics. These components are due to population interactions rather than dynamics of single populations.

Therefore, spectral analysis in the low frequency range can be expected to reveal interactions among system components. The richer the functional complexity within the system (i.e., population interactions, feedbacks, physical-chemical reactions and biological turnover rates), the larger the number of peaks in the low frequency region of the power spectra to be effected. Richness in the low frequency region of the power spectra can then be offered as an index of functional complexity and should be directly related to the number of alternative mechanisms available to stabilize a system.

Carbon dioxide evolution (an index of ecosystem metabolism) was selected as a convenient monitoring point for calculation of functional complexity. Since CO_2 efflux can be simultaneously monitored on

replicate systems with a sufficiently short sample interval and for a sufficiently long enough time period, it is possible to analyze the data by spectral analysis. Then rankings for functional complexity could be established based on the power spectra low frequency richness.

Measuring Ecosystem Stability

One index of ecosystem stability is the "perturbation integral" measured through net change in the trajectory of an ecosystem parameter (O'Neill 1976). This measure encompasses both resistance and resilience concepts proposed by Webster et al. (1975). Monitoring an ecosystem parameter during recovery would allow comparison of the stability of different ecosystems irrespective of species composition, density or diversity.

Many ecosystems have developed the ability to selectively accrue elements (Pomeroy 1970). This process is accomplished through either nutrient incorporation into cellular structures or recycling. The efficiency with which the ecosystem is capable of carrying out these processes can be monitored through nutrient export (Bormann and Likens 1967, Jordan et al. 1972). System components involved in these nutrient recycling processes tend to be aligned in series rather than in parallel. That is, recycling has a number of critical step-by-step processes that must be followed in a predetermined order. Thus, changes in nutrient retention or recycling capacity in response to a perturbation might be evidenced irrespective of the affected component because of the series alignment. It is understandable, then, that disruption of terrestrial ecosystems have caused increased nutrient export either

in stream output (Likens et al. 1970), in soil water (Stark 1977, O'Neill et al. 1977), or decreased available nutrient pools (Jackson and Watson 1977). Therefore, nutrient export, as an integrative index of the ecosystem's capacity to retain elements, could be used as a reasonable measure of total system stability.

Calcium has been found to be a consistant indicator of disruption in response to a broad spectra of perturbations (Likens et al. 1970, Richardson and Lund 1975, Stark 1977, Ausmus et al. 1977, N. T. Edwards unpublished data). Shugart et al. (1976) analyzed a forest calcium model and identified Ca in soil H_2O as a sensitive monitoring point. Calcium export in soil leachate was chosen, therefore, as a suitable monitoring point for ranking the stability of different ecosystems.

Experimental Units

Ecosystems are difficult or impossible to study under controlled environmental conditions due to size and cost. As an alternate approach, the microcosm offers reasonable size and cost, and can be placed under controlled conditions. The use of microcosms to investigate population or community functions is not new (Warrington 1857, Forbes 1887). The use of microcosms as ecosystem analogs to answer questions on transport and fate of toxic substances in the environment is a more recent development (Metcalf 1975, Witherspoon et al. 1976, Witt and Gillett 1977, Ausmus et al. 1977, Draggan and Giddings 1977). Microcosms were selected as ecological systems to test the complexity-stability hypothesis at the ecosystem level or organization.

Terrestrial ecosystems are dominated by producer-soil interaction with 80-90% of net primary production cycled directly to decomposers (Odum 1971). Many of these soil-based, functional interactions are regulated by microsite and spatial heterogeneity on a small scale. The need to investigate those naturally occurring component interactions led to the the selection of intact microcosms to test the hypothesis.

Goal of Research

The approach in this study has been to test experimentally the complexity-stability hypothesis using microcosms as ecological systems. A new approach to complexity, based on an index of the nature of functional component interactions, is postulated for this test. A measure of ecosystem relative stability in the sense of Webster et al. (1975) and O'Neill (1976) is tested. Correlation of the functional complexity index with the stability index is used as a test of the complexity-stability hypothesis.

CHAPTER II

MATERIALS AND METHODS

Site Description and History

An old-field located on the U.S. DOE reservation at Oak Ridge National Laboratory in Roane County, Tennessee, was used as the research site for both field measurements and intact microcosm extraction. The 16-ha old-field is co-dominated by Festuca arundinacea Schreb. and Andropogon virginicus L. with species representing the following genera scattered throughout: Rubus, Solidago, Plantago, Daucus, Diodia, Lespedeza, Trifolium, Acalypha, and Fragaria (Van Hook 1971). This site has been used in a number of previous studies and detailed descriptions of vegetation and history of land use are available elsewhere (Kelly et al. 1969, Van Hook et al. 1970, Auerbach et al. 1973, Matti et al. 1975).

The soil series is a Captina silt loam, which is a low to intermediate terrace soil developed as an alluvium of the Clinch River. The soil is moderately well drained, with a fragipan occurring approximately 60 cm below the surface causing a perched water table during the winter months. The pH (6.3) is fairly constant through the entire soil profile (Kelly et al. 1969). The climatic regime of the Ridge and Valley Province of Eastern Tennessee is humid-mesothermic (Holland 1953) with 28 year means for precipitation and temperature being 140.1 cm and 14.4 C, respectively (Atmospheric Turbulence and Diffusion Laboratory 1975).

Microcosm Extraction, Encasement and Equilibration

Thirteen intact cores were extracted from the approximate center of the old-field using a 15 x 15 cm circular stainless steel coring device. This size microcosm (15 cm diameter x 10 cm depth) was selected as the smallest soil section that could maintain autotrophic components for a reasonable period of time. A 100 m^2 plot was marked, and all microcosms were randomly extracted from within this plot. The only criterion was that the soil surface be reasonably level. Smaller cores (5 x 10 cm) were taken around each microcosm to estimate population/community parameters associated with the microcosm without destructively sampling the microcosm itself.

Each microcosm, with litter and autotrophs intact, was trimmed to predetermined size (15 x 10 cm) and sleeved with 0.10 cm thick polyvinyl chloride (PVC) (Van Hook et al. 1974). A Plexiglas disk, with leachate port attached, was pressed to the bottom of the soil profile, and the PVC heat shrunk until taut. The encased microcosm was placed in a small polyethylene pot, medium-grain acid-washed quartz sand packed between the PVC and pot, and then placed in an environmental chamber (Figure 1).

A lengthy equilibration period (21 weeks) was allowed prior to encapsulation with the cuvette for CO_2 monitoring. During this period day/night lengths followed civil daylight and twilight schedules for 36° 00' north latitude. Day/night temperature regimes were based on 1975 weekly means for the Oak Ridge area (Atmospheric Turbulence and Diffusion Laboratory 1975). (For details on encasement and environmental conditions see Appendix A.)

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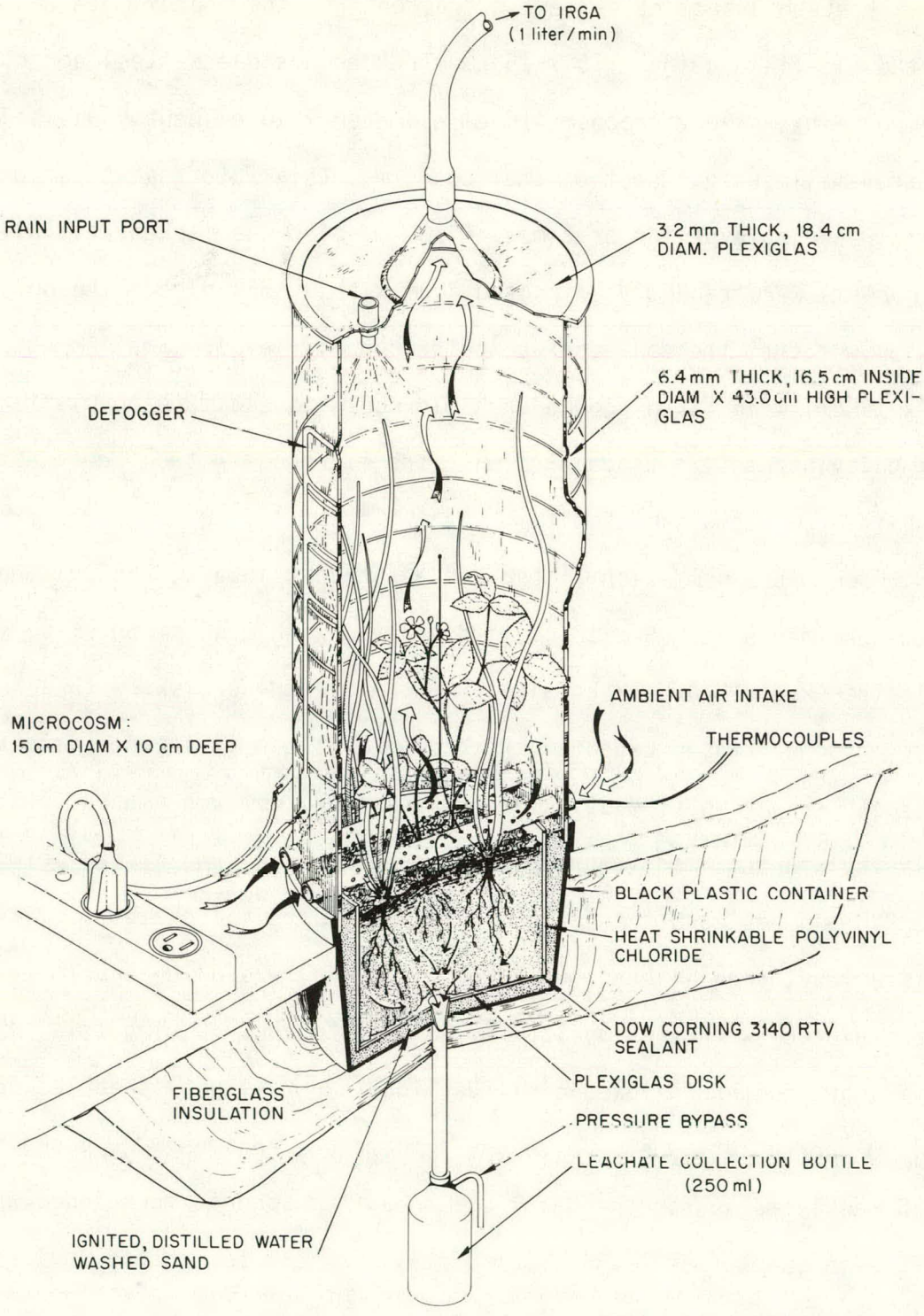

Figure 1. Three dimensional cross-section of encased and cuvette covered microcosm showing the two ecosystem level monitoring points of CO_2 and nutrient export.

Nutrient Export and Ecosystem Stability

During the equilibration period (May to October) and for the duration of the experiment (October to April), filtered rain water was added weekly to each microcosm in adequate volume (250 ml) to yield sufficient leachate for analytical determinations. Leachate volumes were recorded, aliquots syringed through a Nuclepore$^{(R)}$ (0.45 μ) membrane filters, and along with rain water, nutrient concentrations were determined. Analytical results for nutrient output from each microcosm were expressed as μeq/liter, except for dissolved organic carbon (DOC), which was expressed as mg/liter.

During the initial eight weeks of the equilibration period, a full suite of nutrients were examined (Ca, Na, Mg, K, total P, DOC NO_3-N, and NH_3-N) to screen for a key nutrient which might be a good measure of ecosystem stability. Analysis showed mean calcium concentrations and coefficients of variation (i.e., across microcosm and through time) to be less variable. Comparisons of Ca concentrations in soil H_2O from the same old-field and the same depth (10 cm) to microcosm equilibration period data showed no significant differences (D. R. Jackson unpublished data). Previous theoretical work (Shugart et al. 1976) and experimental work with microcosms (O'Neill et al. 1977, Jackson et al. 1977, Ausmus et al. 1977a) had also shown Ca to be a consistent indicator of ecosystem disruption. On this basis, analytical determinations were reduced to calcium and three other key nutrients (DOC, NO_3-N and NH_3-N) for the remainder of the experiment. After perturbation, nutrient export monitoring was continued for 10 weeks. One microcosm was randomly

selected as a control to verify that the systems level effect was the result of perturbation and not normal fluctuations in the microcosms. (For details pertaining to analytical procedures and equilibration period nutrient export consult Appendix A.)

Carbon Dioxide Monitoring and Functional Complexity

A system was fabricated to monitor CO_2 on an hourly basis from each microcosm. The basic design was a modification of Eckardt (1968), Edwards et al. (1971), and Edwards (1974). By means of an automated switching device, the stream of air passing through each cuvette (Figure 1) was sampled, CO_2 determined by infrared gas analysis, and results printed. Carbon dioxide data were expressed as mg/hr after subtracting ambient values and correcting for standard temperature and pressure. After installation of the cuvettes, microcosms were maintained in an environmental chamber with a day/night air temperature of 27.5° and 16.5°C, respectively. Day length during CO_2 monitoring was held constant at 12 hours. (For details on CO_2 monitoring system and environmental factors during monitoring see Appendix A.)

Hourly CO_2 efflux for each microcosm was monitored for 175.5 consecutive days, with cadmium stress occurring on day 113. A minimum of 85 days of uninterrupted measurements for each microcosm prior to perturbation were necessary to accurately estimate the richness of interactions through power spectral density (Bloomfield 1976, Blackman and Tukey 1958). (See Appendix E for listing of computer codes for spectral analysis.) Post perturbation CO_2 data were used to corroborate evidence that a significant ecosystem level disruption had occurred.

Population/Community Composition

Small cores (5 cm diameter x 10 cm depth) taken around each microcosm at the beginning of the experiment were used to determine if the microcosms were significantly different in biotic composition. At termination of the experiment, cores taken from each microcosm were used to measure the same biotic parameters. The following analyses were made on both sets of cores: soil arthropod and nematode densities (Phillipson 1971); soil fungal biomass (Jones and Mollison 1948, Parkinson et al. 1971, Visser and Parkinson 1975); soil bacterial density (Parkinson et al. 1971, Gorden 1972, Benson 1973); and soil ATP concentration (Ausmus and Witkamp 1974, Ausmus et al. 1977b). In addition, plant species composition for each microcosm was recorded during the experiment and species diversity (H') was calculated (Wilson and Bosert 1971) (Appendix B).

Perturbation

Cadmium as $CdCl_2$ was used to stress the microcosms. Cadmium is recognized as a widespread contaminant in both aquatic and terrestrial environments (Friberg et al. 1974, Fulkerson and Goeller 1973). Cadmium was chosen for the present experiment because it would achieve the desired perturbation stress and because previous studies (e.g., Jackson et al., submitted) had provided valuable background data on the effects of Cd on nutrient loss from microcosms. Based on literature values (Van Hook et al. 1974, Page et al. 1972, Jula 1971), previous microcosm experiments (Jackson et al. submitted) and preliminary dosage experiments on soil microcosms (B. S. Ausmus unpublished data), a dose per

unit area of 0.424 mg/cm^2 was chosen. This level of Cd is well below the acute toxicity level for most soil organisms (Munshower and Behan 1971, Buchauer 1973). Treated microcosms received equal amounts of Cd (1.35 meq). Cadmium loss in the leachate was monitored four weeks prior to perturbation and continued for the duration of the experiment. In addition, Cd distribution in soil and transport into vegetative tissues were determined when microcosms were sacrificed. Non-aqueous sample preparation for final Cd distribution followed methods described by Jackson and Watson (1977). (For results of transport and fate of Cd see Appendix C.)

CHAPTER III

RESULTS

Population/Community Comparisons

The issue at the beginning of the experiment was not whether differences between microcosms based on population/community measures could be identified, but whether any one unit was clearly different from the others as a population of microcosms. Whether the microcosms formed a single population was examined by a statistical test that compared single observations or means with the mean of the remaining samples (Sokal and Rohlf 1969). Comparisons revealed that one microcosm was significantly lower ($p \leq .05$) in arthropod density and another lower ($p \leq .05$) in nematode density. In addition, these same two microcosms showed erratic nutrient export and low vegetative species diversity. Therefore, they were dropped from further monitoring. The remaining eleven microcosms, while showing differences, were determined by this test to be essentially replicates of the same population at the beginning of the experiment (Table 1).

Comparison of initial and final measures showed significant increases between periods for all microcosms for fungal biomass and bacterial density and no obvious unidirectional change for either arthropod or nematode density estimates (Table 2). Comparison of ATP concentrations showed a marked decrease between sample periods and a shift in location of the higher concentration of ATP from the 5-10 cm increment at time zero to the 0-5 cm increment at time final. However, none of the individual microcosms were identified as outliers based on

Table 1. Population/community measures taken at beginning of experiment for the eleven microcosms.

MICROCOSM NUMBER										
1	2	3	4	5	6	7	8	9	10	Control
ARTHROPOD DENSITY/MICROCOSM										
913	1026	918	1143	1106	958	869	949	877	868	1066
NEMATODE DENSITY/MICROCOSM										
0-5 cm										
369	432	373	351	372	356	409	339	328	409	426
5-10 cm										
265	216	175	212	191	162	210	238	220	178	247
FUNGAL BIOMASS (mg/g)										
0-5 cm										
18	25	19	27	27	19	23	26	20	24	29
5-10 cm										
17	21	17	25	17	16	16	23	22	20	25
BACTERIAL DENSITY (10^8/g)										
0-5 cm										
5.2	5.5	4.4	3.5	4.7	3.9	5.9	5.2	4.3	4.4	5.1
5-10 cm										
5.3	7.3	5.9	6.5	6.4	7.9	7.0	6.2	5.8	4.3	4.3
ATP CONCENTRATION (ppm)										
0-5 cm										
3.6	4.3	4.5	3.2	3.5	3.6	3.2	3.6	2.9	4.4	3.2
5-10 cm										
4.5	3.9	4.9	5.9	3.7	4.8	5.6	5.1	4.6	3.9	4.4

Table 2. Population/community measures taken at termination of experiment.
(Where Δ= the change from the beginning of the experiment.)

	MICROCOSM NUMBER										
	1	2	3	4	5	6	7	8	9	10	Control
ARTHROPOD DENSITY/MICROCOSM											
	990	927	998	1073	1023	991	964	908	941	1051	964
NEMATODE DENSITY/MICROCOSM											
0-5 cm											
	342	441	406	364	391	349	384	378	393	373	427
5-10 cm											
	273	321	152	202	227	153	181	193	213	198	260
FUNGAL BIOMASS (mg/g)											
0-5 cm											
	43	38	51	47	39	55	49	38	33	43	48
Δ	+24	+12	+32	+20	+12	+36	+25	+12	+13	+19	+19
5-10 cm											
	30	25	36	40	29	21	40	28	23	36	29
Δ	+15	+5	+19	+14	+13	+6	+23	+5	+4	+5	+16
BACTERIAL DENSITY (10^8/g)											
0-5 cm											
	6.9	9.0	8.9	5.7	6.5	6.8	8.1	6.4	6.3	7.0	6.3
Δ	+1.8	+3.5	+4.2	+2.2	+1.8	+2.9	+2.2	+1.2	+2.0	+2.6	+1.2
5-10 cm											
	8.3	6.3	7.2	7.4	8.3	7.2	8.4	7.5	5.3	5.1	6.6
Δ	+2.8	-1.0	+1.3	+0.9	+1.8	-0.7	+1.4	+1.3	-1.2	+0.8	+2.4
ATP CONCENTRATION (ppm)											
0-5 cm											
	2.6	*	3.0	4.9	2.9	2.9	2.1	3.9	2.7	2.0	2.3
Δ	-0.9	*	-1.5	+1.7	-0.7	-0.7	-1.1	+0.3	-0.2	-2.4	-1.0
5-10 cm											
	1.2	*	0.9	1.3	1.4	1.1	1.0	1.5	1.1	1.3	1.2
Δ	-3.3	*	-4.0	-4.6	-2.3	-3.8	-4.6	-3.6	-3.6	-2.5	-3.2
VEGETATIVE DIVERSITY											
H_s	1.52	1.67	1.71	1.97	1.35	1.76	1.41	1.47	1.37	1.42	1.58
σ	.06	.03	.05	.05	.08	.04	.08	.07	.04	.04	.03

* Radiocalcium treated (45-Ca) no ATP analysis possible

any of the population/community measures. Comparisons of vegetative species diversity, based on Hutcheson (1970), showed the microcosms to be indistinguishable (Table 2).

Carbon Dioxide Analyses

A total of 175.5 days or 4212 measurements of CO_2 efflux were recorded for each microcosm (Figure 2). Typical daytime CO_2 efflux was below zero indicating photosynthesis was occurring. Nighttime CO_2 efflux was always above zero and was the result of respiratory responses of all components of the micro-ecosystems. Spikes of increased CO_2 efflux resulted from weekly additions of rain water (Figure 2) and are postulated to be due to trapped CO_2 being physically forced from the soil matrix.

Carbon dioxide efflux was monitored until the termination of the experiment or 62 days after perturbation. Values of CO_2 two weeks prior to and two weeks after the Cd treatment were examined to determine if a change in carbon production or fixation had occurred. A significant decrease was evident in nighttime sum CO_2 values for all treated microcosms indicating that Cd perturbation had induced an ecosystem response. In addition, weekly CO_2 spikes resulting from watering were absent from all treated microcosms for at least four weeks after Cd treatment (Figure 2).

