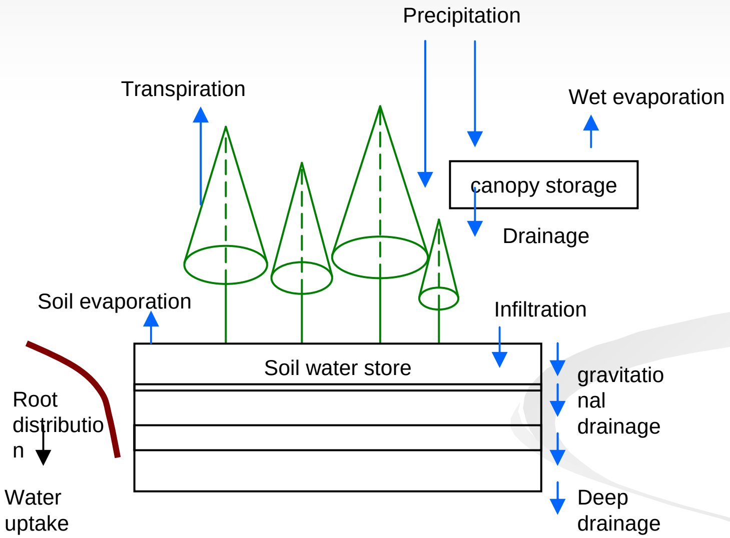
MAESPA: Development of a soil-plant-atmosphere model



Precipitation

Transpiration

Wet evaporation

canopy storage

Drainage

Soil evaporation

Infiltration

Soil water store

gravitational drainage

Root distribution

Water uptake

Deep drainage

Remko Duursma, Dec. 12 2008 UWS

Process-based models of canopy function

- Canopy-level gas exchange (H_2O,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_2O) 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
- <u>Not</u> : growth, allocation (MATE), N cycle (G'DAY), snow/ice routines (SPA).

A Brief History of MAESTRA

- Norman & Jarvis (1974,1975): developed models to predict penetration of radiation in canopies, and effect of canopy structure
- 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

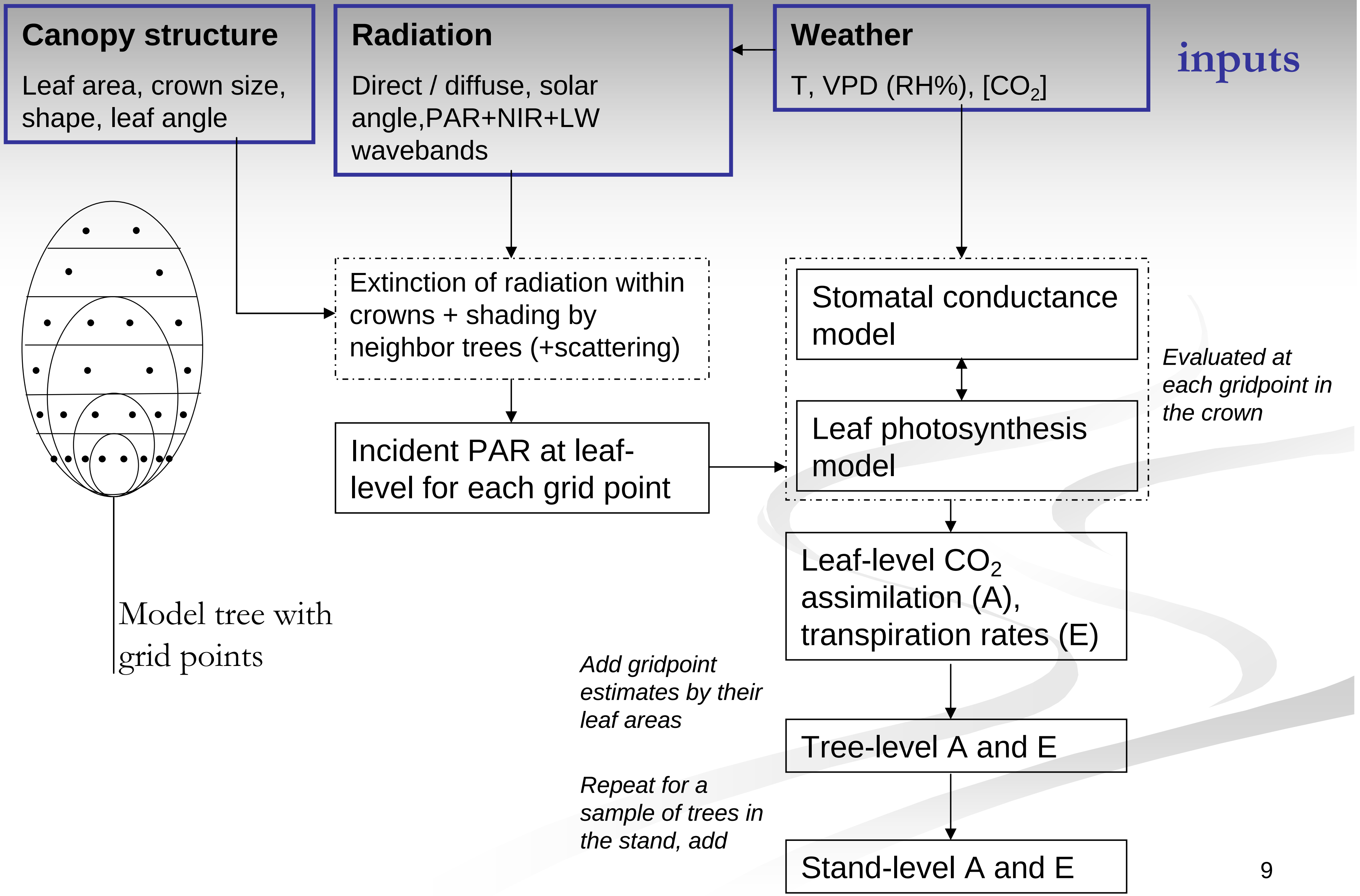
- 50+ publications using MAESTRA

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%), [CO_2]

inputs

Model tree with grid points

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

Incident PAR at leaf-level for each grid point

Stomatal conductance model

Leaf photosynthesis model

Evaluated at each gridpoint in the crown

Leaf-level CO_2 assimilation (A), transpiration rates (E)

