Ecosystem-level evapotranspiration and water-use efficiency in the desert biome of Biosphere 2

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Abstract

We estimate whole-system water and carbon fluxes for the desert biome of Biosphere 2 under two different daily-mean CO₂ concentrations: 450 ppmv and 850 ppmv. The desert mesocosm occupies an area of approximately 1500 m², has a total atmospheric volume of about 25000 m³ and contains a heterogeneous distribution of plants and soils. Atmospheric water content and CO₂ concentrations were measured continuously using a variety of sensors, including a Li-cor 6262 for CO₂ deployed within the experimental area. Daily carbon and water budgets were calculated in the desert biome, isolated from the rest of Biosphere 2 by deploying isolation curtains for 24-h periods. Data collected for six closure periods suggest that elevated CO₂ concentration increased whole-system carbon uptake, while evapotranspiration remained constant. As a result, whole-system water-use efficiency (WUE, defined as net ecosystem carbon uptake per unit water transpired) in the Biosphere 2 desert increased by more than 40%. Our measurements investigate soil-plant processes at a medium scale, ideally bridging the gap between traditional controlled-environment growth chambers and open-field studies. © 1999 Elsevier Science B.V. All rights reserved.

Keywords: Biosphere 2; Evapotranspiration; Elevated CO₂; Ecosystems

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1. Introduction

Despite results of experiments carried out in controlled-environment growth-chambers and in greenhouses, little is known about the actual impacts of elevated CO₂ concentration on ecosystem-level carbon-water relations (Vitousek, 1993). The scale at which such processes operate is large enough so that traditional experiments investigating the behavior of component parts, such as a plant’s leaf-level photosynthesis or soil respiration dynamics, do not provide the information needed to fully describe and understand the entire system. Because of lack of information at the large scale, computer models that extrapolate from leaf processes to whole canopy must be used to assess the effects of climate change on ecosystem dynamics (e.g., Parton et al., 1994; Foley et al., 1996). How can we expand our knowledge base beyond the current restrictions? In order to perform large-scale observations, several open-field experimental campaigns have been launched, focusing on carbon and water exchange processes (e.g.: FIFE, Sellers et al., 1988). These experiments are important, but they present at least two disadvantages when compared to growth-chambers studies: (1) They naturally lack environmental control; and (2) They do not allow for precise mass-balance calculations. There is thus a need for medium-scale facilities that could bridge the current gap (Korner and Arnone, 1992). Such facilities should be large enough to offer spatial variability of soils and vegetation, yet they should be ‘manageable’, that is, they should allow for environmental control as well as for mass-balance calculations. We used Biosphere 2 to perform experiments that investigate processes of natural ecosystems at a medium-scale, under tight environmental control.

2. Materials and methods

Biosphere 2 is comprised of an agricultural section and a wilderness area comprised of several mesocosms: Desert, Savannah, Ocean/Marsh; and Rain Forest. These mesocosms contain several features of the natural systems they reproduce, most importantly for the studies described herein, biome-specific soil-plant distributions of importance to determine whole-system carbon uptake and evapotranspiration.

We have devised an experimental protocol based on the use of single mesocosms of Biosphere 2 as very large, controlled-environment growth-chambers. A first experiment was performed during the 1995–96 winter season. We refer to it hereafter as the ‘winter experiment’. It consisted of repeated 24-h measurements, under mass closure, of whole-system carbon and water exchange under two different daily-mean CO₂ concentrations: ‘ambient’ (about 450 ppm), and ‘elevated’ (about 850 ppm), using both the desert and rain forest mesocosms of Biosphere 2.

1 Another important component of the Winter experiment was the collection of plant-specific measurements of leaf photosynthesis and transpiration, to provide information on species variability, and to serve as a database for scaling-up calculations with ecosystem models.
Mass closure of each mesocosm, defined by minimal material exchange between the sealed area of study and the other parts of Biosphere 2, was obtained by deploying removable plastic curtains at the interface with the other biomes of Biosphere 2. Determination of leakage between the isolated biome and surrounding areas were performed to refine mass-balance calculations, using sulfur exa-fluoride (SF-6) as a trace gas. Leaking rates were found to be constant at about 4% per hour. The winter experiment was conducted over a 2-month period, from December 1995 to January 1996, centered around the winter solstice in order to minimize light variability among replicated measurements (environmental settings are given in Table 1).

Both the desert and rain forest mesocosms of Biosphere 2 were exposed to the specified CO\textsubscript{2} concentrations for about two weeks prior to measurements, to allow for plant acclimation to changes in CO\textsubscript{2}. Atmospheric water content and CO\textsubscript{2} concentration were monitored continuously using a variety of sensors, including a Li-cor 6262 for CO\textsubscript{2}, deployed within the experimental area. We present and discuss here preliminary results relative to measurements in the desert mesocosm alone. Results from the rain forest mesocosms and comparisons are currently being prepared for publication (Lin et al., 1997).

