CLOSED ECOLOGICAL SYSTEMS: FROM TEST TUBES TO EARTH'S BIOSPHERE

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Abstract

Artificially constructed closed ecological systems (C.E.S.) have been researched both experimentally and theoretically for over 25 years. The size of these systems have varied from less than one liter to many thousands of cubic meters in volume. The diversity of the included components has a similarly wide range from purely aquatic systems to soil based systems that incorporate many aspects of Earth's biosphere. While much has been learned about the functioning of these closed systems, much remains to be learned. In this paper we compare and contrast the behavior of closed ecological systems of widely different sizes through an analysis of their atmospheric composition. In addition, we will compare the performance of relatively small C.E.S. with the behavior of Earth's biosphere. We address the applicability of small C.E.S. as replicable analogs for planetary biospheres and discuss the use of small C.E.S. as an experimental milieu for an examination of the evolution of extra-terrestrial colonies.

Introduction

The Biosphere 2 project has recently engendered much discussion on closed ecological systems and indeed has constructed the worlds largest artificial closed ecological system. The research reported here includes some of the data generated in association with the Biosphere 2 project in addition to independent research conducted at the University of Arizona.

Several questions will be addressed in this paper. Are closed ecological systems (C.E.S.) composed of soil and higher plants stable and resilient? Folsome and his colleagues (Folsome and Hanson, 1986; Kearns, 1983; Kearns and Folsome, 1981, 1982; Obenhuber, 1985; Obenhuber and Folsome, 1984, 1988) have demonstrated remarkable persistence of aquatic closed systems, do soil based systems show similar stability and resilience? Do soil based closed ecological systems demonstrate regular and predictable behavior explainable by testable hypotheses? And lastly, can metrics of a predictive value be derived from the study of closed ecological systems which have applicability to Earth's biosphere, the largest known closed ecological system? Lastly, can small closed ecological systems be used to examine the basic functioning of bioregenerative life support systems?

We shall attempt to at least partially answer these questions using data from soil based closed ecological systems of widely different sizes. While we believe that this research represents a promising beginning to the wider acceptance of closed ecological systems research we recognize the very preliminary nature of our work.

Materials and Methods

Closed Ecological Systems

Table 1 lists the closed ecological systems used in this study. The total volume of systems considered in this study varies over five orders of magnitude, from less than 0.02 m^3 to almost 400 m^3.

Table 1. Characteristics of Closed Ecological Systems

C.E.S. #	Closing Date	Opening Date	Duration of Closure (Days)
Large Closed Ecological System (400 m^3)			
1	12/31/86	03/21/87	81.00
2	04/02/87	06/21/87	80.00
3	06/25/87	10/25/87	123.00
4	11/16/87	01/03/88	48.00
5	02/05/88	07/04/88	150.00
Small Closed Ecological Systems (0.03 m^3)			
11	11/02/88	03/13/89	131.00
15	11/02/88	03/13/89	131.00
19	11/02/88	03/13/89	131.00
23	11/02/88	03/13/89	131.00
12	11/02/88	03/13/89	131.00
16	11/02/88	03/13/89	131.00
20	11/02/88	03/13/89	131.00
24	11/02/88	03/13/89	131.00
13	11/02/88	03/13/89	131.00
17	11/02/88	03/13/89	131.00
21	11/02/88	03/13/89	131.00
25	11/02/88	03/13/89	131.00
14	11/02/88	03/13/89	131.00
18	11/02/88	03/13/89	131.00
22	11/02/88	03/13/89	131.00
26	11/02/88	03/13/89	131.00
40	08/31/89	12/17/89	108.00
41	08/31/89	12/17/89	108.00
42	08/31/89	12/17/89	108.00
43	08/31/89	12/17/89	108.00
44	08/31/89	12/17/89	108.00
45	08/31/89	12/17/89	108.00
46	08/31/89	12/17/89	108.00
47	08/31/89	12/17/89	108.00
51	03/29/90	----	----
52	03/29/90	----	----
53	03/29/90	----	----
54	03/29/90	----	----

Small Closed Ecological Systems

The smallest closed ecological systems used was a 0.003 m^3 polycarbonate jar which was 24 cm. high and 16.5 cm. in diameter. These were used in constructing closed ecological systems # 51 and 52. Polycarbonate jars of 0.03 m^3 which are 30 cm. tall and 30 cm. in diameter were used to construct closed ecological systems #52 and #54. Poly carbonate jerricans were used to construct all other small closed ecological systems reported here. These jerricans were approximately 0.03 m^3 in volume with dimensions of 35 cm. x 22 cm. x 30 cm. Atmospheric sampling was through either a simple septum (closed ecological systems #11-47) or through a more permanent Mininert Valve which allows septum replacement without loss of the internal atmosphere.

The atmospheres of the small closed ecological systems were sampled periodically using hypodermic needles and 10 ml. plastic syringes. Duplicate 10 ml. samples were withdrawn and injected into a Hach-Carle gas chromatograph fitted with a 80% Porapak N + 20% Porapak Q column for determination of carbon dioxide. Known standards were run to determine carbon dioxide concentrations. Standard curves were determined for a range of known standards from 0 ppm to 50,000 ppm CO_2. The atmosphere in closed ecological systems #51-54 is currently being sampled using 600 microliter samples to conserve the atmosphere of the systems.

Closed ecological systems were placed under artificial lighting in a laboratory or in greenhouses located at the Environmental Research Laboratory. Soil used in these experiments was commercial potting soil. In closed ecological systems #11 - #26 only one species of plant was used, banana. The other small closed ecological systems were constructed using up to five different species of common house plants.

Large Closed Ecological Systems

The largest closed ecological system reported here was a 400 m^3 sealed greenhouse (Test Module) located at the Biosphere 2 site near Oracle, Arizona. This structure is approximately 3.4 x 3.4 x 3.5 m. and is connected to a variable volume 'lung' used to maintain a positive internal pressure. The structure included automatic watering systems and an automated data acquisition and control system. A detailed description of the facility is reported in Nelson, et. al. (1992).

During the experiments reported here over 100 channels of data were recorded. Instruments for measuring temperature, photosynthetic photon flux density (PFD), black body radiation, and relative humidity sampled the atmosphere inside the Test Module continuously and every 15 minutes the average was computed and recorded. Carbon dioxide concentrations were determined by a PRIVA infrared detector. Data used in this study were hourly averages calculated from these data.

Soil used in the Test Module experiments included both commercial potting soil and a local soil that had been amended with compost. No attempt was made to sterilize the soils used in these experiments. Over 50 plant species were used. Species included C3, C4, and CAM photosynthetic pathways distributed among species from a variety of different habitat types which include fog desert, rain forest, and savanna. In addition, over 20 different cultivars of agronomic species were included during Experiments #2-#5. Plants were grown either in pots or in a large wood planter. Between experimental closures plants were repotted as necessary.

Results and Discussion
CO_2 Dynamics in Closed Ecological Systems

Figure 1-3 are the hourly average carbon dioxide levels, temperature and total daily PFD recorded in the first three experimental closures of the large closed ecological system. An examination of these figures reveals that the carbon dioxide levels respond to changes in both temperature and PFD. In addition, it appears that all three experimental closures reached an equilibrium level of atmospheric carbon dioxide prior to the termination of the experiment. This can be seen more clearly in *Figures 5 - 7* which plot the standardized normal variables of CO_2, temperature and PFD for each experiment at 0600. As standardized normal variables each has a mean of zero and a standard deviation of one. Any trend in the variables will be apparent from these plots. *Figure 5* indicates that while there appears to be some periodicity in the CO_2 levels there is no consistent trend. *Figure 6* and *7* also do not show a consistent trend.

