

The APSIM – MICROMET module

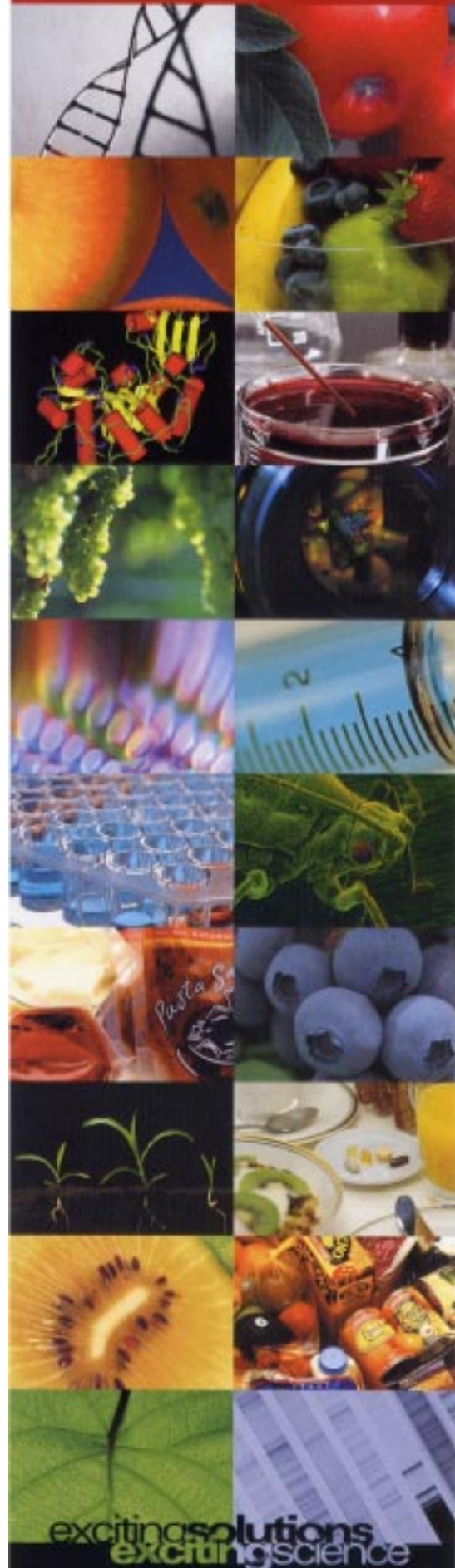
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The Role of MICROMET within APSIM

APSIM, the Agricultural Production Systems Simulator (Keating *et al.* 2003) is a modular simulation model with its origins in the simulation of farm cropping systems but with more recent developments the simulation of plantation forests and natural vegetation systems. With this increased diversity of applications also required is an enhanced description of the potential evapotranspiration for the range of vegetation systems now available in APSIM. The module MICROMET, described here, has been developed to allow the calculation of potential transpiration for multiple competing canopies that can be either layered or intermingled.

The documentation below describes how potential transpiration is calculated as well as the data requirements and inter-dependencies with other modules.

The Scope and Limitations of MICROMET

MICROMET contains the range of calculations required to describe the energy and water balance of the interface between plants and the atmosphere. The processes described include:

- interception of radiation;
- interception of rainfall;
- modification of canopy conductance for the presence of competing canopies, humidity, and nutrition level; and
- potential transpiration of the individual plant canopies.

The driving force in all calculations is the balance of water and energy. The implementation is suitable for canopies of either single or mixed species and the species mix may change within a simulation.

Information describing the state of each component plant canopy is passed to the MICROMET by individual crop modules. The information includes state variables such as canopy height and depth, leaf area index (green and total), and stress indicators for each of the individual canopies. The individual canopies are combined to describe the overall, or combined, plant canopy so that interception of rainfall and irrigation and light interception can be calculated. The scheme allows the calculation of individual canopy and aerodynamic conductance that take account of the competitor canopies. MICROMET does not calculate actual transpiration or growth. Other APSIM modules calculate soil water uptake so MICROMET calculates only the potential water uptake. Here 'potential' means 'unlimited by soil water availability'.

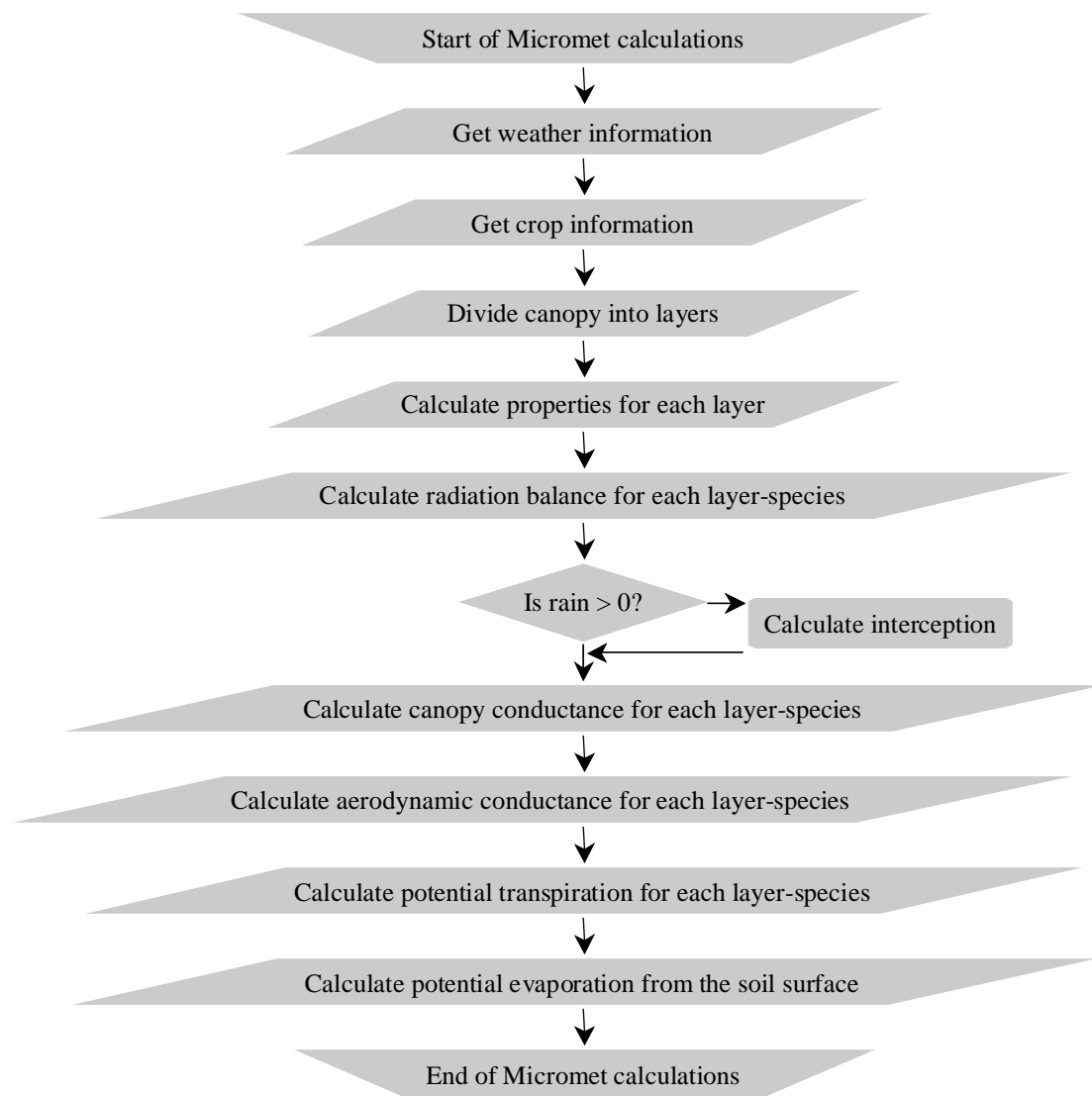
Currently most crop modules calculate the radiation balance and soil water demand internally. In order to be used with MICROMET, those modules will have to be altered to accept an externally-calculated soil water demand as a simulation option.

