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A GRAPHICAL SURFACE-VEGETATION-ATMOSPHERE TRANSFER (SVAT) MODEL AS A PEDAGOGICAL AND RESEARCH TOOL

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ABSTRACT: This paper considers, by example, the use of a Surface-Atmosphere-Vegetation-Transfer (SVAT), Atmospheric Boundary Layer (ABL) model designed as a pedagogical tool. The goal of the computer software and the approach is to improve the efficiency and effectiveness of communicating often complex and mathematical based disciplines (e.g., micrometeorology, land surface processes) to the non-specialist interested in studying problems involving interactions between vegetation and the atmosphere and, in the nature of interactions rather than a description of the components. Topics are addressed within a Socratic framework using a scenario system based approach: As an example of this, the interactions between a vegetation canopy and a carbon dioxide rich (2 times ambient CO_2) atmosphere, are presented. This will illustrate such non-linear interactions between the physical components and in system behavior that would not be intuitively obvious to the student or, would be to complicated to be insightful. This type of approach is another careful, critical way of thinking fostered by interactions with a computer model. The student instead of taking things apart, is looking at them as wholes and is encouraged to make new and important distinctions.

INTRODUCTION

The power of computer software tools to engage learners in intrinsically motivating, experimental learning may be their greatest potential. However, computer programs cannot anticipate every need that a user might have and so, some form of collaborative support is essential. Pedagogical models embody such ideas as two or more learners working together to provide cognitive and affective support or, have a learner work with written scenarios that coach the learner to a level of understanding. Embedded within such a process in the idea of higher order learning to encourage the student to

Frame and resolve problems
Exhibit intellectual curiosity
Strive for life-long learning

In the scenario context, we further pose partnerships (between individuals and computers) for problem-solving, teams for project-based learning, structured controversy, peer teaching and review. This has far reaching implications as it eschews individual differences (e.g., prior knowledge, tolerance for ambiguity, culture, gender, age, etc.) that might prevent effective learning. Moreover, instructors' roles are radically shifted from the traditional norms – the instructors become mentors, coaches, and co-learners. Faculty are challenged to shift from being a "sages on the stage" to "guides on the side." They facilitate learning, not deliver information, they support collaboration, not foster false competition and they assess development rather than test.

What follows is an example of what we term the scenario approach. The example scenario is a final one in a series which comprises a course in Land Surface Processes. In the course we use a SVAT (Soil-Vegetation-Atmosphere-Transfer) computer model as a cognitive tool to help build a systematic understanding of what are complex interactions in a system – the land / atmosphere. We are interested in the nature of interactions rather than a description of its components. To gain an initial understanding of the resultant behavior of a system we avoid confusing details and concentrate on the resultant effects. The course is designed to prove useful to the non-specialist and, more precisely, to those who are interested in studying problems involving interactions between the vegetation and the atmosphere.

Teaching and learning are difficult, but the scenario approach, coupled to a cognitive tool such as a SVAT, can help us overcome the problems of learning complicated systems that are intrinsically inter-disciplinary. It uses the computer as a medium of intellectual curiosity rather than as some might argue, a wasteland for mindless entertainment.

AN EXAMPLE SVAT SIMULATION—CARBON DIOXIDE FLUXES

Preamble

Plants live by taking in carbon dioxide (CO_2) and converting the carbon to its own substance (assimilation). The net carbon gain manifests itself (virtually by definition) as an increase in the biomass, which consists of roots, stem, leaves, flowers, etc. Carbon dioxide enters the plants through the stomates and so, the rate of biomass increase is closely dependent on the stomatal resistance. Not surprisingly therefore, the economic value of a crop is closely tied to the level of transpiration, which also depends on the stomatal resistance. Since transpiration is not beneficial to the plant except to reduce the leaf temperature[4], we might expect plants to favor a maximization of carbon dioxide intake in relation to transpiration. Thus, plants benefit most by keeping the stomates open, regardless of the transpiration, as long as sufficient water reserves are available to the roots. By now you must realize from previous simulations that decreasing soil water content does not necessarily reduce transpiration until the plant perceives itself to be in danger of water stress, although the stress signal does not depend uniquely on soil water content.