The results of the first three closures contrast clearly with the results of the fourth experimental closure (*Figure 4*). It is apparent from this figure that at the termination of the experiment, the composition of the atmosphere was not in equilibrium, CO_2 was continuing to increase. *Figure 8* plots the standardized normal variables for experimental closure #4. The trend in CO_2 apparent in *Figure 8* indicates that this system had not reached an equilibrium level of atmospheric CO_2 when the closure was terminated. When contrasted with *Figures 5 - 7*, the standardized normal variables of carbon dioxide, temperature and PFD for the first three closure experiments, the lack of equilibrium in atmospheric concentrations of CO_2 during the fourth experiment is apparent.

What was the difference in the starting conditions of these four experiments that may have lead to these results? Between experimental closures number 3 and number 4 approximately 6 m^3 of additional soil was placed into the Test Module to investigate the use of a soil ecosystems as a scrubber for atmospheric contaminants (Frye & Hodges, 1989). During experiments 1 - 3 a total of about 2 m^3 of soil was used in the Test Module. The additional soil placed into the Test Module produced CO_2 at a greater rate than the photosynthetic biomass could fix it; thus, atmospheric concentrations of CO_2 increased. Clearly the quantity of respiratory and photosynthetic biomass are important in determining the carbon cycle dynamics of closed ecological systems.

Figure 9 is the carbon dioxide, temperature and PFD data for the last and longest experimental closure with the Test Module. For this closure experiment the soil volume was reduced to about 5 m^3. From *Figure 10* it is clear that the change in respiratory and photosynthesizing biomass was sufficient to allow the atmosphere to reach an apparent equilibrium. *Figure 10* is a plot of the standardized normal variables for CO_2, PFD, and temperature. Notice that even though an increasing trend in temperature and PFD are evident no consistent trend in CO_2 is apparent.

All five experiments also displayed regular diurnal patterns in carbon dioxide concentrations which can be seen in *Figure 14*. Plotted in *Figure 14* are the hourly mean carbon dioxide concentrations for each experiment plus the standard error of the mean. Experiments #1 - #3 show similar maximum and minimum levels but do show regular variation of the time of maximum carbon dioxide. This variation is caused by the seasonal progression of the time of sunrise. The larger standard errors in Experiment #4 reflect the increasing levels of carbon dioxide through the experiment.

Small closed ecological systems were set up and run under laboratory conditions to facilitate the use of replicated experimental design. The first experiment performed with small closed ecological systems examined the effect of variations in starting respiratory biomass and photosynthetic biomass on atmospheric composition and the probability that small systems would not be persistent over time. When these experiments were initiated no experiment using soil and higher plants had been published. Theoretical evidence suggested that the smaller a closed system the higher the probability that the system would fail. It was believed that smaller reservoirs of cycling nutrients would permit less resilience in response to environmental perturbations. *Figure 11* shows the results from this experiment where sixteen small systems were constructed with soil mass/plant biomass (S/P) ratios varying from less than five to over 700. In these experiments we used soil mass as an indication of respiratory biomass. The expected result was that the systems constructed with initially high S/P ratios would have high carbon dioxide concentrations and would be more likely to fail. Failure was defined as the death of the photosynthetic portion of the system. Of the sixteen systems of *Figure 11*, five systems appeared to have not reached an equilibrium level of atmospheric CO_2 at the time the experiment was terminated; *Figures 11a, c, f, j,* and *l*. Of these, plant death occurred in systems of *Figure 11a, c* and *f*. Though the other two systems had not reached an equilibrium level of CO_2, the plants within them remained alive. The reason for the change in photosynthetic activity of these systems is not known.

Two additional experiments have been conducted using small closed ecological systems. In the first, eight closed systems with similar respiratory biomass-photosynthetic biomass ratios were distributed within four different localities at our laboratory. Two locations had high light levels ($PFD > 300$ μmoles m^{-2} s^{-1}) and two had low light levels ($PFD < 150$ μmoles m^{-2} s^{-1}). The influence of light level on atmospheric composition of theses systems is shown in *Figure 12*. Plotted are the mean and standard errors of the CO_2 concentrations of the eight systems. From the figure it is evident that higher light levels had the effect of reducing the initial rise in CO_2 levels. Interestingly, final CO_2 levels were similar.

The last experiment using small closed ecological systems discussed here shows a similar effect of light. *Figure 13* shows the CO_2 levels in four small closed systems. These systems have been closed for over 2 years and appear to have a stable atmospheric concentration of CO_2. *Figure 13* shows the levels of CO_2 just prior to sunrise and just prior to sunset. Though all four systems had similar initial soil mass - plant biomass ratios, two systems had greater absolute amounts of soil (*Figure 13a* & *c*). This greater amount of soil mass is presumable the reason for the higher peak CO_2 levels attained in these two systems. In addition, it appears that these systems had not reached an equilibrium atmospheric composition when they were sampled some 504 days after closing for at that time the CO_2 level in both systems was over 60,000 ppm. On the 510th day of closure all four systems were moved from a low light level laboratory to a laboratory where light levels were about three times greater. The effect on CO_2 levels is apparent from *Figure 13*. All four systems showed a decline in CO_2 levels. Currently these systems show a daily fluctuation in CO_2 concentrations between 0 and 1500 ppm.

One of the questions originally posed concerned the derivation of metrics which could be used for predictive value. *Figure 15* is an example of one such metric. In this figure we have plotted the mean weekly carbon dioxide concentrations (and the standard errors) of the closed systems reported here as a function of the initial soil mass to plant biomass ratios. The carbon dioxide concentrations plotted are from the last six weeks of closure from each experiment. An analysis of covariance indicated that both large and small closed systems did not differ in their response to the soil mass plant biomass ratio. Further, we found that we could explain 77% of the variance in carbon dioxide concentrations with the soil mass to plant biomass ratios.

Can small closed ecological systems be used as analogs for the functioning of Earth's biosphere? We have shown that small closed systems behave in a regular and predictable manner. In addition, we have shown that they behave in ways very similar to Earth's biosphere and its component systems. The primary difference between these systems and Earth's biosphere is the greatly reduced diversity in biogeochemical pathways and the smaller reservoir sizes. We believe, however, that small closed systems are representative of the important biogeochemical pathways of the terrestrial component of Earth's biosphere and as such can be utilized to examine the atmosphere-plant-soil interactions. The advantage of these small systems is their rapid equilibration rate after perturbation. Experimental studies cannot be done on Earth's biosphere in a reasonable time span. Experimental studies of small closed ecological systems can be undertaken relatively inexpensively and quickly.

What can small closed ecological systems teach us about bioregenerative life support systems? While the systems developed to date do not directly simulate bioregenerative life support systems, they do incorporate the major biological units which will make up research colonies located on other planets. Thus, we feel, by studying the behavior of these and other systems constructed using a variety of different biological and technological entities, we can begin to understand the atmospheric dynamics and the biogeochemical cycles of closed systems which will be constructed to support man's endeavors in space.

Conclusions

The CO_2 dynamics in both large and small closed ecological systems show very similar patterns. Both large (*Figure 14*) and small closed systems show regular diurnal fluctuations (*Figure 13*). Earth's biosphere shows similar patterns of variation in carbon dioxide levels. Within intact ecosystems it has been seen that carbon dioxide concentrations will show a diurnal pattern similar to what we have observed (Galoux, et. al., 1973; Keeling, 1961; Odum and Jordan, 1970; Reicosky, 1989; Schnell, et. al., 1981; Wofsy, et. al., 1988). In addition, both large and small systems show similar sensitivity and response to variations in light level as does Earth's component ecosystems (Grulke, et. al., 1990; Idso and Baker, 1968). Lastly we have shown that metrics with predictive value can be derived from the study of closed ecological systems.