Notation Conventions

In order to simplify variable definitions, several notation conventions are defined:

- i and I layer index (numbered from the bottom up) and the highest layer
 j and J species index and the maximum number of species
- X_{ij}
- for variables constant within a layer (e.g. leaf area index) X_{ij} stands for the value in the i 'th layer attributable to the j 'th species;
 - for variables which vary within a layer (e.g. cumulative LAI) X_{ij} refers to the value for the j 'th species at the top of the i 'th layer.
 - a "." may be used to indicate all i or j , e.g. $X_{i.}$.
 - where the meaning is obvious or redundant, i or j may be omitted.
 - X_0 refers to the soil surface; X_I refers to the top of the overall canopy.
- ΔX_{ij} change in X_{ij} within layer i , i.e. $X_{ij} - X_{i-1j}$

Flowchart of MICROMET calculations



Component Canopies Represented within a Combined Canopy

Consistent with the design of APSIM, the individual and combined canopies are assumed to be horizontally homogenous. Each component canopy has a top, a base, green and total leaf area indices and green and total canopy covers. Between the base and top, each component canopy is assumed to be horizontally and vertically homogeneous. Given these assumptions, a leaf area density of each component can be calculated from

$$L_{d j} = \frac{L_j}{z_{top j} - z_{base j}} \quad (1)$$

where L_d is the leaf area density (m^2 leaf / m^3), L is the cumulative leaf area index (m^2 leaf / m^2), and z_{top} and z_{base} are the height of the top and base of the component canopy (m). For many of the existing agricultural crop modules the assumption that the canopy is vertically homogenous to ground level may be reasonable, however it is obvious that such an assumption is not adequate to describe the canopy shape of mature trees. Although each individual canopy has uniform density between its base and top, the leaf density of the combined canopy can vary, in the stepwise fashion, with height depending on the z_{top} and z_{base} of the component canopies. The combined canopy is divided into layers according to where the component composition changes (Figure 1). The layers are numbered from the soil surface upwards.

The cumulative leaf area index, L , of the combined canopy, is calculated from each L_d of the component canopies:

$$L(z) = \int_0^z \left(\sum_{j=1}^J L_{d j} \right) dz \quad (2)$$

where z is height from the soil surface (m). The fraction that each component contributes to ΔL_i , f_{ij} , is calculated by

$$f_{ij} = \frac{\Delta L_{ij}}{\sum_{j=1}^J \Delta L_{ij}} \quad (3)$$

These calculations are shown in graphical form in Figure 1.

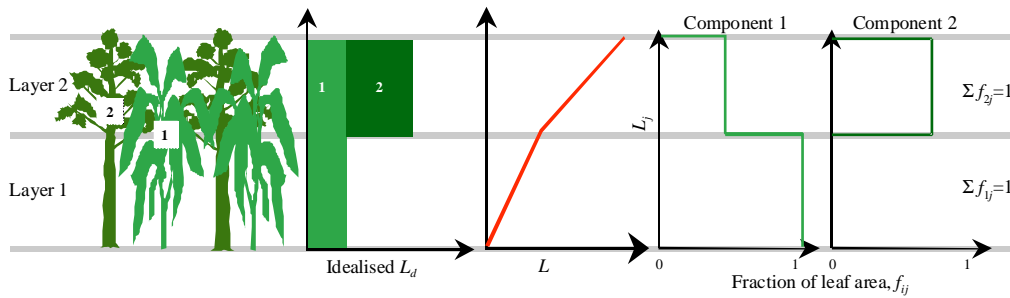


Figure 1. Idealisation of the component canopies

Radiation Available for Evapotranspiration

Incident radiation is calculated for each species and layer.

Short-wave radiation

The decline in solar radiation through the canopy is calculated using the Beer and Lambert law

$$R_{s_i} = R_{s_l} \exp(-k_i (L_l - L_i)) \quad (4)$$

where R_s is the short-wave radiation (W /m^2) and k is the extinction coefficient (-). The canopy can be layered so the value of k may vary with height, and therefore L , because the species mix changes between layers. In this case

$$k_i = \sum_{j=1}^J f_{ij} k_j . \quad (5)$$

Note that the same value of k , and α (see below) are assumed to apply to all of photosynthetically-active, long-wave, and short-wave radiation. The amount of radiation absorbed in any layer is calculated from

$$\Delta R_{s_i} = (1 - \alpha)(R_{s_i} - R_{s_{i-1}}) . \quad (6)$$

where α is the whole system albedo and is calculated from

$$\alpha = \frac{R_{s0}}{R_s} \alpha_{soil} + \sum_{i=1; j=1}^{I:J} \left(\frac{R_{s_{ij}}}{R_s} \alpha_j \right) . \quad (7)$$

During the calculation of the energy available for transpiration the amount of radiation absorbed by each component-layer must be determined. Equation 6 is used to calculate the radiation absorbed in each layer. That absorbed radiation is then partitioned amongst the component species in the layer by

$$\Delta R_{s_{ij}} = \Delta R_{s_i} \frac{f_{ij} k_j}{\sum_{j=1}^J f_{ij} k_j} \quad (8)$$