In these days of the runaway greenhouse effect scare, some researchers take heart that an increase in carbon dioxide concentration in the atmosphere will lead to an enhanced carbon dioxide uptake by the plants and so, to an increased biomass production. Experiments done in the greenhouse and in the field suggest that an increase in carbon dioxide concentration also causes the stomatal resistance to increase, with the net effect being a gain in biomass and a decrease in transpiration, thus doubly benefiting the plant. We can use our simulation model to explore this finding.

Our main purpose, however, is simply to examine the flux of carbon dioxide in a canopy (specifically the carbon dioxide assimilation rate *A*). If time permits we can test the idea that an increase in stomatal resistance associated with an increase in ambient carbon dioxide concentration leads to both an increase in the carbon dioxide assimilation rate and to a decrease in transpiration.

Calculating the carbon dioxide assimilation rate from the outside

Let us return to the idea that a flux of a substance moves down a gradient of potential across a resistance, the Ohm's law analog for diffusive fluxes. The source of carbon dioxide is in the atmosphere, let us say above the plant canopy, where the concentration of carbon dioxide gas (*C*) has a mean value of about 330 parts per million (of CO_2) by volume of air (ppmv), which is numerically equivalent to 330 microbars (ìb) or to 330 mol (CO_2) mol^{-1} (air) times 10^{-6} . We will refer to this ambient carbon dioxide concentration as (C_a). If the drop in carbon dioxide potential is $\triangle C$ and the resistance across that potential drop is *r*, the flux of carbon dioxide (FCO_2) is given by Equation.1a.

$$FCO_2 = \frac{\Delta C}{r} \qquad [1a]$$

If the plant is to ingest carbon molecules there must be a flux of CO_2 downward through the surface layer along decreasing concentration to the leaf surface (see Figure 8.1 from scenario 8 – Microclimate of the Plant Canopy). The appropriate resistances are approximately the same as that for water vapor, but with some adjustments for the differences in diffusivity of carbon dioxide in air. The turbulent resistance in the surface layer will be called . Once inside the canopy the molecules move through the interleaf air-spaces and across the surface boundary layer of the leaf, where the resistance is r_{ahc}. Ignoring the flux of carbon dioxide across the leaf surface (the cuticle), the carbon dioxide molecules then penetrate into the leaf via the stomates where they encounter an internal (or intercellular) carbon dioxide concentration C_i. The stomatal resistance to carbon dioxide flux is r_{sc}. Accordingly, we can write a somewhat more elaborate version of Equation 1a in the form of Equation1b:

$$FCO_2 = \frac{[C_a - C_i]\rho_{CO_2} C_p}{r_{CO_2} + r_{ahc} + r_{sc}} = A \qquad [1b]$$

note that the density (pCO_2) of carbon dioxide gas (kg m^{-3} of CO_2) is necessary to make the units agree with the left hand side of the equation which has the units of kg (CO_2) m^{-2} s^{-1}.

Resistances for carbon dioxide flux are generally somewhat larger than those of water vapor because the molecular diffusivity of carbon dioxide in air is less than that of water vapor in air (possibly because the former is somewhat heavier (molecular weight 46) than water vapor (molecular weight 18)). However, the differences in resistances between carbon dioxide and water vapor in air are generally less than a factor of two (depending on what resistance one is talking about). Accordingly, let us agree for the sake of argument (since it alters no fundamental result) that the two sets of resistances, that for water vapor and that for carbon dioxide, are equal.