Functional Complexity

The power spectral density for CO_2 efflux of the initial 85 days (2048 data points) was estimated for each microcosm using the Fast Fourier transform algorithm. The analyses of the CO_2 time series

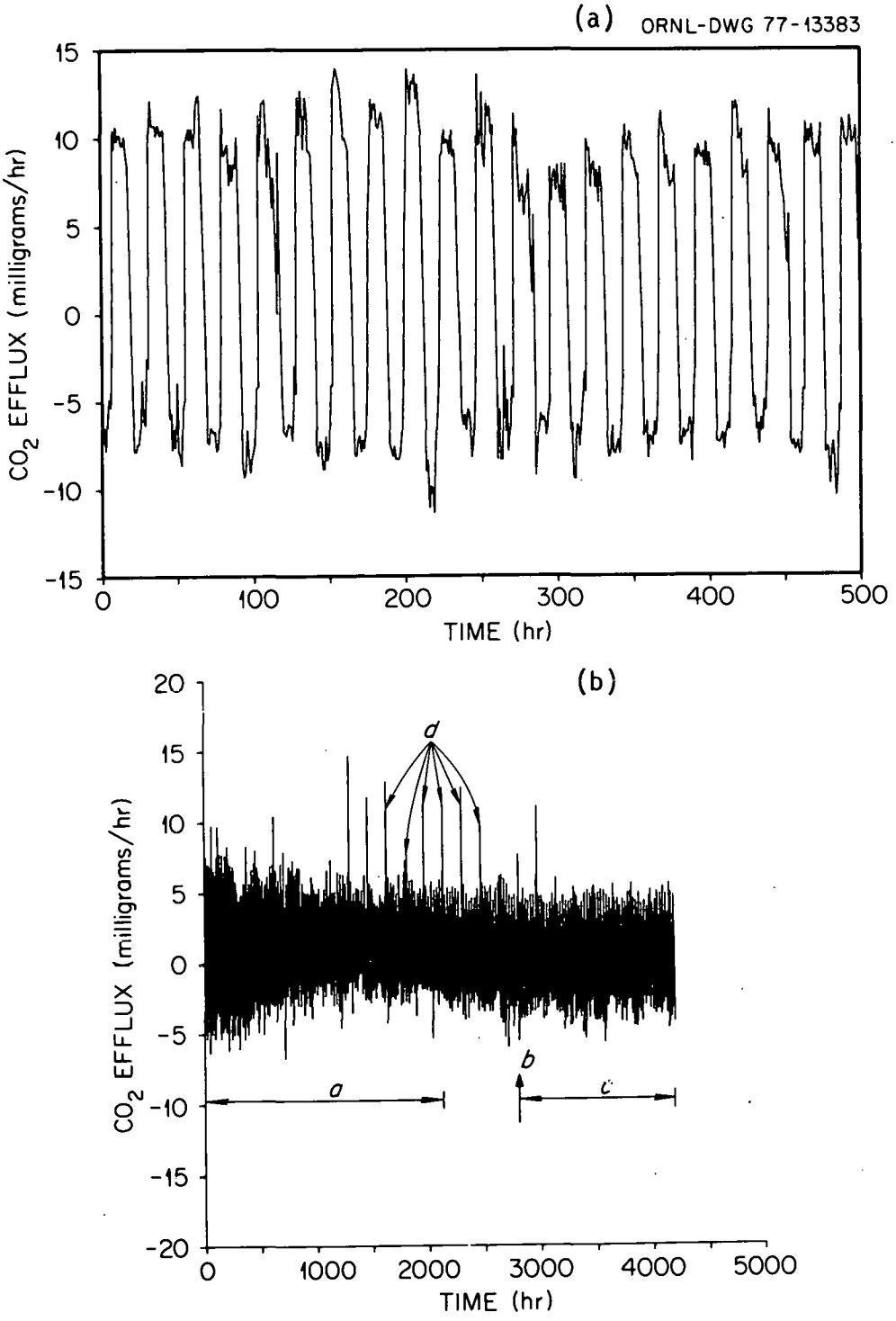

Figure 2. (a) Representative graph (Microcosm No. 5) of the first 21 days of CO_2 efflux showing the diel rhythm and the - and + periods associated with day and night respectively. (b) Example of the full 175.5 days of CO_2 data with (A) representing the portion used for estimating the spectral density, (B) perturbation with Cd, (C) the 62 days post perturbation, and (D) spikes of CO_2 efflux caused by watering.

showed the power spectra to be overwhelmingly dominated by the diel or 24 hour rhythm, with high frequency harmonics (12, 8, 6, and 4 hour cycles) evident. However, the specific peaks of interest for determining functional complexity were in the low frequency region with period greater than 24 hours.

A visual inspection of the low frequency regions of the spectral analysis for each microcosm showed noticeable differences (Figure 3). Some microcosms were strictly dominated by the 7 day cycle (0.0059 frequency) mediated by watering, others were dominated by either a 17 day or longer cycle, and others were frequency rich with no single dominating cycle. Amplitude of the dominant frequency for each microcosm differed and failed to correspond to any known environmental conditions. It was difficult to interpret amplitude or position of peaks with respect to cause and effect or importance in ranking the functional complexity. What had originally been postulated was that the number of peaks was a mesure of richness of component interaction. Thus, the number of peaks occurring above an amplitude of 2.0 for each microcosm was selected as the index of functional complexity (Table 3). More complicated methods (e.g., weighting by peak amplitude and peak-trough searching) did not improve the ability to discriminate between microcosms or did not significantly change the ranking.

Micro-Ecosystem Stability

Export of Ca was used as the measure of the response of these microcosms to stress produced by the toxic effects of Cd. The microcosms treated with identical amounts of Cd showed an immediate increase

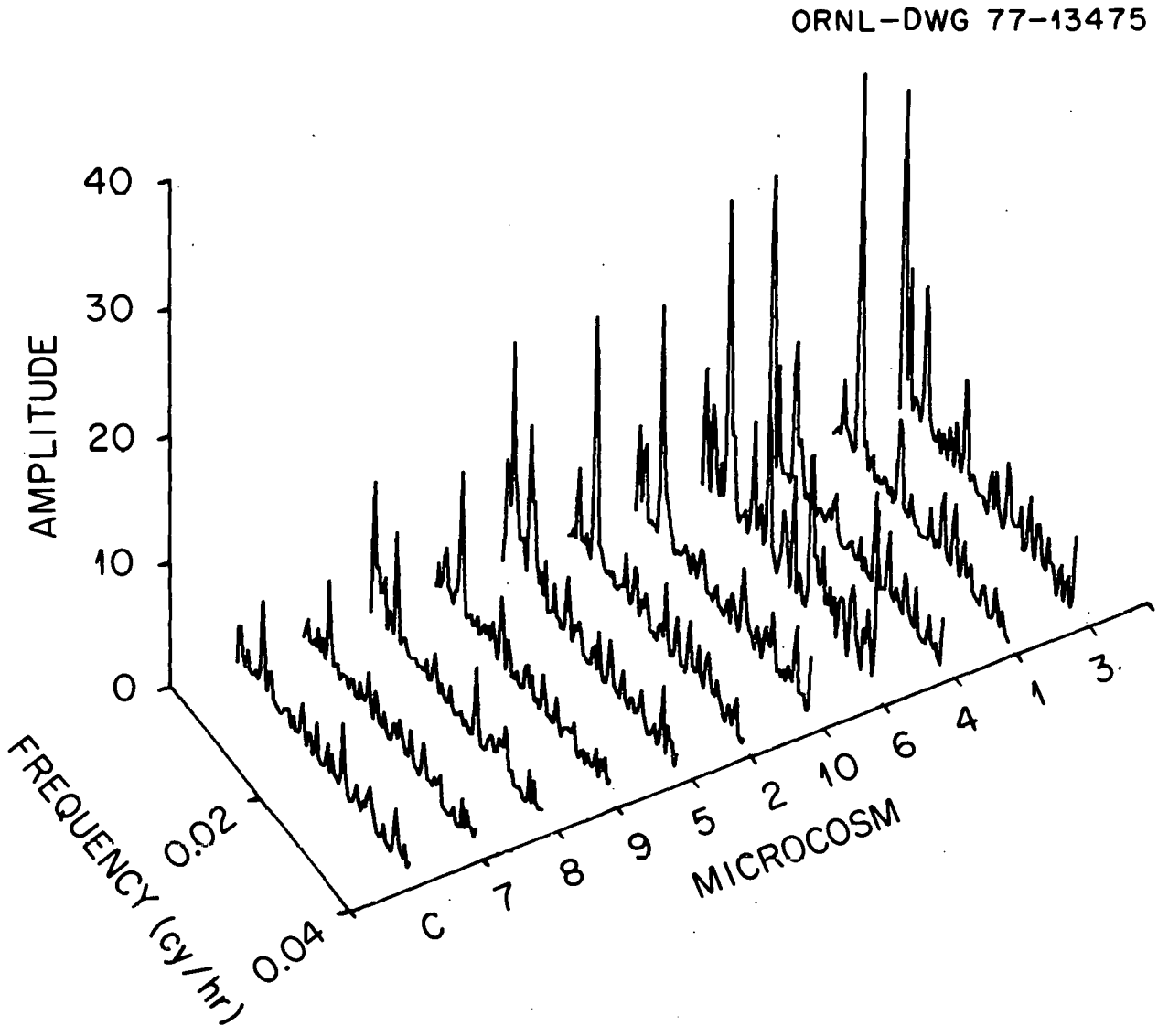

Figure 3. Isometric presentation of power spectra for all microcosms (C = Control) showing differences in richness in frequencies.

Table 3. Rankings of functional complexity and ecosystem stability based monitoring of CO_2 and total Ca export in soil leachate.

	FUNCTIONAL COMPLEXITY		ECOSYSTEM STABILITY	
MICROCOSM NUMBER	Peaks	Rank	Ca Loss	Rank
1	10	8.5	289.5	3
2	12	5	203.6	2
3	13	3.5	315.5	5
4	11	6.5	379.3	7
5	16	1.5	133.3	1
6	16	1.5	314.0	4
7	9	10	434.4	9
8	10	8.5	543.5	10
9	13	3.5	353.0	6
10	11	6.5	420.6	8

* Ca loss expressed as total μeq.

in Ca export (Figure 4). A microcosm was considered to have recovered when Ca concentration returned to within the +95% confidence interval based on the six week pretreatment mean. The magnitude of the immediate response varied between microcosms and is considered to be a measure of the resistance of the systems. The time necessary for the microcosm to return to its original reference state or a new equilibrium condition was a measure of the system's resilience. Differences in resistance and resilence can be seen in Figure 4, with microcosm number 6 being the most resistant and microcosm number 5 most resilient. Ranking of the relative stability of these microcosms was based on a combination of resistance and resilence. The perturbation integral (O'Neill 1976) of net total Ca export from each system or the area between the disturbed and undisturbed trajectories was used to rank the microcosms (Table 3). The area under each curve in Figure 4 is equal to the total export of calcium in excess of the pretreatment mean.

Test of Correlation

Spearman's rank correlation was used to test the complexity-stability hypothesis. Results showed rankings based on numbers of peaks (i.e., index of functional complexity) and Ca loss following perturbation (i.e., index of ecosystem stability) to be significantly ($P < 0.05$, $N=10$) correlated with $r_s = 0.63$ (Olds 1938). The highest and lowest rankings (Table 3) for both indices were well matched (e.g., microcosms 5, 7, and 8). However, shifts or mismatches of rankings are evident in the middle. This may be the result of ignoring the

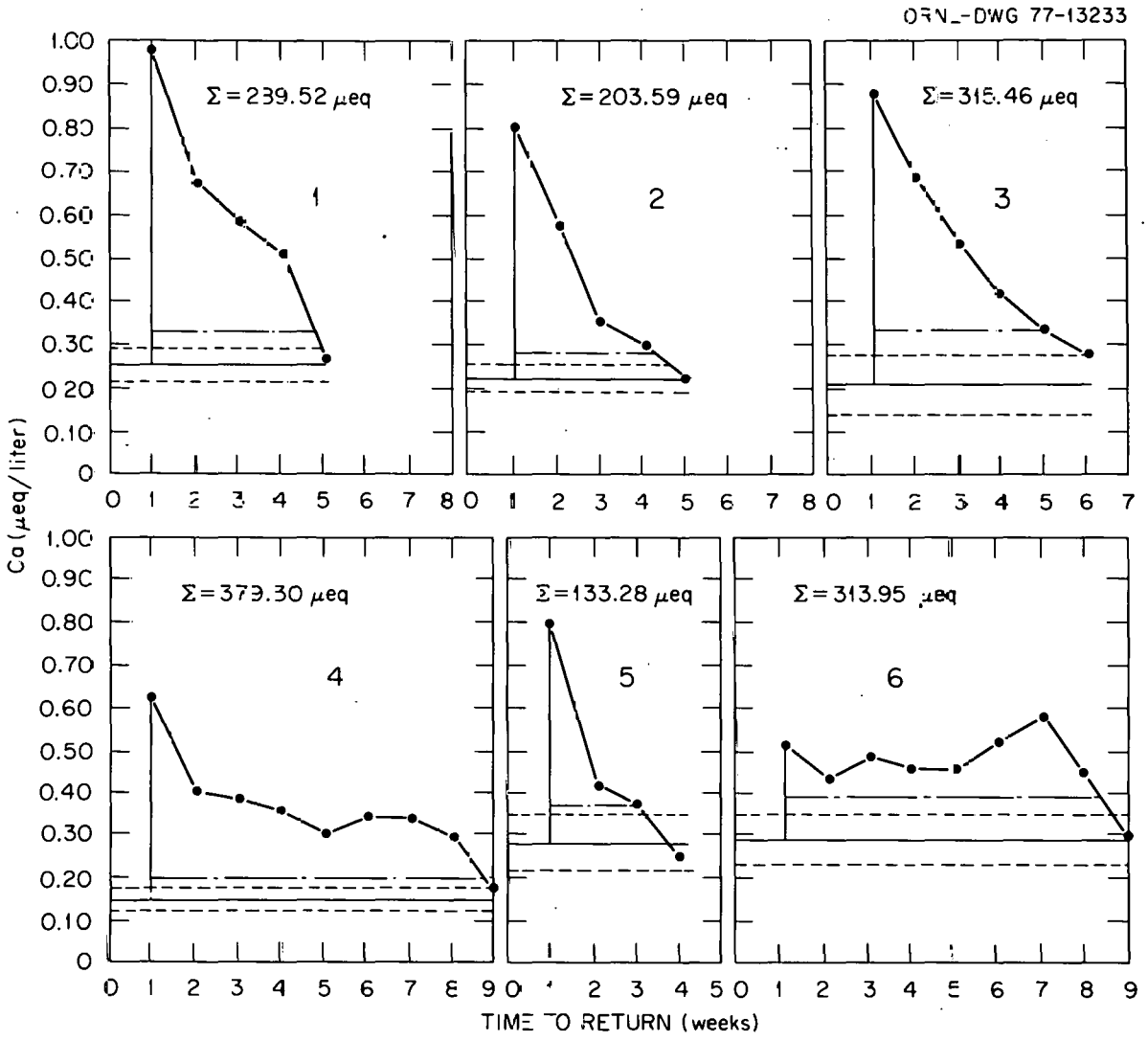

Figure 4. Export of Ca (μeq/liter) in leachate from each of the eleven microcosms with total export in excess of pretreatment mean. [Legend: solid line = mean pretreatment value; dotted line = standard deviation; dash-dot line = +95% confidence interval; Σ = total Ca export.]

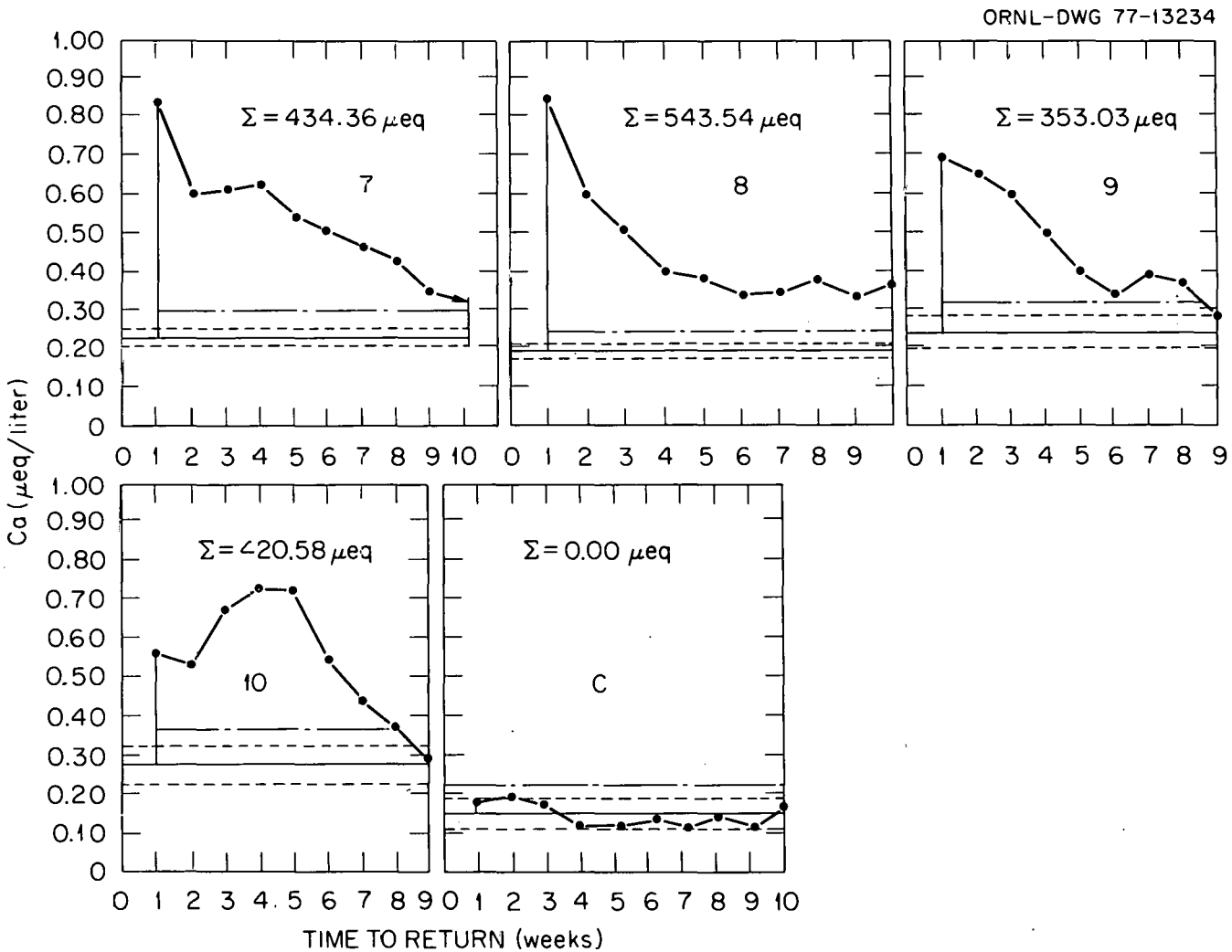

Figure 4. (continued).

differences in Ca loss between adjacent microcosms in the ranking. In addition, by considering only the number of low frequency peaks, rankings are not weighted for strength of the dominant frequency, for differences between peak amplitude, or for the position of the peak in the spectra.

Attempts to rank correlate ecosystem stability (Table 3) with any of the population/community measures at time zero (Table 1) or at time final (Table 2) using both Spearman's and Kendall's coefficients failed. Therefore, the classical or static population/community measures did not correlate with this index of ecosystem stability.

CHAPTER IV

DISCUSSION

For the past quarter century, ecologists have been testing and applying the complexity-stability hypothesis with the assumption that what was measured at the population/community level was axiomatically applicable to the ecosystem as a whole. Thus, until the early 1970's, the ecological community countenanced few arguments against the basic hypothesis or its assumptions. This issue remained somewhat stagnant until recent review articles examined existing evidence and determined that the classical assumptions and foundations had never been adequately supported experimenally (May 1973 and Van Voris 1976). This was evident in failures to relate static population/community measures of complexity to any index of stability (Paine 1966, Watt 1964, Hairston et al. 1968, and Zaret and Paine 1973). Mathematical approaches, recently offered as alternatives, have been characterized as dynamic in nature, yet have offered little help on how ecologists might actually measure either complexity or stability of an ecosystem (Gardner and Ashby 1970, May 1971, May 1973, Holling 1973, and Levins 1974). The purpose of the present study was to demonstrate that what had once been considered a dormant issue could now be operationally tested at an intact system level of organization.

For this to be accomplished, parameters integrating total ecosystem function and response, that could be non-destructively monitored, had to be identified. Ecosystem metabolism, measured through CO_2 efflux, and

nutrient retention or cycling, measured as nutrient export, were selected. Neither of these parameters had been used in any previous study to develop an index of either complexity or stability. Therefore, one contribution of this research was in proposing these parameters as indices of complexity and stability and applying them to test the complexity-stability hypothesis.

Static population/community measures (Table 1 and 2, pages 18 and 19) were collected to determine if stability of the ecosystem was solely dependent on or could be effectively monitored at this level of organization. None of the classic population/community measures (i.e., population densities and diversity) were correlated with system stability. This lack of correlation is supportive of the statement of O'Neill et al. (1977) that population/community measures are not axiomatically applicable to the ecosystem as a whole. Available techniques for measuring population/community are static and do not adequately represent the interactions and feedbacks which are the dynamic properties responsible for stability.

In this study, total system complexity was viewed in a functional sense. That is, components within the system interact in a synchronized fashion and the greater the number of interactions and feedback loops, the more complex the system in a dynamic sense. Each functional interaction offers an alternative mechanism or route by which the system can maintain its integrity. The greater the number of interactions among functional groups, the more likely that the system should be able to withstand or recover from stress. A population of a given species may

be involved in any number of interactions and feedbacks, thus negating the use of species or taxonomic lists alone as an index of complexity. We postulated that interactions would be manifested in oscillations or cyclic patterns which could be taken as an index of the functional complexity within the system. The number of low frequency peaks in the spectral density of CO_2 efflux was postulated to be related to functional complexity and has been shown to be a practical and dynamic measure of system function.

Ecosystem stability was assessed in this study by measuring the system's recovery of the ability to retain Ca following a perturbation. The increased Ca loss and subsequent recovery are not correlated with any changes in the parameters for individual functional groups (Tables 1 and 2, pages 18 and 19). Therefore, the behavior of the Ca export has been shown to be a measure of total ecosystem response, rather than reflecting the behavior of any one of the functional groups monitored.

Consideration also was given to the possibility that Ca loss could result from simple cation exchange with Ca being replaced by Cd. The possibility was evaluated by adding ^{45}Ca to one microcosm that still had 99% of the Cd remaining. (See Appendix D for details.) Results showed that the Ca isotope was totally retained within the top 2.5 cm of the soil, indicating that the Ca loss was not due to cation exchange since the ion exchange sites were not saturated. Tamura and Waller (1965) indicated that this particular Captina silt loam has an exchange capacity for Ca approximtely two orders of magnitude greater than the meq of Cd used to stress the system. Additional evidence that the Ca

loss and recovery was a biological phenomenon is given by the simultaneous deflection of CO_2 efflux. Therefore, evidence gathered in this study seems to support the contention that nutrient export can serve as a practical parameter of total ecosystem behavior.

It would not be anticipated that all ecosystem would have an identical index for stability. If stability is based on functional interactions among components and each ecosystem possesses differing structures and correspondingly different functional interactions, one might anticipate differences in response. Additional differences would be anticipated for different stress agents. However, previous experimental (O'Neill et al. 1977) and theoretical (Shugart et al. 1976) results, combined with the results presented in this study, provide consistent evidence that a change in Ca export rate is a fairly sound index of ecosystem disruption.

This study has taken a "black-box" approach to examining the complexity-stability hypothesis at the ecosystem level. Therefore, no attempt was made here to uncover the mechanisms responsible for low frequency oscillations in CO_2 efflux or for changes in Ca loss rates following perturbation. This was the only reasonable method of attacking the present problem, because as one attempts to isolate one mechanism in the interactive system, the interaction is destroyed. However, the study has raised several important new questions. What is the nature of the interactions and feedback exchanges which resulted in the low frequency oscillations in CO_2 efflux? Are some components or interactions more important than others in generating these

oscillations? Since the number of low frequency peaks (Table 3, page 24) was correlated with the system's ability to recover from perturbation (Fig. 4, page 23), these questions have important implications for our understanding of the functional dynamics of ecosystems.

The data presented in this study show that the microcosms recovered their ability to retain Ca following a perturbation, and yet no consistent changes can be detected in the population/community measurements. Was the initial loss of Ca due to physiological damage to a single population or functional group? Was a single population, highly sensitive to Cd, removed from the system and replaced by a "functionally equivalent" population? Or was one set of interaction pathways broken down and replaced by different, "equivalent" pathways? The answers to these questions could yield significant new insight into ecosystem mechanisms for recovery from perturbation. If functional interactions result in recovery of the microcosm's ability to retain Ca then they can be proposed as "homeostatic mechanisms" on the total ecosystem level.

