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Response of Carbon Dioxide Efflux from a 550m^3 Soil Bed to a Range of Soil Temperatures

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Introduction: At the global scale soil respiration is one of the major flux pathways in the global carbon cycle, second only to gross primary productivity (Houghton and Woodwell 1989). Also, within the context of global climate change, an increase in soil temperature would result in an increase in soil respiration. Unfortunately, soil respiration is highly variable. This variability could be attributed to measurement methodologies and the techniques used in studying response of soil respiration to soil warming, and to inherent variability of the soil. Measurements of soil respiration in the field and laboratory are prone to inconsistencies such as changes in soil structure, microbial population, and subtrate material. Further, we encounter tremendous small scale spatial variability which could be a source of error when scaling from smaller to point to larger areas and may not necessarily reflect an overall system response. The objectives of this study were to: (1) determine the relationship between soil respiration and soil temperature using a systems approach. (2) Determine a simple scaling factor for point measurements to the system level. (3) Compare the two approaches, i.e. Point vs. Whole system. (4) Demonstrate the usefulness of large-scale environmentally controlled facilities such as the Biosphere 2 Center for mechanistically understanding the response of soil respiration to environmental conditions.

Materials and Methods:

Site: The study was conducted in the Intensive Forestry Biome at the Biosphere 2 Center located in Arizona, USA. The biome has a total land surface area of 2,000 m^2 and an air volume of 38,000 m^3. It consists of 3 mesocosms designated as east, center, and west bays. Each bay measures approximately 41x18 m with a surface area of 550 m^2 , an air volume of 11,700 m^3 and average height available for plant growth of 14 meters. The soil bed is 1 m deep with 2-3% SOC and a C:N of 9.9. Two hundred and eighty two cuttings of eastern cottonwoods (*Populus deltoides* Bartr) have been grown int he 3 biomes since 1998 as a coppice system. The present study was conducted in February-March 2000 when there were no above ground tree biomass, the tree stumps had a 2-yr root system capable of heterotrophic and autotrophic respiration.

Temperature and Atmospheric CO_2 manipulation and monitoring: The objective of the experiment required operation of the bays in a closed mode in order to obtain near uniform temperature over the entire one-meter depth of the soil profile and to allow for CO_2 buildup in the bay to be able to measure steady state soil CO_2 efflux. Heating of the soil profile was acheived by warming the air circulating in the bays and maintaining air temperature at a fixed level until the soil temperature measured at all depths was near uniform (±3 ^{o}C). The bays were closed to the outside atmosphere with the exception of two hours at dawn and dusk each day. This was done to purge the bays and the concentration of CO_2 to ambient. Each flush was 1.25 air volume exchange. Air within the bay circulated by three large air handlers located in the basement of each bay and four other fans. CO_2 concentration was measured and stored every 15 m. Drip irrigation added approximately 484 liters of water per bay resulting in average soil volumetric water content of 0.31% across bays. No nutrients were added.

Calculations: Whole system CO_2 efflux was calculated as the slope of the linear regression fit to the atmospheric CO_2 data (Figure 2) as a function of time between two consecutive flushes for each bay. Slope was adjusted for bay volume and area, yielding the *whole system respiration rate (R_w)* in mmol CO_2 m^{-2} soil surface area s^{-1} for each day and night period. *Daily whole system respiration (R_{day})* was calculated by multiplying R_w by total amount of time between fluxes and bay soil surface area. R_{day} is the sum for 2 consecutive periods (day and night) expressed as mols

CO_2 $bay^{-1}day^{-1}$. *Point measurements (R_p)* of soil respiration were made at 9 locations (6 dry and 3 wet) using the Li-Cor 6200 IRGA equipped with a Li-Cor 6000-09 soil respiration chamber. Measurements were made about 3 times per week during the study period, spanning different soil temperatures. Simultaneous surface soil temperatures (10 cm depth) were also recorded.

