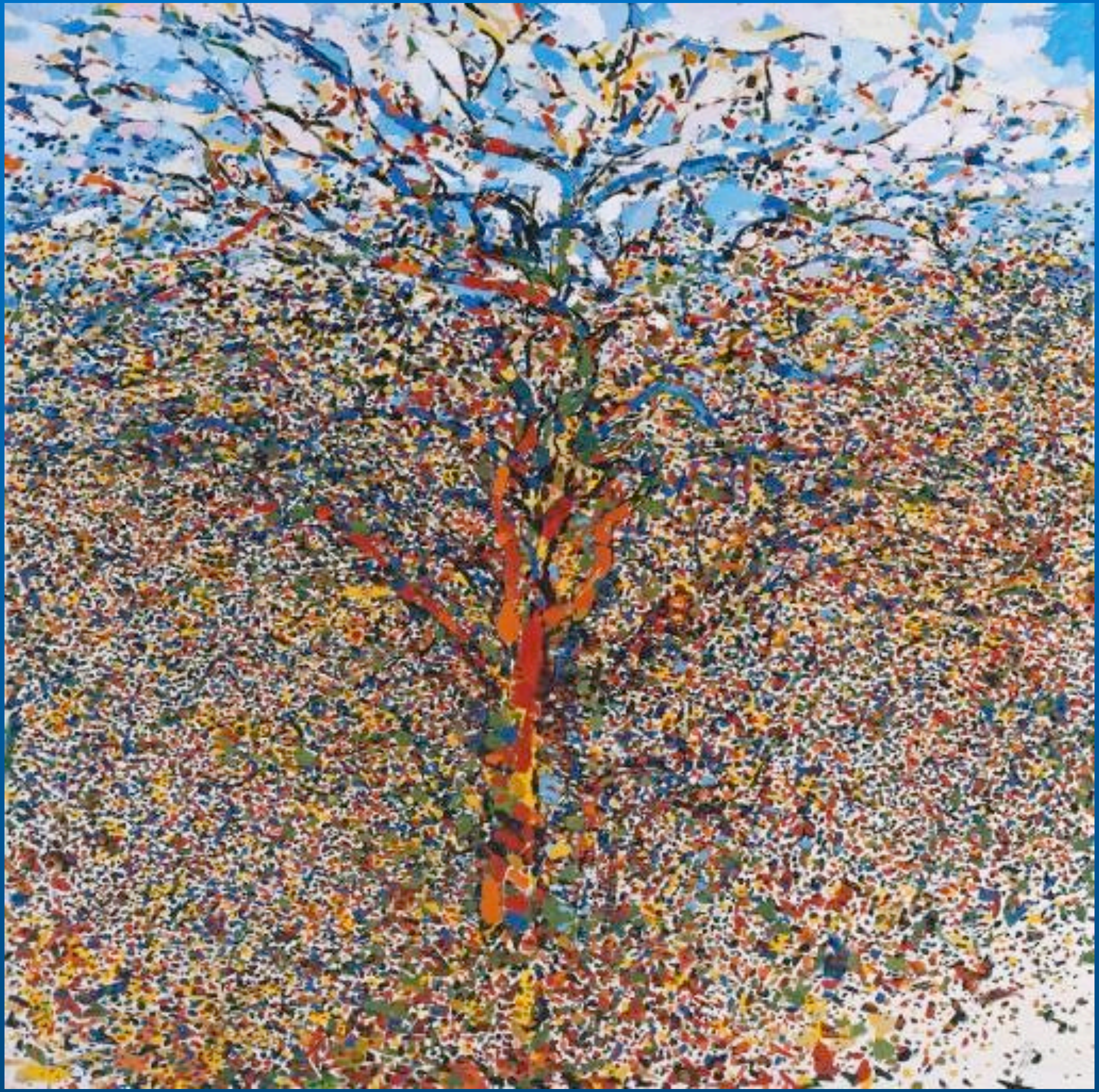
Evapotranspiration - I



P. Sutton, Tree, 1958 - Tate Modern

Riccardo Rigon

For as the rain and snow come down from heaven,
And do not ***return**** *there without watering the earth*
And making it bear and sprout, ... ,
So ...

Isaia, 55:10

**It always seemed logical to me that water should "come down". It's surprising that it should return.*
Ric

Evaporation

Processes where water changes phase, from liquid to vapour, involving water surfaces and soils

Evaporation

Processes where water changes phase, from liquid to vapour, involving water surfaces and soils

Transpiration

Processes where water changes phase, from liquid to vapour, in order to maintain the thermal equilibrium of plants and animals

Evapotranspiration

A single word that encases the various evaporative and transpiration phenomena. It is a flux:

- of energy
- of water
- of vapour
- of entropy

Educational Goals

- To know which conditions cause evaporation and/or transpiration;
- To understand which factors control the speed of evaporation and/or transpiration;
- To learn to estimate evapotranspiration;
- To understand the difference between potential and effective evapotranspiration;
- To understand how evapotranspiration varies in space and time

Evaporation

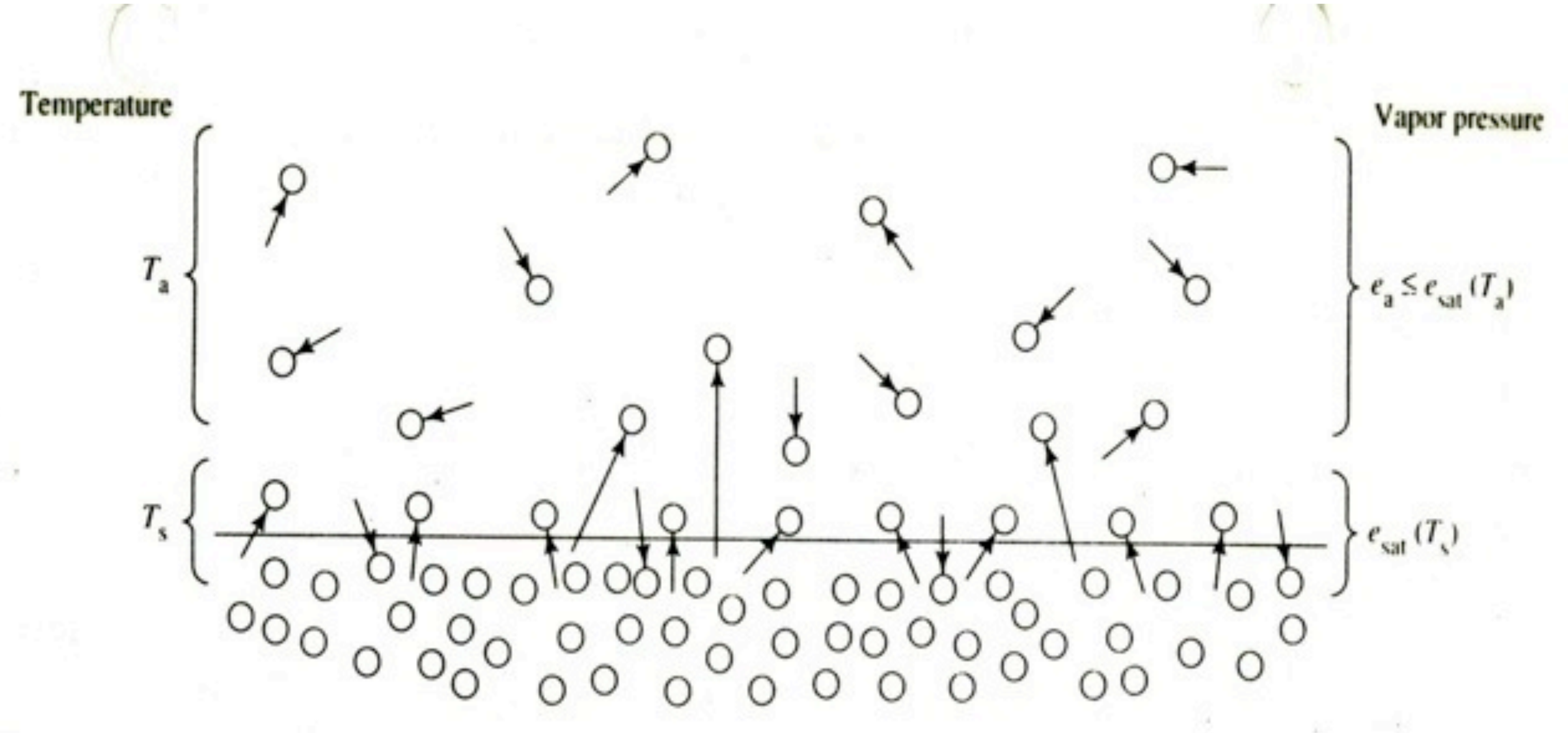
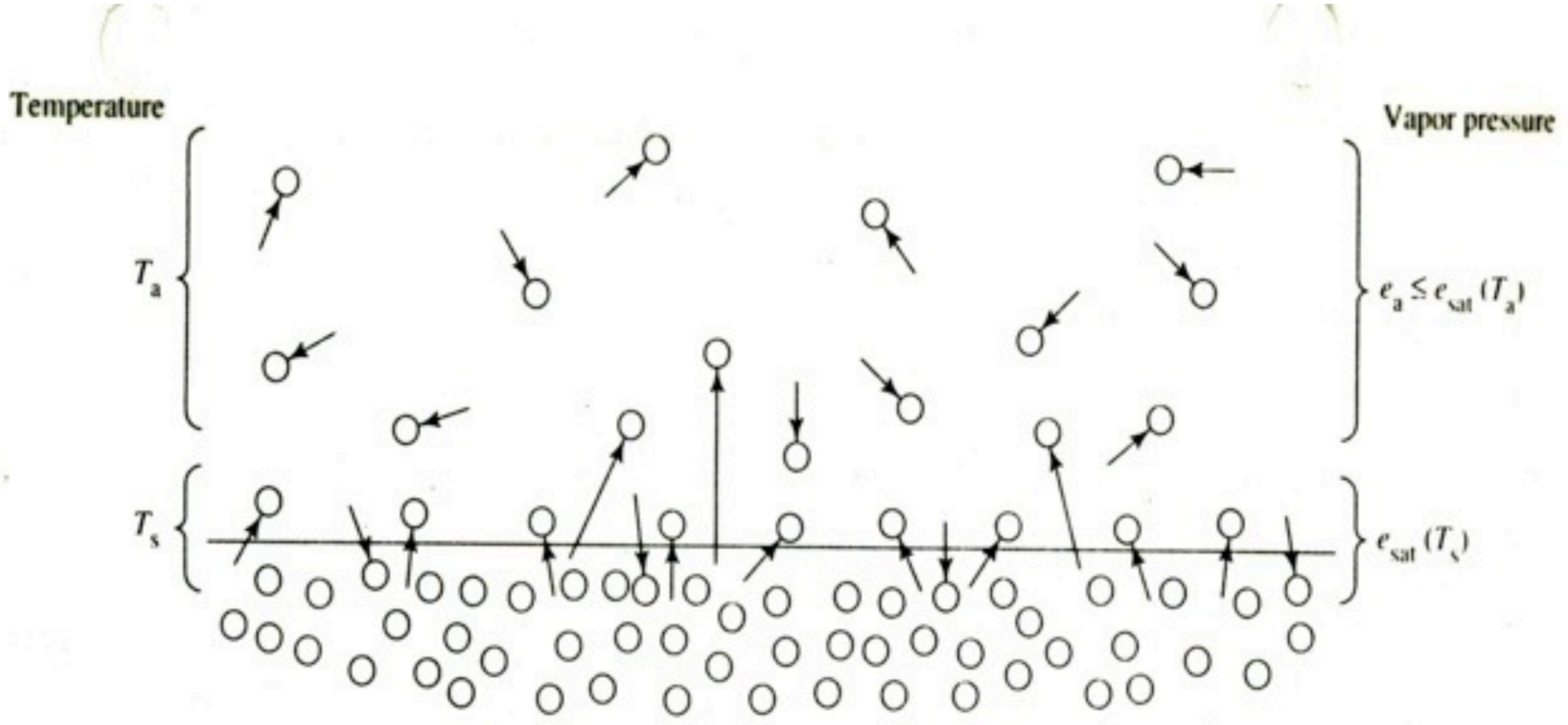


FIGURE D-4
Schematic diagram of flux of water molecules over a water surface. The vapor pressure at the surface is $e_{sat}(T_s)$; the vapor pressure of the overlying air is less than or equal to $e_{sat}(T_a)$. The rate of evaporation is proportional to $[e_{sat}(T_s) - e_a]$ [Equation (D-10)].

The hydrogen bonds in the liquid break and the vapour diffuses from areas of higher partial pressure to areas of lower partial pressure (Dalton's law).

Evaporation



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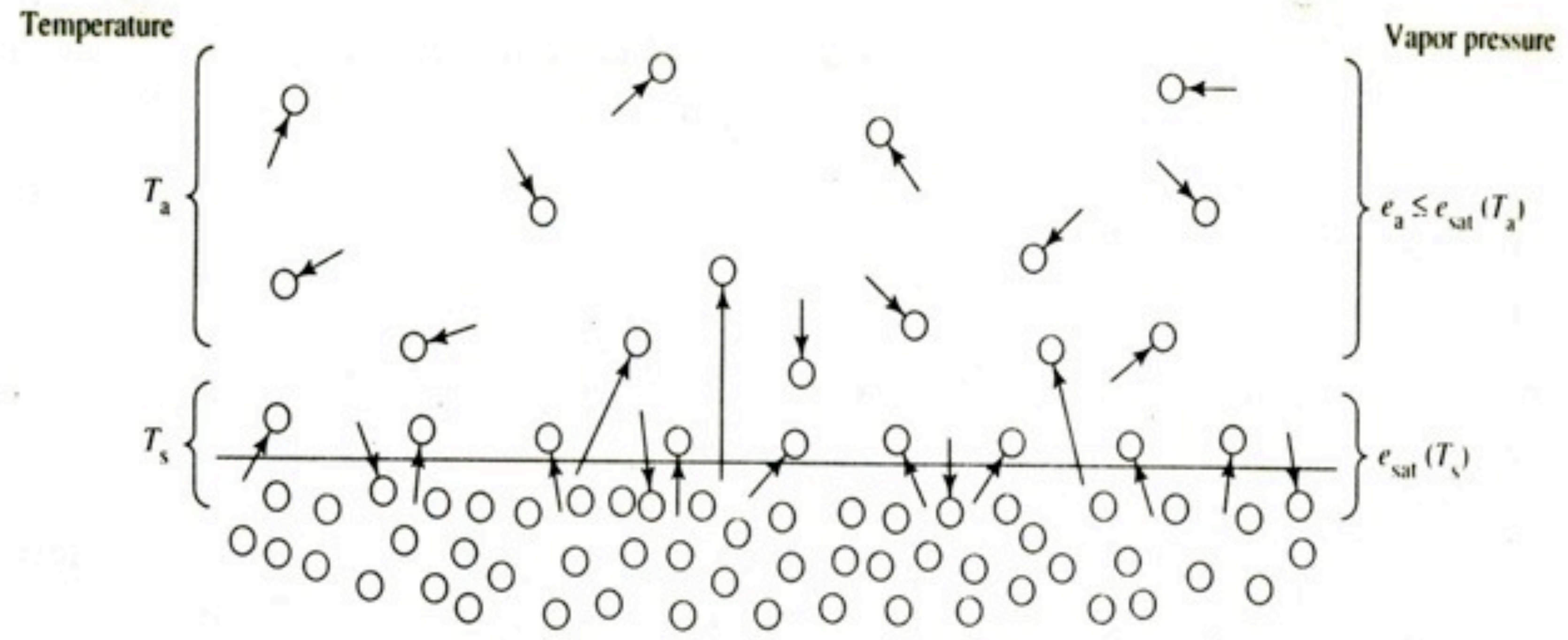
Over a free water surface this process manifests the molecular nature of water and it happens continuously.

