MAESPA: Development of a soil-plant-atmosphere model

Remko Duursma, Dec. 12 2008 UWS
Process-based models of canopy function

- Canopy-level gas exchange ($\text{H}_2\text{O}, \text{CO}_2$) notoriously hard to measure
  - before whole-tree chambers, eddy flux, no real way to measure
- Use of models to scale up leaf-level fluxes (which are ‘easy’ to measure) to the canopy goes back to C.T. de Wit’s “Photosynthesis of leaf canopies”, 1965.
Process-based models of canopy function

- Why complex over-parameterized models?
  - Similar predictive power can be reached with simple models

- Complex models very useful research tools to integrate detailed knowledge, test hypotheses, study system behaviour
  - “what-if” analyses
  - do measurements add up
  - scaling up (spatially and temporally)
  - exploring different process hypotheses
Process-based models of canopy function

- Complex models should be flexible
  - Not view it as a black box where all processes are represented in the ‘best possible way’
  - Our understanding is incomplete, models should have options to test different mechanisms (submodels)
Outline

- Development of MAESPA
  - Details, details
  - Implementation

- How and why do we use models like this?
MAESPA Components

- Scaling of leaf gas exchange (CO$_2$, H$_2$O) to the tree canopy (MAESTRA)
  - Radiation extinction and leaf physiology models
- Respiration (MAESTRA) (leaf + woody biomass)
- Stand water balance (SPA)
  - Rainfall interception, infiltration and drainage, soil evaporation, water uptake
- Soil energy balance (SPA)
  - Used in estimating soil evaporation, not mandatory
- Not: growth, allocation (MATE), N cycle (G’DAY), snow/ice routines (SPA).
A Brief History of MAESTRA

- Grace (1987): important development of the radiation model, with influence from Norman and Welles.
- Wang and Jarvis (1990): publishes MAESTRO as result of his Ph.D. research with Paul Jarvis.
- Belinda Medlyn: re-organized the original Fortran code, added many options, and renamed it MAESTRA.

- 50+ publications using MAESTRA.
A Briefer History of SPA

- Soil-Plant-Atmosphere model developed by Mat Williams (Williams et al. 1996, 2001a, 2001b)
- Horizontally homogenous canopy (as is usual), but a detailed coupled water and energy balance

- SPA also written in Fortran, mechanistic detail good match to MAESTRA
**MAESTRA**

**Canopy structure**
Leaf area, crown size, shape, leaf angle

**Radiation**
Direct / diffuse, solar angle, PAR+NIR+LW wavebands

**Weather**
T, VPD (RH%), [CO₂]

**Model tree with grid points**

Incident PAR at leaf-level for each grid point

Extinction of radiation within crowns + shading by neighbor trees (+scattering)

Add gridpoint estimates by their leaf areas

Repeat for a sample of trees in the stand, add

Evaluated at each gridpoint in the crown

**Stomatal conductance model**

**Leaf photosynthesis model**

Leaf-level CO₂ assimilation (A), transpiration rates (E)

Tree-level A and E

Stand-level A and E
Radiation penetration

- Shading within trees, and between trees
- At each grid point, estimation of PAR, NIR, long-wave radiation
- Data needed:
  - leaf angle distribution, leaf reflectance, clumping of foliage (conifer shoots)
  - crown size (length, width), shape (ellipsoid, paraboloid, cone, cylinder, box)
  - position of neighbour trees
  - latitude, incident radiation
  - vertical and horizontal distribution of foliage in crowns (or assume evenly filled)
Stomatal conductance models (1)

- $g_s = f(PAR, VPD, CO_2, A)$
- Several options:
  - Jarvis model
  - Ball-Berry
  - Ball-Berry-Leuning
- … other models easily added
  - optimal stomatal control

Data needed: leaf-level $g_s$, $A$, at varying $PAR$, $VPD$, ($CO_2$)

![Graph showing stomatal conductance vs. VPD](image)

Data from Ellsworth et al., HFE
Leaf photosynthesis model

- Farquhar et al. (1980) model of photosynthesis

- Temperature dependence of $V_{\text{cmax}}$, $J_{\text{max}}$, etc.