*Modeling soil respiration as a function of temperature:*Dependence of soil respiration rate (R_p and R_w) on temperature was modeled using a modified version of the Arrhenius function (1).

$$R = R_{10} * \exp\left[\left(\frac{b_0 + b_1 * T + b_2 * T^2}{\Re}\right) * \left(\frac{1}{T_{10}} - \frac{1}{T}\right)\right]$$

where, R = soil respiration rate in µmols m^{-2} s^{-1} and is the dependent variable, R_{10} = respiration rate at 10°C (µmols m^{-2} s^{-1}), T = average soil profile temperature (Kelvin) and is the independent variable, b_0, b_1, and b_2 = parameters of the quadratic equation relating activation energy (E_o) and T. $\Re$ = the ideal gas constant (8.314 joules $mole^{-1}$ K^{-1}), T_{10} = the average soil profile temperature (Kelvin) at 10°C. The parameters b_0, b_1, b_2, and R_{10} were estimated.

*Scaling of R_p and R_w to ER_{pday} and Er_{wday}*was accomplished by substituting for temperature in Fn.1 and scaling to the whole bay by the equation $ER_{pday} = R_{pavg} * A * t$, where, ER_{pday} = daily whole system soil respiration estimates (mols $bay^{-1}day^{-1}$) for either the wet or dry location, R_{pavg} = daily average rate of estimated soil respiration (µmol m^{-2} s^{-1}) for either the dry or wet location, A = Total soil surface area (m^2) of the bay. (A is the area for either the wet or dry locations for the entire bay. The surface area of the wet locations were estimated by multiplying the average area one drip nozzle could distribute water by the total number of nozzles in each bay), t = Total time CO_2 efflux occurred (seconds). Total time occurred was 24 hours per day minus the time used for flushing the air out of the bays resulting in approximately 20 hours during which CO_2 efflux occurred.

Results:

CO_2 concentration in each bay increased linearly by an average of 150 µmol CO_2 mol^{-1} in a 10 h period between two consecutive flushes as a result of increasing soil temperature in a closed environment. Increasing soil temperature resulted in an increase in soil respiration in all three bays (Figure 4). Graphical representations of the observed and predicted whole system soil respiration rates (R_w) indicate a good fit of function 1 (Figure 4 a-c)). Point (R_p) and whole system (R_w) soil respiration rates were scaled to provide daily total soil respiration for each bay (ER_{pday}, ER_{wday}) and compared against daily whole system values (R_{day}). When compared to R_{day}, ER_{pday} overestimated the daily totals by approximately 60% in the East and West bays but underestimated the Center bay by 13% (Figure 4). ER_{wday} obtained by scaling R_w overestimated R_{day} in the East and Center by approximately 8% and underestimated the same in the West bay by 1.2%. On an average across all bays ER_{pday} estimations overestimated R_{day} by 36% and ER_{wday} by 5%.

Discussion:

By operating this facility in a 'closed' mode we were able to arrive at good estimates of daily total system soil CO_2 efflux (R_{day}). The magnitude of the difference between point measurement derived estimates and bay estimates underlines a problem that is faced in a number of physiological measurements. Most of the current physiological measurements are taken on individual leaves, sections of soil in the ground or laboratory, or individual organs of a plant. There not only occurs tremendous variability among the various measurements but the response could potentially vary depending on whether the perturbation is on the entire system or on an isolated organ or component (Griffin et al. 2001). In addition, scaling from point measurements introduces and magnifies the error observed at the point locations. This could pose serious problems when such parameters are used in models for large-scale predictions. Scaling of point measurements in this study was rather simplistic and overestimated the system CO_2 efflux by 36%, which translates to an additional 15 kg of carbon from a 550 m^3 volume of soil over a 41

day period. Several factors such as uneven watering and root distribution, simplified scaling of total surface area of wet and dry locations, and uneven organic matter and nutrient distribution could be responsible for the observed variability and possible overestimation of point measurements. However, these are uncertainties that are usually observed under field conditions and that associated with point measurements making scaling difficult. Even if we were to assign an overestimation of 18% (half of what we observed), the final outcome in terms of total C over a period of one year would be 62 kg. This is a crude estimate but strongly indicates that model development based on extrapolated point measurements could have misleading conclusions and larger ramifications when trying to estimate local to global carbon cycle dynamics. Therefore, at the present time given the results from various studies conducted on a short-term scale or at point locations, we cannot confidently extrapolate knowledge to larger scales.

