Simultaneous Carbon Dioxide and Oxygen Measurements to Improve Soil Efflux Estimates

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Summary

Fossil fuel emissions are a major source of the atmospheric CO_2, the concentration of which continues to rise annually. Global climate models predict significant air temperature increases during the following decades, caused by greenhouse gases such as CO_2. Although most North American terrestrial ecosystems are estimated to be a major sink of carbon (one to two Pg carbon per year, see Pacala et al. 2001), agricultural soils are significant sources of CO_2 efflux back into the atmosphere. Therefore accurate estimation of the soil CO_2 efflux is an important component in the role of understanding carbon sequestration in terrestrial ecosystems.

This project addresses both theoretical and experimental analysis of the simultaneous transport of O_2 and CO_2 in the soil. The soil efflux estimation uses oxygen concentration measurements, simultaneously with CO_2 measurements. The results show that there are significant concentration gradients from the soil depth toward the surface with upward flux of CO_2 and downward O_2 flux.

The project, although officially funded at the beginning of the year, did not begin until the summer when oxygen and carbon dioxide instruments arrived. There were also multiple instrument problems that postponed field work such as one of the oxygen sensor failed during the research period and the CO_2 analyzer were sent back for factory recalibration. In addition, the graduate students involved with this project shared their duties between this and other projects.

Possible outcomes of our research would be improved quantitative theories and practical methods on the soil carbon dioxide efflux estimation. The end result of the simultaneous O_2 and CO_2 measurements would be an improved methodology to determine carbon efflux from soils without having to assume soil transfer coefficients. In addition, the determination of the soil respiration quotient (RQ) may yield ecological information on soil nutrient status and root, versus microbial activities.

Objectives

1. To develop a theoretical basis for the dual-gas gradient method.
2. To carry out experiments to implement the theory from objective (1).
3. To determine and quantify the significance of barometric pressure pumping of soil CO_2 on the theory and experiments described in objectives (1) and (2).

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Approach and Procedures

The field study was conducted at the LAWR Campbell Field tract, located at 38º N and 122º W, off Hutchison road at the University of California, Davis. The tract is approximately 550 m by 550 m in dimension. The climate is Mediterranean with hot and dry summers, and cold and wet winters. The mean height of the vegetation is about 3 cm, with root zone reaching 15-cm in depth. The soil is Yolo loam with 31% sand, 52% silt, and 17% clay.

Six Tygon tubes were buried in the soil (5 cm, 15 cm, 25 cm, 43 cm, 69 cm, and 88 cm in depth) and used to connect the sample ports to the sensors that were all at the same location in an instrument enclosure. Air temperature and soil temperatures were measured with thermocouples (Type K, Chromel-Alumel). Volumetric soil moisture content was measured with the time domain reflectometer sensors (Decagon ECH2O probe model EC-20). The oxygen concentrations were measured with three different oxygen sensors: Figaro KE-25 (sensor 1), Apogee Model O2S (sensor 2), and Qubit System flow through O_2 Sensor (sensor 3). Carbon dioxide concentrations were measured with a Licor 6251 infrared gas analyzer (IRGA). The air was sampled from different depths with the tubes, and fed through a small gas-settling chamber and then into the oxygen and Licor sensors for measurements. The air was drawn using a slow air pump at a rate of 200cm^3/min. The slow pumping rate avoided air deficits in the soil due to negative pressure from pumping. The air was then fed into the oxygen and carbon dioxide sensors for measurements before exiting through the air pump. Three oxygen sensors were employed here for cross comparison; however, one of the oxygen sensors failed during the research period. Moisture sensors also were installed to measure the soil moisture content at five different depths (0-20 cm, 20-40 cm, 40-60 cm, 50-70 cm, and 70-90 cm). Data from all sensors were collected and logged on a CR-23x data logger (Campbell Scientific Inc., Utah, USA). A schematic of the sensor setup is shown in figure 1.

