Photo: J. Verfaillie

31 Evapotranspiration

Learning objectives

- Describe how we can measure and model evapotranspiration.
- Explain the controls evapotranspiration.
- Explain how we can measure transpiration from individual leaves.

Why do we care about evapotranspiration?

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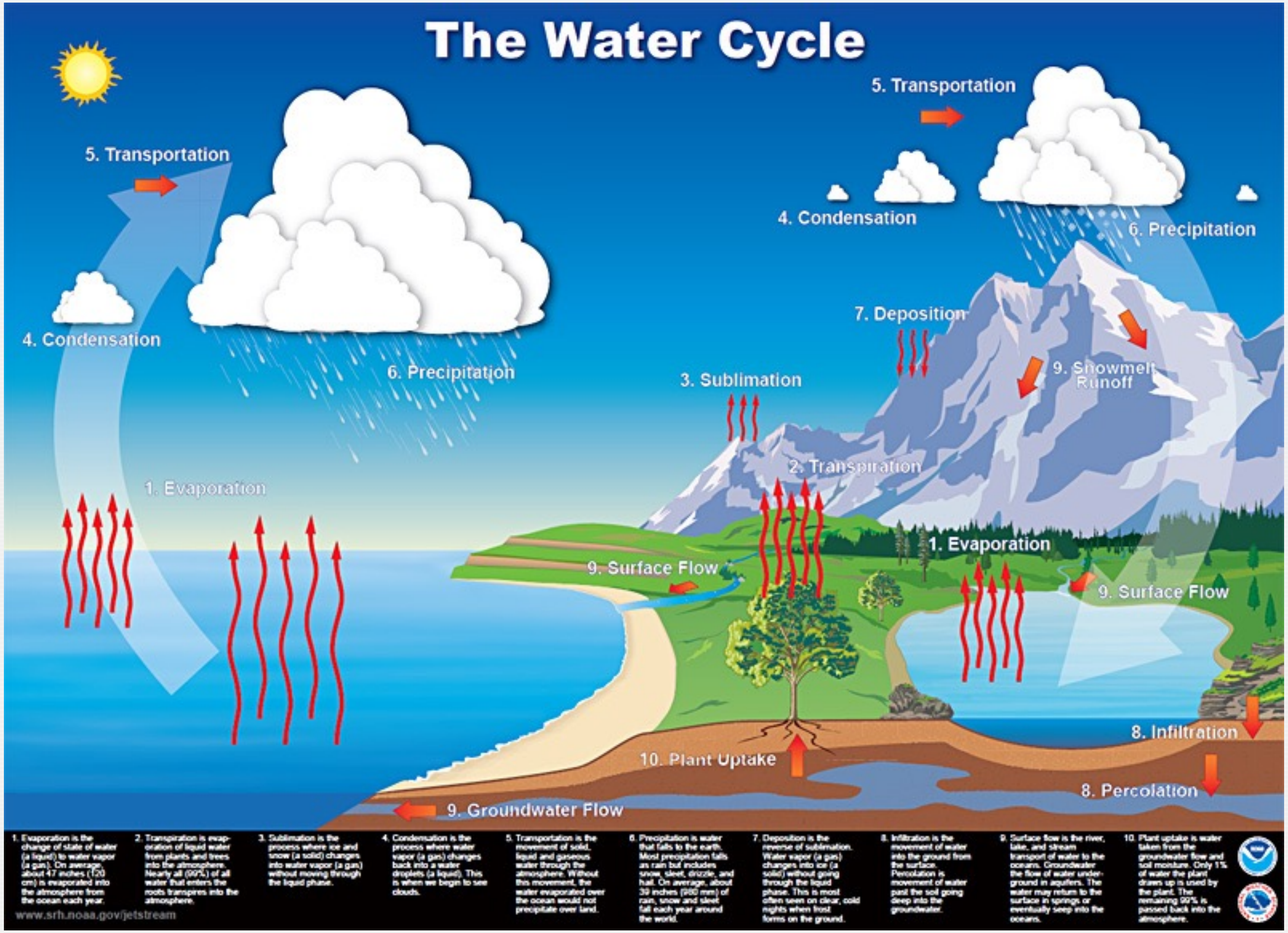
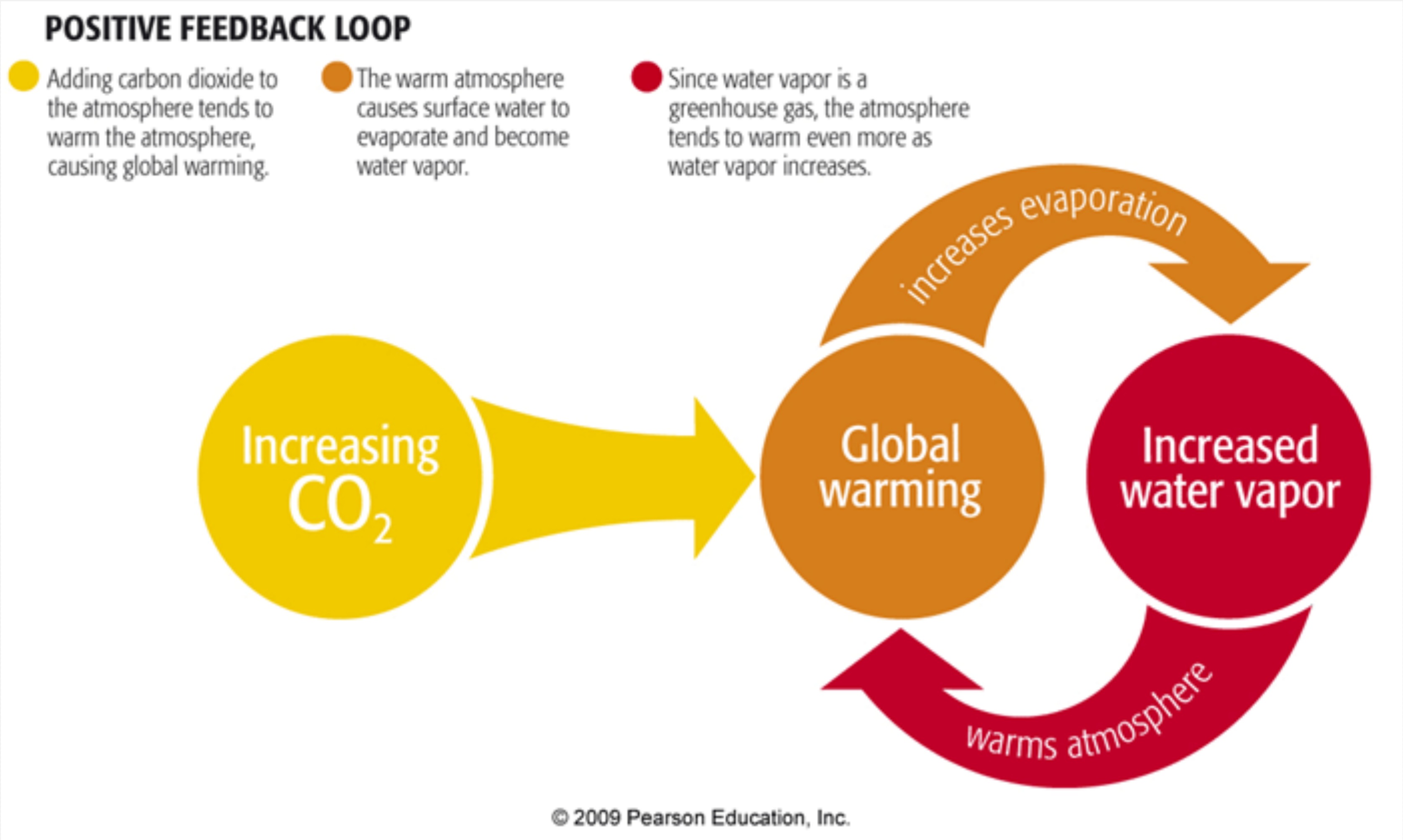


