

EXAMINATION OF MONTEITH'S PARAMETERIZATION
OF CANOPY RESISTANCE

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INTRODUCTION

For more than twenty years, the most common approach to parameterize the effect of environmental factors on stomatal behaviour has been the so-called Jarvis type models (Jarvis, 1976), in which stomatal resistance is expressed as a minimum resistance multiplied by a series of independent stress functions combined in a multiplicative way (each function representing the influence of one factor). Recently, the response of stomata to humidity has been reinterpreted in a different way: It seems that the correlation between stomatal resistance and atmospheric humidity is purely empirical and that the mechanism underneath is based on the water-loss rate of the leaf (Mott and Parkhurst, 1991). Stomata appear to respond to the rate of transpiration rather to air humidity per se. Monteith (1995a,b) showed that the leaf stomatal conductance can be interpreted as a linear decreasing function of transpiration with two empirical parameters: a maximum conductance and a maximum rate of transpiration. He suggested also that this relationship between stomatal conductance and transpiration rate could be up-scaled from leaf to canopy, in the same way as the Jarvis model. The aim of this paper is to assess and discuss this new formulation of stomatal behaviour proposed by Monteith and to interpret the parameters at canopy scale.

MONTEITH'S FORMULATION

The Penman-Monteith single-source model (Monteith, 1981) gives the flux of evaporation from a fully-covering canopy in the form of the following equation

$$\lambda E = \frac{\varepsilon A + \rho \lambda D / r_a}{\varepsilon + 1 + r_s / r_a} \quad (1)$$

where $A = R_n - G$ is the available energy (with R_n the net radiation and G the soil heat flux), $D = q^*(\theta) - q$ is the potential saturation deficit of the air (with θ the air temperature and q the specific

humidity of the air), ε is the dimensionless slope of the saturation specific humidity q^* and varies with air temperature, r_a is the bulk aerodynamic resistance to heat and water vapour transfer through the surface layer, r_s is the bulk surface resistance to water vapour transfer, ρ is the air density and λ is the latent heat of vaporisation. Defining potential evaporation from a given vegetation canopy (denoted by E_p) as the evaporation from this canopy when all the exchange surfaces are saturated, i.e., when $r_s = 0$ in Eq.(1), evaporation can also be expressed as a function of E_p as

$$E = k E_p \quad \text{with} \quad k = 1 / \left(1 + \frac{1}{\varepsilon} \frac{r_s}{r_a} \right) \quad (2)$$

According to Monteith (1995a,b) the canopy surface resistance reads as

$$r_s / r_{sn} = E_x / (E_x - E) \quad (3)$$

In this analysis soil evaporation is assumed to be negligible, which means that transpiration rate in Eq.(3) is strictly the same as canopy evaporation in Eq.(1) or (2). Consequently, combining Eq.(2), expressing the thermodynamic dependence of E on r_s , with Eq.(3), expressing the physiological dependence of E on r_s , leads to a quadratic dependence for r_s , whose appropriate root is

$$r_s = \left[-\Lambda + \sqrt{\Lambda^2 + 4(1 + \varepsilon)r_a r_{sn}} \right] / 2 \quad (4)$$

with $\Lambda = (1 + \varepsilon)r_a(1 - E_p / E_x) - r_{sn}$

When the quadratic equation obtained by combining Eq.(2) with Eq.(3) is solved in E instead of r_s , the appropriate root gives (Monteith, 1995b)

$$E = \left[E_p + \alpha_n E_x - \sqrt{(E_p + \alpha_n E_x)^2 - 4 E_x E_p} \right] / 2 \quad (5)$$

$$\text{with} \quad \alpha_n = 1 + \frac{1}{\varepsilon + 1} \frac{r_{sn}}{r_a}$$

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The limit rate of transpiration E_x is a notional maximum rate of water supply, the precise significance of which is not known. However, a simple physical interpretation can be inferred from Eq.(5). When atmospheric demand becomes very large, i.e., when E_p tends to infinity (all other parameters being kept constant), it can be shown from Eq.(5) that evaporation tends to E_x . So, E_x can be interpreted as the limit value of actual evaporation when the atmospheric demand tends to infinity. In other words, it is a notional maximum amount of water available in the soil for extraction by the canopy per unit time. Little is known also on the significance and possible values of r_{sn} .