Manual measurements of the sensors were made periodically. The experimental data were examined for the simultaneous transport of O_2 and CO_2 at the surface and at depth, and further data collection and statistical analysis were taken, such as daily, monthly, and annual transport of the two gases and their correlations to soil properties.

Since the current system setup required manual switch of air input from different soil depth, measurements were made only during the daytime.

Measurements were made for the period between January 3, 2007, and January 25, 2007. There was no precipitation during this period of time, and the soil surface was dry with minimal vegetation.

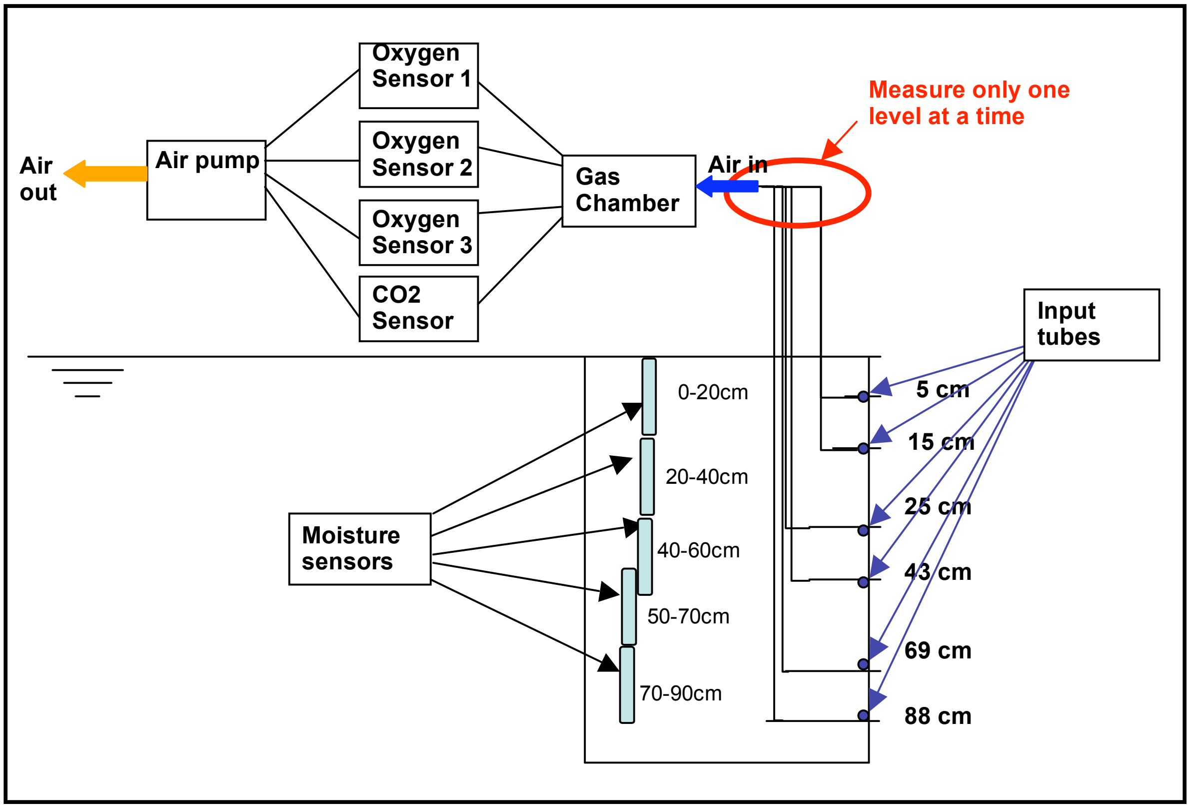

Figure 1. Schematic diagram of the sensors setup.

Results

Oxygen data was measured by all three different oxygen sensors (results from only Oxygen Sensor #1 and #3 are shown here because Oxygen Sensor #2 failed during the research period) and showed similar profile patterns. Figure 2 shows the two soil profiles in terms of oxygen concentration and soil depth.