Testing of the complexity-stability hypothesis was performed on intact terrestrial microcosms. The microcosms were employed as surrogate ecosystems. Microcosms proved to be reasonable tools because of their size, controllability and cost effectiveness. The intact microcosms retained sufficient natural complexity that they could served as credible analogs for ecosystems. The results show that microcosms are useful tools for system level investigations. Nevertheless, the microcosms were merely intact portions of a system, not complete ecosystems. It would be more accurate to state that the hypothesis test was

performed on a complex ecological system, rather than an intact ecosystem. This study indicates that the complexity-stability hypothesis holds for a complex analog of an ecosystem, but does not prove the hypothesis for a total ecosystem. The remaining question is whether it would be reasonable to pursue a field test of the hypothesis, given the scale and monetary investment that would be required.

Data presented here support the hypothesis that functional complexity is correlated with ecosystem stability. The fact that the indices for both complexity and stability were based on system level parameters makes this a reasonable test of the hypothesis for an intact ecological system. The lack of correlation of any of the population/community measures with ecosystem stability lends credence to the argument presented by O'Neill et al. (1977) that these measures are insensitive and do not characterize total system dynamics. The key issue here is that functional complexity of the ecosystem, represented by a microcosm, was a reasonable predictive index of the system's capacity to recover from stress.

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APPENDICES

APPENDIX A

DETAILED MATERIALS AND METHODS

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Microcosm Encasement

A number of encasement criteria had to be satisfied for this experiment. Negligible boundary flow was required so that rain water or contaminant would flow through the soil profile and CO_2 would rise only from the soil surface, rather than either being channeled along the sides. The second criterion was to encase the microcosm with materials which would have no effect on either of the system-level parameters being monitored. Finally, the materials used to satisfy the first and second criteria would act as insulation and significantly reduce lateral penetration of photosynthetically active light. After much testing, it was felt that the approach selected adequately satisfied the criteria.

Microcosms were brought to the laboratory for encasement within one hour of extraction. Preparation consisted of cutting all root protrusions along the outside edge and removing the bottom 5 cm to ensure dimensions of 15 x 10 cm. The microcosms were carefully placed in the middle of a 16 cm diameter by 40.5 cm length sleeve of 0.1 cm thick heat shrinkable polyvinyl chloride (PVC) (Van Hook et al. 1974). A 15 cm diameter by 0.63 cm thick Plexiglas disk with a thin layer of Dow Corning 3140-RTV coating around the edge was placed inside the bottom of the PVC sleeve and pressed to the bottom of the soil profile. A cardboard tube, 15 cm in diameter, was placed inside the top portion of the

sleeve to cover the aboveground tissues. The PVC was slowly heat shrunk, using a hot air gun, until taut around the edge of the microcosm, Plexiglas disk, and cardboard tube. In preliminary tests it was determined that if care was taken to avoid overheating the PVC a temperature rise in the soil of less than 3°C could be anticipated 1 cm from the edge. Excess PVC was trimmed from both top and bottom, leaving approximately a 2 cm lip on the top. A wormscrew hose clamp was tightened around the outside edge of the PVC-Plexiglas juncture, and additional 3140-RTV coating was squeezed along the bottom edge of the Plexiglas. The encased microcosm was not disturbed for 24 hours to allow the RTV coating to cure.

After the RTV coating had cured, the hose clamp was removed and a plastic port was inserted into a 1.23 cm diameter predrilled hole in the center of the Plexiglas disk (Figure A-1). No sealant was used around this hole because of the extremely tight fit. Each microcosm was tested for leaks by adding a sufficient quantity of rain water to bring the soil profile to field capacity. Pin-sized holes found in the PVC were sealed with small beads of RTV coating. The encased microcosm was then placed in a polyethylene pot (18 x 15 cm) which had been painted black on the outside to decrease lateral light penetration. With the leachate port protruding through a small hole in the bottom of the pot, medium-grain quartz sand which had been ignited (600°C), 0.1 N HCl rinsed, and distilled water washed was packed between the PVC-wrapped microcosm and the blackened pot. The sand was prepared in this fashion to: (1) destroy microsites for potential microbial invasion, (2) ensure low

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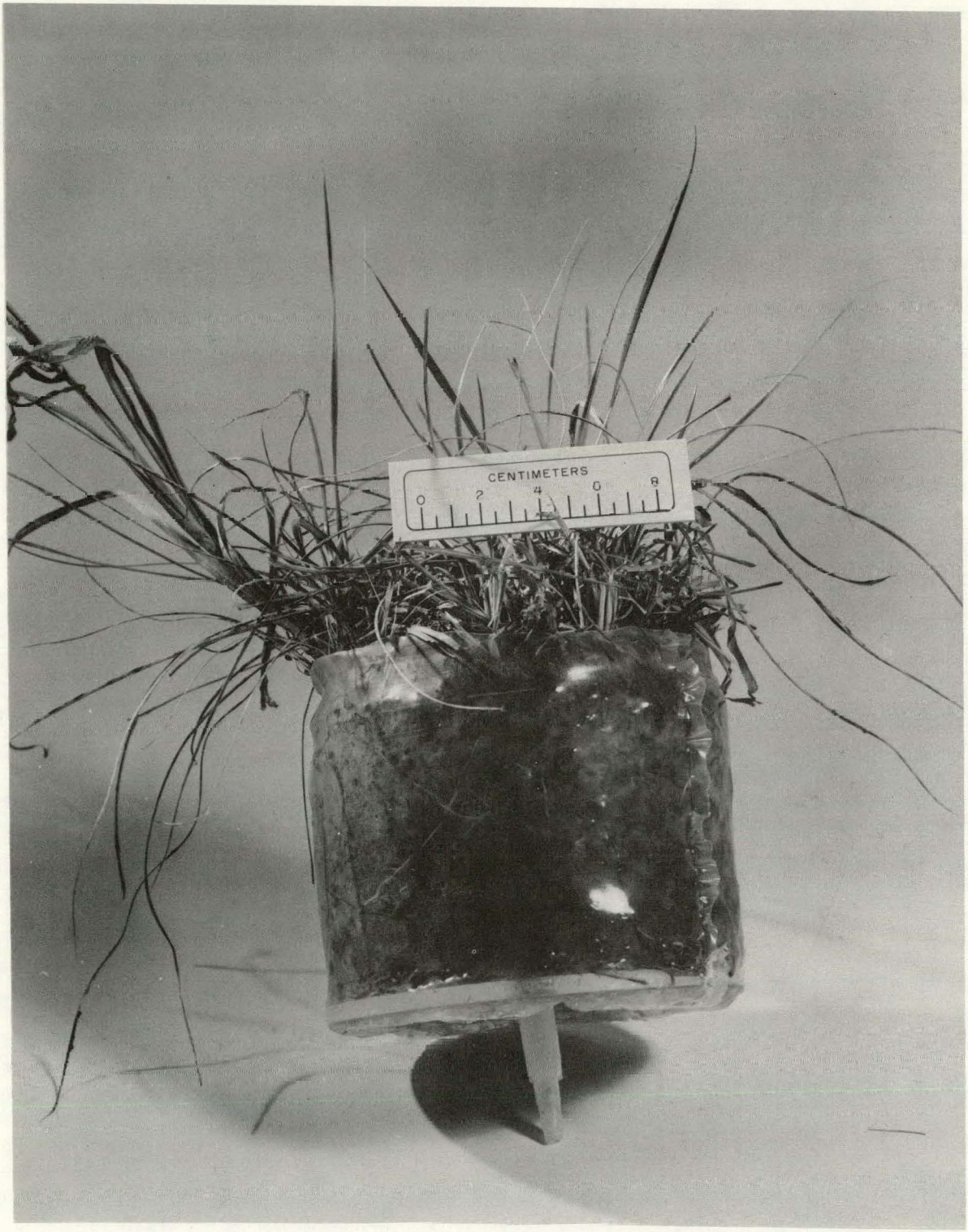

Figure A-1. Encased microcosm showing heat shrunk PVC, Plexiglas disk, and leachate port. Photograph taken nine months after encasement.

contaminant level in case of PVC breakage, and (3) restrict mesoinvertebrate colonization of any area other than the microcosm itself.

Once the encasements were completed, the microcosms were placed in a holding rack in an environmental chamber (Figure A-2). A polyethylene bottle (250 ml) was attached to the leachate port of each microcosm using vinyl plastic tubing. The leachate collection bottles were painted black to stop light penetration and were fitted with a pressure bypass tube to ensure free flow during leachate collection. Fiberglass insulation secured with heavy insulation tape was packed around the outside portion of the polyethylene pot which protruded below the wooden platform (Figure A-2).

Test of Encasement Materials

Tests were performed on encasement materials to answer two questions. Are nutrients exuded from the materials in sufficient concentrations to obscure nutrient analysis? If the materials under question do leak nutrients, does this phenomenon disappear over time? Heat shrinkable polyvinyl chloride (PVC), Dow Corning 3140-RTV coating, Plexiglas, sand, leachate port, vinyl tubing, polyethylene bottle, and Nuclepore$^{(R)}$ filter were tested for nutrient leaching. Three replicate samples were placed in separate 125 ml flasks containing 100 ml of distilled water. Flasks were shaken at 250 RPM for 48 hours, and water removed for element analysis. Fresh distilled water was added and the procedure repeated. At each sample period (2, 4, and 8 days), the water was analyzed for Ca, DOC, and NO_3-N. Results of analysis of

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Figure A-2. (a) Top view of old-field microcosms six weeks into equilibration period, and (b) side view showing insulation and leachate collection bottles.

distilled water (N=3), placed under the same experimental conditions, were subtracted from sample values at each time period.

Results show that only Dow Corning 3140-RTV coating might obscure nutrient export as a measure of ecosystem disruption and only with DOC (Table A-1). However, leaking of DOC dissipates with time and would not be expected to significantly interfere with nutrient leachate analysis after a three to four week equilibration period. The significance of the DOC leakage from RTV is most likely the result of time necessary for curing. In addition, the tests were conducted under much more rigorous conditions than would be experienced in the microcosm; and the amount of RTV tested (5 g) was much greater than the amount that would come in contact with either soil or leachate in the microcosms. Therefore, it is felt that all materials used for encasement are highly unlikely to obscure nutrient leachate analyses.

Rain Water

Rain water was collected in 12, 45-cm diameter plastic tubs. The rain water was passed through a Reeve Angle Inc. grade 934AH glass fiber filter using suction filtration to remove any particulate. The filtered rain water was then poured into two large carboys and stored at 3°C in a light-tight refrigerator. Twenty-four hours prior to leaching, rain water was taken from storage, poured into a polyethylene container, and placed in the environmental chamber to allow for temperature equilibration.

Table A-1. Test of materials used for encasing grassland microcosms. Values expressed as mean (N=3) concentration after subtracting mean distilled water values. Only one material (RTV) and one nutrient (DOC) was significantly different from 0.00.

Material	Time in Days	Calcium (μeq/l)	Dissolved Organic Carbon (mg/l)	Nitrate Nitrogen (μeq/l)
Vinyl Tubing[1]	2	0.002	0.33	0.003
	4	0.001	0.00	0.000
	8	0.000	0.33	0.000
Leachate Bottle	2	0.001	0.00	0.004
	4	0.000	0.00	0.000
	8	0.000	0.41	0.000
Leachate Port	2	0.001	0.00	0.003
	4	0.001	0.00	0.000
	8	0.000	0.23	0.000
Nuclepore(R) Filter	2	0.000	0.05	0.001
	4	0.001	0.00	0.000
	8	0.000	0.17	0.000
Sand	2	0.000	0.00	0.003
	4	0.001	0.05	0.000
	8	0.000	0.00	0.000
PVC	2	0.001	0.00	0.002
	4	0.000	0.02	0.001
	8	0.000	0.31	0.000
Plexiglas Disk	2	0.000	0.00	0.002
	4	0.000	0.00	0.000
	8	0.000	0.14	0.000
RTV[2]	2	0.003	2.67*	0.000
	4	0.000	1.68*	0.000
	8	0.001	1.12*	0.000

*Significant ($P \leq 0.05$).

[1]Vinyl tubing used between leachate port and leachate bottle and as ambient air inlets.

[2]RTV is Dow Corning 3140-RTV Coating normally used as an aquarium sealant.

Leaching and Analytical Procedures

The mean weekly volume of 250 ml/microcosm of rain water was equivalent to 54% of the weekly mean precipitation for the same time period for Oak Ridge (Atmospheric Turbulence and Diffusion Laboratory 1977). The rain water was applied with an air-pressurized spraying apparatus and length of time necessary for application was approximately eight minutes for each microcosm. Rain water was routinely added to the microcosms starting at precisely the same time every Monday (8:00 a.m. E.D.T. or 7:00 a.m. E.S.T.) for 47 weeks.

After allowing six hours for the rain water to leach through the microcosm, the leachate was collected, volume recorded, and an aliquot taken for further processing. The leachate collection bottles were rinsed with 0.01 N HCl, distilled water, and reattached to the collection port. The pH of each aliquot was recorded; the sample was syringed through a 0.45μ Nuclepore(R) membrane filter and then stored at 3°C for analytical determinations. All materials used for leachate collection and processing were washed in 0.2 N HCl and distilled water rinsed.

Leachate sample aliquots were analyzed for total elemental Ca, Mg, and K using a Perkin-Elmer 403 flame atomic absorption spectrophotometer. Total phosphorus was determined, after perchloric acid digestion, by the automated Technicon(R) method (Lundgren 1960). Analysis for NO_3-N and NH_3-N was done using standard automated Technicon(R) methods. For dissolved organic carbon (DOC) analysis, 10 ml was placed into an ampule containing persulfate. The ampules were sealed and heated to 120°C causing the DOC to be oxidized to CO_2. Analysis of

the DOC as CO_2 was executed using a model 0524 Oceanography International Total Carbon System.

Equilibration Period

During the 21 week equilibration period, prior to encapsulation with cuvettes, only Ca, DOC, NO_3-N, and NH_3-N were analyzed in leachate. Based on arguments posed in the body of the paper and additional evidence (O'Neill et al. 1977; Jackson et al., submitted, and Ausmus et al., in press), these nutrients were sufficient indicators to detect any radical departures during the equilibration period.

Analytical results for Ca, DOC, NO_3-N, and NH_3-N are shown in Table A-2. Statistical analyses for the same period by microcosm and by year-day (Julian calendar) are shown in Tables A-3 and A-4, respectively. Examination of coefficients of variation either by microcosm or year-day show that calcium is always significantly less variable than other nutrients monitored. This was an additional rationale for using calcium as a monitoring point for ecosystem recovery following stress.

Some interesting trends were detected in nutrient export during this equilibration period. For example, Figure A-3 shows both a reduction in NO_3-N losses and a simultaneous increase in loss of DOC. The increased DOC loss is postulated to be associated with the natural senescent behavior of the autotrophic components and decreased NO_3-N losses can be associated with microbial immobilization of essential nutrients for the system for the following spring growth (Van Voris and Ausmus 1976).

Table A-2. Equilibration period nutrient export values by microcosm. Values expressed as μeq/l for Ca, NO_3-N, and NH_3-N and as mg/l for DOC. [Legend: YRDAY = year-day (Julian calender) of sample, PH = pH of leachate, VOLUME = volume of leachate in ml.]

COSM=1

YRDAY	PH	VOLUME	CA	NO3	NH3	DOC
138	5.82	113	0.283	0.007	0.003	6.09
145	5.51	109	0.270	0.009	0.003	9.17
152	5.81	92	0.245	0.007	0.001	9.93
159	5.93	94	0.269	0.010	0.003	6.75
166	6.57	177	0.209	0.010	0.002	10.20
173	5.72	168	0.175	0.010	0.004	7.61
180	5.66	152	0.203	0.011	0.003	7.79
187	5.78	118	0.167	0.026	0.007	7.82
194	6.49	102	0.169	0.020	0.002	8.60
201	6.20	103	0.194	0.031	0.003	7.25
208	6.31	99	0.480	0.025	0.005	5.25
215	6.20	173	0.204	0.032	0.008	7.04
222	5.89	149	0.206	0.029	0.010	7.66
229	6.21	145	0.192	0.008	0.003	6.10
236	6.21	119	0.189	0.029	0.002	8.31
243	5.94	189	0.247	0.001	0.000	17.62
250	6.16	186	0.217	0.001	0.001	20.47
257	6.20	104	0.158	0.004	0.009	15.42
264	5.86	108	0.235	0.001	0.001	62.53
271	6.03	96	0.190	0.016	0.006	58.52
278	6.24	139	0.135	0.015	0.008	13.72

COSM=2

YRDAY	PH	VOLUME	CA	NO3	NH3	DOC
138	5.87	116	0.261	0.006	0.007	6.36
145	5.67	133	0.316	0.009	0.002	9.11
152	5.87	149	0.284	0.007	0.000	8.99
159	6.01	97	0.276	0.008	0.001	9.26
166	6.30	150	0.241	0.010	0.001	9.02
173	5.81	154	0.232	0.012	0.002	7.12
180	5.59	122	0.206	0.016	0.006	9.63
187	5.57	81	0.148	0.023	0.001	6.52
194	6.02	64	0.141	0.023	0.002	6.70
201	6.34	38	0.221	0.029	0.002	7.25
208	6.42	68	0.170	0.023	0.002	5.50
215	6.09	160	0.184	0.020	0.002	7.30
222	5.87	94	0.183	0.025	0.010	5.63
229	6.16	96	0.198	0.007	0.006	5.55
236	6.25	80	0.189	0.027	0.001	7.57
243	5.89	137	0.256	0.001	0.001	16.84
250	6.19	154	0.282	0.006	0.002	18.20
257	6.11	58	0.202	0.001	0.007	48.25
264	5.97	68	0.210	0.001	0.001	31.62
271	6.02	82	0.162	0.001	0.004	3.02
278	6.17	102	0.144	0.010	0.006	11.19

Table A-2. (continued).

COSM=3

YRDAY	PH	VOLUME	CA	NO3	NH3	DOC
138	6.03	139	0.312	0.009	0.056	6.75
145	5.63	73	0.196	0.015	0.042	6.70
152	6.05	80	0.115	0.021	0.010	3.69
159	5.99	63	0.125	0.021	0.003	5.91
166	6.49	71	0.125	0.006	0.000	8.53
173	5.84	56	0.188	0.025	0.006	6.88
180	5.89	36	0.124	0.022	0.007	5.87
187	5.62	45	0.143	0.024	0.004	7.06
194	6.45	93	0.164	0.013	0.000	9.40
201	6.31	56	0.175	0.023	0.000	9.25
208	6.29	94	0.170	0.018	0.000	9.00
215	5.92	120	0.190	0.021	0.006	7.92
222	5.85	69	0.183	0.020	0.001	10.90
229	5.89	92	0.185	0.005	0.005	9.54
236	6.14	60	0.196	0.022	0.002	16.65
243	5.93	176	0.233	0.000	0.001	30.26
250	6.08	162	0.226	0.000	0.000	34.92
257	6.07	87	0.210	0.001	0.004	21.50
264	5.83	62	0.234	0.000	0.001	38.79
271	6.06	90	0.196	0.008	0.004	16.25
278	6.12	99	0.181	0.010	0.007	33.10

COSM=4

YRDAY	PH	VOLUME	CA	NO3	NH3	DOC
138	6.31	136	0.321	0.009	0.013	6.19
145	5.69	150	0.304	0.012	0.005	6.53
152	6.07	200	0.253	0.014	0.000	4.06
159	5.87	158	0.282	0.013	0.001	5.75
166	6.45	208	0.218	0.016	0.002	7.08
173	5.73	203	0.180	0.017	0.002	4.82
180	5.63	184	0.163	0.017	0.003	4.23
187	5.92	112	0.140	0.023	0.002	3.83
194	6.54	96	0.154	0.023	0.002	3.75
201	6.34	100	0.202	0.030	0.006	6.05
208	6.34	91	0.260	0.030	0.002	6.80
215	6.11	173	0.190	0.030	0.010	4.38
222	6.01	129	0.205	0.031	0.013	5.23
229	6.20	148	0.179	0.034	0.004	3.48
236	6.31	144	0.190	0.031	0.009	4.65
243	6.03	197	0.196	0.024	0.002	7.21
250	6.09	249	0.193	0.012	0.001	8.71
257	6.25	122	0.166	0.015	0.005	6.73
264	6.05	130	0.208	0.017	0.008	5.74
271	6.04	151	0.178	0.010	0.007	15.16
278	6.09	137	0.132	0.015	0.009	5.09

Table A-2. (continued).

COSM=5

YRDAY	PH	VOLUME	CA	NO3	NH3	DOC
138	6.09	54	0.266	0.003	0.001	6.63
145	5.48	57	0.242	0.007	0.002	8.57
152	5.92	60	0.246	0.015	0.001	4.12
159	6.03	116	0.262	0.006	0.002	8.49
166	6.42	82	0.208	0.004	0.002	8.63
173	5.37	108	0.190	0.008	0.002	8.91
180	5.60	86	0.157	0.008	0.002	6.72
187	6.02	55	0.168	0.024	0.004	5.26
194	6.42	33	0.140	0.019	0.001	4.76
201	6.37	76	0.189	0.022	0.001	8.00
208	6.32	93	0.176	0.007	0.002	6.30
215	6.06	172	0.182	0.013	0.002	5.20
222	5.96	128	0.203	0.018	0.007	9.87
229	5.97	112	0.180	0.014	0.002	7.05
236	6.19	82	0.200	0.026	0.004	11.45
243	5.87	156	0.296	0.001	0.001	17.30
250	6.12	218	0.257	0.001	0.001	27.20
257	6.15	54	0.210	0.000	0.001	22.19
264	5.89	66	0.222	0.001	0.001	31.84
271	6.02	86	0.239	0.001	0.005	18.47
278	6.16	108	0.172	0.010	0.008	7.95

COSM=6

YRDAY	PH	VOLUME	CA	NO3	NH3	DOC
138	5.98	36	0.243	0.005	0.002	6.08
145	5.82	71	0.263	0.005	0.002	7.37
152	6.17	137	0.183	0.014	0.001	5.82
159	5.89	39	0.183	0.021	0.005	6.79
166	6.32	96	0.160	0.020	0.002	8.80
173	5.65	68	0.166	0.015	0.002	7.25
180	5.90	88	0.156	0.019	0.004	5.22
187	5.81	48	0.146	0.024	0.005	4.73
194	6.51	30	0.140	0.022	0.001	4.88
201	6.21	39	0.198	0.019	0.000	11.00
208	6.25	50	0.180	0.026	0.001	5.85
215	6.01	88	0.179	0.022	0.006	6.73
222	6.06	74	0.223	0.013	0.007	8.85
229	6.10	89	0.209	0.010	0.001	5.90
236	6.19	52	0.216	0.018	0.002	9.56
243	5.91	148	0.257	0.010	0.001	14.61
250	6.21	142	0.246	0.001	0.002	14.51
257	6.12	106	0.212	0.003	0.006	9.42
264	5.96	86	0.210	0.006	0.008	11.30
271	6.05	98	0.193	0.005	0.006	18.86
278	6.12	128	0.181	0.010	0.007	7.25

Table A-2. (continued).

