Thirty years of research in ecophysiology & micrometeorology – a personal journey

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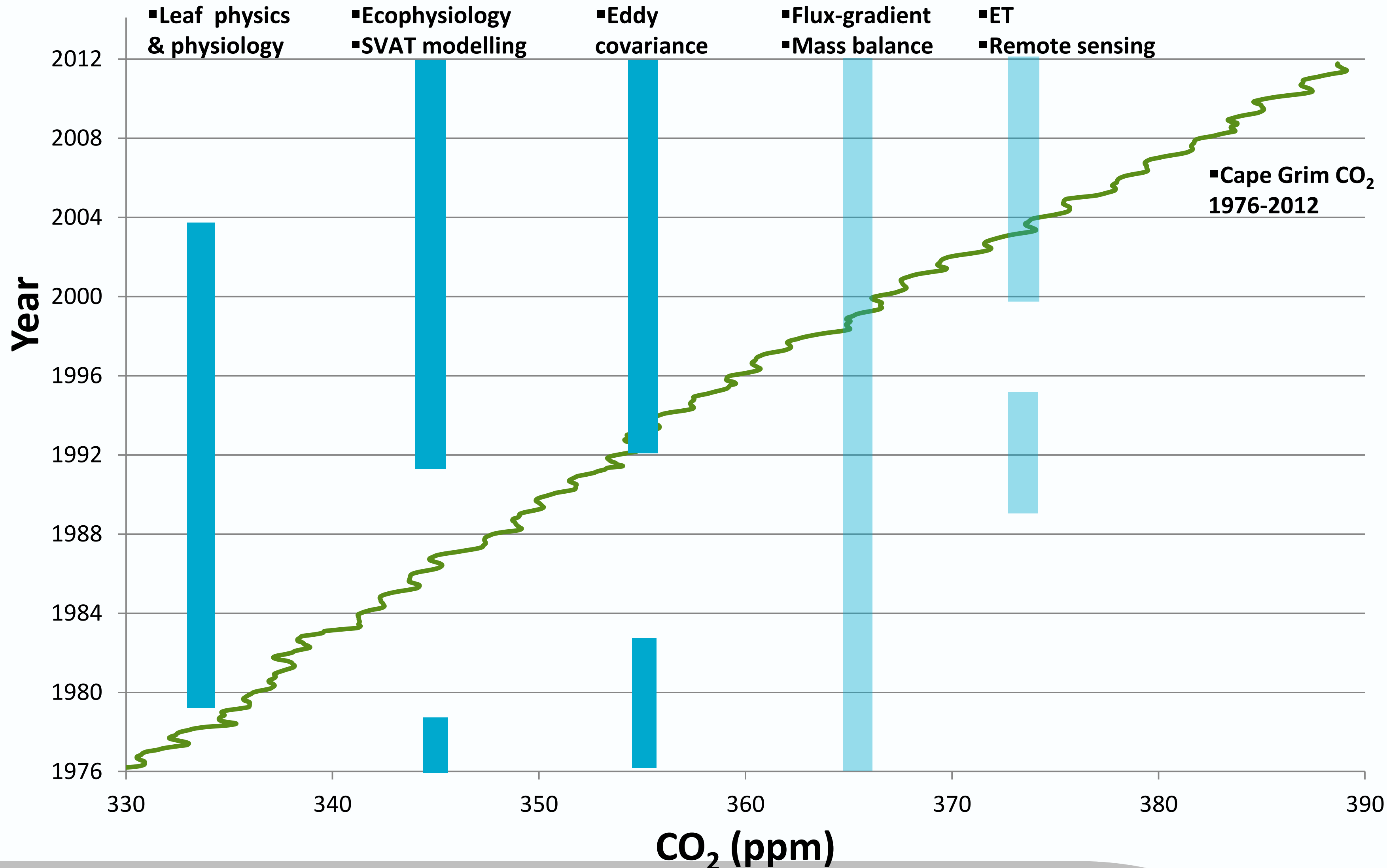
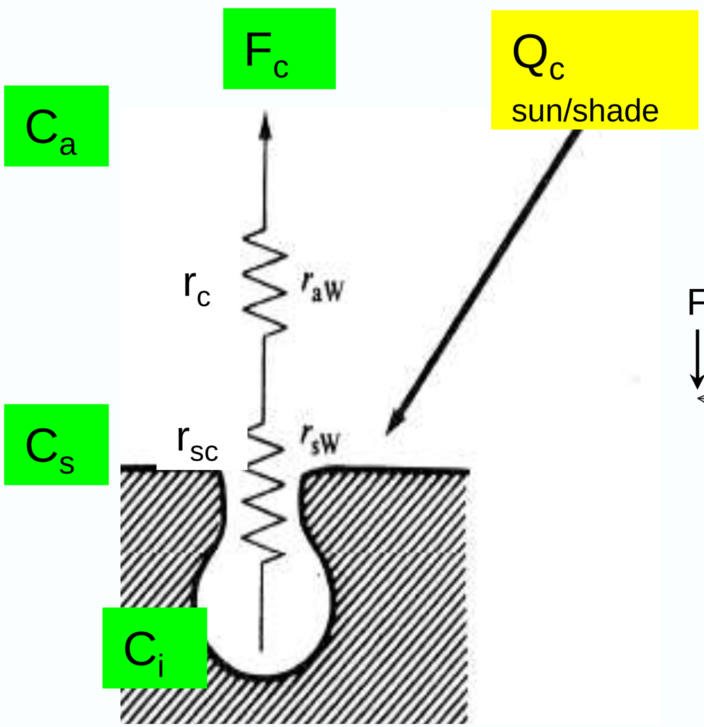
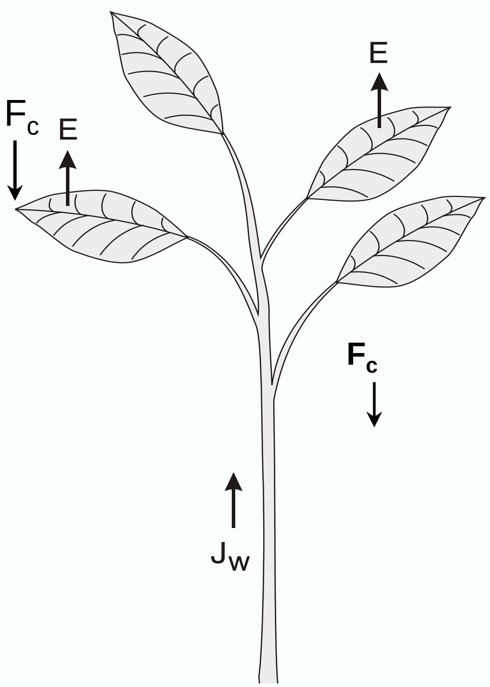
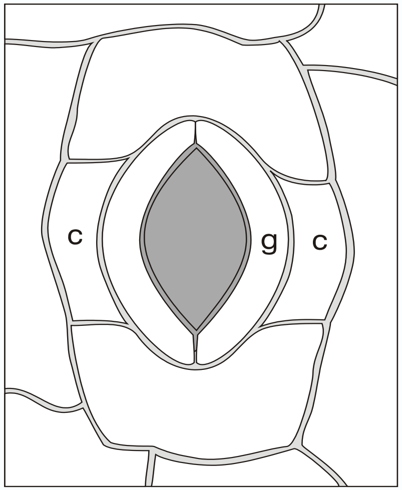
Research over 30 years of rising CO_2

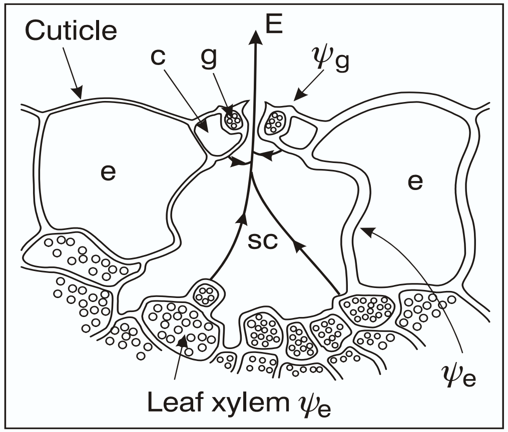


Leaf physics & physiology
Stomata – linking photosynthesis, heat flux & transpiration

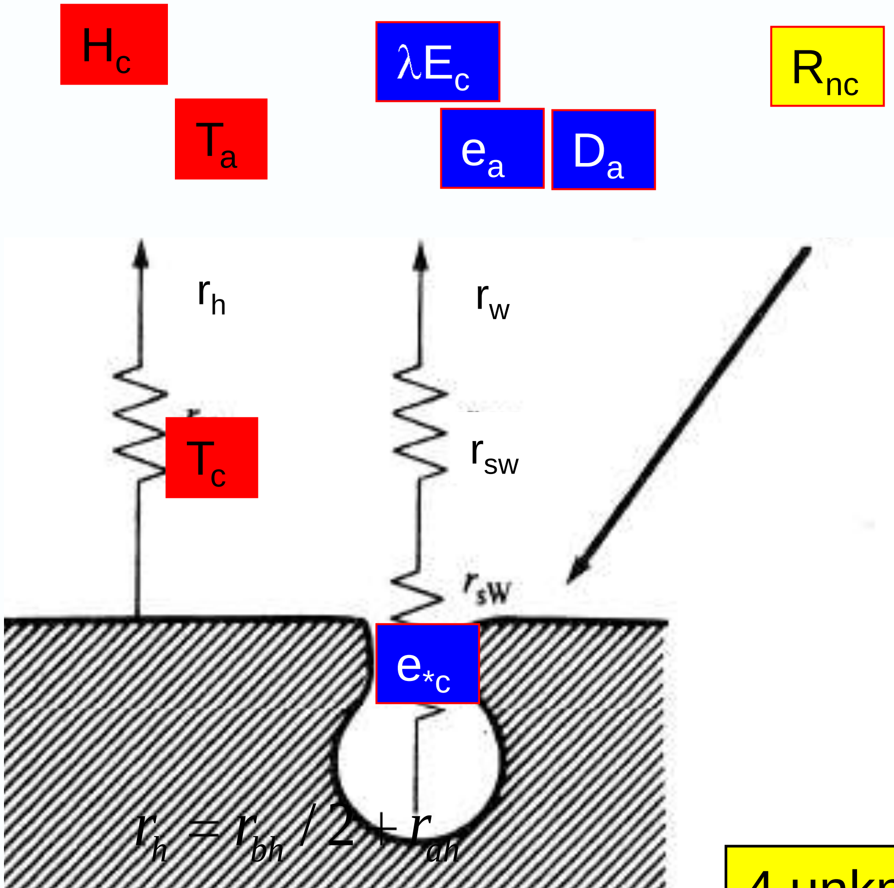








Leaf energy balance



$$r_h = r_{bh}/2 + r_{ah}$$

$$r_w = r_{bw} + r_{aw}$$

$$R_{nc} - \Delta J_c = \lambda E_c + H_c$$

$$H_c = c_p \rho_a (T_c - T_a) / r_h$$

$$\lambda E_c = \frac{\rho_a c_p}{\gamma} \frac{e_c^* - e_a}{r_w + r_{sw}}$$

Unknowns

$$H_c, E_c, T_c \;\&\; r_{sw}$$

4 unknowns with only three equations?

