Application of a Mock-Up based Transpiration and Photosynthesis Model on a Coffee Plantation in Costa Rica

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Introduction

The Coffee tree (*Coffea arabica* L.) is not a full sun growing species and does accommodate well with the shade cast by major trees. In Costa Rica, Erythrina (*Erythrina poeppigiana*) is used as shade tree in most coffee plantations. This nitrogen fixing tree is generally cut down twice a year and benefits the association with large amounts of N. Nevertheless, it also competes with the coffee trees for the other mineral nutrients, for water, and also for radiation.

The balance between benefits and disadvantages of this association for the coffee production probably depends on the local environmental conditions. The use of simulations from computer models of transpiration and photosynthesis could help to find out where the environmental conditions are met to ensure the beneficial effects of the presence of Erythrina in a plantation.

The transpiration of a plant or plant stand in a given environment is difficult to model due to the interaction of complex physical and physiological phenomena, and to the multiplicity of exchange surfaces, mostly leaves, between plant and atmosphere. The available transpiration models generally simplify the representation of vegetation. When this kind of model is used, one of the major problems is to assess the value of vegetation resistances for water vapor difusion, integrating the stomatal resistances of individual leaves for the whole canopy or canopy layers.

Calculating the radiative and energy balance of individual leaves is likely to substantially improve the transpiration estimation. This approach may also give the opportunity of dealing separately with different species or individuals associated in a plantation. That was the choice made for the model used and shortly described here. Beside the fact that this choice involves relatively long calculation times, it also requires the calculation of net radiation on an individual leaf scale. This was made possible by the development of specific models, MIR and MUSC (Dauzat, 1994) simulating radiative transfers on computerized plant mock-ups. The geometrical information contained in the mock-ups gives the position and orientation of each leaf and enables quite precise calculation of its lighting according to its environment.

This paper describes a model of transpiration and photosynthesis based on this approach and its application on a coffee stand in the Turrialba region, Costa Rica.

Materials and Methods

The model

The model consists of six main modules fulfilling the following tasks:

- Calculation of **leaf radiative balance** for the photosynthetically active radiation (*PAR*), the near infrared (*NIR*) and the thermal infrared (*TIR*). Calculations are carried out for each leaf of the

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plant using specific radiative transfer models working on computerized mock-ups of plants. Input data are the directional PAR and NIR impinging on the canopy and the atmospheric TIR radiation. Outputs are the net radiation (*Rn*) of each leaf in each spectral range.

- Calculations of one dimensional **turbulent transfers** above and within the canopy. Wind speed and heat and water vapour aerodynamic resistances are calculated from the leaf area index profile. Outputs are the temperature and water vapour profiles within the canopy and the boundary layer resistance (*rb*) of leaves according to their dimensions.
- Calculation of **leaf energy balance**, taking into account their radiative balance and their stomatal conductance. The outputs are the latent (*E*) and sensible (*H*) heat flux of each leaf as well as its temperature (*Ts*).
- Calculation of **leaf stomatal conductance** (*gs*). Stomatal conductance values are calculated for each leaf according to its lighting, water potential and temperature, and to the temperature and relative humidity of the air. Stomatal conductance is given for individual leaves.
- Calculation of **sap flow** in the aerial part of the plant using the hydraulic architecture of the plant. Calculations take into account hydraulic resistances for sap flow and storage-release of water in the woody parts. These inputs are deduced from the geometrical and topological data of the computerized mock-ups. Outputs are the sap flow and water potential ( ) in each leaf and each internode of the plant.
- Calculation of the gross photosynthesis of each leaf, using the information of leaf temperature, leaf intercepted PAR, and stomatal conductance given by other modules of the model.

Transpiration and sap flow simulations are carried out for discrete time steps selected by the user. For each time interval, the model proceeds by iterations, switching backwards and forwards between the modules up to convergence. For example, the radiative balance of a base serves as an input for establishing its energy balance and, in return, the leaf temperature calculated by the energy balance is used to correct the radiative balance in the thermal infrared range. Similarly, stomatal conductance affects leaf temperature through the energy balance and, in return, leaf temperature affects stomatal conductance. Lastly, the leaf transpiration values determine sap flow and, ultimately, the leaf water potentials, which retroactively affect stomatal conductance.
The model description is detailed elsewhere (Dauzat and Rapidel, 1998).