Evaporation



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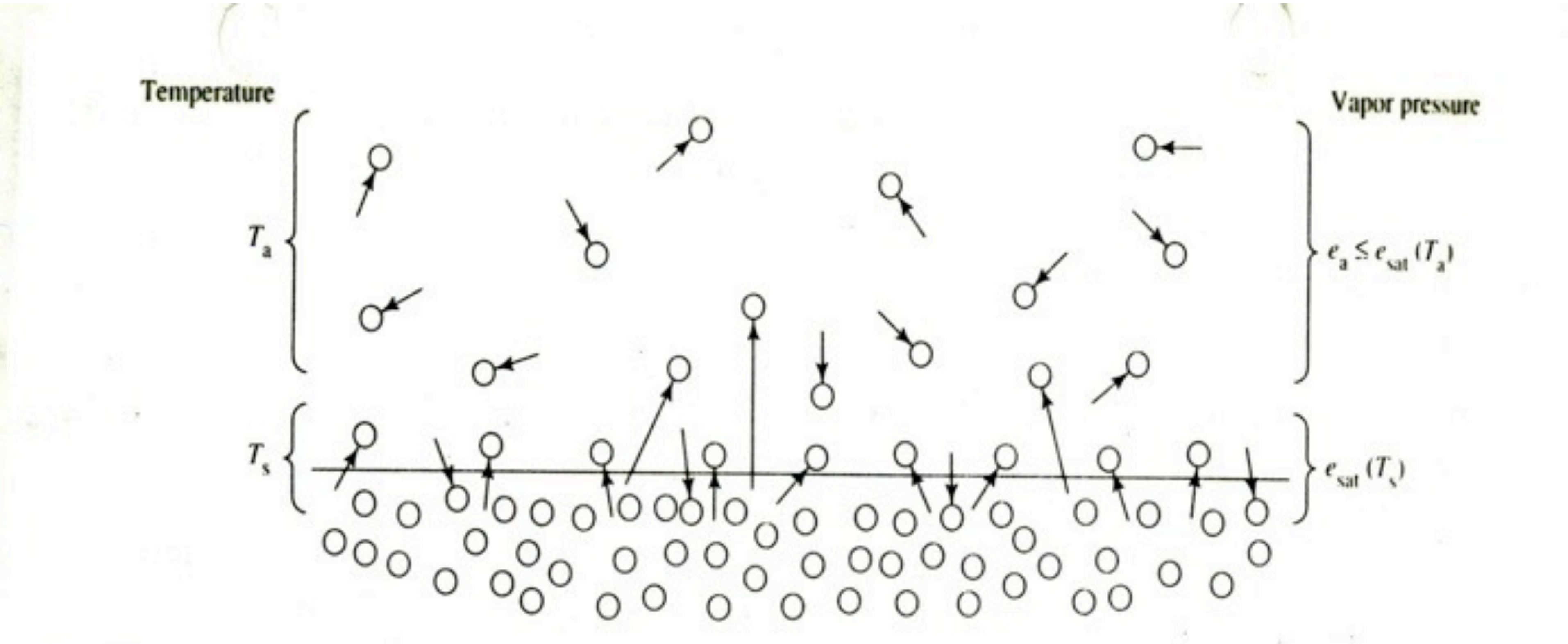
If the volume of air in contact with the liquid surface were sealed off with a lid, the number of vapour molecules in this volume would reach quite a stable value, function of the temperature of the system.

Evaporation



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Given that there is no lid the water tends to evaporate completely. The engine of evaporation is the second principle of thermodynamics (the system evolves towards an entropy maximum).

Evaporation

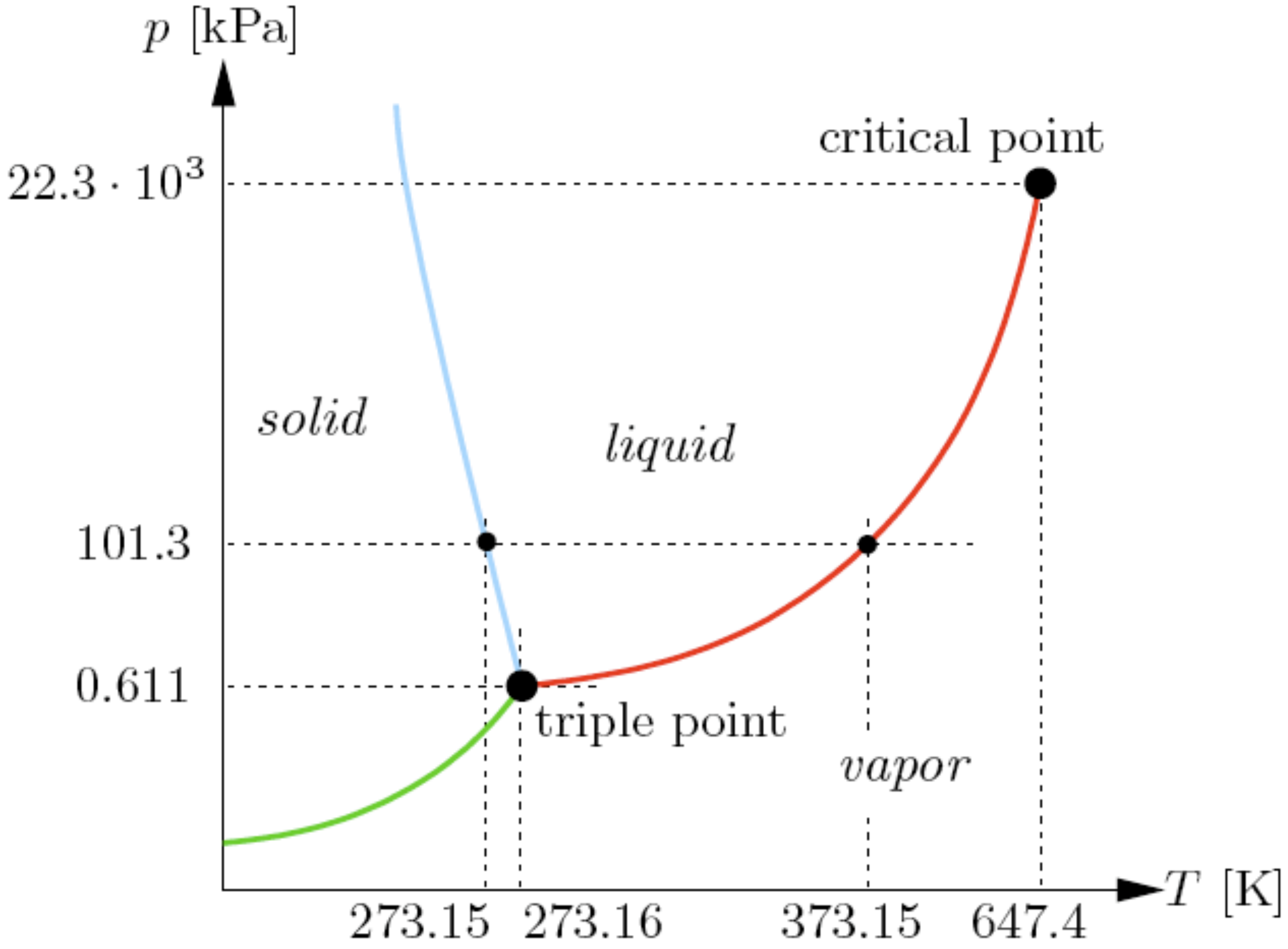


Figure 7.1. Schematic phase diagram of free water with evaporation (vapor pressure) curve (red), freezing curve (blue), and sublimation curve (green). Notice that axes are not to scale.

The physics of evaporation

The preceding graph, however, is often used in the wrong way. Beware! This graph identifies the phase present at a given temperature and pressure in conditions of thermodynamic equilibrium.

The curves define for which temperature-pressure pairs two (or more) phases are in equilibrium.

The necessary condition for thermodynamic equilibrium is that the entropy is maximum or, equivalently, that the Gibbs free energy is minimum (second principle of thermodynamics).

The physics of evaporation

This last principle implies that a liquid (or a solid) will always be in equilibrium with its vapour, as long as vapour has a partial pressure such that its chemical potential is the same as the chemical potential of the liquid phase of the same substance at the same temperature.

I was forgetting ... **the chemical potential is the Gibbs free energy per unit mass**

The physics of evaporation

- Of course, it is subject to the basic principles of:
  - Conservation of Mass
  - Conservation of Energy
  - Maximisation of Entropy (minimisation of the Gibbs free energy)
- Furthermore:
  - the ideal gas law relative to water vapour
  - the latent heat of vaporisation
  - the laws of turbulent transfer (diffusion of momentum) in proximity of the soil surface
  - diffusive processes linked to the humidity gradient in the air

Definitions

- Mixing ratio:

$$w = \frac{M_v}{M_a} = \frac{\rho_v}{\rho_a}$$

- Specific humidity

$$q = \frac{M_v}{M_a + M_v} = \frac{\rho_v}{\rho_a + \rho_v} \approx w$$

Ideal Gas Law

Mi sa che qua c'erano effetti speciali che ho perso - non ho ancora capito come fare le animazioni!

$$p = \rho \; R \; T$$

$$R_d = 287 J ^\circ K^{-1} kg^{-1}, \text{ for dry air}$$

$$R_v = 461 J \; ^\circ K^{-1} \;\; kg^{-1} \text{ for water vapour}$$

Ideal Gas Law

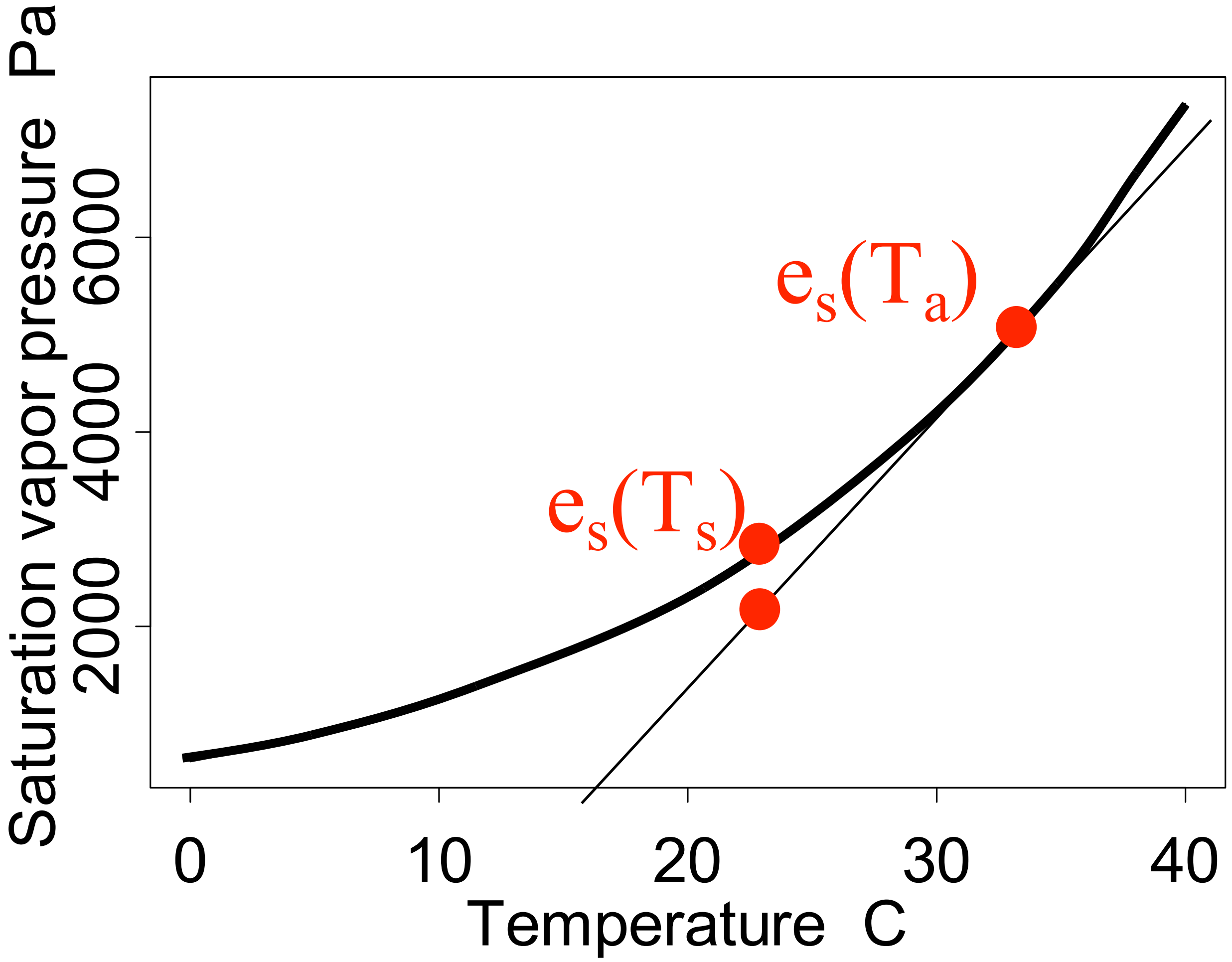
- The ideal gas law is also valid for the single gas components separately (**Dalton's** law)

$$
\begin{aligned}
e &= R_v \rho_v T \\
p_d &= R_d \rho_d T \\
p &= p_d + e
\end{aligned}
$$