Coupled leaf energy balance, photosynthesis & stomatal conductance

$$R_{nc} = \lambda E_c + H_c$$

$$H_c = c_p \rho_a (T_c - T_a) / r_h$$

$$\lambda E_c = \frac{c_p \rho_a}{\gamma} \frac{e_c^* - e_a}{r_w + r_{sw}}$$

$$A_n = \min\ V_c, V_j\ - R_d$$

$$A_n = g_{sc} (c_s - c_i)$$

$$g_{sc} = g_{c0} + \frac{a\,A_n}{c_i - \Gamma} \cdot f_{\psi c}$$

Ball-Berry-Leuning model

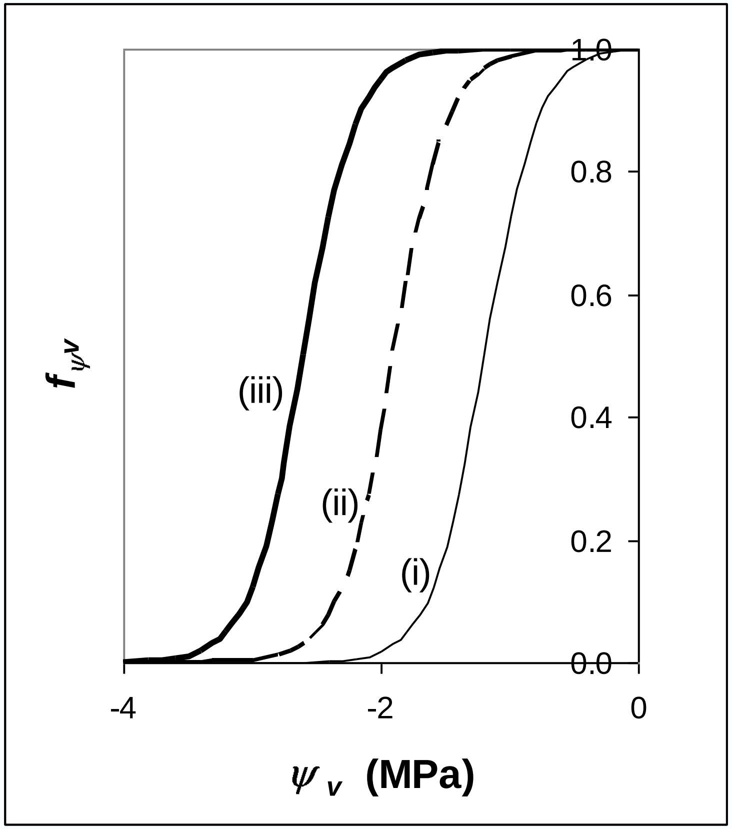
Links photosynthesis, stomatal conductance and transpiration

Unknowns

$$H_c, E_c, T_c, \psi_c, C_i, A_n, \&\ g_{sc}$$

7 unknowns with 7independent equations & many parameters for auxiliary equations

Stomatal conductance, assimilation rate & leaf water potential



$$g_{CO2} = g_0 + \frac{a A_n}{c_i - \Gamma} \cdot f_{\psi v}$$

$$A_n = \min\left(V_c, V_j\right) - R_d$$

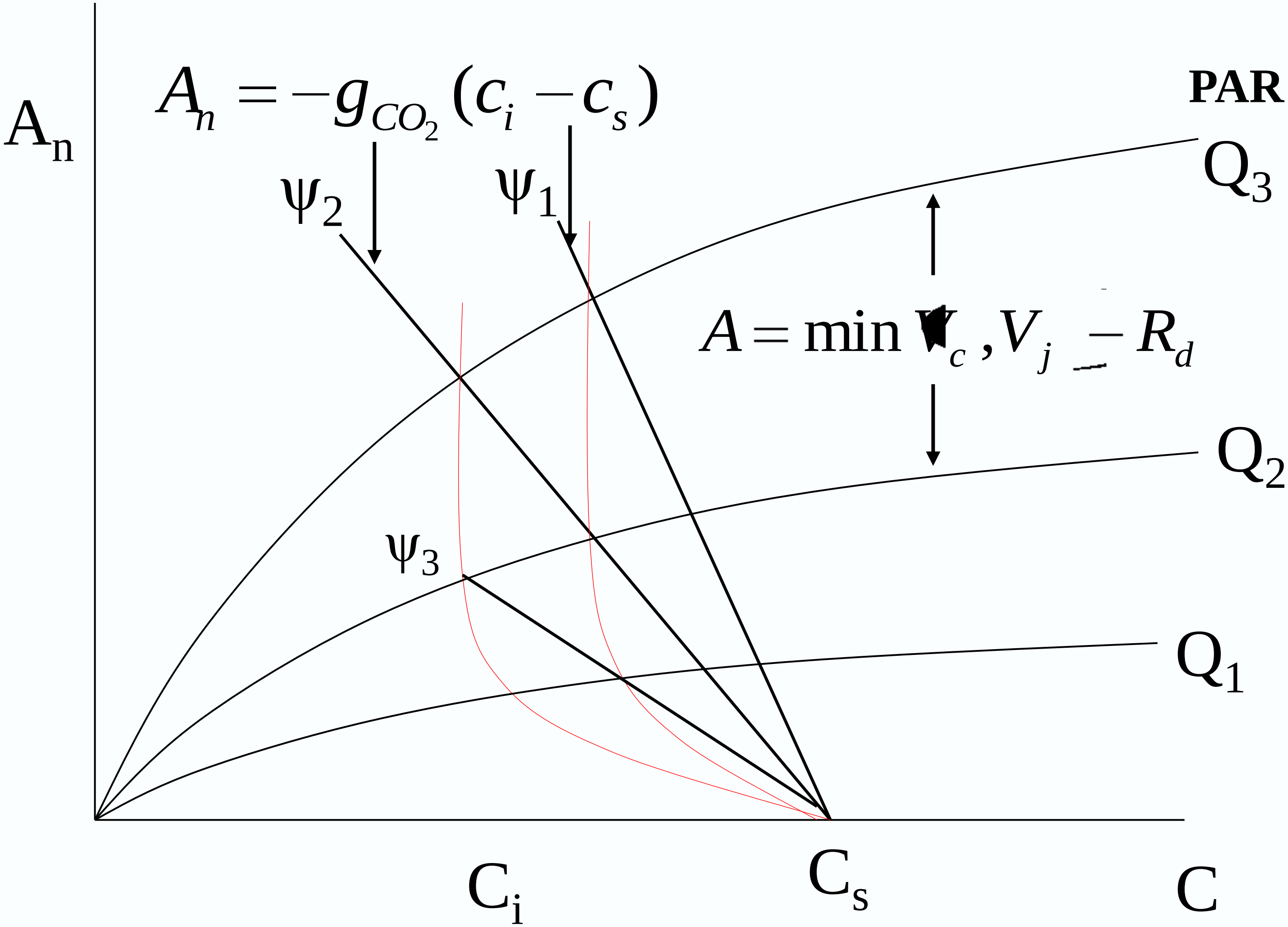
$$A_n = -g_{CO2}(c_i - c_s)$$

where

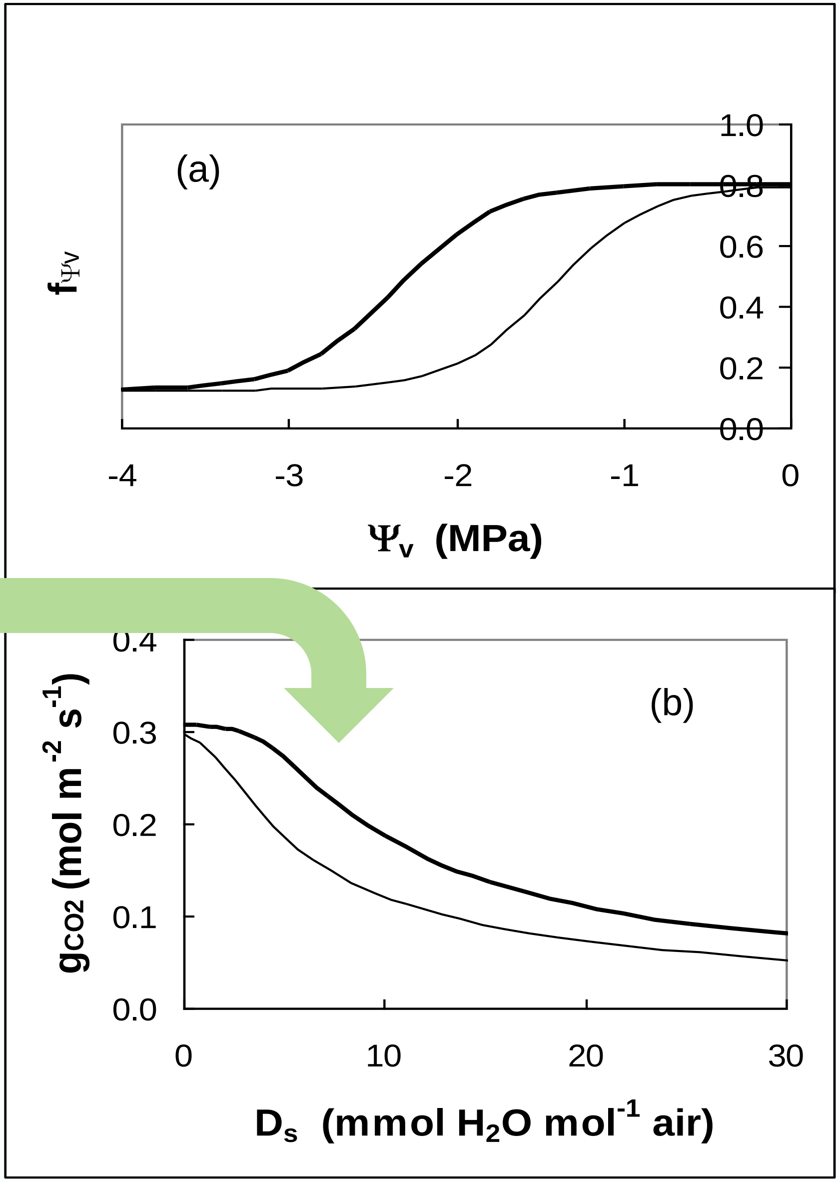
$$f_{\psi v} = \frac{1 + \exp\left[-s_f a_f\right]}{1 + \exp\left[s_f\left(\psi_v - a_f\right)\right]}$$

Tuzet, A., Perrier, A. and Leuning, R. (2003). A coupled model of stomatal conductance, photosynthesis and transpiration. *Plant, Cell and Environment*, 26:1097-1116.

Demand - supply for CO_2



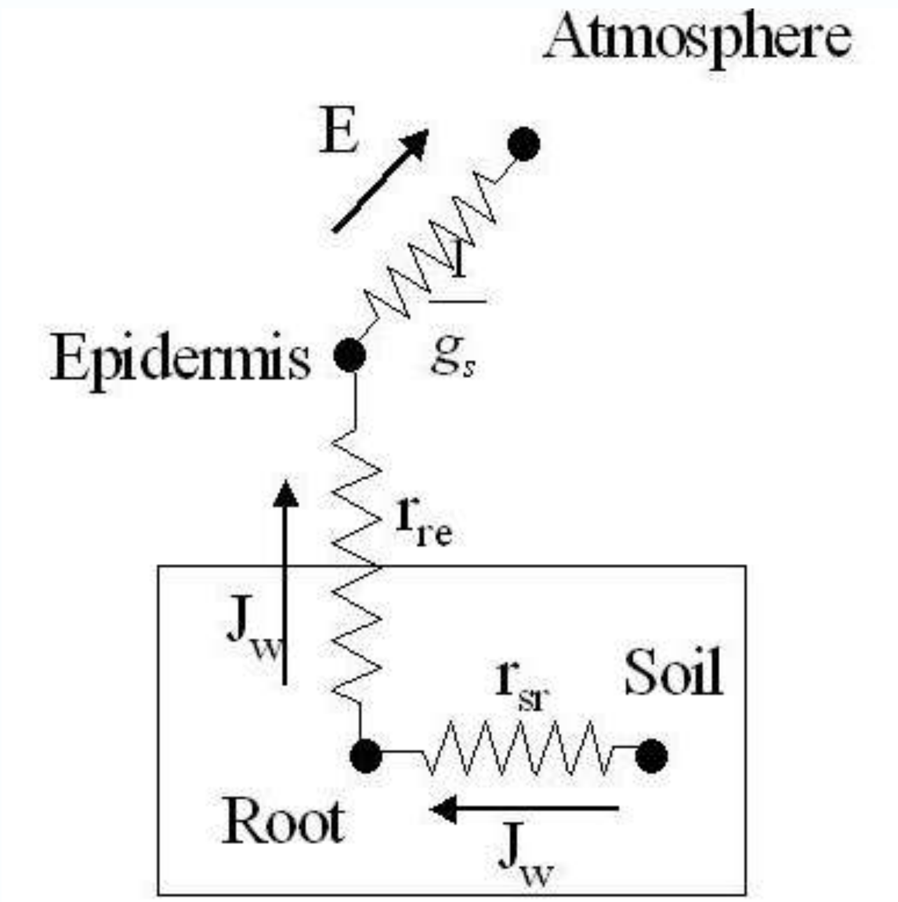
Stomatal conductance vs D_s – well watered plants