Because no CO\textsubscript{2} control system was in place during the winter experiment, carbon dioxide concentrations varied around the specified daily-means by several hundred ppmv as a function of photosynthesis and respiration. Repeating these experiments under constant CO\textsubscript{2} levels may greatly enhance the applicability of the results to natural systems.

2.1. Mass-balance calculations: carbon dioxide

Carbon dioxide concentrations were measured using a Licor 6262 with four ports appropriately located in the study area. A more detailed description of the instrumental settings and calibration techniques is given by Rosenthal et al. (1999). Whole-system carbon fluxes were then calculated and corrected for, (1) Air exchange through the isolation curtains; and (2) Carbon uptake by concrete surfaces, a process first identified at Biosphere 2 by Severinghaus et al. (1994).

With reference to a schematic of the processes involved in carbon uptake under mass-closure (Fig. 1) we wrote:

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Environmental settings for the desert mesocosm during the winter experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameter</td>
<td>Min</td>
</tr>
<tr>
<td>Temperature (°C)</td>
<td>17</td>
</tr>
<tr>
<td>Relative humidity (%)</td>
<td>30</td>
</tr>
<tr>
<td>Light (\textmu m\textsuperscript{-2} s\textsuperscript{-1})</td>
<td>0</td>
</tr>
<tr>
<td>CO\textsubscript{2} -low (ppmv)</td>
<td>300</td>
</tr>
<tr>
<td>CO\textsubscript{2} -high (ppmv)</td>
<td>400</td>
</tr>
</tbody>
</table>
where the term to the right hand-side of Eq. (1), the time-derivative of CO₂ concentration in the biome, represents whole-system net carbon fluxes. These are due to uptake (positive sign in our convention) by plants through gross photosynthesis, \( P_g \), and by the concrete structure, \( U_c \). Releases of carbon (negative sign) into the system are due to plant and soil respiration, \( R_p \) and \( R_S \), respectively. A correction term, \( L \), accounted for exchange of carbon with other biomes due to leakage. In accordance with the current literature, we defined net ecosystem exchange of carbon, NEE, as gross photosynthesis minus plant and soil respiration, and calculated it by:

\[
\text{NEE} = (P_g - R_p) - R_S = \frac{dC}{dt} - U_c - L
\]

The above definition is operationally simple, representing net carbon exchange between the atmosphere and the soil-plant system. Eq. (2) mixes net photosynthetic uptake by plants with soil respiration. Separate measurements of soil respiration (not available to us for the experiments presented here) are necessary if one wishes to further separate the plant and soil components of NEE.

2.2. Mass-balance calculations: water vapor

Whole-system evapotranspiration, or the combined loss of water through both canopy and soil, was not measured directly but estimated using conservation of mass considerations. As also shown in Fig. 1, under the specified experimental
protocol, three components of the water balance in each isolated mesocosm could be identified; (1) Changes in atmospheric water vapor, \( \Delta A \); (2) Condensate production by air-handlers units, \( P \); and (3) Whole-system evapotranspiration, \( ET \), or the amount of water added to the atmosphere by the soil-plant system. Such components are linked via the following mass-conservation equation:

\[
\Delta A = ET - P - L 
\]  

(3)

where \( L \) indicates losses due to air exchange across isolation curtains. Whole-system evapotranspiration could thus be determined by combining independent measurements of changes in atmospheric water vapor, \( \Delta A \), air handlers production, \( P \), and leak rates, \( L \). Both \( \Delta A \) and \( P \) were measured every 15 min, while losses due to leak-rates were estimated over the same interval from observed SF-6 decay rates. Three-hour period averages were then generated to account for air-mixing inside the closed system. The errors in our calculations were about 15\%, as indicated by measurements performed on all sensors involved in data collection. Errors were dominated by the accuracy range of the flow sensors used to monitor air-handlers production (for a more detailed description of the components of the water cycle in Biosphere 2, see Tubiello et al., 1999).

2.3. Whole-system water-use efficiency

Measurements of carbon uptake and water loss were combined to estimate system-level water-use efficiency, or WUE, defined here as the amount of whole-system carbon uptake over water lost. Because it is important to relate WUE to carbon sequestration during the day, we performed WUE calculations during the daylight period (roughly a 9-h interval), when carbon uptake into the system was positive.