The coffee Stand
The measurement plot was a large coffee estate in the Turrialba valley, in Costa Rica. The climate at Turrialba (600 m above sea level) is hot and humid. The soils in the plot are very deep andic type with a single horizon.

The coffee variety planted was Caturra, with limited vertical growth (2 metres). Planting densities under shade fluctuated around 6 000 plants per hectare, in rows two metres apart. A row of coffee trees consists of groups of plants 0.85 m apart, each group comprising two stumps on average (from one or two seeds). Each stump bears two suckers on average.

For work load reasons, the studies described in this paper were confined to 2½-year-old suckers, with 35 to 45 nodes, bearing 40 to 60 branches of 20 to 25 nodes. The approximate diameters were: 30 to 40 mm for the stump, 20 to 25 mm for the base of the sucker, and 8 to 9 mm for the base of the largest branches.

Architectural measurements

We reconstituted a 5.15 x 5.70 m^2 scene, including 18 groups of plants in three rows. The architecture of the single middle row was measured and corresponded exactly to reality. The row situated immediately to the North of the first row (1.9 m away) had recently been cut back (three months). The plants were therefore very small and did not cast any shade on the study row. They were constructed artificially from photographs. The row situated immediately to the South (2 m away) showed similar development to that of the study row. We reproduced the measured row, in the same sequence, but beginning with a tree chosen at random. This row was only involved in the interception of direct incident radiation by the 6 measured groups of plants at the end of the day.

The measured middle row included 6 groups of coffee trees bearing 15 suckers. The topology was determined for all the axes. The 3-D positions, cumulated lengths and diameters were determined every ten nodes starting from the bottom of each axis to its tip. On two axes of a plant, each internode length and its diameter were measured, making it possible to determine the laws of interpolation between the successive measurements on the other axes. The individual leaf areas were subsequently measured in the laboratory using a Li-Cor 3000 LAI-meter, previously calibrated.

Leaf shape and orientation in relation to the bearing axis were not measured. A leaf symbol was chosen and its dimensions adapted to the length:width ratio measured in our plot. Leaf orientations around the axes and variation of their orientation along the axes were fixed arbitrarily from photographs.

Hydric measurements

Measurements were taken in the plantation as a whole to determine the parameters of the model. Other measurements were performed on 5 stumps of the simulated scene to verify the functioning of the model.

More than 2000 measurements of stomatal conductance were taken, to establish the parameters of a stomatal conductance model, as proposed by Jarvis (1976). The model requires simultaneous measurements of stomatal conductance, leaf temperature, intercepted PAR, water vapour pressure difference between leaf and air and water potential of the leaf. They were performed using a LI-COR 1600 steady –state porometer, a Soil Moisture pressure chamber and data of air humidity from a meteorological station installed in the stand.

Measurements of hydraulic conductivity of the wood were taken from different plants of the stand, in the laboratory, as described by Sperry *et al.* (1988). Hydraulic conductivity of the petioles were determined by an indirect method using water potential differences and transpiration measurements. To check the functioning of the model, sap flows, leaf temperatures and leaf water potentials were measured. The precise places of each measure were precisely determined, in order to check the simulated value in the same situation of the mock-ups. Leaf temperature were measured with the thermocouple of the LI-COR clamp. The sap-flow meter used are probes designed by Granier (1985). Water potential were measured with a Soil Moisture pressure chamber, using the covered leaf method to determine the water potential in the sapwood vessels (Turner 1981).

Results

The transpiration models has very detailed outputs, at the scale of the leaves of each plant simulated. These outputs were checked against the measurements at each level.

The comparison of the leaf temperatures showed a systematic under-estimation by the model. The calculus of the laminar boundary layer thickness of the leaves has been modified to correct this bias. Once this modification was made, the model rendered correctly the other checking variables, water potentials and sap-flows at the base of the suckers (figure). Some differences remain between measured and modeled flows, but they have been considered as minor and no further modification of the model have been made.