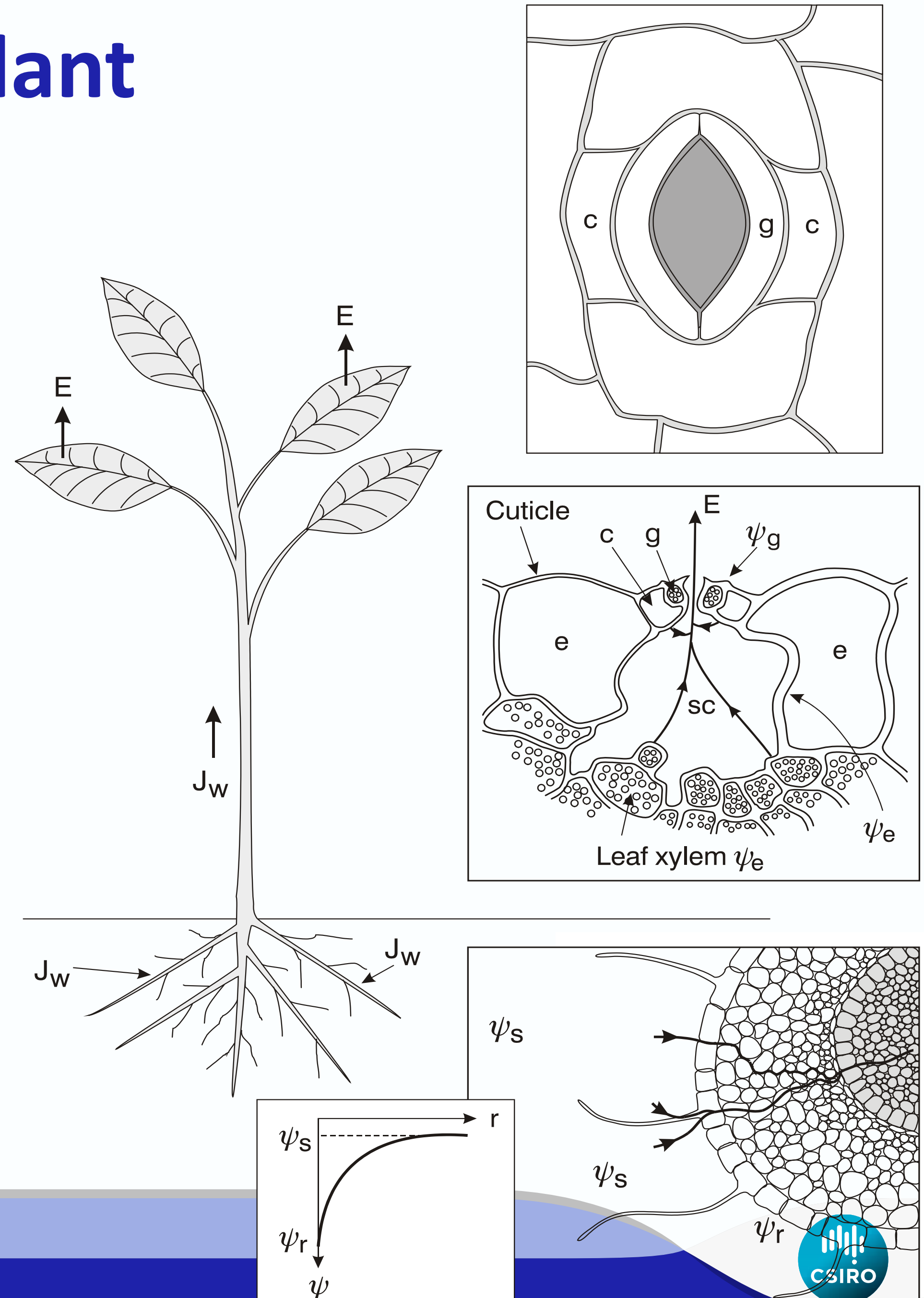


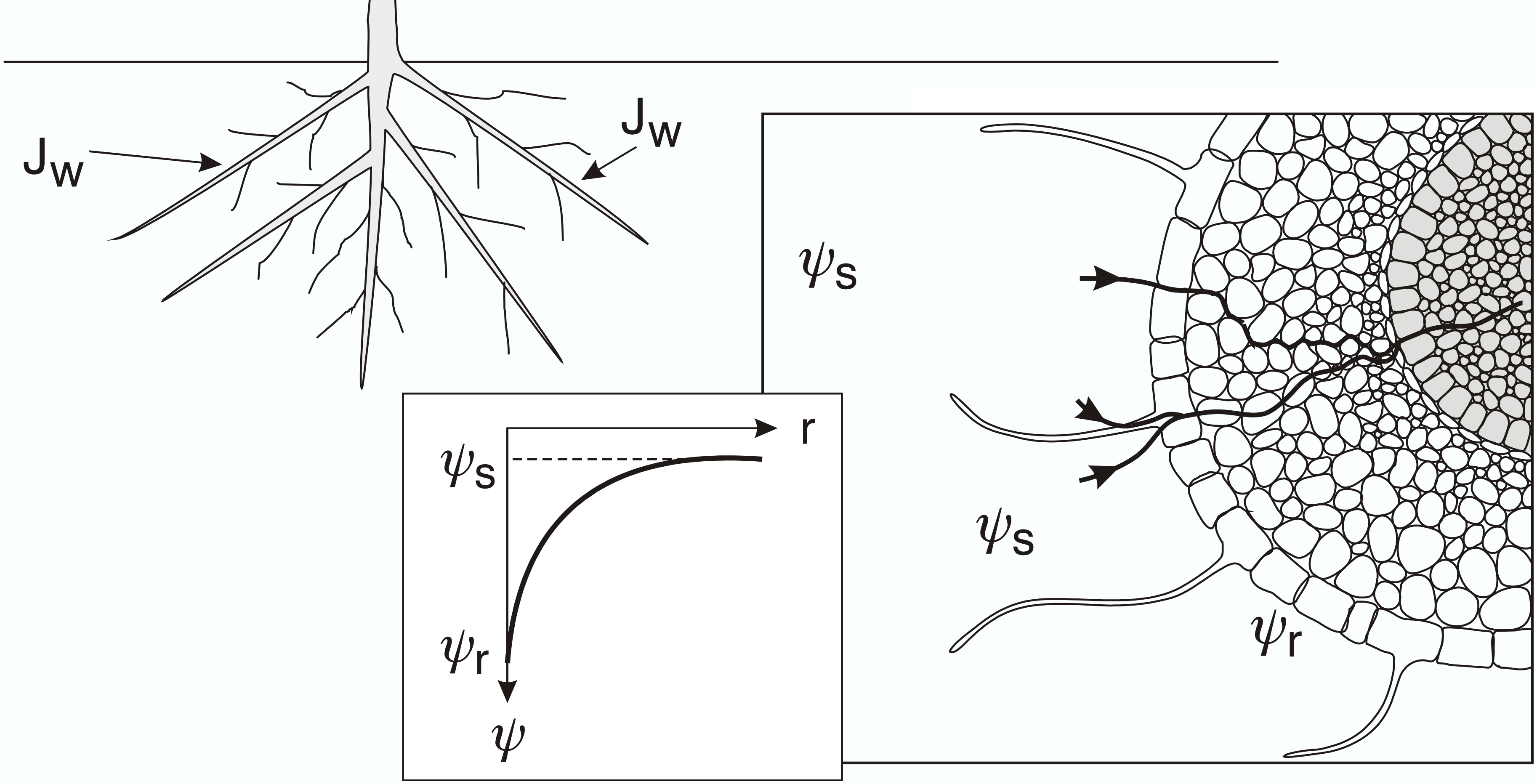
$$g_{sc} \propto D^{-1} \quad or \quad g_{sc} \propto D^{-1/2} \; ?$$

Leuning, R., Tuzet, A., and Perrier, A. (2004). Stomata as part of the soil-plant-atmosphere continuum. In '*Forests at the Land-Atmosphere Interface*'. M. Mencuccini, J. Grace, J. Moncrieff, and K. McNaughton (Editors), pp. 9-28. CAB International, Wallingford UK.

Water flow through plant







Water flow to roots

Water flow through soil and plant

Solve Richard's Eq. for soil- root water supply

$$\frac{\partial \theta}{\partial t} = \frac{2\pi L z_r}{r} \frac{\partial}{\partial r}\left(r K_S \frac{\partial \psi_s}{\partial r} \right)$$

Equate water flow through plant with transpiration

$$J_w = \frac{\psi_r - \psi_v}{\chi_v} = \frac{M_v}{R} \frac{1}{r_{H2O} + r_{bV}} \left(\frac{h_i e^* \; T_{sv}}{T_{sv}} - \frac{e^* \; T_{rv}}{T_{av}} \right)$$

Relative humidity – links transpiration & leaf water potential

$$h_i = \exp\left(M_v \psi_v / \rho_v R T_{sv} \right)$$

Tuzet, A., Perrier, A. and Leuning, R. (2003). A coupled model of stomatal conductance, photosynthesis and transpiration. *Plant, Cell and Environment*, 26:1097-1116.

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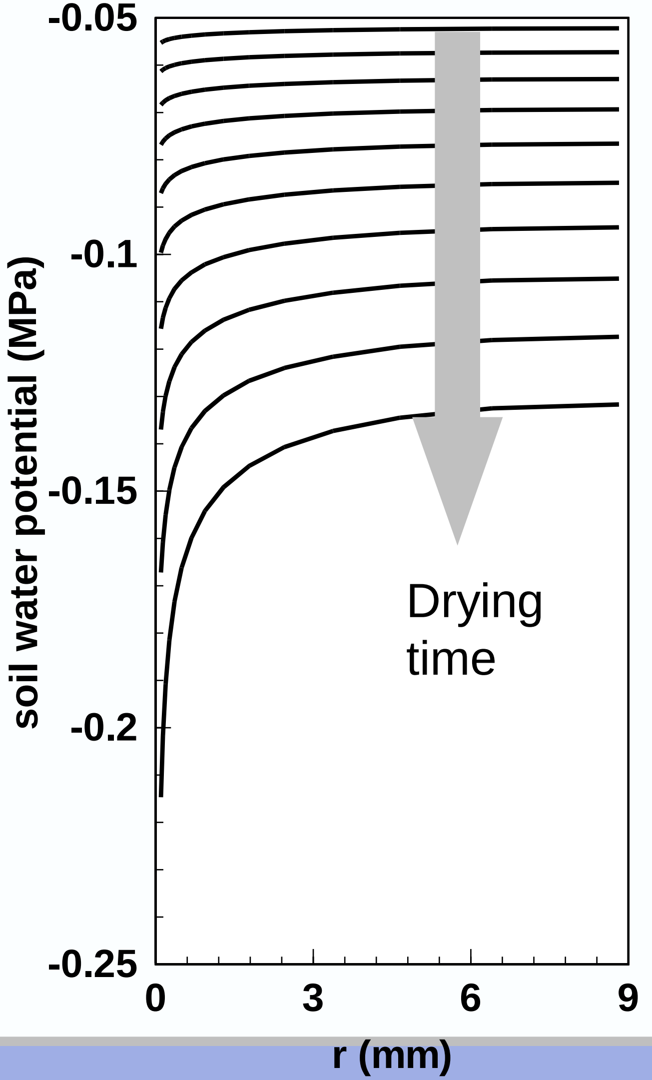
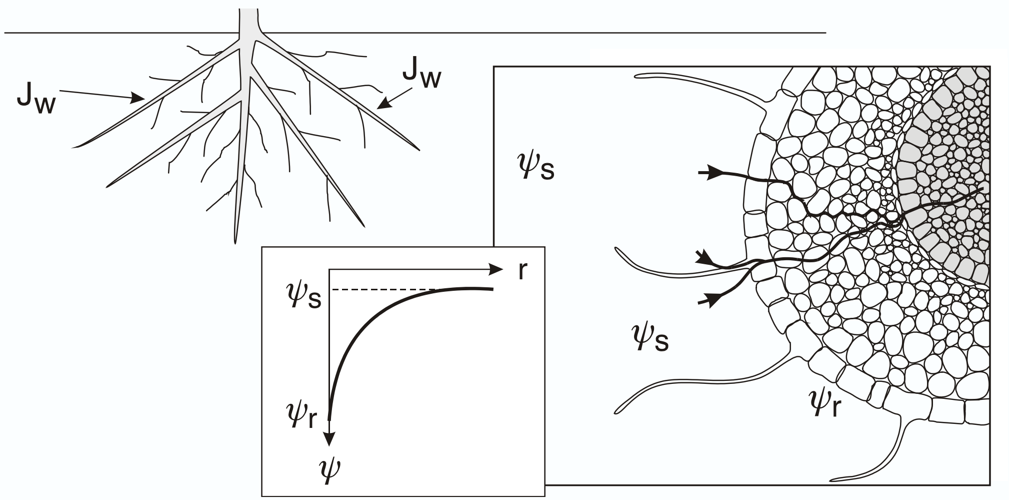
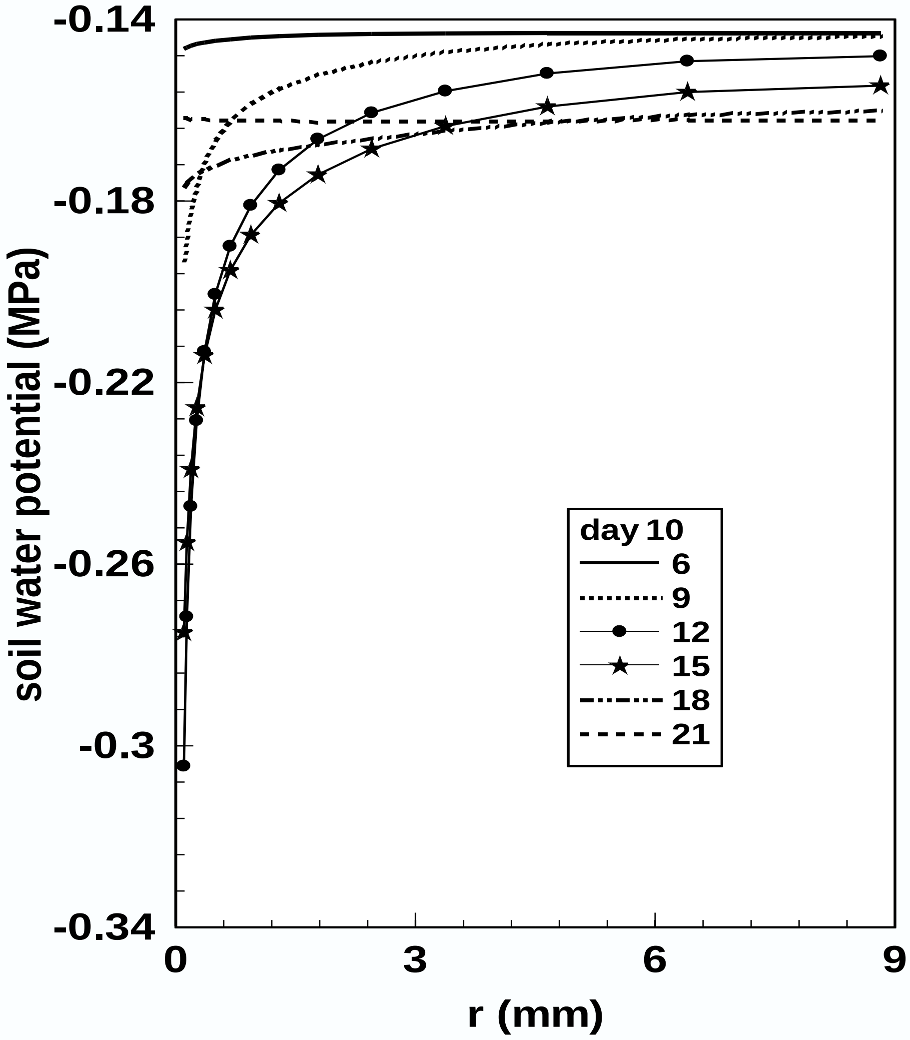
Soil water potential vs radial distance from root

