

**Sensing Technology for the Soil Environment**  
**CENS 2007 Summer Course**  
**9-12 July, 2007, James Reserve, Riverside, CA**

**Course Outline**

Mornings: lectures and labs  
 Afternoons: Field measurements and emplacements  
 Evenings: Data Analysis

**Monday July 9: travel day, begin 6:00 pm**

Welcome: Michael Hamilton  
 Overview: Deborah Estrin

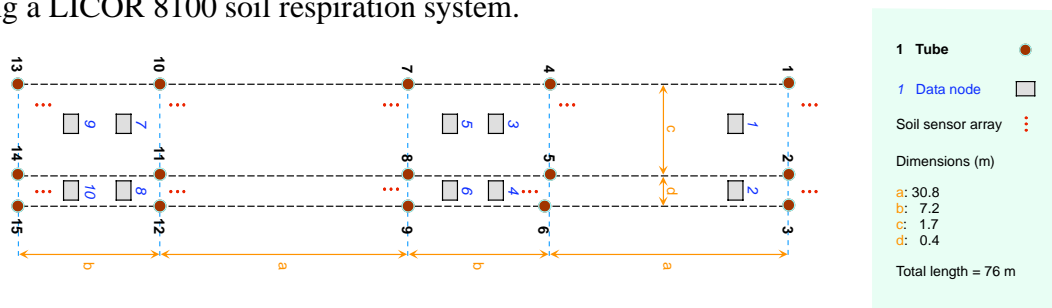
**Tuesday July 10: Soil Sensing**

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Lecture: Soil organisms and their environment

**Experimental Transect and Sensors**

The AMARSS project installed 10 weather stations (nodes) in an 80 x 10 mts transect under the NIMS RD project. Each node consists of an array of below and above ground sensors. The below ground sensors are: 1 minirhizotron tube (to study root and mycorrhizae growth and turnover), three solid state CO<sub>2</sub> sensors (Vaisala Carbocap GMP220) installed at 2, 8, and 16 cm depth, coupled with soil temperature sensors and three soil moisture sensors (ECHO). Each Vaisala CO<sub>2</sub> sensor required 100 mA and 12V to work. We installed 30 of these sensors at the site (3 x node x 10 nodes) that are continuously working since November 2005. The above ground sensors consist of air temperature, relative humidity and photosynthetic active radiation (PAR). The CO<sub>2</sub> solid-state sensors measure concentration of CO<sub>2</sub> in the soil profile and we applied gas diffusivity theory to model soil respiration as  $\mu\text{mol}/\text{CO}_2/\text{m}^2/\text{s}$ . In addition, we validate the modeled soil respiration with manual and automatic measurements of soil respiration using a LICOR 8100 soil respiration system.



**Figure 1-** Diagram of AMARSS transect at the James Reserve.

**Microbial Composition and changes**

Soil microorganisms have key functions in decomposition and nutrient cycling, and basically reflect factors that regulate nutrient cycling. Their analyses have become crucial parameters in monitoring carbon and nutrient dynamics.

Fungi play dominant role in soil processes of recycling nutrients from above and below ground and interactions with all other soil-inhabiting organisms. Saprotrophic fungi colonize dead substrate, while necrotrophic and mutualistic fungal species colonize living tissues by means of highly specialized infection structure. The fungi form mutualistic associations with the roots of vascular and nonvascular plants, called mycorrhizae. Mycorrhizal fungi provide plants with nutrients and protection from drought and root pathogens. Most mycorrhizal plants provide their associated fungi with photosynthetically derived carbon.

A wide range of methods has been used to assess the amount (biomass), activity and diversity of soil fungi. In the past, detection and identification of fungi relied on classification of the fungi's fruiting bodies or on cultivation-based methods to distinguish hyphal growth, infection structures and resting spores. Since many fungi do not produce fruit bodies, are refractory to cultivation or do not form observable sexual structures, these identification methods have limited the numbers of species currently recognized. The development of molecular techniques provides new possibilities for fungal and bacterial species identification and community characterization.

**Using Minirhizotrons and AMR.**

Images are taken at time intervals dictated by the project of interest. For the conventional minirhizotron (e.g., Bartz unit), images are taken by hand, and either digitized or counted, according to the objectives. The traditional use focuses on a 1cm<sup>2</sup> unit of the tube but magnification can be increased as needed. Bartz has a resolution to about 10µm.

The Automated Minirhizotron (AMR) that we have designed has a resolution predetermined by the magnification of the lens chosen. For the test unit, we are using a 100x USB-port microscope. The machining allows for moving the camera to a preset location or in a scanning mode for imaging the entire tube.

**Soil Environmental Instrumentation**

Associated each automated minirhizotron tube will be a suite of environmental probes (soil moisture Echo dielectric probe, soil temperature, and CO<sub>2</sub> Vaisala Carbocap GMP220) placed at four depths (0, 2, 8 and 16 cm). This array of sensors constitutes a “node” for our network array.