COSM=7

YRDAY	PH	VOLUME	CA	NO3	NH3	DOC
138	5.63	103	0.218	0.009	0.001	6.14
145	5.77	88	0.170	0.014	0.003	7.33
152	5.90	89	0.128	0.016	0.001	5.05
159	5.94	71	0.166	0.020	0.002	9.91
166	6.80	133	0.165	0.012	0.003	9.61
173	5.40	122	0.147	0.015	0.003	8.64
180	5.59	110	0.150	0.015	0.003	7.11
187	5.91	98	0.139	0.025	0.001	7.51
194	6.52	95	0.134	0.004	0.000	4.91
201	6.29	99	0.218	0.031	0.003	7.00
208	6.16	115	0.181	0.018	0.004	5.40
215	6.06	193	0.185	0.024	0.051	6.08
222	5.97	166	0.194	0.022	0.009	7.49
229	5.98	160	0.183	0.024	0.001	8.43
236	6.22	122	0.202	0.030	0.000	15.10
243	6.07	195	0.231	0.007	0.004	13.59
250	6.11	208	0.230	0.001	0.001	36.85
257	6.15	101	0.223	0.001	0.006	29.45
264	5.89	94	0.196	0.001	0.001	38.75
271	5.93	118	0.223	0.005	0.007	21.81
278	6.03	142	0.136	0.011	0.007	11.30

COSM=8

YRDAY	PH	VOLUME	CA	NO3	NH3	DOC
138	5.89	84	0.197	0.012	0.001	9.31
145	5.47	99	0.166	0.013	0.002	8.05
152	5.98	120	0.146	0.013	0.001	3.91
159	6.00	109	0.188	0.016	0.004	7.47
166	6.79	156	0.147	0.016	0.001	7.03
173	5.85	166	0.139	0.016	0.003	6.95
180	5.92	128	0.147	0.016	0.004	6.15
187	5.98	76	0.142	0.024	0.003	5.20
194	6.49	81	0.144	0.021	0.004	6.60
201	6.26	79	0.186	0.029	0.005	7.65
208	6.21	105	0.185	0.021	0.004	5.10
215	6.08	190	0.194	0.024	0.003	6.36
222	5.85	148	0.222	0.027	0.001	8.43
229	6.03	155	0.107	0.017	0.004	11.90
236	6.14	133	0.216	0.004	0.002	9.43
243	5.93	203	0.240	0.001	0.001	29.25
250	6.05	200	0.204	0.001	0.001	20.85
257	6.19	113	0.183	0.001	0.005	20.30
264	5.88	122	0.196	0.000	0.001	27.45
271	6.08	116	0.198	0.004	0.006	24.10
278	6.06	148	0.137	0.012	0.006	16.24

Table A-2. (continued).

COSM=9

YRDAY	PH	VOLUME	CA	NO3	NH3	DOC
138	4.21	55	0.235	0.012	0.004	8.63
145	5.72	110	0.158	0.015	0.002	7.26
152	6.17	76	0.125	0.015	0.001	6.60
159	5.99	73	0.144	0.022	0.008	9.63
166	6.35	102	0.120	0.020	0.006	4.80
173	5.79	100	0.134	0.022	0.004	6.13
180	5.66	101	0.144	0.018	0.006	6.48
187	6.08	57	0.131	0.021	0.001	7.29
194	6.60	53	0.144	0.020	0.001	5.55
201	6.34	70	0.210	0.029	0.001	8.80
208	6.26	92	0.180	0.014	0.001	7.00
215	6.04	152	0.196	0.010	0.005	8.17
222	5.77	139	0.192	0.005	0.002	16.20
229	6.10	150	0.183	0.032	0.000	12.73
236	6.25	156	0.205	0.027	0.001	18.00
243	5.87	228	0.375	0.000	0.001	18.65
250	6.20	212	0.225	0.001	0.001	34.28
257	6.12	142	0.179	0.000	0.006	16.45
264	6.00	154	0.227	0.000	0.002	28.60
271	6.11	166	0.217	0.004	0.006	25.57
278	6.19	126	0.161	0.010	0.007	18.10

COSM=10

YRDAY	PH	VOLUME	CA	NO3	NH3	DOC
138	5.75	34	0.275	0.007	0.011	10.11
145	5.62	34	0.211	0.010	0.005	9.65
152	5.93	50	0.142	0.010	0.000	7.17
159	6.08	83	0.193	0.012	0.006	7.91
166	6.63	108	0.150	0.010	0.002	8.50
173	5.63	106	0.165	0.008	0.002	9.60
180	5.82	86	0.176	0.015	0.007	5.66
187	6.05	54	0.135	0.017	0.001	8.69
194	6.59	97	0.117	0.017	0.001	6.80
201	6.39	83	0.196	0.029	0.003	7.70
208	6.28	80	0.180	0.025	0.002	5.65
215	6.02	150	0.185	0.001	0.001	11.81
222	5.94	123	0.220	0.001	0.002	16.90
229	6.06	138	0.193	0.003	0.002	11.40
236	6.07	119	0.212	0.022	0.000	14.85
243	6.07	152	0.248	0.000	0.004	17.42
250	6.09	216	0.238	0.000	0.002	21.93
257	6.06	134	0.192	0.001	0.005	16.81
264	5.94	114	0.227	0.000	0.001	23.30
271	6.04	112	0.200	0.003	0.005	10.94
278	6.14	190	0.175	0.003	0.008	11.27

Table A-2. (continued).

COSM= C

YRDAY	PH	VOLUME	CA	NO3	NH3	DOC
138	5.96	64	0.170	0.019	0.001	9.17
145	5.56	96	0.143	0.015	0.002	8.15
152	6.21	108	0.148	0.016	0.000	4.74
159	5.97	71	0.185	0.019	0.002	9.03
166	6.53	128	0.150	0.023	0.002	8.77
173	6.63	150	0.142	0.024	0.007	7.16
180	5.72	130	0.153	0.024	0.011	7.11
187	5.90	114	0.153	0.021	0.000	9.58
194	6.38	105	0.133	0.005	0.001	10.50
201	6.22	99	0.212	0.017	0.005	11.60
208	6.29	114	0.202	0.001	0.000	7.00
215	6.14	192	0.228	0.001	0.001	13.00
222	6.09	174	0.224	0.001	0.002	13.62
229	6.13	188	0.209	0.022	0.001	16.70
236	6.27	170	0.218	0.036	0.000	15.05
243	5.94	169	0.223	0.001	0.001	17.26
250	6.14	224	0.205	0.000	0.002	31.65
257	6.10	130	0.166	0.001	0.007	19.10
264	5.96	160	0.181	0.001	0.001	25.95
271	6.01	146	0.233	0.001	0.009	28.32
278	6.21	160	0.130	0.013	0.009	14.53

Table A-3. Mean concentrations and coefficients of variation for equilibration period (N=21) by microcosm. Mean values expressed as μeq/l for Ca, NO_3-N, and NH_3-N and as mg/l for DOC.

	MEAN AND CV VALUES BY MICROCOSM							
COSM	CA_MEAN	CV_CA	NO3_MEAN	CV_NO3	NH3_MEAN	CV_NH3	DOC_MEAN	CV_DOC
1	0.221	32.14	0.0143	74.04	0.0040	70.38	14.47	109.40
2	0.215	23.54	0.0126	74.82	0.0030	89.36	11.46	91.07
3	0.184	24.83	0.0135	66.22	0.0077	184.23	14.23	76.27
4	0.205	25.02	0.0203	39.78	0.0051	77.35	5.97	41.97
5	0.210	19.51	0.0099	82.64	0.0026	79.68	11.19	68.86
6	0.197	17.98	0.0137	55.78	0.0034	72.37	8.61	42.85
7	0.182	18.86	0.0145	65.34	0.0053	203.17	12.74	80.30
8	0.179	16.86	0.0138	65.64	0.0030	57.63	11.80	66.57
9	0.185	30.56	0.0142	69.00	0.0031	76.58	13.09	63.58
10	0.192	20.05	0.0093	93.92	0.0033	85.28	11.62	43.63
C	0.181	19.30	0.0124	87.80	0.0031	110.03	13.71	53.59

Table A-4. Mean concentrations and coefficients of variation for equilibration period (N=13) by year-day. Mean values expressed as μeq/l for Ca, NO_3-N and NH_3-N and as mg/l for DOC.

MEAN AND CV VALUES BY YEAR-DAY								
YRDAY	CA_MEAN	CV_CA	NO3_MEAN	CV_NO3	NH3_MEAN	CV_NO3	DOC_MEAN	CV_DOC
138	0.253	18.30	0.0090	46.63	0.0090	46.63	7.41	21.03
145	0.222	27.40	0.0114	31.20	0.0065	31.20	7.99	13.08
152	0.183	33.74	0.0134	31.73	0.0014	31.73	5.83	36.54
159	0.207	27.05	0.0153	36.07	0.0035	36.07	7.90	18.70
166	0.172	23.42	0.0133	47.97	0.0021	47.97	8.27	17.88
173	0.169	17.05	0.0157	39.30	0.0033	39.30	7.37	18.00
180	0.162	15.26	0.0166	26.57	0.0052	26.57	6.54	21.75
187	0.147	8.16	0.0229	10.37	0.0027	10.37	6.68	26.40
194	0.144	10.12	0.0168	40.26	0.0014	40.26	6.59	32.39
201	0.200	7.09	0.0263	19.37	0.0026	19.37	8.32	20.52
208	0.215	42.58	0.0189	46.62	0.0022	46.62	6.26	18.30
215	0.192	7.16	0.0181	57.89	0.0087	57.09	7.64	34.26
222	0.205	7.65	0.0176	62.78	0.0057	62.78	10.07	39.39
229	0.191	5.61	0.0182	66.34	0.0027	66.34	8.98	43.44
236	0.203	5.55	0.0248	34.50	0.0022	34.50	11.87	36.18
243	0.255	18.41	0.0042	174.42	0.0016	174.42	18.18	35.94
250	0.229	11.22	0.0021	175.74	0.0013	175.74	24.51	37.40
257	0.191	11.54	0.0025	179.25	0.0054	179.25	20.51	53.94
264	0.213	8.18	0.0025	197.23	0.0024	197.23	29.62	50.35
271	0.203	11.52	0.0052	86.63	0.0059	86.63	21.91	64.15
278	0.153	13.70	0.0108	28.79	0.0075	28.79	13.61	55.44

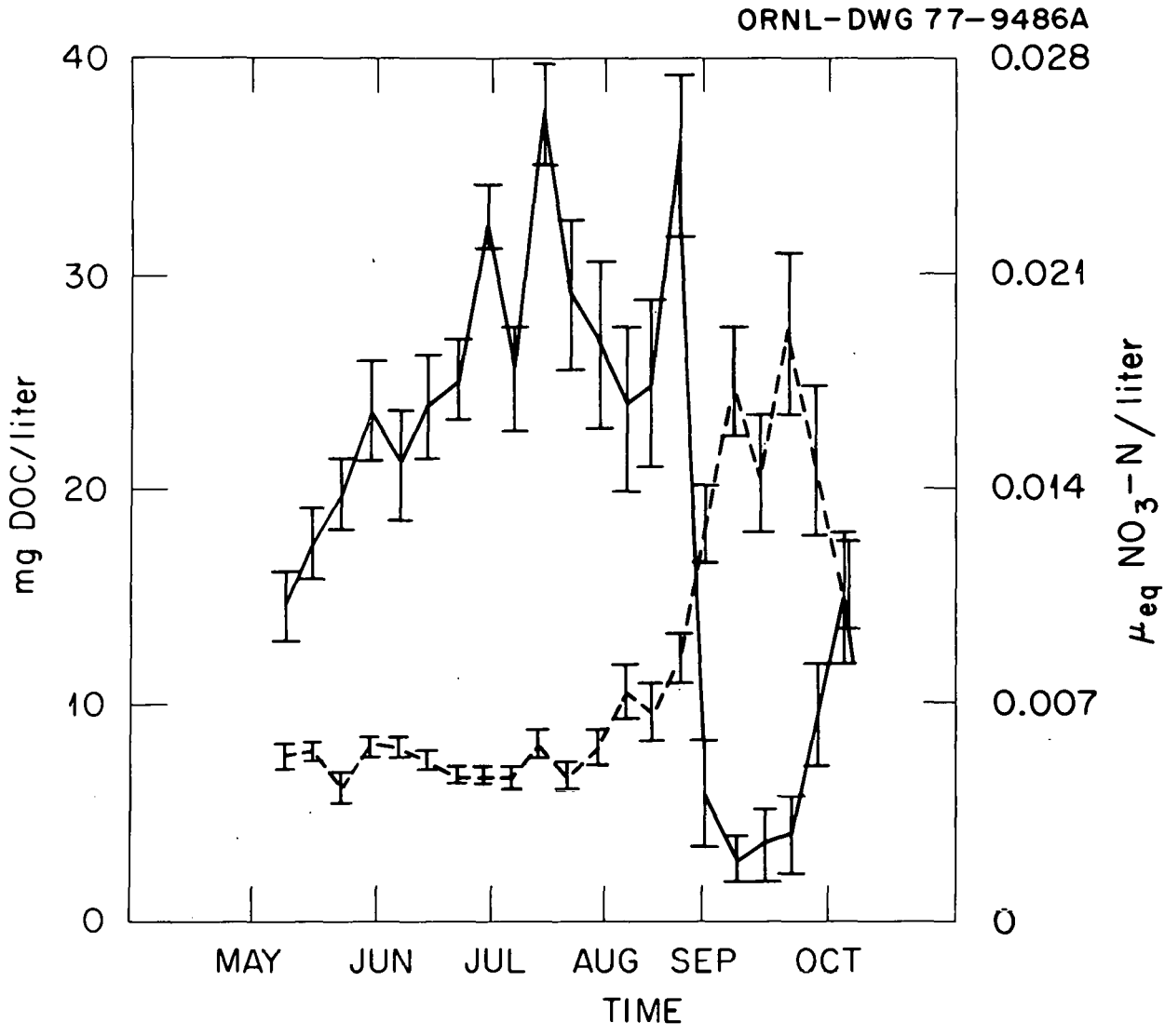

Figure A-3. Mean DOC (---) and NO_3-N (——) losses during equilibration period (± 1 S.E.).

Carbon Dioxide Monitoring

A system was designed and fabricated at Oak Ridge National Laboratory to monitor CO_2 on an hourly basis for each microcosm. The monitoring system can be isolated into four discrete units: (1) cuvette, (2) pneumatic system, (3) infrared gas analysis system, and (4) switching and data recording system.

Cuvette

The cylindrically shaped cuvette was 43 cm high with an inside diameter of 16.5 cm and a side wall 6.4 mm thick. It was made from one piece of extruded polymethymethacyrulate (Plexiglas) which did not possess ultraviolet refractory crystals. The optical properties of this Dupont Lucite$^{(R)}$ 140T acrylic resin Plexiglas guaranteed approximately 92% transmittance of environmental chamber light.

Each cuvette was fitted with a 3.2 mm thick by 18.4 cm diameter Plexiglas top with an inverted glass funnel sealed to the center and 1.5 m of 1 cm inside diameter vinyl tubing leading from the funnel to a quick disconnect panel inside the environmental chamber. The top end of the cylinder portion of the cuvette had been machined to assure a good seal with the Plexiglas top. Only a thin layer of vacuum grease was needed to prevent air leaks. A small hole was placed in the top and stoppered with a serum cap. This hole was used for weekly amendments of rain water and the $CdCl_2$ perturbation.

Three ambient air intake tubes were equally spaced 2.5 cm above the bottom edge of the cuvette so that the tubes would be at the soil surface when the cuvette was placed over the microcosm. Each tube had

15 holes, 3.2 mm in diameter, that were arranged to ensure good vortexing and equal air flow throughout the cuvette (Schlichting 1968 and R. T. Hosker personal communication 1975).

The cuvette was fitted with a defogger to lightly heat the walls and prevent condensation build up on the inside of the cylinder. A 24-hour timer with two selector switches coupled with a pair of voltage regulators and six, 6 volt 10 amp transformers were used to control the operation of the defoggers (Figure A-4). The cuvette was placed over each microcosm and the thermocouples were inserted through the ambient air intake tubes for temperature recording of either soil or air (Figures 1, page 12; A-5; and A-6).

Only 11 of the 13 microcosms were encapsulated with cuvettes. Two of the microcosms were omitted because of low autotrophic diversity and erratic nutrient export data. The twelfth (empty) cuvette was sealed on the bottom with Plexiglas and used for ambient CO_2 readings.

Pneumatic System

After the air had been drawn through the cuvette, it traveled via 10 m of 4 mm inside diameter air line through a canister of desiccant ($CaSO_4$). Color-indicating desiccant was used and changed daily. The air was then drawn into a pneumatic chassis containing flow meters and three-way solenoid valves. Each flow meter was adjusted for a flow rate of 1.0 l/min to allow for seven air changes per hour. This is within the range of typical wind speeds for grasslands (Sellers 1967, Rosenberg 1974, and Edwards and Sollins 1973). The solenoid valves directed the

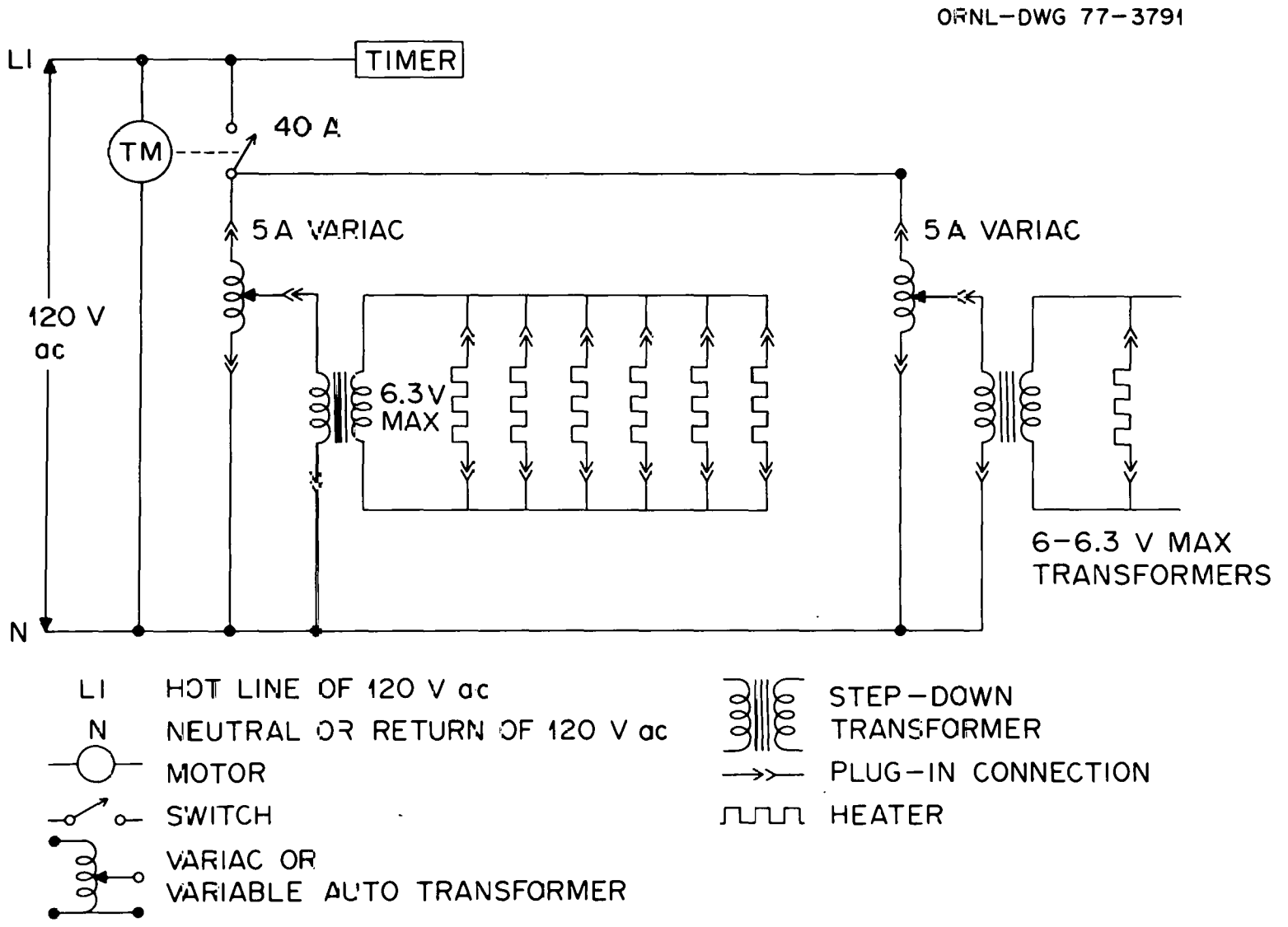

Figure A-4. Schematic of electronic controlling system for defoggers.

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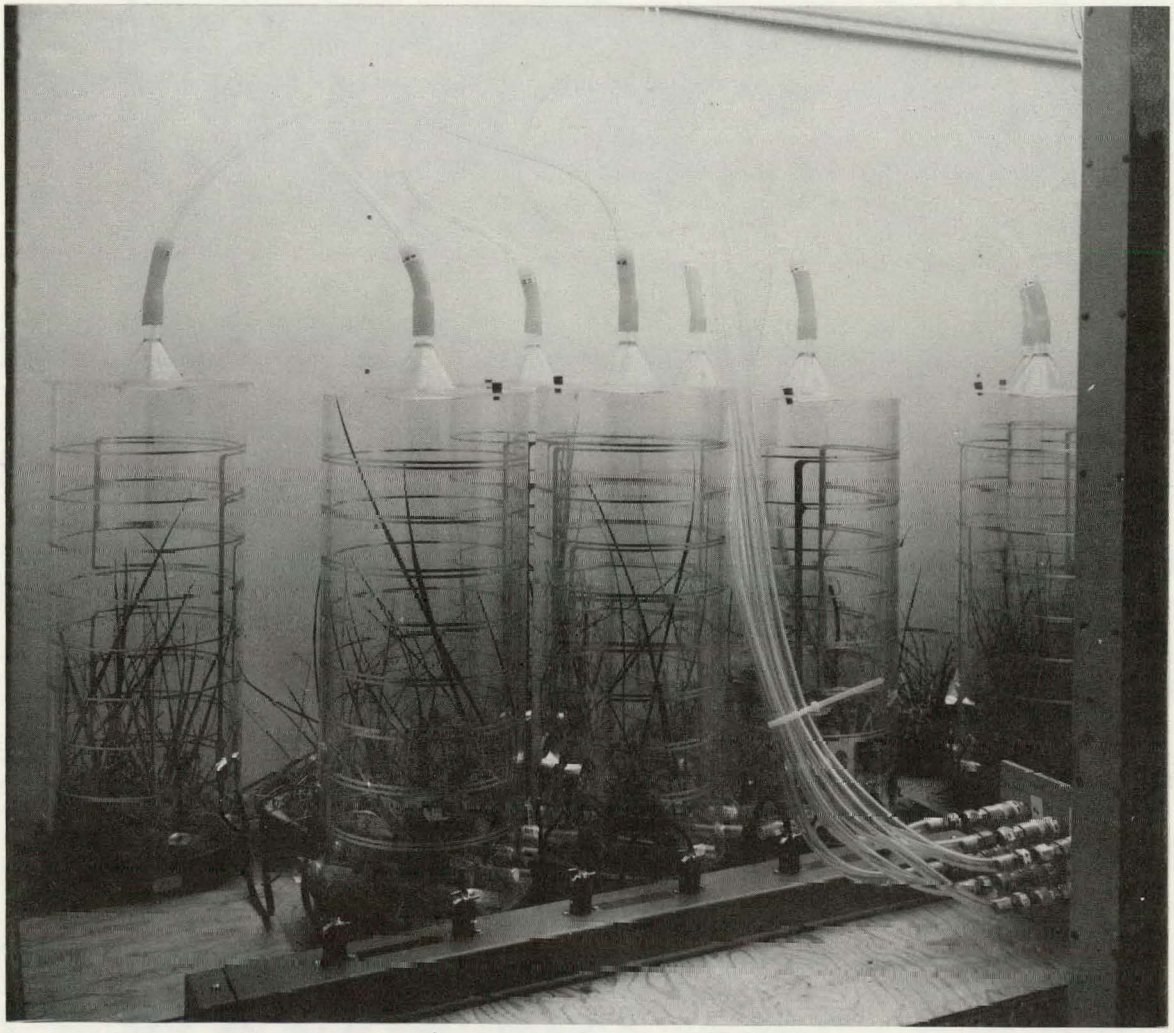

Figure A-5. Final experimental setup showing seven of eleven microcosms one month after initiation of CO_2 monitoring.