Clausius-Clapeyron Law

$$e^*(T) = e_0^* \exp\left[\frac{\lambda}{R_v}\left(\frac{1}{T_0} - \frac{1}{T}\right)\right]$$

$$e_0^* = 611\ Pa \text{ e } T_0 = 273.15\ ^oK.$$



Definitions

$$\epsilon = R_d/R_v \approx 0.622$$

- Mixing ratio

$$w = \frac{\rho_v}{\rho_d} = \epsilon \frac{e}{p - e} \approx \epsilon \frac{e}{p}$$

- Relative humidity

$$f = 100 \frac{e}{e^*(T)} \approx 100 \frac{q}{q^*(T)}$$

The physics of evaporation

- Dalton's law II

$$\mathrm{E} \propto e^*(T_s) - e(T_a)$$

The physics of evaporation

- Dalton's law II

$$\mathrm{E} \propto \boxed{e^*(T_s)} - e(T_a)$$

- saturation at the temperature of the soil (or liquid)

The physics of evaporation

- Dalton' law II

$$\mathrm{E} \propto e^*(T_s) - e(T_a)$$

- There is evaporation when the term at the second member is positive
- When the term at the second member is negative there is condensation
- Please note that the second member can be positive even when the air is saturated

The physics of evaporation

- Dalton’s law becomes an equality by introducing the appropriate coefficients

$$\mathrm{Ev} = \boxed{K_e}\, u\,\left(e^*(T_s) - e(T_a)\right)$$

- Units: E = $(LT^2M^{-1})(LT^{-1})(ML^{-1}T^{-2})$ = L/T

Ev is the evaporation

K_e is the evaporative conductivity

u is the windspeed

$e * (T_s)$ is the saturated vapour pressure (at the soil/water surface)

$e(T_a)$ is the vapour pressure in the air

The physics of evaporation

- By evaporating, the water brings latent energy with it (internal energy). Dalton’s law is therefore also associated with energy transfer from the soil to the atmosphere and/or vice versa.

$$\mathrm{Ev} = K_{le}\ u\ (e^*(T_s) - e(T_a)) \qquad \lambda\ \mathrm{E}\ \text{è}\ [\mathrm{E}\ \mathrm{L}^{-2}\ \mathrm{T}^{-1}]$$

where λ is the latent heat of vaporisation

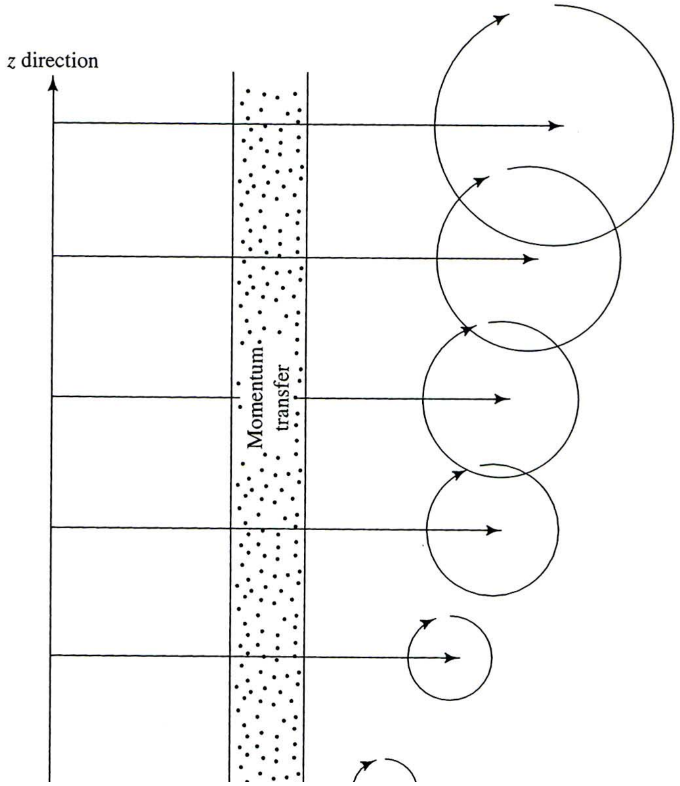
$$K_{le} \equiv \rho_v\ \lambda K_e$$

The physics of evaporation

- The proportionality constants K is linked to the turbulent transfer mechanisms of air over a surface, which can be calculated as follows:

Turbulent Transfer of Momentum

FIGURE D-9
Conceptual diagram of the process of momentum transfer by turbulent diffusion. Friction caused by surface roughness reduces average velocities (straight arrows) near the surface and produces turbulent eddies (circular arrows), resulting in a net downward transfer of momentum. The vertical component of the eddies moves heat and water vapor upward or downward, depending on the directions of temperature and vapor-pressure gradients.



The physics of evaporation

$$\text{Ev} = K_e \; u \; (e^*(T_s) - e(T_a))$$

$$K_e := \frac{\epsilon}{p \; \rho_{wa}} \frac{k^2}{\frac{ln(z_m - z_d)}{z_0}}$$

$\epsilon = 0.622$

k=0.41 is the von Kármán's constant

p is the atmospheric pressure

ρ_w is the density of water vapour

$z - m$ is the reference height

z_d is the zero displacement height

z_0 is the equivalent roughness of the surface

The physics of evaporation

z_d and z_0 over a vegetated surface

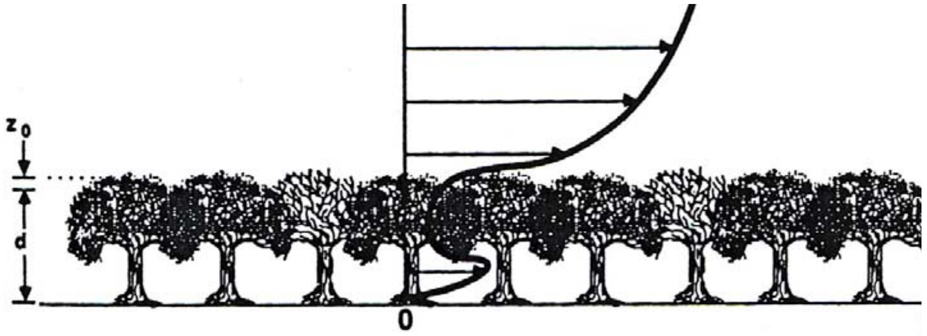
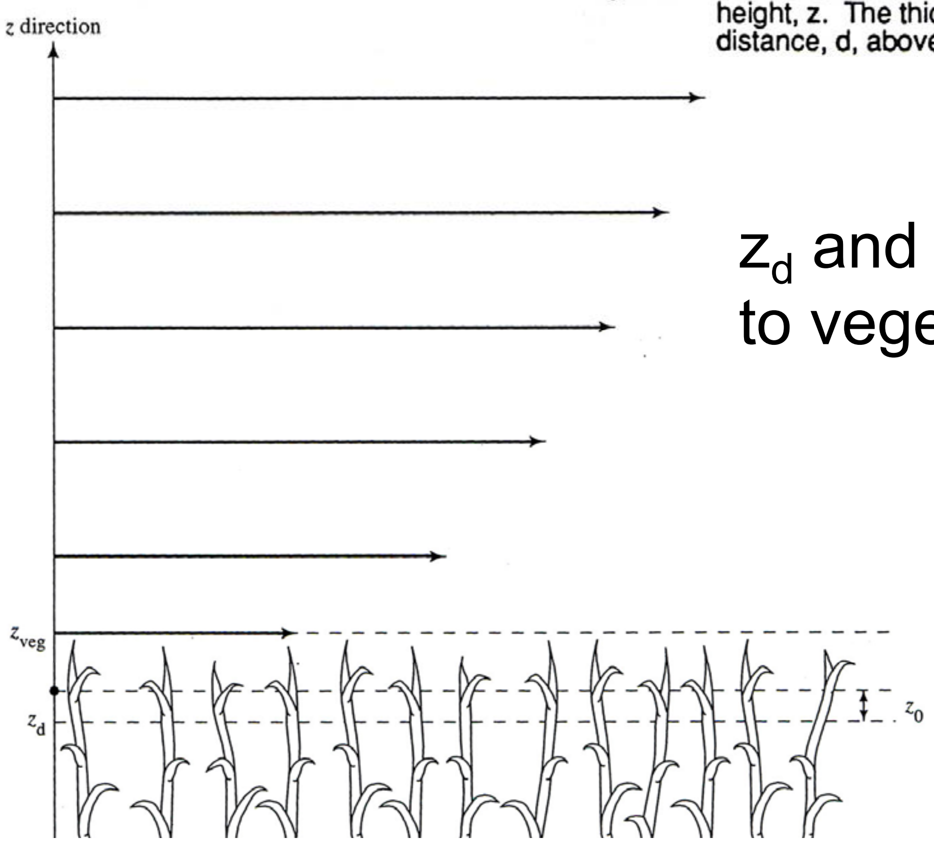


Fig. 9.7 Flow over forest canopy showing wind speed, M, as a function c height, z. The thick canopy layer acts like a surface displaced a distance, d, above the true surface. z_0 = roughness length.

FIGURE D-10
Vertical distribution of wind velocity over a vegetative surface of height z_{veg}. The profile follows the logarithmic relation of Equation (D-22). The zero-plane displacement, z_d, is about $0.7 \cdot z_{veg}$, and the roughness height, z_0, is about $0.1 \cdot z_{veg}$. Note that Equation (D-22) gives $v_a = 0$ when $z = z_d + z_0$.



z_d and z_0 are proportional to vegetation height z_{veg}

$$z_d = 0.7\ z_{veg}$$

$$z_0 = 0.1\ z_{veg}$$

The physics of evaporation

- We can conclude that there are necessarily four conditions in order for evaporation to take place:

- that there is **available energy** for the change phase to take place
- that there is **available water** on the surface of the ground (this is linked to the mass balance)
- that there is a **vapour pressure gradient** along the vertical (this is linked to the maximisation of entropy)
- that there is **wind** which removes humidity from the air (this is linked to the flux of momentum).

What controls evaporation?

Evaporation is an energetically intense phenomenon, given that the vaporisation constant is 540 cal/gramme

This energy is prevalently provided by:

- solar radiation
- heat (sensible) transferred by convection and conduction
- kinetic energy, internal energy of the water

What controls evaporation?

1. **The energy balance**
2. The temperature
3. The vapour content
4. The wind
5. The availability of water

The energy balance

$$R_n = \lambda \, \mathrm{ET} + H + G + P_S$$

- The net radiation is determined by the quantities of incoming and outgoing radiation with relation to the control volume (in this case the “surface” of the ground.
- If the radiation is positive, it is then divided up into latent heat, sensible heat, heat fluxes towards the ground, and energy used in photosynthesis
- The radiation itself, remember, does not only originate from the Sun, but also from the surfaces themselves, as described by Stefan-Boltzmann

Surface radiation and energy budgets

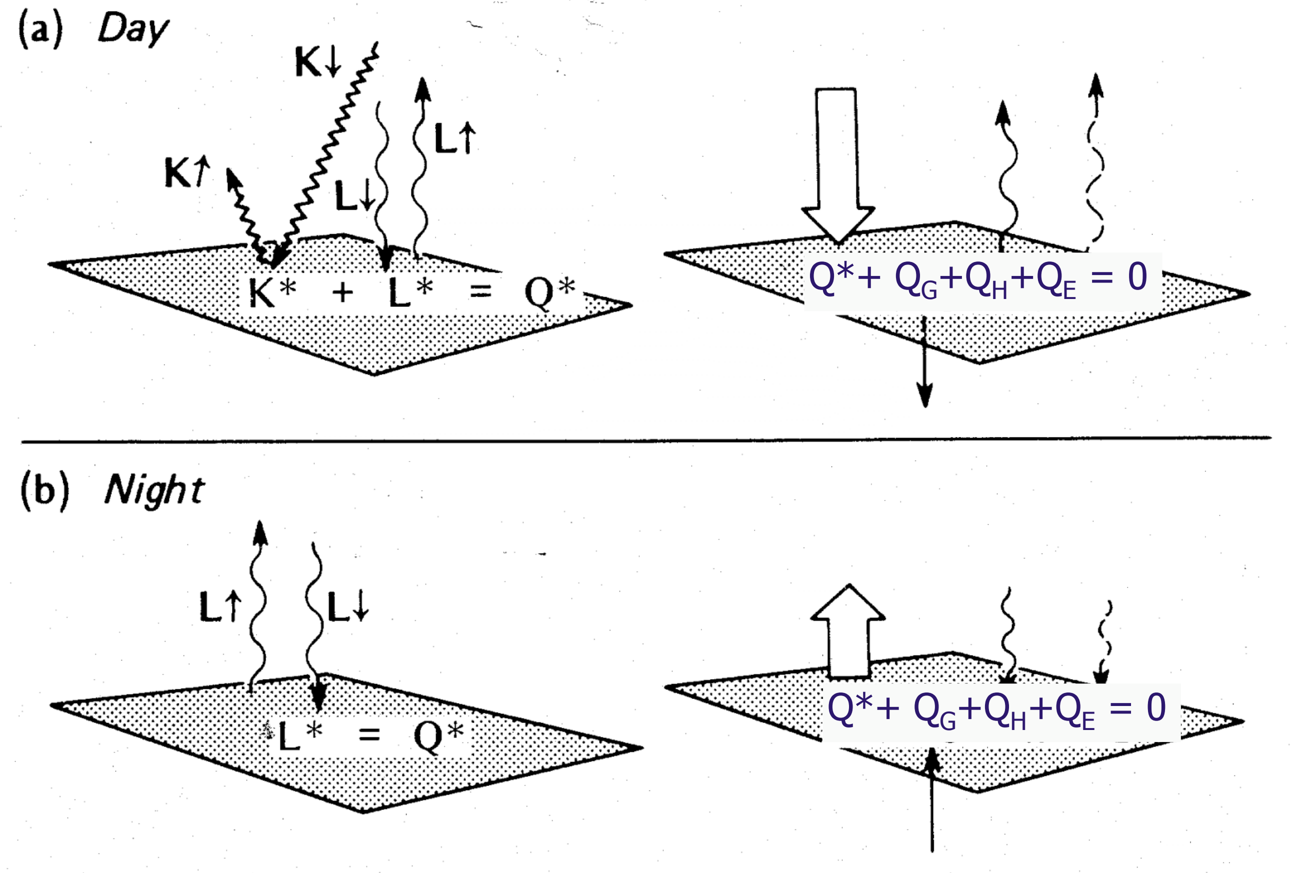


Figure 1.11 Schematic summary of the fluxes involved in the radiation budget and energy balance of an 'ideal' site, (a) by day and (b) at night.