Imagine a flux of water vapor from the stomates into the surrounding interleaf air-spaces, as in Equation 7c from scenario 7 – Stomatal Resistance, and thence into the surface layer above the canopy through resistance r_v. Ignoring the parallel water vapor flux from the ground below the canopy, the flux of water vapor between the leaf and the atmospheric surface layer (in kg m^{-2} s^{-1}) is given by Eqn. 1c.

$$FH_2O = \frac{[e_s(T_1) - e_{af}]\rho C_P}{\gamma L_e(r_v + r_{ah} + r_s)} \qquad [1c]$$

Note that e_a here refers to the vapor pressure above the canopy, i.e., at some elevation where the carbon dioxide concentration is not immediately affected by transient perturbations in the canopy fluxes[5].

Now, if we equate the resistances and take a ratio of the two fluxes (dividing Equation 1b by Equation 1c to yield Equation 1d) we obtain a measure of the water use efficiency (WUE), which is the essentially the ratio of the carbon dioxide concentration gradient between the atmosphere above the plant canopy and that in the sub-stomatal cavities to the gradient in vapor pressure between the inside of the leaf and that in the surface layer above the canopy.

$$\frac{A}{T_r} = WUE = \frac{\rho_{CO_2}}{\gamma L_e}\left[\frac{C_a - C_i}{e_s(T_l) - e_{af}}\right]$$

$$\gamma = pC_p / 0.622 L_e \qquad [1d]$$

Note, however, that because of the 30-fold smaller concentration of carbon dioxide than water vapor in the atmosphere, the magnitude of the water fluxes will be much larger than those for CO_2. A typical value for FCO_2 at noon on a sunny summer day is 1×10^{-6} kg m^{-2} s^{-1} or 20 micromoles per square meter per second. The sub-stomatal concentration C_i is known to be approximately constant under normal atmospheric and plant conditions. It is about 220 ppvm for C_3 plants, such as wheat, rice and potatoes, and 120 ppmv for C_4 plants, such as corn and sorghum. We will have more to say about this intriguing parameter later in these notes. Equation 1d show us that the primary control of water use efficiency is exerted by the vapor pressure deficit between that at the leaf surface and the that above the canopy.

Assuming that the latter is largely controlled by the atmosphere, the single most important variable in the WUE relationship is the vapor pressure in the leaf, which is to say that control rests with the leaf temperature. We might imagine that the plant is trying to maximize the WUE but, at the same time maximize its rate of carbon intake. Blum (1989) cites a formula relating plant yield (YE) to WUE, more specifically the product of WUE times the evapotrananspiration. He also cites another formula relating biomass creation to the ratio of transpiration to potential evapotranspiration, which is a little bit like the moisture availability you saw defined in an earlier scenario.

Calculating the carbon dioxide assimilation rate from the inside

Well beyond the scope of this course is the frightening terrain of pure plant physiology. Nevertheless, plant physiologists are also struggling with the modeling aspects of assimilation rates. One of the most well known of the current assimilation models is one constructed by Farquhar (1989); of feed-forward fame. The Farquhar model, which deals primarily with C_3 plants, attempts to describe the curve shown in Figure 1, which emerges from numerous experiments in which C_i is varied as a function of assimilation rate.

We see that A increases first rapidly and almost linearly with increasing C_i and then much more slowly beyond a bend in the curve which is actually not far from the characteristic value of C_i for the plant. Typically, C_3 plants tend to have a more gradual transition from rapidly increasing assimilation rate to slowly increasing assimilation rate than C_4 plants, as shown in Figure 1. The bend in the two curves occurs close to the present-day normal values for internal carbon dioxide concentrations.

The bend also represents a transition between two physiological states of the plant, one in which the photosynthesis is limited by the availability of an organic compound called Rubisco, which is involved in the reduction and oxidation in the C_3 pathway (low C_i), and the other in which photosynthesis is limited by the availability of photon flux (high C_i). Clearly, an increase in internal carbon dioxide concentration causes the assimilation rate to increase, although at a rapidly decreasing rate with increasing concentration. We will later touch on the importance of this decrease in assimilation rate with increasing carbon dioxide concentration.