Add gridpoint estimates by their leaf areas

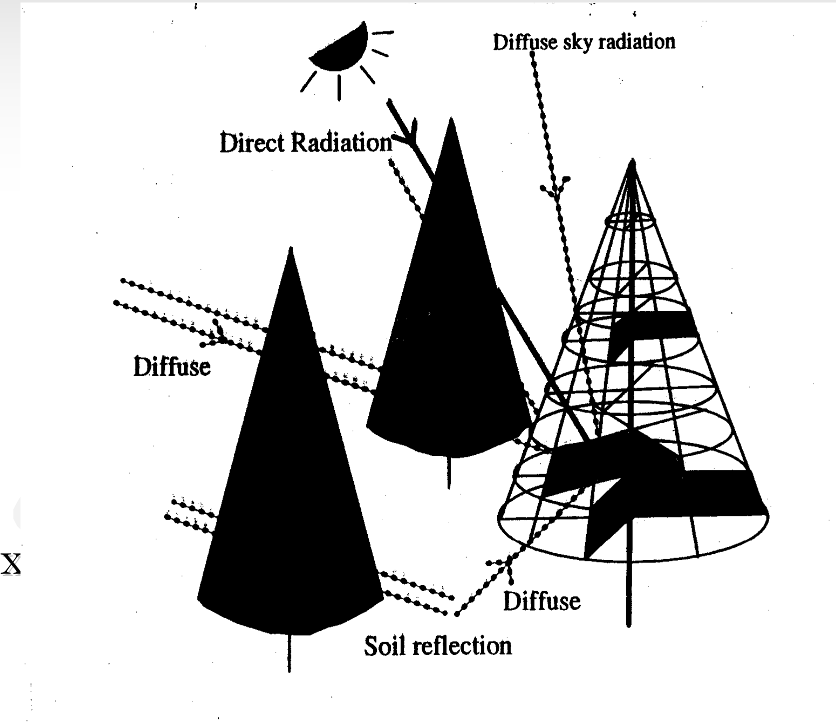
Tree-level A and E

Repeat for a sample of trees in the stand, add

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)

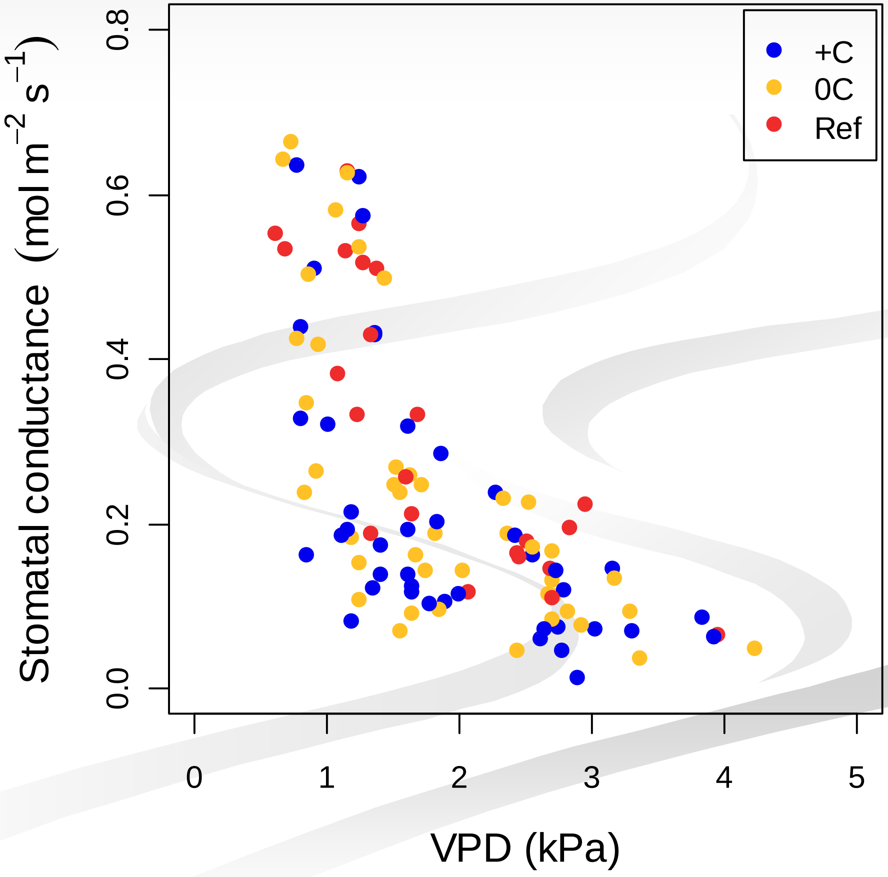


Stomatal conductance models (1)

- $g_s = f(PAR, VPD, CO_2, A)$
- Several options:
  - Jarvis model
  - Ball-Berry
  - Ball-Berry-Leuning