Long-wave radiation

Net longwave radiation follows the relationship (Linacre 1968, Leuning *et al.* 1991),

$$R_{L\downarrow} = \left(C_L + (1 - C_L) \frac{n}{N} \right) (\varepsilon_A - \varepsilon_C) \sigma (T + T_{abs})^4 \quad (9)$$

where $R_{L\downarrow}$ is the net longwave rations, positive downwards (W /m^2), C_L is a constant between 0 and 1 to account for the effects of cloud cover (-), n is the length of time with clear sunshine (s), N is the day length (s), ε_A and ε_C are the clear sky and canopy emissivities (-), σ is the Stefan-Boltzmann constant ($\text{W /m}^2 \cdot \text{K}^4$) T and T_{abs} are the average air temperature at measurement height and the constant to correct from Celsius to Kelvin ($^{\circ}\text{C}$). By default $C_L = 0.1$. The emissivity of the atmosphere is calculated using (Swinbank, 1963)

$$\varepsilon_A = 9.37 \cdot 10^{-6} (T + T_{abs})^2 \quad (10)$$

The emissivity of the whole surface (canopy and soil) is calculated in a fashion similar to that employed for the whole surface albedo.

$$\varepsilon_c = \frac{R_{s0}}{R_s} \varepsilon_{soil} + \sum_{i=1; j=1}^{I:J} \left(\frac{R_{s_{ij}}}{R_s} \varepsilon_j \right) \quad (11)$$

Partitioning of long-wave radiation between layers and components is analogous to that for short-wave radiation as described above.

Radiation energy available for evapotranspiration

The general equation describing the energy intercepted and available for evapotranspiration is:

$$\Delta R_{ij} = \Delta R_{s\downarrow ij} + \Delta R_{L\downarrow ij} \quad (12)$$

Interception of Rainfall

Interception of rainfall is calculated using a flexible equation with user settable parameters. This equation is

$$P_{int} = AP^B + CL_I + D \quad (13)$$

where P_{int} is the total amount of interception and A , B , C , and D are empirical parameters describing the relationship between rainfall and leaf area index on interception. Stem-flow is assumed to be zero as there is no mechanism for dealing with spatially non-uniform water input in APSIM. The intercepted rainfall does not reach the soil surface. For the purposes of calculating the effect of the evaporation of intercepted rainfall in reducing evaporative demand we assume that half the evaporation of intercepted rainfall occurs at night. Obviously this is incorrect for any single rainfall event but it is considered adequate as most APSIM simulation runs are for more than a year.

Evaporation of intercepted rainfall from the wet leaves is assumed to take place at a rate defined by the Penman-Monteith equation (see below) with zero surface resistance. This evaporation rate is used to calculate the length of time required to dry the leaves, t_{int} , and this is deducted from the day length. The daytime energy required to evaporate the intercepted rainfall, R_{int} is calculated from $\lambda P_{int}/2$ where the division by 2 is to reflect the assumption that half the intercepted rainfall evaporates at night.

Currently there is no allowance for the interception of irrigation in MICROMET.

Canopy Conductance for component canopies

The canopy conductance is calculated for each component in each layer. This allows for the differing contribution to leaf area index and radiation environment within the combined canopy to be taken into account before aggregating the layers to find the canopy conductance for each component.

Scaling from stomatal to canopy conductance

The canopy conductance term used in the Penman-Monteith equation is calculated from a modified version of the scheme described in Kelliher *et al.* (1995). The modification is the inclusion of f to account for multiple species within a layer and therefore the scheme of Kelliher *et al.* (1995) to multiple canopy layers. In order to develop the equation describing the canopy conductance we begin by stating that the canopy conductance is the sum of the individual leaf stomatal conductances

$$G_c = \sum_{i=1}^I \sum_{j=1}^J G_{cij} = \sum_{i=1}^I \sum_{j=1}^J \left(f_{ij} \int_0^{L_i} g_{sij}(L') dL' \right) \quad (14)$$

where G_c is the canopy conductance (m/s) and g_s is the stomatal conductance, (m/s).

Stomatal conductance is assumed to respond to photosynthetically-active radiation (PAR) level, and therefore to short-wave radiation, according to a hyperbolic function (Kelliher *et al.* 1995)

$$g_s = \frac{g_{s\max} R_a}{R_a + R_{a50}} F_{rgr} = \frac{g_{s\max} R_s}{R_s + R_{s50}} F_{rgr} \quad (15)$$

where $g_{s\max}$ is the maximum stomatal conductance (m/s), R_a is the PAR absorbed by an individual leaf (W/m^2), R_{a50} is R_a at which $g_s = g_{s\max} / 2$, (W/m^2), R_{s50} is R_s at which $g_s = g_{s\max} / 2$ (W/m^2), F_{rgr} is a relative growth rate or stress factor for the canopy to capture effects of nutrition, temperature and atmospheric saturation deficit (-) and is supplied to MICROMET by the relevant crop module. The second equality in eq. 15 comes about because

$$R_s = k f_{sw \rightarrow PAR} R_a \quad (16)$$

where $R_{sw \rightarrow PAR}$ is the factor converting short-wave radiation to PAR (-). The decline in R_s through the canopy has been described in eq. 4.

The equations above can be combined to give

$$G_{cij} = f_{ij} F_{rgrj} \int_0^{\Delta_i} \frac{g_{s\max j} p_{ij} k_i R_i \exp(-k_i L)}{p_{ij} k_i R_i \exp(-k_i L) + k_i p_{ij} R_{s0j}} dL', \quad (17)$$

where

$$k_i = \frac{\sum_{j=1}^J L_{ij} k_j}{\sum_{j=1}^J L_{ij}}, \quad (18)$$

and

$$p_{ij} = L_{ij} k_j / \sum_{j=1}^J L_{ij} k_j \quad (19)$$

which can be solved to give

$$G_{cij} = \frac{F_{rgrj} f_{ij} g_{s\max j}}{k_i} \ln \left(\frac{R_i + R_{s0j}}{R_i \exp(-k_i \Delta_i) + R_{s0j}} \right) \quad (20)$$

When there is only one species and under no nutritional or vapour pressure deficit stress, after correcting to the different unit system, equation 20 reduces to Equation 6 of Kelliher *et al.* (1995).

Whole-system canopy conductance

Although not required for the calculation of the potential transpiration, the canopy conductance of the combined canopy can be of interest in the interpretation and comparison of simulations. First the canopy conductance of each component species, $G_{c j}$, is calculated by summing the appropriate $G_{c ij}$'s. Then a scheme adapted from McNaughton (1994) is used to combine the $G_{c j}$'s into an overall conductance, G_c (see below for the derivation):

$$G_c = \frac{\sum_{j=1; i=1}^{J; I} G_{aij} \omega_j}{\frac{\Delta R'}{\sum_{j=1; i=1}^{J; I} \Delta R'_{ij} \omega_j} - 1 - \varepsilon} \quad (21)$$

where

$$\omega_{ij} = \frac{1}{1 + \varepsilon + G_{aij}/G_{cij}} . \quad (22)$$

Aerodynamic Conductance for Multiple Canopies

The aerodynamic conductance is calculated for the whole system and then disaggregated in the component species. The effect of atmospheric stability on the conductance is ignored.