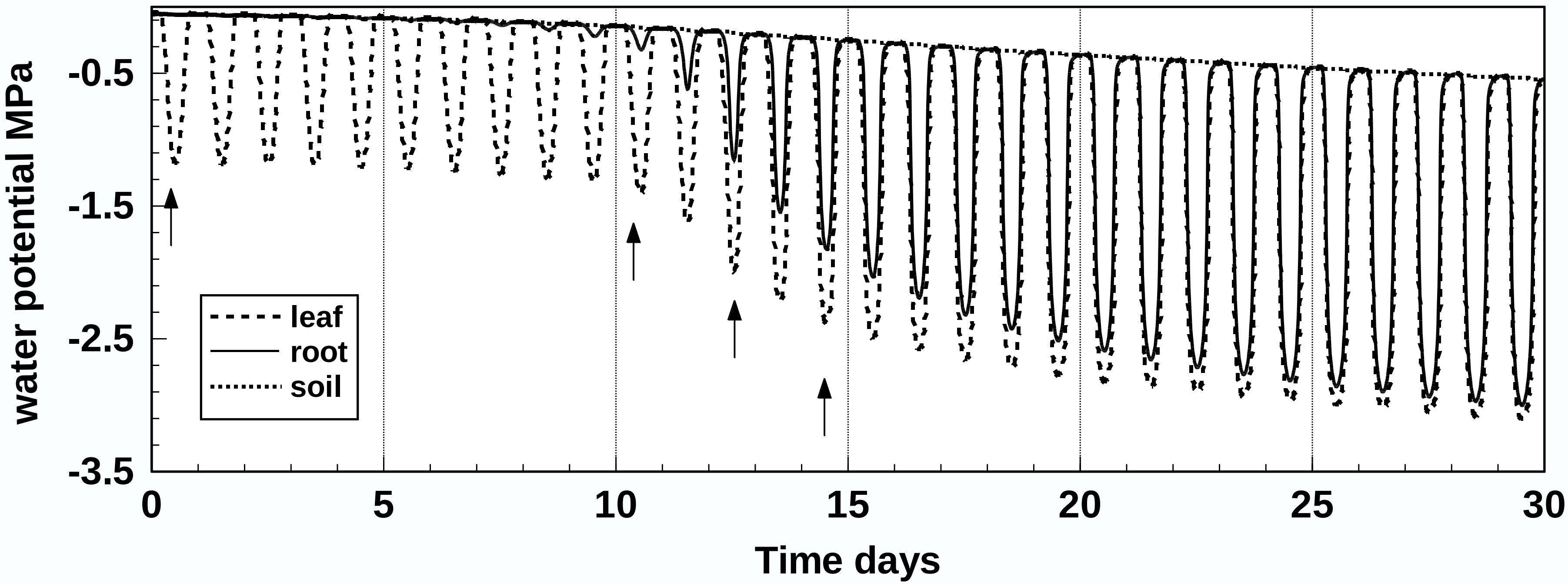




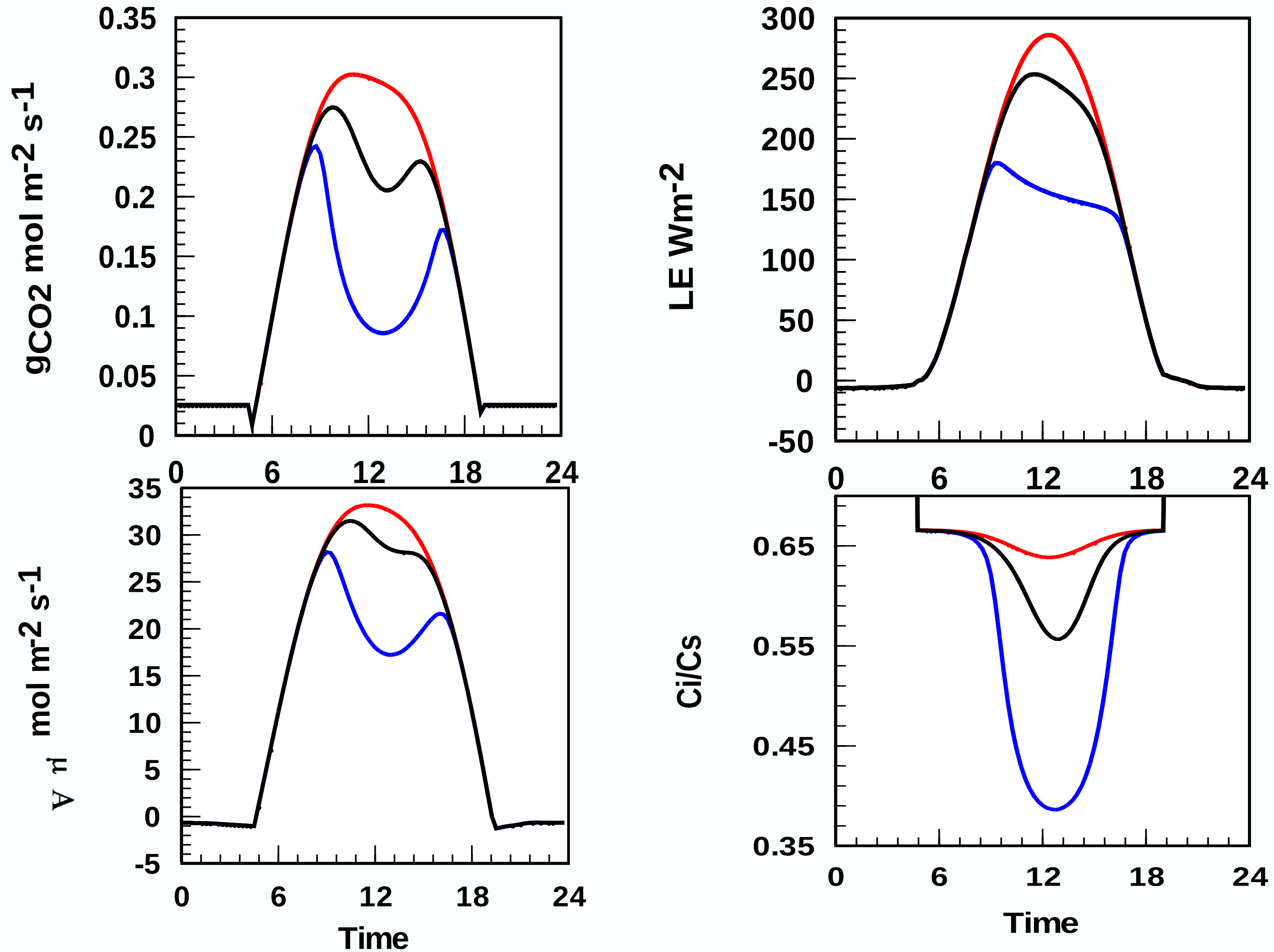
Soil water potential dynamics



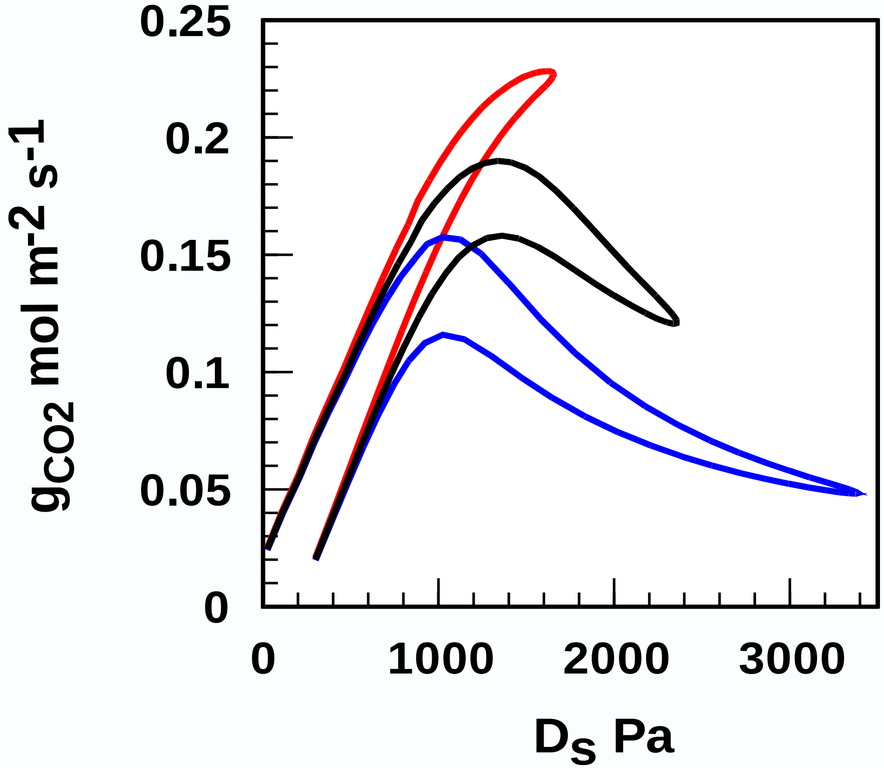
Water potentials during drying cycle

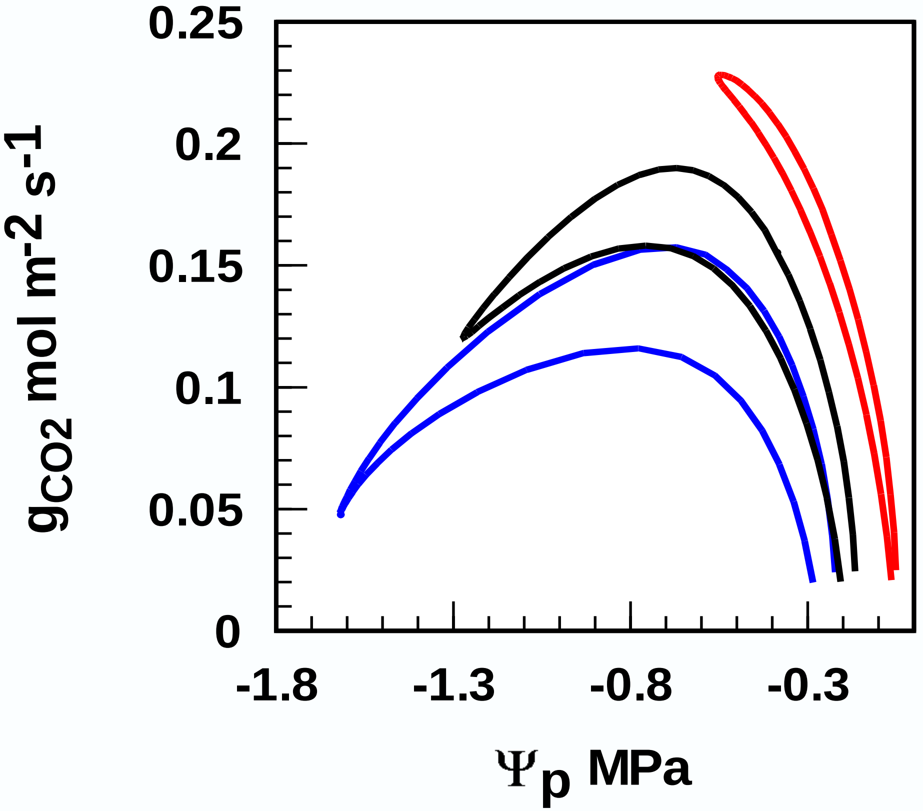


G_{sc} *LE A* & c_i/c_s as soil dries

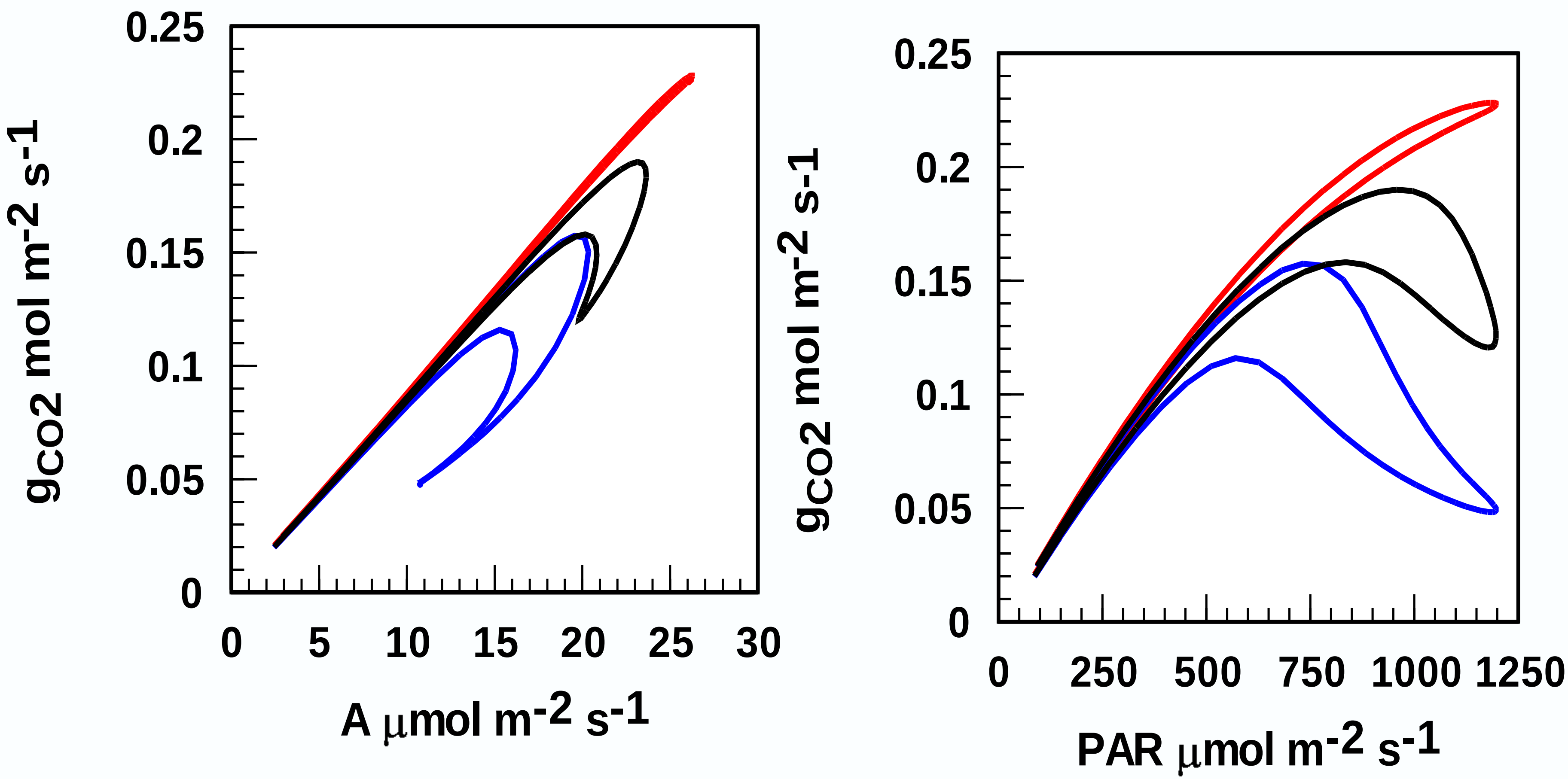


Conductance vs D_s and ψ_p

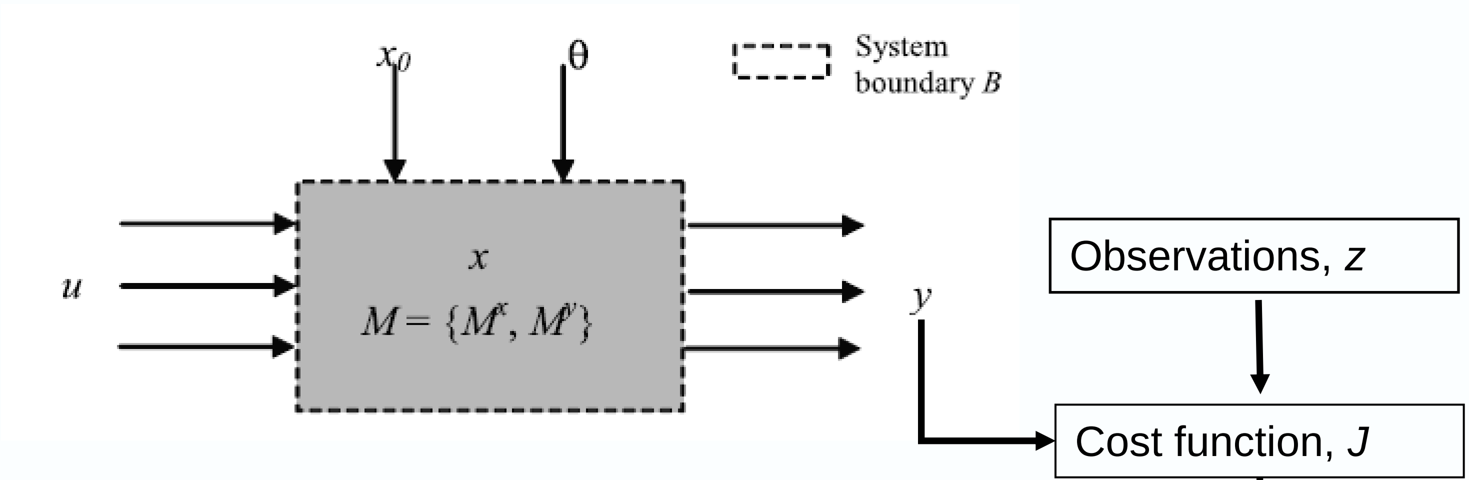




Conductance vs A & PAR



Models need measurements for parameters & testing



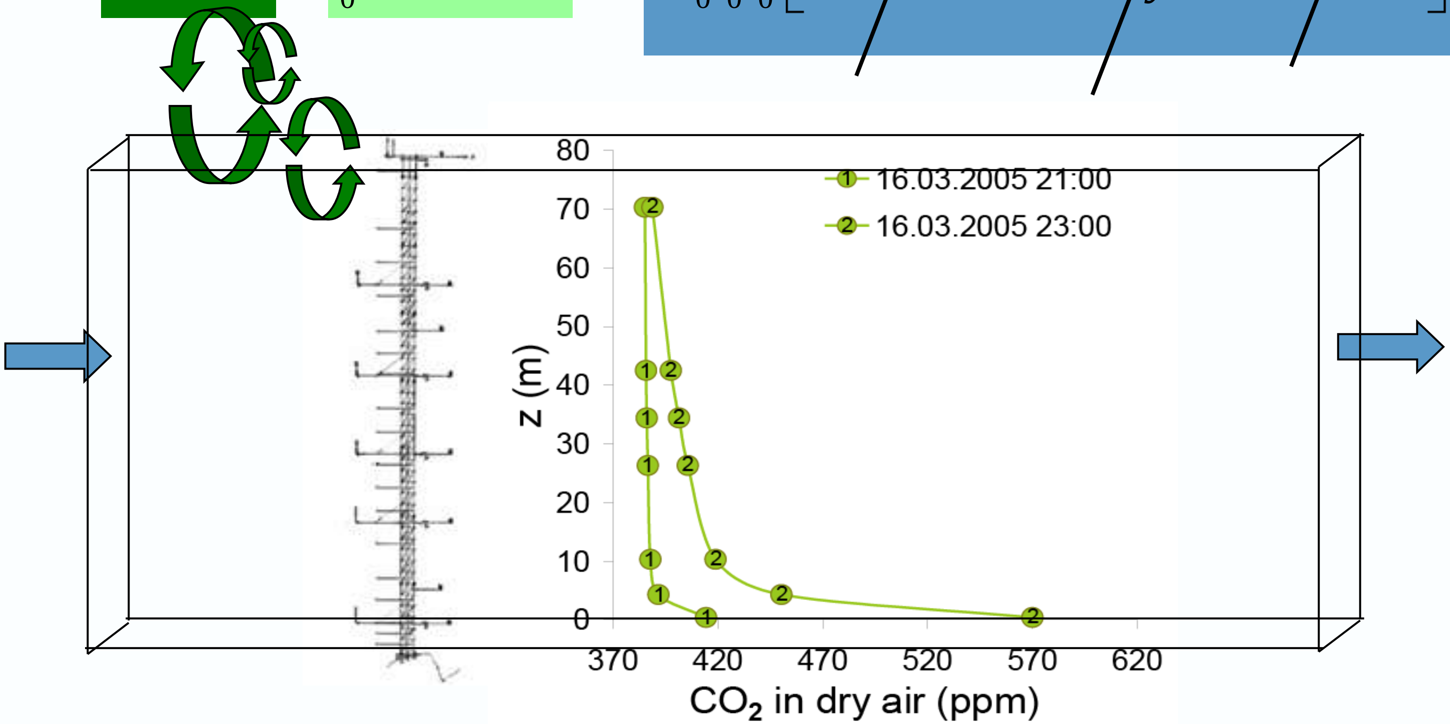
1. system boundary, *B*
2. inputs, *u*
3. model structure, *M*
4. model states, *x*
5. initial states, x_0
6. parameters, *θ*
7. outputs, *y*
8. *observations, z*

Errors in each component affects model performance

Liu, Y. Q. and Gupta, H. V. (2007). *Water Resources Research* 43, W07401, doi:10.1029/2006/WR005756.

Micrometeorology
Mass balance for horizontally homogeneous flow

$$F_c = \overline{c_d}\,\overline{w'\chi_c'} + \int_0^h \overline{c_d}\,\overline{\frac{\partial \chi_c}{\partial t}}\,dz + \frac{1}{L^2}\int_0^L\!\!\int_0^L\!\!\int_0^h \left[\overline{uc_d}\,\overline{\frac{\partial \chi_c}{\partial x}} + \overline{vc_d}\,\overline{\frac{\partial \chi_c}{\partial y}} + \overline{wc_d}\,\overline{\frac{\partial \chi_c}{\partial z}}\right] dx\,dy\,dz$$