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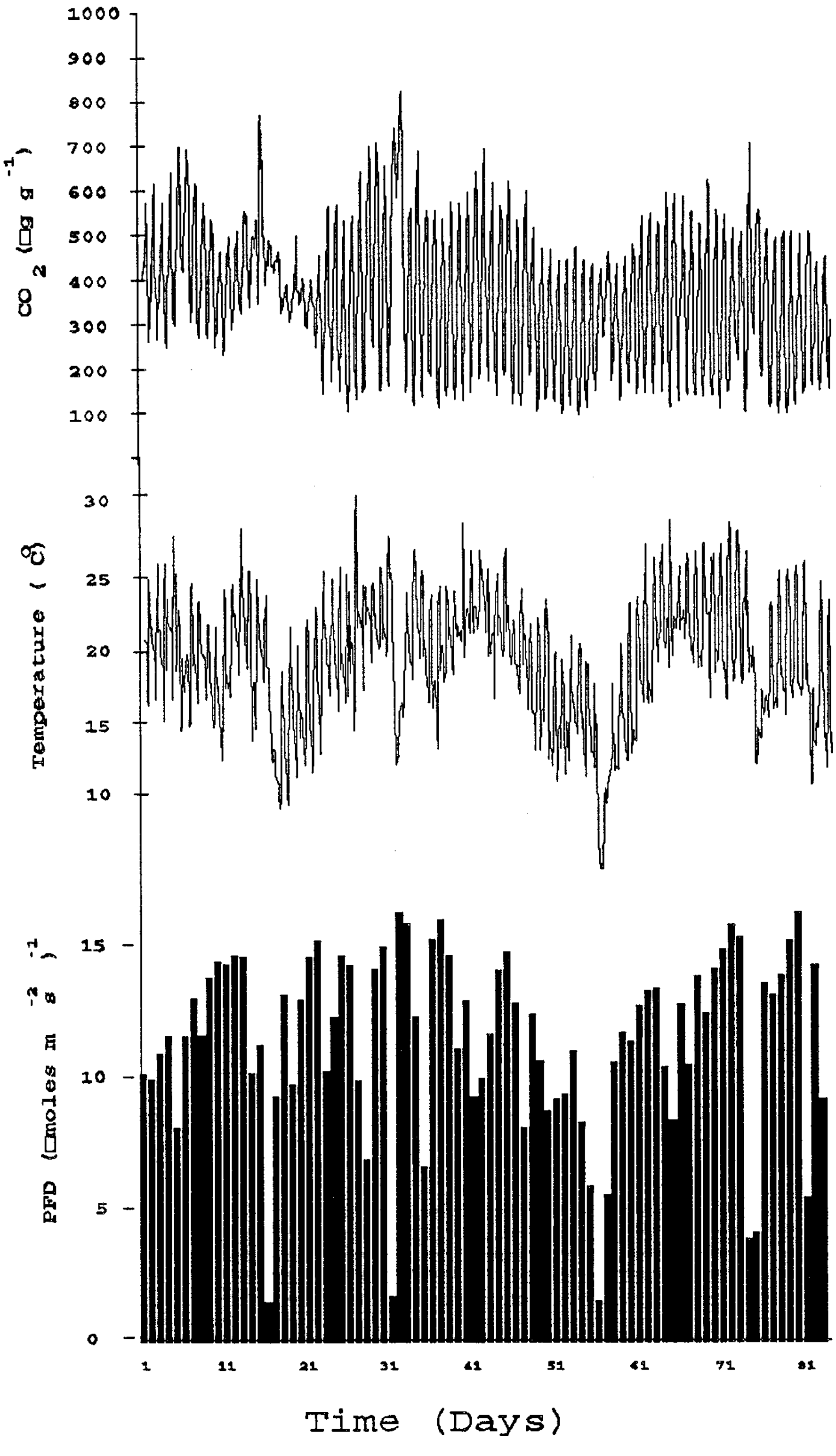

Figure 1. Hourly CO_2, Temperature, and Photon Flux Density for Large C.E.S. Experiment #1.

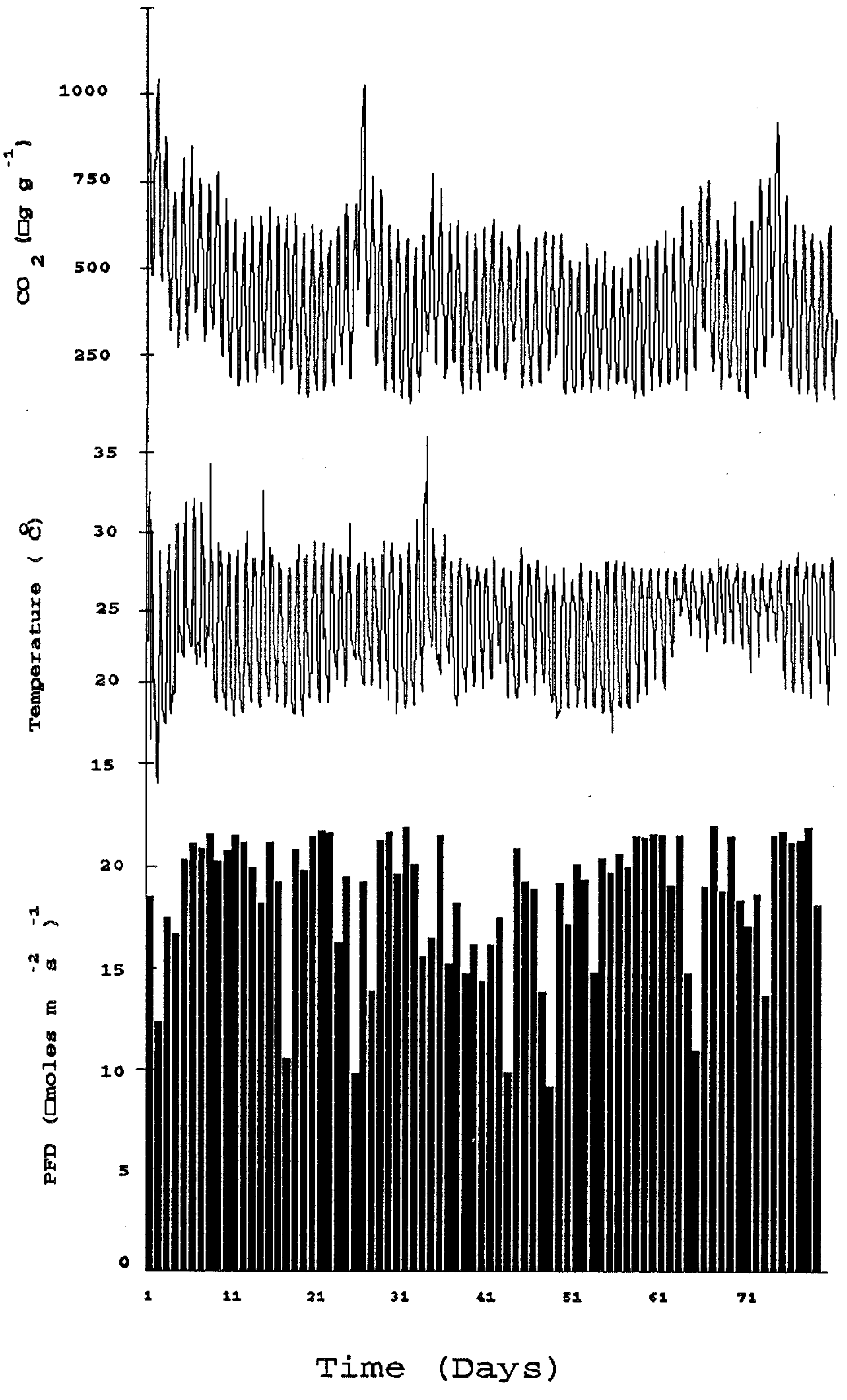

Figure 2. Hourly CO_2, Temperature, and Photon Flux Density for Large C.E.S. Experiment #2.