Why do we care about evapotranspiration?

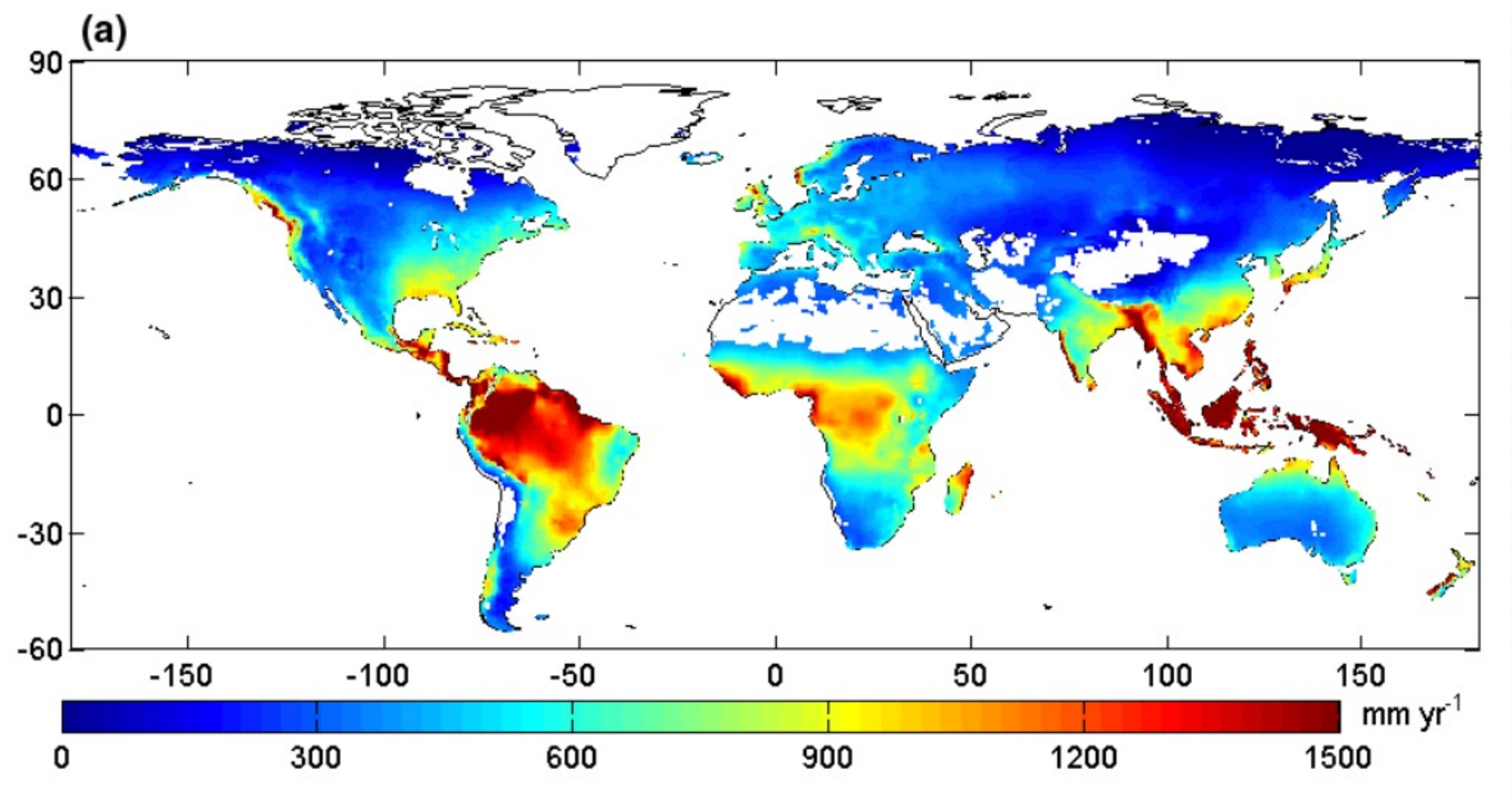


Natural vegetation growth & agriculture

Photo: S. Knox

Photo: J. Verfaillie

Global evapotranspiration



Source: Zeng et al. 2012 ERL

There are many ways to measure/estimate ET

Can you name 2 based on what we've discussed so far in class?

There are many ways to measure/estimate ET

Micrometeorology

a) Eddy covariance
b) Aerodynamic approach
c) M-O similarity framework (*not discussed*)
d) Bowen-ratio energy balance
e) Combination model (Penman-Monteith)