- Quantum yield of electron transport
  - apparent quantum yield of CO$_2$ uptake equally as useful for parameterizing
Water balance: components borrowed from SPA

- Precipitation
- Transpiration
- Soil evaporation
- Root distribution
- Water uptake
- Canopy storage
- Drainage
- Infiltration
- Soil water store
- Deep drainage
- Gravitational drainage
- Wet evaporation
Soil evaporation

Choudhury and Monteith (1988) one-layer model

\[ \text{LE}_{\text{soil}} = \alpha \frac{e_a - e_s}{r_{\text{soil}} + r_{\text{bl}}} \]

Where

- \( \alpha \) – combination of (near-) constants (J m\(^{-3}\) Pa\(^{-1}\))
- \( e_a \) – air vapour pressure (Pa)
- \( e_s \) – soil pore vapour pressure (= function of \( T_{\text{soil}} \) and \( \Psi_{\text{soil}} \))
- \( r_{\text{soil}} \) – soil resistance (= function of dry layer thickness)
- \( r_{\text{bl}} \) – boundary layer resistance (s m\(^{-1}\)), function of windspeed, aerodynamic properties of canopy
Soil evaporation (2)

- Constant weather, no rain: initial high rates of evaporation decline as dry layer increases
Canopy throughfall

- The classic Rutter et al. (1975) model of canopy throughfall, interception, drainage and evaporation
- Four parameters: could be derived from measurements, but often set to Rutter’s defaults
Drainage and infiltration

- Gravitational drainage is calculated from hydraulic conductivity
- Integration of the Richards’ equation
  - Very standard method in soil hydrology
- No macropore flow: could be important

- Infiltration of rainfall: SPA assumed complete infiltration in top layer
- MAESPA includes option for immediate infiltration of rainfall into deeper layers (macropore idea, based on BROOK90 model)
Drainage (2)

- Example simulation: 1m deep soil, 10 layers
- Top 5 layers saturated at t=0
- Bottom 5 layers dry
- No transpiration
Soil water potential and hydraulic conductivity

- Campbell’s (1974) coupled retention and conductivity curves

\[
\Psi_{\text{soil}} = \Psi_e \left( \frac{\theta}{\theta_{\text{sat}}} \right)^{-b}
\]

\[
K_{\text{soil}} = K_{\text{sat}} \left( \frac{\theta}{\theta_{\text{sat}}} \right)^{2b+3}
\]
Limits on leaf transpiration: one option

- Ohm’s analogy to water flow, one-dimensional
- Assumption of a critical minimum leaf water potential
- Maximum transpiration rate is then:

$$E_{\text{max}} = k_{\text{tot}} \times (\Psi_{\text{soil}} - \Psi_{\text{min}})$$

where $k_{\text{tot}}$ conductance from soil to leaf, $\Psi_{\text{min}}$ minimum leaf water potential, $\Psi_{\text{soil}}$ a weighted soil water potential (by the layers)

If calculated $E$ from the stomatal conductance model exceeds $E_{\text{max}}$, $E$ is set to $E_{\text{max}}$ (and $g_s$ and $A$ recalculated)
Soil to root surface conductance

- Gardner’s (1960) single root model

\[
k_{soil} = \frac{RLI}{LAI} \times C_R \times K_{soil}(\Psi_{soil})
\]

where: \( k_{soil} \) leaf-specific soil hydraulic conductance (mol m\(^{-2}\) s\(^{-1}\) MPa\(^{-1}\)), \( RLI \) root length index (m m\(^{-2}\)), \( LAI \) leaf area index, \( K_{soil} \) hydr. conductivity, \( C_R \) a root index function
Soil water uptake (3)

- Fraction uptake in each of the soil layers is determined from soil conductance in each layer
  - This is a SPA hypothesis, and should be tested more! Other alternatives may exist as well