The Farquhar model can be used to calculate C_i. When combined with another type of formulation, called The Ball-Berry model, which determines stomatal resistance as a function of the rate of photosynthesis, the photosynthesis can be calculated directly without having to specify either C_i or stomatal resistance because the latter can be calculated as a solution to the combined Ball-Berry / Farquhar equations. Of course, this combined formulation requires additional, and perhaps more exotic, parameters to obtain real numbers. Although further discussion of this approach lies beyond the scope of these notes, the model does offer an option for calculating photosynthesis and carbon dioxide fluxes directly by specifying the Ball-Berry model. We suggest that only the most serious plant scientists among you venture to call upon this option!
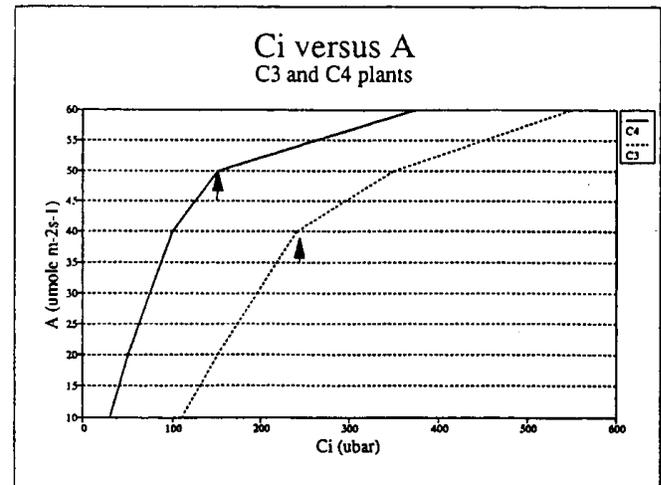

Ci versus A
C3 and C4 plants

Figure 1 Schematic illustration of variation of assimilation rate versus internal CO_2 concentration for C_3 and C_4 plants. Arrows denote present day internal CO_2 concentrations.

Changes in assimilation rate and transpiration with increasing carbon dioxide concentration

Worst-case scenarios (not one of ours) suggests a doubling of ambient carbon dioxide concentration by the middle of the next century, from the present 330 ppmv to about 660 ppmv as the result of continue fossil fuel burning. This increase already comes on top of an increase from 280 ppmv from the middle of the last century. A first guess based on Equation 1b is that the doubling in C_a would cause the assimilation rate A to increase by a factor of about 4 for C_3 plants and about 2.5 for C_4 plants (assuming no change in the values for C_i). In fact, Cure and Acock (1986) examined all the published measurements they could find that were related to the response of plants to an increase of carbon dioxide. Their results show that the increase in assimilation rate is likely to be only about 40% for C_3 plants and about 25% for C_4 plants. Moreover, they show that plants grown under ambient concentrations of 660 ppmv or allowed to come into equilibrium with their new enriched CO_2 environment show an even lower increase in assimilation rate, about 30% for C_3 plants and less than 10% for C_4 plants. These increases in assimilation rate translate into approximately equivalent percent increases in biomass production.

Laboratory measurements show that an increase in carbon dioxide concentration at the surface of the leaf induces an increase in stomatal resistance. A glance at Figure 1 shows that assimilation rate does not increase rapidly with an increase in internal carbon dioxide concentration beyond present-day concentrations. Experiments further show that while fluctuations in stomatal resistance and other local factors do not significantly affect internal carbon dioxide concentration, an increase in ambient carbon dioxide concentration moves the entire curves for both C_3 and C_4 plants, shown in Figure 1, toward the right. Despite this shift, the net effect is one of an increase

in assimilation rate even for C_4 plants (although the sharper transition at the bend in the curves followed by a nearly constant value of assimilation rate of the C_4 curve above the bend translates to a smaller gain in *A* for C_4 plants than for C_3 plants with an increase in C_a).