- … other models easily added
  - optimal stomatal control

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

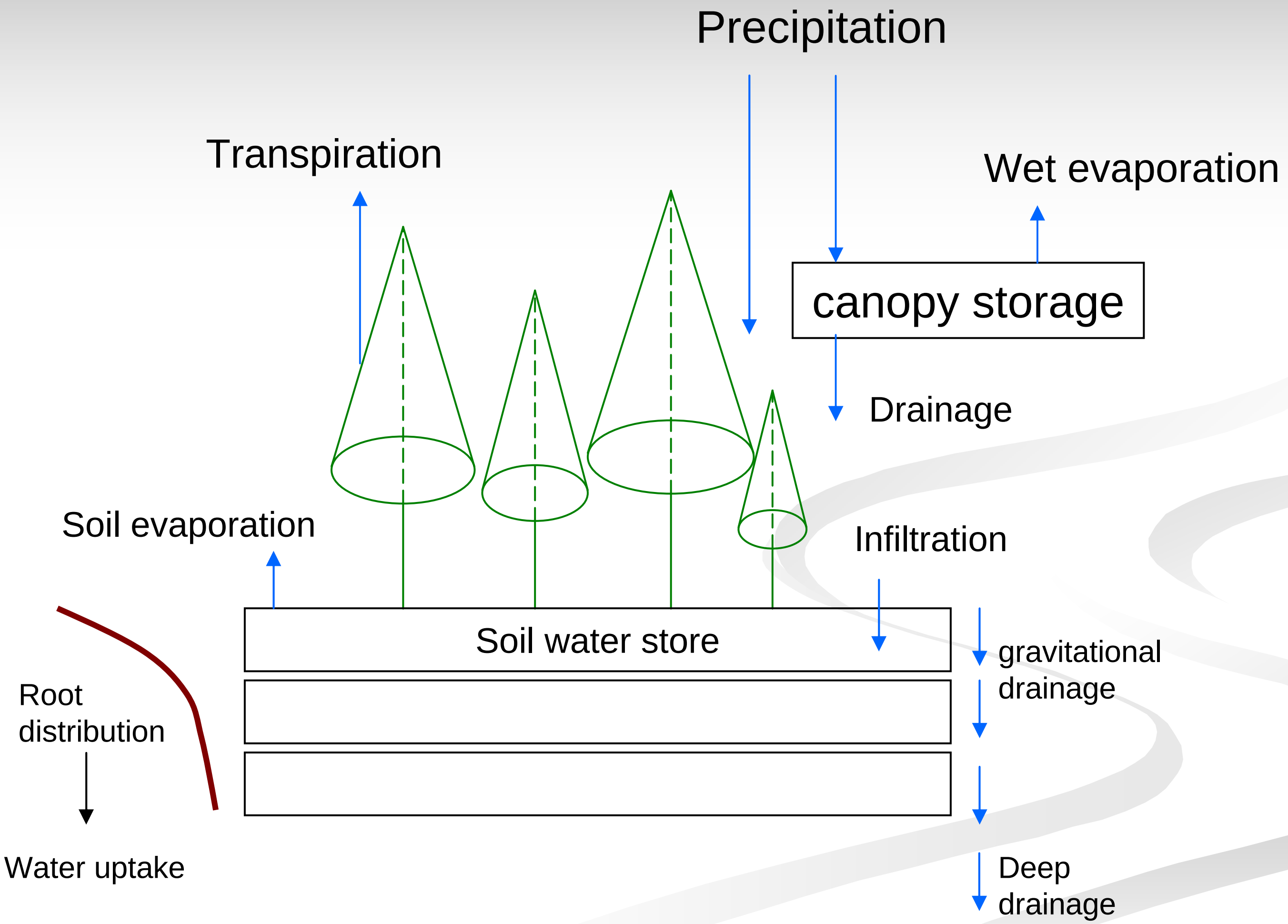


Data from Ellsworth et al., HFE

Leaf photosynthesis model

- Farquhar et al. (1980) model of photosynthesis
- Temperature dependence of V_{cmax}, $J_{max,}$ 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

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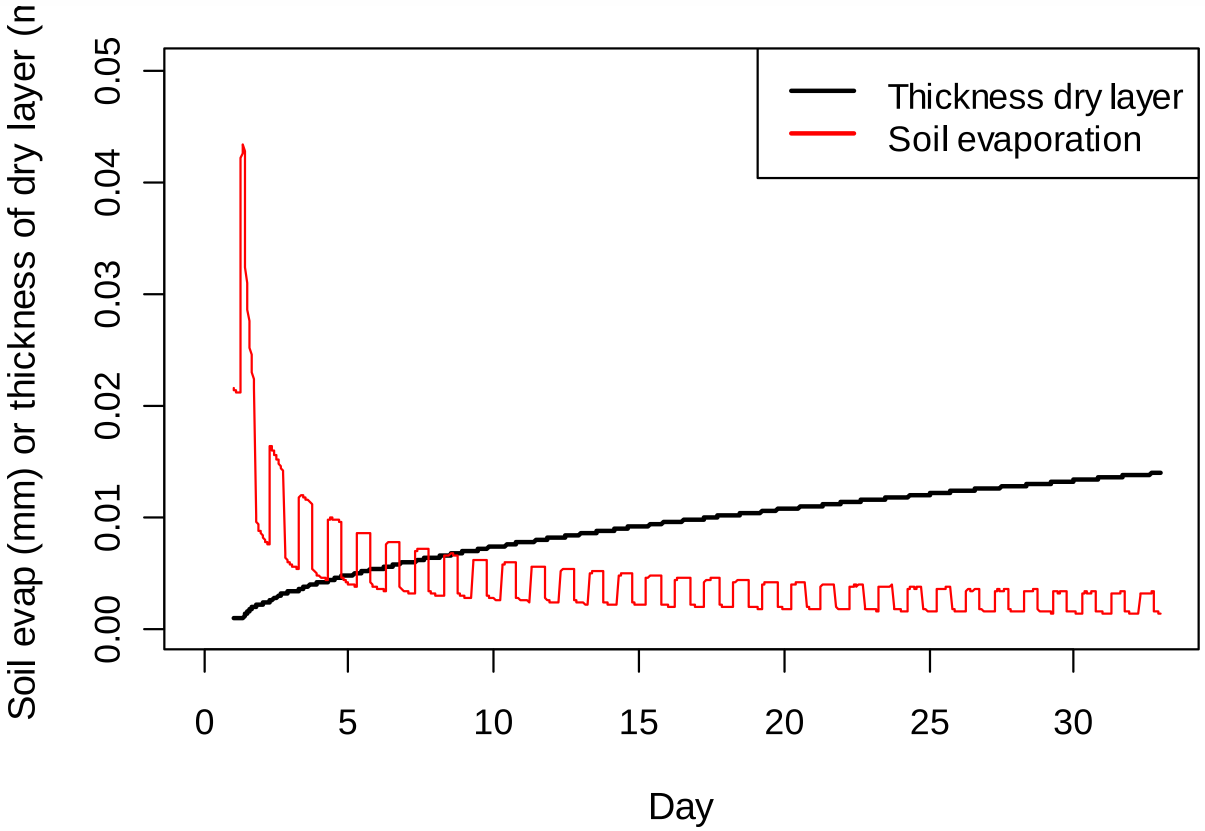
Choudhury and Monteith (1988) one-layer model

$$LE_{soil} = \alpha \frac{e_a - e_s}{r_{soil} + r_{bl}}$$

- Where
  - α – combination of (near-) constants (J m^{-3} Pa^{-1})
  - e_a – air vapour pressure (Pa)
  - e_s – soil pore vapour pressure (= function of $\mathbf{T_{soil}}$ and Ψ_{soil})
  - r_{soil} – soil resistance (= function of dry layer thickness)
  - r_{bl} – boundary layer resistance (s m^{-1}), function of windspeed, aerodynamic properties of canopy

Soil evaporation (2)

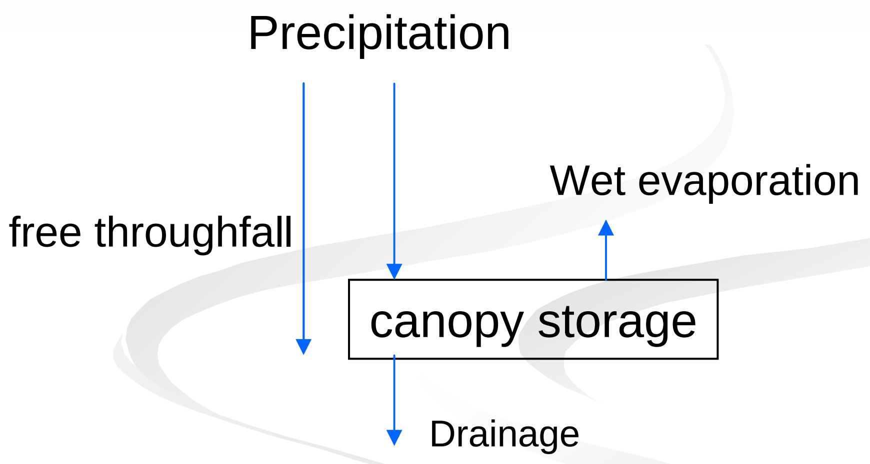
- Constant weather, no rain: initial high rates of evaporation decline as dry layer increases



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

- Rutter, A.J., A.J. Morton and P.C. Robins 1975. A predictive model of rainfall interception in forests. III. Generalization of the model and comparison with observations in some coniferous and hardwood stands. Journal of Applied Ecology. 12:367-380.



