
MODELS IN AGRICULTURE AND FOREST RESEARCH

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SIMULATION OF MICROMETEOROLOGICAL EFFECTS OF STRUCTURE AND FUNCTIONING OF PLANT CANOPIES

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INTRODUCTION

Vegetation grows at the interface between atmosphere and earth, so that its environment is closely connected to both the meteorological conditions above and the soil conditions underneath. Transport in air is relatively fast compared to transport in soil, and so as a first approximation the plants experience the meteorological conditions as measured by standard methods. However, quite often this assumption must be refined since strong gradients may occur within the vegetation, even within its limited height. The subject of this paper is how these gradients can be estimated by theoretical methods in order to provide good estimates of exchange fluxes between vegetation and atmosphere. Simulation is one of the most powerful tools to do so, as it enables a synthesis of theories on different but simultaneous processes (Goudriaan, 1977). In this contribution I would like to briefly mention some elements and results.

Independent evaluations of this model were given by others (Halldin, 1978; Hiramatsu et al., 1984; Vygodskaya and Gorshkova, 1978).

A sound general introduction to environmental plant physiology was given by Jones (1983).

VERTICAL PROFILES

For homogeneous plant canopies the dominating direction of the exchange fluxes is vertical, whether they are fluxes of water vapour, heat, CO₂, momentum or air pollutants. The gradient of the connected air characteristics is therefore vertical as well. The fluxes are generated at the usually vegetated earth surface.

The distribution of the sources and sinks of these fluxes is important, and is strongly affected by canopy structure. The canopy structure also influences absorption of momentum, and the profiles of wind and of ventilation.

RADIATION

Within the plant canopy the most important profile is the radiation profile, because it drives the processes of sensible and latent heat loss, of photosynthesis, and influences stomatal aperture. Sufficient knowledge exists of radiation transfer in plant canopies for a reliable

description of the profiles of various radiations components, such as diffuse and direct radiation, photosynthetically active radiation and of reflected radiation (Ross, 1975; Goudriaan, 1977; Spitters et al., 1986). It is important to distinguish diffused and direct solar radiation, at various depths in the plant canopy, because rate of photosynthesis and also stomatal aperture are strongly non-linear dependent on radiation level. Therefore just average figures for radiations are not sufficient, the distribution of intensities over the leaf surfaces as influenced by their inclination must be known as well. When this distribution is calculated, the contribution of photosynthesis and transpiration at each canopy level and illumination class must be accumulated to find the canopy totals.

PHOTOSYNTHESIS

The process of photosynthesis rarely depletes the CO_2 - content of the air between the canopy to such an extent that photosynthesis is considerably reduced. In other words, there is hardly any feed-back between the process itself and its effect on the areal profile of CO_2 . In such a situation of absence of feed-back the numerical integration of leaf photosynthesis over canopy height can be considerably simplified by the application of the principle of Gaussian integration (Goudriaan, 1986). Usually a three-point method is accurate enough for this application. This method has now also been implemented in a model for crop growth like SUCROS (Penning de Vries and Van Laar, 1982; Van Kraalingen, 1988). In fact, the Gaussian method has replaced the utilization of tables or of a descriptive summary routine as was published earlier by Goudriaan and Van Laar (1978). Even more important is that the simulation can now incorporate processes modifying the photosynthetic properties of leaves as a function of location in the canopy, or of time during the day, without almost any increase in computational effort.

CANOPY TRANSPIRATION

For transpiration the situation is more complicated. Canopy air is moistened by the transpiration of the leaves, and heated by the excess radiant energy not spent in transpiration. Only if moistening and heating occur precisely at a ratio s (slope of the saturated vapour pressure curve, in units mbar K⁻¹), will the vapour pressure deficit not be altered. Otherwise vapour pressure deficit inside the canopy will either increase, typically under high irradiation in combination with closed stomata, or decrease, especially when the leaves are still wet by previous rainfall.

The principle of this phenomenon is best explained in a situation where only homogeneous air conditions inside canopy are considered.