Eddy Covariance – measurements at canopy scale

$$\overline{\tau} = -\overline{\rho}\,\overline{w'u'}$$

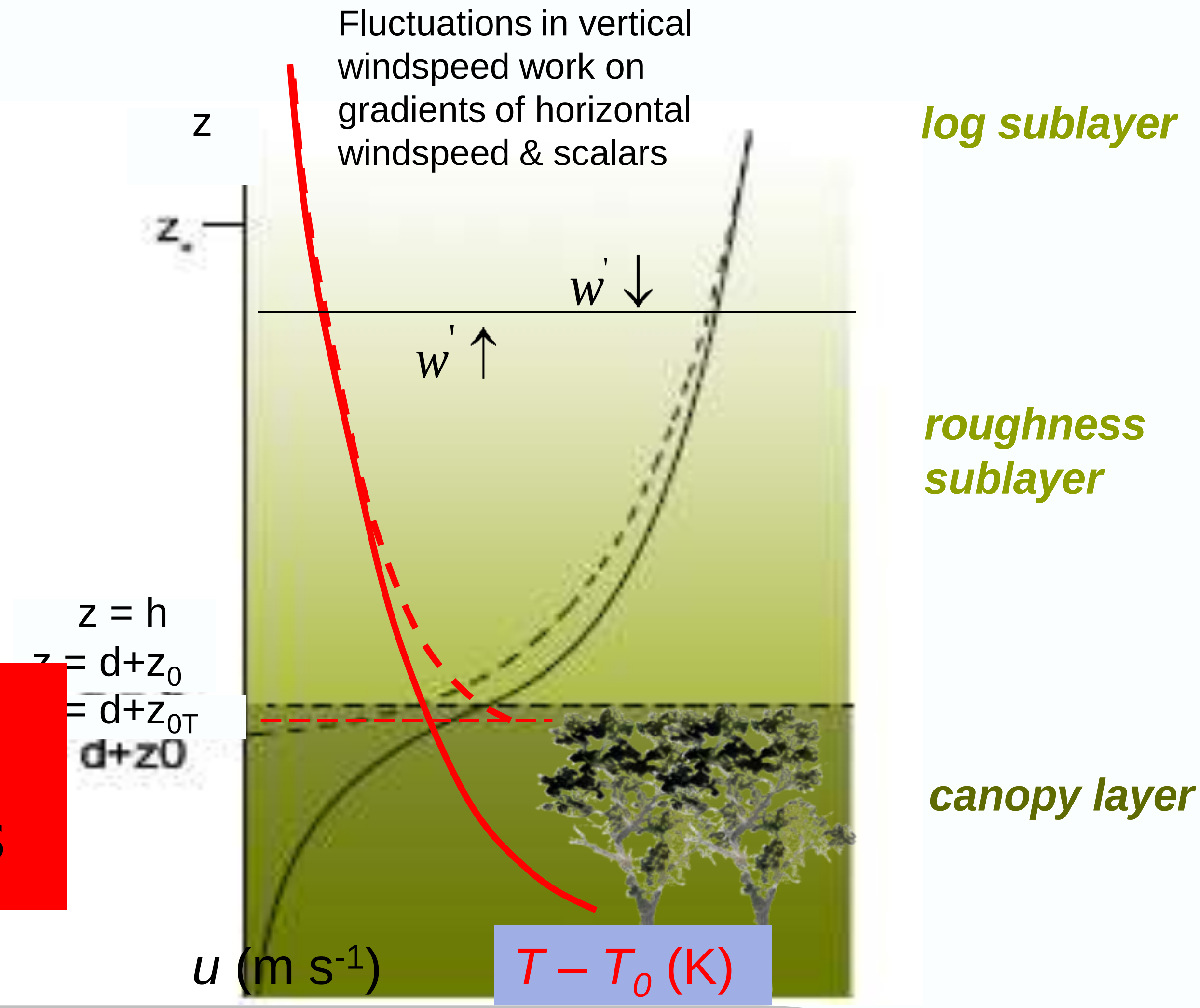
$$\overline{H} = \overline{\rho}c_p\overline{w'T'}$$

$$\overline{E} = \overline{\rho_a}\,\overline{w'\chi_v'}$$

$$\overline{F_c} = \overline{\rho_a}\,\overline{w'\chi_c'}$$

Covariances

Using mixing ratios



Webb, Pearman & Leuning (1980) theory
Steady state, horiz. homogeneous flow

Can write trace gas flux using concentrations

$$\overline{F_c} = \overline{wc_c} = \overline{w}\,\overline{c_c} + \overline{w'c_c'} \quad \textbf{but} \quad \overline{w} \neq 0$$

What is $\overline{w}$? WPL assumed no net flux of dry air

$$\overline{F_d} = 0 = \overline{w}\,\overline{c_d} + \overline{w'c_d'} \;\Rightarrow\; \overline{w} = -\overline{w'c_d'}\,/\,\overline{c_d}$$

WPL theory

$$\overline{w} = -\overline{w'c'_d} \,/\, \overline{c_d}$$

Need expression for c'_d

WPL showed

$$\overline{w} = \frac{1}{\overline{c_d}}\left[\overline{w'c'_v} + \overline{c}\,\frac{\overline{w'T'}}{\overline{T}}\right]$$

$< 3 \ mm\,s^{-1}$

Water vapor flux

Heat flux

Cannot measure $\overline{w}$ directly

Fundamentals - eddy flux for trace gases

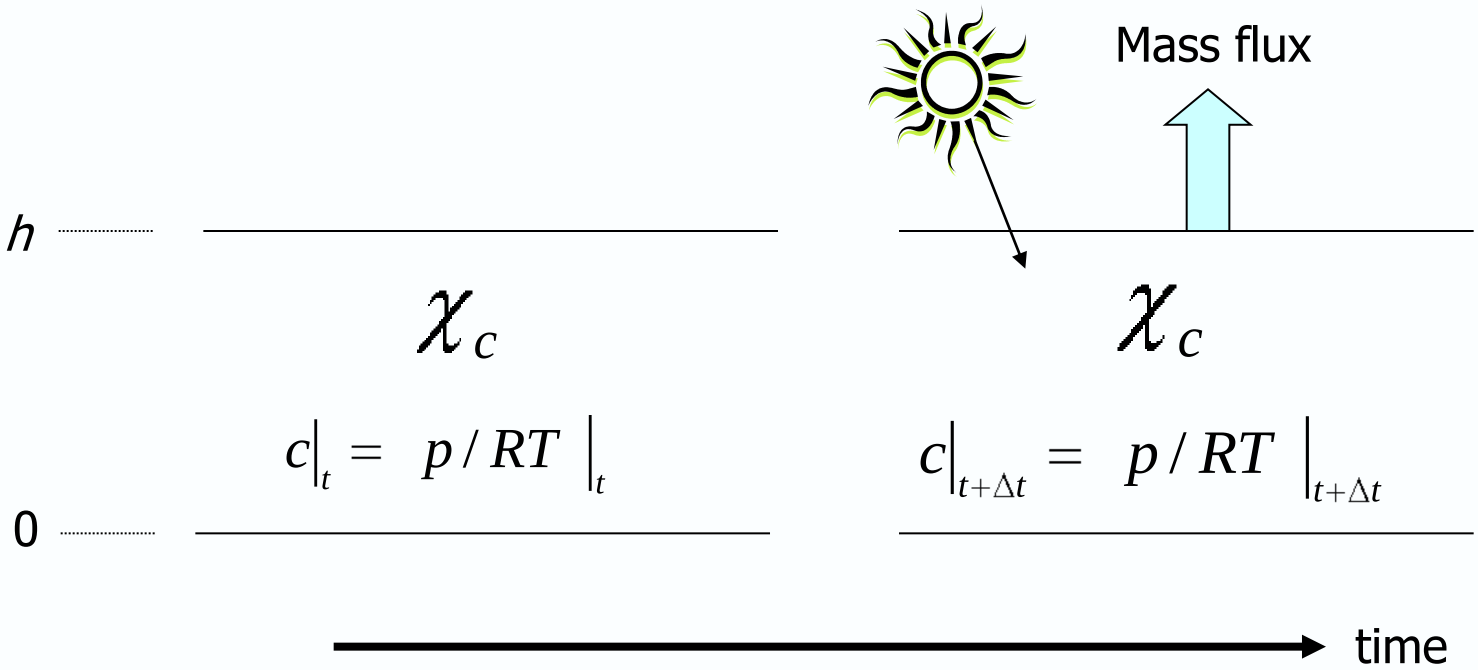
Webb, Pearman & Leuning (1980)

$$\overline{F_c} = \bar{c}_d\,\overline{w'\chi_c'} = \overline{w'c_c'} + \overline{\chi_c}\left[\overline{w'c_v'} + \bar{c}\,\frac{\overline{w'T'}}{\overline{T}}\right]$$

Raw CO_2 flux | Water vapor flux | Heat flux

Leuning (2007) showed original WPL applies to both steady & non-steady horizontally homogeneous flows

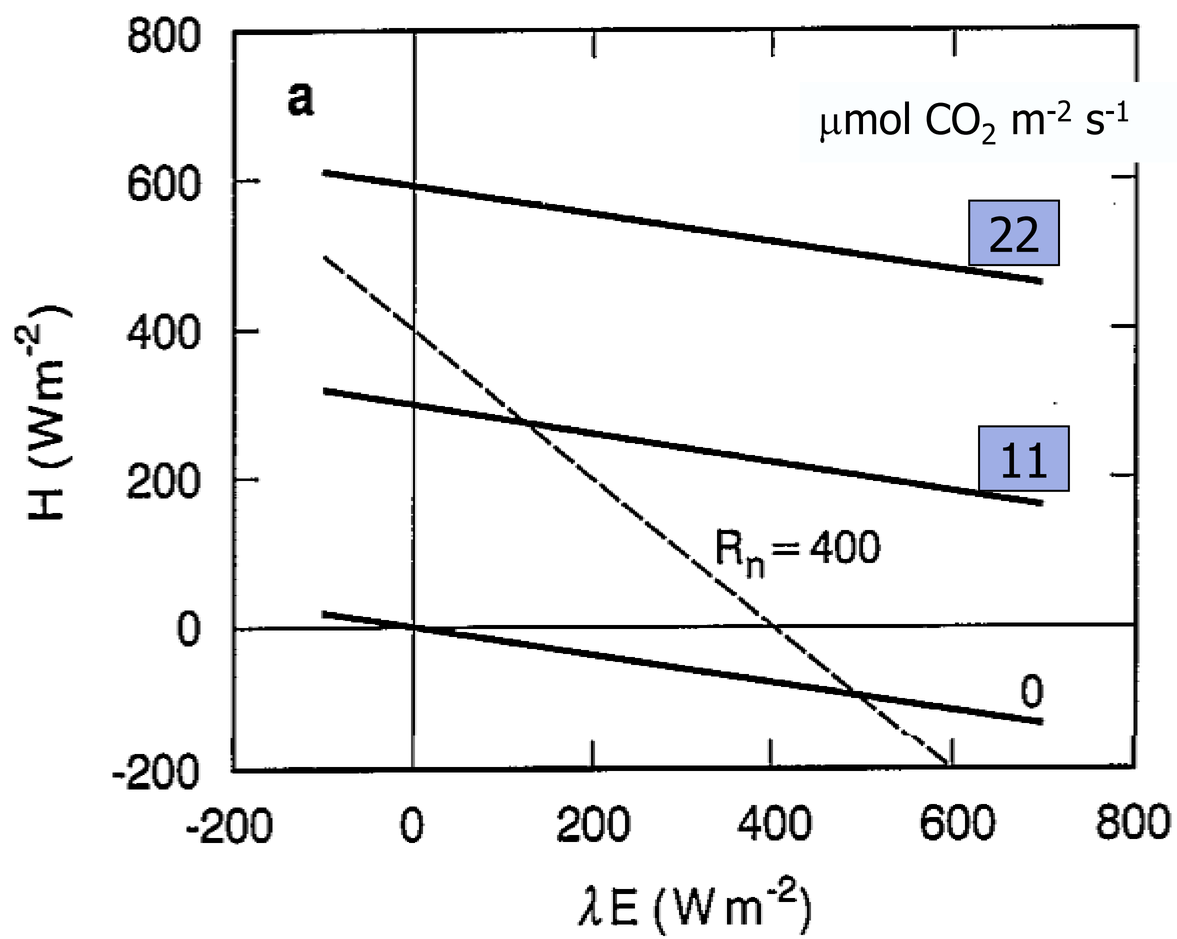
Non steady-state, horizontally homogeneous flow?



There is a mass flux – matched exactly by change in storage

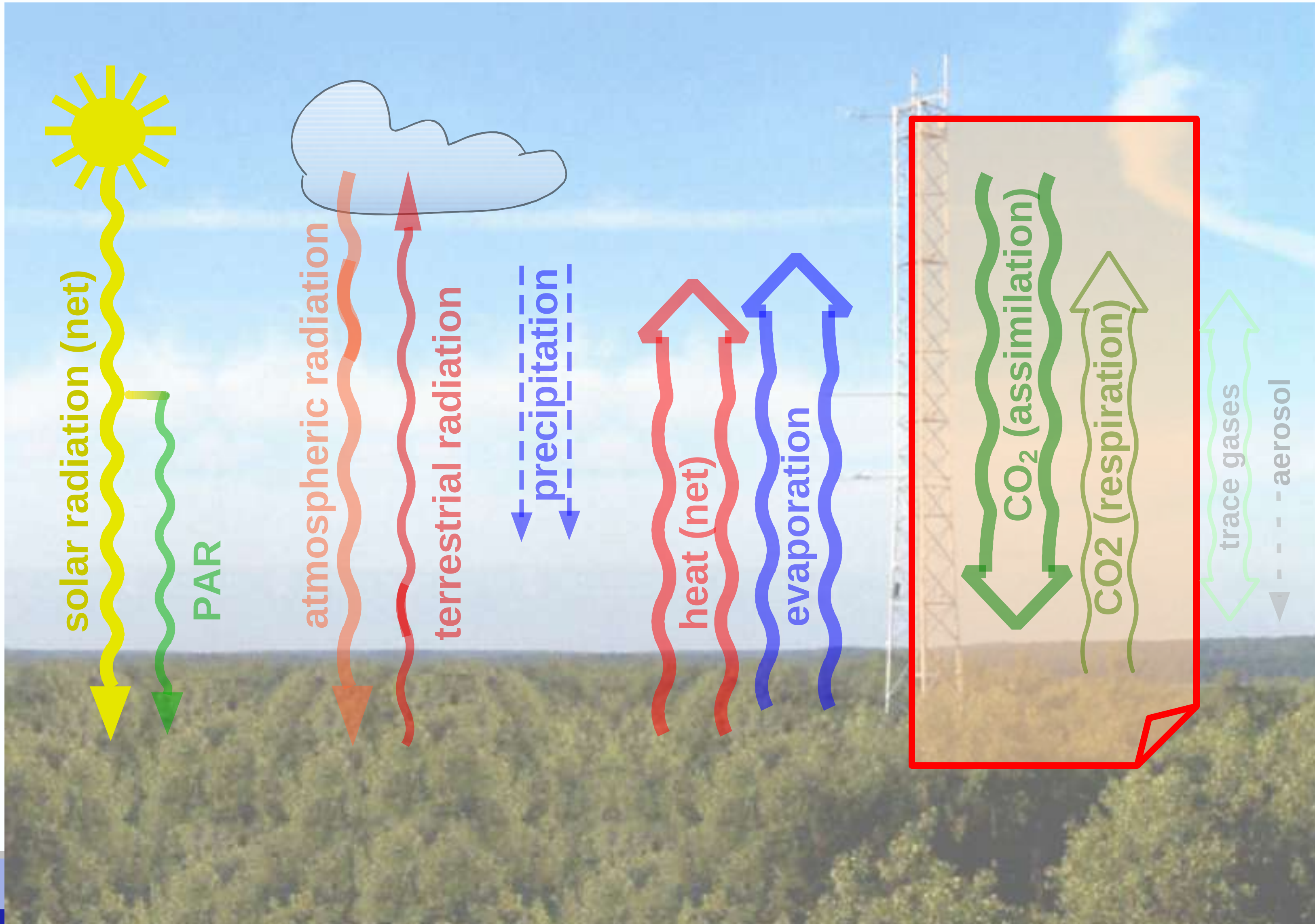
Mixing ratio easier to use – no WPL corrections needed

