Process Based CO_2 Modeling in a Desert Ecosystem

IGERT Internship Report by J. M. Zobitz[1], under direction of D. R. Bowling[2]
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Statement of Problem

What causes belowground carbon dioxide concentrations to fluctuate in a desert grassland? This research project was an attempt to model and answer such a question. CO_2 sensors were placed belowground at 5 and 15 cm at three different locations–below two of the dominant plant species, *Stipa hymeniodes* and *Hilaria jamesii*, and in the interspace between them. Such sensors record the CO_2 levels every 20 minutes. Output from the sensors indicates a strong diurnal variation along with a marked increase in concentrations during rain events (see Figure 1). The model results indicate that CO_2 concentrations increase due to physical and chemical processes and *not* biological processes.

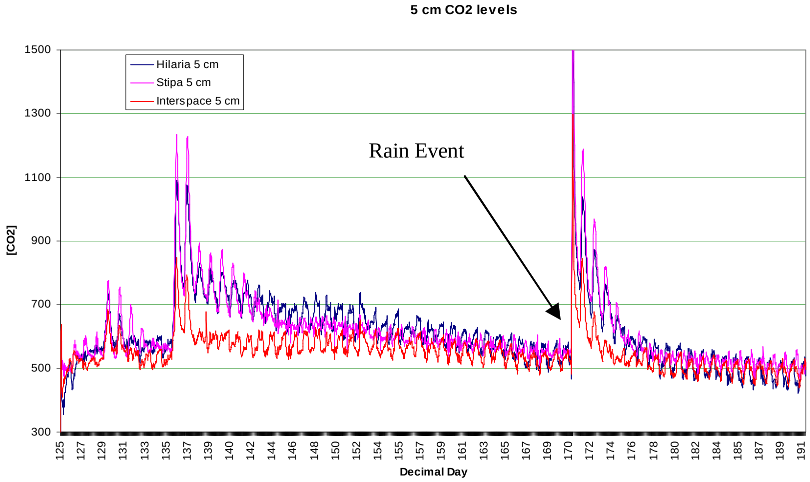

Figure 1: CO_2 concentration

Model Formulation

We can model the movement of carbon dioxide with a diffusion model with a production term and appropriate boundary conditions:

$$\frac{\partial c}{\partial t} = D_s \frac{\partial^2 c}{\partial z^2} + S(z,t) \qquad \begin{array}{ll} z = 0 & c = c_{atm} \\ z = L & \frac{\partial c}{\partial z} = 0 \\ t = 0 & c = c_0(z) \end{array} \quad ,$$

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[1] Department of Mathematics, University of Utah, Salt Lake City, UT.

[2] Department of Biology, University of Utah, Salt Lake City, UT

thus *S(z,t)* is the production term, D_s is the diffusion coefficient in the soil, and c is the concentration of CO_2. This is a one dimensional model with the variable z being the vertical distance.

Inputs to D_s

Figure 2 shows the inputs into the diffusion coefficient:

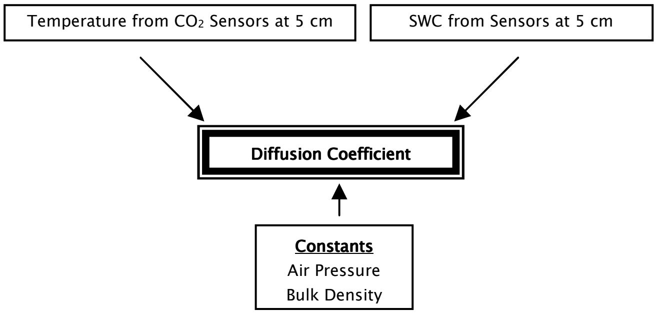

Figure 2: Diffusion Coefficient Inputs

SWC represents the volumetric soil water content, and it is measured at a different spatial locations every 20 minutes than the sensors that measure CO_2. We recognize this as a source of error as deserts are extremely patchy environments and different locations experience different conditions. Using the formulation of Tang, et al:

$$D_s = \xi \cdot D_a$$
$$\xi = {(\phi - \theta_v)^{10/3}} \Big/ {\phi^2}$$

Where D_a is the diffusion coefficient of air, φ is the porosity, θ_v is the volumetric soil water content.

The diffusion coefficient is extremely sensitive to changes in volumetric soil water content, and to a certain degree temperature, as shown Figure 3. The reason for this is that as the soil water content approaches the soil porosity, the air filled pores become saturated with water this effectively slows down diffusive processes. As a result, CO_2 will accumulate at these saturated depths.