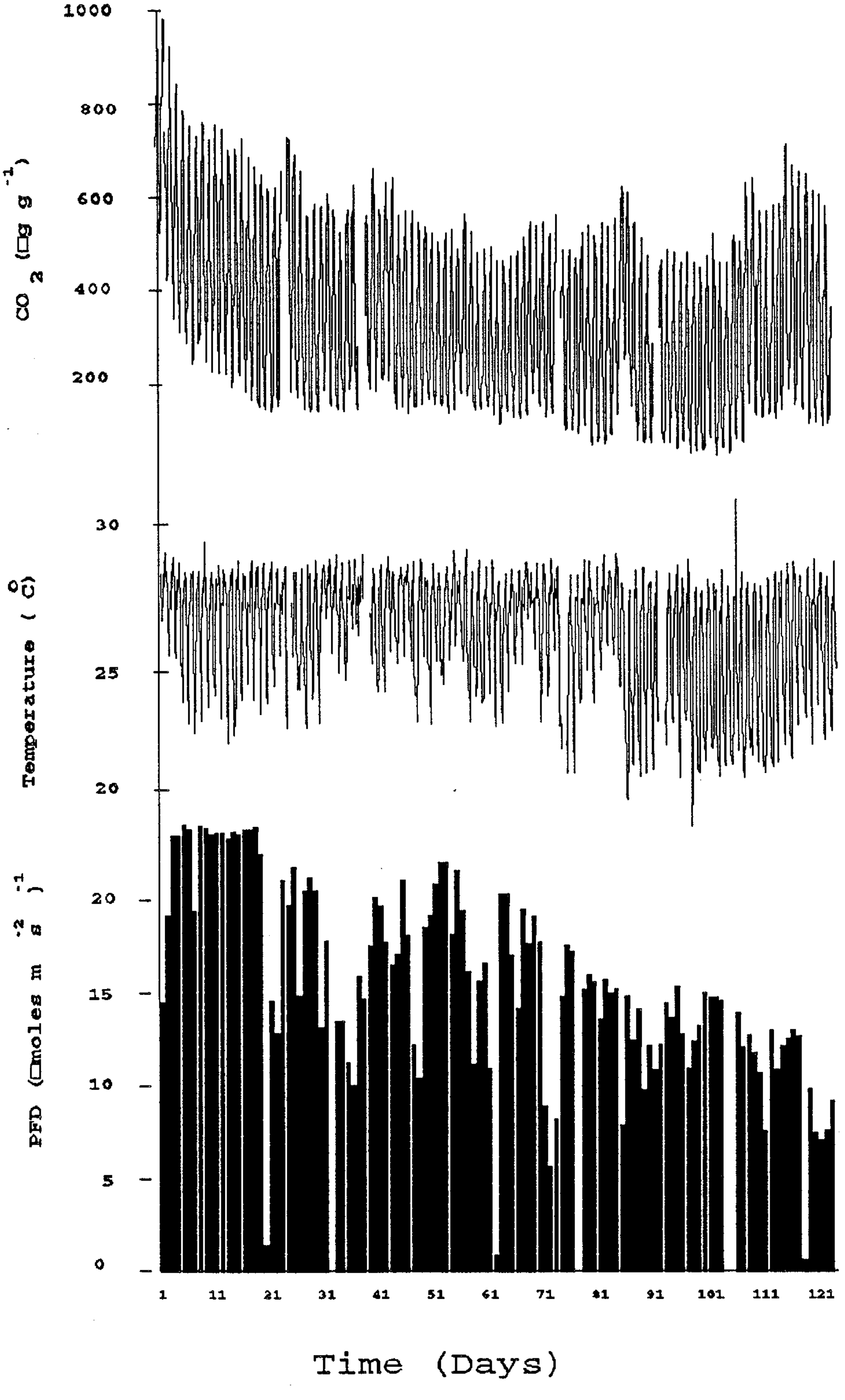

Figure 3. Hourly CO_2, Temperature, and Photon Flux Density for Large C.E.S. Experiment 3.

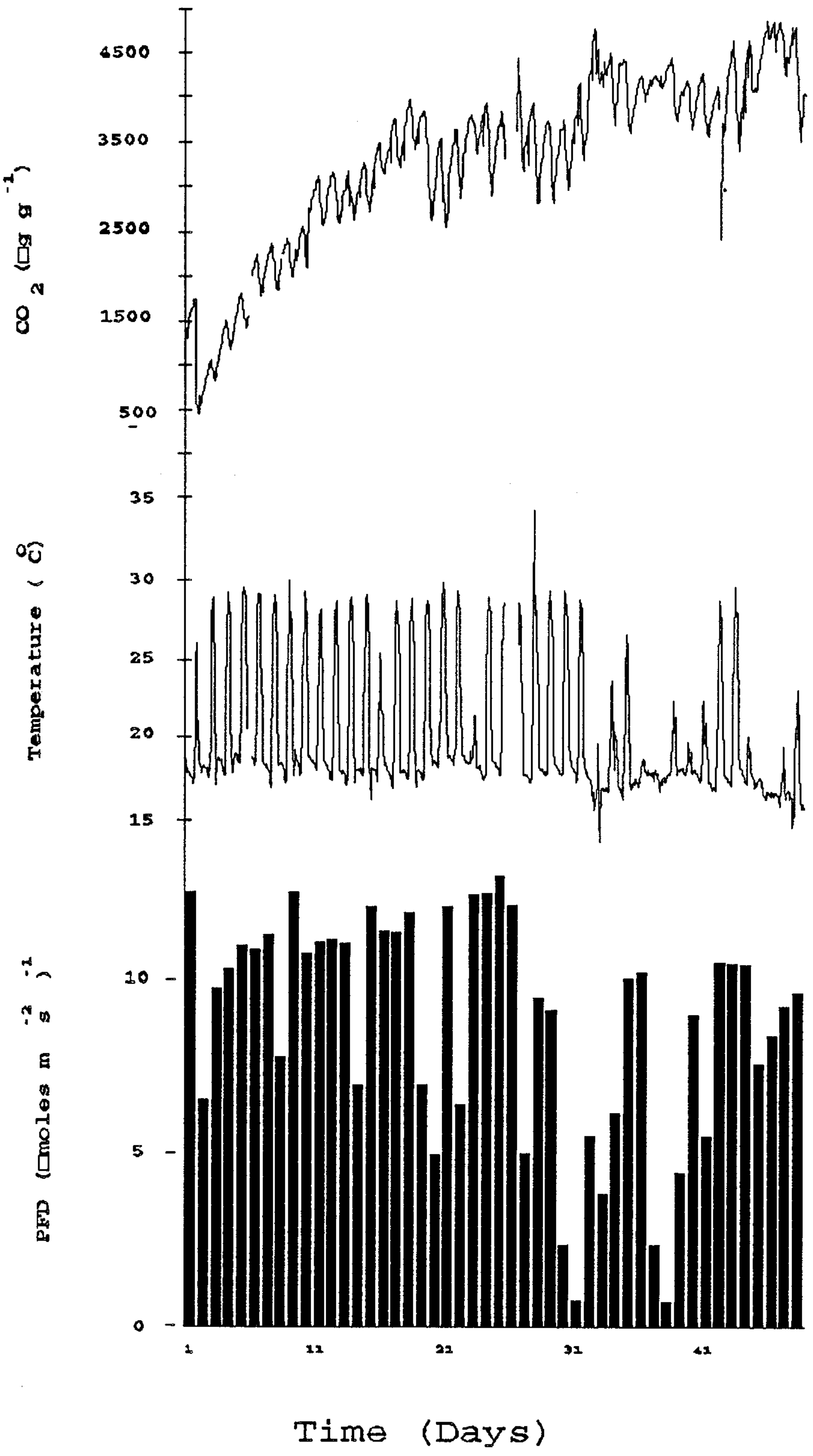

Figure 4. Hourly CO_2, Temperature, and Photon Flux Density for Large C.E.S. Experiment #4.