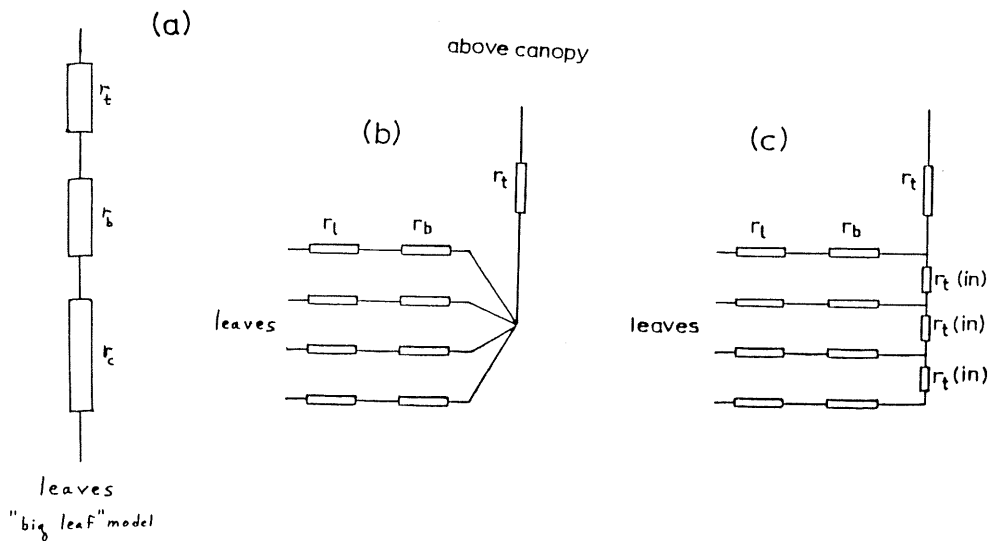


Fig. 1 Resistance schemes for gas exchange between the canopy layers and the air above the canopy. Fig. 1a describes the "big leaf" model. In this model all leaves experience the same irradiation and ambient air conditions.

In Fig. 1b a stratification of the canopy has been applied for the profile or radiations. There is only one status of air inside the canopy.

In Fig. 1c profiles of air temperature and humidity can occur as well due to resistances between the strata.

This approximation is one step more detailed than the so-called big leaf model (Fig. 1a), because stratification and classification of leaves is retained with respect to radiation (Fig. 1b). In this situation all fluxes originating from the leaves flow together to the in-canopy space, and it is their sum which generates the gradient across a turbulence resistance r_t on the way from the canopy to the air above:

$$T_i = T_a + \frac{r_t}{\rho c_p} \int_0^{LAI} CdL \quad (1a)$$

$$e_i = e_a + \frac{\gamma r_t}{\rho c_p} \int_0^{LAI} \lambda E dL \quad (1b)$$

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with:

T_a	air temperature at reference height	C
T_i	air temperature within the crop	C
e_a	air humidity at reference height	mbar
e_i	air humidity within the crop	mbar
C	sensible heat flux per unit leaf area	$W m^{-2}$
λE	latent heat flux per unit leaf area	$W m^{-2}$
γ	psychrometric constant (0.67)	$mbar K^{-1}$
ρc_p	volumetric heat capacity of air (1240)	$J m^{-3} K^{-1}$

LEAF TRANSPIRATION

The fluxes of sensible and latent C and λE are expressed on a leaf area basis. They depend on the difference ΔT (leaf-air) for C and on Δe (leaf-air) for λE :

$$\lambda E = \frac{\Delta e \rho c_p}{\gamma(r_b + r_l)} \quad (2)$$

$$C = \frac{\Delta t \rho c_p}{r_b} \quad (3)$$

where

r_b leaf boundary layer resistance $s m^{-1}$
 r_l leaf resistance (stomata / cuticle) $s m^{-1}$

Because the cell walls are wet, the water vapour pressure inside a leaf is equal to the saturated vapour pressure at leaf temperature, given by

$$e_s = 6.107 \exp (17.4 T / (239 + T)) \quad (4)$$

By linearization of this expression around air temperature Δe can be expressed in ΔT :

$$\Delta e = \text{“VPD”} + s \Delta T \quad (5)$$

where “VPD” is the vapour pressure deficit of the air surrounding the leaf and s the slope of the saturated vapour pressure curve at air temperature.