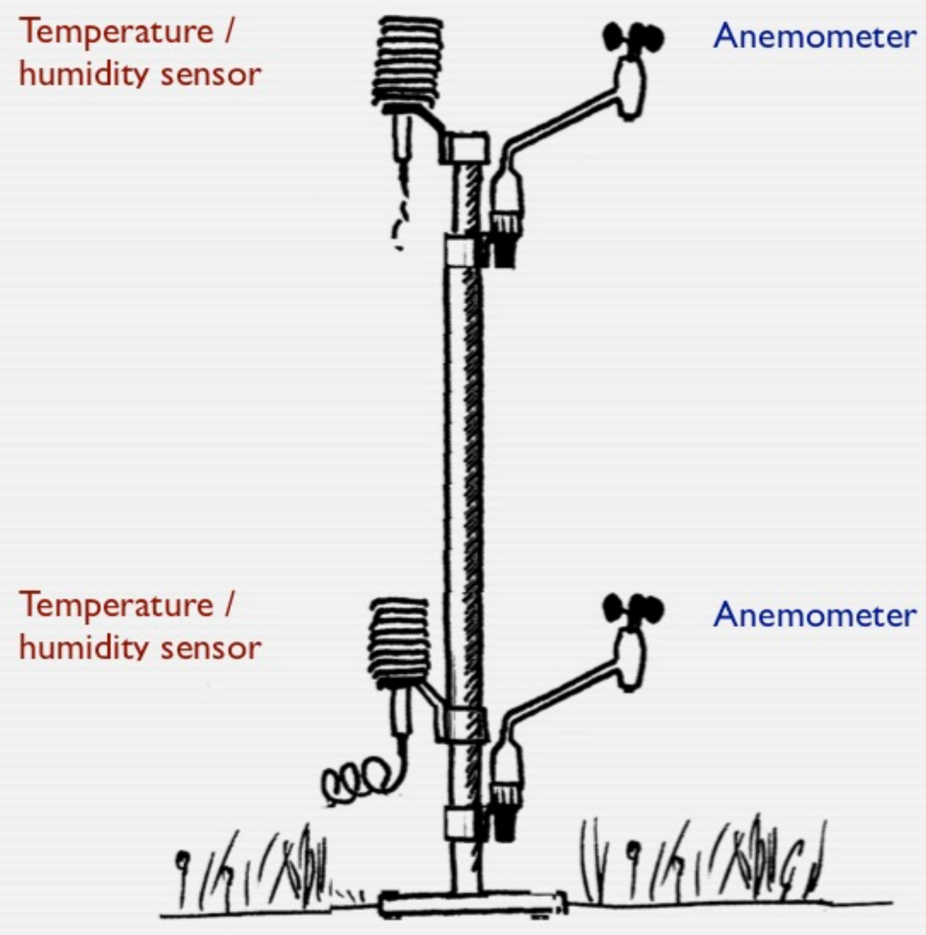
Water balance

a) Lysimetry
b) Evaporation pans (potential E only)
c) Soil moisture change (TDR)

Plant physiology

a) Sap flow measurements (transpiration)
b) Porometry (transpiration only)

There are many ways to measure/estimate ET

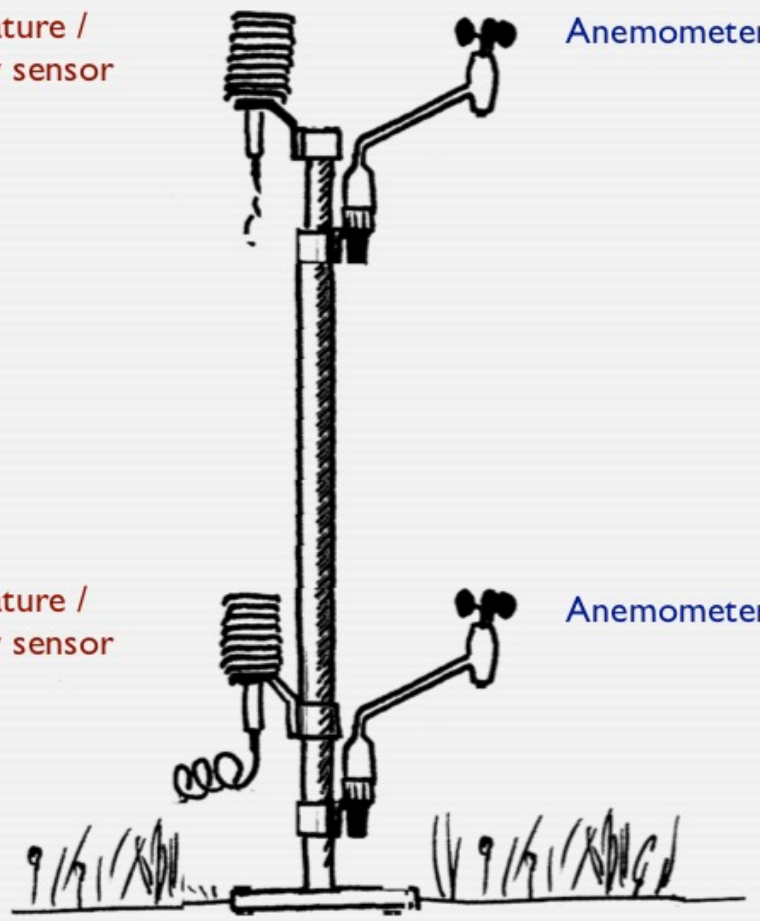


Review: The aerodynamic method.

The aerodynamic method applied to Q_E .

$$Q_E = -\frac{L_v k^2 \Delta\overline{u}\Delta\overline{\rho_v}}{[\ln(z_2/z_1)]^2}$$

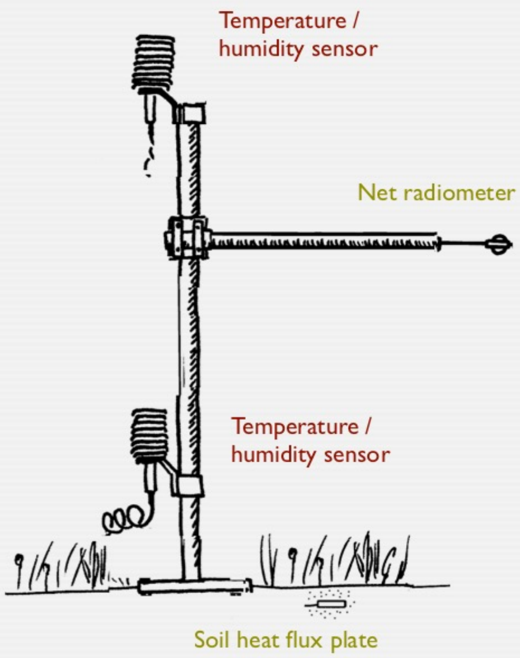
Requires a rather **special experimental set-up** with high accuracy instruments typically not found at standard climatological or agrometeorological surface stations. And: empirical corrections for non-neutral conditions are needed.



The Bowen ratio energy balance approach (1/3)

Assumptions: Steady state, constant flux layer, similarity of turbulent fluxes ($K_H = K_E$).

The assumption $K_H = K_E$ is much better than the assumptions in the aerodynamic and resistance approaches where $K_H = K_E = K_M$. The approach can be used regardless of stability.