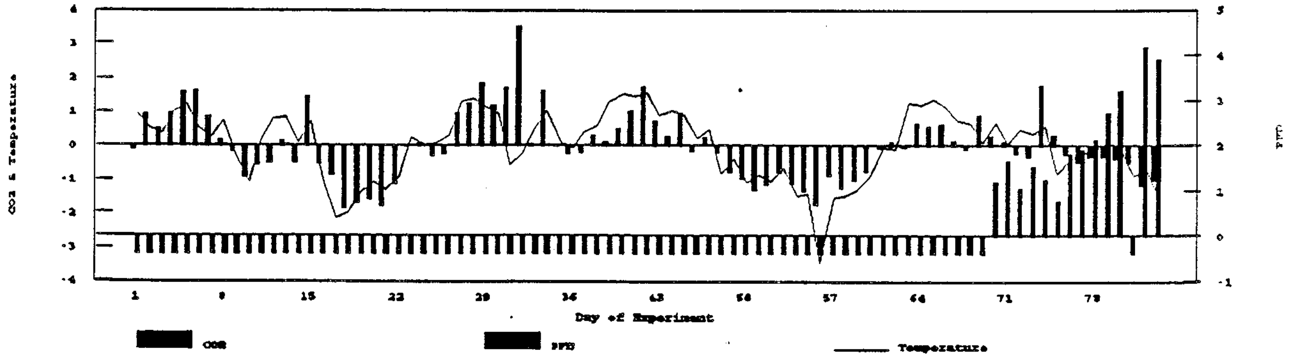

Figure 5. Standardized Normal Variables of CO_2, Temperature, and Photon Flux Density for Large C.E.S. Experiment #1.

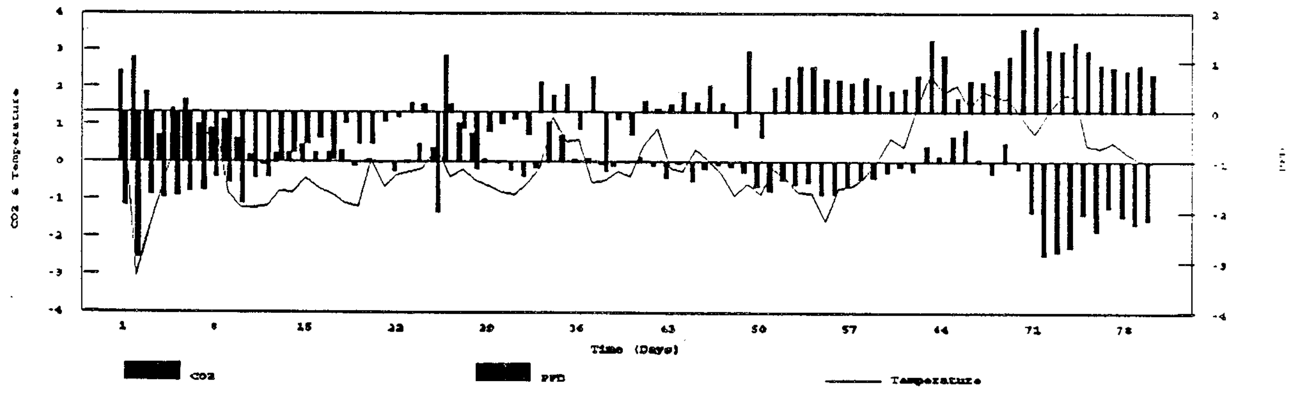

Figure 6. Standardized Normal Variables of CO_2, Temperature, and Photon Flux Density for Large C.E.S. Experiment #2.

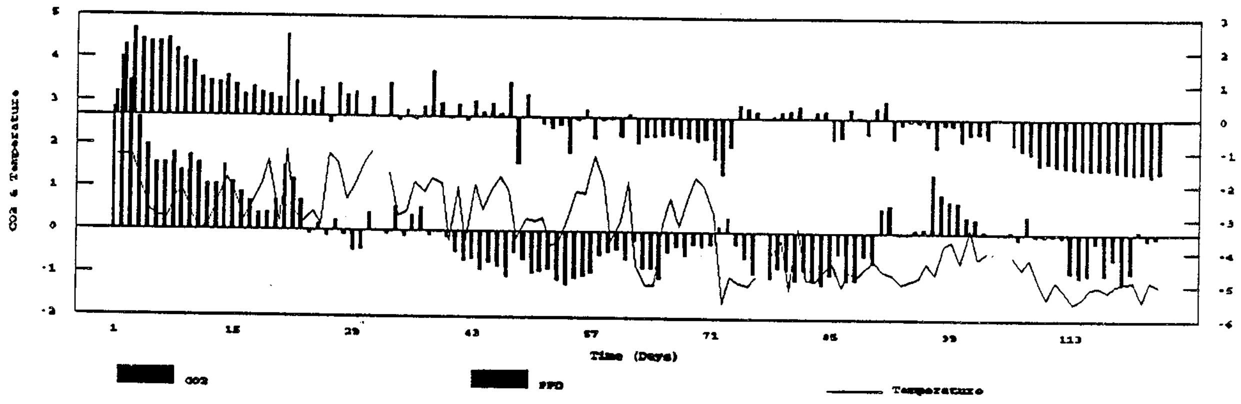

Figure 7. Standardized Normal Variables of CO_2, Temperature, and Photon Flux Density for Large C.E.S. Experiment #3.

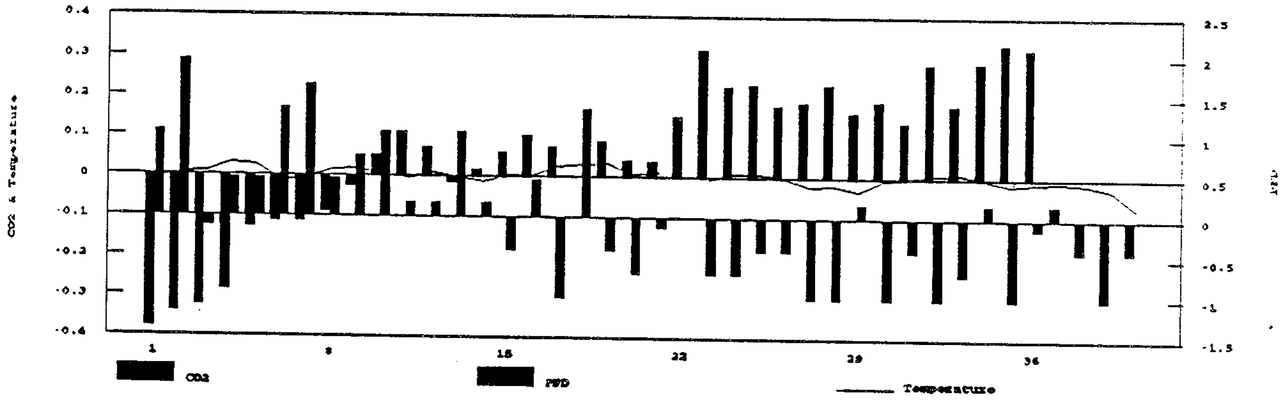

Figure 8. Standardized Normal Variables of CO_2, Temperature, and Photon Flux Density for Large C.E.S. Experiment #4.