Precipitation

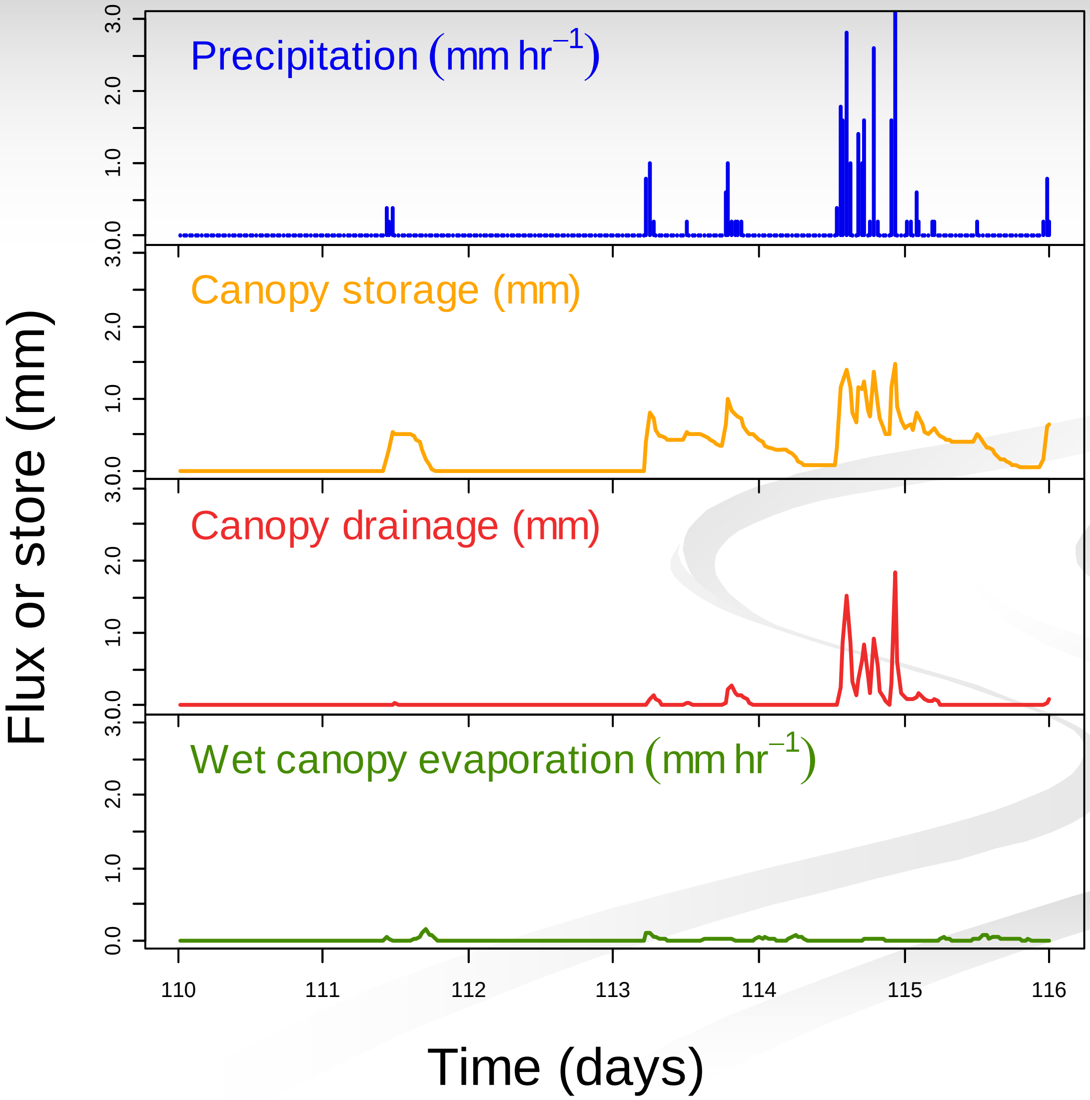
free throughfall

Wet evaporation

canopy storage

Drainage

Canopy throughfall (2)