Oke (1978)

Q^* = R = net radiation

Kdn = incoming solar

Kup = reflected solar

K^* = net solar

Ldn = incoming longwave

Lup = outgoing longwave

L^* = net longwave

Q_G = G = ground heat flux

Q_H = H = sensible heat flux

Q_E = L = latent heat flux

$$Q^* = K^* + L^* = Kdn + Kup + Ldn + Lup$$

The energy balance

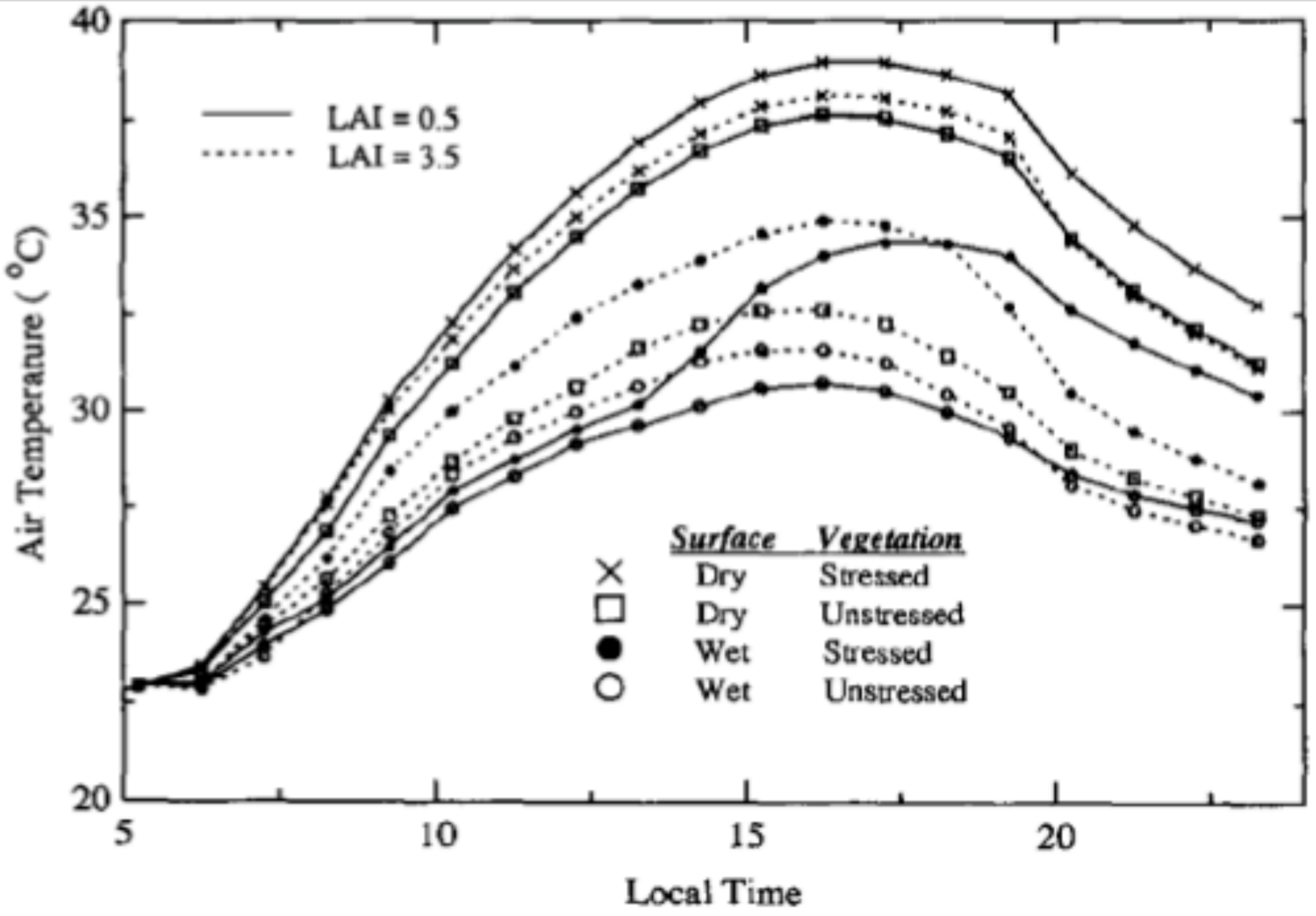
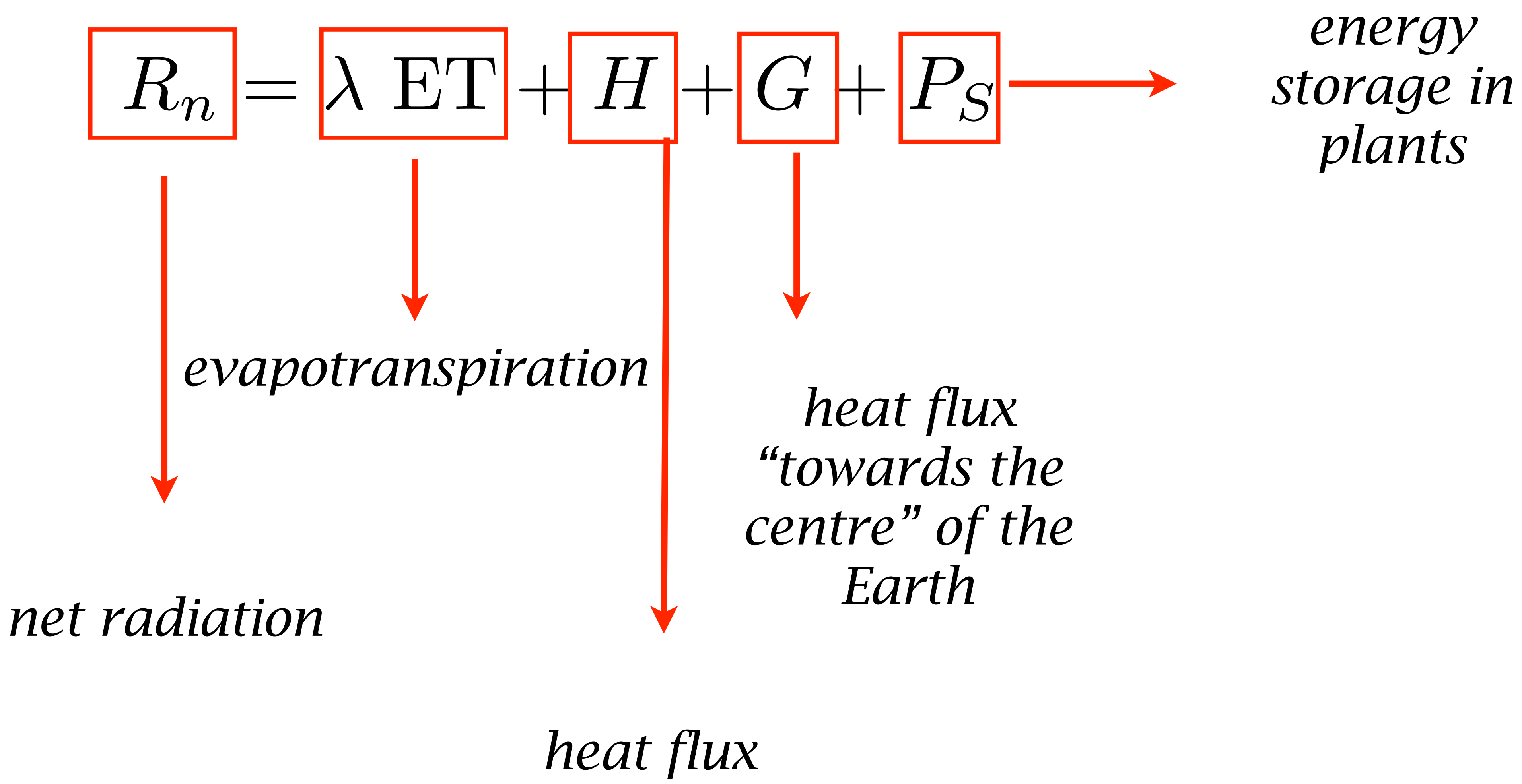


Figure 1. Variation in air temperature at 2 m above a surface with a vegetative cover 0.6 m in height, as predicted by a combined soil-plant-atmosphere and planetary boundary layer model. The words "dry" and "wet" refer to the condition of the soil surface, and the words "stressed" and "unstressed" refer to the available water (below the surface) in the root zone and thus the water status of the plant. All model runs began at 5:00 A.M. local time with the same air temperature.

Anderson et al. Rem Sens Environ 60:195-216.

The energy balance



$$\boxed{R_n} = \boxed{\lambda\ \mathrm{ET}} + \boxed{H} + \boxed{G} + \boxed{P_S}$$

energy storage in plants

evapotranspiration

heat flux “towards the centre” of the Earth

net radiation

heat flux

The energy balance

$$R_n = \lambda \, \mathrm{ET} + H + G + P_S$$

- It should be remembered that latent and sensible heats can originate from areas adjacent to the one considered by means of advection.
- A typical example of this is an oasis that receives large quantities of sensible heat from the surrounding arid areas (by advection)
- Convection of sensible heat usually causes vertical heat transfer

The energy balance

$$R_n = \lambda \, \mathrm{ET} + H + G + P_S$$

There is a term missing in the balance. Which?

* The storage of energy in the control volume itself

What controls evaporation?

1. The energy balance
2. **The temperature**
3. The vapour content
4. The wind
5. The availability of water

Temperature

- It is a measure of the internal energy of a system
- It affects the condensation vapour pressure* (Clausius - Clapeyron law)
- It is needed to define the deficit with respect to equilibrium vapour pressure (condensation vapour pressure, cvp)

*The vapour pressure above which the Gibbs free energy of the vapour exceeds that of liquid water in free state at the same temperature.

What controls evaporation?

1. The energy balance
2. The temperature
3. **The vapour content**
4. The wind
5. The availability of water

The vapour content

- It is needed to **define the deficit** with respect of the condensation pressure, that is to say, the pressure for which vapour has the same Gibbs free energy as liquid water in a free state (where surface tensions are negligible).
- The aforementioned condition is necessary, but not sufficient, for condensation to occur, given that condensation necessarily requires separation surfaces (microscopic droplets of water), the generation of which requires further energy.

What controls evaporation?

1. The energy balance
2. The temperature
3. The vapour content
4. **The wind**
5. The availability of water

The wind

- It generates **turbulent diffusion** and **maintains the vapour pressure gradient**

- Turbulence is a function of the windspeed and the surface roughness

- Evaporation increases considerably with the windspeed, up to a limit value which is function solely of the energy and temperature of the evaporating surface.

The availability of water

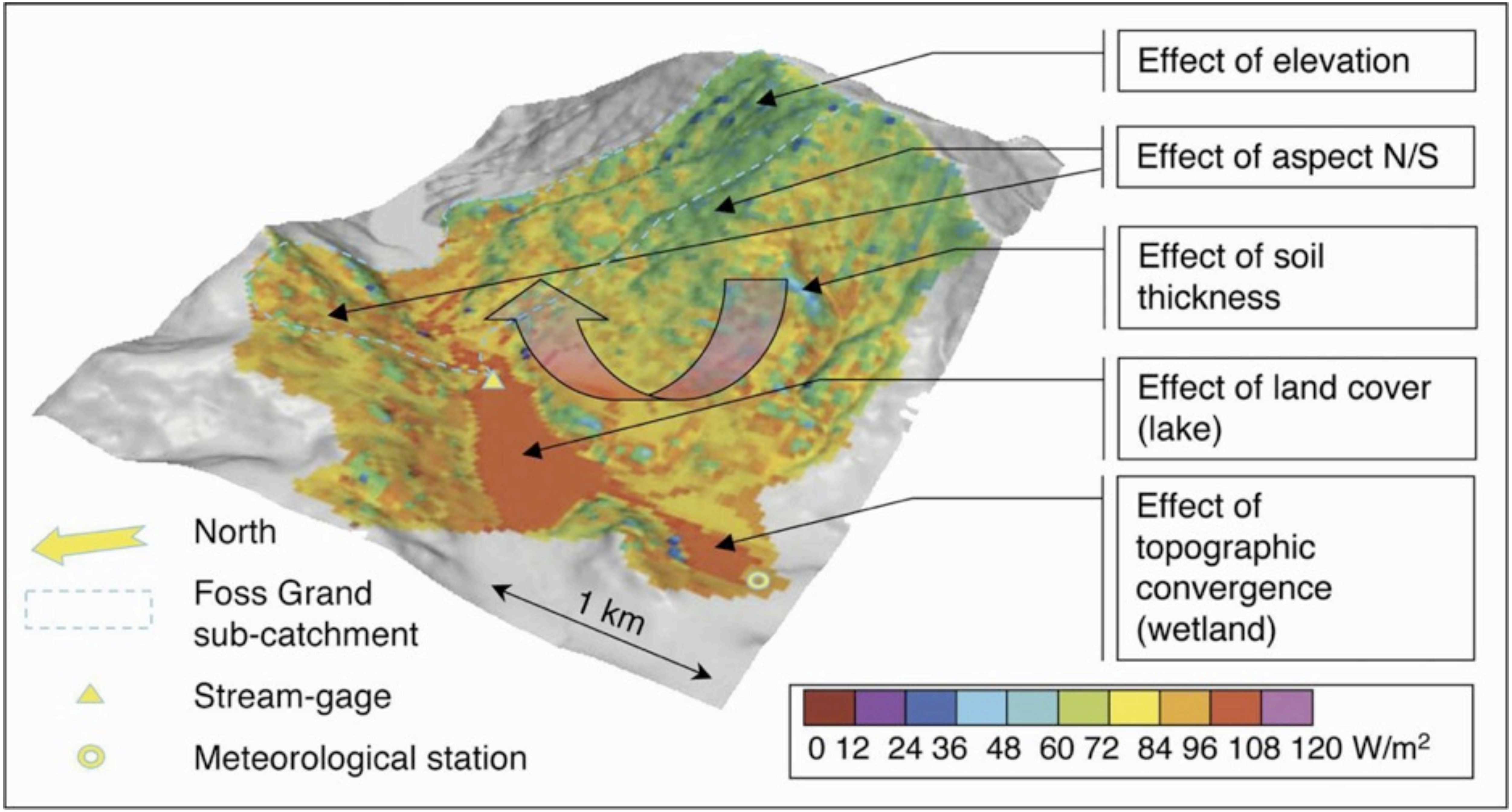
- Water is not equally available across a surface. Obviously, it evaporates more easily where there is more available.

Additional factors

- The water **quality**: more saline waters evaporate less readily than less saline waters.
- The **depth** of waterbodies: deeper waterbodies have more thermal inertia and they tend to evaporate more readily than shallower waterbodies, even during the winter months. Shallow waterbodies can freeze over in winter, bringing evaporation to a halt.

- The **extents** of a waterbody: overall evaporation is function of the **evaporating surface**. The greatest values of evaporation are recorded for large, surface waterbodies in arid regions.