Oxygen concentrations decrease immediately below the soil surface (from 20.947% at the surface to 20.927% at 5cm depth for Oxygen Sensor #1, and from 20.95% to 20.91% for Oxygen Sensor #3), which resulted because of oxygen consumption by plant roots and soil microbes. Moreover, these values also indicate the present of a concentration gradient from the surface layer toward the lower soil layer with downward flux of O_2. Oxygen Sensor #1, (a), shows that there is a small increase in oxygen concentration just below the root zone. The Oxygen Sensor #3, (b), also shows a small oxygen increase, but a few centimeters later. Interestingly, both oxygen profiles show second concentration peaks (20.9326% O_2 for Oxygen Sensor #1, and 20.93% O_2 for Oxygen Sensor #3 at around 43 cm below the sol surface. The oxygen concentration gradient between the 15-cm layer and the 43-cm layer indicates there is an upward flow of oxygen toward the root zone from below. The largest depletion of oxygen occurred at 69 cm soil depth (20.683% O_2 for Oxygen Sensor #1 and 20.58% O_2 for Oxygen Sensor #3). This large depletion of oxygen concentration may be related to the volumetric water content shown in figure 3.

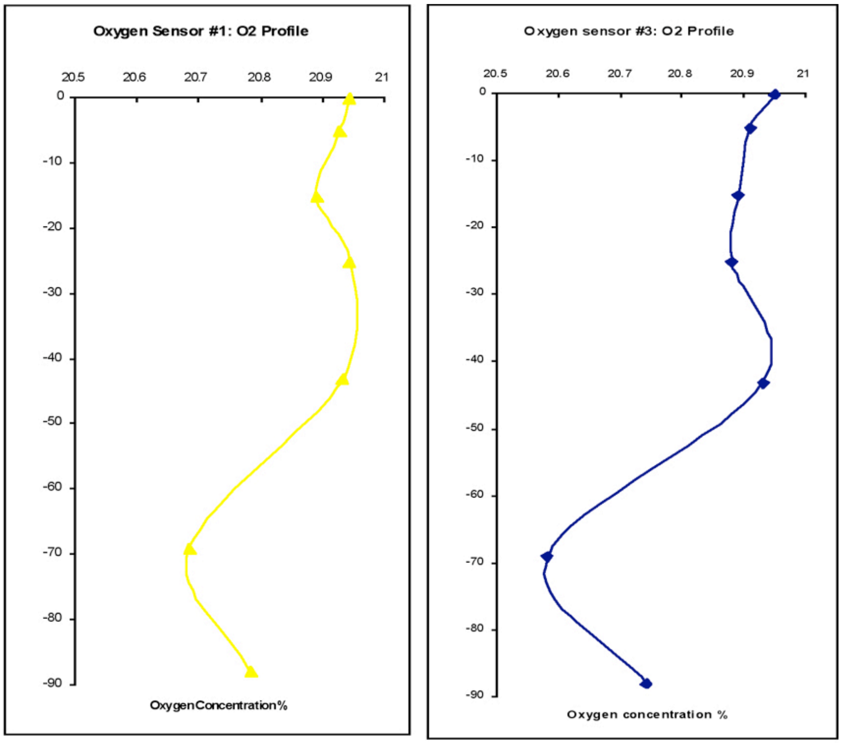

Figure 2. The two oxygen profiles from Oxygen Sensor #1 (a), and Oxygen Sensor #3 (b) for the period between January 3, 2007, and January 25, 2007. Each point represents a composed average of the 23-day period for one soil depth during the daytime.