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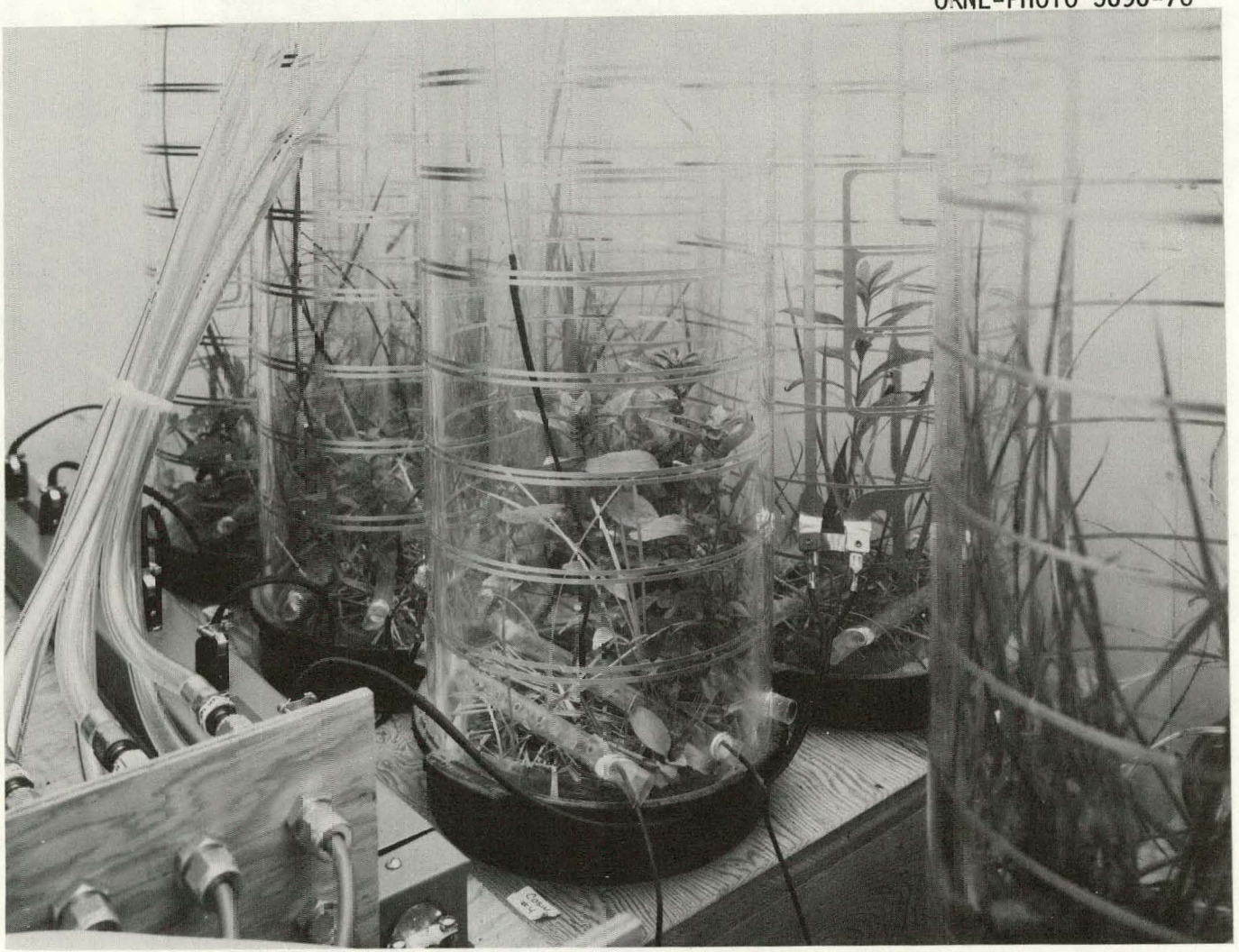

Figure A-6. Close-up of encapsulated microcosm showing defogger, ambient air inlets, and thermocouples.

air through either a Beckman 215 Infrared Gas Analyzer (IRGA) or directly to an exhaust port (Figure A-7).

Air flow for the system was created by using two separate pumps. The larger pump was used for drawing air from 11 of the 12 cuvettes at all times. The smaller pump drew air from the particular cuvette being sampled and forced it through an additional flow meter into the IRGA. Since the air lines and cuvettes were being purged continuously, preventing a build up of CO_2, only a 10 second delay was encountered in the IRGA readings after switching from one cuvette to the next.

Infrared Gas Analysis

The principle of infrared analysis is based on two identical infrared beams passing through two parallel gas cells. One cell contains a CO_2-free gas, in this case nitrogen, and the other cell contains the sample gas. The infrared beam alternately passes through each gas, and the difference in absorbance of the infrared beams is detected and converted to a meter reading. A series of known concentrations of CO_2 were used to calibrate and check IRGA meter readings against the original curve supplied by the manufacturer. Using a non-linear polynomial curve fitting computer program, an equation was developed to convert the meter readings of the IRGA to the proper ppm CO_2 concentration. The calibration curve and equation for the curve are shown in Figure A-8.

Calibration of the Beckman 215 IRGA was checked and corrected daily. Calibration was a two-step procedure. Initially, a CO_2-free gas (pure nitrogen) was passed through both cells, and the meter was

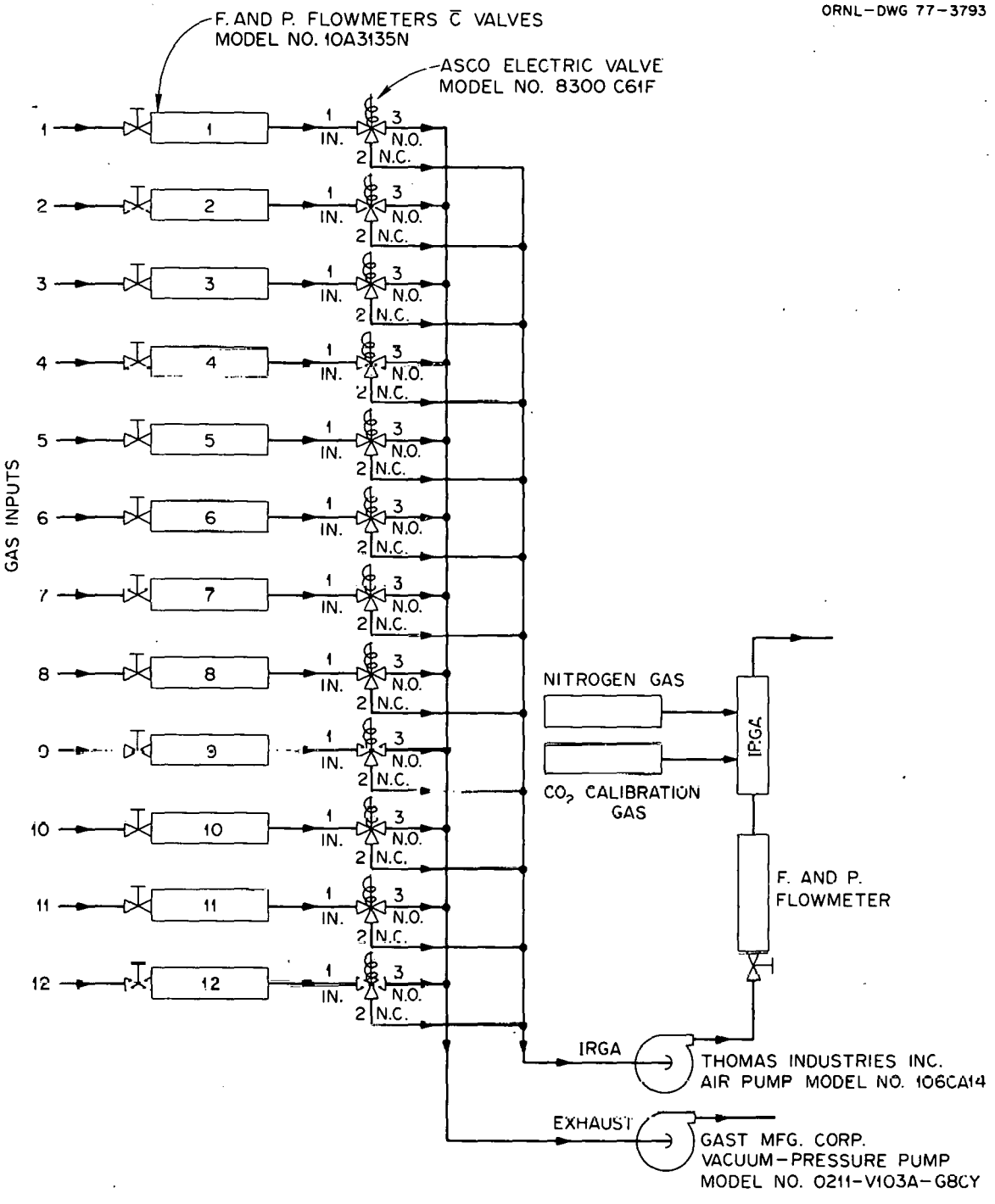

Figure A-7. Diagram of pneumatics chassis allowing for serial sampling of air streams from microcosms for CO_2 concentrations.

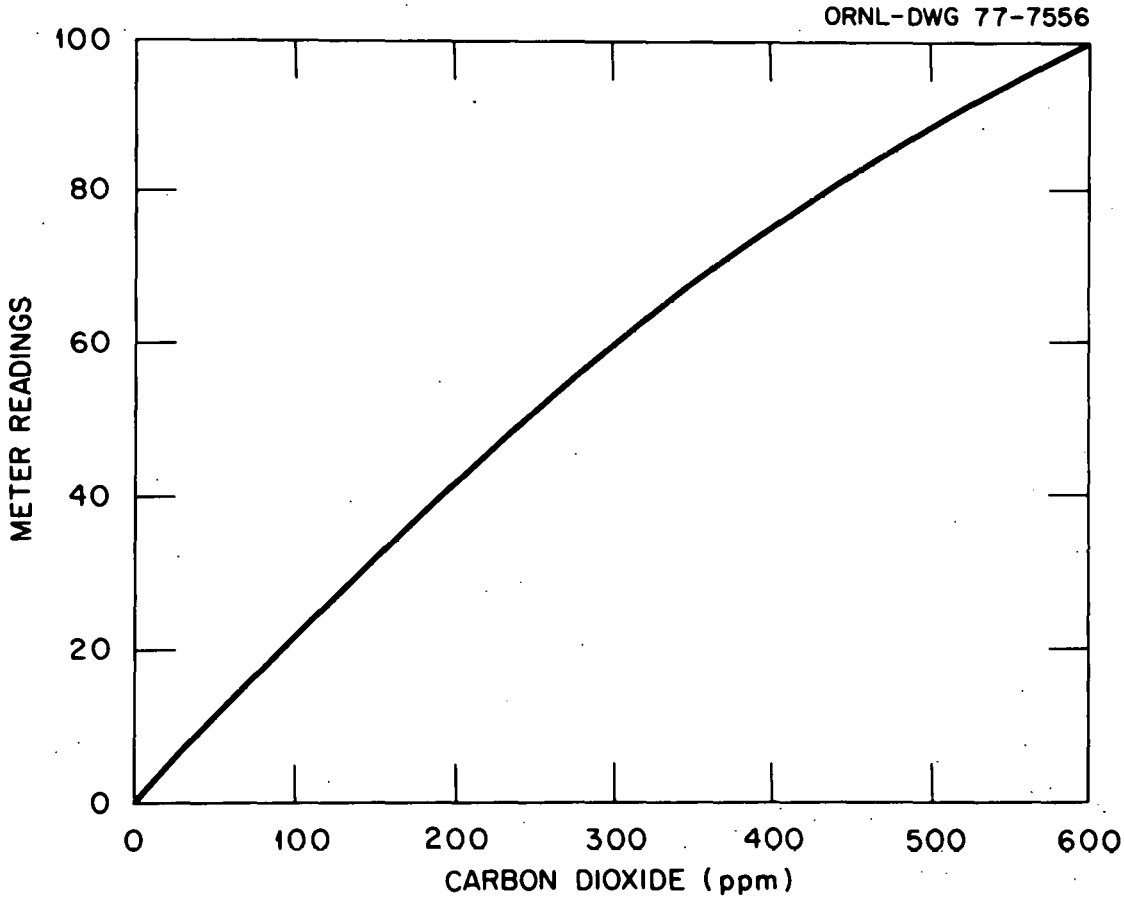

Figure A-8. Calibration curve for Beckman 215 Infrared Gas Analyzer showing CO_2 in ppm at a given meter reading. The equation for converting meter readings to absolute ppm of CO_2 is given:

C=((2.27-SQRT(5.12-4.06E-3*(0.286-R)))/2.03E-3)-AM;

where C = absolute ppm CO_2, R = meter reading, and AM = ambient ppm CO_2.

adjusted to 0.00. The second step utilized a 343 ppm CO_2 concentration gas and the meter adjusted to its appropriate reading based on the calibration curve. The CO_2 calibration gas was channeled through the IRGA flow meter to keep the flow rate the same as the sample gas. The entire calibration process required approximately two minutes and was done without interrupting the normal sample reading cycle. To avoid significant CO_2 fluctuations due to moderate human activity, a Plexiglas enclosure was placed around the IRGA, and the nitrogen which was flowing through the IRGA was shunted back into the Plexiglas housing, thus increasing accuracy (Figure A-9).

Switching and Data Recording Systems

The solenoid valves in the pneumatic chassis were electronically controlled. The switching chassis permitted manual stepping, or automatic sequencing through the 12 channels every hour. Once placed in the automatic sequence mode, the switching unit would serially open and close the appropriate solenoid valve allowing a different sample gas to be passed into the IRGA for CO_2 analysis. A schematic of the switching system is shown in Figure A-10.

A Beckman 3108 Intercoupler analog to digital converter was the main data processing unit. It received electrical signals from both the IRGA and the switching unit and sent the outgoing digital signals for channel number, clock time, and IRGA meter readings to both a teletype and Honeywell stripchart recorder. Three separate meter readings were digitized at 10 second intervals during the last 30 seconds of the five minute sampling period. This allowed for equilibration of the IRGA for

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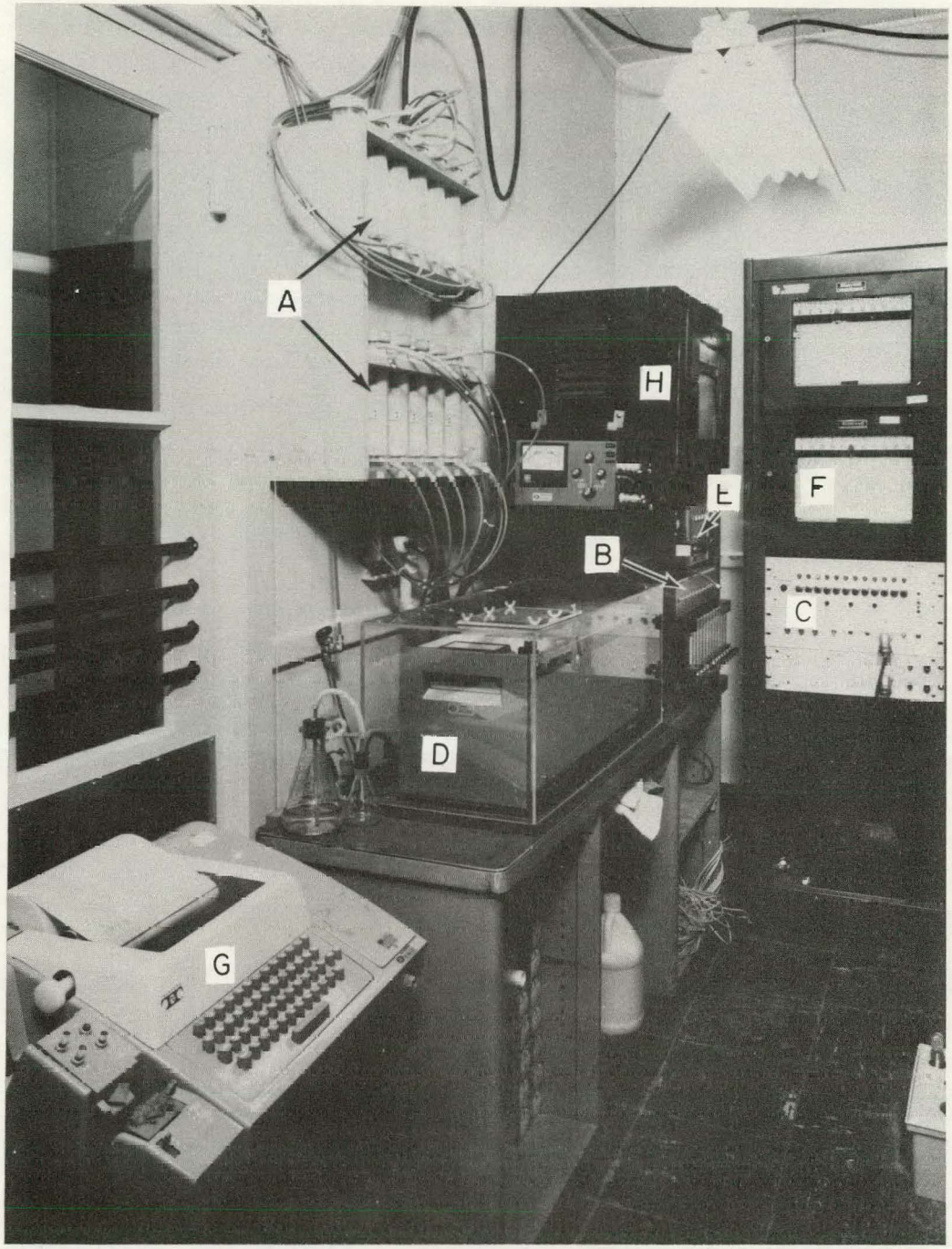

Figure A-9. Front view of CO_2 monitoring setup. Parts visible are: (A) desiccant; (B) pneumatic system; (C) switching system; (D) IRGA and Plexiglas enclosure; (E) analog to digital converter; (F) CO_2 stripchart recorder; (G) teletype; and (H) temperature recorder.

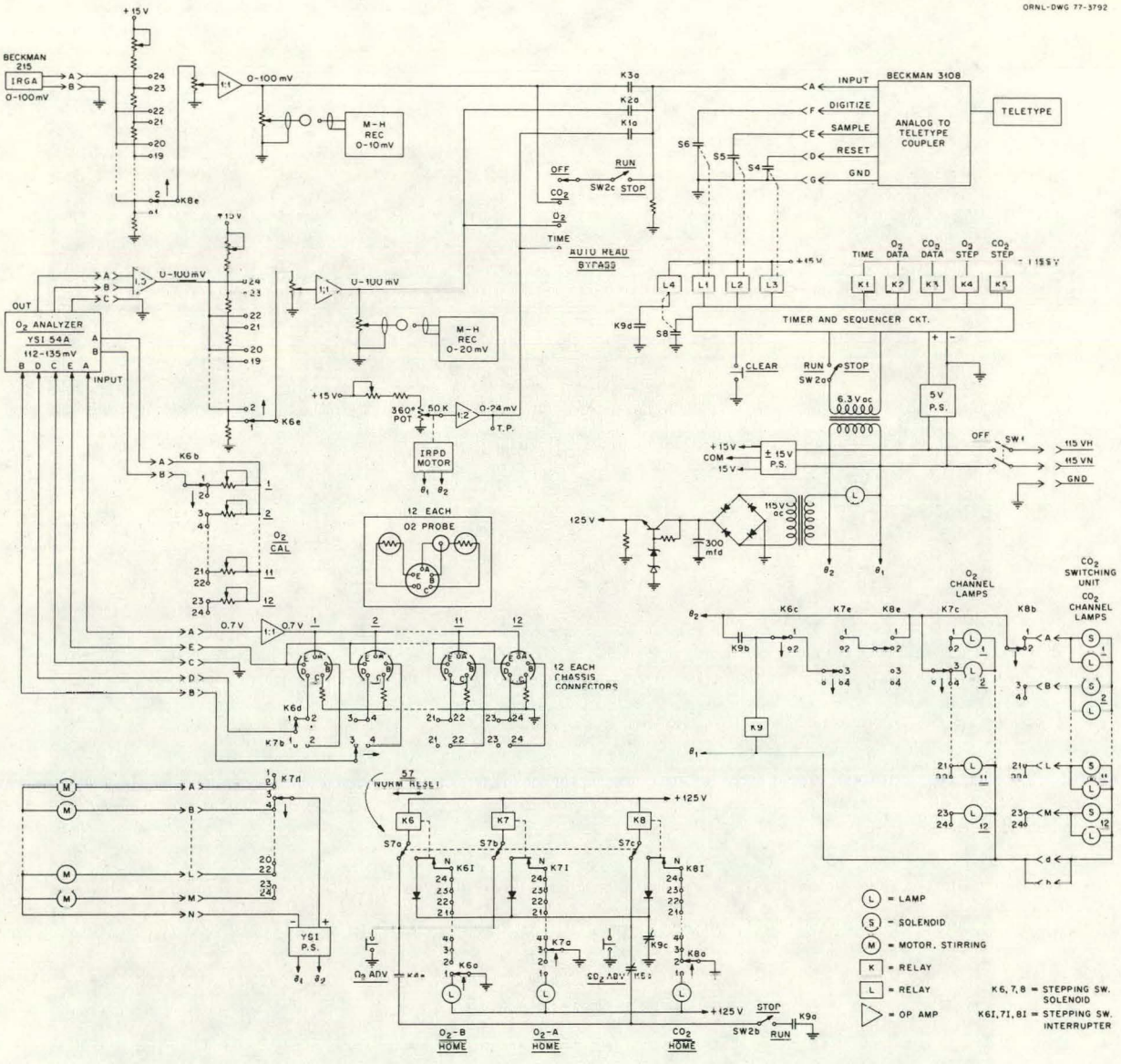

Figure A-10. Schematic of switching system for CO_2 monitoring.

that particular sample and the averaging of the three meter readings for each cuvette.