A further intriguing implication of Cure and Acock's (1986) data is that transpiration should decrease by about 20% as the result of carbon dioxide doubling! What Figure 1 shows clearly is that an increase of 20% in stomatal resistance is not sufficiently large to hold the assimilation rate to only a 40% increase; rather, both C_i and stomatal resistance must increase as ambient carbon dioxide concentration is increased. This increase, in stomatal resistance, seems to be associated with the leaf 's ability to sense an increase in carbon dioxide concentration at its surface.

Stated alternately, if one doubles the amount of food on the table (ambient carbon dioxide concentration), people will stuff their mouths more (internal carbon dioxide concentration), but they will not ingest twice as much food. Moreover, given some time to equilibrate, people may get sufficiently fed up (literally) that they will become more resistant to temptation and not ingest much more food than before, although it is certainly true that the more food available the more one eats (up to a point). Thus stomatal resistance increases in response to the plant's inability to assimilate all that is put on its plate, given the amount of available sunshine and nutrients for carrying out all its chemical reactions. (Speaking of resistance, anyone who has ever tried to feed an infant would know what happens when you try to increase the food intake rate by increasing the mass of goop on the end of a spoon! You do get more inside the infant, but a lot of resistance is put forth and a lot of goop ends up on the walls).

Simulations

The SVAT model calculates carbon dioxide flux and outputs it in units of kg m^{-2} s^{-1}. As with water vapor fluxes, the calculations refer to flux per unit sunlit leaf area, but the output is in terms of flux per unit horizontal surface area. The problem therefore, is to scale from a leaf to a canopy. One way of dealing with this is to calculate fluxes for each leaf or leaf strata. Another approach is to divide the leaf resistances by the leaf area index multiplied by a scaling factor called a 'shelter factor.' The reason why we divide by the leaf area index is that we must sum up all the individual leaf fluxes for one-sided transpiration. Were we to simply divide by LAI (equivalent to multiplying the transpiration fluxes by LAI) the resultant fluxes would generally be too large because the transpiring area would be overestimated, since many leaves are shaded by other leaves and thus have a larger stomatal resistance. Accordingly, we use an equation that reduces the leaf resistances by an amount that varies between about 1.0 for a fairly low leaf area index to about 2.0 for very large leaf area indices. Both the carbon dioxide and water vapor fluxes have been scaled in this way.

Simulation # 1.

Re-run the base case simulation, but this time examine the carbon dioxide fluxes and the water vapor fluxes together. Don't forget to use a large LAI in order to effectively suppress the evaporation component of the evapotranspiration. (We will output the transpiration in the same units to make it easier for you to compute a WUE ratio). Then run a simulation in which water stress manifests itself as a plateau in the evapotranspiration and note the changes in WUE, carbon dioxide fluxes

and transpiration during the day and from the unstressed run. Use the field results of Figures 2 and 3 as a comparative platform from which to discuss the SVAT's results for transpiration and photosynthesis.

Simulation # 2.

Run the case with double root / stem hydraulic resistance again and examine the carbon dioxide fluxes, WUE and transpiration. Changes in the root / stem hydraulic resistance occur during the life of the plant. It probably decreases in the early stages of the plant's life and increases again with time as the plant matures and then senesces.

Simulation # 3.

Finally, and only if you have oodles of time to burn, check out the carbon dioxide doubling issue referred to by Cure and Acock (1986). First, increase the ambient carbon dioxide concentration to 660 ppmv. Note the increase in the fluxes of carbon dioxide from the base case and see if it is similar to the 30% increase indicated by the results of Cure and Acock. It isn't ! So then increase the minimum stomatal resistance by 30% and see if you reduce the carbon dioxide fluxes by 30%. You can't unless you also increase C_i which you can also do. So finally increase the internal CO_2 concentration until the assimilation rate is 30% above your reference case. To increase the stomatal resistance increase r_{smin} by the appropriate factor. Thus, if you wish to increase the stomatal resistance by factor of 2 simple double the minimum stomatal resistance. At this point, look at the decrease in transpiration from the base case. Does that value agree with the 20% decrease anticipated by the results of Cure and Acock ? If not, is the model full of baloney? Are Cure and Acock out to lunch ? Or is something up here that is a little more profound than scientific silliness ?