When the stomatal resistance increases, λE will be reduced according

to Eqn. 2. However, the concurrent increase in leaf temperature and consequently leaf-air vapour pressure difference will be not as much reduced as might be expected on basis of Eqn 2 alone. The best way to include this feed-back loop is by starting from Eqn. 5, and replace Δe and ΔT by their expressions in C and λE from Eqn 2 and 3:

$$\frac{(r_b + r_l)}{\rho c_p} \lambda E = \text{“VPD”} + \frac{s r_b C}{\rho c_p} \quad (6)$$

$$(r_b + r_l) \gamma \lambda E = \rho c_p \text{“VPD”} + s r_b C \quad (7)$$

or, using that the sum of C and λE is equal to the absorbed net radiation R_n per leaf area:

$$(r_b (s + \gamma) + r_l \gamma) \lambda E = \rho c_p \text{“VPD”} + s r_b R_n \quad (8)$$

Now for brevity of notation a new variable α is introduced, signifying the ratio $\gamma/(s + \gamma)$. The value of α is temperature dependent, and is about 0.3 at 20 C.

With this change of notation, Eqn 8 can be written as

$$(r_b + \alpha r_l) \lambda E = \rho c_p \text{“VPD”} / (s + \gamma) + (1 - \alpha) r_b R_n \quad (9)$$

or

$$\lambda E = \frac{(1 - \alpha) r_b R_n + \rho c_p \text{“VPD”} / (s + \gamma)}{r_b + \alpha r_l} \quad (10)$$

This way of writing λE clearly shows that the impact of r_l in comparison to r_b is reduced by a factor α . The physical reason of this reduction is feed-back through increase of leaf temperature. Also the radiation term and drying power term can be clearly distinguished in the numerator.

The complement of λE is the sensible heat loss C , which is given by

$$C = \frac{\alpha (r_b + r_l) R_n - \rho c_p \text{“VPD”} / (s + \gamma)}{r_b + \alpha r_l} \quad (11)$$

Back to canopy transpiration

The integrations in Eqn 1 are done over all the leaf layers, and yield the fluxes expressed per unit ground area. The vapour pressure deficit

inside the canopy “VPD” can be approximated in the same way as in Eqn.5, using the slope of e_s :

$$“VPD_i” = “VPD_a + s(T_i - T_a) - (e_i - e_a) \quad (12)$$

Substituting the Eqns 1 into Eqn. 12 yields:

$$“VPD_i” = “VPD_a” + \frac{r_t}{\rho c_p} \int_0^{LAI} (s C - \gamma \lambda E) dL \quad (13)$$

The change in “VPD_i” depends on a linear combination C and λE which are a function of “VPD_i” itself, as shown by Eqn 10 and 11.

Substitution of Eqn 10 and 11 into Eqn 13 gives

$$“VPD_i” = “VPD_a” + \frac{r_t}{\rho c_p} \int_0^{LAI} \frac{\alpha s r_l R_n - \rho c_p “VPD”}{r_b + \alpha r_l} dL \quad (14)$$

Collecting the terms with “VPD_i”:

$$“VPD_i” \left\{ 1 + r_t \int_0^{LAI} \frac{dL}{r_b + \alpha r_l} \right\} = “VPD_a” + \frac{r_t}{\rho c_p} \int_0^{LAI} \frac{\alpha r_l R_n - \rho c_p “VPD_a”}{r_b + \alpha r_l} dL \quad (15)$$

which enables a direct calculation of the vapour pressure deficit inside the canopy, incorporating the feed-back of transpiration. When resistances between air layers inside the canopy are no longer neglected, a distributed scheme emerges which gives rise to profiles of VPD (Fig. 1c). The equations for such a profile can be derived along similar lines as given above, but the complicating factor appears to be interdependence of the VPD's in all layers. In such a situation matrix algebra is necessary to find the solution of the profile (the “vector”) of VPD_i, or similarly of T_i and e_i. In earlier methods (see for instance Goudriaan and Waggoner, 1971) a matrix inversions was used to find this solution. Later, Chen (1984) presented a recurrent method to solve this profile without the necessity to call a matrix inversion routine. He discovered that the particular mathematical structure permits the calculation of the matrix determinant immediately within the same numerical loop from canopy bottom to canopy top as in which all leaf energy balances are calculated. The profiles of VPD_i, T_i and e_i are