The Bowen ratio energy balance approach (2/3)

Taking the ratio of the K-forms of flux-gradient equations for the two turbulent fluxes, i.e. the Bowen ratio β:

$$\beta = \frac{Q_H}{Q_E} \quad =$$

The Bowen ratio energy balance approach (2/3)

Taking the ratio of the K-forms of flux-gradient equations for the two turbulent fluxes, i.e. the Bowen ratio β:

$$\beta = \frac{Q_H}{Q_E} = \frac{\cancel{K_H}\, \rho_a\, c_p\, (\Delta\overline{\theta}/\cancel{\Delta z})}{\cancel{K_E}\, L_v\, (\Delta\overline{\rho_v}/\cancel{\Delta z})}$$

$$= \frac{\rho_a\, c_p \Delta\overline{\theta}}{L_v\, \Delta\overline{\rho_v}} = \gamma \frac{\Delta\overline{\theta}}{\Delta\overline{\rho_v}}$$

Where $\gamma = \rho c_p / L_v = C_a / L_v$ is the psychrometric 'constant' which depends on temperature and atmospheric pressure.

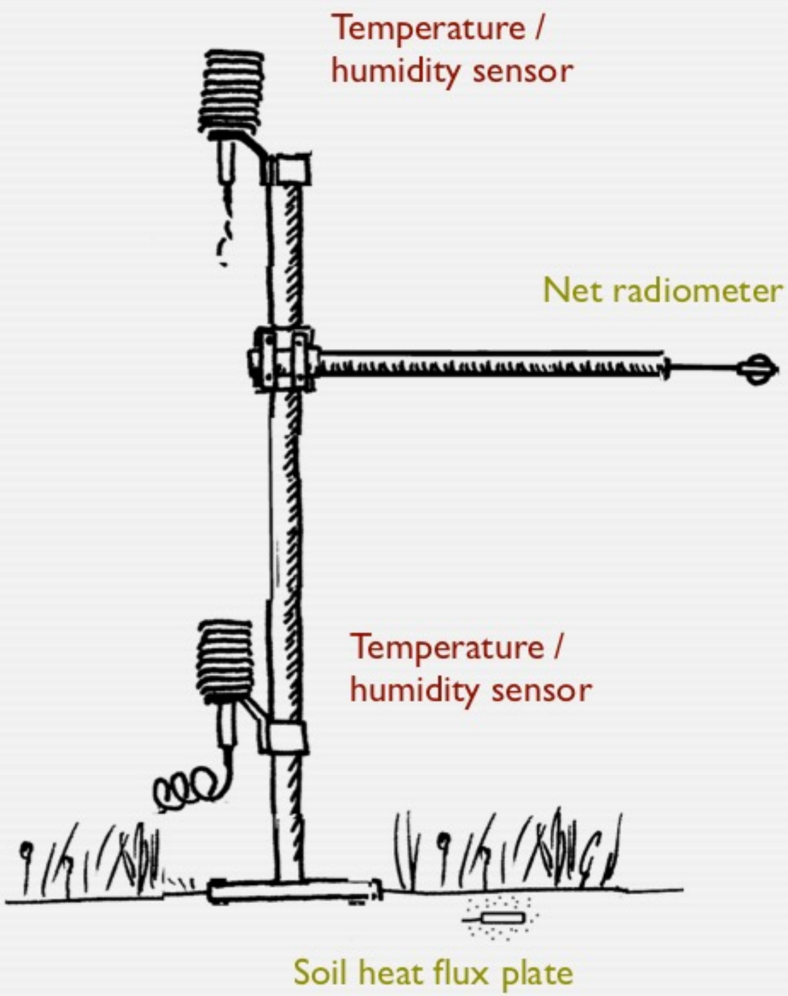
The Bowen ratio energy balance approach (3/3)

From the energy balance equation

$$
\begin{aligned}
Q^* - Q_G &= Q_E + Q_H \\
&= Q_E(1+\beta)
\end{aligned}
$$

$$
\begin{aligned}
\boxed{Q_E} &= \frac{Q^* - Q_G}{1+\beta} \quad \bigstar \\
&= \boxed{\frac{Q^* - Q_G}{1 + \left(\gamma \frac{\Delta\bar{\theta}}{\Delta\overline{\rho_v}}\right)}}
\end{aligned}
$$

We require: Net radiometer (Q^*), soil heat flux plate (Q_G) and two heights of temperature θ and absolute humidity ρ_v.



The combination model approach

The most used evaporation framework combines the **aerodynamic equations** (in the resistance format) and the **energy balance principle**. This is operational using relatively easily observable terms representing

- energy availability
- drying power
- level of turbulent activity

The whole scheme is made possible by a linearization of the saturation vapour concentration vs. temperature curve (by **Howard Penman**).

Combination model: Penman's linearization

The vapour density difference driving evaporation of a wet surface is the difference between the saturation value ρ^*_{v0} at surface temperature T_0 and the actual value in the air ρ_{va} (i.e. $\rho^*_{v0} - \rho_{va}$). This can be split into two parts, $\rho^*_{v0} - \rho^*_{va}$ and $\rho^*_{va} - \rho_{va}$

The 1st term can be approximated using a linearization of the surface-air vapour difference, the 2nd term is the vapour density deficit of the air (vdd_a):

$$\rho^*_{v0} - \rho_{va} = s(T_0 - T_a) + vdd_a \qquad (1)$$

$$s = \frac{\partial \rho^*_v}{\partial T} \approx \frac{\Delta \rho^*_v}{\Delta T}$$