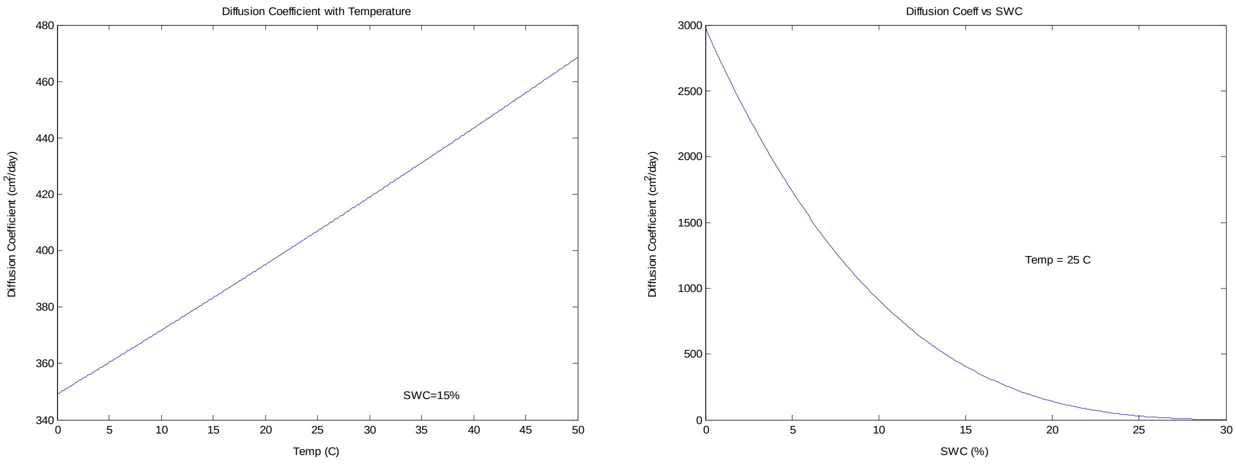

Figure 3: Sensitivity of Diffusion Coefficient

Formulation of CO_2 production

Using the approach outlined in Simunek & Suarez, we consider the sources of CO_2 production as independent, and their effects multiply together. The total production is the takes into account the CO_2 exuded by soil microorganisms, plant roots (different from plant to plant), and the chemical response of rate of reaction of CO_2 with increasing temperature. The following flowchart identifies these processes:

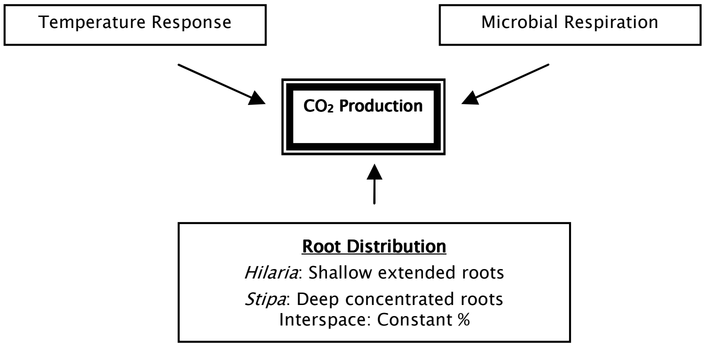

Figure 4: CO_2 Production Inputs

As a result, if we take *f(z)* to be the functional response of root distribution, *f(m)* the functional response of soil microbes, and *f(T)* to be the functional response of temperature, we have the following for *S(z,t):*

$$S(z,t) = \gamma_0 f(z) f(m) f(T)$$

The factor γ_0 represents an “optimal” value for the whole profile at 297.15 K, water, and concentration conditions. The task now is to identify each functional response.

The temperature response data was fit exponentially from soil respiration data collected with an IRGA machine from permanent plots on the Corral Pocket site, as shown in Figure 5.