THE JARVIS TYPE REPRESENTATION

The Jarvis type models (Jarvis, 1976; Stewart, 1988) describe the response of stomata to environmental factors (at leaf scale as well as at canopy scale) in the form of a minimal resistance multiplied by the product of independent stress functions interacting without synergy

$$r_s = r_{smin} F_1(S) F_2(T) F_3(D) F_4(\Psi_l) \quad (6)$$

Here, r_{smin} is the minimum stomatal resistance observed in optimal conditions, i.e., if none of the controlling variables is limiting (it is taken to be equal to 40 s m^{-1} in our analysis). S is the incoming solar radiation, T is the air temperature, D is the water vapour saturation deficit, Ψ_l is the leaf water potential, which at the scale of a stand of vegetation is often replaced by the bulk soil water potential or the soil water content averaged over the root zone. Each function (F_i) varies from unity to infinity.

The influence of solar radiation can be expressed in terms of a hyperbolic function of the

$$F_3(D) = (1 - \alpha D)^{-1} \quad \text{with} \quad 0 < D < 1/\alpha \quad (8)$$

For the Konza Prairie in Kansas (FIFE data), Stewart and Gay (1989) give a mean value of about 24 to the empirical coefficient α , with D expressed in kg kg^{-1} . However, Lynn and Carlson (1990, p.17) question the real effect of air humidity on stomatal resistance. They think the role played by the saturation deficit is indirect. An increase of D damps the leaf water potential which, in turn, is responsible for an increase of stomatal resistance. As to the dependence of stomatal resistance on leaf water potential it can be expressed in different ways (Jarvis, 1976; Choudhury and Idso, 1985). In their IAGL (Institut d'Astronomie et de Géophysique Georges Lemaître) land surface model, de Ridder and Schayes (1997) employ an hyperbolic dependence of the form

$$F_4(\Psi_l) = (1 - \Psi_l / \Psi_{cc})^{-1} \quad (9)$$

where Ψ_{cc} represents the value of leaf water potential at which a complete stomatal closure occurs ($\Psi_{cc} \approx -2.5$ bars).

MATCHING THE TWO FORMULATIONS

In this section we show how the Jarvis model can be transformed and put in the same form as the Monteith model.

The bulk leaf water potential Ψ_l is related to the bulk soil water potential Ψ_s by means of the Ohm's law type equation originally proposed by van den Honert (1948)

$$\Psi_l = \Psi_s - r_{sp} \lambda E \quad (10)$$

where r_{sp} is the total soil-plant resistance and E is the water flux through the soil-plant system, assumed here to be equal to the total evaporation rate. The significance and value of

where 0.0013 (m²) is the ratio of a parameter relating root distance and geometry to the reciprocal of the effective rooting depth; k_1 is a conversion factor equal to 0.4 10⁻¹⁰ when r_{SN} is expressed in bar (Wm⁻²)⁻¹; Z_{ef} is the effective rooting depth (m), assumed to be 1 m in our analysis; K_S is the soil hydraulic conductivity (m s⁻¹), which is linked to the soil water potential by $K_S = K_{Sat}(\Psi_{Sat}/\Psi_S)^{3/b+2}$ (Campbell, 1974), where K_{Sat} and Ψ_{Sat} are respectively the conductivity and the water potential at field saturation.