Whole system aerodynamic conductance

The aerodynamic conductance of the combined canopy is calculated from the scheme summarised by Grayson *et al.* (1996),

$$G_a = \frac{k_v^2 u_z}{\ln\left(\frac{z_m - d}{z_{0m}}\right) \ln\left(\frac{z_h - d}{z_{0h}}\right)} , \quad (23)$$

where k_v is the von Karman constant (-), u_z is the wind speed at the reference height (m/s), z_h and z_m are the height of the temperature/humidity and windspeed measurements (m), d is the zero plane displacement height (m), z_{0h} and z_{0m} are the roughness height for sensible heat and momentum transfer (m). Following Allen *et al.* (1998) $d = 0.667 z_I$, $z_{0m} = 0.123 z_I$, $z_{0h} = 0.1 z_{0m}$ and $z_h = z_m = z_I + z_{ref}$.

Dissaggregation of G_a to G_{aij}

In order to calculate the Penman-Monteith soil water demand for each layer-species combination it is necessary to disaggregate G_a to G_{aij} . In MICROMET this disaggregation is done quite simply by assuming that G_a is apportioned proportionally to R_{aij} so that,

$$G_{aij} = G_a \frac{R'_{ij}}{R'} . \quad (24)$$

This equation assumes that the upper layers (that intercept more radiation) where the wind speed is highest have the greatest aerodynamic conductance. There is no particular physical or physiological justification for this disaggregation except that the evaporation is relatively insensitive to the value of the aerodynamic conductance (Raupach and Finnigan, 1988). Testing was done of varying disaggregation schemes (see below) confirming the insensitivity of the assumed scheme to total evaporation.

Whole-system aerodynamic conductance

Using the McNaughton (1994) scheme, the aerodynamic conductance of the whole system is:

$$G_a = \frac{\Delta R'_{J;I}}{\sum_{j=1; i=1}^{J;I} \Delta R'_{ij} \omega_{ij}} \sum_{j=1; i=1}^{J;I} G_{aij} \omega_{ij} \quad (25)$$

Penman-Monteith Water Demand for Multiple Canopies

Potential transpiration, or soil water demand, for each species-layer combination is calculated using the Penman-Monteith approach:

$$E_{ij} = \left(\frac{1000 (N - t_{\text{int}})}{\lambda \rho_{\text{water}}} \right) \frac{\varepsilon \Delta R'_{ij} + \rho_{\text{air}} \lambda D G_{air}}{\varepsilon + G_{air}/G_{cij} + 1}, \quad (26)$$

E is the potential transpiration (mm). The potential transpiration for each species is calculated by summing E_{ij} over all layers. ε is the slope of the vapour saturation-temperature curve (-), ρ_{air} is the density of air (kg /m³), λ is the latent heat of vaporisation (J /kg), and D is the specific vapour pressure deficit (kg /kg).

Conclusions

The APSIM module MICROMET, described here, has been developed to allow the calculation of potential transpiration for multiple competing canopies that can be either layered or intermingled. The documentation above describes how potential transpiration is calculated as well as the data requirements and inter-dependencies with other modules.

In summary, MICROMET contains the range of calculations required to describe the energy and water balance of the interface between plants and the atmosphere. The processes described include:

- interception of radiation,
- interception of rainfall,
- modification of canopy conductance for the presence of competing canopies, and
- potential transpiration of the individual plant canopies.

The driving force in all calculations is the balance of water and energy. The implementation is suitable for canopies of either single or mixed species and the species mix may change within a simulation.

Currently most crop modules calculate the radiation balance and soil water demand internally. In order to be used with MICROMET, those modules will have to be altered to accept an externally-calculated soil water demand as a simulation option.

Appendix 1: List of Symbols

Symbol	Definition	Units
c_p	specific heat of air at constant temperature	J/kg
C_L	constant between 0 and 1 for the effects of cloud cover	-
d	zero plane displacement height	m
de_{sat}/dT	slope of e_{sat} with temperature	mbar / °C
D	specific vapour pressure deficit	kg /kg
e	Humidity	mbar
e_{sat}	saturated vapour pressure	mbar
E	potential transpiration	mm
f_{ji}	fractional contribution of ΔL_{ij} to ΔL_i	-
$F_{\text{gr}j}$	stress factor or relative growth rate for canopy	-
$f_{\text{sw} \rightarrow \text{PAR}}$	Factor to convert total short wave radiation to PAR	-

Symbol	Definition	Units
g_s	stomatal conductance	m / s
$g_{s \max}$	maximum, or unstressed, canopy conductance	m / s
G_a	aerodynamic conductance	m / s
G_c	canopy conductance	m / s
k	extinction coefficient	-
k_v	dimensionless von Karman constant	0.4
L	cumulative leaf area index	m ² leaf / m ²
L'_i	$L_T - L_i$ (i.e. accumulated from the top downwards)	m ² / m ²
L_d	leaf area density	m ² leaf / m ³
n	duration of clear sunshine	s
N	Duration of net positive radiation throughout the day	s
P	rainfall	mm
P_{int}	amount of interception	mm
P_{air}	air pressure	hPa
Q	specific humidity	kg / kg
Q_{sat}	specific humidity at saturation	kg / kg
R_a	PAR absorbed by an individual leaf	W / m ²
$R_{L\downarrow}$	net long-wave radiation, positive downwards	W / m ²
R_{a50}	R_a at which $g_s = g_{s \max} / 2$	W / m ²
R_s	short-wave radiation	W / m ²
R_{s50}	R_s at which $g_s = g_{s \max} / 2$	W / m ²
ΔR	energy available for evapotranspiration	W / m ²
Δt_{int}	duration of evaporation of intercepted rainfall	S
T	average air temperature at measurement height	°C
T_{abs}	constant to correct from Celsius to Kelvin = 273.15 °C	°C
u	wind speed	m / s
u^*	friction velocity	m / s
Z	height from the soil surface	m
z_m	reference height for momentum	m
z_h	reference height for heat	m
z_{ref}	reference height for meteorological measurements	m
z_0	roughness length	m
z_{0m}	roughness length for momentum	m
z_{0h}	roughness length for heat	m
z_{base}	height of the base of the component canopy	m
z_{top}	height of the top of the component canopy	m
α	canopy albedo	-
α_{soil}	soil albedo	-
ϵ	slope of the vapour saturation-temperature curve	-
ϵ_A	clear sky emissivity	-
ϵ_C	emissivity of the canopy	-
λ	latent heat of vaporisation	J / kg
ρ_{air}	density of air	kg / m ³
ρ_{water}	density of water	kg / m ³
σ	Stefan-Boltzmann constant = 5.67×10^{-8} W / m ² .K ⁴	W / m ² .K ⁴
ω	see Eq. (22)	W / m ² .K ⁴