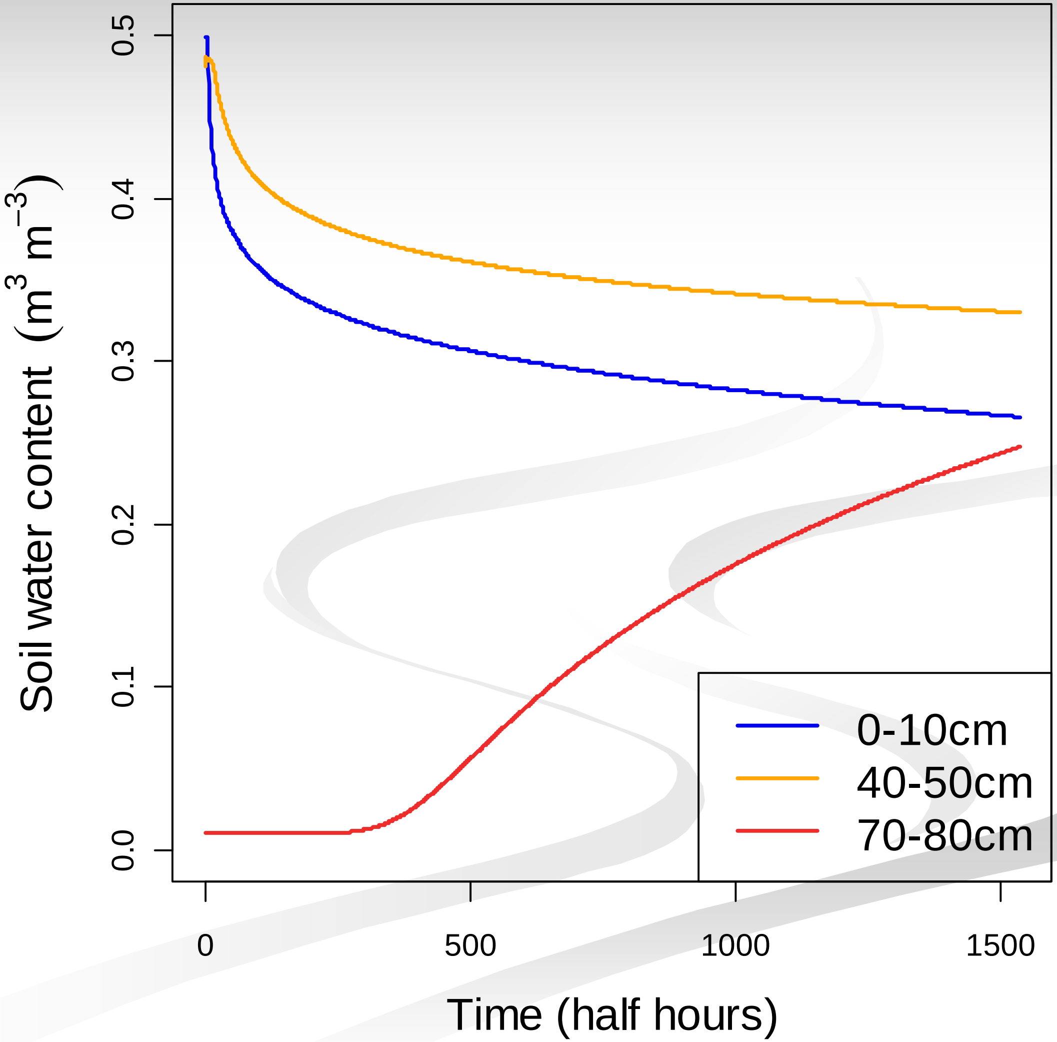
Drainage and infiltration

- 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

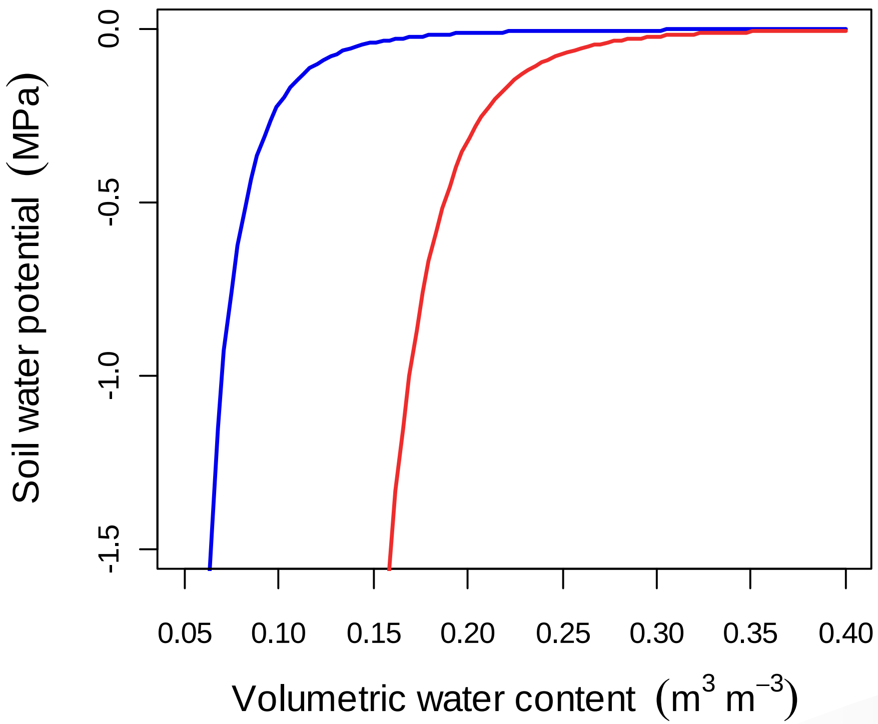


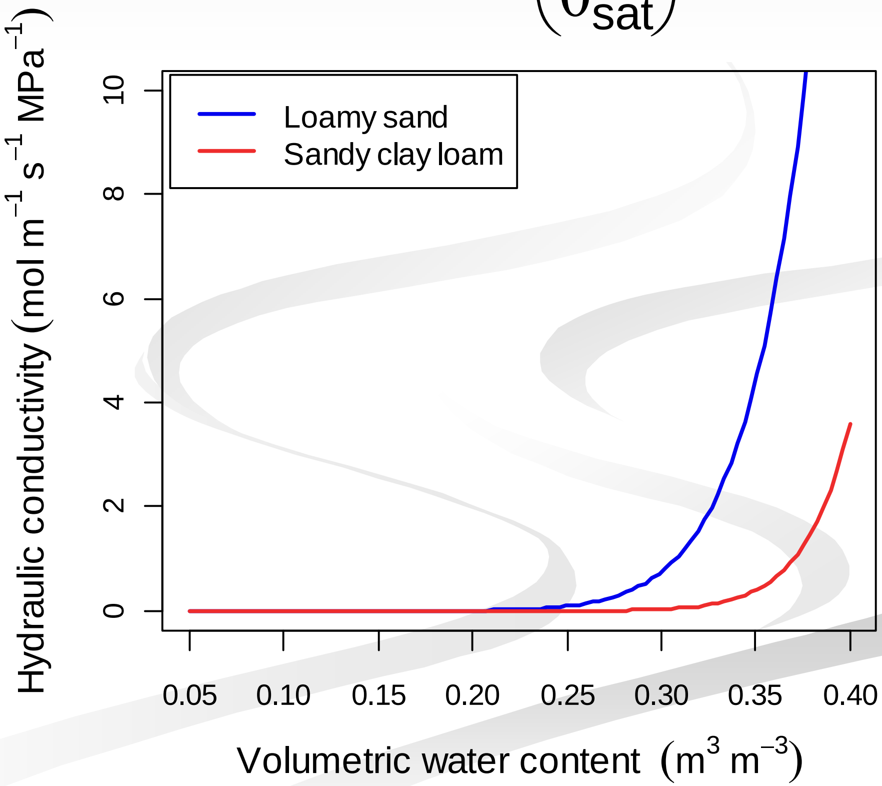
Soil water potential and hydraulic conductivity

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

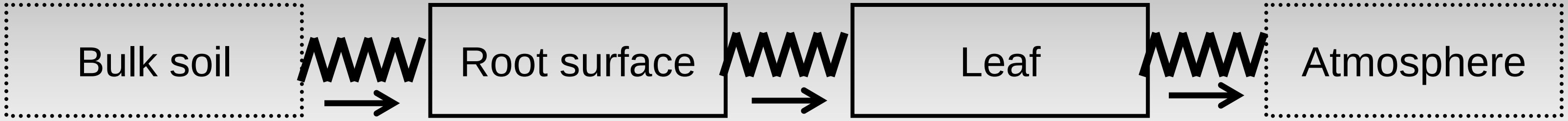
$$\Psi_{soil} = \Psi_e\left(\frac{\theta}{\theta_{sat}}\right)^{-b}$$

$$K_{soil} = K_{sat}\left(\frac{\theta}{\theta_{sat}}\right)^{2b+3}$$





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:

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

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

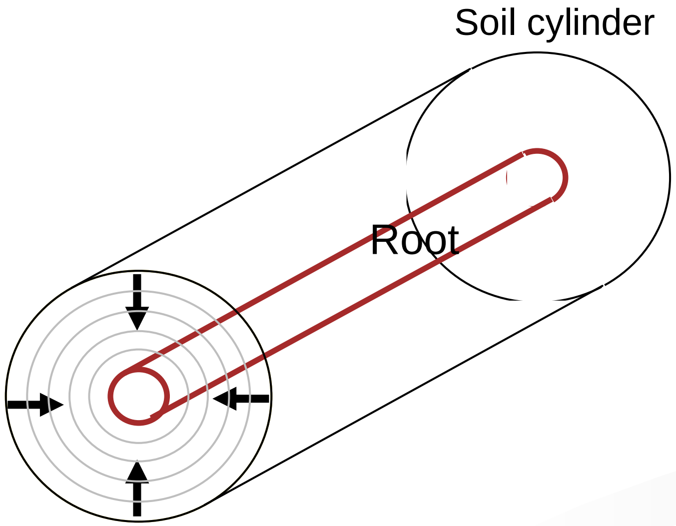
If calculated E from the stomatal conductance model exceeds E_{max}, E is set to E_{max} (and g_s and A recalculated)

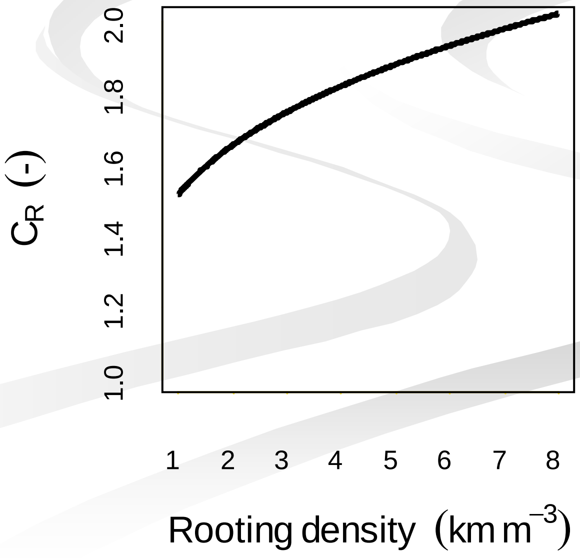
Soil to root surface conductance

- Gardner's (1960) single root model

$$k_{soil} = \frac{RLI}{LAI} \times C_R \times K_{soil}\left(\Psi_{soil}\right)$$

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

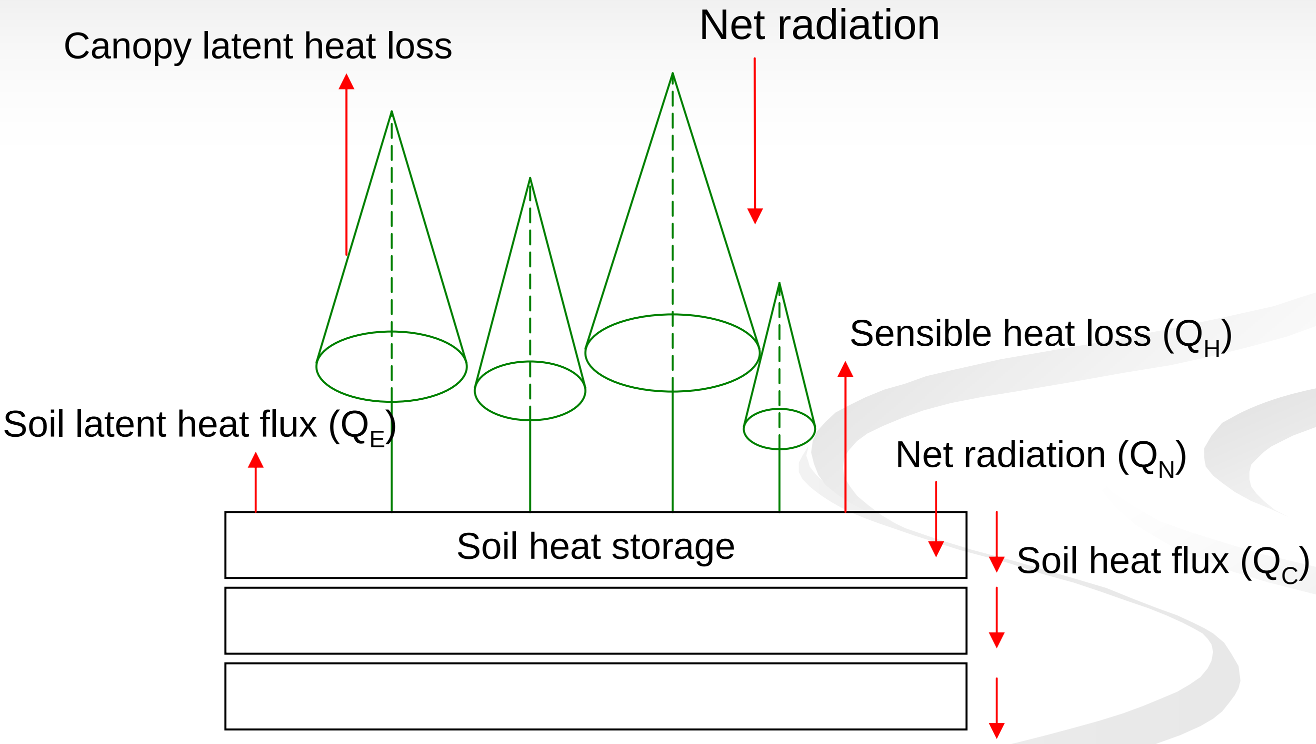




Soil water uptake (3)

- 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



Energy balance (2)