3. Results and discussion

We present results from measurements for 4 days (January 8, 12, 18 and 26, 1996) at ambient CO\(_2\) levels and 2 days (December 20, 1995; February 14, 1996) at elevated CO\(_2\) levels. Data collected at ambient CO\(_2\) concentration indicate a good level of experimental reproducibility. Fig. 2 shows measured whole-system evapotranspiration and carbon fluxes in the desert mesocosm. Both the magnitude and time-dependence of the data at ambient CO\(_2\) were highly consistent, as the four time-series of water and carbon fluxes were not significantly different from each other at the \( p = 0.01 \) level. Whole-system evapotranspiration under ambient CO\(_2\) was similar to that measured under elevated concentrations, while whole system carbon uptake may have been higher under elevated CO\(_2\) (no significant statistics were possible with \( n = 2 \)). These results are consistent with previous findings at the whole-plant or canopy level under CO\(_2\) enrichment. It has often been found that although water loss per unit leaf area can decrease under elevated CO\(_2\), total water use at the plant level may remain unchanged. Several other factors beyond CO\(_2\)
effects on stomatal closure drive evapotranspiration—most importantly the energy budget at the soil-plant interface.

Measurements of water and carbon fluxes were combined to generate whole-system WUE in Table 2, providing a unifying picture of CO₂ effects at the mesocosm level. As illustrated in Fig. 3, the difference in the time-series of WUE data as a function of CO₂ concentration was more easily discernible than for its single component fluxes, showing a sharp increase under elevated CO₂ conditions.

Because of the overall difficulty to sort out differences in observed data by using time-series that span several hours of measurements, we also calculated daily-integrals of the observed whole-system photosynthetic production, evapotranspiration,

Table 2

<table>
<thead>
<tr>
<th>Date</th>
<th>CO₂</th>
<th>Net ecosystem exchange (mol CO₂ d⁻¹)</th>
<th>Transpiration (l d⁻¹)</th>
<th>WUE (mmol CO₂ mol⁻¹ H₂O)</th>
</tr>
</thead>
<tbody>
<tr>
<td>January 8</td>
<td>Low</td>
<td>142.7</td>
<td>828.5</td>
<td>3.10</td>
</tr>
<tr>
<td>January 12</td>
<td>Low</td>
<td>144.1</td>
<td>917.8</td>
<td>2.83</td>
</tr>
<tr>
<td>January 18</td>
<td>Low</td>
<td>139.9</td>
<td>782.1</td>
<td>3.25</td>
</tr>
<tr>
<td>January 26</td>
<td>Low</td>
<td>159.7</td>
<td>812.9</td>
<td>3.54</td>
</tr>
<tr>
<td>December 20</td>
<td>High</td>
<td>202.1</td>
<td>766.8</td>
<td>4.74</td>
</tr>
<tr>
<td>February 14</td>
<td>High</td>
<td>233.1</td>
<td>916.5</td>
<td>4.58</td>
</tr>
<tr>
<td>Mean</td>
<td>Low</td>
<td>146.6 ± 8.9</td>
<td>835.3 ± 58.3</td>
<td>3.18 ± 0.30</td>
</tr>
<tr>
<td>Mean</td>
<td>High</td>
<td>217.6 ± 21.9</td>
<td>841.7 ± 105.6</td>
<td>4.67 ± 0.05</td>
</tr>
</tbody>
</table>
and water-use efficiency. These quantities were computed by selecting the time interval when carbon fluxes into the soil-plant system were positive, usually between 9:00 and 17:00 h. Table 2 lists our results, characterized by an enhancement of total carbon uptake (+48%, from about 150 to more than 230 mol CO$_2$ d$^{-1}$) and no change in total ET (from 835 to 840 l d$^{-1}$) under elevated CO$_2$ with respect to ambient conditions. Once the above calculated daily totals were normalized for total surface area (1413 m$^2$) and length of day (about 9 h), the resulting daily-mean carbon uptake was found to be within the range for typical desert ecosystems, or NEE $\sim$ 3.5 µmol CO$_2$ m$^{-2}$ s$^{-1}$ (Foley et al., 1996). Daily-total ET corresponded to about 0.6 mm d$^{-1}$. Potential ET could not be calculated from the data collected in these experiments.

As a result of the observed changes in water and carbon fluxes, total WUE increased by about 44% from ambient (3.18 mmol CO$_2$/mol H$_2$O) to elevated (4.67 mmol CO$_2$/mol H$_2$O) CO$_2$ conditions. Such an increase is consistent with the current view on climate change effects on ecosystems, characterized by predictions of a more efficient use of water per unit dry matter produced (IPCC, 1995). There are however large uncertainties regarding the magnitude and even the direction of changes in whole-system carbon and water fluxes upon which changes in WUE depend (e.g., Jarvis, 1989; Gifford, 1994; Tubiello et al., 1995). In our experiments overall increases in ecosystem WUE were achieved primarily
due to a marked enhancement of net carbon uptake, with little changes in evapotranspiration.

4. Conclusions

We devised a method for monitoring carbon and water exchange in isolated biomes of Biosphere 2, providing ecosystem-level information which bridges a spatial gap between current growth-chamber and field measuring techniques. Our preliminary data showed that elevated CO₂ increased whole system carbon uptake in the desert biome of Biosphere 2, while evapotranspiration remained constant. Because CO₂ levels varied substantially during the day in each of our experiments, we cannot readily extrapolate our data to a natural setting.

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References