Magnitude of WPL corrections – add to raw flux

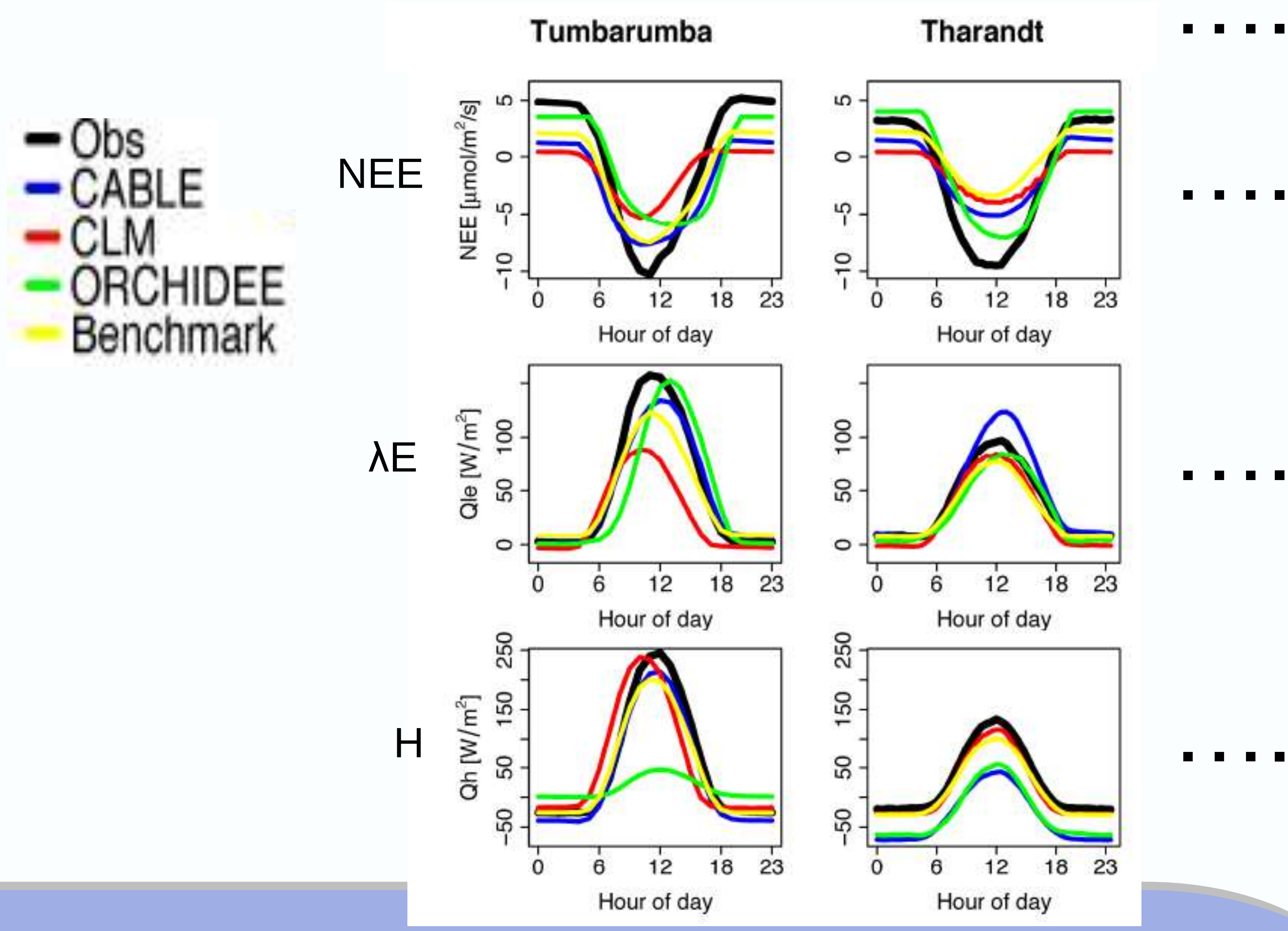


Leuning & Judd, 1996

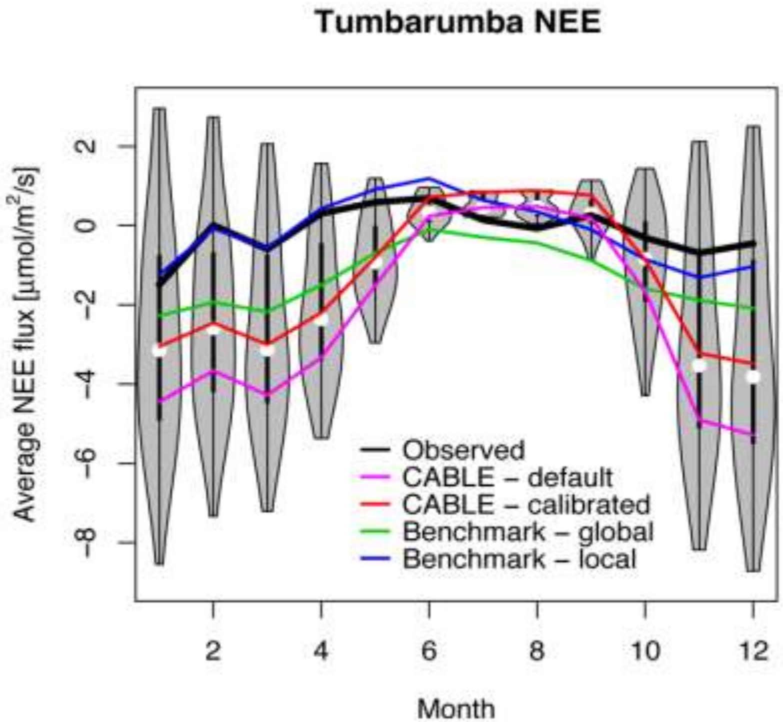
SVAT modelling

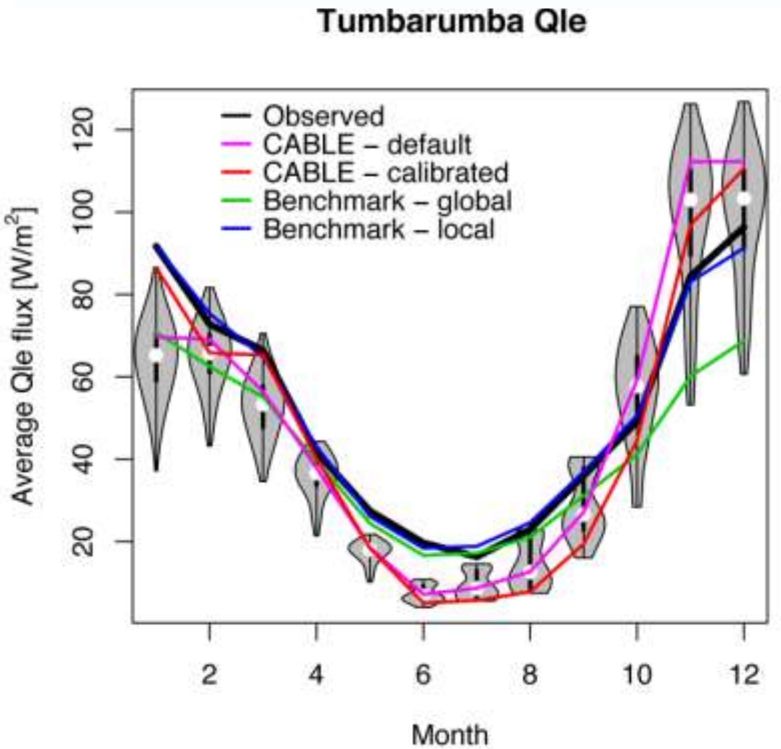


Compare measurements & models at multiple sites



Acceptable parameter sets cannot account for model structural problems

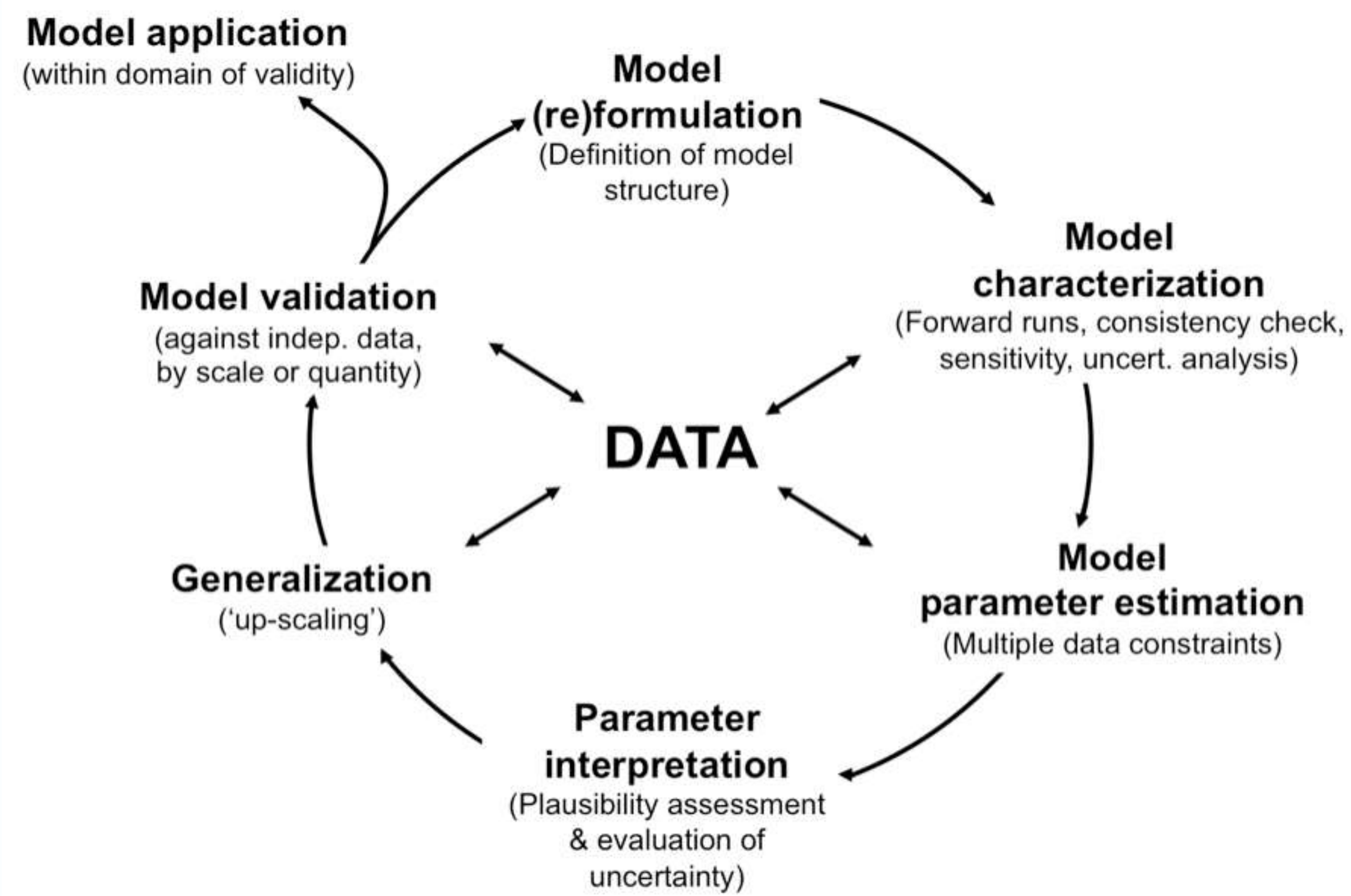




Model systematically different from measurements for reasonable combination of parameter values

Model structural errors or data problems?