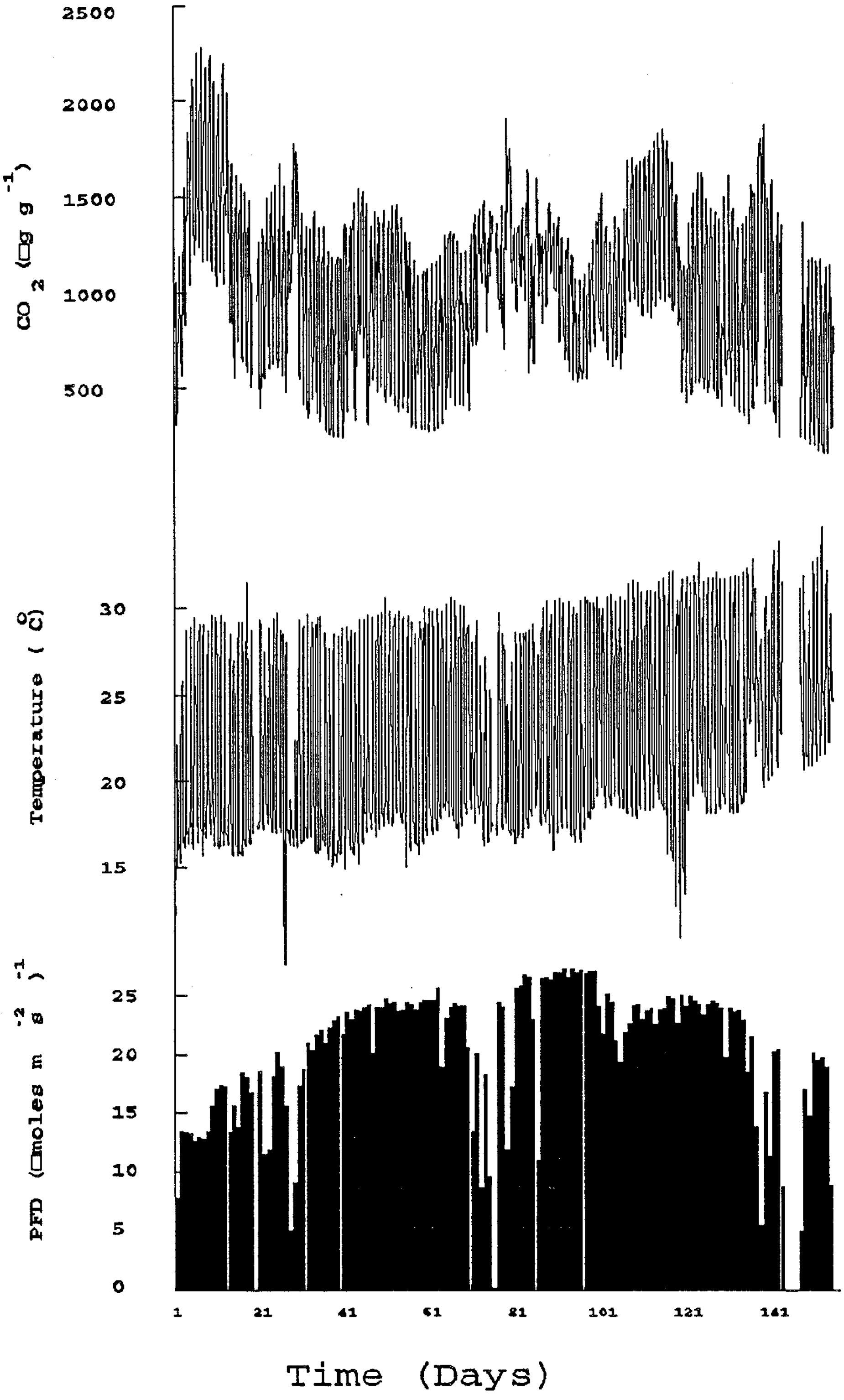

Figure 9. Hourly CO_2, Temperature and Photon Flux Density for Large C.E.S. Experiment #5.

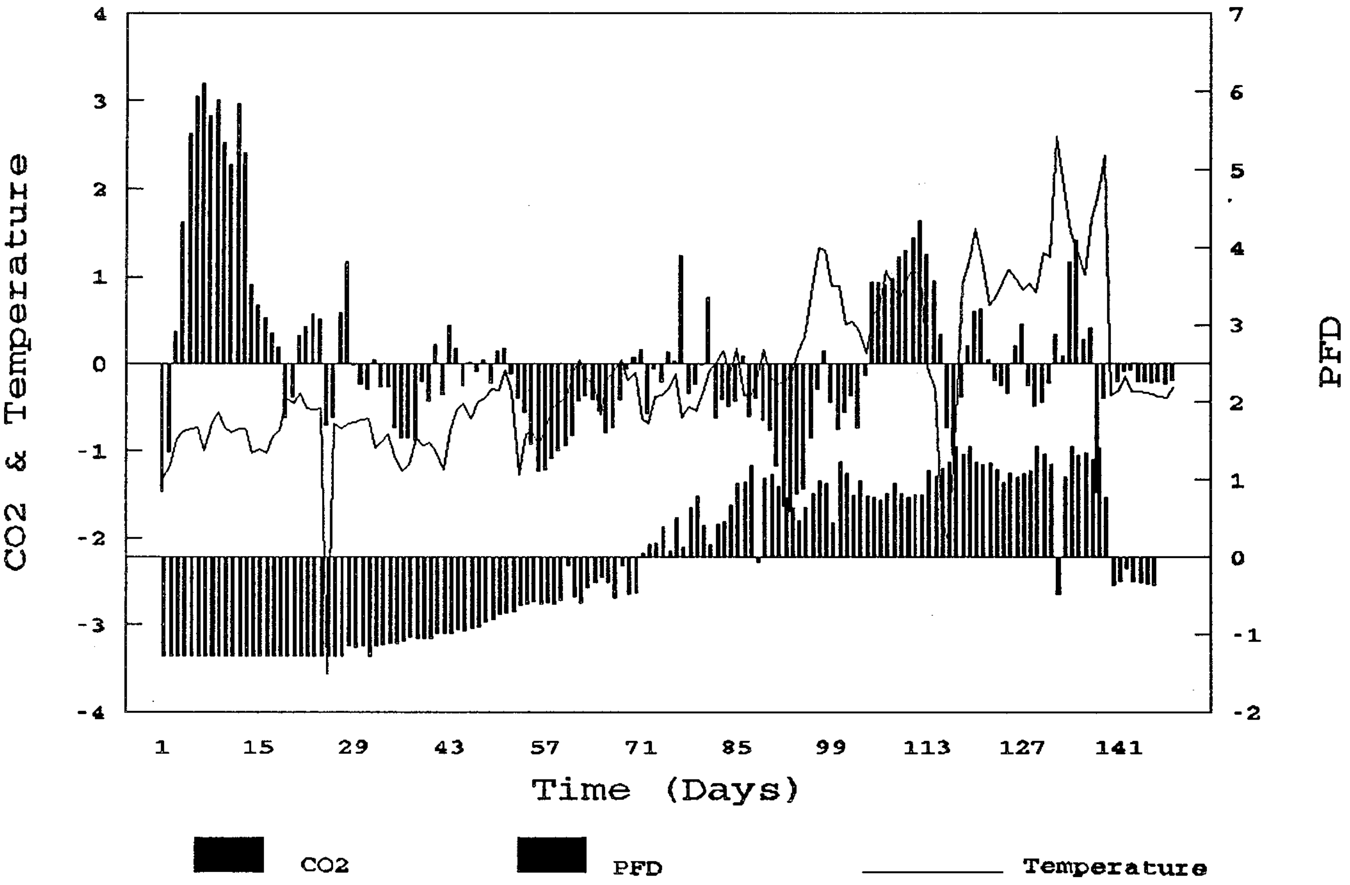

Figure 10. Standardized Normal Variables of CO_2, Temperature, Photon Flux Density for Large C.E.S. Experiment #5.