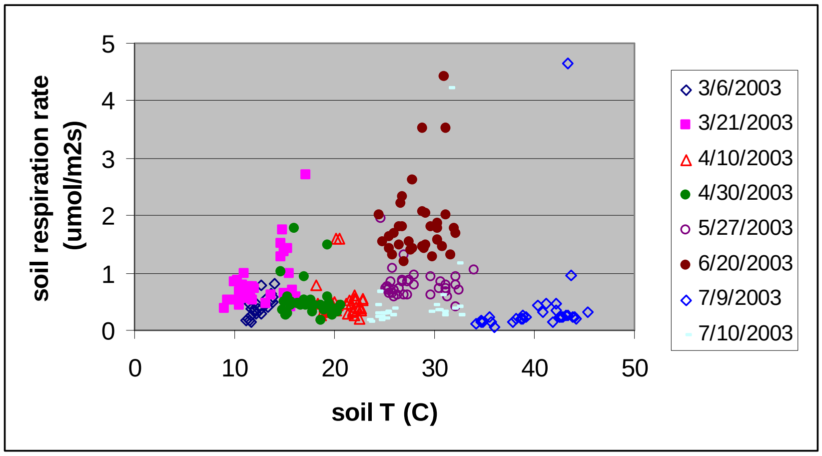

Figure 5: CO$_2$ respiration as a function of temperature

Taking the average of all this data shown in the above graph, the mean is 23.85 C, with a respiration rate of 2.5 umol/m^2 s at that temperature. It still plausible that the soil respiration rate would be a function of soil water content, but soil water content data for each site at the time of sampling in the permanent plots doesn't exist.

The two approaches to determining the functional form of the soil respiration is to fit the data (leaving out the data collected on 7/9/03) to an exponential. This yields the equation $f(T) = .1405 \cdot e^{.0699T}$. On the other hand, if we that the functional response is optimal at 23.85 C, we can use the following equation, modified from Simunek and Suarez (1993): $f(T) = e^{\frac{T-23.85}{23.85}}$. The two different responses are graphed below in Figure 6.

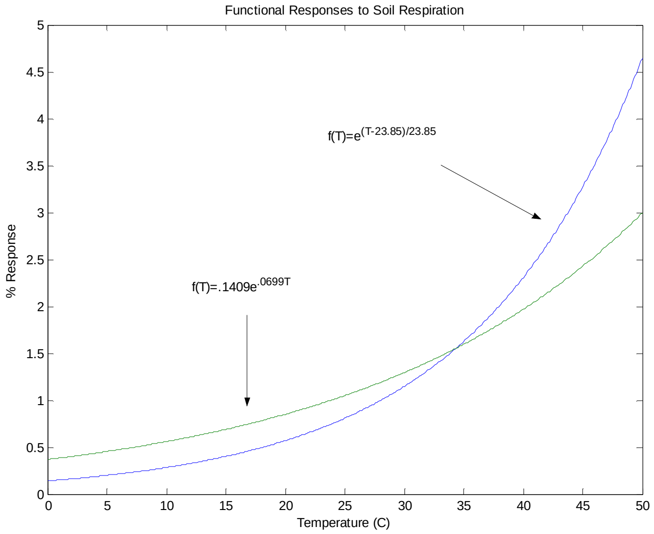

Figure 6: Fit CO_2 functional response

For rooting distribution, data for the *Hilaria jamesii* and *Stipa hymenoides* plants does not exist, so the rooting density was estimated from *H. mutica* and *S. tenuis* from the articles by Nobel, and Distel & Fernandez, respectively.

Also proposed in the model by Simunek and Suarez, a normalized rooting distribution can be found by knowing the mean root length. Such a distribution is called the Van Genuchten distribution. The comparison of both distributions is shown in Figure 7.

As can be seen, the theoretical distribution predicts more dense roots in the top layers of the soil.

For the CO_2 response of soil microbes, a function used in Pumpanen, et al, was used. It is dependent on the soil water content, and given by:

$$f(\theta_v) = \min(a\theta_v{}^d, b(E_0 - \theta_v), 1)$$

In the above, θ_v is the volumetric water content, E_0 the total porosity, and *a* and *b* are fitted parameters from data. Although such a construction seems highly contrived, it actually has its theoretical formulation in measuring steady-state diffusive fluxes. (Skopp, 1990) The values for *a* and *b* used in the model came from Skopp's original paper for pooled, scaled, Valentine soil, as it seemed that Valentine soil had characteristics similar to soil at our study site.