Taking into account Eqs.(9) and (10), Eq.(6) can be rewritten as

$$r_s = \frac{\eta_{13} / (1 - \Psi_s / \Psi_{cc})}{1 - (r_{sp} \lambda E) / (\Psi_s - \Psi_{cc})} \quad (12)$$

with $r_{13} = r_{smin} F_1(S) F_3(D)$. Eq.(12) is an expression similar and functionally equivalent to Eq.(5), when rewritten as $r_s = r_{SN} / (1 - E/E_x)$. Matching term by term these two equations leads to

$$r_{SN} = \eta_{13} / (1 - \Psi_s / \Psi_{cc}) = \eta_{13} F_4(\Psi_s) \quad (13)$$

and

$$\lambda E_x = (\Psi_s - \Psi_{cc}) / r_{sp} \quad (14)$$

Consequently, it appears that Monteith's parameterization of canopy stomatal resistance is not different from the Jarvis approach since the former can be inferred from the latter. The two parameters (r_{SN} and E_x) of Monteith's relationship can be interpreted in terms of the parameters and functions making up the Jarvis model and their physical significance appears now clearly. r_{SN} represents the canopy stomatal resistance when the leaf water potential is equal to the soil water potential ($\Psi_l = \Psi_s$), i.e., at zero transpiration (conditions experimentally encountered at pre-dawn). E_x represents the flux of water extracted from the soil when the leaf water potential is equal to the limit value Ψ_{cc} (i.e. its lowest possible value according to the parameterization used for F_4). It is the maximum flux of water the canopy can potentially extract from the soil.

The issue that arises now is the dependence of the canopy minimal stomatal resistance r_{SN} upon water vapour saturation deficit. To Monteith's mind, r_{SN} cannot depend upon saturation deficit, since in Eq.(3) the dependence of canopy resistance upon transpiration theoretically replaces the dependence upon saturation deficit. However, the matching of the two models leads to this apparent double dependence (r_{SN} is a function of

r_{13} and then of $F_3(D)$, as shown by Eq.(13)). It is possible to keep only one dependence (that upon transpiration) by assuming with Lynn and Carlson (1990) that stomata do not respond directly to D (but indirectly through Ψ_l) and by putting then $F_3(D)=1$. From a pragmatic viewpoint this idea seems recommendable. In effect, this alternative leads to a sound and simple interpretation of the action of saturation deficit on stomatal aperture: When D increases, transpiration increases and consequently leaf water potential decreases according to Eq.(10) (assuming Ψ_s and r_{sp} to remain constant), which provokes a stronger stomatal closure.

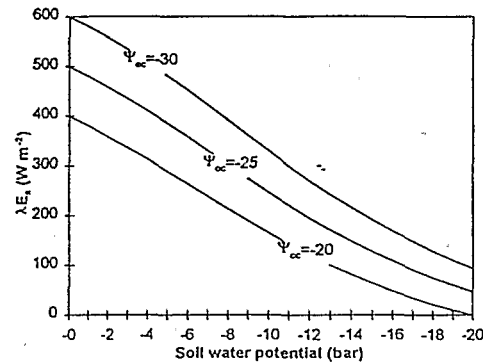


Fig.1- Maximum canopy evaporation λE_x (given by Eq.(14)) versus soil water potential Ψ_s for different values of leaf water potential Ψ_{cc} corresponding to a complete stomatal closure (defined by Eq. (9)).

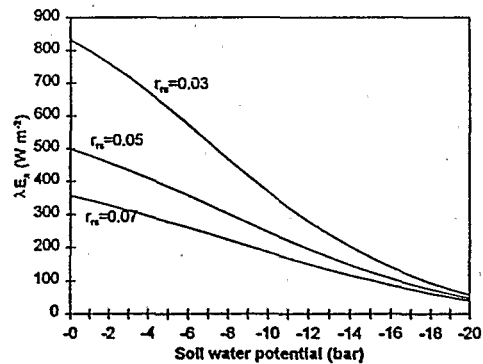
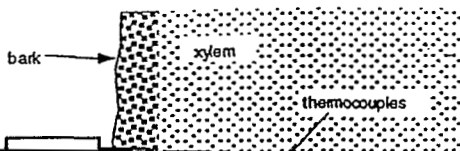


Fig.2- Maximum canopy evaporation λE_x versus soil water potential Ψ_s for different values of the root-stem resistance r_{rs} .