Constants

Variable	Comments	Description	Units
Albedo	species specific value	canopy albedo	W /m ²
Emissivity	species specific value	emissivity of the canopy	-
gs_max	species specific value	maximum, or unstressed, canopy conductance	m /s
R50	species specific value	R_s at which $g_s = g_{s,max} / 2$	W /m ²
Soil_emissivity	Constant value	<i>Emissivity of bare soil</i>	
Air_pressure			
Sun_angle	Constant value	Solar altitude at which net radiation becomes positive	degrees
Night_interception_Fraction			
Soil_heat_flux_fraction			

Inputs from other modules

Variable	Comments	Description	Units
MET module			
day	required if no sun_hrs information	day of year	-
vp	atmospheric pressure	vapour atmospheric vapour pressure	mbar
latitude	required if no sun_hrs information	latitude of the simulation site	dec. degrees
maxt	required	maximum air temperature	°C
mint	required	minimum air temperature	°C
radn	required	short-wave radiation	W /m ²
rain	required	rainfall	mm
Windspeed	default 3 m/s	wind speed at reference height	m /s
CROP modules (from each crop module in the simulation)			
crop_type	Required to look up stomatal and canopy constants	name of the crop	-
Fgr	default 1 (no stress)	stress factor for photosynthesis	
height	required	height of the top of the component canopy	m
depth			
Cover_green	required	Fractional green leaf cover	-
Cover_tot			
lai	required	cumulative leaf area index	m ² /m ²
Lat_tot			

Variables available to other modules

Variable	Description	Units
Interception	Intercepted rainfall	mm
Gc	Whole system canopy conductance	mm /s
Ga	Whole system aerodynamic conductance	mm /s
petr	Radiation term in the potential evaporation	mm /day
peta	Aerodynamic term in the potential evaporation	mm /day
net_radn	Net all wave radiation	MJ /day

Variable	Description	Units
net_rs	Net short wave radiation	MJ /day
net_rl	Net long wave radiation	MJ /day
soil_heat	Energy used to heat the soil	MJ /day
dryleafract	Fraction of the daytime that the leaves are dry	-

Appendix 3: Humidity functions used in the Code

Function purpose	Function	Units
saturated vapour pressure	$e_{sat}(T) = 6.106 \exp\left(\frac{17.27T}{T + 237.3}\right)$	hPa
slope of sat. vapour pressure – temperature	$\frac{de_{sat}(T)}{dT} = \frac{4098.2 e_{sat}(T)}{(T + T_{abs})^2}$	hPa
calculation of specific humidity from humidity in hPa	$Q(T, P_{air}) = \frac{18.0}{29.0} \frac{e}{P_{air}}$	kg/kg
slope of the vapour saturation-temperature curve, c_p is the specific heat of air	$\varepsilon(T, P_{air}) = \frac{28.0 \lambda}{29.0 c_p P_{air}} \frac{de_{sat}(T)}{dT}$	-

Appendix 4: Derivation of Canopy Conductance Multiple Layers and Components

Following Raupach and Finnigan (1988), Kelliher *et al.* (1995) defined canopy conductance as the parallel sum of leaf stomatal conductance, so that

$$G_c = \int_0^L g_s(L') dL', \quad (27)$$

where G_c is the canopy conductance, L is the leaf area index of the canopy, g_s is the leaf stomatal conductance, and L' is a dummy variable of integration. Equation 27 can be expanded to account for layers in the canopy by,

$$G_c = \sum_{i=1}^I G_{ci} = \sum_{i=1}^I \left(\int_0^{\Delta L_i} g_{si}(L') dL' \right), \quad (28)$$

where I is the total number of layers in the canopy, G_{ci} is the conductance attributable to the i th layer in the canopy, and ΔL_i is the leaf area index in the i th layer. In our scheme there may be more than one species within any layer so the contribution of each species must also be taken into account. We do this using a scheme analogous to the two-leaf model of Wang and Leuning (1998) but rather than separating leaves into shaded and lit, we separate leaves by species. The expansion of G_{ci} into multiple species is,

$$G_{ci} = \sum_{j=1}^J G_{cij} = \sum_{j=1}^J \left(f_{ij} \int_0^{\Delta L_i} g_{sij}(L') dL' \right), \quad (29)$$

where J is the total number of species, f_{ij} is the fraction of ΔL_i attributable to the j th species in the i th layer, and g_{sij} is the stomatal conductance of the j th species.

Following Kelliher *et al.* (1995) we assume that stomatal conductance responds to absorbed radiation by a hyperbolic function. In contrast to Kelliher *et al.* (1995) we

express this relationship with respect to absorbed total radiation (R_a) rather than photosynthetically-active radiation,

$$g_{sij} = \frac{g_{smax} j R_{aij}}{R_{aij} + R_{a50j}}, \quad (30)$$

where g_{smax} is the maximum stomatal conductance, R_{a50j} is the R_a at which g_s drops to 50% of g_{smax} . Two other relationships are required to scale g_s to G_c . The attenuation of radiation through the canopy is given by,

$$R = R_i \exp(-k_i L_i), \quad (31)$$

where R_i is the radiation at the top of the layer, L_i is the leaf area index all all species accumulated from the top downwards through the i^{th} layer, and k_i is the species-averaged light extinction coefficient for the i^{th} layer given by,

$$k_i = \frac{\sum_{j=1}^J L_{ij} k_j}{\sum_{j=1}^J L_{ij}}, \quad (32)$$

where k_j is the light extinction coefficient of the j^{th} species. In the transmission though and absorption of radiation by the canopy layers account is taken of the effect of dead material in absorbing radiation but not contributing to the stomatal conductance. From equation 31, $R_{ai} = -dR / dL = k_i R_i$ and the radiation absorbed by a particular species (Rimington 1984) is $p_{ij} k_i R_i$ where

$$p_{ij} = L_{ij} k_j / \sum_{j=1}^J L_{ij} k_j. \quad (33)$$

Now the equation for the canopy conductance attributable to the j^{th} species in the i^{th} layer can be derived. From the expression,

$$G_{cij} = f_{ij} \int_0^{\Delta L_i} g_{sj}(L') dL', \quad (34)$$

insert the relationship between stomatal conductance and radiation,

$$G_{cij} = f_{ij} \int_0^{\Delta L_i} \frac{g_{smaxj} R_{aij}}{R_{aij} + R_{a50j}} dL', \quad (35)$$

and the relationship between absorbed radiation and radiation level,

$$G_{cij} = f_{ij} \int_0^{\Delta L_i} \frac{g_{smaxj} p_{ij} k_i R}{p_{ij} k_i R + k_i p_{ij} R_{50j}} dL', \quad (36)$$

and the attenuation of radiation through the canopy

$$G_{cij} = f_{ij} \int_0^{\Delta L_i} \frac{g_{smaxj} p_{ij} k_i R_i \exp(-k_i L)}{p_{ij} k_i R_i \exp(-k_i L) + k_i p_{ij} R_{50j}} dL'. \quad (37)$$