Sensors for each node:

- Vaisala Carbocap CO<sub>2</sub> probes 3
- Vaisala Carbocap transmitter 3
- Soil moisture ECHO probe 3
- Soil temperature probe 12 bit 3
- PAR sensor 1
- Air temperature/RH 1

Equipment needed for each node:

- 12-bit 4-20 mA Input Adapter 3  
For recording CO<sub>2</sub> values in data logger
- HOBO Weather station model H21-001 1  
Capacity up to 15 channels for sensors

- Solar radiation shield (for RH/temp sensor) 1
- PAR sensor bracket 1

Hardware for each node:

- Mounting pole for data logger and sensors
- Weather proof box for CO<sub>2</sub> transmitters (Pelican box?)
- PVC pipes for CO<sub>2</sub> probes
- Gore-Tex fabric to protect CO<sub>2</sub> probes
- Cables for electrical connections

Surface soil respiration: LiCor 8100 soil respiration measurement system.

Bartz System Minirhizotron

Automated Minirhizotron (AMR)

### *Modeling CO<sub>2</sub> flux*

We use a CO<sub>2</sub> gradient flux method to model CO<sub>2</sub> flux from the soil at the James Reserve. The gradient method using soil-state CO<sub>2</sub> sensors has been used in previous studies to understand vertical partitioning of the sources of CO<sub>2</sub> in the soil profile.

Measurements of CO<sub>2</sub> concentration from the sensors are corrected for temperature and pressure according to the manufacturer (Vaisala) and these corrected values are used to calculate CO<sub>2</sub> flux. According to Fick's first law of diffusion CO<sub>2</sub> diffused from the soil can be expressed as a differential equation:

$$F = -D_s \frac{\partial C}{\partial z} \quad (1)$$

where  $F$  is the CO<sub>2</sub> flux ( $\mu\text{mol m}^{-3} \text{s}^{-1}$ ),  $D_s$  the gaseous CO<sub>2</sub> diffusion coefficient in the soil ( $\text{m}^2 \text{s}^{-2}$ ),  $C$  is the mole CO<sub>2</sub> concentration ( $\mu\text{mol m}^{-3}$ ) at a  $z$  depth, and  $z$  is the depth (m).  $D_s$  can be estimated as:

$$D_s = D_a \varepsilon \tau \quad (2)$$

where  $D_a$  is the CO<sub>2</sub> molecular diffusivity of CO<sub>2</sub> in the air,  $\varepsilon$  is the soil air-filled porosity and  $\tau$  is the tortuosity. The product of  $\varepsilon \tau$  has been defined as the tortuosity factor  $\xi$ .

Then:

$$D_s = D_a \xi \quad (3)$$

The effect of temperature and pressure on  $D_a$  is given by:

$$D_a = D_{a_0} \left( \frac{T}{T_0} \right)^{1.75} \left( \frac{P_0}{P} \right) \quad (4)$$

where  $D_{a_0}$  is a reference value of  $D_a$  ( $1.47 \times 10^{-5} \text{ m}^2 \text{ s}^{-1}$ ) at  $T_0$  (293.15 K) and  $P_0$  ( $1.013 \times 10^5 \text{ Pa}$ ) according to Jones (1992).

The ratio of diffusivity in the soil ( $D_s$ ) to diffusivity in the air ( $D_a$ ) or tortuosity factor, may be calculated using several general models. We calculated  $\xi$  using the Moldrup model, which is based on diffusion through porous media:

$$\frac{D_s}{D_a} = \xi = \phi^2 \left( \frac{\varepsilon}{\phi} \right)^{\beta S} \quad (5)$$

where  $\beta$  is a constant ( $\beta = 2.9$ ),  $S$  = silt + sand content ( $S = 85$ ), and  $\phi$  is the porosity defined as:

$$\phi = 1 - \frac{\rho_b}{\rho_m} = \varepsilon + \theta \quad (6)$$

where  $\rho_b$  is the bulk density,  $\rho_m$  the particle density with a typical value of  $2.65 \text{ g cm}^{-3}$ , and  $\theta$  volumetric water content. At our study site,  $\phi$  was a constant value of 0.77.

At a certain depth interval ( $z_i$  and  $z_{i+1}$ ) we can calculate the  $\text{CO}_2$  efflux if we know the  $\text{CO}_2$  concentrations ( $C_i$  and  $C_{i+1}$ ) assuming a steady state in  $\text{CO}_2$  diffusivity according to equation (1). We calculated  $\text{CO}_2$  fluxes between depths 0.02-0.08 m and 0.08-0.16 m based on the concentrations measured in the soil profile. For the  $\text{CO}_2$  flux at the surface ( $F_o$ ) we extrapolated linearly assuming  $\text{CO}_2$  production constant (steady state) in the soil profile (see Tang *et al.*, 2005b):

$$F_z = pz + F_o \quad (7)$$

where  $F_z$  is the  $\text{CO}_2$  flux ( $\mu\text{mol m}^{-2} \text{ s}^{-1}$ ) at any depth  $z$  (m) where  $z$  is  $-0.16 \text{ m} \leq z \leq 0 \text{ m}$ ,  $p$  is the slope representing  $\text{CO}_2$  production in the soil profile, and  $F_o$  the  $\text{CO}_2$  flux ( $\mu\text{mol m}^{-2} \text{ s}^{-1}$ ) at the surface when  $z = 0$ .