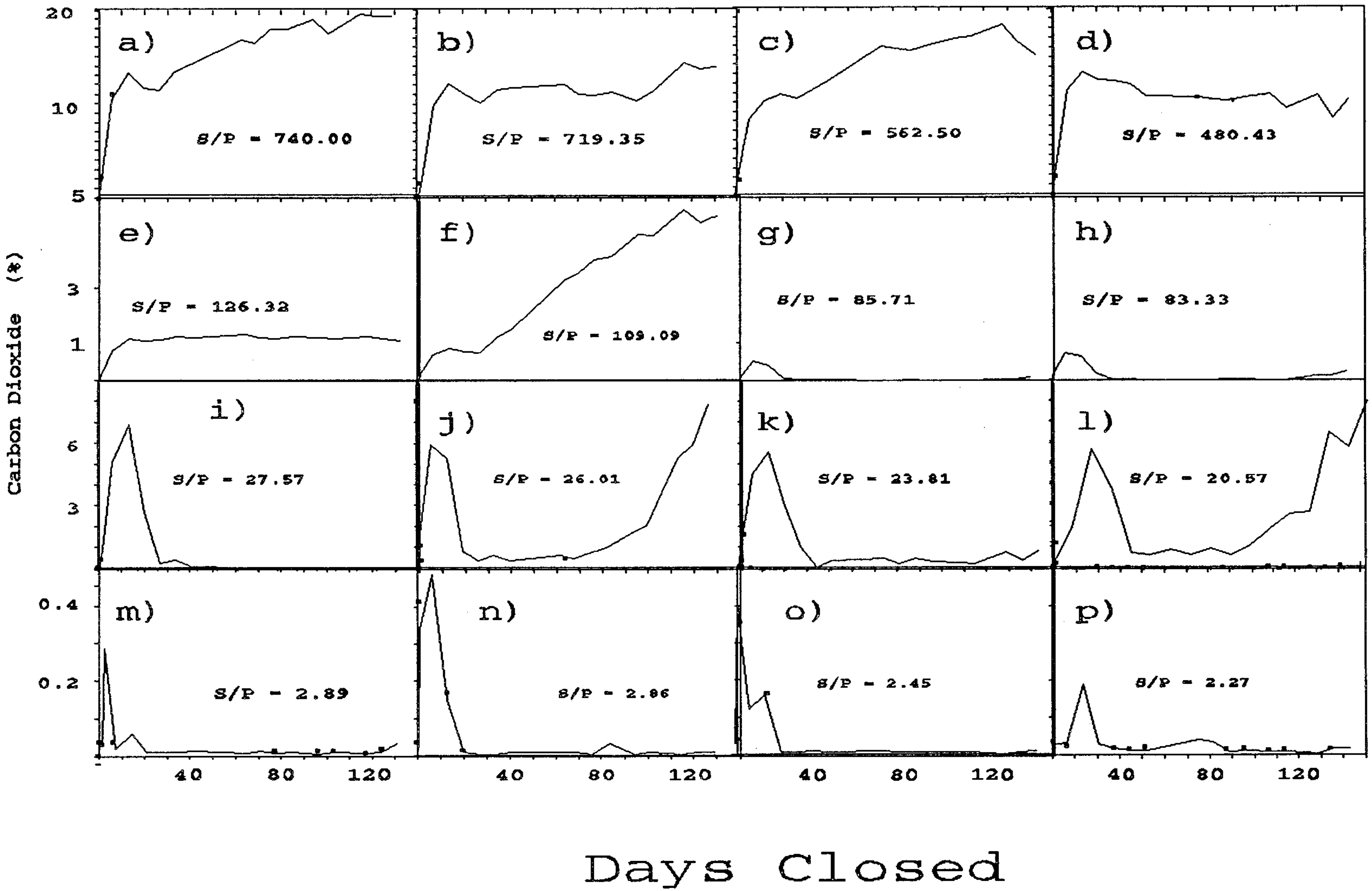

Figure 11. CO_2 Concentrations in Sixteen Small C.E.S.

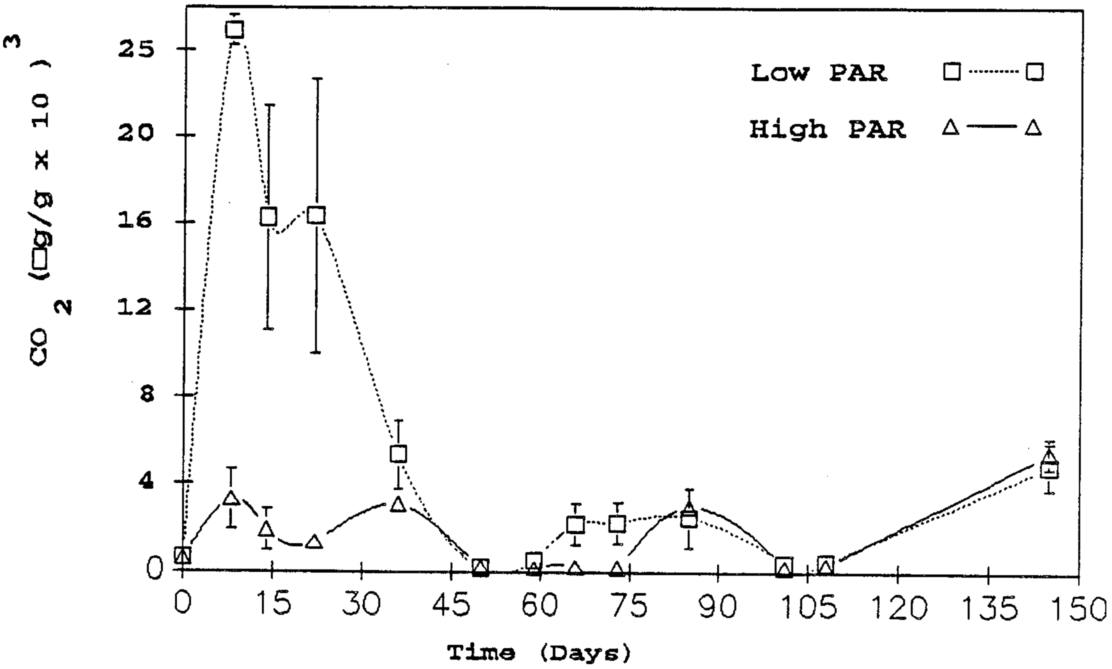

Figure 12. Effect of Photon Flux Density on CO_2 Concentrations in Small C.E.S.