When integrated equation 37 gives,

$$G_{cij} = \left[-\frac{f_{ij} g_{smaxj}}{k_i} \ln(p_{ij} k_i R_i \exp(-k_i L) + k_i p_{ij} R_{50j}) \right]_0^{\Delta L_i}, \quad (38)$$

to which the limits are applied resulting in,

$$G_{cij} = \frac{f_{ij} g_{smaxj}}{k_i} \ln(p_{ij} k_i R_i \exp(-k_i 0) + k_i p_{ij} R_{50j}) - \frac{f_{ij} g_{smaxj}}{k_i} \ln(p_{ij} k_i R_i \exp(-k_i \Delta L_i) + k_i p_{ij} R_{50j}), \quad (39)$$

which simplifies to,

$$G_{cij} = \frac{f_{ij} g_{smaxj}}{k_i} \ln \left(\frac{p_{ij} k_i R_i + k_i p_{ij} R_{50j}}{p_{ij} k_i R_i \exp(-k_i \Delta L_i) + k_i p_{ij} R_{50j}} \right), \quad (40)$$

and is further simplified by eliminating the $k_i p_{ij}$ terms,

$$G_{cij} = \frac{f_{ij} g_{smaxj}}{k_i} \ln \left(\frac{R_i + R_{50j}}{R_i \exp(-k_i \Delta L_i) + R_{50j}} \right). \quad (41)$$

In the special case of a single species single layer, $f_{ij}=1$, $R_i=R_L$, $L_{i-1}=0$ and the equation above reduces to,

$$G_c = \frac{g_{smax}}{k} \ln \left(\frac{R_L + R_{50}}{R_L \exp(-kL) + R_{50}} \right) \quad (42)$$

which is equivalent to the expression derived by Kelliher *et al.* (1995).

Appendix 5: Derivation of Equations 21 and 25

Equations 21 and 25 are derived following the scheme of McNaughton (1994). We want to find the canopy-averaged values of canopy and aerodynamic conductance subject to:

$$\sum_{j=1; i=1}^{J; I} \left(\frac{\varepsilon \Delta R'_{ij} + \rho_{air} \lambda D G_{a ij}}{1 + \varepsilon + G_{a ij} / G_{c ij}} \right) = \frac{\varepsilon \Delta R' + \rho_{air} \lambda D G_a}{1 + \varepsilon + G_a / G_c}, \quad (43)$$

$$\sum_{j=1; i=1}^{J; I} (\varepsilon \Delta R'_{ij} \omega_{ij}) = \frac{\varepsilon \Delta R'}{1 + \varepsilon + G_a / G_c}, \quad (44)$$

$$\sum_{j=1; i=1}^{J; I} (\rho_{air} \lambda D G_{a ij} \omega_{ij}) = \frac{\rho_{air} \lambda D G_a}{1 + \varepsilon + G_a / G_c}, \quad (45)$$

and

$$\sum_{j=1; i=1}^{J; I} \Delta R'_{ij} = \Delta R', \quad (46)$$

where

$$\omega_{ij} = \frac{1}{1 + \varepsilon + G_{a ij} / G_{c ij}} \quad (47)$$

From these equations:

$$1 + \varepsilon + G_a / G_c = \frac{\Delta R'}{\sum_{j=1; i=1}^{J; I} \Delta R'_{ij} \omega_{ij}} = \frac{G_a}{\sum_{j=1; i=1}^{J; I} G_{a ij} \omega_{ij}} \quad (48)$$

$$G_a = \frac{\Delta R'}{\sum_{j=1; i=1}^{J; I} \Delta R'_{ij} \omega_{ij}} \sum_{j=1; i=1}^{J; I} G_{a ij} \omega_{ij} \quad (49)$$

and

$$G_c = \frac{\frac{\Delta R'}{\sum_{j=1; i=1}^{J; I} \Delta R'_{ij} \omega_{ij}} \sum_{j=1; i=1}^{J; I} G_{aij} \omega_{ij}}{\frac{\Delta R'}{\sum_{j=1; i=1}^{J; I} \Delta R'_{ij} \omega_{ij}} - 1 - \varepsilon} \quad (50)$$

Appendix 6: Disaggregation of G_a

In order to calculate the water demand for each component species it is necessary to disaggregate the whole system value of G_a . While various schemes exist for aggregating conductances (e.g. McNaughton 1994, Hall 2002) these schemes cannot be used in the inverse sense to disaggregate the aerodynamic conductance. In the absence of a sound theoretical basis, and armed with the knowledge that whole system potential transpiration is relatively insensitive to G_a (Raupach and Finnigan, 1988), we assume that the conductance can be disaggregated assuming that it is proportional to the intercepted radiation. Such a scheme will allocate most of the conductance to the upper layers of the canopy, where windspeed is highest, and so makes physical sense. In order to test the sensitivity of the calculations to the assumption we also tested an allocation scheme where the component aerodynamic conductance was inversely proportional to the intercepted radiation. This is a physically non-sensible assumption and is only used to test the degree of sensitivity to the allocation scheme.

One necessary, but not sufficient, condition is that a uniform canopy can be broken down into several parts and the sum of the parts should equal the single canopy. This was tested using the four canopy structures as shown in Figure 2. In this test all the components were set up with the same stomatal properties and the calculated potential transpiration, E , was compared. In a successful test the whole system E for each configuration would be equal and as well $E_2 = E_6 + E_8$, $E_4 = E_6 + E_7$, etc. The disaggregation scheme passed this test. The whole system water demands were within 0.28 mm /day of each other and the maximum difference when components were compared was also 0.28 mm /day. These values are sufficiently small as to be functionally equal.

The first test was run with the same stomatal properties in all components but it is likely that in practise the components will have differing stomatal properties and such a systems is likely to show more sensitivity to assumptions in the disaggregation of G_a than a uniform system. Unfortunately, unlike the first test, there is no absolute truth to compare against so in this series of tests we choose a contrary assumption on the disaggregation to test the sensitivity of the assumption.