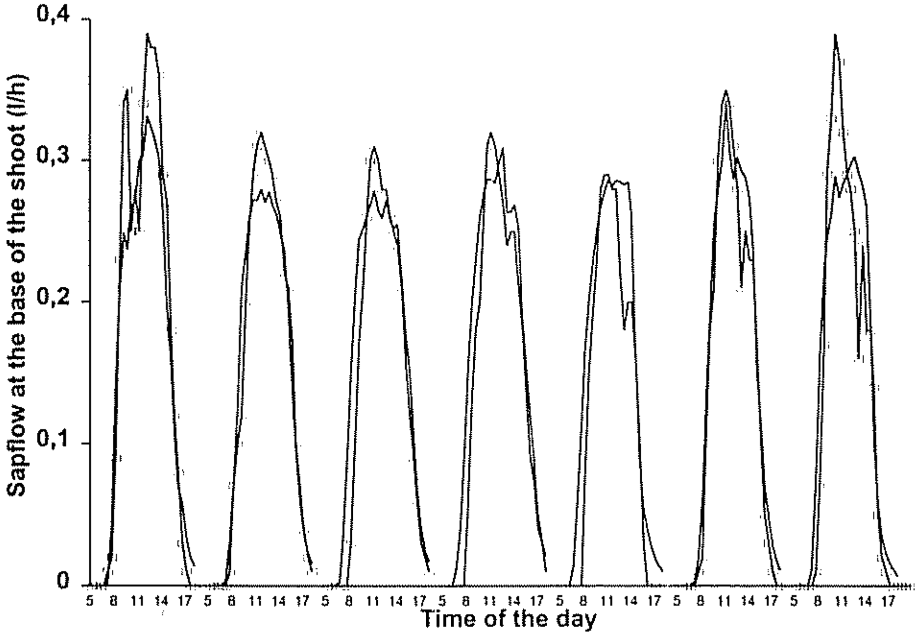

Figure 1. Comparison between measured (squares) and simulated (thin line) sap flow at collar level in a coffee tree. The data are given for 7 non consecutive days of march and April, 1993.

The main characteristic of this approach is the calculus of stomatal conductance of each leaf. The transpiration is then a function of this conductance and of the intercepted radiation. To check if this burdensome method is worthy, an alternative model was run (Shuttleworth and Wallace, 1985). It was parametrized with information extracted from our model, such as surface conductance of the stand, bulk intercepted radiation of the leaves and of the soil. It gave estimates much more different from the measured transpiration than our model (Rapidel, 1995).

The model has then been used to explore the physiological functioning of the stand. It has been shown that the transpiration is much more sensitive to the temperature of the leaves (that depends on air temperature, wind and radiation) than to the water potential in the soil.

The modeling was checked in the absence of Erythrina, cut down at the moment of the measurements. Two previous campaigns of architectural measures on Erythrina allowed us to build the corresponding mock-ups. So we could carry out simulation introducing Erythrina in the stand, in different environmental set of conditions (chosen from the data collected by the meteorological station during the experiment). The effect of the extraction of the water by Erythrina was not taken into account. It was shown that the presence of Erythrina actually disminished the transpiration and the photosynthesis of the coffee trees during cloudy or sunny and windy days. Nevertheless, during hot and still days, the negative effect of the radiation intercepted by the Erythrina trees was counterbalanced by the positive effects of the cooling of the leaves and daily transpiration remained similar as when the shade trees were absent.

Discussion and Conclusion

The model effectively renders the main parameters of hydric functioning in a plant, sap flow and potentials. However, a major modification concerning aerodynamic exchanges between the leaf and the atmosphere had to be made in order for sap flow, and especially surface temperatures to be correctly rendered.

3-D modelling of turbulent transfers is a serious theoretical problem that is still far from being solved, as already mentioned. The consequences of these missing elements for modelling will doubtless not always be negligible and efforts need to be made in this direction. More complete validation of the model in its current state would have required heat and water vapour profile measurements.

The model, which we tested on a few coffee plants, functions correctly. In particular, it seems possible to reconstitute flow within the plant by calculating the energy balance of each of its leaves. However, the precise description of its architecture then becomes necessary. This model also correctly renders the distribution of potentials within the crown.

The volume of measurements required for its precise and complete validation is large, especially as regards architectural description. Nevertheless, we feel this model has most interesting capabilities that would enable us in the short term to acquire a better understanding of the hydric and physiological functioning of intercrops and of agroforestry systems. Its application can be justified for such systems. For monocultures, the use of simpler models will probably suffice. In the heterogeneous systems mentioned, taking into account the competition between species, essential for comprehending the merits of such a combination, can be largely facilitated by developing this type of model, which considers plant geometry.

This model will then have to be completed, particularly by adding a module for water uptake and circulation in roots. Usable models, that are compatible with the one described here, exist (Ozier-Lafontaine *et al.* 1995) and in theory it should not be difficult to make the corresponding linkage. On the other hand, the type of validation measurements and application of such a model will remain to be designed.

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