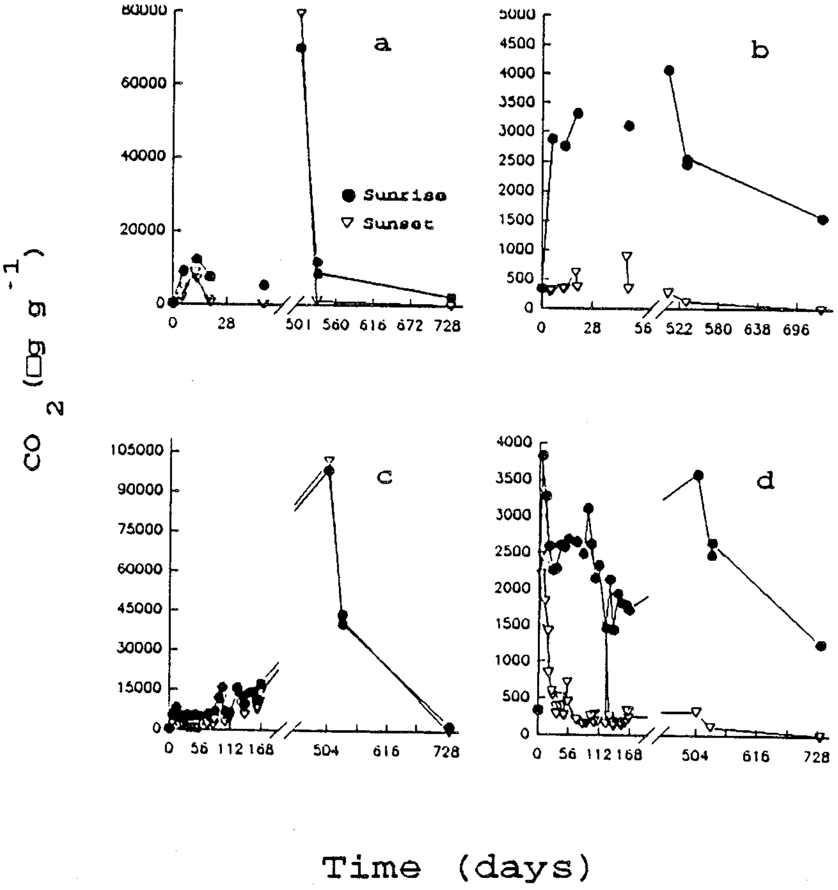

Figure 13. CO_2 Concentrations of Four Small C.E.S.

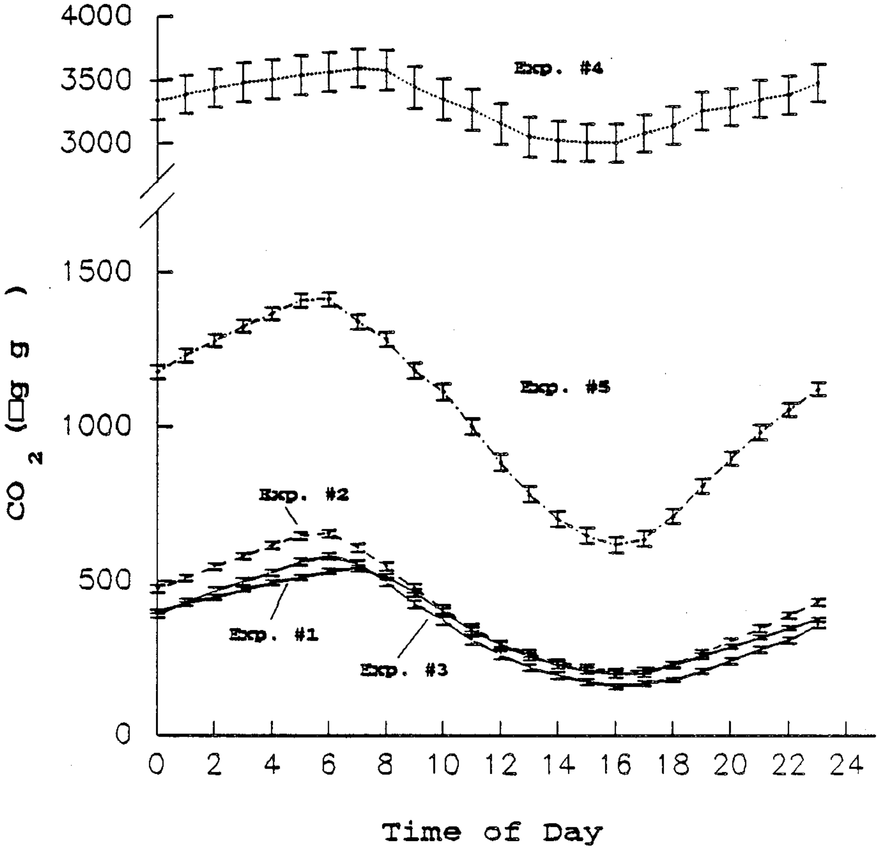

Figure 14. Mean Diurnal CO_2 Concentrations for the Five Large C.E.S. Experiments.

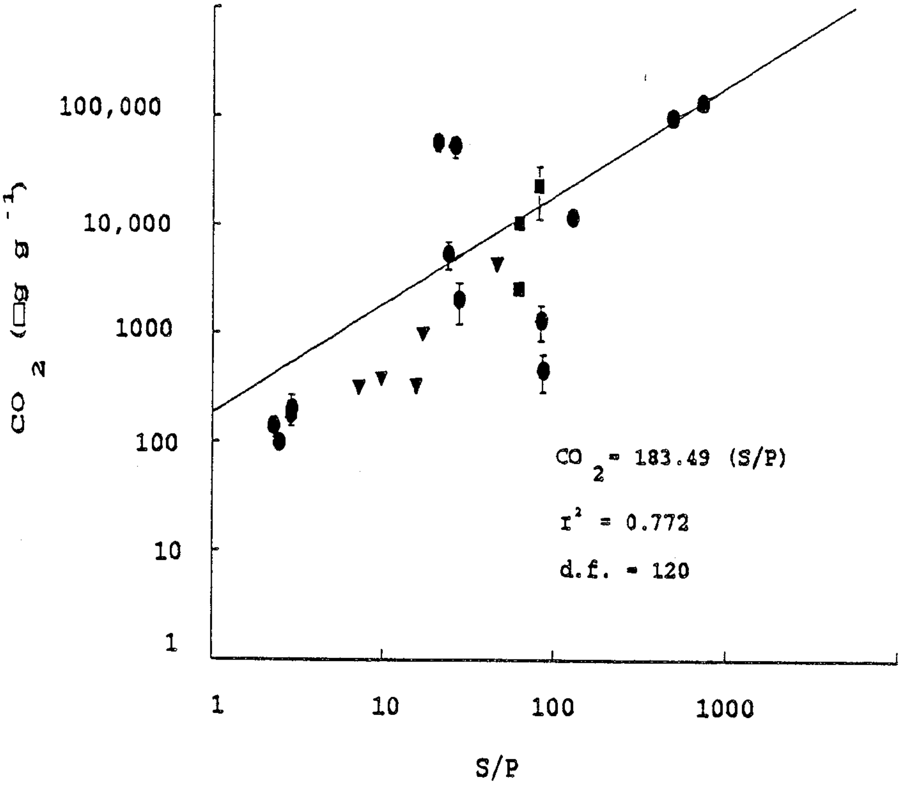

Figure 15. Final CO_2 Concentrations of C.E.S. as a Function of Initial Soil Mass to Plant Biomass Ratios.