Available online at www.sciencedirect.com
SCIENCE DIRECT®
Advances in Space Research 35 (2005) 1552–1556
ADVANCES IN SPACE RESEARCH (a COSPAR publication)
www.elsevier.com/locate/asr

# Atmospheric dynamics in the "Laboratory Biosphere" with wheat and sweet potato crops

William F. Dempster [a,*], J.P. Allen [a], A. Alling [b], S. Silverstone [b], M. Van Thillo [b]

[a] *Biospheric Design, Inc., 26 Synergia Road, Santa Fe, NM 87508, USA*
[b] *Biosphere Foundation, 9 Silver Hills Road, Santa Fe, NM 87508, USA*

Received 13 October 2004; received in revised form 15 December 2004; accepted 24 December 2004

**Abstract**

Laboratory Biosphere is a 40-$m^3$ closed life system equipped with 12,000 W of high pressure sodium lamps over planting beds with 5.37 $m^2$ of soil. Atmospheric composition changes due to photosynthetic fixation of carbon dioxide and corresponding production of oxygen or the reverse, respiration, are observed in short timeframes, e.g., hourly. To focus on inherent characteristics of the crop as distinct from its area or the volume of the chamber, we report fixation and respiration rates in mmol $h^{-1}$ $m^{-2}$ of planted area. An 85-day crop of USU Apogee wheat under a 16-h lighted/8-h dark regime peaked in fixation rate at about 100 mmol $h^{-1}$ $m^{-2}$ approximately 24 days after planting. Light intensity was about 840 μmol $m^{-2}$ $s^{-1}$. Dark respiration peaked at about 31 mmol $h^{-1}$ $m^{-2}$ at the same time. Thereafter, both fixation and respiration declined toward zero as harvest time approached. A residual soil respiration rate of about 1.9 mmol $h^{-1}$ $m^{-2}$ was observed in the dark closed chamber for 100 days after the harvest. A 126-day crop of Tuskegee TU-82-155 sweet potato behaved quite differently. Under a 680 μmol $m^{-2}$ $s^{-1}$, 18-h lighted/6-h dark regime, fixation during lighted hours rose to a plateau ranging from about 27 to 48 mmol $h^{-1}$ $m^{-2}$ after 42 days and dark respiration settled into a range of 12–23 mmol $h^{-1}$ $m^{-2}$. These rates continued unabated until the harvest at 126 days, suggesting that tuber biomass production might have continued at about the same rate for some time beyond the harvest time that was exercised in this experiment. In both experiments $CO_2$ levels were allowed to range widely from a few hundred to about 3000 ppm, which permitted observation of fixation rates both at varying $CO_2$ concentrations and at each number of days after planting. This enables plotting the fixation rate as a function of both variables. Understanding the atmospheric dynamics of individual crops will be essential for design and atmospheric management of more complex CELSS which integrate the simultaneous growth of several crops as in a sustainable remote life support system.


*Keywords:* Closed ecological system; Atmospheric dynamics; Fixation; Respiration; Photosynthesis; Laboratory Biosphere; Carbon dioxide

## 1. Introduction

Laboratory Biosphere is an airtight closed ecological system in the shape of a horizontal steel cylinder 3.68 m long × 3.65 m diameter. Two soil beds on the east and west side of a central walkway are each 2.13 m long × 1.26 m wide × 30 cm deep providing a total growing area of 5.37 $m^2$. Twelve 1000 W high pressure sodium lamps provide plant growth lighting. An internal air handling system through which cold refrigerant is delivered from outside is provided for temperature control. A complete technical description of Laboratory Biosphere is found in Dempster et al. (2004) and an early experiment with soybeans is discussed in Nelson et al. (2003). For the wheat crop discussed here, ten lamps were used in a 16-h photoperiod for 90 days, and for sweet potato, eight lamps were used in an 18-h photoperiod for 125 days. More details about these crop experiments are found in Nelson et al. (2005). The focus

* Corresponding author.
*E-mail address:* Wfdempster@Aol.Com (W.F. Dempster).