NUMERICAL RESULTS

For a particular type of soil, characterised by fixed values of K_{Sat} , Ψ_{Sat} and b , and a given vegetation, characterised by fixed values of Ψ_{cc} , r_{rs} and Z_{ef} , the soil-plant resistance r_{sp} and then the maximum canopy transpiration λE_x depend only upon the soil water potential Ψ_s . The values of the parameters used in the simulations are those given in the text. For the soil we took: $K_{Sat} = 6.3 \cdot 10^{-6}$ m s⁻¹,



diameters proportional to size class distributions determined from vegetation surveys of both cottonwood and willow. Nine trees of cottonwood were selected with DBH's ranging from 0.14 to 0.75m. Six trees of willow were selected with DBH's ranging from 0.15 to 0.24m.

Tree Species	DBH (m)	Sapwood Area (m ²)	Maximum Flow (kg H ₂ O hr ⁻¹)	Maximum Flux (cm ³ cm ⁻² hr ⁻¹)	Total Daily Water Use (kg d ⁻¹)
Cottonwood	0.14	0.009	3.0	32.7	20.4
	0.19	0.015	6.6	43.7	50.2
	0.20	0.016	4.7	29.2	35.9
	0.43	0.068	25.1	37.2	219.9
	0.48	0.081	28.2	34.9	256.8
	0.50	0.085	34.4	40.4	308.4
	0.69	0.143	68.5	48.1	574.1
	0.71	0.150	58.8	39.1	520.1
	0.75	0.162	87.8	54.3	702.9
Willow	0.15	0.002	4.6	42.5	36.7
	0.24	0.027	14.9	66.5	120.7
	0.24	0.027	5.1	19.3	39.7
	0.24	0.027	7.9	29.9	52.1

Table 1. Physical characteristics along with transpiration for 9 cottonwood and 4 willow trees along the San Pedro River. Data are for julian day 223 (August 11). DBH is bole diameter at 1.5m height. Sapwood area = basal area - heartwood area - bark area.

$$\rho c = \frac{Q}{(\epsilon \pi r^2 \Delta T_m)} \quad (3)$$

ΔT_m is the maximum temperature rise recorded by the thermocouple. Q is the heat input ($J m^{-1}$) of the heat pulse and is calculated using equation (4):

$$Q = tI^2 \left(\frac{R_h}{l} \right) \quad (4)$$

4. RESULTS

Table 1 shows all trees measured for sap flux at Lewis Springs during the August 1997 SALSA field campaign. DBH and sapwood area are given for each tree, as well as maximum observed daily transpirational rate ($kg H_2O hr^{-1}$), maximum flux density ($cm^3 H_2O cm^{-2} sapwood hr^{-1}$), and the total daily transpiration ($kg H_2O d^{-1}$) for julian day 223 (August 11). Mass flow rate (kg of

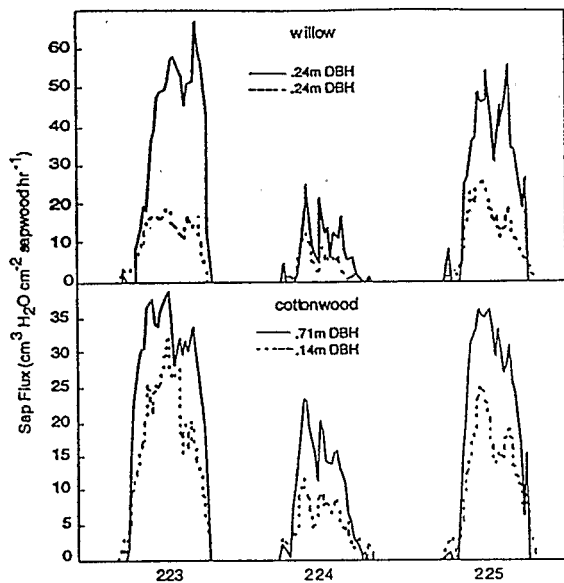


Fig. 3. Sap flux density for two representative cottonwood and two representative willow for Julian days 223-225 (August 11-13).