The power supply (115 volt 15 amp) for the system (environmental chamber, temperature recording, defoggers, pneumatics, IRGA, channel switcher, and data recording) was connected to an automatic relay. This relay was responsible for switching the system to an emergency generator in case of power failure in the building. A 15-hour power failure was experienced during system operation, and the relay enabled data collection to continue without interruption.

CO_2 Data Reduction and Processing

Teletype output was transcribed daily with the stripchart recorder used only as a backup and as a visual reference for checking the proper operation of the system. The three meter readings were averaged to the nearest integer and recorded on code sheets. Computer processing of the hourly data consisted of converting recorded meter readings to ppm CO_2 concentrations based on the calibration equation (Figure A-8, page 71) and subtracting ambient CO_2 concentrations. The values were then converted to mg CO_2/hour and corrected for standard temperature and pressure (STP). Correcting for STP was simplified by the fact that the small vacuum-pressure pump used with the IRGA kept the temperature of the sample air stream at 27°C regardless of the environmental chamber temperature. Correction for barometric pressure differences was based on a daily mean value taken from stripcharts supplied by the U.S. Department of Commerce Atmospheric Turbulence and Diffusion Laboratory (S. Swisher, personal communication 1976-1977) located 12 miles to the

east of Oak Ridge National Laboratory. The step-by-step process for converting ppm CO_2 concentrations to mg CO_2/hour is reported in Edwards et al. (1971).

A total of 29 CO_2 measurements per microcosm were lost due to equipment failures. This was less than 0.7% of the total record length for each microcosm. Missing meter readings were fit into the time series by calculating mean values for each hour, each microcosm, the particular day of the week, for three weeks prior to and three weeks after the missing point, and then estimating the value based on linear regression. A test for goodness of fit of missing values followed Chow and Lin (1976).

Environmental Chamber

The environmental chamber has a 1.4 m^2 growth area, electronic temperature controller for ± 0.5°C, UNIFLOOR flooring designed to ensure identical temperature throughout the chamber, and provides a maximum of 34 x 10^3 lux at 90-cm from the light source.

The environmental chamber was lamped with 16, 160 watt cool-white fluorescent lamps and 12 extended-life 60 watt incandescent lamps. Programming of light sequences was accomplished through three 24-hour timers and six selector switches and was used to roughly simulate dawn, morning, high-noon, evening, and dusk. Chamber temperatures were programmed by using one 24-hour timer and two selector switches. Heat generated by the lamps was removed by refrigeration, thus allowing accurate air temperatures to be maintained throughout the chamber.

Lighting

An Instrumentation Specialties Company Spectroradiometer, model SR, was used to measure the energy intensity or flux density of the incident light between 380 and 750 millimicrons ($m\mu$) in the environmental chamber, under the cuvette, and in the old-field. The purpose of these measurements was: (1) to determine if there was adequate energy in the photosynthetically active portion of the spectrum; (2) to determine the percent transmission through the polymethylmethacrylate (Plexiglas) cuvette; (3) to determine if there was a significant difference in either quality or quantity of any portion of the spectrum within the chamber; and (4) to determine the percent of total sunlight lux for the portion of the spectra measured that was simulated in the environmental chamber.

Spectroradiometer readings (N=3) were recorded every 5 $m\mu$ between 380 and 750 $m\mu$ during three lighting sequences (dawn, morning, and high-noon) with and without the cuvette at two locations and two heights inside the environmental chamber (Figure A-11). Only three of the five lighting sequences were examined because morning and evening, and dawn and dusk lighting were the same. Finally, a series of three spectroradiometer readings were recorded at the old-field research site. The means of each set of meter readings were integrated to determine total cal $cm^{-2}sec^{-1}$ and comparisons were made (Table A-5).

Results indicate that there was no significant difference associated with position in the environmental chamber with respect to total flux density. The mean percent transmission of environmental

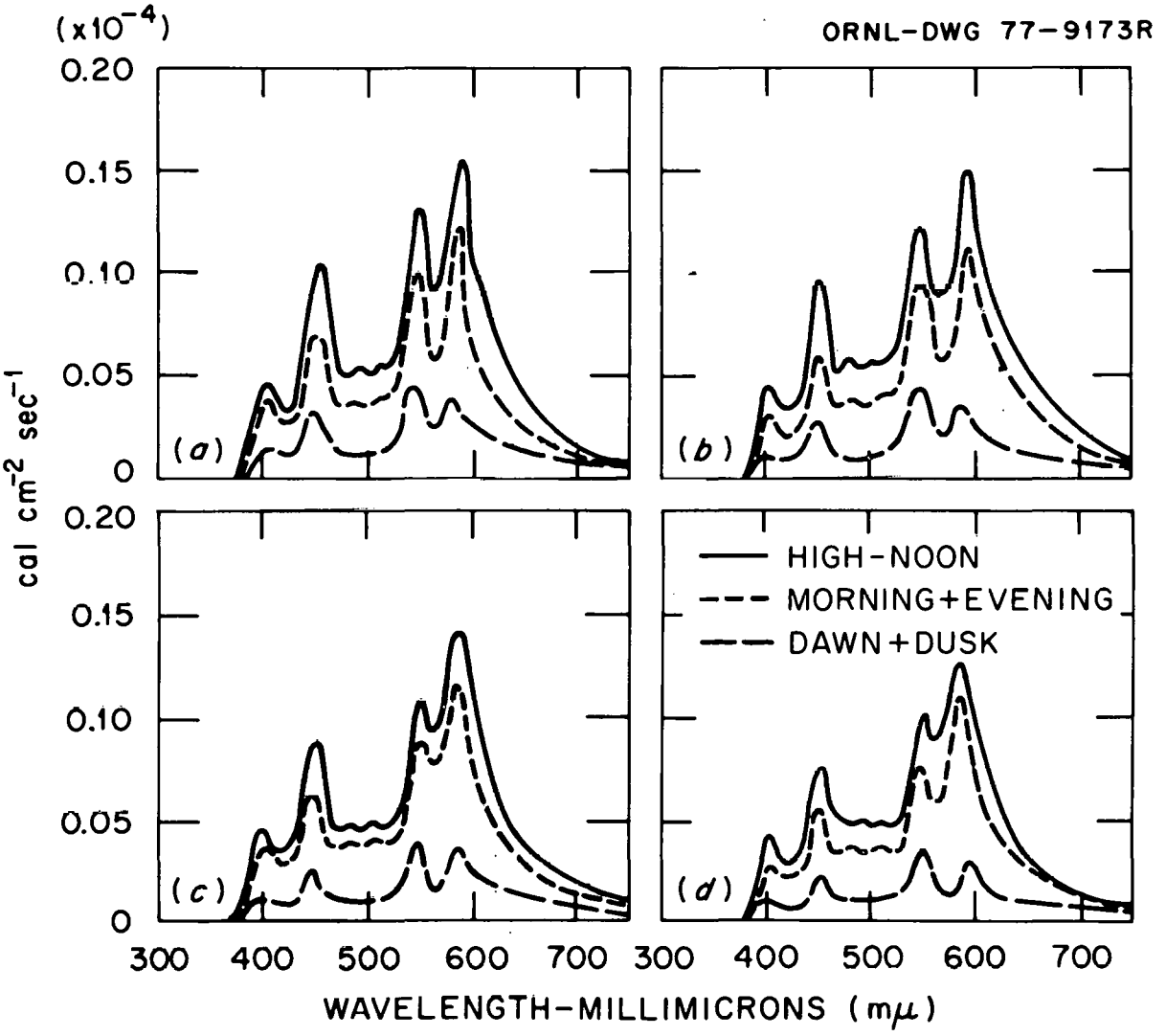

Figure A-11. Spectroradiometer readings in the environmental chamber: (a) 21.5 cm above soil surface outside cuvette; (b) 21.5 cm above soil surface inside cuvette; (c) at soil surface outside cuvette; (d) at soil surface inside cuvette.

Table A-5. Results of integration of spectroradiometer readings (N=3) between 380 and 750 millimicrons (mμ). All values reported in cal cm^{-2} sec^{-1}

Position and Location	Dawn & Dusk	Morning & Evening	High-Noon
Soil Surface Outside Cuvette	0.2539 E-03	0.7676 E-03	0.1695 E-02
Soil Surface Under Cuvette	0.2273 E-03	0.7413 E-03	0.1591 E-02
Percent Transmittance thru Cuvette at Soil Surface	89.5%	96.8%	93.8%
21.5 cm from Soil Surface Outside Cuvette	0.3020 E-03	0.9133 E-03	0.2015 E-02
21.5 cm from Soil Surface Under Cuvette	0.2879 E-03	0.8795 E-03	0.1826 E-02
Percent Transmittance thru Cuvette at 21.5 cm from Soil Surface	95.3%	96.2%	90.6%
Sun Light (7/1/76)			0.1261 E-01
Percent of Total Lux of Environmental Chamber Versus the Sun			15.9%

chamber lighting through the cuvette was 93.7% for all positions and heights. Combined fluorescent and incandescent lamps supplied adequate, but not overabundant, amounts of the photosynthetically active portions of the spectrum (Bickford and Dunn 1972). This was evidenced by good, healthy growth of all vegetation even though the percent of total sunlight (15.9%) was low.

Lighting regimes from May 12, 1976 to October 7, 1976 followed what are usually considered to be civil daylight and darkness schedules for 36° 00' north latitude. The three lighting selector switches used to simulate dawn, morning, high-noon, evening, and dusk were changed weekly to account for this change. However, the same time differential between the selector switches was held constant. The second bank of lights was activated three-fourths of one hour after the first, and the third set was activated three-fourths of one hour after the second. This was the same for both daylight and darkness schedules. The lighting regime, after the cuvettes were in place, was held constant in order to avoid adversely influencing CO_2 data peaks.

Temperatures

Temperatures in the environmental chamber were electronically regulated to within ± 0.5°C of the desired setting. Chamber temperatures were recorded using a single thermocouple probe which was shielded from the lights. The probe was connected to a Honeywell multipoint strip-chart recorder, and temperature was recorded once every 3.5 minutes.

Temperature regimes between early May and late September were based on 1975 data for the Oak Ridge area (Atmospheric Turbulence and

Diffusion Laboratory 1975). Weekly mean day/night temperatures were calculated, and temperature settings were corrected accordingly using the 24-hour timer and the two selector switches (Figure A-12). Two weeks prior to encapsulation with the cuvette, the day-night temperatures were slowly adjusted upwards until settings corresponded with the predetermined temperatures after encapsulation (Figure A-12). These temperatures were maintained, after cuvettes had been installed, for the duration of the experiment. Air and soil temperatures were monitored using PVC-tip-covered thermocouples connected to a Honeywell 12 point recorder. Soil thermocouple probes were placed in the center of microcosm numbers 1, 3, 4, 5, 8, and 10 midway through the soil profile (5 cm). Air thermocouple probes were correspondingly placed in the center of the cuvette, 21 cm above the soil surface of microcosm numbers 2, 4, 6, 7, 9, and control. Temperatures were recorded hourly for each thermocouple; however, a special control timer could be adjusted for continuous operation.

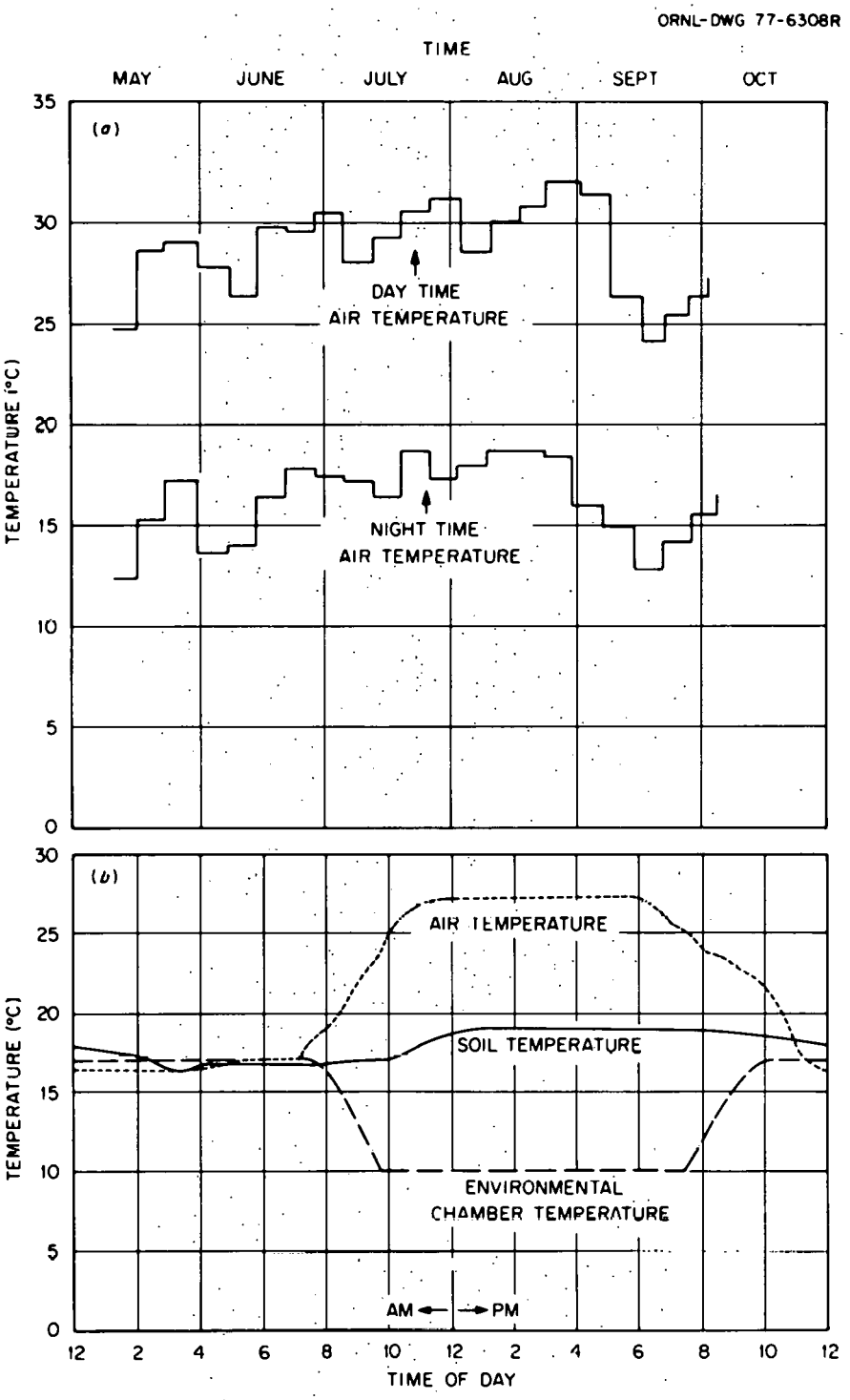

Figure A-12. (a) Day/night temperature regimes during 21 week equilibration period, and (b) 24-hr air and soil temperatures during CO_2 monitoring.

APPENDIX B

MICROCOSM FLORA

Table B-1. Floristic list of species occurring in old-field microcosms during experimentation. Shannon index and variance of H_s are included for each.

Microcosm #1	Number
Festuca arundinacea Schreb.	(6)
Rubus spp.	(2)
Acalypha virginica L.	(2)
Daucus carota L.	(1)
Paspalum dilatatum Poir.	(1)
Andropogon virginicus L.	(1)
H_s = 1.52	
σ = 0.05	
Microcosm #2	
Festuca arundinacea Schreb.	(4)
Rubus spp.	(3)
Acalypha virginica L.	(2)
Hieracium venosum L.	(1)
Daucus carota L.	(1)
Digitaria spp.	(2)
H_s = 1.67	
σ = 0.03	
Microcosm #3	
Festuca arundinacea Schreb.	(6)
Rubus spp.	(1)
Acalypha virginica L.	(1)
Fragaria virginiana Duchesne	(2)
Panicum spp.	(2)
Andropogon virginicus L.	(?)
Plantago rugelii Dcne.	(1)
H_s = 1.71	
σ = 0.05	

Table B-1. (continued)

Microcosm #4	Number
Carex spp.	(2)
Trifolium repens L.	(1)
Solanum nigrum L.	(1)
Rubus spp.	(1)
Acalypha virginica L.	(3)
Plantago rugelii Dcne.	(1)
Paspalum dilatatum Poir.	(1)
Sida spp.	(1)
H_s = 1.97	
σ = 0.05	
Microcosm #5	
Festuca arundinacea Schreb.	(8)
Fragaria virginiana Duchesne	(1)
Acalypha virginica L.	(2)
Daucus carota L.	(1)
Agrimonia spp.	(1)
Paspalum dilatatum Poir.	(1)
H_s = 1.35	
σ = 0.08	
Microcosm #6	
Festuca arundinacea Schreb.	(8)
Digitaria spp.	(2)
Trifolium repens L.	(3)
Acalypha virginica L.	(1)
Fragaria virginiana Duchesne	(1)
Rubus spp.	(3)
Cardamine hirsuta L.	(1)
Chrysanthemum leucanthemum L.	(1)
H_s = 1.76	
σ = 0.04	

Table B-1. (continued)

Microcosm #7	Number
Festuca arundinacea Schreb.	(7)
Rubus spp.	(1)
Convolvulus spp.	(2)
Diodia virginiana L.	(1)
Cerastium spp.	(1)
Arabidopsis thaliana L.	(1)
H_s = 1.41	
σ = 0.07	
Microcosm #8	
Festuca arundinacea Schreb.	(6)
Rubus spp.	(1)
Acalypha virginica L.	(1)
Lespedeza stipulacea Maxim.	(1)
Andropogon virginicus L.	(2)
Paspalum dilatatum Poir.	(1)
H_s = 1.47	
σ = 0.07	
Microcosm #9	
Festuca arundinacea Schreb.	(6)
Andropogon virginicus L.	(4)
Acalypha virginica L.	(2)
Gnaphalium obtusifolium L.	(1)
Plantago rugelii Dene.	(1)
H_s = 1.37	
σ = 0.04	
Microcosm #10	
Festuca arundinacea Schreb.	(5)
Rubus spp.	(1)
Acalypha virginica L.	(3)
Galium aparine L.	(1)
Andropogon virginicus L.	(2)
H_s = 1.42	
σ = 0.04	

Table B-1. (continued)

Microcosm Control	Number
Festuca arundinacea Schreb.	(6)
Acalypha virginica L.	(4)
Solidago canadensis L.	(1)
Paspalum dilatatum Poir.	(1)
Digitaria spp.	(2)
Trifolium repens L.	(2)
$H_s = 1.58$	
$\sigma = 0.03$	

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APPENDIX C

CADMIUM TRANSPORT AND FATE

APPENDIX C

CADMIUM TRANSPORT AND FATE

Evaluation of terrestrial microcosms as screening tools for assessing contaminant transport and fate was an important, if tangential, aspect of this experiment. If transport and fate of a toxicant introduced into the intact grassland microcosm is radically different from field data, then use of nutrient export as a predictive index of ecosystem response would be suspect.

Soil and plant tissue samples were collected at the time of microcosm extraction to determine Cd background levels (Matti et al. 1975). A circular 0.10 m^2 plot (Harris et al. 1975) was located one meter from each microcosm extraction site (Figure C-1). All aboveground tissues within the ring were removed, sorted into living and dead tissues (Harris 1966), dry weights (105° for 48 hrs) recorded, and samples prepared for Cd determinations.

Soil and root samples were collected with a power-driven coring device which drove a 20-cm diameter tube to a depth of 40-cm (Kelly et al. 1969). Large roots were hand-extracted after sectioning the core into 10-cm increments. A modification of the McKell et al. (1961) floatation technique was employed for small root extraction. Ultrasonic cleaning was used for final processing of all roots before drying, weighing and preparation for Cd analysis (Edwards and Bremmer 1967, and Van Voris and Dahlman 1976).

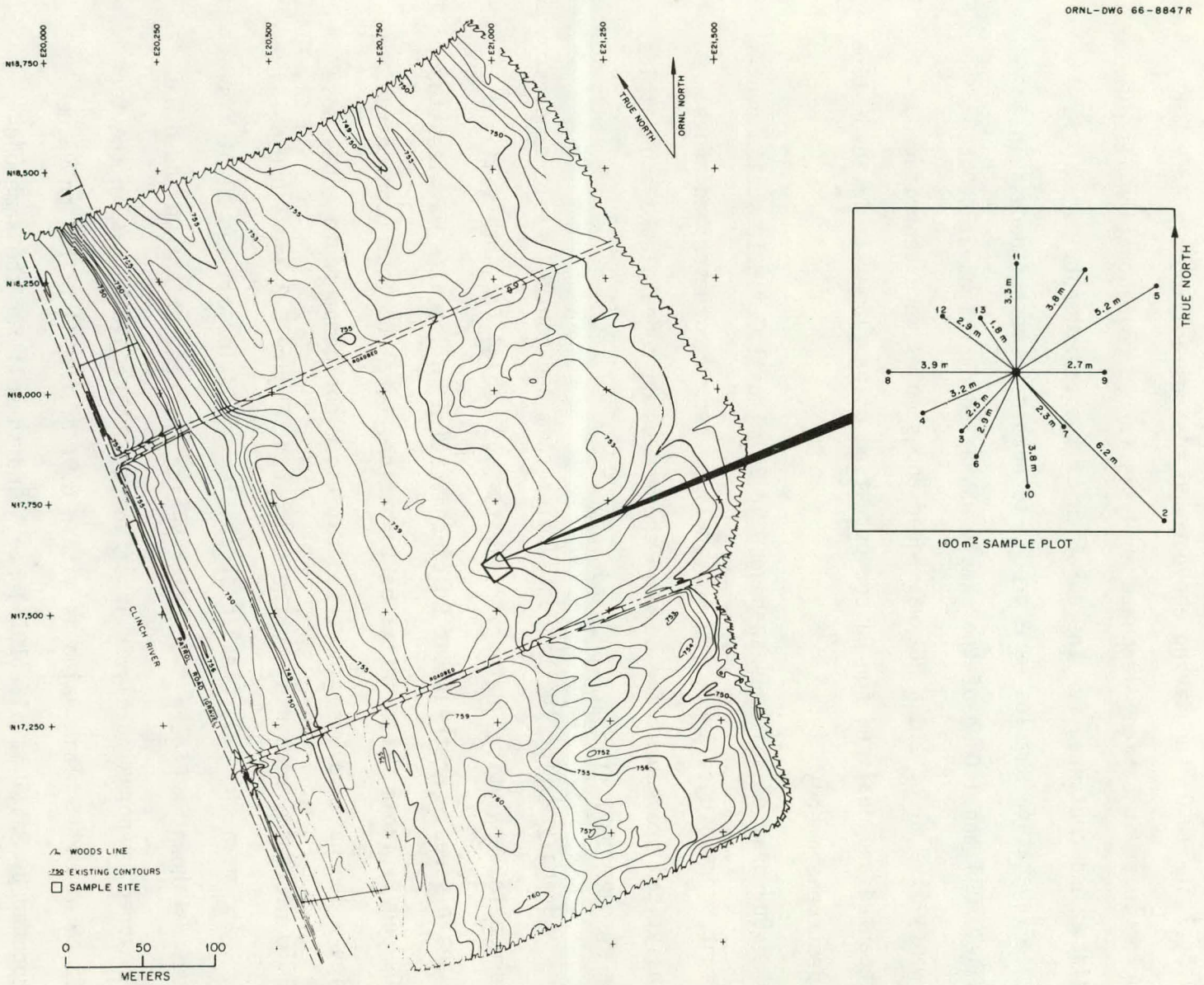

Figure C-1. Contour map of old-field research site showing area of microcosm extraction and field sample collection.