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

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

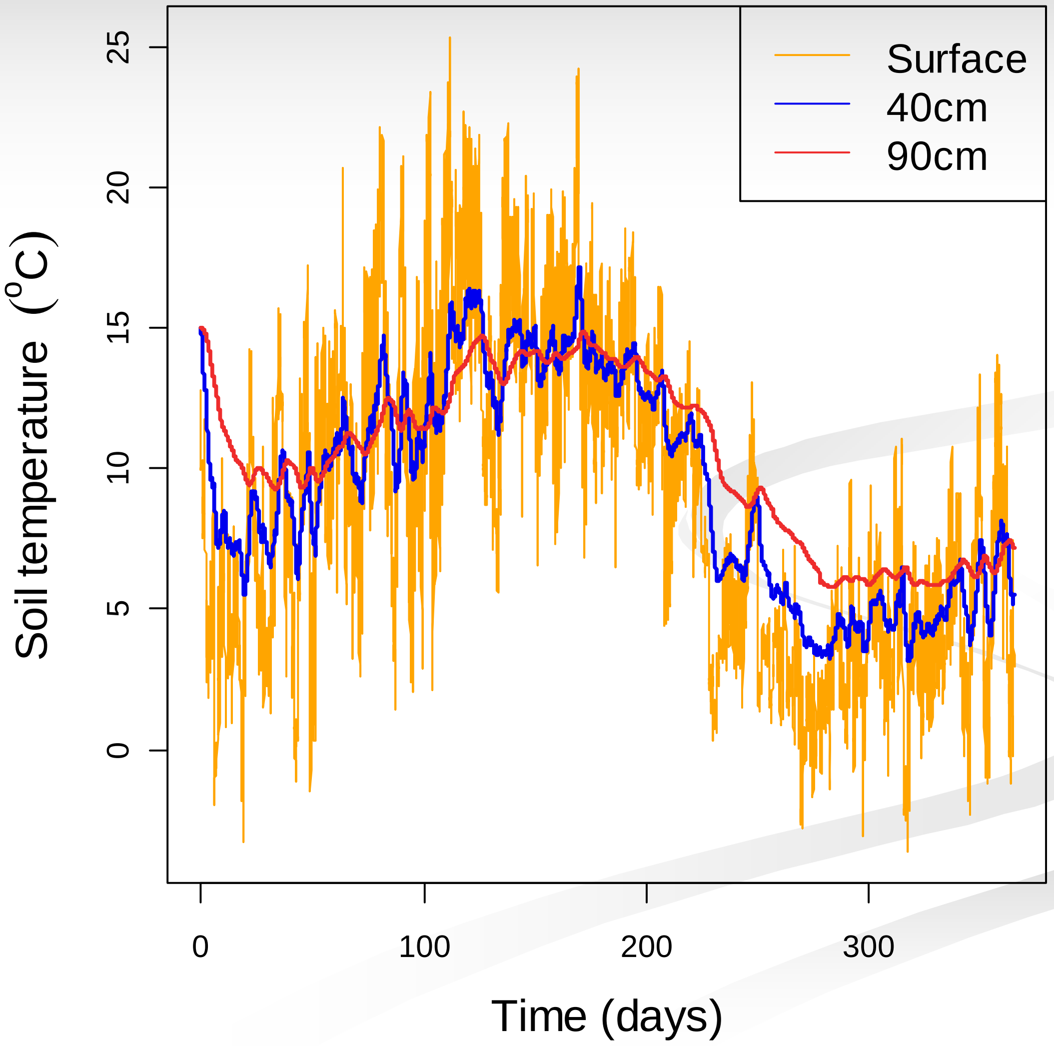
Where R_n is net radiation, Q_e latent heat loss (soil evaporation), Q_h soil heat flux, Q_c sensible heat loss, all in W m^{-2}.

- 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
- Lu, S., T. Ren, Y. Gong and R. Horton 2007. An Improved Model for Predicting Soil Thermal Conductivity from Water Content at Room Temperature. Soil Sci Soc Am J. 71:8-14.

Soil temperature profile example

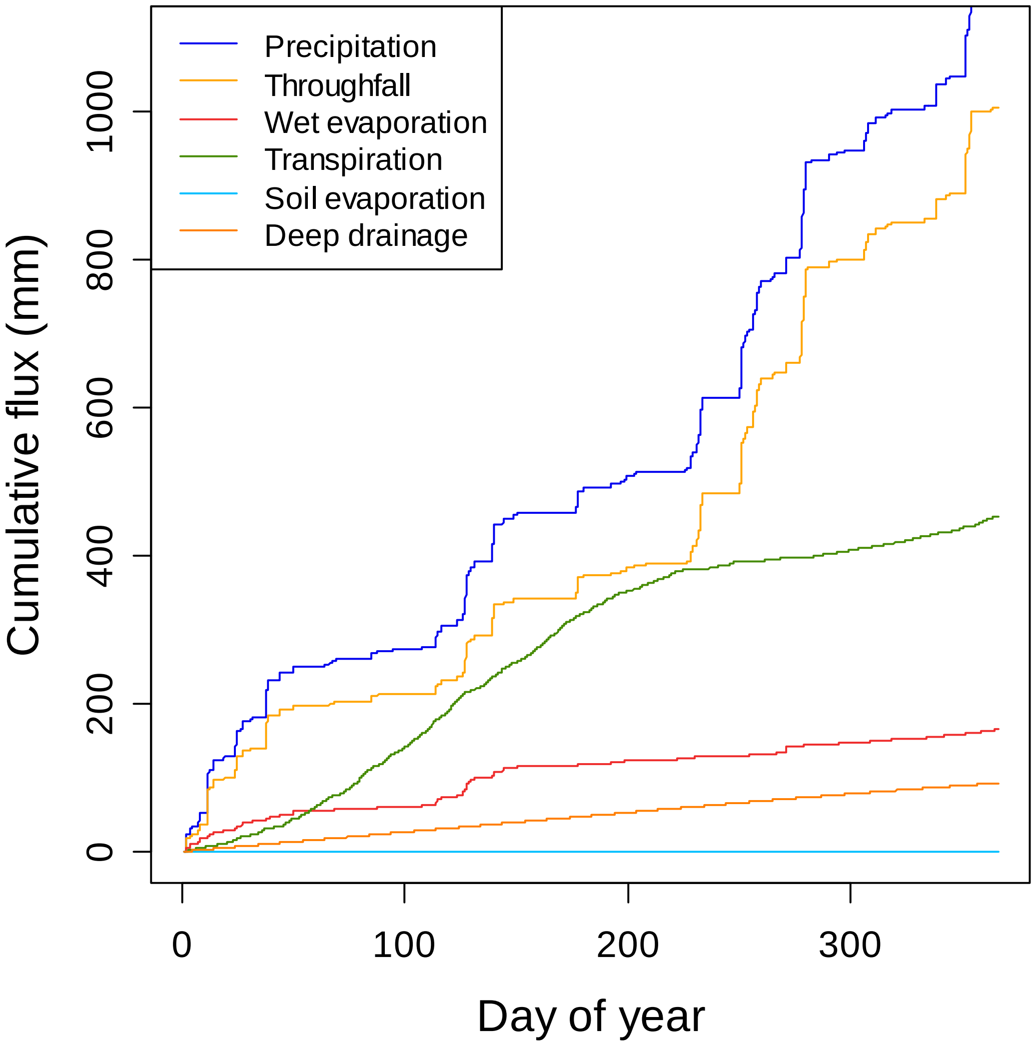


Implementation and user interface

- 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`)