- Data needed for the soil water uptake module:
  - Plant hydraulic conductance (leaf-specific) (from sapflux and drop in leaf water potential).
  - Minimum leaf water potential (MPa)
  - Soil water retention data (or soil texture at the least), saturated hydraulic conductivity
  - Rooting depth, rooting density, vertical profile
Energy balance

- Canopy latent heat loss
- Net radiation
- Soil latent heat flux (Q_E)
- Sensible heat loss (Q_H)
- Net radiation (Q_N)
- Soil heat storage
- Soil heat flux (Q_C)
Energy balance (2)

- Soil surface temperature ($T_s$) is calculated from closing the energy balance equation:

$$R_n + Q_e + Q_h + Q_c = 0$$

Where $R_n$ is net radiation, $Q_e$ latent heat loss (soil evaporation), $Q_h$ soil heat flux, $Q_c$ sensible heat loss, all in W m$^{-2}$.

- All heat fluxes depend on $T_s$, so it is possible to solve the energy balance equation for $T_s$.

- Soil evaporation is then calculated from this surface temperature.
Soil heat flux and temperature profile

- Flux of heat in the soil depends on soil thermal conductivity
  - Function of water content, porosity, organic matter content (Lu et al. 2007)
- Litter layer is 100% organic matter, has very low conductivity
- Given the thermal conductivity for each layer, and their temperatures, we can calculate the flux of heat between layers
- This gives the soil temperature profile
- Solution of the so-called Fourier heat transport equation, standard method

Soil temperature profile example

![Graph showing soil temperature profile over time](image)

- Surface
- 40cm
- 90cm
Implementation and user interface

- MAESPA is written in Fortran (as are MAESTRA, SPA)
- SPA code heavily re-organized, style and functionality matches MAESTRA
- Input text files, input error checking
  - One file for water balance parameters (watpars.dat)
- Output files:
  - (Half-)Hourly water balance file (watbal.dat)
  - Soil temperature profile (hourly) (watsoilt.dat)
  - Relative water uptake profile (hourly) (watupt.dat)
  - Water content by layer (hourly) (watlay.dat)
Example output (\textit{watbal.dat})

- Tumbarumba flux site, \textit{Eucalyptus delegatensis}, LAI = 1.5 m$^2$ m$^{-2}$
Batch Utility

- A collection of functions written in R for multiple simulations of MAESPA/MAESTRA
- Can be used for other models that use namelists in input files (Fortran)
- Available as an R package

- Also available a number of functions that graph MAESPA output

```
Scenarios, parameter values

R Script ("Wrapper")
```

```
Input files

MaeSpa24.exe

Output files
```

```
writes
runs
reads

Summary output
```
HFE

- Whole-tree fluxes of CO₂ and H₂O ideal for model testing
- Very preliminary runs: no competitive shading, stomatal conductance model not properly calibrated.
- One Saturday’s data in April 2008 – total leaf areas estimated in April

Data from Barton et al.
Potential model applications at the HFE

- Where is the water coming from?
  - Do fluxes of water add up?
  - Depth of water uptake?
  - Can we predict effects of drought treatment?
- $\text{CO}_2$ effect: contributions of LA, LUE, $g_s$, etc.
- Testing mechanisms: poor understanding of drought
- Are leaf-level measurements consistent with whole-tree fluxes?
- Impacts of reduced $g_s$ on soil water balance, sensitivity to drought: do model predictions match tree fluxes?
Other applications

- Testing at other sites (eddy-flux, sap-flux sites)
- Development of response surfaces to aid development and parameterization of simple models (e.g. MATE, MATEY)
  - Scaling up from the HFE to...
- Sensitivity analyses:
  - Important parameters?
  - What-if? (e.g. “What if there would be no downregulation?”)
- Strength of MAESTRA: 3D canopy structure
  - Effect on energy and water balance?
  - Do simple models need to be adjusted?