SUPPLEMENTARY FIGURES
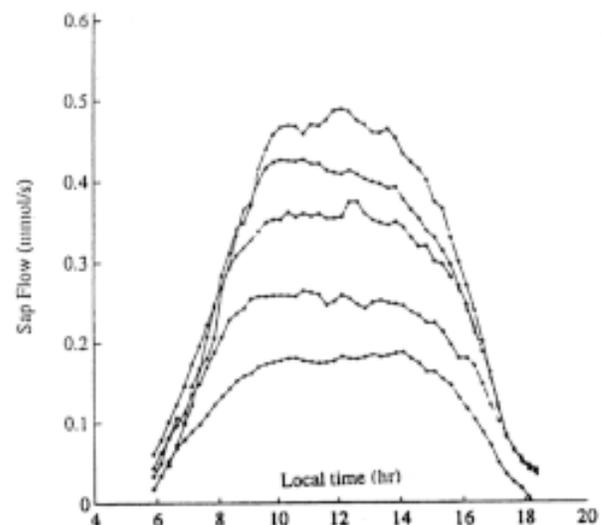
Figure 2 Diurnal evolution of sap flow measurements on selected days. The selected days are (by decreasing magnitude of sap flow): Julian days 246, 248, 251, & 255 near Avignon, France.
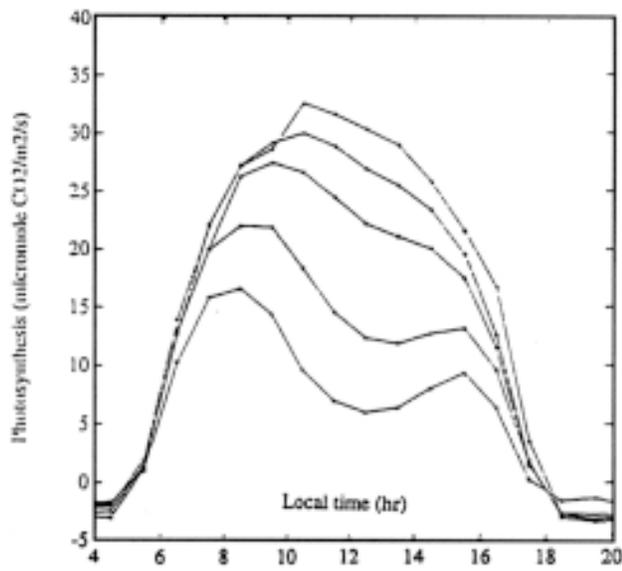
Figure 3 Diurnal evolution of photosynthesis in *u*moles-m⁻¹-s⁻¹. The selected days are identical to those in Figure 2.

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Farquhar, G. D., 1989, Models of integrated photosynthesis of cells and leaves, **Phil. Trans. Roy. Soc. London,** B., 323, 357-367.

Cure, J. D. and B. Acock, 1986, Crop responses to carbon dioxide doubling: a literature survey, **Ag. and Forest Meteor**., 38, 127-145.

[4] Water transport from root to leaf is nevertheless critical in bringing nutrients and hormones to the plant factory. Transpiration is also necessary to maintain a reasonable leaf temperature, since photochemical processes tend to be more efficient at higher temperatures. Very high temperatures, however, will not force the plant to lose more water through the leaves but will tend to destroy cellular function.

[5] Plant scientists often prefer the units of micromoles per square meter per second. Fluxes in these units can be obtained by dividing those of kilograms per square meter per second by 44 and then multiplying the result by 10^9.