The Biosphere 2 Center offers some unique features and several advantages that allowed us to conduct this experiment at a whole system level. Soil warming experiments have been conducted using electrical heat-resistance ground cables (Peterjohn et al. 1993, 1994), passive heating greenhouses (Kennedy 1995), field chambers (Tingey et al. 1996), overhead infrared lamps (Bridgham et al. 1999), suspended electric heaters (Harte et al. 1995), and large screens (Luxmoore et al. 1998). With some exception most of these methods are restrictive in terms of the total soil surface area, volume, and depth over which temperature can be manipulated. Most methods are able to heat only the upper layer of the soil profile, for example 10 cm (Peterjohn et al. 1993), and generally can only manipulate soil temperature to within $\pm 5^{o}C$ of ambient. In the present study, soil warming was achieved by actively warming the air mass, similar to the expected mechanism under global warming scenarios, with very good results. Despite the large soil volume and surface area we were able to successfully warm the entire soil mass over a range of approximately 20 ^{o}C, and maintain this increase in temperature over a one-meter depth of soil. Techniques used for measuring soil CO_2 efflux range from static chamber methods with soda lime (Edwards 1982), to open or closed flow through chamber methods utilizing gas chromatography (Billings et al. 1998) or infrared gas analysis (Howard and Howard 1993). Other methods have used calculations based on soil air CO_2 concentrations and diffusivity constants (De Jong and Schappert 1972), to micrometeorological techniques based on eddy covariance and concentration gradients (Valentini et al. 2000), to isotope techniques (Trumbore et al. 1995, Townsend et al. 1997). However, with the exception of eddy covariance all other methods are invasive and would cause some disruption of the soil material. In the present system all sampling can be done in a non-invasive method with the least amount of disturbance to the soil structure. More importantly, measurements could be achieved for the whole system rather than for sections of soil, thereby not limiting our scope of inference.

Small-scale warming facilities with short vegetation or only litter may be constructed for specific investigation; however, our objective was to demonstrate the utility of this facility in research at the stand scale. Assessment of ecosystem responses to global change requires that much more information be gained at the ecosystem scale. This present system has several advantages over other systems for ecosystem research. It is more suitable to address mass balance issues as it can be operated as a closed system and CO_2 fluxes can be measured on the whole system. Also, we have greater control of environmental parameters over a large system that allows us to study the response of a whole system to small perturbations. Hence, we conclude that this facility should prove very useful in the study of model whole systems under changing environments.

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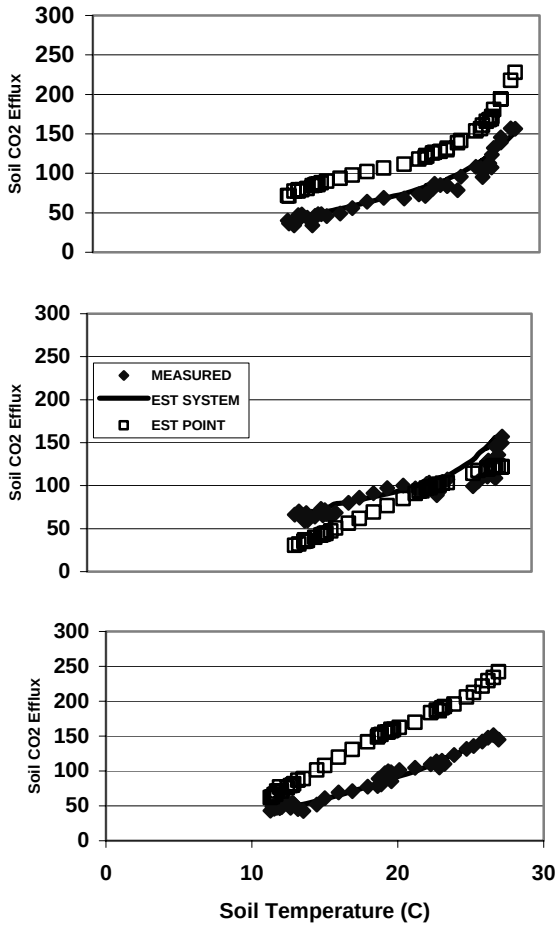

Figure 1: Measured and predicted soil CO2 efflux rates. Open symbols indicate rates predicted using point measurements, closed symbols indicate the actual measured value and the solid line indicates the rates predicted using whole system measurements.