subsequently calculated in another loop from top to bottom. By this method the time interval of the simulation could be increased from 1 s up to about 300 s. Further increase of the time interval is impeded by the time coefficients of heat transfer in the soil.

COUNTER-GRADIENT TRANSPORT

The schemes given so far amply transport driven by gradients between layers. Necessarily gradients and fluxes have the same orientation. However, especially in forests measurements frequently indicate inversed temperature profiles under conditions that the mean flux of sensible heat is upward. This apparent anomaly can be solved by accounting for correlation between fluctuations of wind and of temperature (Finnigan, 1985). The theory, which represents the turbulent structure of the transport by means of cross-wise products of fluctuations, is fairly complicated (Raupach and Shaw, 1982). A simple visualization of what actually happens can be obtained by considering the following hypothetical example.

On a clear day with much radiation brief but strong wind gusts interrupt periods of low wind with intervals of about 5 minutes. During the calm periods transport is small, and temperature and humidity build up, driven by the sources formed by the leaf surfaces. These sources are much stronger high up in the canopy, where the absorption of radiation is most intense. Therefore the rate of increase of temperature and humidity is much faster there than in the lower half of the canopy (Fig. 2). An inverse profile develops with a downward but small transport of heat and moisture. Given ample time the temperature in the lower half would creep up and reach higher values than above, but before this steady state profile can be formed an interrupting wind gust simply sweeps away all excess heat and moisture stored in the canopy air. This brief gust dominates the time-averaged profile of air temperature and humidity. The conclusion is that profile measurements of air properties inside leaf canopies cannot be used to calculate fluxes.

This process is especially important in forests, because of the thermal inertia of the large volume of air. In short canopies the steady state profile predominates because it will develop much faster. For simulation of mean fluxes of transpiration the steady state approach is usually good enough, because rate of transpiration is mainly driven by radiation. Cyclic wind gusts only slightly shift the mean values of fluxes if the mean wind run is correct (Ch. 4.5 in Goudriaan, 1977), but may reduce mean temperature gradients.

MICROCLIMATE OR MICROWEATHER?

The word "climate" has a tendency to be used in the meaning of

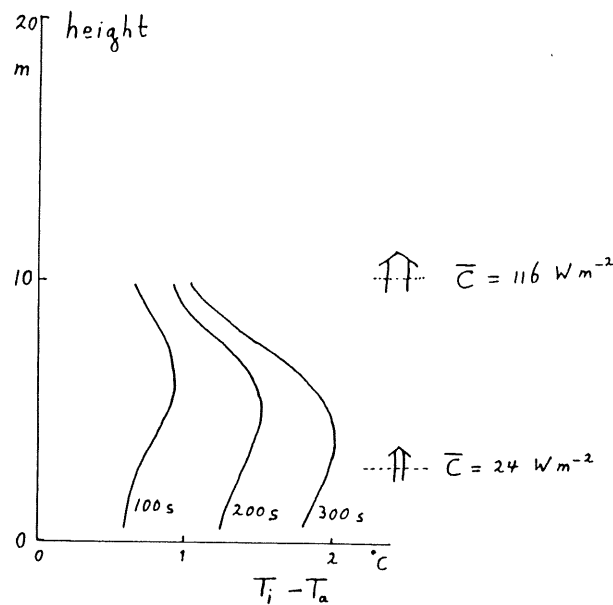


Fig. 2 Simulated profiles of air temperature in a forest, at subsequent time intervals after the passage of a wind gust. The time averaged upward heat flux \bar{C} is given at two levels. In spite of the average negative gradient of air temperature in the lower half, the average heat flux is positive, due to predominance of the large transport during the brief gust.