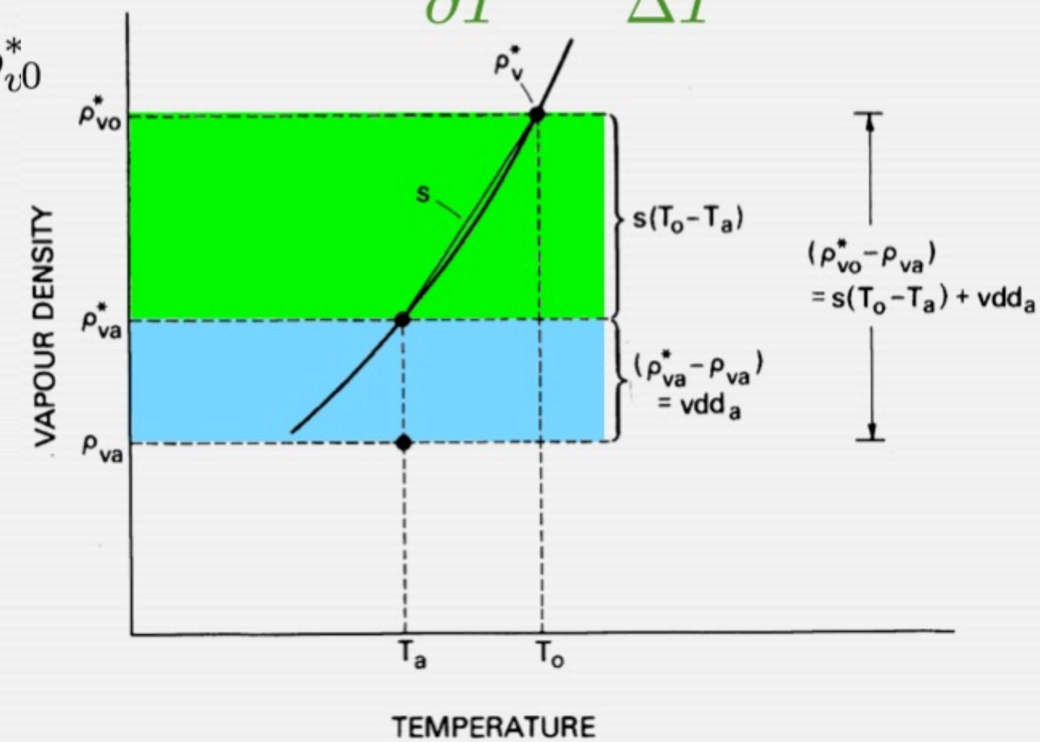


Figure A2.9 Saturation vapour density vs temperature diagram showing Penman's transformation.

Combination model: saturated surface

The simple resistance formulation for a saturated surface for Q_E:

$$Q_E = L_v \frac{\rho^*_{v0} - \rho_{va}}{r_{a_V}} \qquad (2)$$

The resistance formulation for Q_H:

$$Q_H = C_a \frac{\boxed{T_0 - T_a}}{r_{a_H}} \qquad (3)$$

substitution of (1) into (2)

$$Q_E = \frac{L_v\, s\, (\boxed{T_0 - T_a}) + L_v\, vdd_a}{r_{aV}} \qquad (4)$$

Replace $T_0 - T_a$ using (3), and assume similarity i.e. $K_H = K_E$ and therefore $r_{aH} = r_{aV}$

$$Q_E = \frac{L_v\, s\, \boxed{Q_H\, \cancel{r_{aH}}}}{\boxed{C_a}\, \cancel{r_{aV}}} + \frac{L_v\, vdd_a}{r_{aV}} \qquad (5)$$

Combination model: the Penman model

$$Q_E = \frac{L_v\, s\, Q_H}{C_a} + \frac{L_v\, vdd_a}{r_{aV}} \qquad (6)$$

Now, we replace Q_H using the energy balance equation ($Q_H = Q^*$ - Q_G - Q_E), use the psychrometeric constant $\gamma = C_a / L_v$ and similarity $r_{av} = r_{aH}$.

$$Q_E = \frac{s}{\gamma}(Q^* - Q_G - Q_E) + \frac{C_a\, vdd_a / r_{aH}}{\gamma} \qquad (7)$$

re-arrange gives the **Penman (1948) equation** for a <u>saturated</u> surface:

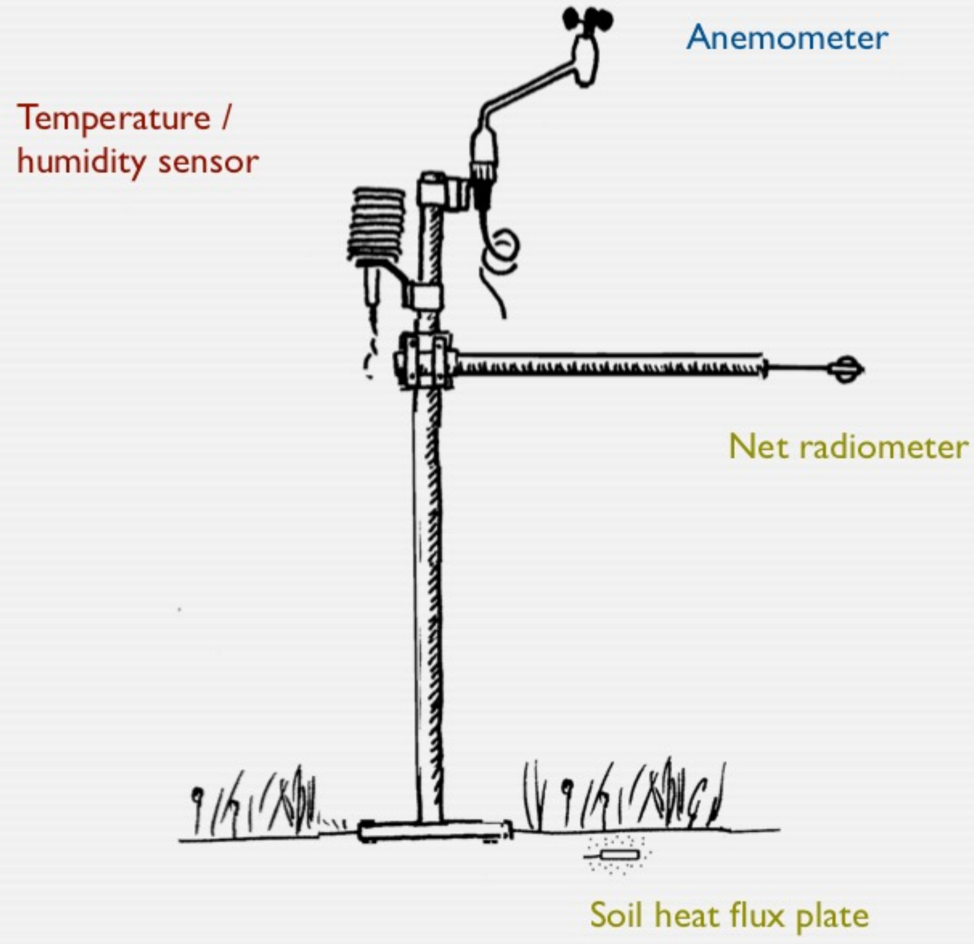
$$Q_E = \underbrace{\frac{s}{s+\gamma}(Q^* - Q_G)}_{\text{available energy term}} + \underbrace{\frac{C_a\, vdd_a / r_{aH}}{s+\gamma}}_{\text{vapour deficit term}} \qquad (8) \quad \star$$

Combination method: Instrumental needs

For the combination we need:

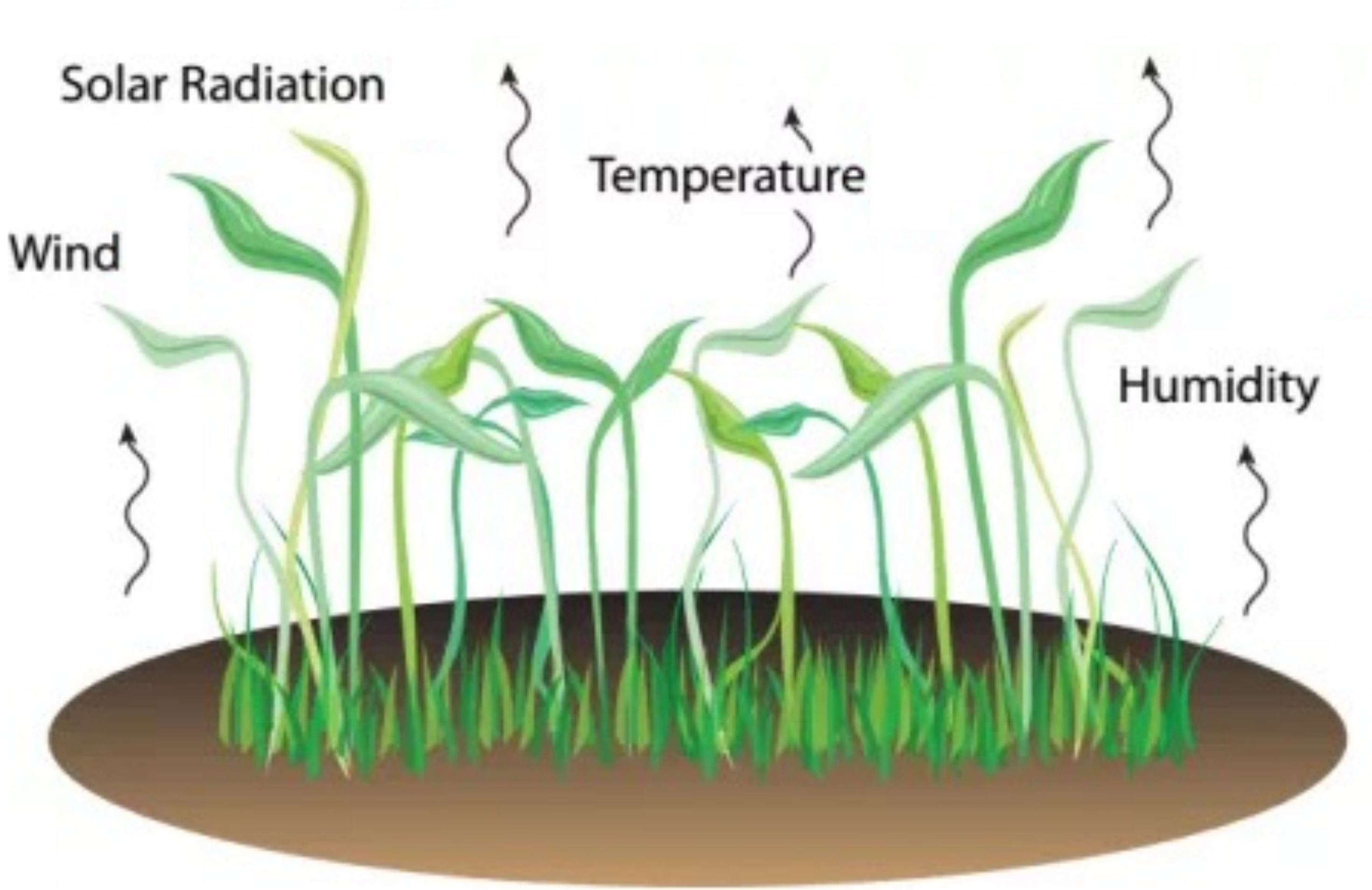
- Air temperature / humidity measurements at only <u>one</u> level
- Available energy (net radiometer and heat flux plate).
- A method to estimate r_{aH}, usually wind at one level (knowledge of z_0, for neutral stability only).

The approach has neatly eliminated profiles and T_0, both difficult to measure.



What are the controls on evapotranspiration?

Controls on evapotranspiration



Source: https://www.campbellsci.com/blog/evapotranspiration-101

Direct approaches to measure evapotranspiration

The eddy covariance approach (lab visit and lecture 24) allows a direct determination of the mass flux density of water vapour E, if **vertical wind speed** w and **absolute humidity** ρ_v are measured at high frequency at same location:

$$\underbrace{E}_{\text{kg m}^{-2}\text{ s}^{-1}} = \overline{\underbrace{w'}_{\text{m s}^{-1}}\underbrace{\rho_v'}_{\text{kg m}^{-3}}}$$

E can be converted to an energy flux density - multiplying by the **latent heat of vaporization** L_v:

$$\underbrace{Q_E}_{\text{J m}^{-2}\text{ s}^{-1} = \text{W m}^{-2}} = \underbrace{L_v}_{\text{J kg}^{-1}}\ \underbrace{E}_{\text{kg m}^{-2}\text{ s}^{-1}}$$