In the second tests the two-component layered configuration was used. Each of the components was given different stomatal properties the comparisons were run for allocation for G_a either proportional or inversely proportional to the amount of radiation intercepted by the component. These tests were run for both short and tall vegetation with appropriate stomatal properties. The results are shown in Figure 3.

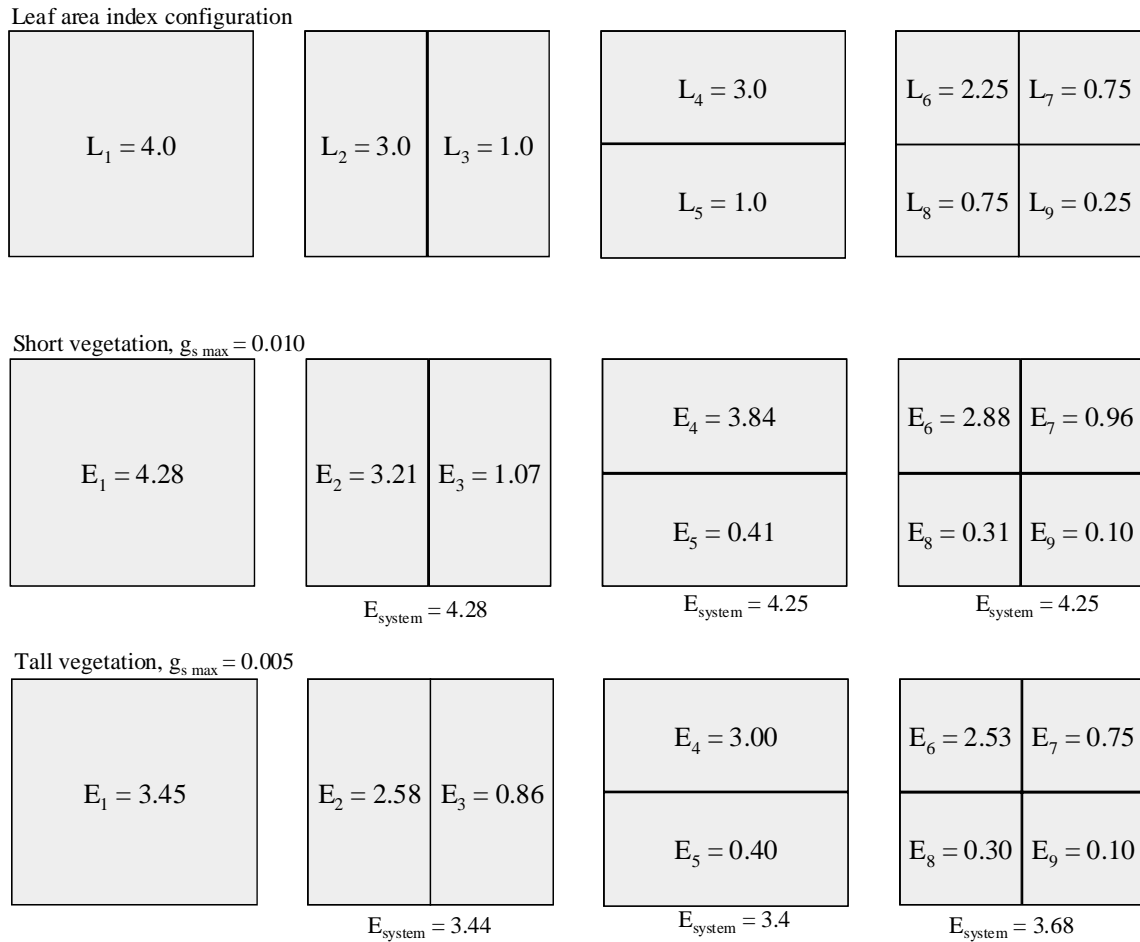


Figure 2. Canopy structures (leaf area indices defined in the upper row) and potential transpiration results for testing the disaggregation of G_a for short and tall vegetation when all components are assigned the same stomatal properties and $G_a \propto R_{int}$.

As expected, the total system water demand was lower when G_a was allocated inversely proportional to R_{int} . This is because in the inverse allocation the canopy that intercepts the most radiation has the lowest conductance and therefore total water demand is reduced. The greatest difference in total water demand was for the tall vegetation, where G_a is always of greater importance than in short vegetation, where the difference amounted to 0.92 mm /day or 20% of the total.

The third test performed was similar in concept to the layered example above but in this case the configuration was for two intermingled species of equal height and with greater leaf area index in the upper part of the canopy. Again this test was performed for both short and tall vegetation and proportional and inversely proportional allocation schemes were compared. The results are shown in Figure 4.

In this third test the greatest difference in any component resulting from the two allocation schemes was 0.34 mm /day for the upper component of the tall vegetation with the highest $g_{s \max}$. This however is not a value that by itself is used in any simulation. The important comparisons are the individual species comparisons and the total system water demand. The greatest difference when comparing species was for the tall vegetation with the highest $g_{s \max}$ which produced a difference of 0.09 mm /day, a difference too small to be functionally different.