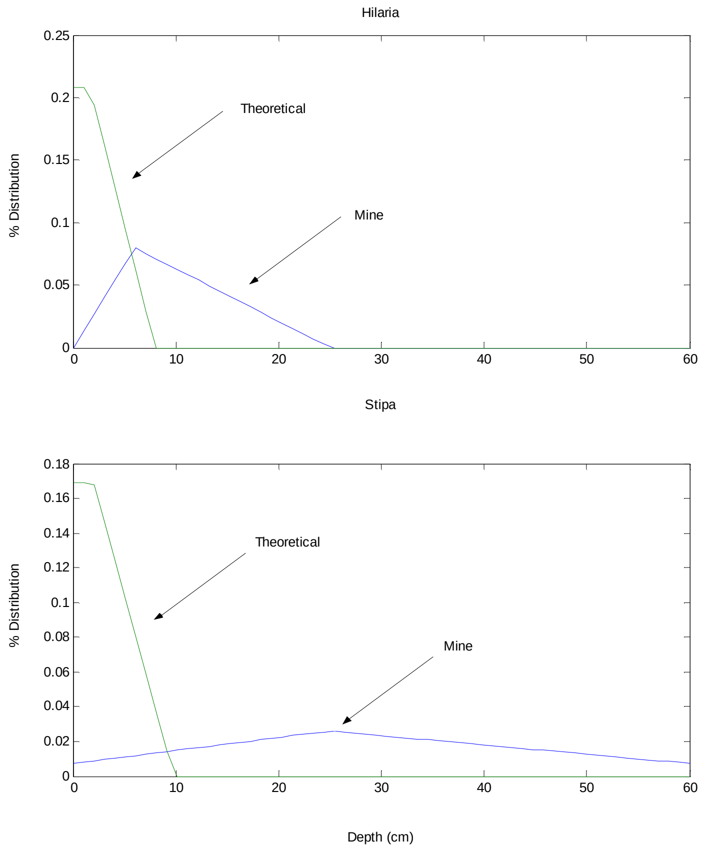

Figure 7: Rooting distribution response

Results of Simulations

The model was solved both analytically and numerically using a finite element method. If we use a constant function for CO_2 rather than the one developed above, we have the following model output shown in Figure 8.

While this does not mirror the CO_2 concentrations observed from the sensors, it does suggest that levels are increased by a purely physical (not biological) process. As water enters the soil, it effectively traps the CO_2 molecules from diffusing out of the soil, thus allowing the CO_2 levels to accumulate until the soil desiccates.

If we use the more CO_2 production function developed above, we have the following output, shown in Figure 9 for *S. hymenoides* at 5 cm.

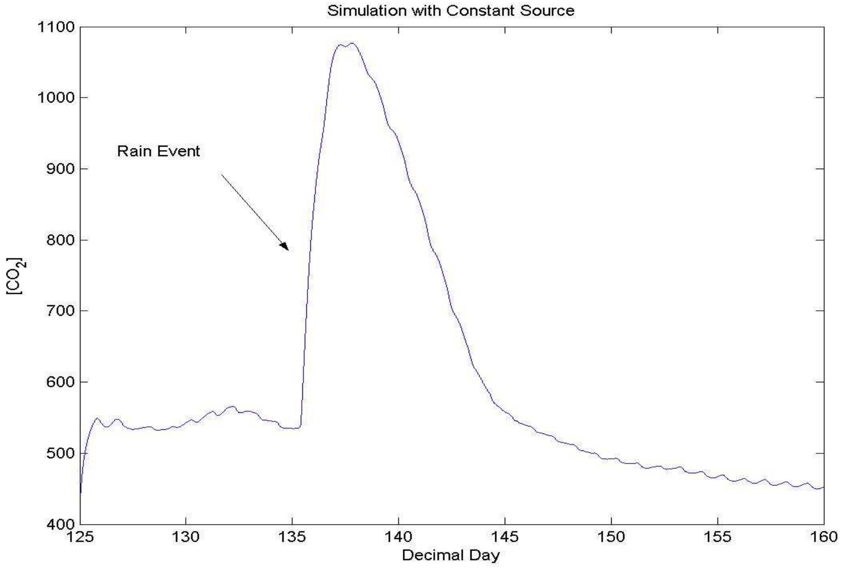

Figure 8: Simulation with constant source

By doing a linear regression on the sensor output to model prediction, we see that a linear relationship is present. As seen in Figure 10, the model performs strongest at lower concentrations than at higher ones. This is to be expected, since there the soil water content registered by the sensors indicate that the soil is wetter longer than what is predicted from the CO_2 sensors. The r^2 and slope of the linear regression lines for the other simulations is given in Table 2.