weather conditions present during a certain period of time. In my opinion this meaning is not precise enough, since it would make climate dependent on the duration of measurement. I would prefer to use the word "climate" in the meaning of "expectation value of the weather", which, in accordance with statistical theory, can only be estimated, but never precisely determined. Climate, then, is the background structure of the weather machinery to realize actual weather. This realization process has both deterministic and stochastic features. Mean values such as of temperature are deterministic features, whereas standard deviations of more complicated statistical characteristics describe the stochastic components of the weather generation process. To assess climatic change a long enough period of observation is needed to reduce the statistical error in the estimate of climate. Traditionally this period is taken as 30 years.

In this meaning of the word "climate" we often deal with microweather, and not with microclimate. The duration of simulation of microweather is usually too short to use the word microclimate. Only by a sensible choice of situations can the results be generalized to say something about microclimate.

Sometimes locations may be characterized as having a deviating microclimate, for instance on basis of their exposition, or of their soil characteristics.

SOME RESULTS

To investigate the effect of structure of vegetation a simulation was done with the same functional leaf characteristics of photosynthesis and leaf conductance, but different structural parameters. The difference was expressed by canopy height and leaf width. These geometrical factors influence leaf boundary layer resistance and the profiles of wind and turbulent exchange. As explained above, under tall canopies the thermal inertia of air becomes important. The simulated temperature profiles around noon on a summer day are shown in Fig. 3. A clear result is the strong gradient in short grass as compared to taller canopies. The soil surface was considered to be wet, so that there was a large direct evaporation. Soil evaporation was the strongest under sugarbeet and the smallest under grass.

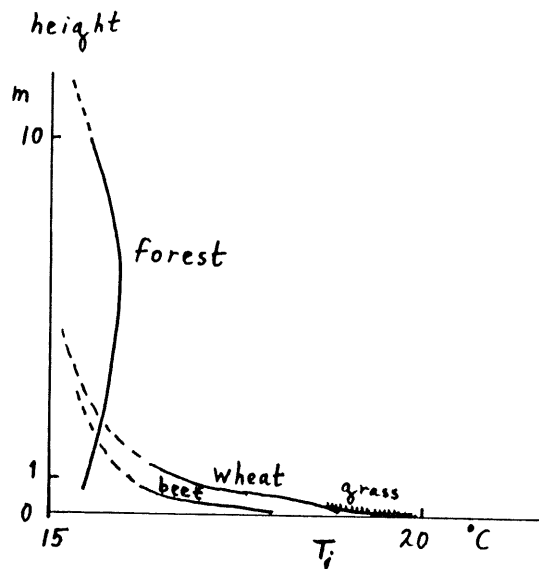


Fig. 3 Profiles of air temperature, simulated for different vegetation types, in the middle of a clear summer day. The profile for the forest was simulated as the mean profile over a period of 450 seconds between two gusts.

Under conditions of water shortage stomatal closure will occur, reducing both transpiration and rate of CO_2 assimilation. At the same time the canopy temperature, and it would be desirable if its measurement could give an indication of the water status of the canopy. To assess the relationship between them theoretically I have modelled the radiometric canopy temperature in relation with increasing water shortage. The simulated relationship between net CO_2 assimilation and observable radiometric canopy temperature is given in Fig. 4 for a wheat crop. This figure shows that a drop of about 30% in net CO_2 assimilation can be inferred from only one degree increase in observed canopy-air temperature difference. However, the figure also shows that a similar change in canopy-air temperature difference may be caused by a different canopy structure. Generally spoken the radiometrically observable canopy temperature increases with decreasing canopy height, without loss of net CO_2 assimilation.