It appears that cottonwood has a relatively stable water source to draw on, and consequently patterns of transpiration are driven by climatic conditions (i.e. solar radiation) and less by soil water availability.

Snyder *et al.* (this issue) found that midday plant water potential remained constant for cottonwood over a variety of climatic conditions, suggesting that these plants may be adjusting stomatal aperture to regulate water potential and transpirational flux. The observation that sap flux density is similar between individuals of cottonwood of different size supports the idea that these trees may be operating at some threshold level for transpirational flux.

Position in the canopy may also play an important role in sap flux. Both cottonwood trees in Fig. 3, although of different size, had portions of their crowns located in the overstory. This would put them in a position to receive unobstructed solar radiation throughout the day. Of the willow trees however, only the one with the highest flux shown in Fig. 3 had any portion of its crown located in the overstory. It was located on the western edge of the forest and was in a position to receive unobstructed afternoon sunlight. These differences in overall stand structure may lead to large differences in sap flux, and transpiration for sub-dominant species or individuals, but relatively small differences for dominant/co-dominant species or individuals.

In conclusion, stand structure and climatic factors both play important roles in controlling riparian water fluxes. Canopy position (dominant, co-dominant, and sub-dominant) affects the amount of solar radiation incident on an individual plant canopy. This information could support the effort to scale the consumptive water use of individual trees to the level of the stand and

provides important information about species' roles in ecosystem processes (Williams *et al.*, this issue).

6. ACKNOWLEDGMENTS

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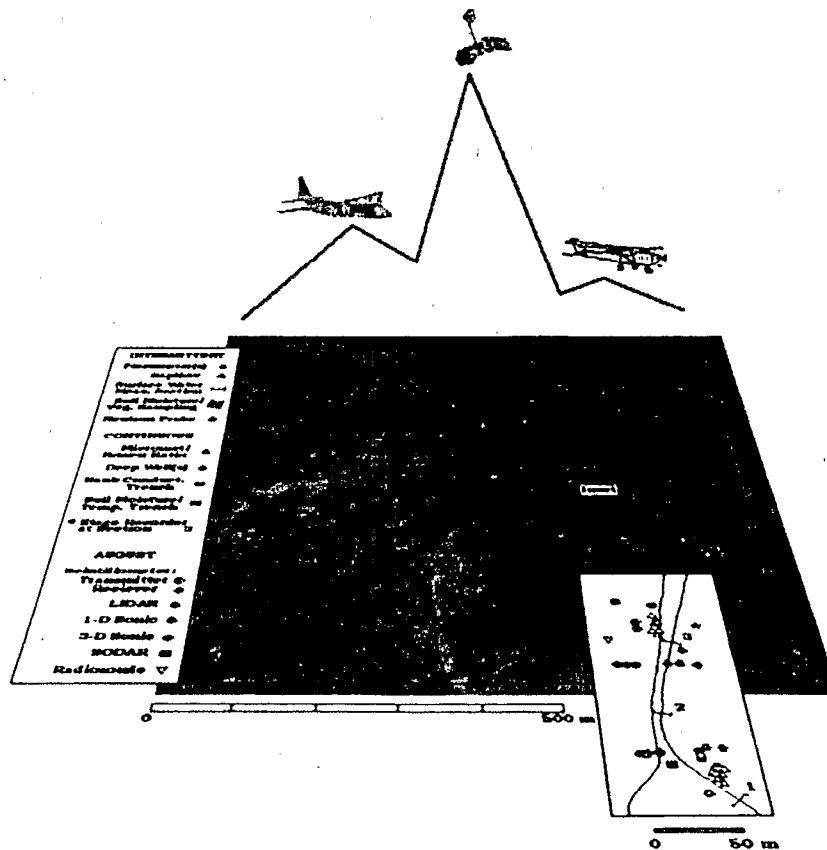
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Semi-Arid Land-Surface-Atmosphere (SALSA) Program



Preliminary Results of 1997 Activities

Papers to be Presented at a Special Symposium on Hydrology, Session on Integrated Observations of Semi-Arid Land-Surface-Atmosphere Interactions
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