Other aspects



Evaporation of surface waters

Figure 3. (left) Campbell Sci. CSAT3 3D sonic system, and (right) REBS Bowen ratio system.

- is only limited by atmospheric forcings

Evaporation of surface waters

- The evaporation of surface waters is only limited by atmospheric forcings and its formal expression is:

$$\mathrm{ET} = \rho_v \overline{w'\ q} = -\rho_v \frac{k^2 |u| (q_m - q_0)}{\ln^2\left(\frac{z_m - z_d}{z_0}\right)} = -\rho_v \frac{1}{r}(q_m - q_0)$$

$$r^{-1} := \frac{|u|\ k^2}{\ln^2\left(\frac{z_m - z_d}{z_0}\right)}$$

Evaporation of surface waters

- the second member represents the turbulent transfer of humidity along the vertical. The bar indicates the time average.

$$\mathrm{ET} = \ \rho_v \overline{w' \ q}$$

Evaporation of surface waters

- the second member represents the turbulent transfer of humidity along the vertical. The bar indicates the time average.

$$\mathrm{ET} = \rho_v \overline{\boxed{w'}\, q}$$

fluctuation of the windspeed in the vertical direction due to turbulence

Evaporation of surface waters

- the second member represents the turbulent transfer of humidity along the vertical. The bar indicates the time average.

$$\mathrm{ET} = \rho_v \overline{\boxed{w'}\,\boxed{q}}$$

specific humidity due to turbulence

fluctuation of the windspeed in the vertical direction due to turbulence

Evaporation of surface waters

- The third member represents the explication of the turbulent transfer

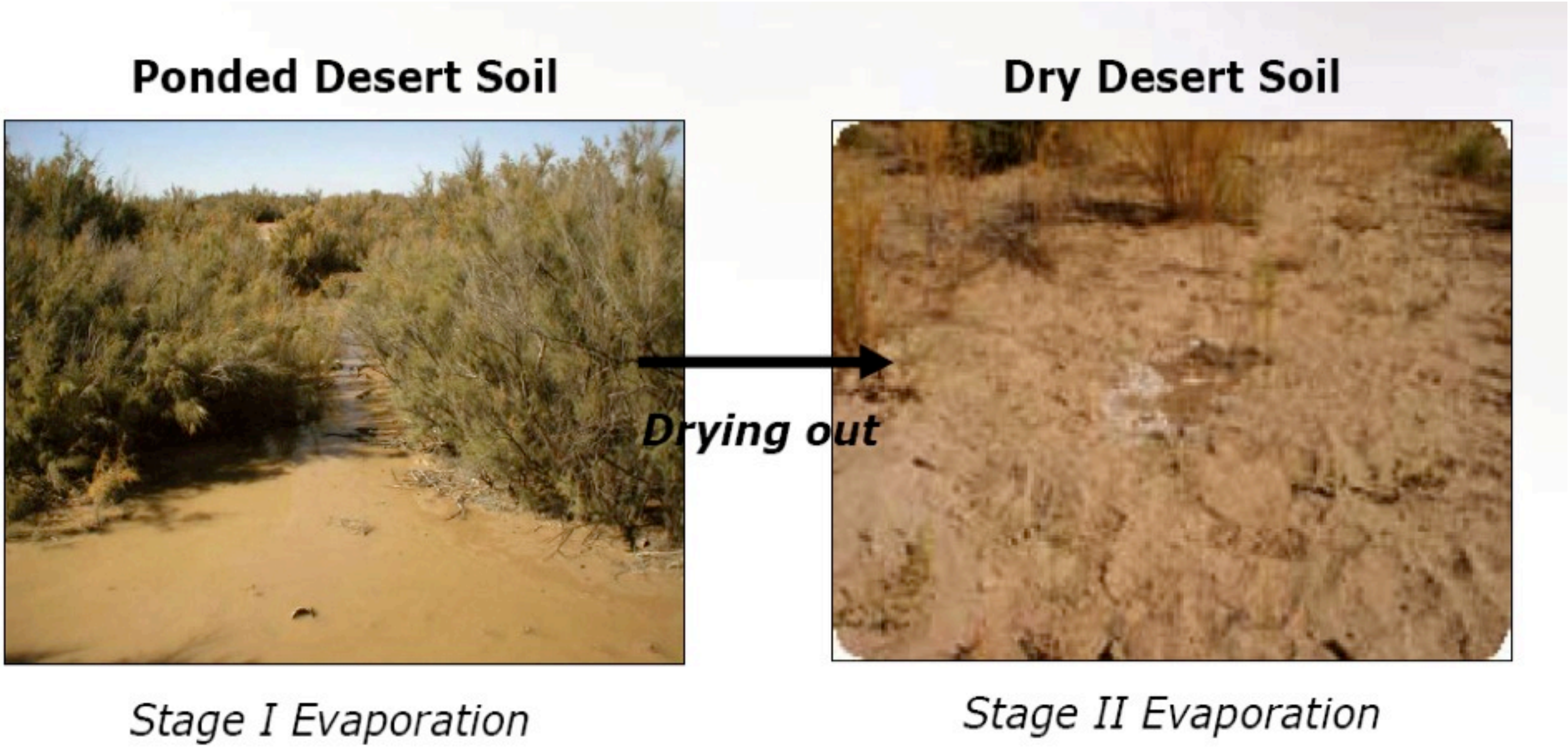
$$\mathrm{ET} = \rho_v \overline{w' \; q} = -\rho_v \boxed{\frac{k^2|u|(q_m - q_0)}{\ln^2\left(\frac{z_m - z_d}{z_0}\right)}} = -\rho_v \; \frac{1}{r}(q_m - q_0)$$

It's turbulence baby!

Evaporation from soils

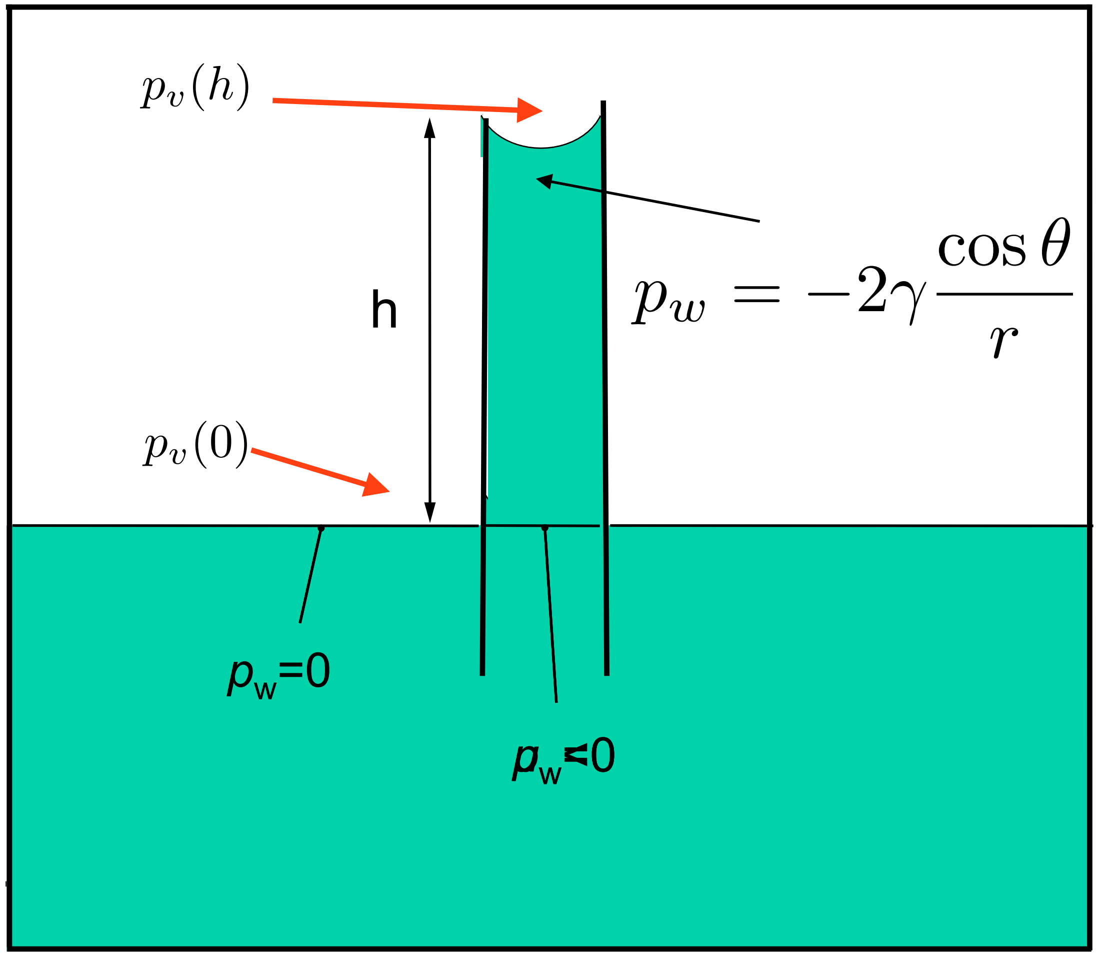
- The availability of water is essential: evaporation reduces when the **soil dries out**. The deeper the water-table, the lower the evaporation.
- The **texture** of the soil is important. In fact, for saturated soils evaporation is limited. However, the suction potential plays an essential role. Soils with finer texture are subject to slower evaporation which is more protracted in time.
- The **colour** of the soils contributes to its albedo value, and therefore to the influx of radiant energy.
- If soils are covered in **vegetation**, this will act as a screen against solar radiation.

Evaporation from soils



Evaporation from soils

In the presence of capillary forces not only is the water pressure measured in the capillaries less than atmospheric pressure, due to surface tension, but the vapour pressure in equilibrium with the capillary water, *$p_v(h)$,* is less than the vapour pressure in equilibrium with the free water, *$p_v(0)$*.



$$p_w = -2\gamma \frac{\cos\theta}{r}$$

Evaporation from soils

- With respect to free bodies of water, in the case of soils the evaporation is limited by suction.

- A direct thermodynamic approach to this problem would be necessary, but the standard approach is different and it shall be illustrated in the following slides.

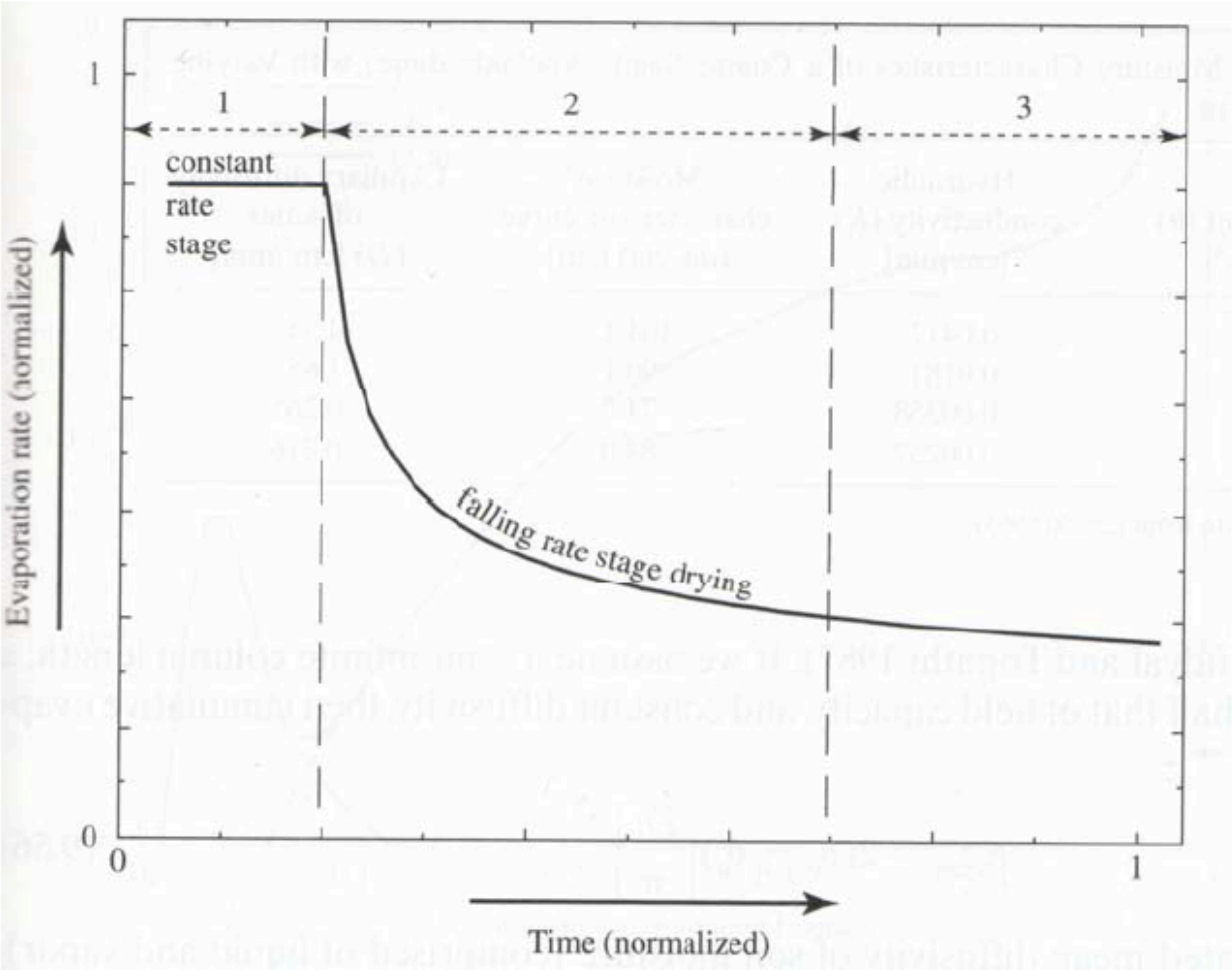
Evaporation from soils

- **Evaporation from soil is considered to occur in two separate stages.**

- **Stage I: Soil surface at or near saturation:**
  - Evaporation is controlled by the heat input and turbulent transport (winds) at the surface.
  - No soil water content control. (Atmospheric control).
  - Evaporation occurs near maximum rate.

- **Stage II: Soil surface drying**
  - Upper soil layer drying out, water limitation.
  - Transport of water vapour through soil becomes critical.
  - Soil-controlled or falling stage.

Evaporation from soils



Evaporation from soils

In the “standard” approach the formal translation of the phenomenon is obtained by introducing a resistance “in series” to the aerodynamic resistance and maintaining Dalton’s law unchanged.

$$\mathrm{ET} = \rho \frac{1}{r_a + r_s}(q^*(T_L) - q_a)$$

Evaporation from soils

In the “standard” approach the formal translation of the phenomenon is obtained by introducing a resistance “in series” to the aerodynamic resistance and maintaining Dalton’s law unchanged.

