A MULTI-LAYER MODEL INCORPORATING LAGRANGIAN DISPERSION
FOR SCALING UP FROM LEAF TO CANOPY

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Introduction

The correct estimation of plant evapotranspiration is of paramount importance in many applications. One of the most widely used approaches is the Penman-Monteith equation; this "combination equation" includes the effects of both the energy supply and the dispersion of water vapour away from the evaporating surface and it can be applied at the leaf level or, more often, at the canopy level. The attractiveness of its application at the whole canopy level is that only a few parameters are needed; however, "correctness and usefulness of this equation depends entirely on how accurately and easily we can determine the bulk aerodynamic and surface resistances" (Raupach and Finnigan, 1988).

Rochette *et al.* (1991) measured leaf conductance within a maize canopy and concluded that none of the scaling up methods they tried were appropriate to estimate the bulk canopy resistance (r_{res}). However, they do recognize that measurements made on horizontal sections of leaves may not be representative of the light regime at that level. Raupach (1995) compared, analytically, different model canopies and concluded that, for typical dry canopies, the r_{res} is close to the parallel sum and is therefore approximately a physiological parameter of the system. Alves *et al.*, (1998) stated that "the bulk surface resistance of dense crops cannot be obtained by simple averaging stomatal resistances because the driving force [profile of saturation deficit] is not kept constant within the canopy". Raupach and Finnigan (1988) concluded that r_{res} could be approximated by the inverse of the parallel sum in cases without significant soil evaporation or free water in the canopy, accepting uncertainties of the order of 20%. The purpose of this study is to explore the scaling up problem with more detail using a simple multi-layer canopy model where the turbulent transfer is described by Lagrangian theory.

Methodology

In this model, the canopy and the air above it are each divided into several layers; vertical leaf distribution is described with a beta function. Within the canopy, net radiation and irradiance are simulated with a simple exponential decay function; no distinction is made between shaded and sunlit leaves. The leaf boundary layer resistance is proportional to the square root of the ratio between leaf width and local wind speed. The leaf stomatal conductance is modeled in two ways: one approach uses the relationship with net radiation (the sole factor) presented by Denmead and Millar (1976) whereas the other approach uses the Ball & Berry model as described in Collatz *et al.* (1991). The partition of the net radiation at the soil surface is imposed; soil latent and sensible heat fluxes are boundary conditions to the canopy lowest layer.

The final profiles of latent (LE) and sensible (H) heat fluxes within the canopy have to match these two conditions: firstly, within each layer, fluxes between leaves and the air should be describable by the Ohm's analogy, secondly, the concentration profiles of temperature and water vapour within the canopy air should be defined by the flux profiles (*i.e.*: source strengths) through the dispersion matrix derived from Lagrangian theory presented by Warland and Thurtell (2000). In order to accomplish this, an initial partition of net radiation into LE and H profiles is imposed which, in turn, originate profiles of scalars within the canopy air (via the dispersion matrix); since resistances are known, the Ohm's analogy is used, in each layer, to estimate the resultant leaf temperature from H (TfH) and from LE (TfE). If these temperatures do not coincide, the first condition is not matched and a "next foliar temperature" (and its saturation vapor value) is estimated, for each layer, based on the difference between TfH and TfE, so that new profiles of LE and H can be calculated for the next iteration, again with the Ohm's law. In this next iteration, the dispersion matrix is used again and new profiles of TfH and TfE are determined. With each iteration, the difference between TfH and TfE becomes smaller until both TfE and TfH coincide; then, the two conditions mentioned above have been matched.

The bulk surface resistance that corresponds to the total evapotranspiration (r_{res}) is obtained as a residual term by rearrangement of the Penman-Monteith equation once the bulk aerodynamic resistance has been estimated. The energy available only to the canopy and the canopy transpiration are taken into account in this calculation.

Results and Conclusions

When the Denmead & Millar algorithm for leaf conductance is used, the value of the inverse of the parallel sum of leaf conductances (R_{tot}) obtained is 63.33 s m^{-1} for a full canopy cover (LAI=5) whereas calculated r_{res} ranges from 61.45 to 66.0 for a varying set of conditions (*i.e.*: temperature, RH, u* and σ_w) if z_{oH} = z_o is assumed in the estimation of the bulk aerodynamic resistance. If z_{oH} = $0.2z_o$ is used instead, the values obtained range between 57.53 and 88.06 s m^{-1}. In the case of a sparser crop (LAI=3) and when the soil evaporation is close to the equilibrium value, r_{res} is quite close to the R_{tot} value of 75.86 s m^{-1} when RH is ~ 50% but it ranges between 67.98 and 72.99 when RH is higher (~ 80%); as before, the use of z_{oH} = $0.2z_o$ gives a poorer agreement. When the soil evaporation is diminished, r_{res} begins to be quite consistently lower

than R_{tot}; this difference is, again, more dramatic for higher RH.

The Ball and Berry model was incorporated to explore how a better description of the feedback mechanisms within the canopy would affect the relationship between R_{tot} and r_{res}. This incorporation was not completed at the time of this writing. However, preliminary results suggest the same pattern described above for the Denmead and Millar model.

The effect of changing the shape of the σ_w profile is small. Boundary conditions of temperature and water vapour are defined at a reference height well above the canopy; the effect of a change in σ_w is thus expected to be evident only in the lowest levels of the canopy where leaf conductances and fluxes are already quite small and this is what we see.

Our model was successfully able to produce unique, reasonable profiles of fluxes and scalar concentrations that satisfied both the leaf model and the dispersion model. Furthermore, when the canopy cover was complete we found that $R_{tot} \cong r_{res}$ for a varied set of conditions. This relationship between R_{tot} and r_{res} was not as strong in sparser canopies, less so when the soil became fairly dry, but this was expected since the use of the Penman-Monteith equation is quite questionable then.

When discrepancies between R_{tot} and r_{res} are reported in the literature, some caution is advisable. It could be the case that the models involved in the estimation of these resistances (the Penman-Monteith equation for r_{res} and some other for the estimation of R_{tot}) are not both able to adequately describe the scenarios under consideration. Therefore, a practical inconsistency between r_{res} and R_{tot} should not automatically imply that the first one is not close to being a physiological parameter because it could also mean that R_{tot} or the profile of leaf conductances is not being modeled or measured with enough precision. On the other hand, the "measured" r_{res} is just a residual term so that its value, in practice, is merely the one that makes the Penman-Monteith equation work in a specific situation.

We expect that when this work is finished we will be able to provide some new insight into this difficulty.

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