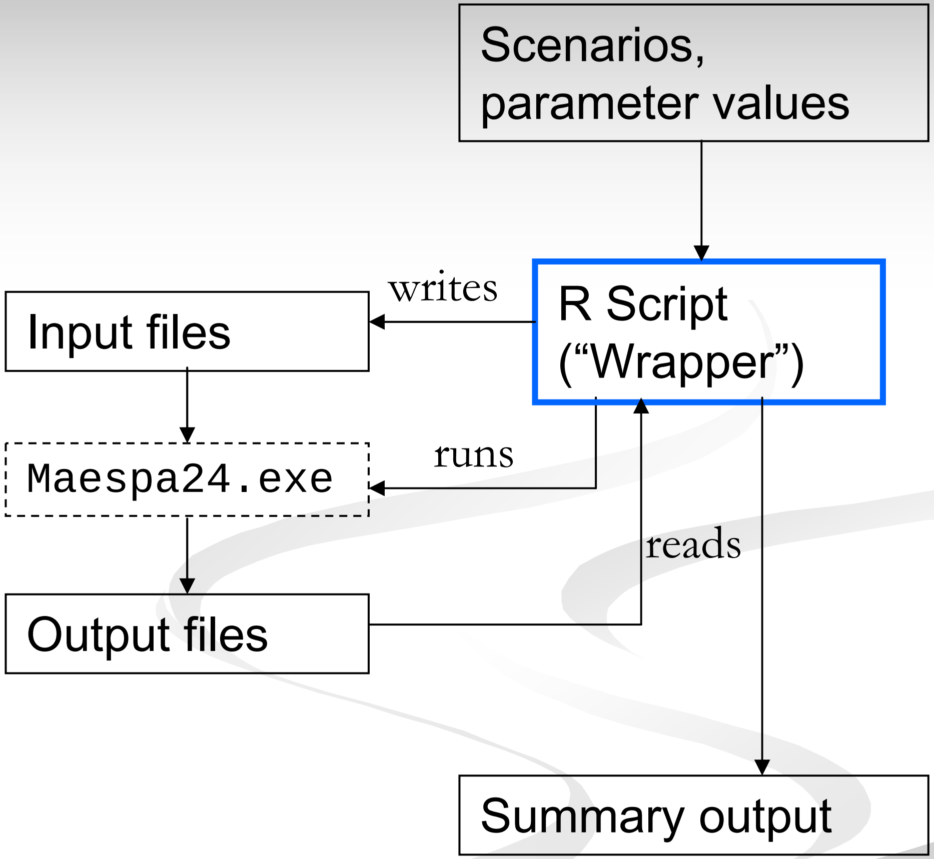
Example output (`watbal.dat`)

- Tumbarumba flux site, *Eucalyptus delegatensis*, LAI = 1.5 m^2 m^{-2}



Batch Utility

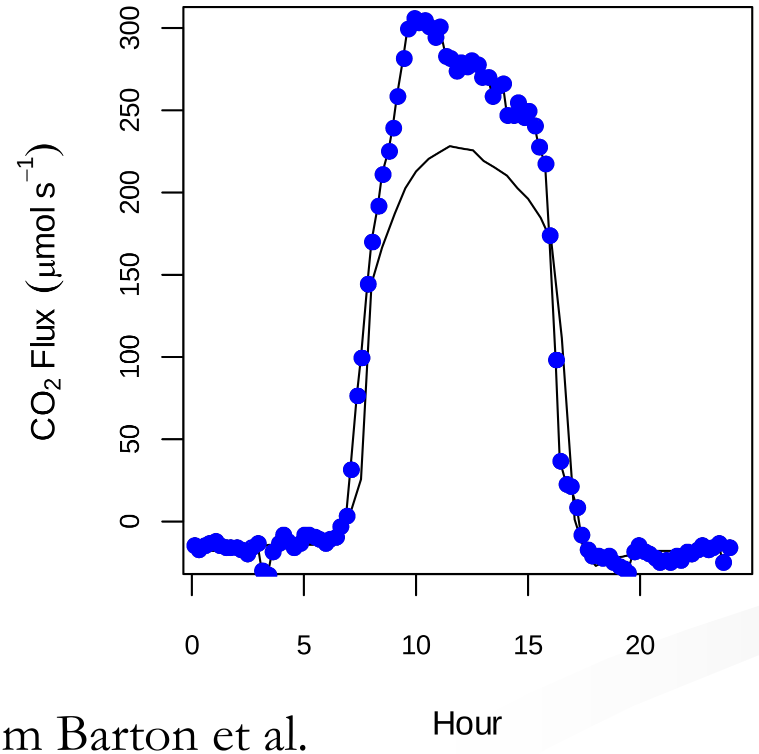
- A collection of functions written in R for multiple simulations of MAESPA/MAESTRA
- Can be used for other models that use namelists in input files (Fortran)
- Available as an R package

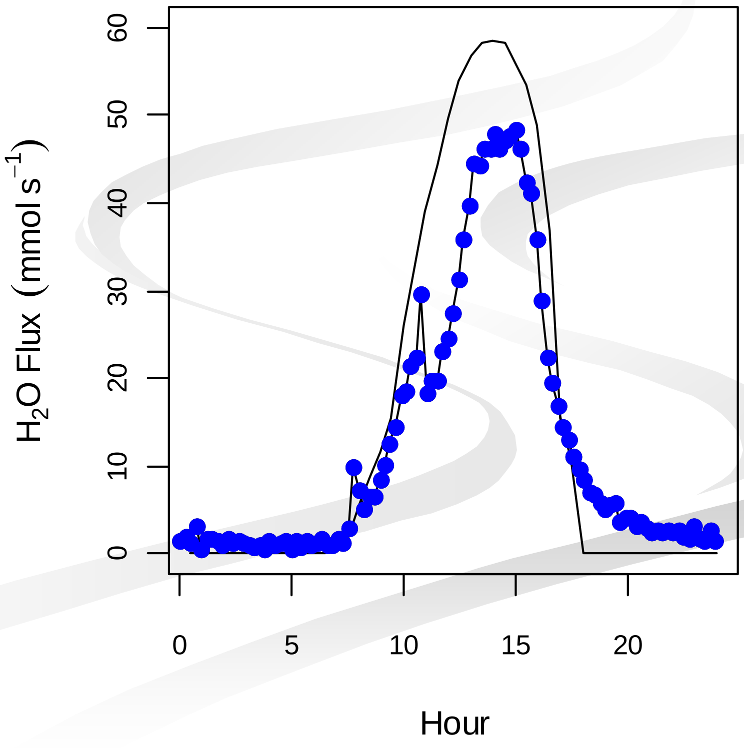


- Also available a number of functions that graph MAESPA output

HFE

- Whole-tree fluxes of CO_2 and H_2O 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?
- 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?