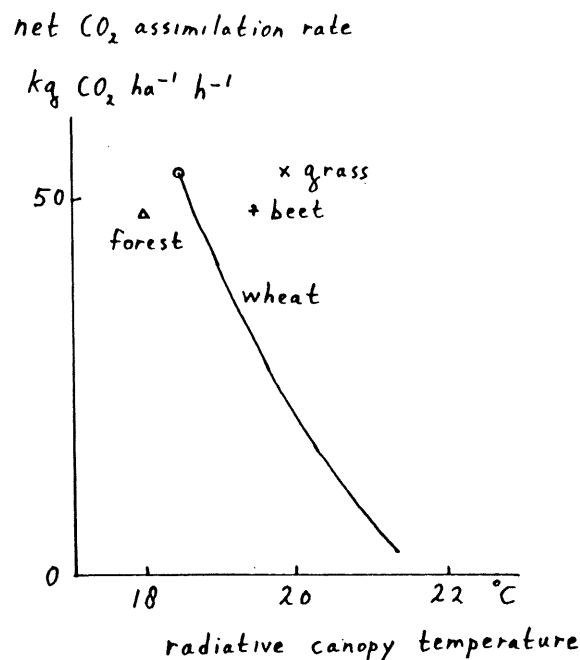


Fig. 4 Simulated relationship between net CO_2 assimilation and radiative canopy temperature as viewed from above, both in response to stomatal closure under increasing water shortage. Even under good water supply differences in radiative canopy temperature occur for different vegetation types, due to canopy structure.

These examples concern a few measurable quantities only. Others may be considered as well, such as the radiometric canopy temperature in the hot spot, which is measured with the radiometer pointed at its own shade. If the radiometer is moved fast enough the leaf temperature is still at its fully sunlit value, which is several degrees higher than the mean radiometric temperature. Again, structural characteristics such as leaf width, are very important for a correct interpretation.

REFERENCES

- [1] Chen, J. 1984. Mathematical analysis and simulation of crop micrometeorology. PhD Thesis, Agricultural University, Wageningen.
- [2] Finnigan, J.J. 1985. Turbulent transport in flexible plant canopies. In Hutschison and Hicks (Eds), *The Forest-Atmosphere Interaction*, 443-480. Reidel Publishing Company.
- [3] Goudriaan, J., 1977. Crop micrometeorology: a simulation study. Simulation monographs, Pudoc, Wageningen.
- [4] Goudriaan, J. and H.H. van Laar, 1978. Calculation of daily totals of the gross CO₂ assimilation of leaf canopies. *Neth. J. agric. Sci.* 26: 373-382.
- [5] Goudriaan, J., 1986. A simple and fast numerical method for the computation of daily totals of crop photosynthesis. *Agricultural and Forest Meteorology*, 38: 249-254.
- [6] Halldin, S., 1978. Comparison of forest water and energy exchange models. ISEM, Copenhagen.
- [7] Hiramatsu, Y., T. Seo and T. Maitani, 1984. Goudriaan's model of crop micrometeorology applied to the rice crop. *Berichte des Ohara Instituts fur landwirtschaftliche Biologie, Okayama Universitat*, Bd. XVIII, Heft 4, 183-209.
- [8] Kraalingen, D.W.G., 1988. An improved version of the assimilation calculations in SUCROS 87. CABO/TT Simulation Reports, Agricultural University, Wageningen
- [9] Penning de Vries, F.W.T. and H.H. van Laar (Eds), 1982. Simulation of plant growth and crop production. *Simulation Monographs*, Pudoc, Wageningen.
- [10] Raupach, M.R. and R.H. Shaw, 1982. Averaging procedures for flow within vegetation. *Boundary Layer Meteorology* 22, 79-90.
- [11] Ross, J., 1975. Radiative transfer in plant canopies. In: J.L. Monteith (Ed), 1975. *Vegetation and the atmosphere*, Vol. 1:13-52. Academic Press London
- [12] Spitters, C.J.T., H.A.J.M. Toussaint and J. Goudriaan, 1986. Separating the diffuse and direct component of global radiation and its implications for modelling canopy photosynthesis. Part I. Components of incoming radiation. *Agricultural and Forest Meteorology*,

38, 217-229

[13] Vygodskaya, N.N. and I.I. Gorshkova, 1978. Theory and experiment in vegetation remote sensing. (In Russian). Hidrometeoizdat, Leningrad

ESPECIALLY RECOMMENDED:

Jones, H.G., 1973. Plants and microclimate. A quantitative approach to environmental plant physiology. Cambridge University Press.