0273-1177/$30 © 2005 Published by Elsevier Ltd on behalf of COSPAR.
doi:10.1016/j.asr.2004.12.060

of this paper is on fixation and respiration of $CO_2$ and what that suggests about production of biomass in the crop. The methodology presented can be applied to the design of complex CELSS in which multiple crops are grown in a shared atmosphere and it is desired to understand the combined effects on atmospheric composition.

## 2. Measurement methodology

### 2.1. Sample collection and sensor calibration

Laboratory Biosphere is equipped with a small atmospheric extraction pump which continuously delivers a sample stream of air to two Vaisala $CO_2$ sensors, models GMT222 (0–5000 ppm $CO_2$) and GMT221 (0–10% $CO_2$). After passing through the sensors, the sample stream is routed back into Laboratory Biosphere so that the continuous sampling does not constitute a leak in the system. The site of Laboratory Biosphere is at 1900 m elevation and barometric pressure typically ranges from 790–825 mBar. The Vaisala sensors were calibrated for use at an atmospheric pressure of 805 mBar and their readings were verified with ambient air at 370 ppm $CO_2$. The site is in a rural setting without any significant nearby sources of $CO_2$. Calibration at higher $CO_2$ concentrations by comparison with known standard samples has not been done, but it should be noted that the primary focus of this paper is on first and second differentials of $CO_2$ concentration and high accuracy of the absolute reading is not critical.

### 2.2. Raw data corrections

Data from the $CO_2$ sensors are reported by a 4–20 mA output signal to a National Instruments Field Point Analog Input module, model FP-AI-110 (16-bits). These raw data are fed to a continuously operating personal computer and recorded every 15 min on hard disk along with other data from approximately 60 sensors of various types (mostly for temperature). To obtain true $CO_2$ concentration values, the raw $CO_2$ data are corrected for fluctuations of barometric pressure and for temperature at the sensor according to a correction algorithm supplied by Vaisala. Consideration of heat transfer rates between the sample supply tubing and the gas sample stream led to the conclusion that the applicable temperature (within a small fraction of a degree) to be used for temperature correction of the raw data would be the ambient room temperature of the $CO_2$ sensor and the supply tubing in its immediate vicinity. This temperature data are available as one of the many temperature sensors recorded on disk. The corrected $CO_2$ data for wheat and sweet potato are shown in Fig. 1.

### 2.3. Determination of fixation and respiration rates

We are interested in net fixation/respiration rates of $CO_2$. These are the first time derivative of $CO_2$ concen-