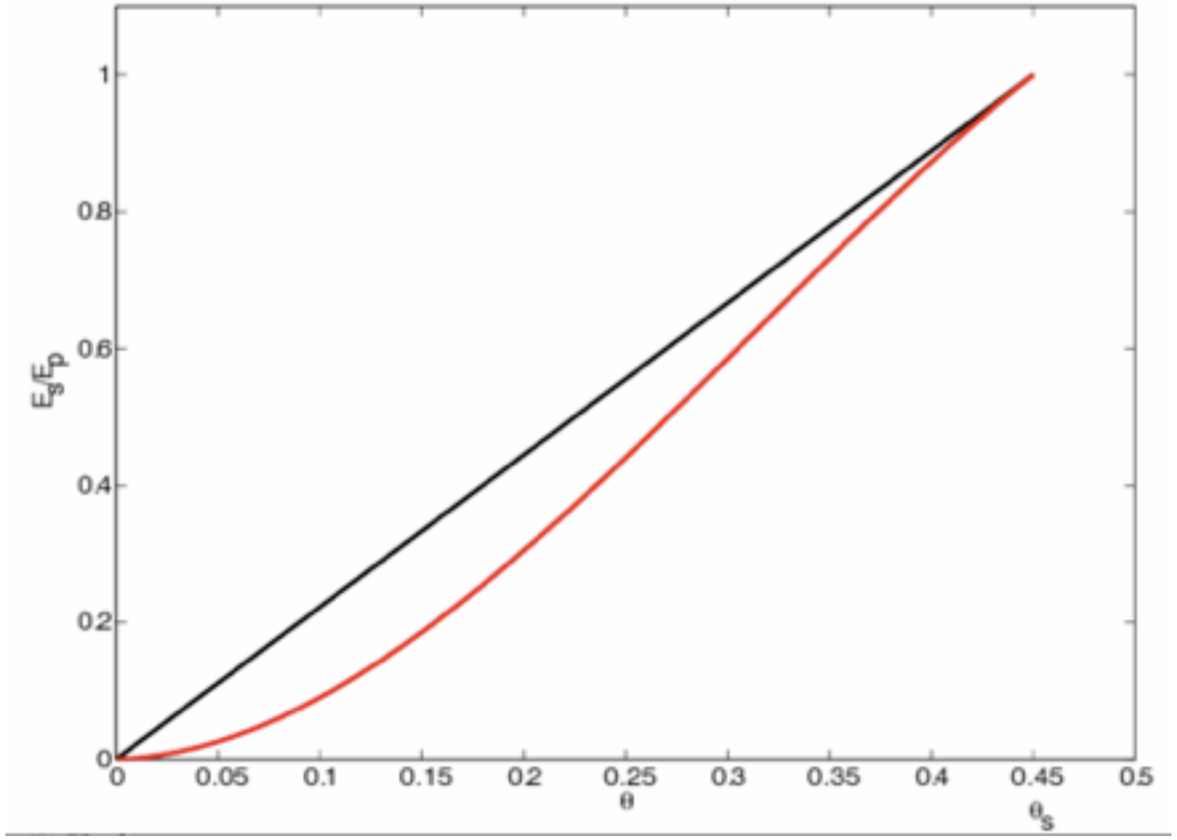
$$\mathrm{ET} = \rho \frac{1}{r_a + \boxed{r_s}} (q^*(T_L) - q_a)$$

resistance to evaporation due to unsaturated conditions

Evaporation from soils

Alternatively, the “potential” evaporation can be reduced with a reducing factor, which is usually only a function of the soil water content.

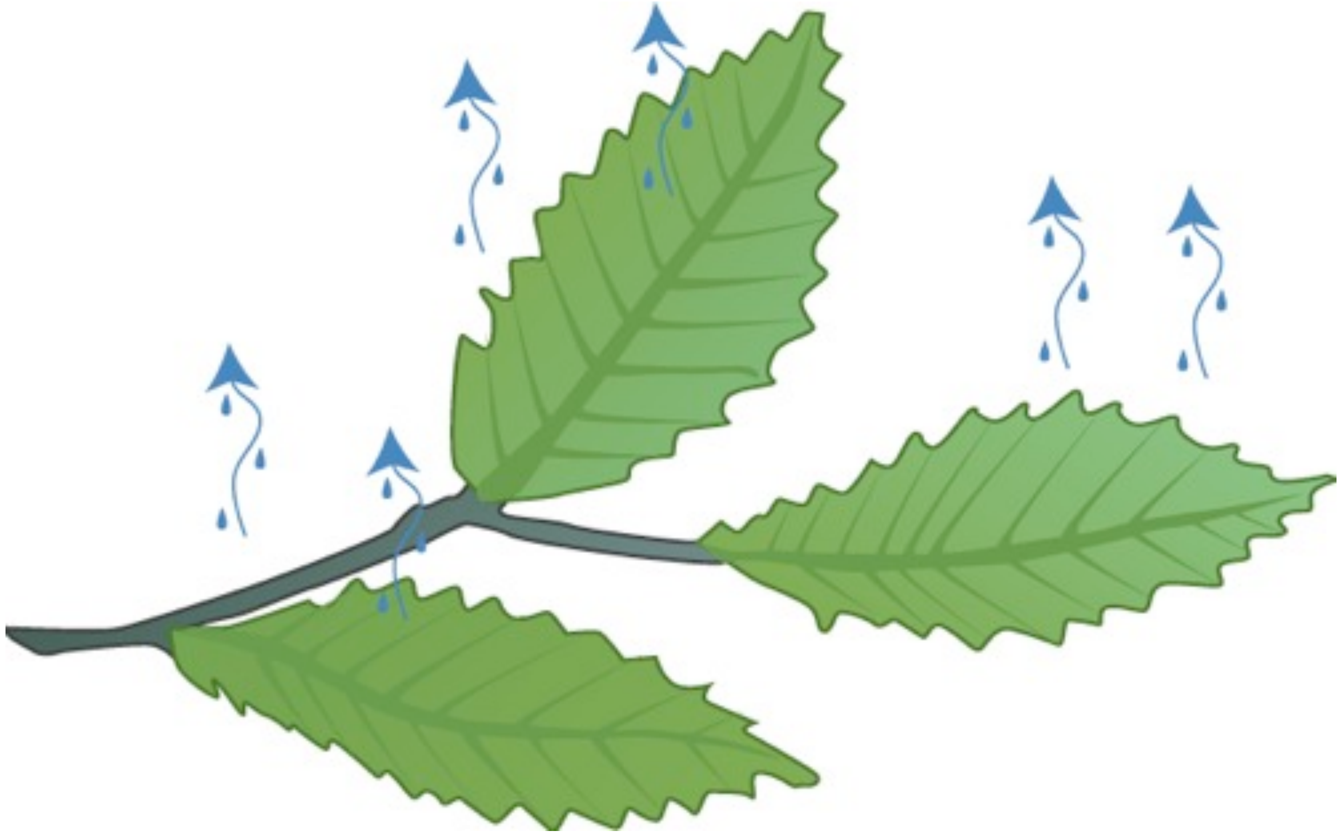
After Parlange et al.,



$$AET = x \; PET = x \; \lambda\rho \frac{1}{r_a}(q_0^* - q)$$

$$x(\theta) = 0.082 \; \theta + 9.137\theta^2 - 9.815\theta^3$$

Transpiration



Transpiration

- It is the evaporation from plants.
- It occurs simultaneously with the physiological process of carbon fixation during photosynthesis.
- Of the water required by a plant, ~95% is needed for transpiration and only ~5% becomes biomass!

Transpiration

- Transpiration is based on the capacity of a plant to extract water from the soil through its roots and release it to the atmosphere through its stomates.

- The ultimate controlling factor in the transpiration process is Dalton's law, where, however, the vapour pressure gradient considered is between just inside the stomates and just above the surface of the leaf.

Transpiration

It depends on the following factors:

- the type of vegetation and its vegetative state;

. the density and size of the vegetation (trees, bushes, grass);

- the soil structure;
- the environmental temperature;
- the CO_2 concentration in the atmosphere.

Transpiration

It is limited by:

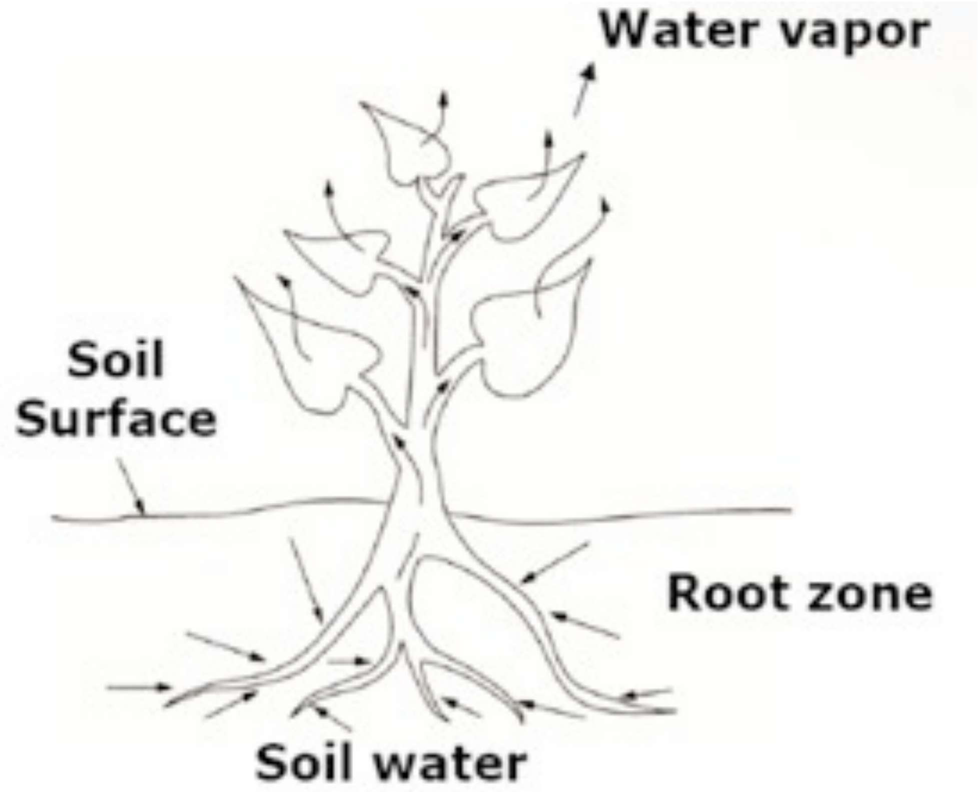
- energy availability;
- water availability;
- the development of turbulence.

Transpiration

It happens through the plant's vascular system.

Three processes can be identified:

1. the absorption of water in the roots;
2. the transfer along the trunk towards the stomates;
3. evaporation.



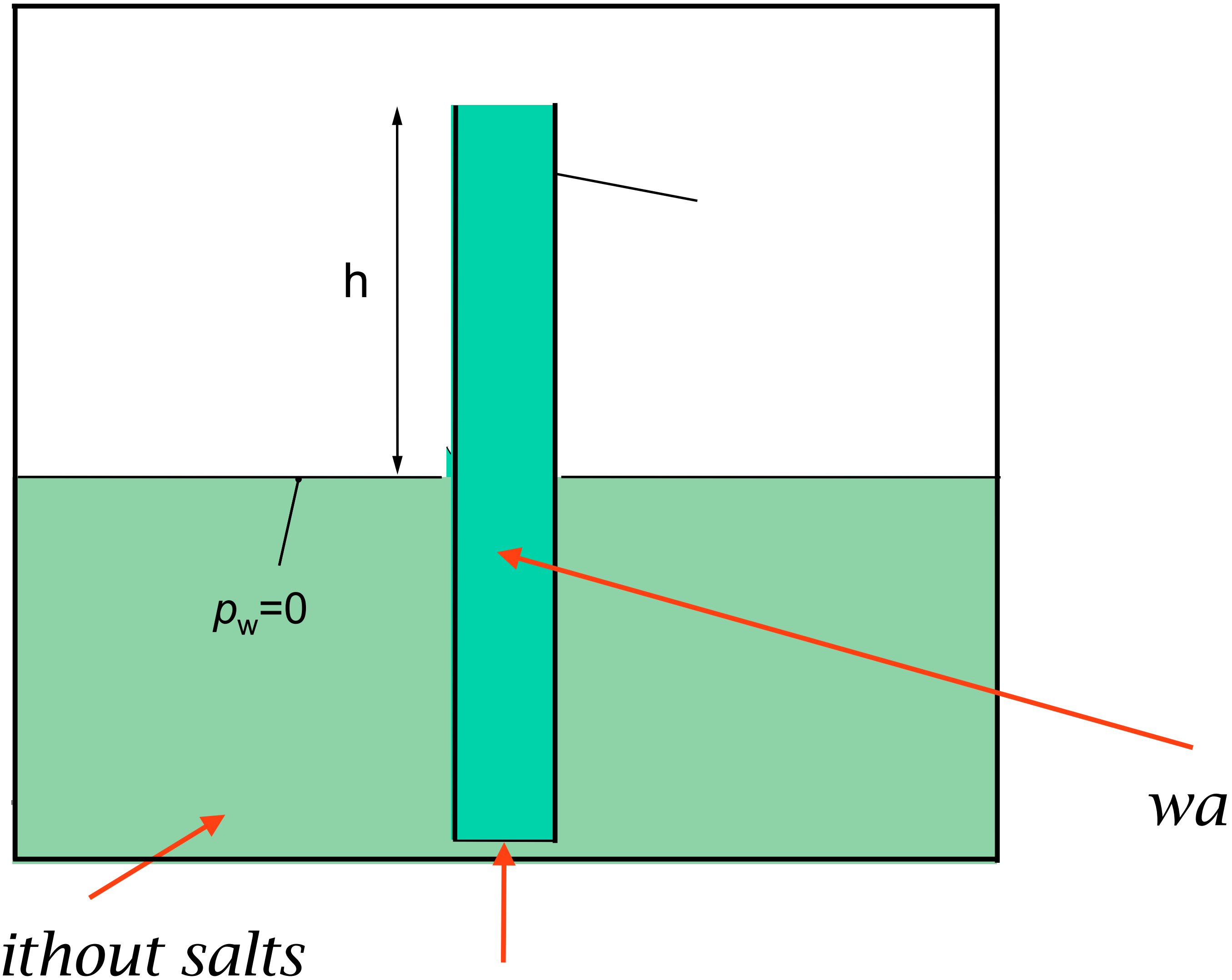
Capillarity and osmosis

- Plants do not have a heart (to pump the water)!
- The flow of water from the roots to the leaves is maintained, therefore, by the pressure difference between the soil and the roots, the roots and the the trunk, and, gradually, all the way to the leaves.
- This difference in pressure has two source: **capillary forces** and **osmotic forces.**