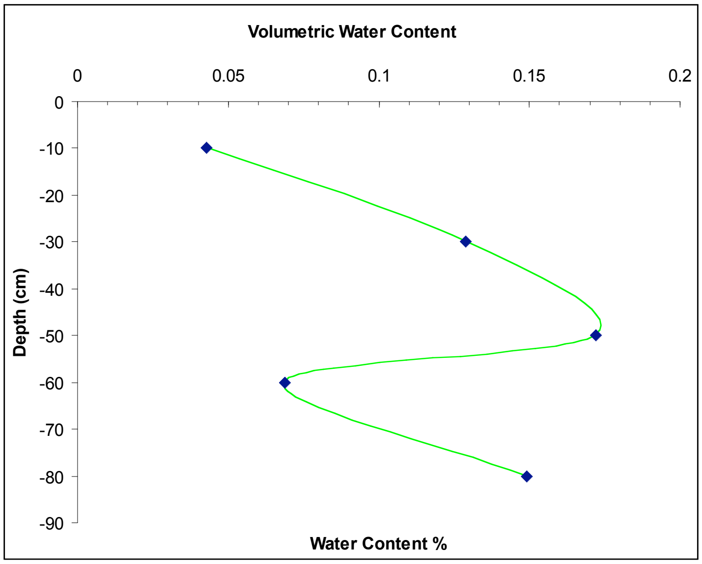

Figure 3. Average daytime volumetric water content at the LAWR Campbell Field tract, University of California, Davis, for the period between January, 3, 2007, and January, 25, 2007. Each point represents average volumetric water content at 0-20cm, 20-40cm, 40-60cm, 50-70cm, or 70-90cm at soil depth.

The volumetric water contents taken from 0-20 cm, 20-40 cm, 40-60 cm, 50-70 cm, and 70-90 cm at soil depth show a similar pattern at the shallow soil depth (from around 40-cm depth to 9-cm depth) as the oxygen concentration profiles. The low soil volumetric water content at 60-70 cm layer and the largest depletion of oxygen concentration may be a result of compacted soil layer. Ouyang and Boersma (1992) showed that compacted soil layers induce depletion of O_2 concentration.

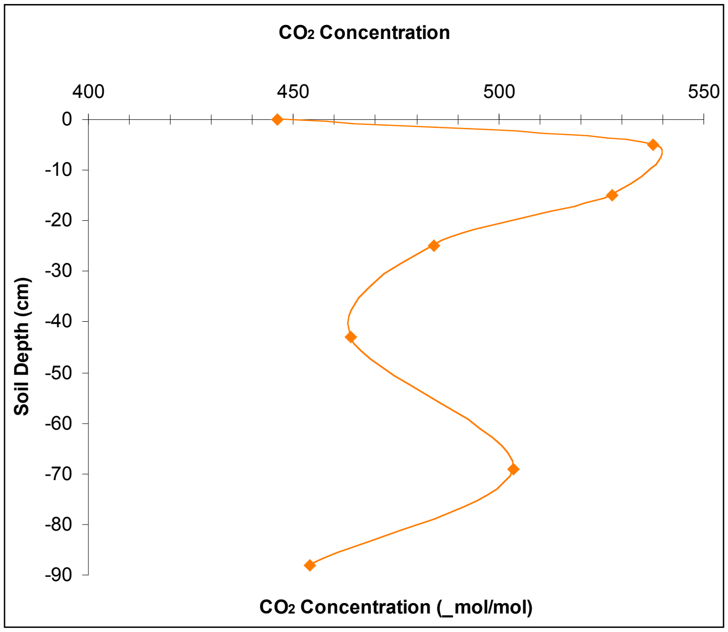

Figure 4. CO_2 concentration measured by Licor 6251 at the Campbell Tract for the period between January 3, 2007, and January 25, 2007. Each point is a composed average for the 23-day period for one soil depth.

Table 1. *CO_2 concentrations at different soil depths taken from Turcu, et al. (2005) and the Campbell Tract Data.*

Campbell Track		Turcu, et al. (2005)	
Depth (cm)	CO2 (μmol mol^{-1})	Depth (cm)	CO2(μmol mol^{-1})
0	446.1838	0	400
-5	537.6345	-9	1544
-15	527.819	-24.5	3200
-25	484.1466	30	3905
-43	463.9077		
-69	503.653		
-88	453.9339		