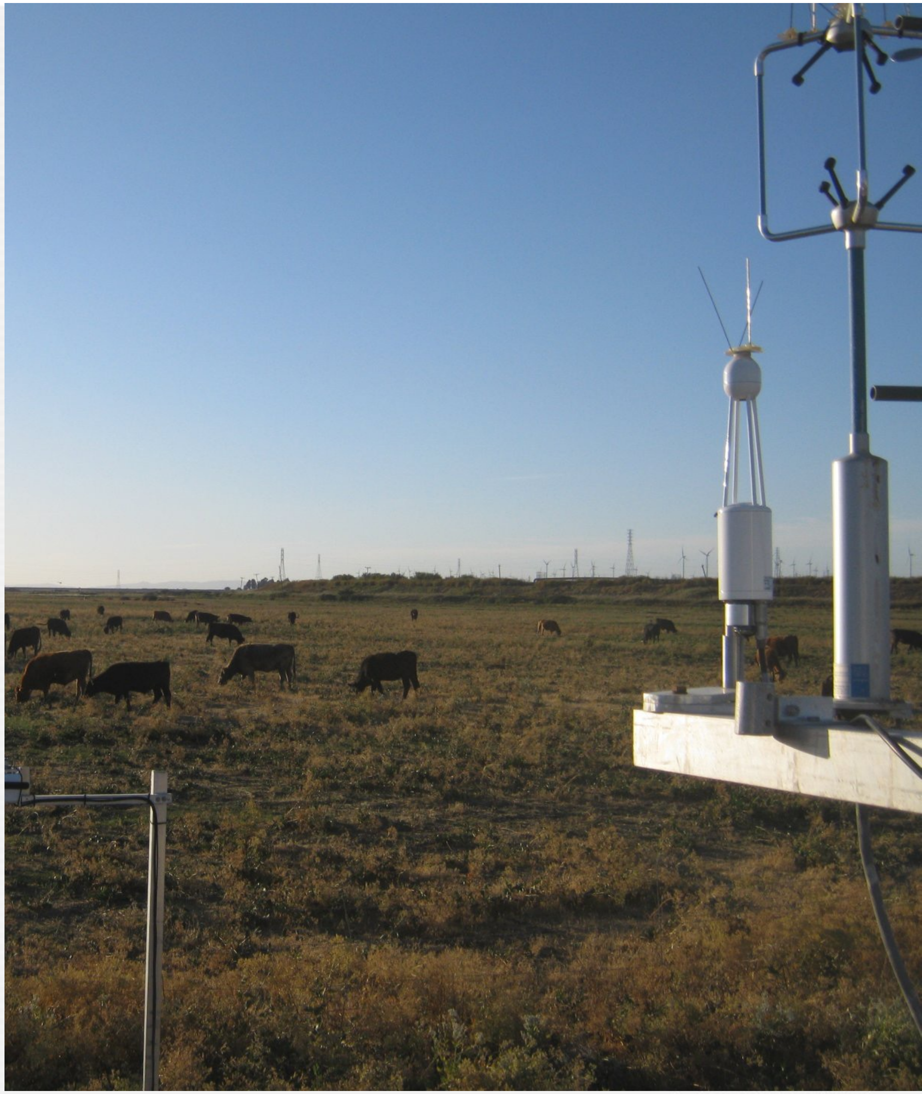
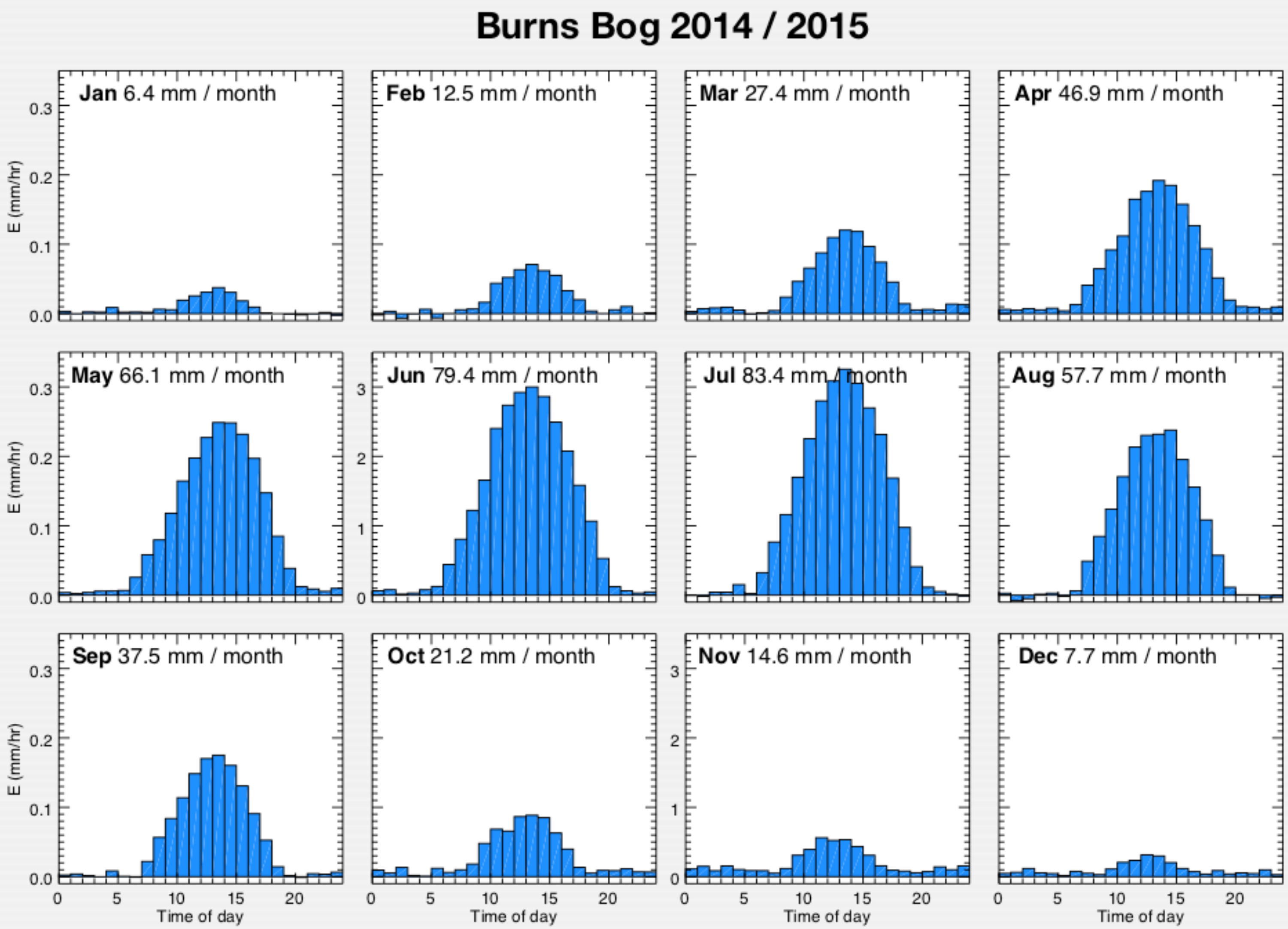


Photo: S. Knox

EC is most suited for continuous ET measurements



Lysimeter

In a lysimeter, the **weight changes** of a representative soil plus vegetation monolith (isolated from the environmental soil) are continuously monitored. Simultaneous measurements of precipitation allow to solve the water balance for E for this one-sided closed system.