Osmotic forces

The tube is not a capillary tube. But the column of water rises in the tube to compensate the chemical potential (negative) which is generated in the tube due to the coexistence of two substances.

$$\Pi := \rho_w \; g \; h$$



water with salts

water without salts

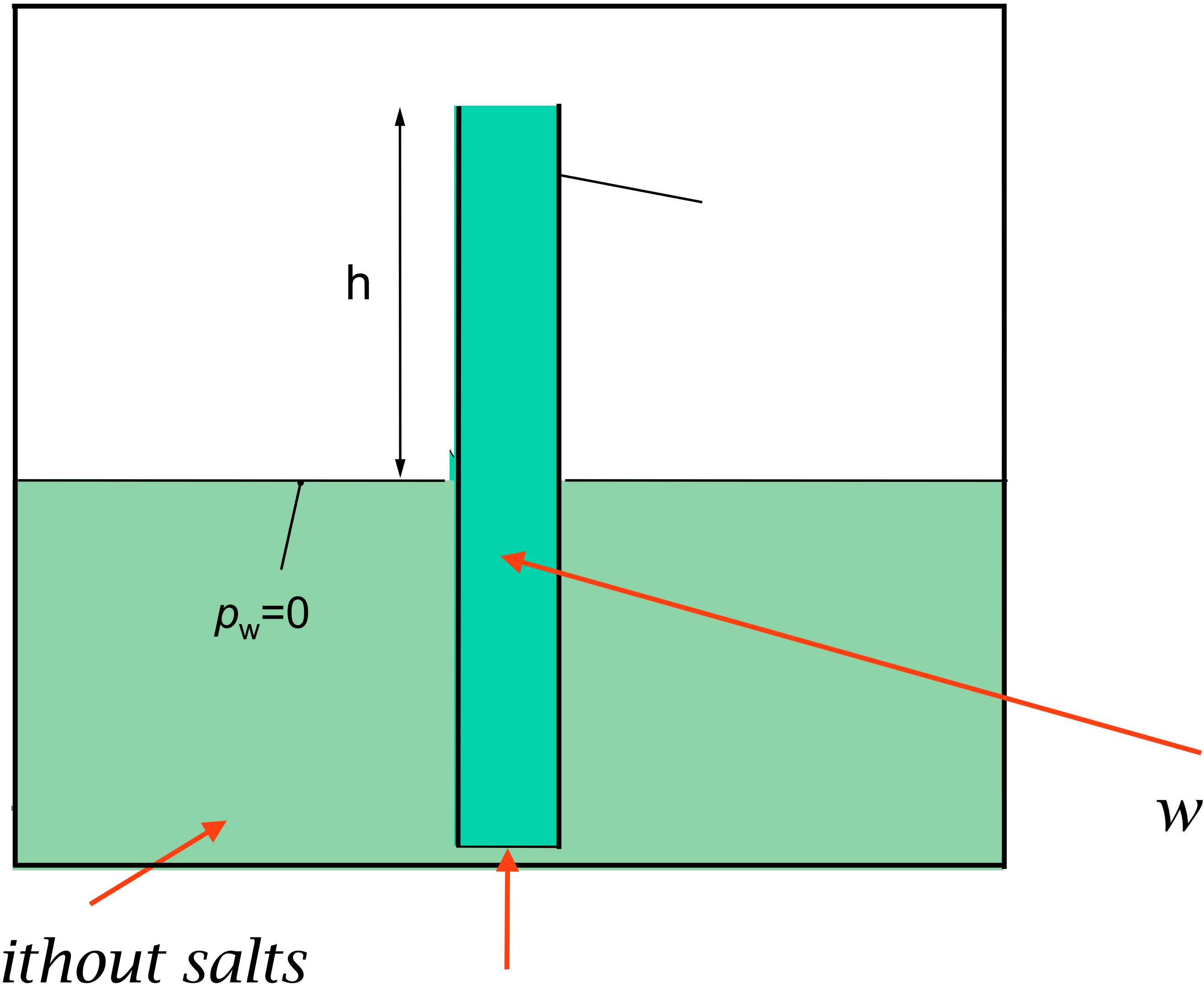
semipermeable membrane

Osmotic forces

The tube is not a capillary tube. But the column of water rises in the tube to compensate the chemical potential (negative) which is generated in the tube due to the coexistence of two substances.

$$\boxed{\Pi} := \rho_w \; g \; h$$

osmotic pressure



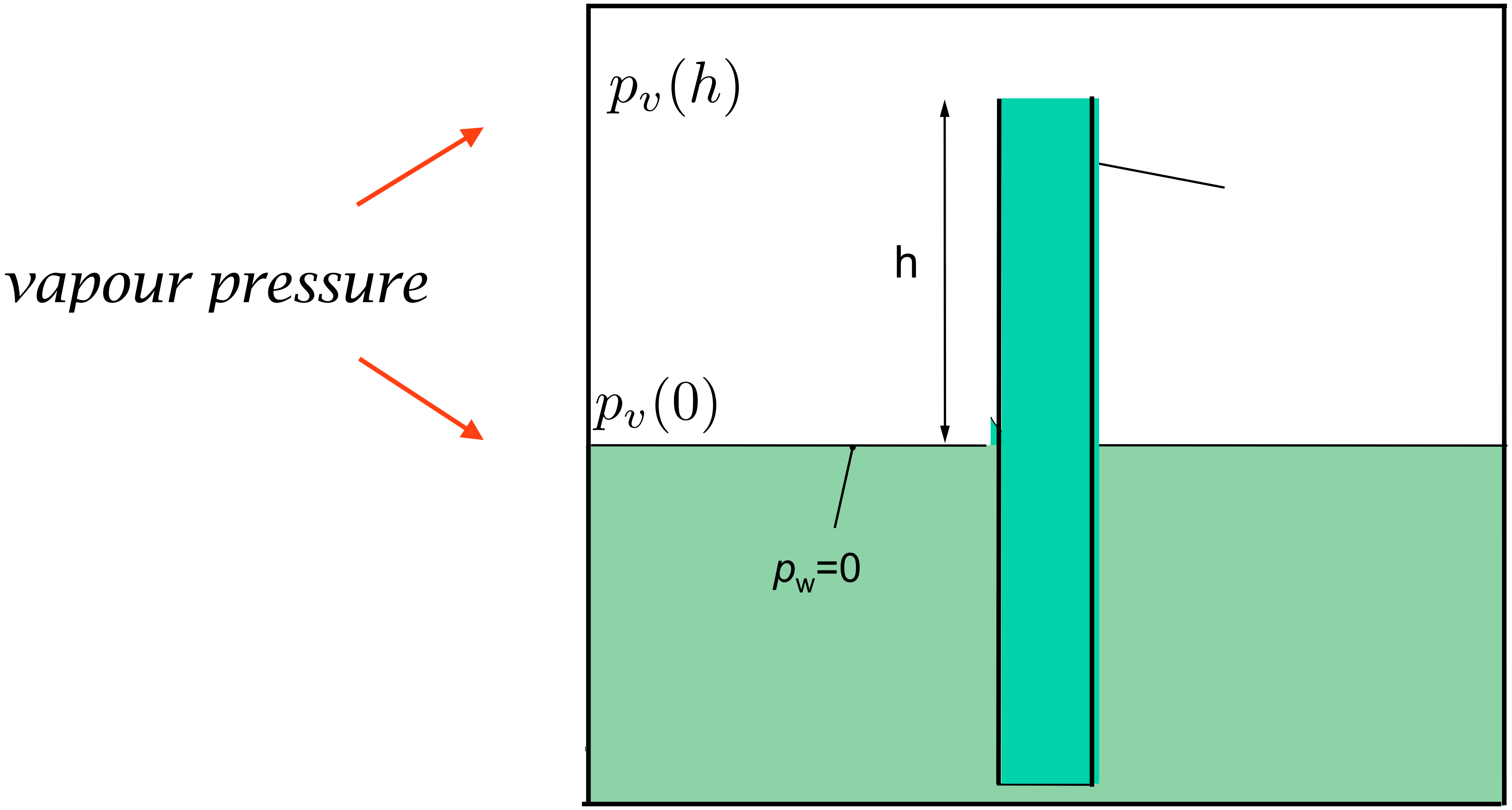
water with salts

water without salts

semipermeable membrane

Osmotic forces

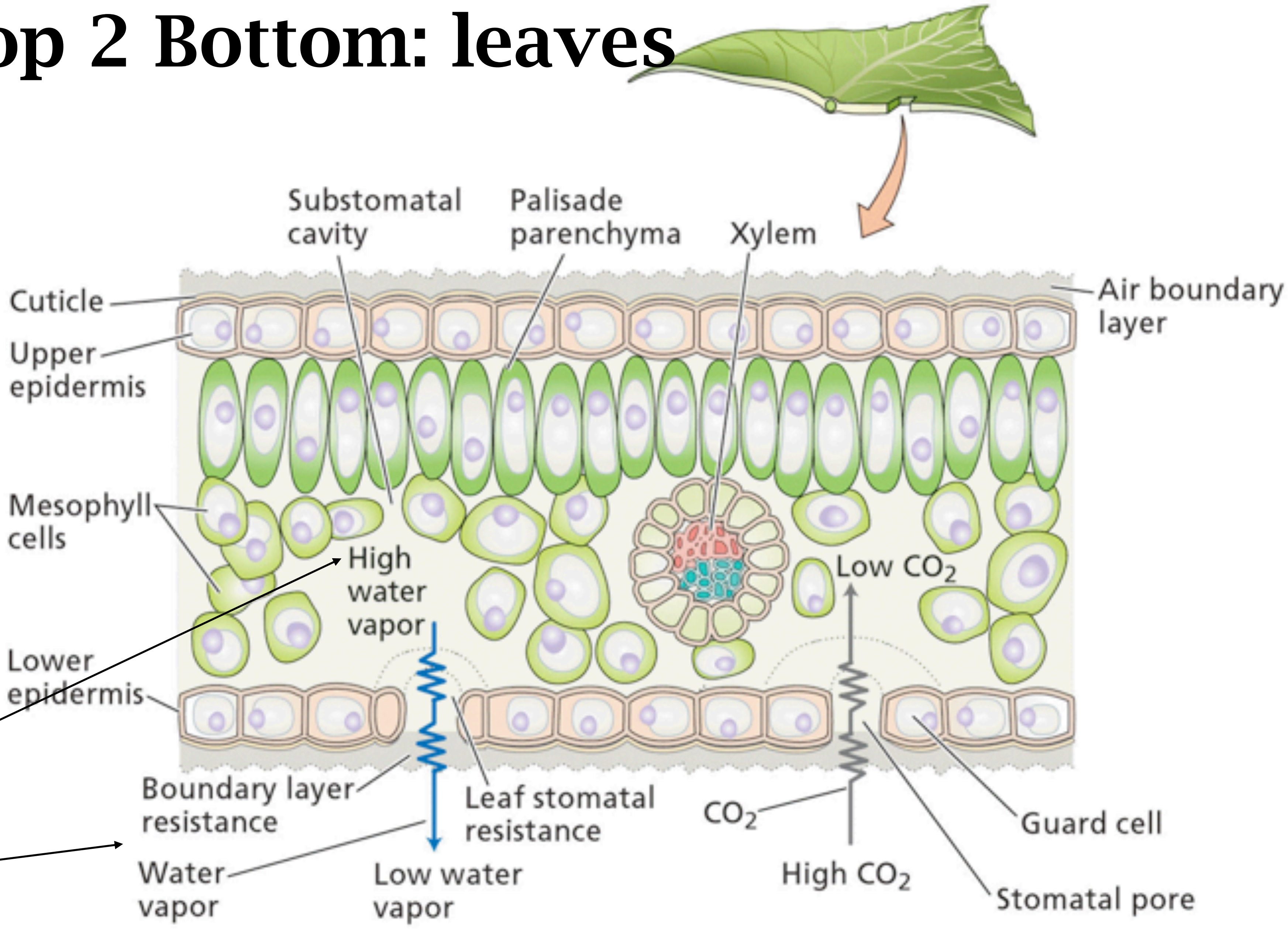
The two vapour pressures at different levels have to be different in order to be in equilibrium. Therefore, the effect of the coexistence of substances in solution **reduces** the vapour pressure (which is analogous to the capillary case).



www.fsl.orst.edu/~bond/fs561/lectures/humidity%20and%20transpiration.ppt

Top 2 Bottom: leaves

The force that activates transpiration is the pressure gradient: specifically, it is the pressure difference that exists between the interior of the leaf and the atmospheric pressure around it.

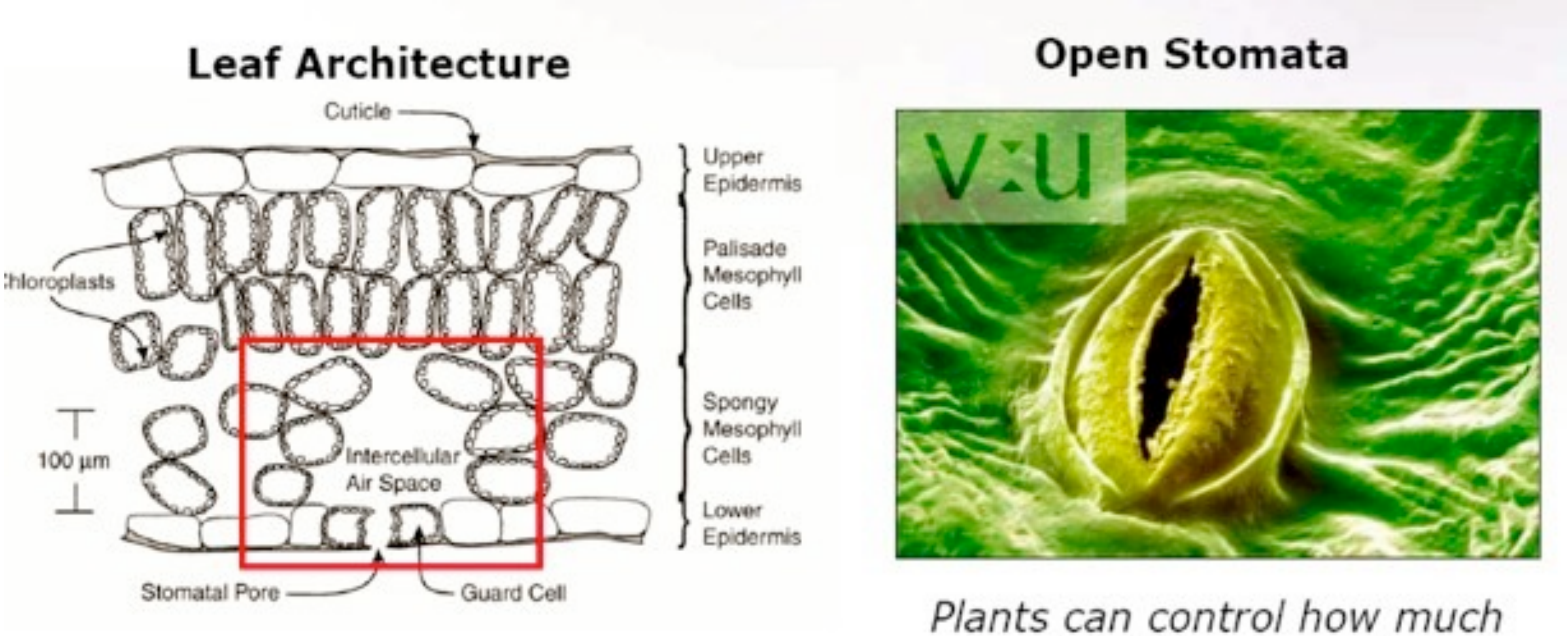


PLANT PHYSIOLOGY, Third Edition, Figure 4.10 © 2002 Sinauer Associates, Inc.