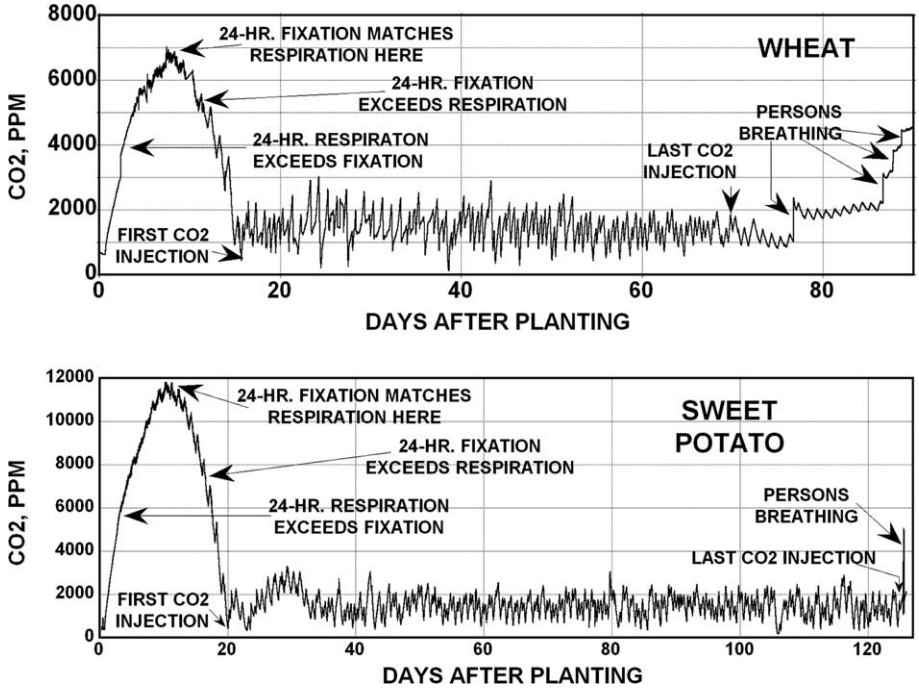


Fig. 1. $CO_2$ in Laboratory Biosphere during wheat and sweet potato experiments. $CO_2$ initially rises while the new plants are very small then falls rapidly as they grow larger and photosynthesis increases. 58 injections maintain $CO_2$ levels for wheat (days 15–69) and 91 injections for sweet potato (days 20–124).

tration in the system. It is seriously inaccurate to equate the derivative to the difference between two successive $CO_2$ data points divided by the time because, noise errors of each individual reading can be significant compared to their difference. Therefore, sets of at least eight consecutive readings were fit with a cubic polynomial and the time derivative of the fitted polynomial is taken to determine the rate of net fixation or respiration. A quadratic fit was not used because a quadratic fit inherently forces a relationship between its first derivatives at the beginning and the end of the data set determined by its concavity/convexity (the second derivative of a quadratic is a constant). Using a cubic fit allows the beginning and ending first derivatives a degree of independence.

*2.3.1. Operational interruptions*

Operation of the system was interrupted by three kinds of events.

1. At the end of a photoperiod, the lights were turned off and dark respiration began. Conversely, at the end of a dark period, the lights were turned on and photosynthetic fixation commenced.
2. Laboratory Biosphere's atmosphere is too small to hold enough $CO_2$ buffer to meet the fixation demand for a vigorously growing crop through all photoperiods. Soil respiration is too little to balance the fixation demand. In the interest of maintaining high crop productivity, $CO_2$ was injected when $CO_2$ concentration became too low to sustain high fixation rates. This was generally when $CO_2$ declined into the range of a few hundred to 1000 ppm. $CO_2$ injection was usually done slowly, raising the level into the range 2000–3000 ppm over a few hours.
3. On various occasions, a researcher would enter/exit through the airtight door, exchanging an estimated 1% of the atmosphere with outside air, and also adding $CO_2$ by their own breathing while inside.

*2.3.2. Selection of undisturbed data sets*

We select undisturbed periods of at least eight sequential data points (i.e., $8 \times 15$ min = 2 h minimum). A typical day would include 2 or 3 undisturbed lighted periods of 3–5 h and 1 undisturbed dark period of 6–8 h. Following either darkness or a $CO_2$ injection, the $CO_2$ level would often be high (2000–3000 ppm) and subsequently descend to below 1000 ppm due to $CO_2$ uptake by the growing crop. Cubic curve fits and their derivatives yielded data for hundreds of "mini-experiments" for determining the fixation rate for both a wide range of $CO_2$ levels and for each day after planting, although lacking the accuracy that might be obtained by many repetitions of separate experiments. Nevertheless, rough consistency of pattern throughout the ranges of $CO_2$ level and days after planting supports the results obtained. Examples of the sequential data points, the cubic fits and derivatives are shown in Fig. 2.