Evapotranspiration (kg m^{-2} h^{-1})

Change is soil water (kg m^{-2} h^{-1}) = Mass change of monolith

$$E = p - \frac{\Delta m_w}{\Delta t}$$

Precipitation (kg m^{-2} h^{-1} = mm h^{-1})

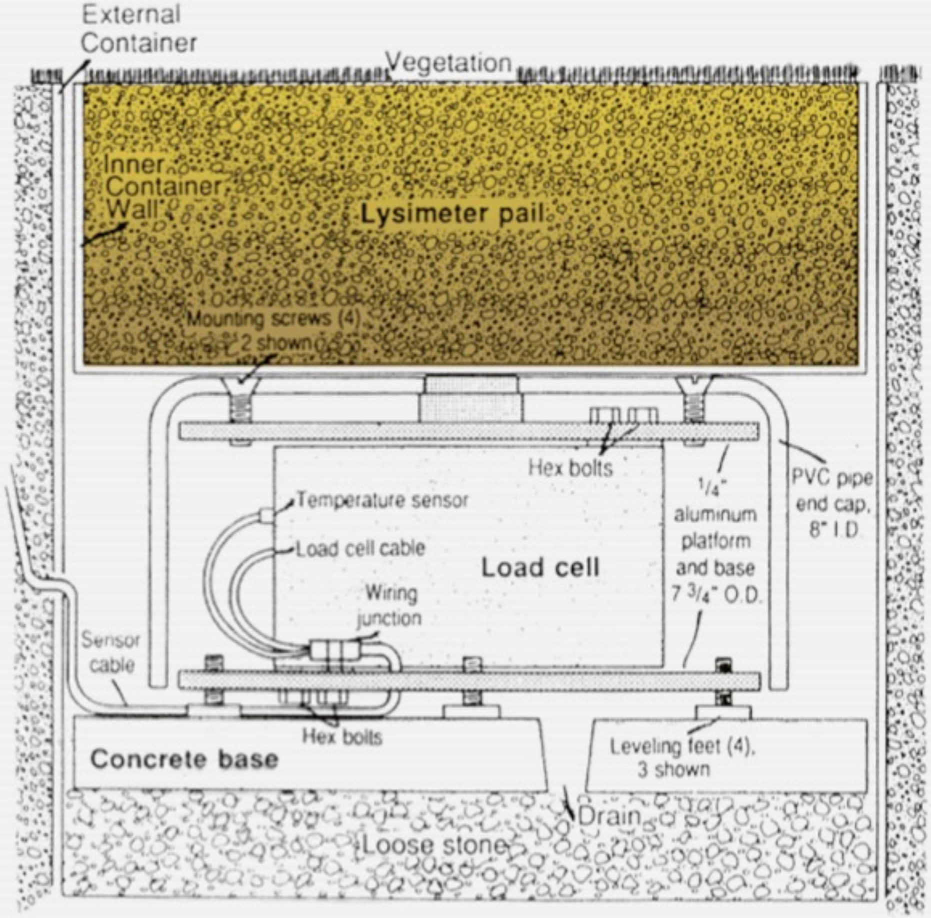


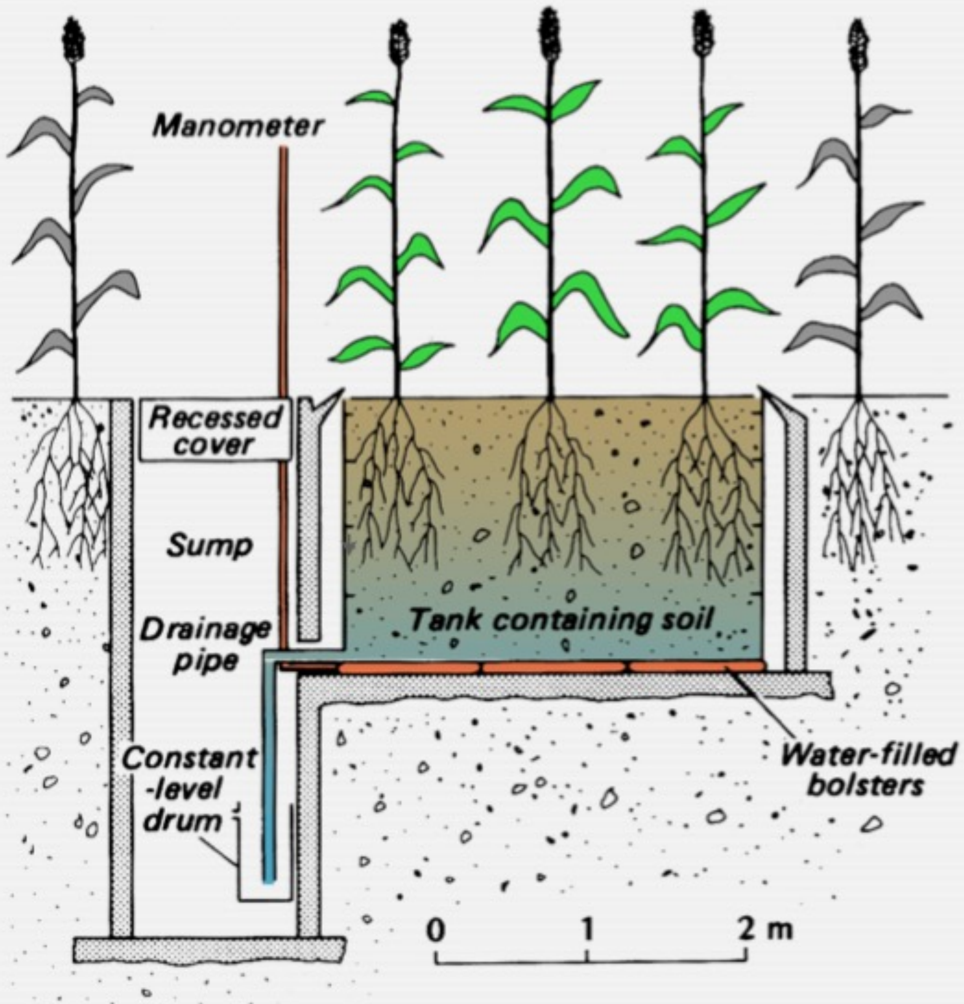
Fig. 2. Lysimeter design (modified from Isard and Belding, 1989).

Installation of large weighing lysimeter over bare soil

All photos provided by A. Black, UBC.

Lysimeter array over bare soil (Photo: TU Berlin, Thomas Zenker)

Lysimeter



In a more realistic design, deep vertical water movements in the soil (percolated water) are monitored - at least in one direction, by collecting drainage water (d) in a sump:

$$E = p - d - \frac{\Delta m_w}{\Delta t}$$

deep soil drainage rate (kg m^{-2} h^{-1} or mm h^{-1})

Sap flow

SAPFLUXNET

Sap-flow measurements are a method to quantify **transpiration** of a single tree.

A local heating source is introduced into the stem of the tree. In a defined distance Δz above, the temperature increase of the stem is measured. This can be related to the rate of heat transfer by moving water in the stem.

Two sap flow measurements at the stem of an olive tree

Photo: A. Christen

Assuming an equilibrium state, sap flow is equal the rate of transpiration

Porometry

A **porometer** measures the rate of water vapour diffusing from a dry leaf (no evaporation, only transpiration) into a chamber held against the leaf.

Summary – Measurements of evapotranspiration

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