### Key Papers:

Moldrup P, Olesen T, Komatsu T, Yoshikawa S, Schjonning P, Rolston DE. 2003. Modeling diffusion and reaction in soils: X. A unifying model for solute and gas diffusivity in unsaturated soil. *Soil Science* 168: 321-337

Tang, J., DD Baldocchi, Y. Qi, and L. Xu. 2003. Assessing soil  $\text{CO}_2$  efflux using continuous measurement of the  $\text{CO}_2$  profiles in soils with small solid-state sensors. *Agricultural and Forest Meteorology* 118: 207-220.

Tang J., L. Misson, A. Gershenson, W. Cheng and A.H. Goldstein. 2005. Continuous measurements of soil respiration with and without roots in a ponderosa pine plantation in the Sierra Nevada Mountains. *Agric.For. Meteorol.* 132, 212-227

### Wednesday July 11: Soil Energy Balance and the Abiotic Environment

Eric Graham –

Lecture: Surface energy balance theory

### Experimental Transect and Sensors

A short experimental transect has been established on the AMARSS soil transect to study methods of soil surface energy balance measurements and below-ground temperature and moisture modeling. Combined with below-ground information on  $\text{CO}_2$  fluxes and root and fungal activity, we are setting the stage for the development of new models.

## **Instrumentation**

### *Aboveground Mobile Sensors*

- Kipp & Zonen all-wave precision radiometer for four-component solar and terrestrial radiation.
- Licor silicon pyranometer.
- Licor PAR sensor.
- Everest infrared thermometer for soil surface temperature.
- Air temperature and relative humidity sensor in a ventilated radiation shield.

### *Static Sensors*

- Fritschen-type Q7.1 net radiometers for total net radiation.
- Thermocouples for air, soil surface, and sub-surface temperatures.
- Cup anemometer for wind speed at 2 m height.
- Soil surface GaAsP photodiodes for shortwave radiation.
- Hukseflux soil heat flux plates.

## **The Simple Model**

The simplified soil-surface energy balance is the sum of the components of energy flux (in  $\text{W m}^{-2}$ ), which should be zero:

$$\text{Net radiation (R}_n\text{)} - \text{soil heat flux (G)} - \text{sensible heat flux (H)} - \text{latent heat flux (LE)} = 0$$

$R_n$  is the solar shortwave radiation plus the above-ground terrestrial longwave radiation minus the reflected shortwave radiation minus the emitted longwave radiation from the soil surface. There are various ways of measuring and modeling this. We will be measuring this directly with the total net radiometer and also by measuring the component radiation with the Kipp and Zonen net radiometer. Additionally, we will use some inexpensive photodiodes to measure solar shortwave radiation, both incoming and reflected, and model incoming long wave radiation. Outgoing longwave radiation is a function of soil surface temperature, which will also be measured with surface thermocouples and an infrared thermometer.

G is the energy flux passing conductively into the soil profile and will be measured with buried soil heat flux plates. We will also be using thermocouples at different depths in the soil and use soil properties to calculate the heat flux.

H is the energy flux transferred convectively between the soil surface and the layer of air over the soil and will be calculated using the wind speed and the air and soil surface temperatures. It can also be calculated using two thermocouples in the air at different heights above the soil surface, part of the Bowen ratio method. It will also be calculated using experimental cylinders of dry and wet soil at the site.

LE is the flux of energy associated with evaporation from the soil surface. Evaporation can be calculated if all other components are known, measured, or calculated. It is the relationship between latent heat and evaporation that links energy balance measurements and the water balance of the soil.

### **Key papers**

Qui G.Y., Yano, T., and Momii, K. 1998. An improved methodology to measure evaporation from bare soil based on comparison of surface temperature with a dry soil surface. *Journal of Hydrology* 210:93-105.

Harp, D.R., Stormont, J.C., Reda Taha, M.M., Farfan, E., and Coonrod, J. 2005. UNM simplified energy balance experiment: [http://www.istec.org/~bosque/fuzzy\\_report.pdf](http://www.istec.org/~bosque/fuzzy_report.pdf)

### **Thursday July 12: Putting the pieces together**

The goal for the last morning is to take final readings for instruments installed, and to link data from all scales. The goal is to begin to develop an ecosystem view, rather than a belowground- or above-ground ecosystem view. The types of questions that we can address include:

How does nighttime respiration relate to 24h respiration estimates?

How does photosynthesis relate to respiration?

How does respiration relate to observation of roots and soil organisms?