Cadmium distribution at the termination of the experiment was determined for the soil by 2.5 cm increments (0 - 2.5, 2.5 - 5.0, 5.0 - 7.5, 7.5 - 10.0) for living aboveground tissues and roots. Four weeks prior to perturbation, leachate analysis for Cd concentration was initiated and continued for the duration of the experiment.

Vegetation samples were ground to number 60 mesh fineness in a Wiley mill and 1.00 g of the sample was ashed overnight at 450°C. Twenty-five ml of 1.0 N HCl was added and samples were centrifuged, decanted and analyzed for Cd concentration using flame atomic absorption spectrophotometry.

One gram of soil was suspended in 25 ml of 1.0 N HCl, shaken overnight, centrifuged, decanted and analyzed for Cd as described above. Analytical procedures for Cd were checked using coded blanks and samples of NBS-SRM-1571 standard orchard leaves.

Cd analyses for the untreated microcosm and control field samples were below analytical detection limits (.45 μeq/g) for both soil and plant tissues. Pretreatment Cd concentration in leachate was less than .09 μeq/l (Table C-1). After perturbation, total Cd loss (concentration x leachate volume) increased but was minor compared to total dose (1350 μeq/cosm) remaining in the microcosm (Figure C-2 and Table C-1).

The mean (N = 10) final distribution of Cd in soil and plant tissues is shown in Figure C-3. Ninety-eight percent of the Cd added was recovered. Approximately 88.4% of the amount recovered was in the top 2.5 cm of soil. This value is within 0.9% of the distribution value reported by Matti et al. (1975) for ^{109}Cd in soil for the same old-field research site. Aboveground vegetation concentrations were

Table C-1. Cadmium leachate loss data. [Legend: YRDAY = year-day; YR = year; MEQ_CDI = μeq of Cd in (rain water); MEQ_CDO = total μeq of Cd lost (concentration x volume); and MEQCD_RT = μeq of Cd retained in the system.]

COSM=1

	YRDAY	YR	PH	MEQ_CDI	MEQ_CDO	MEQCD_RT
	3	77	6.11	0	0.0000	0.00
	10	77	6.13	0	0.0000	0.00
	17	77	6.10	0	0.0000	0.00
	24	77	6.13	0	0.0000	0.00
STRESS				1350	0.0000	1350.00
	31	77	6.10	0	0.0000	1350.00
	38	77	5.91	0	0.0486	1349.95
	45	77	5.96	0	0.0402	1349.91
	52	77	5.97	0	0.0278	1349.88
	59	77	6.01	0	0.0256	1349.86
	66	77	6.03	0	0.0464	1349.81
	73	77	6.05	0	0.0000	1349.81
	80	77	6.07	0	0.0310	1349.78
	87	77	6.03	0	0.0713	1349.71
	94	77	6.03	0	0.0328	1349.68

COSM=2

	YRDAY	YR	PH	MEQ_CDI	MEQ_CDO	MEQCD_RT
	3	77	6.10	0	0.0000	0.00
	10	77	6.07	0	0.0000	0.00
	17	77	6.14	0	0.0000	0.00
	24	77	6.09	0	0.0000	0.00
STRESS				1350	0.0000	1350.00
	31	77	5.97	0	1.9898	1348.01
	38	77	5.94	0	1.7587	1346.25
	45	77	5.91	0	0.2893	1345.96
	52	77	5.93	0	3.1197	1342.84
	59	77	6.04	0	2.2464	1340.60
	66	77	6.11	0	0.5229	1340.07
	73	77	6.04	0	0.1170	1339.96
	80	77	6.02	0	0.1027	1339.85
	87	77	6.01	0	0.3313	1339.52
	94	77	6.05	0	0.3552	1339.17

COSM=3

	YRDAY	YR	PH	MEQ_CDI	MEQ_CDO	MEQCD_RT
	3	77	6.09	0	0.0000	0.00
	10	77	6.01	0	0.0000	0.00
	17	77	6.15	0	0.0000	0.00
	24	77	6.14	0	0.0000	0.00
STRESS				1350	0.0000	1350.00
	31	77	6.05	0	0.0373	1349.96
	38	77	5.93	0	0.0302	1349.93
	45	77	5.81	0	0.0000	1349.93
	52	77	5.81	0	0.0000	1349.93
	59	77	5.97	0	0.0000	1349.93

Table C-1. (continued).

COSM=3

	YRDAY	YR	PH	MEQ_CDI	MEQ_CDO	MEQCD_RT
	66	77	6.02	0	0.0000	1349.93
	73	77	6.10	0	0.0000	1349.93
	80	77	6.07	0	0.0183	1349.91
	87	77	5.93	0	0.0181	1349.90
	94	77	5.98	0	0.0200	1349.88

COSM=4

	YRDAY	YR	PH	MEQ_CDI	MEQ_CDO	MEQCD_RT
	3	77	6.13	0	0.0000	0.00
	10	77	6.02	0	0.0000	0.00
	17	77	6.09	0	0.0000	0.00
	24	77	6.10	0	0.0000	0.00
STRESS				1350	0.0000	1350.00
	31	77	6.17	0	0.6545	1349.35
	38	77	6.01	0	0.2677	1349.08
	45	77	5.90	0	0.1894	1348.89
	52	77	5.99	0	0.1289	1348.76
	59	77	6.10	0	0.0958	1348.66
	66	77	6.05	0	0.1043	1348.56
	73	77	6.03	0	0.0226	1348.54
	80	77	6.03	0	0.0917	1348.45
	87	77	5.97	0	0.0689	1348.38
	94	77	5.99	0	0.2436	1348.13

COSM=5

	YRDAY	YR	PH	MEQ_CDI	MEQ_CDO	MEQCD_RT
	3	77	6.14	0	0.0000	0.00
	10	77	6.14	0	0.0000	0.00
	17	77	6.10	0	0.0000	0.00
	24	77	6.17	0	0.0000	0.00
STRESS				1350	0.0000	1350.00
	31	77	5.95	0	0.0000	1350.00
	38	77	5.83	0	0.3096	1349.69
	45	77	6.10	0	0.4782	1349.21
	52	77	6.03	0	0.2601	1348.95
	59	77	6.01	0	0.3079	1348.64
	66	77	6.07	0	0.2627	1348.38
	73	77	5.97	0	0.3175	1348.06
	80	77	6.08	0	0.3208	1347.74
	87	77	6.01	0	0.3222	1347.42
	94	77	6.04	0	0.2534	1347.17

Table C-1. (continued).

COSM=6

	YRDAY	YR	PH	MEQ_CDI	MEQ_CDO	MEQCD_RT
	3	77	6.08	0	0.0000	0.00
	10	77	6.16	0	0.0000	0.00
	17	77	6.02	0	0.0000	0.00
	24	77	6.13	0	0.0000	0.00
STRESS				1350	0.0000	1350.00
	31	77	6.06	0	0.0000	1350.00
	38	77	5.99	0	0.0268	1349.97
	45	77	6.01	0	0.0000	1349.97
	52	77	6.10	0	0.0000	1349.97
	59	77	6.12	0	0.0000	1349.97
	66	77	6.10	0	0.0000	1349.97
	73	77	6.01	0	0.0000	1349.97
	80	77	6.03	0	0.0000	1349.97
	87	77	6.03	0	0.0000	1349.97
	94	77	6.02	0	0.0193	1349.95

COSM=7

	YRDAY	YR	PH	MEQ_CDI	MEQ_CDO	MEQCD_RT
	3	77	6.05	0	0.0000	0.00
	10	77	6.09	0	0.0000	0.00
	17	77	6.17	0	0.0000	0.00
	24	77	6.04	0	0.0000	0.00
STRESS				1350	0.0000	1350.00
	31	77	6.07	0	0.9311	1349.07
	38	77	5.97	0	0.3089	1348.76
	45	77	5.94	0	0.0244	1348.74
	52	77	5.81	0	0.0000	1348.74
	59	77	6.03	0	0.0000	1348.74
	66	77	6.03	0	0.0000	1348.74
	73	77	6.06	0	0.0000	1348.74
	80	77	6.01	0	0.0274	1348.71
	87	77	6.05	0	0.0000	1348.71
	94	77	6.05	0	0.0160	1348.69

COSM=8

	YRDAY	YR	PH	MEQ_CDI	MEQ_CDO	MEQCD_RT
	3	77	6.16	0	0.0000	0.00
	10	77	6.13	0	0.0000	0.00
	17	77	6.23	0	0.0000	0.00
	24	77	6.12	0	0.0000	0.00
STRESS				1350	0.0000	1350.00
	31	77	5.98	0	2.3011	1347.70
	38	77	5.98	0	0.6602	1347.04
	45	77	5.92	0	0.5299	1346.51
	52	77	5.97	0	0.4172	1346.09
	59	77	5.96	0	0.2305	1345.86

Table C-1. (continued).

COSM=8

	YRDAY	YR	PH	MEQ_CDI	MEQ_CDO	MEQCD_RT
	66	77	6.04	0	0.2050	1345.66
	73	77	6.00	0	0.1547	1345.50
	80	77	5.98	0	0.1429	1345.36
	87	77	6.04	0	0.1354	1345.22
	94	77	6.07	0	0.0729	1345.15

COSM=9

	YRDAY	YR	PH	MEQ_CDI	MEQ_CDO	MEQCD_RT
	3	77	6.10	0	0.0000	0.00
	10	77	6.18	0	0.0000	0.00
	17	77	6.19	0	0.0000	0.00
	24	77	6.04	0	0.0000	0.00
STRESS				1350	0.0000	1350.00
	31	77	6.04	0	0.1434	1349.86
	38	77	5.97	0	0.2694	1349.59
	45	77	6.12	0	0.6430	1348.94
	52	77	6.07	0	0.5657	1348.38
	59	77	5.99	0	0.3548	1348.02
	66	77	6.01	0	0.2471	1347.78
	73	77	6.01	0	0.1782	1347.60
	80	77	6.01	0	0.2235	1347.37
	87	77	6.11	0	0.1310	1347.24
	94	77	6.07	0	0.1847	1347.06

COSM=10

	YRDAY	YR	PH	MEQ_CDI	MEQ_CDO	MEQCD_RT
	3	77	6.18	0	0.0000	0.00
	10	77	6.08	0	0.0000	0.00
	17	77	6.13	0	0.0000	0.00
	24	77	6.15	0	0.0000	0.00
STRESS				1350	0.0000	1350.00
	31	77	5.96	0	0.8340	1349.17
	38	77	6.03	0	0.0400	1349.13
	45	77	5.87	0	0.1877	1348.94
	52	77	6.23	0	0.0302	1348.91
	59	77	6.03	0	0.0000	1348.91
	66	77	6.03	0	0.0000	1348.91
	73	77	6.01	0	0.0000	1348.91
	80	77	6.07	0	0.0000	1348.91
	87	77	6.02	0	0.0000	1348.91
	94	77	6.00	0	0.0000	1348.91

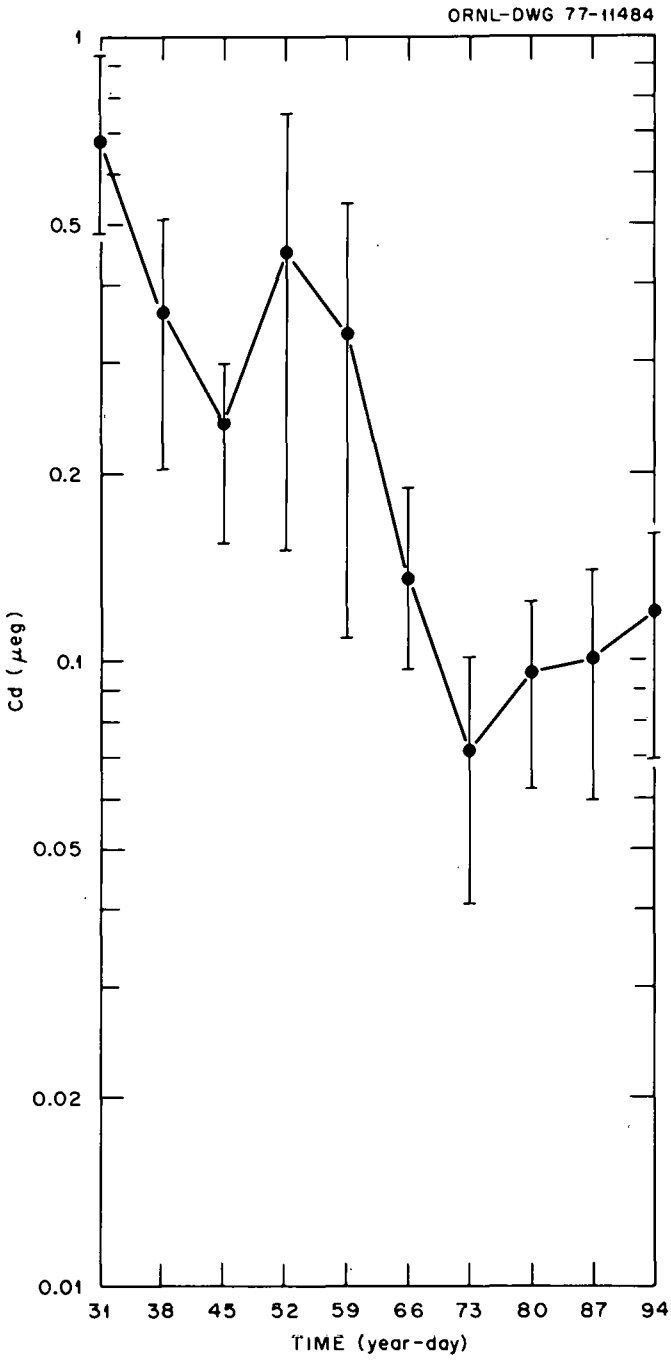

Figure C-2. Mean (± 1 standard error) total cadmium loss from microcosms in leachate by year-day (1977). Mean cadmium retained as of the last year-day (94) was 1347.37 ± 1.03 μeq) or 99.8% of original input.

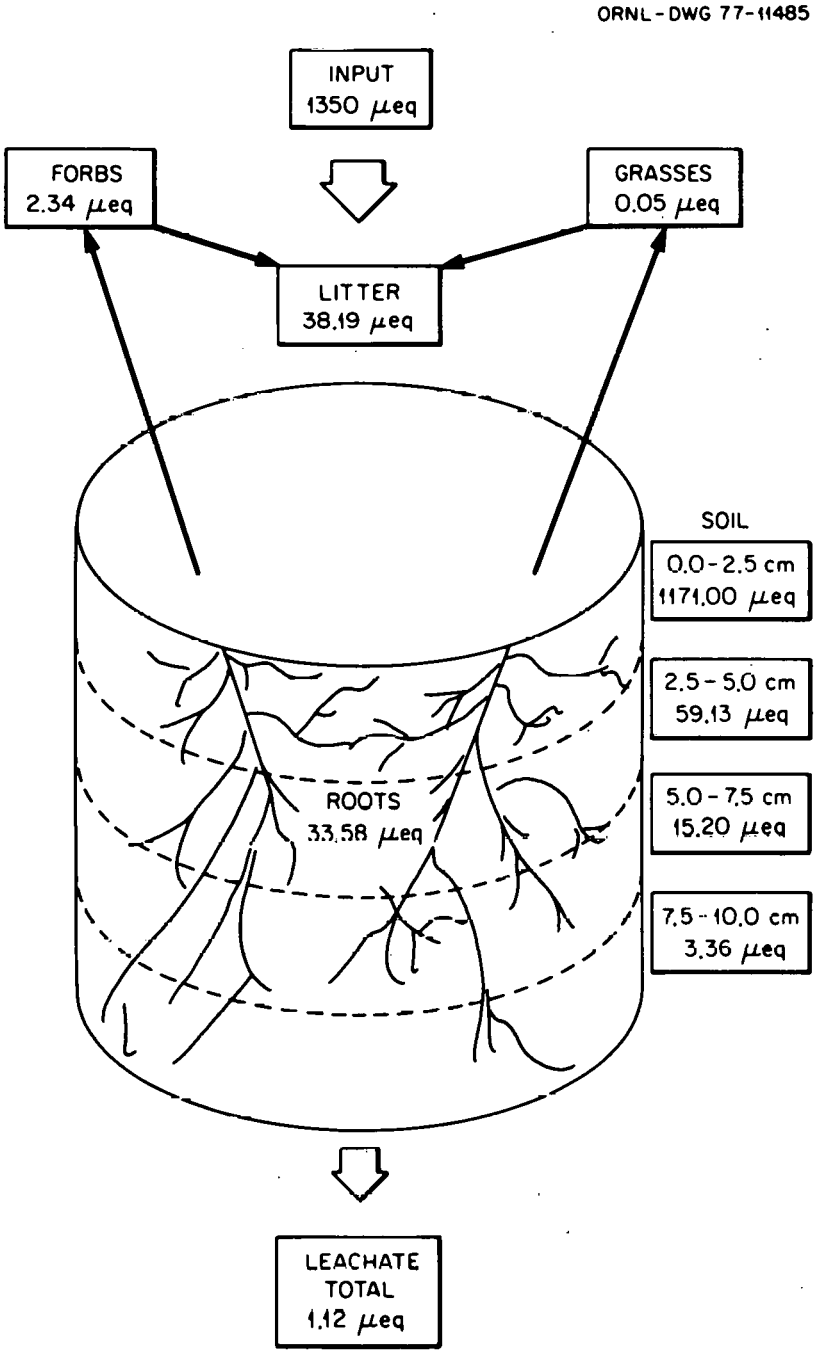

Figure C-3. Final mean cadmium distribution in major compartments (N=10).

somewhat lower than those reported by both Munshower (1972) and Jordan (1973) for different soil types. The slightly acid soil (pH = 6.3) of the microcosm soil might tend to restrict uptake and translocation of cadmium as suggested by Munshower and Bremmer (1971) and Lagerwerff and Riersdorf (1972), thus accounting for lower plant tissue Cd concentrations. Therefore, when compared to Matti et al. (1975), the microcosms seemed to give reasonable estimates of transport and fate of Cd.

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APPENDIX D

TEST FOR CATION EXCHANGE SITE SATURATION

APPENDIX D

TEST FOR CATION EXCHANGE SITE SATURATION

Calcium loss might be explained by a physical-chemical (i.e., cation exchange) reaction in the soil rather than by disruption of the ecological (i.e., living) system. If the system were saturated with Ca, cadmium would displace equal microequivalents of calcium, which would appear in the leachate. Under these conditions, increased calcium loss would be a poor indicator of ecosystem disruption.

This possibility was tested by adding ^{45}Ca to microcosm number 2 when 99.2% of the original 1.35 meq of Cd were still in the system. If cation exchange sites were saturated, the isotope would be expected to flow through the soil profile and appear in the leachate. Thus, if significant amounts of calcium-45 were found in the first leachate samples, either the encasement of the microcosm was not as tight as originally thought, or the cation exchange sites were saturated.

The 250 ml of rain water that was to be added to microcosm number 2 on March 14, 1977 contained 0.50 μc of ^{45}Ca (2.0 nc/ml). The rain water was added in the normal fashion, leachate collected, and counted for ^{45}Ca with a Beckman Instruments Inc. Widebeta II planchet counting system. Radioassay data were corrected for machine efficiency, background radioactivity in control samples and radiological decay. During three consecutive weeks following the ^{45}Ca amendment, the normal amount of rain water was added, leachate collected and then counted. When the microcosm was sacrificed, ^{45}Ca distribution in soil, roots, vegetation, and litter was determined (Thomas 1967).

Results showed that all 0.50 μc was retained in the microcosm during the four weeks of sampling. Therefore, the cation exchange sites were not saturated, and calcium losses measured after Cd addition could not be accounted for by cation exchange phenomena. Additional supporting evidence pertaining to the cation exchange capacity of this particular Captina silt loam shows that the exchange capacity for Ca alone is approximately 67 times greater than the meq of Cd added (Tamura and Waller 1965).

Final distribution analysis showed no ^{45}Ca below a soil depth of 2.5 cm, 89.2% (± 2.8) in the top 2.5 cm of soil, 3.6% (± 0.6) in roots, 1.5% (± 0.7) in vegetation, and 1.6% (± 0.3) in the litter. Percent distributions are expressed as mean values plus or minus 1 standard error of the mean. Total percent of calcium-45 in the top 2.5 cm of soil was based on a bulk density of 1.05 for the 0-2.5 cm depth. Tissue values are based on total dry weight for microcosm number 2. A total of 95.9% (± 4.4) of the original 0.50 μc of ^{45}Ca (after correcting for radiological decay) was accounted for.