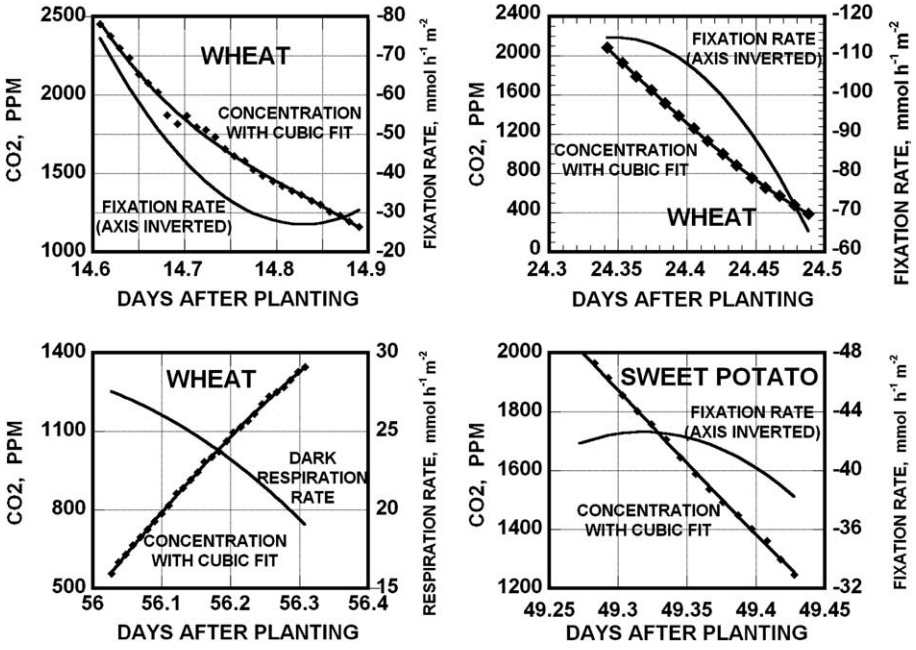


Fig. 2. Selected "mini-experiments" from $CO_2$ concentration data during undisturbed periods. The data points are shown with the curve of a cubic polynomial fit (scale on left axis). The derivative curve estimates the fixation or respiration rate (scale on right axis). Fixation is denoted as negative values with axis inverted so that higher rates are higher on the graph.

## 3. A note about units

We seek to find characteristic behavior of individual crops independent of the peculiarities of a given test chamber or how much area was planted. To that end we express the results of fixation or respiration experiments in units of millimoles per (hour × square meter), i.e., mmol $h^{-1}$ $m^{-2}$ of planted area rather than ppm of $CO_2$ per unit time. The latter units would compel the reader to become involved in calculating this system's volume, planted area, barometric pressure, and perhaps temperature in order to compare the results with those of other experiments. This choice of units does not avoid the necessity to consider other factors such as light level, growing conditions, etc. Since the raw data are available as $CO_2$ concentration, we compute fixation or respiration rates according to rate (mmol $h^{-1}$ $m^{-2}$) = concentration change (ppm) × $10^{-3}$ × atmospheric volume (mol) ÷ planted area ($m^2$) ÷ time (h), where atmospheric volume = 1110 mol and planted area = 5.37 $m^2$.

## 4. Results

Each mini-experiment yields either a fixation or respiration rate for a particular day and a range of $CO_2$ concentrations. We select the available cases for both 2000 and 1200 ppm $CO_2$ to plot in the graphs of Figs. 3 and 4. These show very different behavior of the wheat and sweet potato crops. The rates for wheat increase rapidly until about day 26 and then diminish rapidly toward zero approaching harvest time. The rates for sweet potato increased until about day 42 and then maintained a range until harvest at day 126. The wheat crop had obviously reached the end of productivity having turned brown and dry, but these data suggest that the sweet potato tubers were continuing to grow at the arbitrarily chosen harvest time. We see that the points plotted each day for 2000 ppm $CO_2$ (dots) are generally shifted lower on the graph than the points for 1200 ppm (squares). This represents higher fixation rates and lower respiration rates for 2000 ppm $CO_2$ as compared to 1200 ppm $CO_2$.

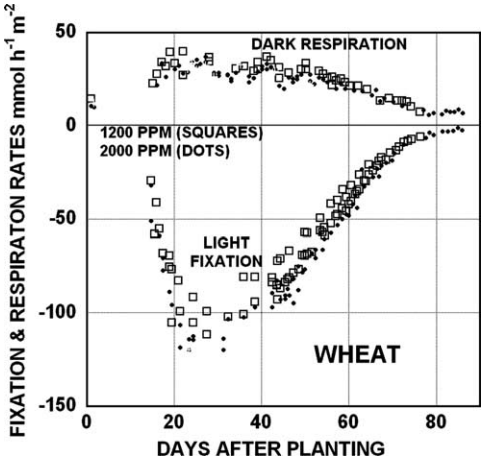


Fig. 3. Fixation and respiration rates for wheat at 1200 (squares) and 2000 ppm (dots).