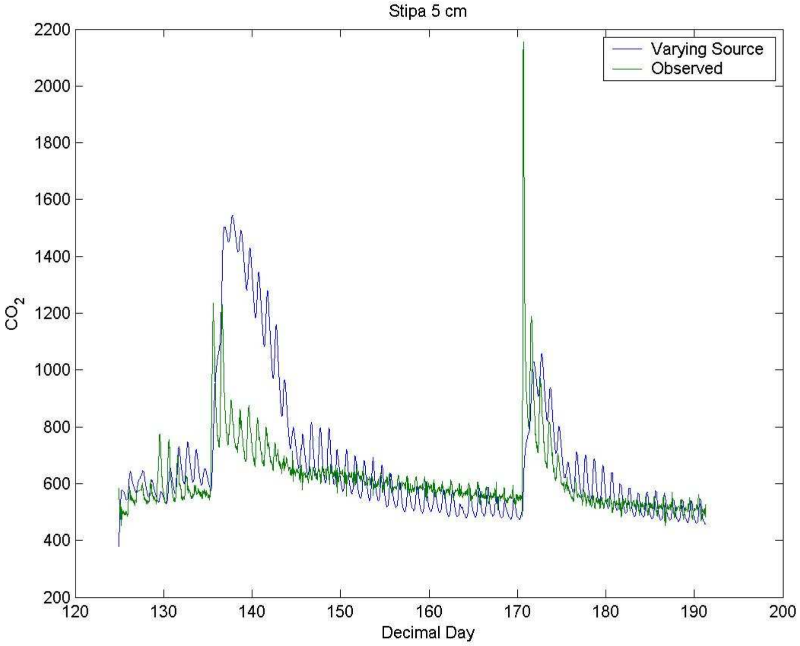

Figure 9: *S. Hymenoides* model output at 5 cm

As can be seen from the fit comparisons in Table 2, the predictive power of the model for *Stipa* plants is quite good. For *Hilaria*, there are strong correlations at 5 cm. The 15 cm correlations are not quite as strong, and I believe that is due to the fact the diffusion coefficient is depth dependent (contrary to our assumptions), and we might not have the correct values for it. Yet the results do indicate that the model does correspond with the observed values. In adjusting the interspace “background” contribution in the absence of roots, it seems that improving the r^2 value cannot be done, only a slope *m* closer to 1. From trial and error, it seems that 9% gives a good base value.

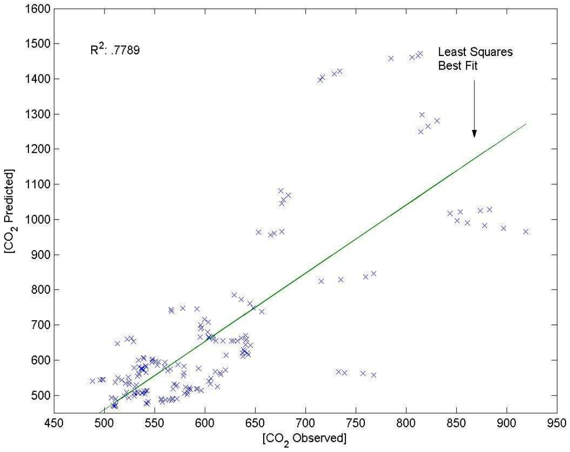

Figure 10: Observed vs. Predicted Linear Regression

Conclusions

Clearly water availability determines CO_2 concentrations. Although this study did not examine the effect on the ecology of *H. jamesii* and *S. hymenoides,* many questions could be examine using this model as a starting point. The model has poor predictive power for sudden changes in moisture and precipitation due to the fact that the soil water content sensors are at a different spatial location than the CO_2 sensors. If we can characterize the rooting density better for both *H. jamesii* and *S. hymenoides* at the site then more accurate results can be obtained. Preliminary results do show that there is a correlation between the flux measured at the site and the predicted fluxes from the model. To what extent this correlation is needs to be further investigated.

Plant	Root Density	Fit Values	5 cm	15 cm
Stipa	Experimental	R^2	.779	.6518
		m	1.13	.918
	Theoretical	R^2	.756	.697
		m	.817	.732
Hilaria	Experimental	R^2	.746	.652
		m	.512	.451
	Theoretical	R^2	.726	.688
		m	.689	.658
Interspace	3 %	R^2	.479	.640
		m	.421	.374
	9 %	R^2	.479	.640
		m	1.26	1.12

Table 2: Statistical regression results of model

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