Simultaneous measurements of CO_2 were made at the same location as O_2. Figure 4 and table 1 show CO_2 concentrations at six soil depths. The CO_2 concentration increases from 446 μmol mol^{-1} at the surface layer to 537 μmol mol^{-1} at the 5 cm layer. The CO_2 concentration remains high at the root zone from 0 cm to 15 cm before it decreases again. Table 1 compares the CO_2 concentrations from Turcu et al. (2005), and the data collected in the Campbell Field tract. The CO_2 concentrations collected from the Campbell site are noticeably smaller than the results reported in Turcu et al. (2005). Also unlike the result in Turcu, et al. (2005), the CO_2 profile from the Campbell Field tract shows both positive and negative gradients within the soil column. These differences may be due to the discrepancy in soil use. The soil used in Turcu et al. (2005) is an air-dried and uniformly packed Millville silt loam column in the laboratory with negligible microbial CO_2 production, whereas the soil tested in this project is a Yolo loam in its natural environment with minimal disturbance and considerable microbial activities.

The oxygen and CO_2 concentrations in terms of soil depth at 0 cm, 5 cm, 15 cm, 25 cm, 43 cm, 69 cm, and 88 cm are shown in figure 5. Aspects of the nature of the bioactivities play important roles in CO_2 and O_2 concentration in the soil. Oxygen level decreases at the root zone from 0 cm to 15 cm, whereas the CO_2 is produced in the same layer. Figure 5 shows that the changes in oxygen and CO_2 concentrations occurred concurrently and oppositely. The depletion of O_2 is due to respiration by roots and microorganisms and the simultaneous increase of CO_2 concentration. On the same graph, the increase of O_2 concentration at 69-cm level is correlated with a decrease CO_2 concentration at the same location. This relationship between O_2 and CO_2 concentration will be explored further for the development of theoretical equations to estimate soil CO_2 efflux by dual gas (O_2 and CO_2) gradients and measurements.

Soil temperature also contributes greatly to root respiration and microorganism activity, hence, it is important to include soil temperature when estimating O_2 and CO_2 concentration in the soil. The soil temperature profile during the day is shown in figure 6 from the same soil depths as the O_2 and CO_2 measurements. The soil temperature pattern shows that higher soil temperature at the soil surface and the top soil layer induces the microorganism activities to consume oxygen and produce CO_2.

The soil efflux of CO_2 can be calculated by Fick's fist law of diffusion:

$$F(CO_2) = -D\frac{d[CO_2]}{dz}, \qquad (1)$$

Where $F(CO_2)$ is the CO_2 flux in μmol mol^{-2} s^{-1}, D is the diffusion coefficient or diffusivity (m^2 s^{-1}), $[CO_2]$ is the CO_2 concentration in μmol mol^{-3}, z is the depth in m. In this case, the diffusion coefficient, D, will be substituted by Ds for diffusion coefficient in the soil. The value of Ds can be estimated by (J. Tang et al. 2003)

$$Ds = \xi(D_{air}), \qquad (2)$$

where ξ is the gas tortuosity factor, which is a function of volumetric air content and the soil porosity. D_{air} is the CO2 diffusion coefficient in the free air, and it can be estimated by (Campbell 1985).

The soil efflux of CO_2 calculated by on these equations and assumption is 49.97635 μmol mol^{-2} s^{-1}. This shows that there is a considerable amount of CO2 emitted from the soil into the atmosphere.