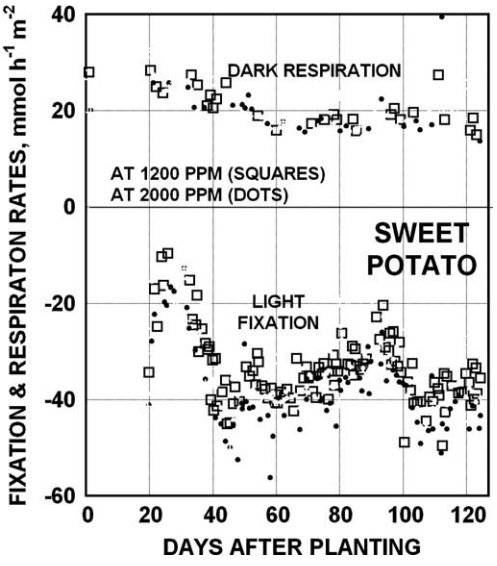


Fig. 4. Fixation and respiration rates for sweet potato at 1200 (squares) and 2000 ppm (dots).

## 5. Further implications

The methodology gives us single observations of fixation rates every day for a range of $CO_2$ concentrations,

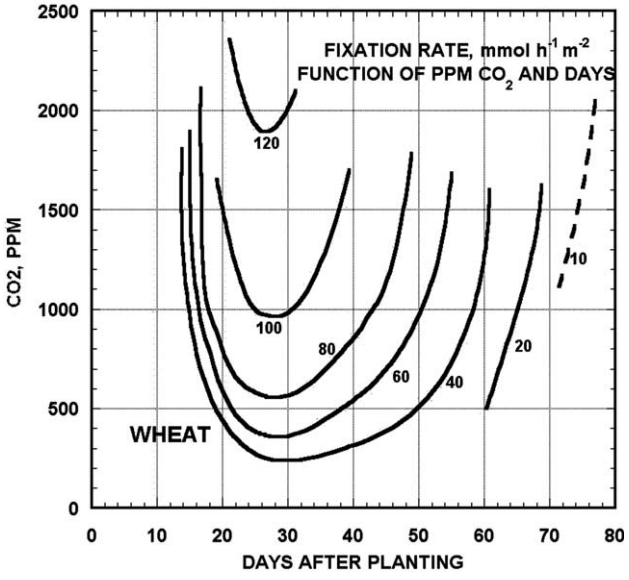


Fig. 5. Contour plot showing fixation rates for wheat as function of days after planting (*x*-axis) and $CO_2$ concentration (*y*-axis) interpolated by inspection from results of 108 mini-experiments.

i.e., fixation rates as a function of both the variables days after planting and $CO_2$ concentration. This enables the construction of a three dimensional plot, contour lines of fixation rates. For wheat, this is shown as Fig. 5. While lack of replications must limit the accuracy of individual data points and accepting that these data are observed under particular conditions of temperature, humidity, light regime, etc., the contour forms of Fig. 5 are instructive for the design of complex closed ecological life support systems. Visualize a future CELSS with numerous crops growing in a common atmosphere and each crop at different stages of growth. For such a system to approximate to atmospheric balance, its cropping plan must be designed with knowledge of the atmospheric dynamic of each crop at each day of growth and at a wide range of $CO_2$ concentrations. The plot of Fig. 5 illustrates that knowledge for USU Apogee wheat.

## References

Dempster, W.F., Van Thillo, M., Alling, A., Allen, J.P., Silverstone, S., Nelson, M. Technical review of the Laboratory Biosphere closed ecological system facility. Adv. Space Res. 34, 1477–1482, 2004.

Nelson, M., Dempster, W.F., Alling, A., Allen, J.P., Rasmussen, R., Silverstone, S., Van Thillo, M. Initial experimental results from the Laboratory Biosphere closed ecological system facility. Adv. Space Res. 31 (7), 1721–1730, 2003.

Nelson, M., Dempster, W.F., Silverstone, S., Alling, A., Allen, J.P., Van Thillo, M., Crop yield and light/energy efficiency in a closed ecological system: Laboratory Biosphere experiments with wheat and sweet potato. Adv. Space Res., in press.