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APPENDIX E

SPECTRAL DENSITY PROGRAMS

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C*************************************************************************
C                                                                        *
C  SPECTRAL ANALYSIS BY FAST FOURIER TRANSFORM                           *
C  OLD FIELD MICROCOSM CO2 TIME SERIES                                   *
C                                                                        *
C  W. R. EMANUEL   ENVIRONMENTAL SCIENCES DIVISION                       *
C  OAK RIDGE NATIONAL LABORATORY                                         *
C  OAK RIDGE, TENN.   37830                                              *
C                                                                        *
C*************************************************************************
C
C   ESTIMATES OF THE POWER SPECTRAL DENSITY ARE COMPUTED
C   XR--REAL PART OF SEQ
C   XI--IMAG PART OF SEQ
C   N--NUMBER OF DATA POINTS
C
C  SET DOUBLE PRECISION VARIABLES FOR ALL CALCULATIONS
C  THESE STATEMENTS SHOULD BE DELETED FOR COMPUTERS
C  OF SUFFICIENT WORD LENGTH
C  NOTE THIS PROGRAM IS DESIGNED TO HANDLE ONLY REAL TIME SERIES
C  VARIABLES SPECIFIED DOUBLE PRECISION HAVE BEEN LIMITED
      DOUBLE PRECISION XR,XI,A,B,E,P
C
C  DIMENSION ARRAYS
      DIMENSION XR(2048),XI(2048)
      DIMENSION T(2048)
      DIMENSION E(1025),FR(1025)
      COMMON/DATA/XR
      COMMON/TREND/A,B(3)
      COMMON/TIM/TI
      COMMON/SINGLE/TSS(2500),XSS(2500)
C
C   SET UNIT RECORD NUMBERS
      JN=5
      JOUT=6
C
C   SKIP HEADER CARD AND READ TIME SERIES PARAMETERS
      READ(JN,50) N,NU,NPTS,TI,TS
   50 FORMAT(/,3I5,5X,2E10.0)
C
C   INPUT PROGRAM CONTROL PARAMETERS
      READ(JN,51) ITREND,IAVG,IPRT,ISM
   51 FORMAT(4I2)
C
C  GRAPHICS CONTROL INPUT
C   IPLT=0   NO PLOTS
C   IPLT=1   SPECTRAL DENSITY PLOT
C   IPLT=2   ALL PLOTS
      READ(JN,51) IPLT
C
C  SET UP FOR CALCOMP PLOTS
      IF(IPLT.NE.0) CALL CALCMP
C
C  COMPUTE FREQUENCY PARAMETERS
      ND2=N/2
      FMIN=1./(TS*FLOAT(N))
```

```
      FMAX=1./(2.*TS)
C
C   PRINT TITLE
      WRITE(JOUT,1)N,TS,FMIN,FMAX
    1 FORMAT(1H1,24HSPECTRAL ANALYSIS BY FFT,/,
     11H ,12HNO OF PTS = ,I5,/,
     21H ,18HSAMPLING PERIOD = ,E14.7,/,
     31H ,15HMINIMUM FREQ = ,E14.7,/,
     41H ,15HMAXIMUM FREQ = ,E14.7)
C
C  CALL DATAIN TO INPUT THE TIME SERIES DATA
      CALL DATAIN(XI,N)
C
C  DEVELOP THE INDEPENDENT VARIABLE
      DO 207 J=1,N
      JM1=J-1
      T(J)=FLOAT(JM1)*TS+TI
  207 CONTINUE
C
C    PLOT REAL PART OF DATA
      IF(IPLT.EQ.0) GO TO 200
      NPPS=N
      ICOUNT=0
  401 CALL BGNPL(-1)
      CALL TITLE('TIME SERIES$',-100,'TIME  (HOURS)$',100,
     1'CO2 EFFLUX  (MILLIGRAMS/HR)$',100,9.5,6.5)
      CALL DPL(NPPS,T,XR)
      ICOUNT=ICOUNT+1
      IF(ICCUNT.EQ.3)  GO TO 200
      IF(ICOUNT.EQ.1)  NPPS=100
      IF(ICOUNT.EQ.2)  NPPS=500
      GO TO 401
  200 CONTINUE
C
C  PLOT TIME SERIES TO SCALE OF EARLIER ANALYSIS
      NPPS=N
      CALL BGNPL(-1)
      CALL TITLE('TIME SERIES$',-100,'TIME  (HOURS)$',
     1100,'CO2 EFFLUX  (MILLIGRAMS/HR)$',100,9.5,6.5)
      CALL FRAME
      CALL GRAF(0.,'SCALE',2200.,-8.,'SCALE',16.)
      CALL CURVE(TSS,XSS,NPPS,0)
      CALL ENDPL(0)
C
C   OUTPUT DATA
      IF(IPRT)21,20,21
   20 WRITE(JOUT,22)
   22 FORMAT(/,1H ,16HTIME SERIES DATA,/,
     11H ,5HINDEX,5X,9HREAL PART,11X,9HIMAG PART)
      DO 23 J=1,N
   23 WRITE(JOUT,24)J,XR(J),XI(J)
   24 FORMAT(1H ,I5,4X,E14.7,6X,E14.7)
   21 CONTINUE
C
C   REMOVE TREND
      IF(ITREND.EQ.0)  GO TO 80
      CALL TREND1(N,TS,TI,ITREND)
      WRITE(JOUT,301)  A,(B(J),J=1,ITREND)
```

```
  301 FORMAT(/,1H 'POLYNOMIAL COEF...',3(5X,E14.7))
      WRITE(JOUT,300) ITREND
  300 FORMAT(/,1H ,'TREND REMOVAL BY METHOD ',I2)
      IF(IPRT) 61,62,61
   62 WRITE(JOUT,63)
   63 FORMAT(/,1H ,'TREND REMOVAL',
     1/,1H ,5HINDEX,5X,4HDATA)
      DO 64 J=1,N
   64 WRITE(JOUT,65) J,XR(J)
   65 FORMAT(1H ,I5,5X,E14.7)
   61 CONTINUE
   80 CONTINUE
C
C    REMOVE SAMPLE MEAN FROM DATA
      IF(IAVG.EQ.0) GO TO 81
      CALL XAVG(N)
C
C    PLOT ZERO MEAN DETRENDED DATA
      IF(IPLT.NE.2) GO TO 81
      NPPS=N
      CALL BGNPL(-1)
      CALL TITLE('ZERO MEAN DETRENDED TIME SERIES$',-100,
     1'TIME   (HOURS)$',100,'CO2 EFFLUX$',100,9.5,6.5)
      CALL DPL(NPPS,T,XR)
   81 CONTINUE
C
C   APPLY SPLIT-COSINE-BELL TAPER TO DATA
C       P=.100
C       CALL TAPER(XR,N,P)
C       CALL XAVG(N)
C
C   APPEND ZEROES TO DATA
      CALL ZERO(N,NPTS)
C
C    CALL FFT
      CALL FFT(XR,XI,N,NU)
C
C   DEVELOP THE FREQUENCY VARIABLE
      DO 208 J=1,ND2
      JM1=J-1
      FR(J)=FLOAT(JM1)/(FLOAT(N)*TS)
  208 CONTINUE
C
C    PLOT REAL PART FOURIER COEFFICIENTS
      IF(IPLT.NE.2) GO TO 202
      NPPS=ND2
      CALL BGNPL(-1)
      CALL TITLE('REAL PART FOURIER COEF.$',-100,
     1'FREQ.   (CY/HR)$',100,'AMPLITUDE$',100,9.5,6.5)
      CALL DPL(NPPS,FR,XR)
C
C    PLOT IMAG PART FOURIER COEFFICIENTS
      NPPS=ND2
      CALL BGNPL(-1)
      CALL TITLE('IMAG. PART FOURIER COEF.$',-100,
     1'FREQ.   (CY/HR)$',100,'AMPLITUDE$',100,9.5,6.5)
      CALL DPL(NPPS,FR,XI)
  202 CONTINUE
```

```
C
C   PRINT FOURIER COEFFICIENTS
      IF(IPRT)27,28,27
   28 WRITE(JOUT,29)
   29 FORMAT(/,1H ,29HFINITE FOURIER TRANSFORM COEF,/,
     11H ,4HFREQ,15X,9HREAL PART,11X,9HIMAG PART)
      DO 30 J=1,ND2
   30 WRITE(JOUT,31) FR(J),XR(J),XI(J)
   31 FORMAT(1H ,E14.7,6X,E14.7,6X,E14.7)
   27 CONTINUE
C
C  SMOOTH THE FOURIER COEFFICIENTS
C  NOTE THAT SMOOTHING OF THE FOURIER COEFFICIENTS IS NOT
C  POSSIBLE IF ZEROS ARE APPENDED TO THE DATA.
      IF(ISM.EQ.0) GO TO 97
      WRITE(JOUT,96) ISM
   96 FORMAT(/,1H ,31HNOTE-SPECTRUM HAS BEEN SMOOTHED,2X,I5,1X,5HTIMES)
      DO 95 J=1,ISM
      CALL SMOOTH(XR,XI,N)
   95 CONTINUE
      IF(IPRT.EQ.1) GO TO 72
      WRITE(JOUT,71)
   71 FORMAT(/,1H ,'TRANSFORM COEF.AFTER SMOOTHING',/,
     11H ,'FREQ',15X,'REAL PART',11X,'IMAG PART')
      DO 70 J=1,ND2
      WRITE(JOUT,31) FR(J),XR(J),XI(J)
      WRITE(JOUT,31) F,XR(J),XI(J)
   70 CONTINUE
   72 CONTINUE
   97 CONTINUE
C
C   COMPUTE POWER SPECTRAL DENSITY AND PRINT
      WRITE(JOUT,32)
   32 FORMAT(/,1H ,22HPOWER SPECTRAL DENSITY,/,
     11H ,4HFREQ,15X,9HMAGNITUDE)
      DO 33 J=1,ND2
      E(J)=(XR(J)**2+XI(J)**2)/DFLOAT(N)
C
C  PROVIDE PUNCH OUTPUT OF THE POWER SPECTRAL DENSITY
C      WRITE(10,9999) FR(J),E(J)
C 9999 FORMAT(2E16.8)
   33 CONTINUE
      CALL OUTPUT(FR,E,80)
      CALL OUTPUT(FR,E,ND2)
C
C   PLOT POWER SPECTRAL DENSITY
      IF(IPIT.EQ.0) GO TO 206
      ICOUNT=0
      NPPS=1024
  500 CALL BGNPL(-1)
      CALL TITLE('POWER SPECTRAL DENSITY$',-100,
     1'FREQ.   (CY/HR)$',100,'AMPLITUDE$',100,9.5,6.5)
      CALL DPL(NPPS,FR,E)
      ICOUNT=ICOUNT+1
      IF(ICOUNT.EQ.2) GO TO 206
      NPPS=80
      GO TO 500
  206 CONTINUE

      STOP
      END
```

```
      SUBROUTINE XAVG(N)
      IMPLICIT REAL*8 (A-H,O-Z)
      DIMENSION XR(2048)
      COMMON/DATA/XR
      SUMR=0.
      DO 10 J=1,N
      SUMR=SUMR+XR(J)
   10 CONTINUE
      AVR=SUMR/FLOAT(N)
      DO 20 J=1,N
      XR(J)=XR(J)-AVR
   20 CONTINUE
      RETURN
      END
```

```
      SUBROUTINE SMOOTH(YR,YI,N)
      IMPLICIT REAL*8 (A-H,O-Z)
C
C  THIS SUBROUTINE SMOOTHS THE FOURIER COEFFICIENTS WITH
C  WEIGHTS CORRESPONDING TO THE HANNING WINDOW.
C  THIS IS REASONABLE SINCE THE TIME SERIES IS NOT MODIFIED BY
C  APPENDING ZEROES.
C
      DIMENSION YR(1),YI(1)
      NM1=N-1
      SR=YR(1)
      SI=YI(1)
      DO 10 K=2,NM1
      KP1=K+1
      TR=YR(K)
      TI=YI(K)
      YR(K)=-.25*SR+.5*TR-.25*YR(KP1)
      YI(K)=-.25*SI+.5*TI-.25*YI(KP1)
      SR=TR
      SI=TI
   10 CONTINUE
      RETURN
      END
```

```
      SUBROUTINE TREND1(M,TS,TI,N)
      IMPLICIT REAL*8 (A-H,O-Z)
      REAL*4 TS,TI
      DIMENSION C(11,11),SX(20),SYX(10),CYX(10),X(2048),Y(2048)
      COMMON/DATA/Y
      COMMON/TREND/A,B(10)
      DATA EPS/1.0E-20/
      DO 11 J=1,10
   11 B(J)=0.
C     DEVELOP THE INDEPENDENT VARIABLE
      DO 50 J=1,M
      JM1=J-1
   50 X(J)=DFLOAT(JM1)*TS+TI
      NTWO=2*N
      NP1=N+1
      SY=0.0
      SYY=0.0
      DO 1 I=1,NTWO
      SX(I)=0.0
    1 SYX(I)=0.0
      DO 3 I=1,M
      SY=SY+Y(I)
      SYY=SYY+Y(I)**2
      DUM=1.0
      DO 2 J=1,N
      DUM=DUM*X(I)
      SX(J)=SX(J)+DUM
    2 SYX(J)=SYX(J)+Y(I)*DUM
      DO 3 J=NP1,NTWO
      DUM=DUM*X(I)
    3 SX(J)=SX(J)+DUM
      FM=M
      CYY=SYY-SY*SY/FM
      DO 4 I=1,N
      CYX(I)=SYX(I)-SY*SX(I)/FM
      C(I,NP1)=CYX(I)
      DO 4 J=1,N
      IPJ=I+J
    4 C(I,J)=SX(IPJ)-SX(I)*SX(J)/FM
      DET=SIMUL(N,C,B,EPS,1,11)
      IF(DET.NE.0.0) GO TO 6
      REGR=0.0
      WRITE(6,10)
   10 FORMAT(///,1H ,'TREND1 REMOVAL FAILURE')
      RETURN
    6 DUM=SY
      TEMP=CYY
      DO 7 I=1,N
      DUM=DUM-B(I)*SX(I)
    7 TEMP=TEMP-B(I)*CYX(I)
      A=DUM/FM
      DENOM=M-N-1
      S=DSQRT(TEMP/DENOM)
      REGR=S
C     SUBTRACT DETRENDING POLYNOMIAL
      DO 60 J=1,M

      JM1=J-1
   60 Y(J)=Y(J)-A-B(1)*(DFLOAT(JM1)*TS+TI)-B(2)*(DFLOAT(JM1)*TS+TI)**2
      RETURN
      END
```

```
      FUNCTION SIMUL(N,A,X,EPS,INDIC,NRC)
      IMPLICIT REAL*8 (A-H,O-Z)
      DIMENSION IROW(50),JCOL(50),JORD(50),Y(50),A(NRC,NRC),X(N)
      MAX=N
      IF(INDIC.GE.0) MAX=N+1
      IF(N.LE.50) GO TO 5
      WRITE(6,200)
      SIMUL=0.
      RETURN
    5 DETER=1.
      DO 18 K=1,N
      KM1=K-1
      PIVOT=0.
      DO 11 I=1,N
      DO 11 J=1,N
      IF(K.EQ.1) GO TO 9
      DO 8 ISCAN=1,KM1
      DO 8 JSCAN=1,KM1
      IF(I.EQ.IROW(ISCAN)) GO TO 11
      IF(J.EQ.JCOL(JSCAN)) GO TO 11
    8 CONTINUE
    9 IF(DABS(A(I,J)).LE.DABS(PIVOT)) GO TO 11
      PIVOT=A(I,J)
      IROW(K)=I
      JCOL(K)=J
   11 CONTINUE
      IF(DABS(PIVOT).GT.EPS) GO TO 13
      SIMUL=0.
      RETURN
   13 IROWK=IROW(K)
      JCOLK=JCOL(K)
      DETER=DETER*PIVOT
      DO 14 J=1,MAX
   14 A(IROWK,J)=A(IROWK,J)/PIVOT
      A(IROWK,JCOLK)=1./PIVOT
      DO 18 I=1,N
      AIJCK=A(I,JCOLK)
      IF(I.EQ.IROWK) GO TO 18
      A(I,JCOLK)=-AIJCK/PIVOT
      DO 17 J=1,MAX
   17 IF(J.NE.JCOLK) A(I,J)=A(I,J)-AIJCK*A(IROWK,J)
   18 CONTINUE
      DO 20 I=1,N
      IROWI=IROW(I)
      JCOLI=JCOL(I)
      JORD(IROWI)=JCOLI
   20 IF(INDIC.GE.0) X(JCOLI)=A(IROWI,MAX)
      INTCH=0
      NM1=N-1
      DO 22 I=1,NM1
      IP1=I+1
      DO 22 J=IP1,N
      IF(JORD(J).GE.JORD(I)) GO TO 22
      JTEMP=JORD(J)
      JORD(J)=JORD(I)
      JORD(I)=JTEMP
```

```
      INTCH=INTCH+1
   22 CONTINUE
      IF(INTCH/2*2.NE.INTCH) DETER=-DETER
      IF(INDIC.LE.0) GO TO 26
      SIMUL=DETER
      RETURN
   26 DO 28 J=1,N
      DO 27 I=1,N
      IROWI=IROW(I)
      JCOLI=JCOL(I)
   27 Y(JCOLI)=A(IROWI,J)
      DO 28 I=1,N
   28 A(I,J)=Y(I)
      DO 30 I=1,N
      DO 29 J=1,N
      IROWJ=IROW(J)
      JCOLJ=JCOL(J)
   29 Y(IROWJ)=A(I,JCOLJ)
      DO 30 J=1,N
   30 A(I,J)=Y(J)
      SIMUL=DETER
      RETURN
  200 FORMAT(10H0N TOO BIG )
      END
```

```
      SUBROUTINE FFT(XREAL,XIMAG,N,NU)
C     REF: E. BRIGHAM, THE FAST FOURIER TRANSFORM, PRENTICE-HALL
      IMPLICIT REAL*8 (A-H,O-Z)
      DIMENSION XREAL(N),XIMAG(N)
      N2=N/2
      NU1=NU-1
      K=0
      DO 100 L=1,NU
  102 DO 101 I=1,N2
      P=IBITR(K/2**NU1,NU)
      ARG=6.283185*P/DFLOAT(N)
      C=DCOS(ARG)
      S=DSIN(ARG)
      K1=K+1
      K1N2=K1+N2
      TREAL=XREAL(K1N2)*C+XIMAG(K1N2)*S
      TIMAG=XIMAG(K1N2)*C-XREAL(K1N2)*S
      XREAL(K1N2)=XREAL(K1)-TREAL
      XIMAG(K1N2)=XIMAG(K1)-TIMAG
      XREAL(K1)=XREAL(K1)+TREAL
      XIMAG(K1)=XIMAG(K1)+TIMAG
  101 K=K+1
      K=K+N2
      IF(K.LT.N) GO TO 102
      K=0
      NU1=NU1-1
  100 N2=N2/2
      DO 103 K=1,N
      I=IBITR(K-1,NU)+1
      IF(I.LE.K) GO TO 103
      TREAL=XREAL(K)
      TIMAG=XIMAG(K)
      XREAL(K)=XREAL(I)
      XIMAG(K)=XIMAG(I)
      XREAL(I)=TREAL
      XIMAG(I)=TIMAG
  103 CONTINUE
      RETURN
      END
```

```
      FUNCTION IBITR(J,NU)
      IMPLICIT REAL*8 (A-H,O-Z)
      J1=J
      IBITR=0
      DO 200 I=1,NU
      J2=J1/2
      IBITR=IBITR*2+(J1-2*J2)
  200 J1=J2
      RETURN
      END
```

```
      SUBROUTINE DPL(NPPS,T,X)
C  SUBROUTINE DPL IS A DRIVER ROUTINE FOR THE
C  DISSPLA GRAPHICS PACKAGE.
C
C  W. R. EMANUEL   ENVIRONMENTAL SCIENCES DIVISION
C  OAK RIDGE NATIONAL LABORATORY
C  OAK RIDGE,  TENN.     37830
C
C  A GRAPH OF X VERSUS T IS PROVIDED ON 8.5 X 11 FRAME
C  ORIENTED HORIZONTAL
C    T--INDEP. VARIABLE ARRAY
C    X--DEPENDENT VARIABLE ARRAY
C    NPPS--NUMBER OF POINTS TO BE PLOTTED
C  CALLING PROGRAM MUST CALL TITLE AND BGNPL ROUTINES
C
C  SET UP DOUBLE PRECISION VARIABLES
      DOUBLE PRECISION X
C
C  DIMENSION APPROPRIATE ARRAYS
      DIMENSION T(NPPS),X(NPPS)
      DIMENSION TS(2500),XS(2500)
      COMMON/SINGLE/TS,XS
C
C  LOAD SINGLE PRECISION ARRAYS
      DO 10 J=1,NPPS
      TS(J) = T(J)
   10 XS(J)=X(J)
C
C  DETERMINE MAXIMUM AND MINIMUM VALUES
      CALL SRMAX(NPPS,TS,TMIN,TMAX,XS,XMIN,XMAX)
C
C  CALL DISSPLA ROUTINES
      CALL FRAME
      CALL GRAF(TMIN,'SCALE',TMAX,XMIN,'SCALE',XMAX)
      CALL CURVE(TS,XS,NPPS,0)
      CALL ENDPL(0)
      RETURN
      END
```

```
      SUBROUTINE SRMAX(NPPS,TS,TMIN,TMAX,XS,XMIN,XMAX)
C
C  SEARCH FOR MAX AND MIN VALUES FROM THE TS AND XS ARRAYS
      DIMENSION TS(NPPS),XS(NPPS)
      TMIN=TS(1)
      XMIN=XS(1)
      TMAX=TS(1)
      XMAX=XS(1)
      DO  10 J=1,NPPS
      IF(TS(J).LT.TMIN) TMIN=TS(J)
      IF(XS(J).LT.XMIN) XMIN=XS(J)
      IF(TS(J).GT.TMAX) TMAX=TS(J)
      IF(XS(J).GT.XMAX) XMAX=XS(J)
   10 CONTINUE
      RETURN
      END
```

```
      SUBROUTINE OUTPUT(X,Y,NPTS)
C**OUTPUT OF DATA WITH LINE PLOT
C**W. R. EMANUEL ENV. SCI. DIV.  OAK RIDGE NAT. LAB.
C**      X-ZRRAY OF INDEP. VARIABLE
C**      Y-ARRAY OF DEP. VARIABLE
C**      NPTS-NUMBER OF POINTS
      DOUBLE PRECISION Y,YMAX,YMIN,DEL
      DIMENSION X(NPTS),Y(NPTS)
      DIMENSION RLINE(150)
      DATA BLANK,AST/1H ,1H*/
      IOUT=6
C**FIND MAXIMUM AND MINIMUM VALUES
      YMAX=Y(1)
      YMIN=Y(1)
      DO 10 J=2,NPTS
      IF(Y(J).GT.YMAX) YMAX=Y(J)
      IF(Y(J).LT.YMIN) YMIN=Y(J)
   10 CONTINUE
      WRITE(IOUT,13) YMIN,YMAX
   13 FORMAT(/1H ,'MIN VALUE= ',E14.7,5X,'MAX VALUE= ',E14.7,/)
C**TEST FOR VARIATION IN DEP. VARIABLE
      IF(YMAX.NE.YMIN) GO TO 11
      WRITE(IOUT,12)
   12 FORMAT(/1H ,'DEP. VAR. VALUES ARE EQUAL')
      RETURN
   11 CONTINUE
C**CALCULATE GRAPH INCREMENT
      DEL=(YMAX-YMIN)/100.D0
C**OUTPUT DATA
      DO 20 J=1,NPTS
      DO 21 K=1,100
   21 RLINE(K)=BLANK
      NUM=(Y(J)-YMIN)/DEL
      IF(NUM.LT.1) NUM=1
      IF(NUM.GT.100) NUM=100
      DO 22 K=1,NUM
   22 RLINE(K)=AST
      WRITE(IOUT,23) X(J),(RLINE(K),K=1,100),Y(J)
   23 FORMAT(1H ,E14.7,1X,100A1,1X,E14.7)
   20 CONTINUE
      RETURN
      END
```

```
      SUBROUTINE DATAIN(XI,N)
C
C  DATA INPUT FOR SPECTRAL ANALYSIS OF CO2 MICROCOSM TIME SERIES
C
      DIMENSION XR(2048),XI(N),XS(11)
      DOUBLE PRECISION XR,XI,XS
      COMMON/DATA/XR
      COMMON/TIM/TI
C
C  INPUT FILE NUMBER OF MICROCOSM TO BE ANALYZED
      READ(5,10) IFI
   10 FORMAT(I2)
      WRITE(6,20) IFI
   20 FORMAT(/1H ,'MICROCOSM ',I2,' IS ANALYZED')
C
C  INPUT TIME SERIES
      DO 15 J=1,N
      READ(5,16) (XS(K),K=1,11)
   16 FORMAT(11E7.0)
   15 XR(J)=XS(IFI)
      DO 100 J=1,N
  100 X(J)=0.
C
```

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