Data-model mandala



Reichstein

Future challenges

1. Improve model structure & processes
   - Fluxes of heat water vapour CO2 agree with measurements simultaneously
2. New ways to distribute parameter values spatially
   - Replace plant functional types?
3. Better understanding of adaptation of vegetation to climate change
   - Allocation of resources: nutrients, carbon water and energy

Thank you to all my mentors, colleagues and friends during a rich, rewarding and varied career over the past 40 years.

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Some reminiscences

Micrometeorological methods for flux measurements

- Eddy covariance instrumentation
- A tribute to Tom Denmead, OA

Mass balance

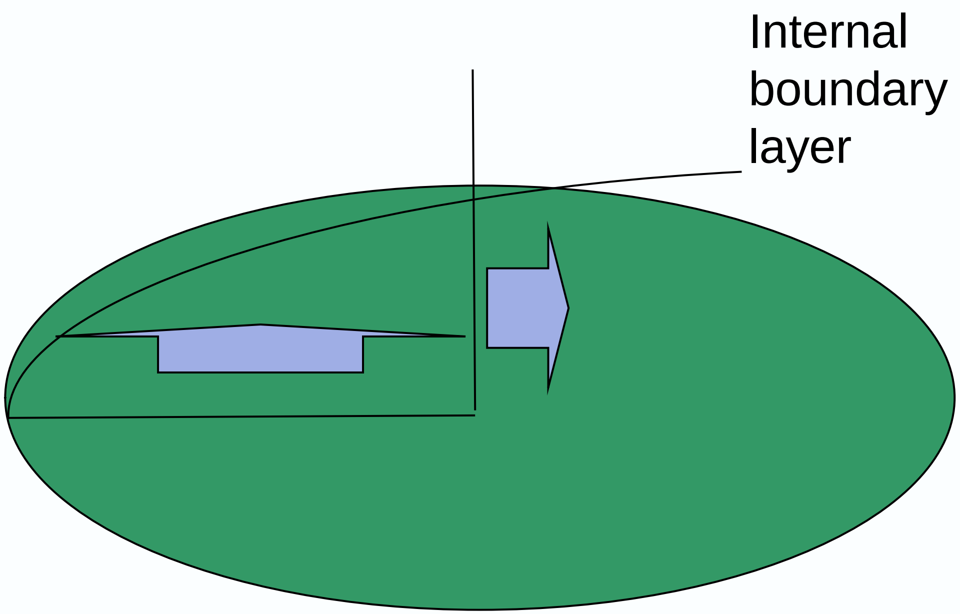
- Ammonia
  - rice paddies
  - pig slurry
- Methane
  - land fill
  - sheep

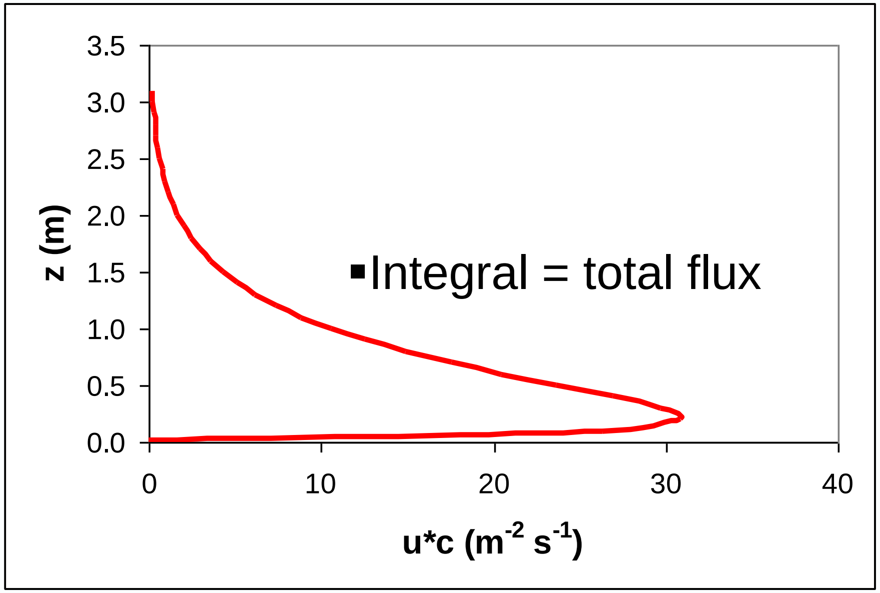
My first eddy covariance system
PhD work 1974

Instrument array at Tumbarumba 2005

Tom Denmead – mentor and innovator

Mass balance on a circle

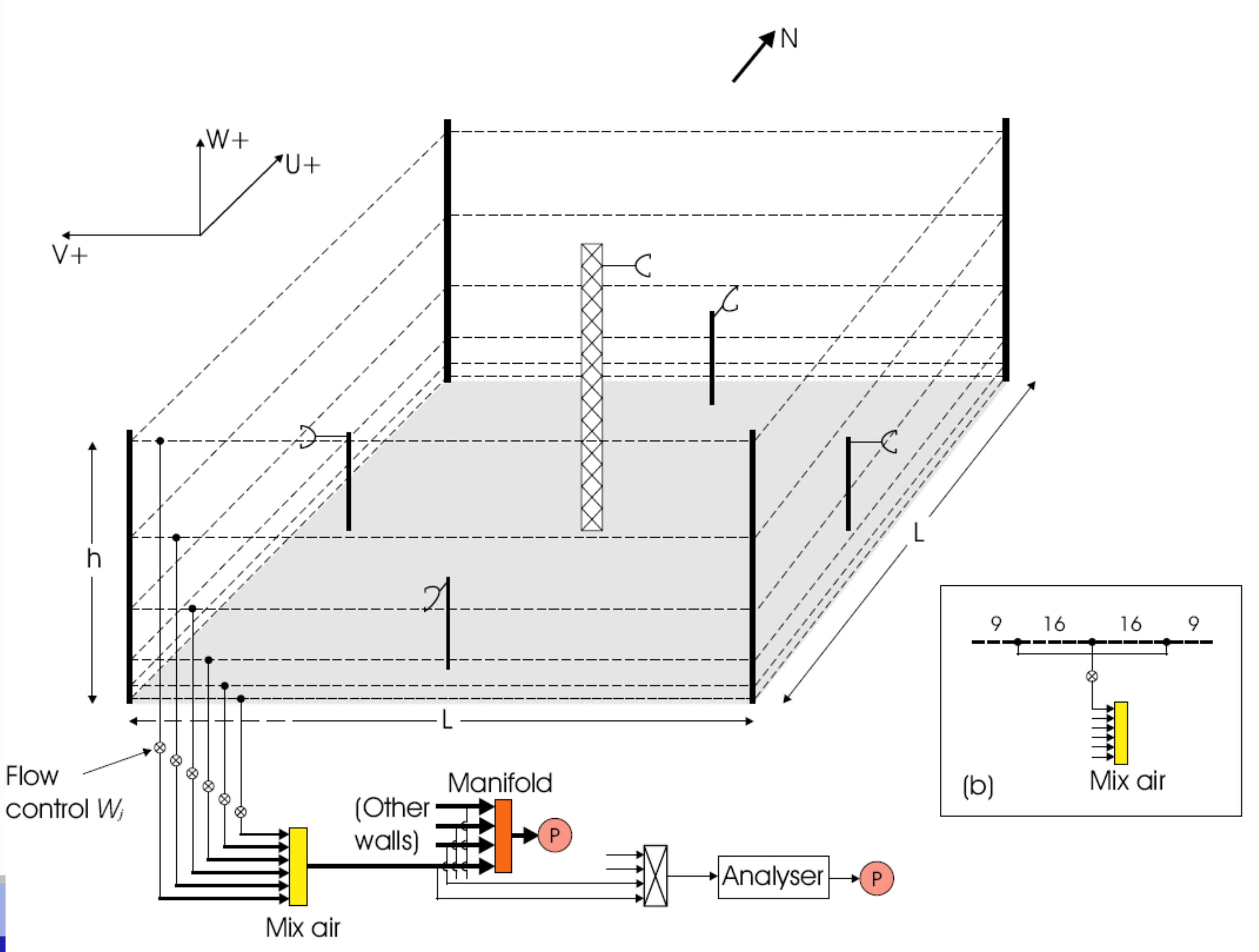




Circular paddy field for NH_3 volatilization

Repairing dyke of paddy field during storm

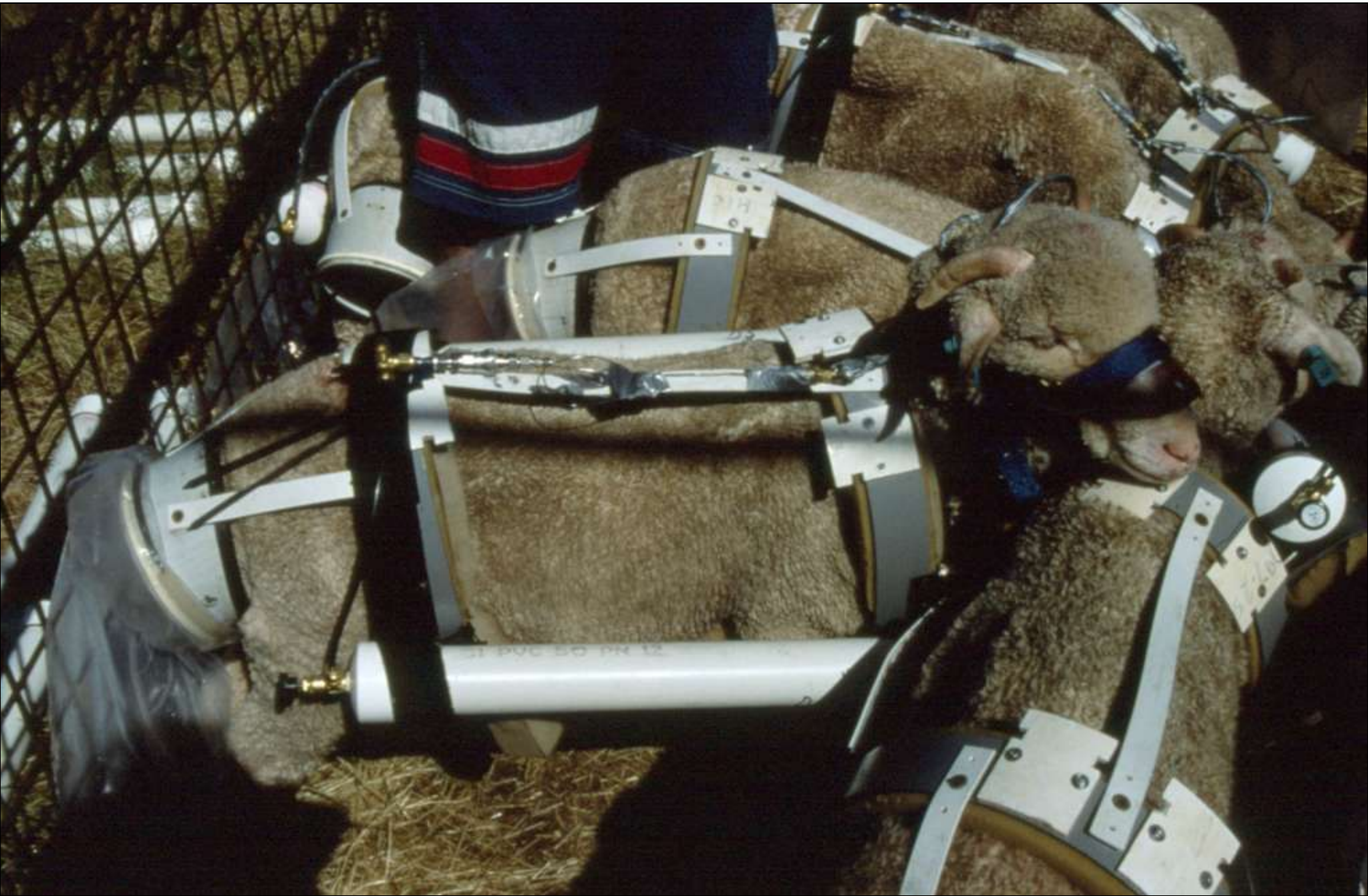
Mass balance on a square



CH_4 from Canberra's landfill

CH_4 Sheep grazing with canisters attached

CH_4 Sheep with canisters attached



A hard day in the office