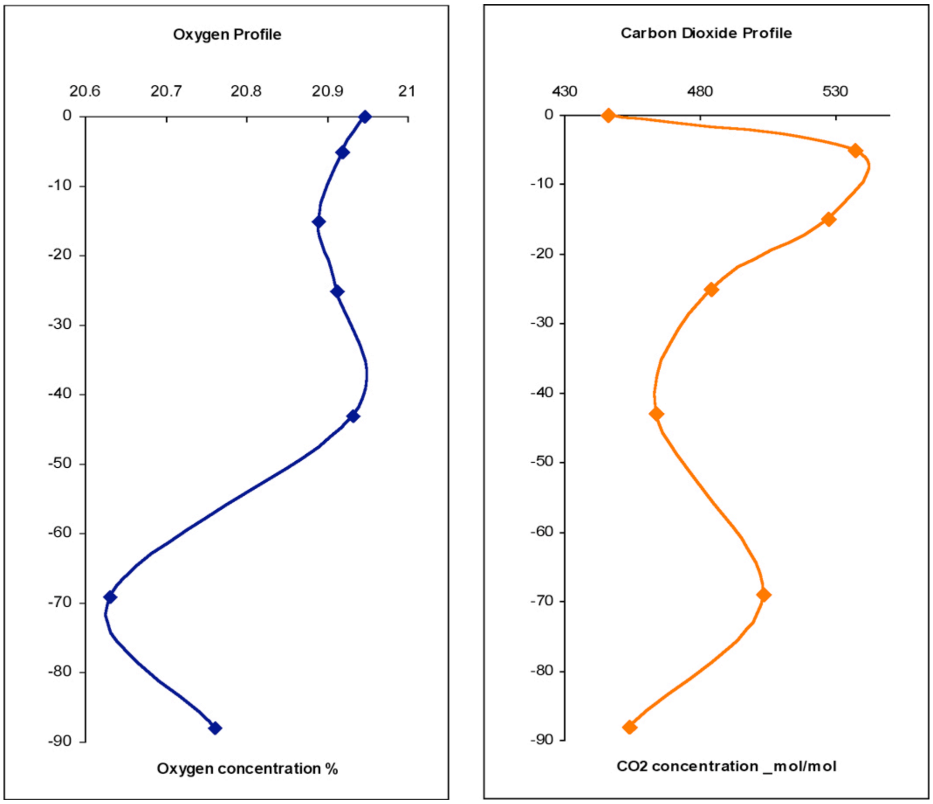

Figure 5. O_2 average profile from Oxygen Sensor #1 and #3 is compared with the CO_2 profile for the period between January 3, 2007, and January 25, 2007. The CO_2 and O_2 concentrations were measured simultaneously at the same location.

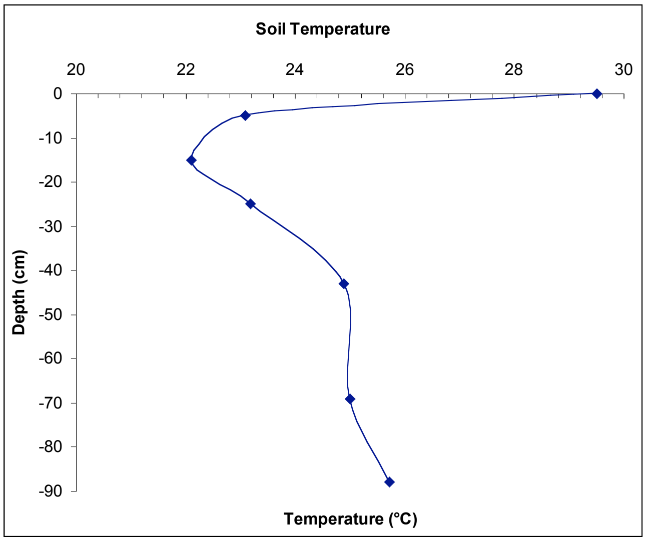

Figure 6. Average soil temperatures for the period between January 3, 2007, and January 25, 2007.

Discussion

Preliminary data show that there is a coherent relationship between the O_2 and CO_2 concentration in the soil layers. Moreover, the soil temperature and volumetric water content also influence the O_2 and CO_2 depletion and production. The majority of root respiration and microorganism activities are located within the root zone (0 cm to 15 cm), hence the changes in O_2 and CO_2 concentration are most significant. Within this layer, CO_2 concentration increases from 446 μmol mol^{-1} at the surface to 527 μmol mol^{-1} at 15 cm, whereas the O_2 concentration decreases from 20.943% to 20.887% for Oxygen Sensor #1 and 20.95% to 20.89% for Oxygen Sensor #3.

These findings are consistent with the hypothesis that simultaneous measurement of O_2 and CO_2 can be used to estimate soil efflux.

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