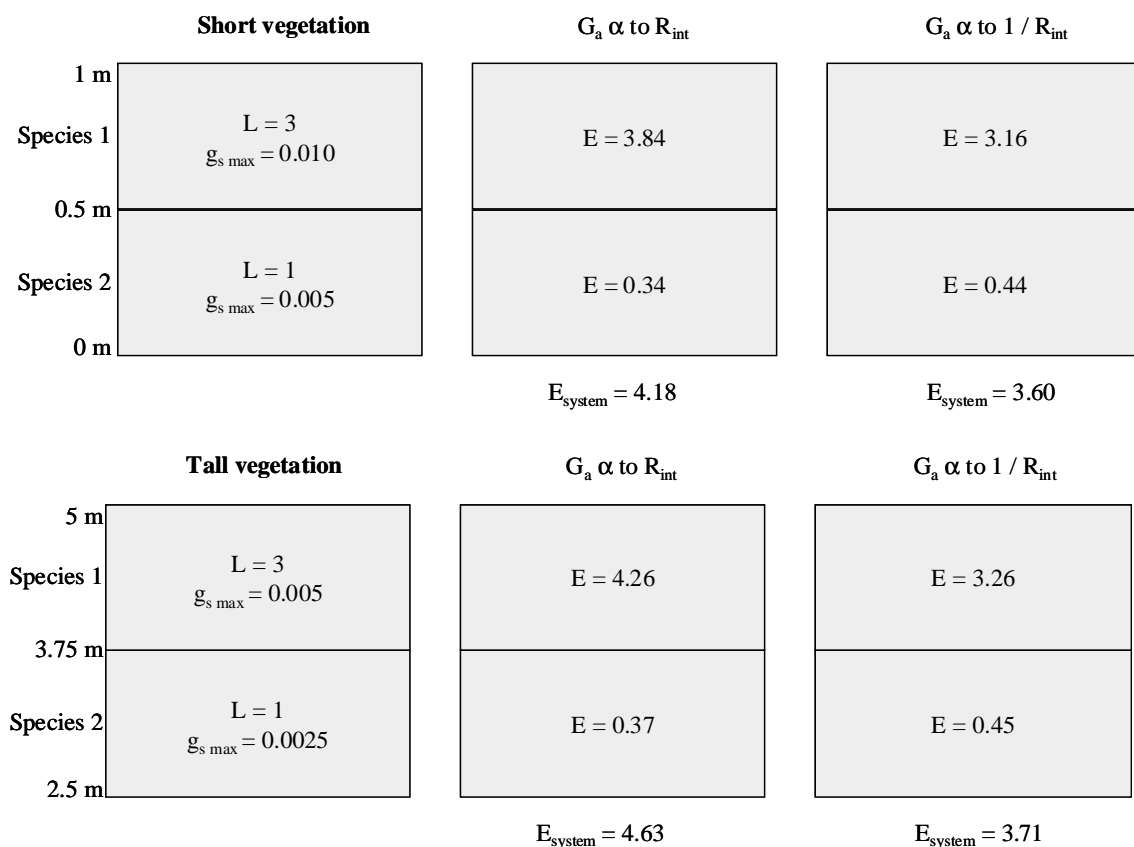


Figure 3. Canopy structures and results for testing the disaggregation of G_a for short and tall layered vegetation when components are assigned differing stomatal properties and $G_a \propto R_{int}$ or $G_a \propto 1/R_{int}$.

Summary and conclusions

The disaggregation scheme used in the MICROMET module is done with the assumption that the total system G_a can be allocated to the component canopies proportional to the amount of radiation that they intercept. This fits two basic properties in that the highest conductances are assigned to components that experience the highest wind speed and that have the greatest leaf area.

Testing showed that a uniform canopy could be subdivided and the sum of the components still equals the single canopy case. Further testing was done by comparing the proportional allocation scheme against an inversely proportional scheme and examining the sensitivity of the resulting calculated water demand to a contrary disaggregation scheme. Two cases were tested; a layered canopy and an intermingled canopy. The worst case in these tests was a 0.09 mm /day difference resulting from assigning a low conductance to a high LAI tall vegetation with a high $g_{s \max}$. Most differences were less than 0.05 mm /day and were well below any value that could be considered functionally important.

Given the results of these tests the proportional allocation scheme was adopted. While this allocation scheme does not have the physical rigour of some of some other schemes (e.g. Hall 2002) it is consistent with the level of detail required in APSIM and represents a pragmatic approach, reasonably tested, and with modest data requirements.

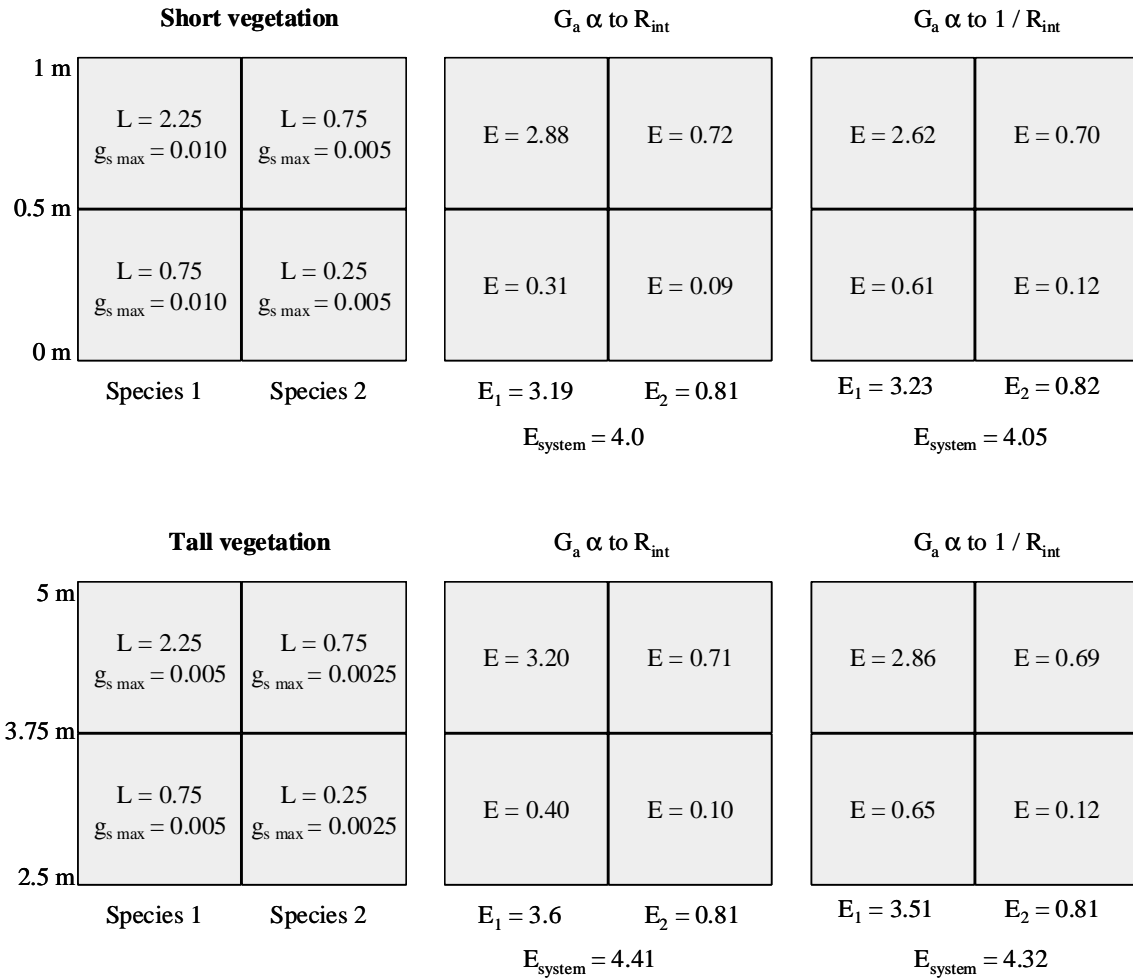


Figure 4. Canopy structures and results for testing the disaggregation of G_a for short and tall intermingled vegetation when components are assigned differing stomatal properties and $G_a \propto R_{int}$ or $G_a \propto 1/R_{int}$.

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