Transpiration

www.fsl.orst.edu/~bond/fs561/lectures/humidity%20and%20transpiration.ppt

The stomates are a critical component of the transpiration process

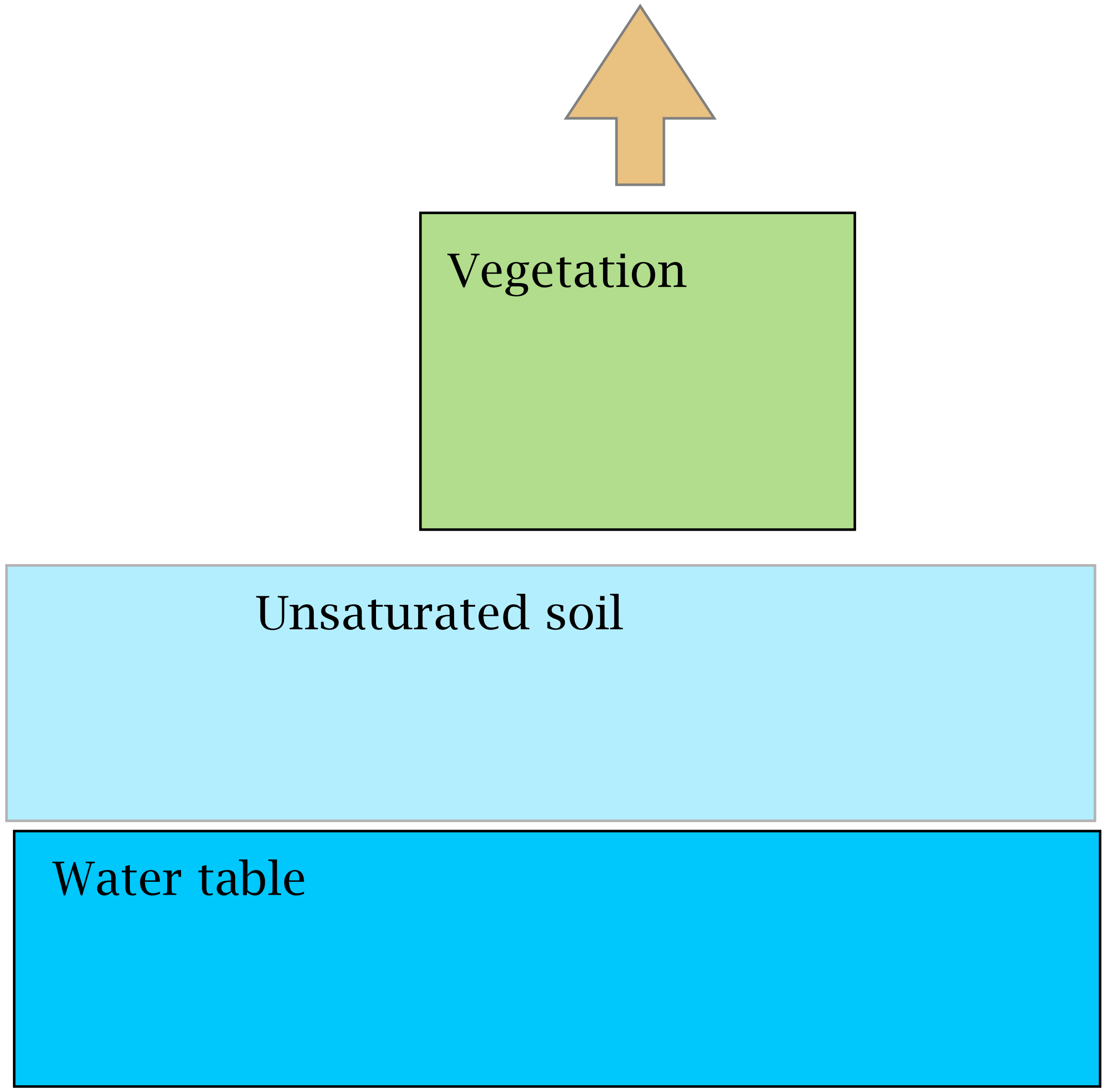


Plants can control how much water is lost to atmosphere by opening and closing stomata.

The physics of transpiration

- The physics of transpiration is the same as that of evaporation. However, two aspects must be taken into account:

1. the evaporation of the film of water on the surface of the leaf;
2. the real transpiration from the stomates of the plants.



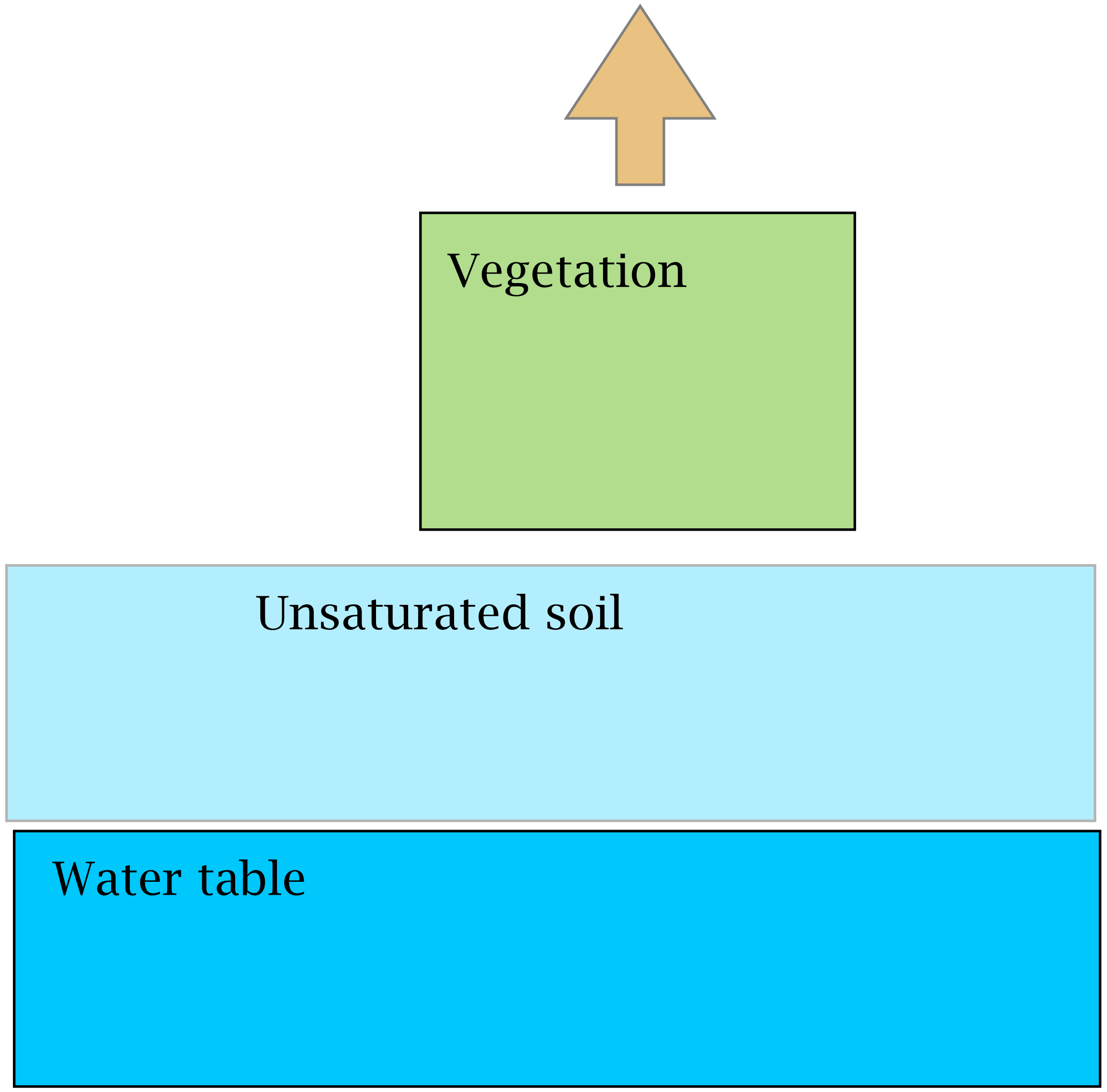
The physics of transpiration

transpiration from the leaves

$$\mathrm{Tr} = C_v\ u\ (e^*(T_v) - e(T_a))$$

$$C_v = \frac{1}{r_a + r_v}$$

$$\frac{1}{r_a} = \frac{\epsilon}{p_a \rho_v} \frac{k^2}{\log^2\left(\frac{z_m - z_d}{z_0}\right)}$$



The physics of transpiration

$$\mathrm{Tr} = C_v\ u\ (e^*(T_v) - e(T_a))$$

$$C_v = \frac{1}{r_a + r_v}$$

$$r_v = \frac{r_{V min}}{(\mathrm{LAI} * (fS\ fee\ fT\ fM))}$$

LAI is the Leaf Area Index”

fS depends on the incident solar radiation

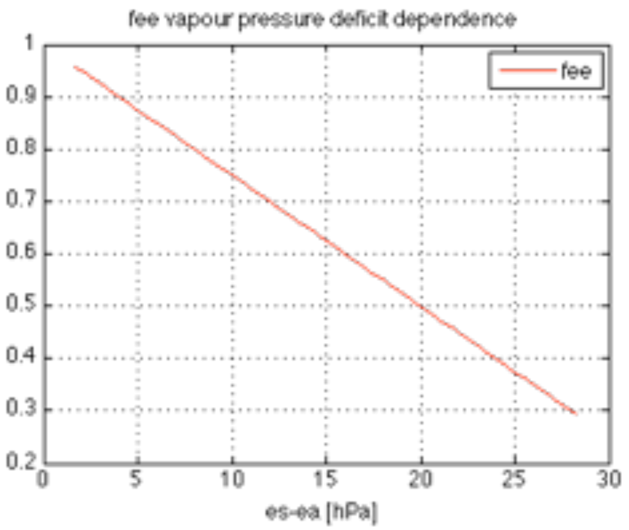
fee depends of the vapour content of the atmosphere

fT depends on the air temperature

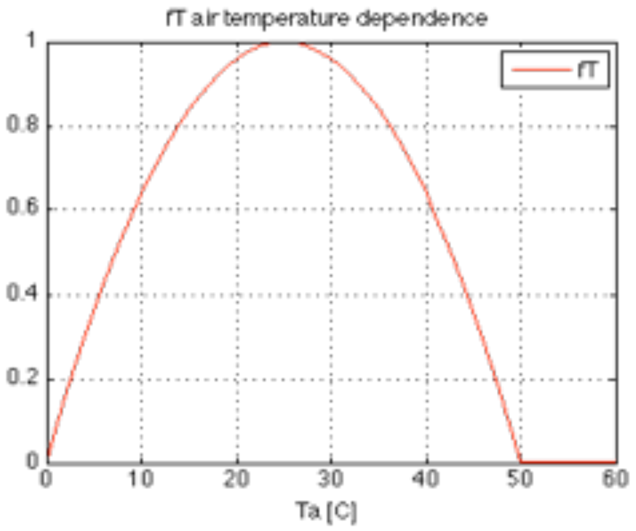
fM depends on the water content of the soil

The physics of transpiration

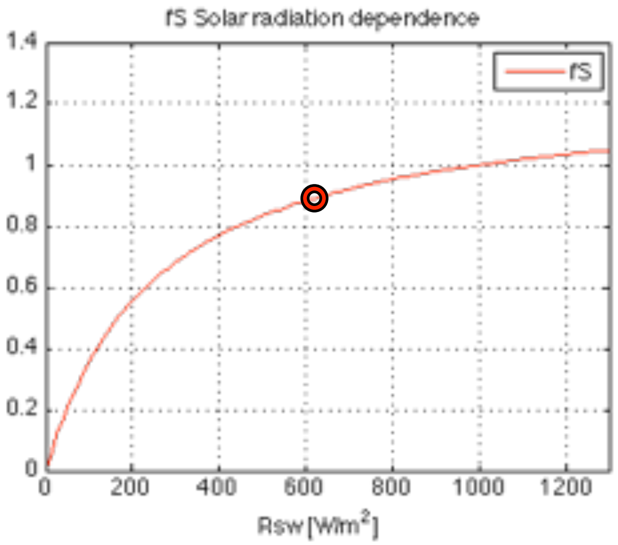
Environmental dependencies of stomata conductance



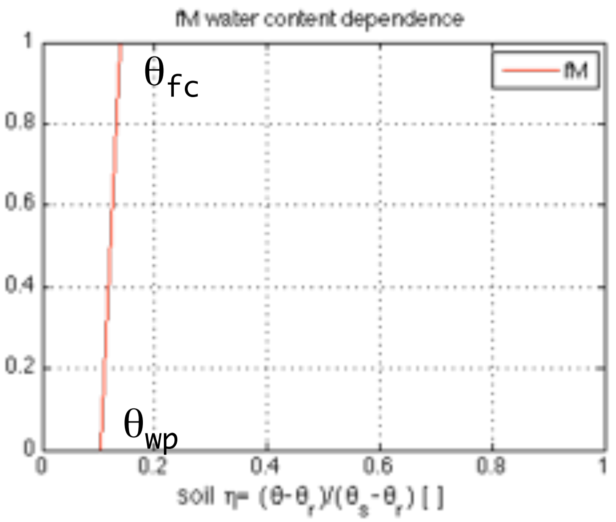
Stomata close for high vapor pressure deficit



Transpiration stop for too high and low Ta



Photosynthesis increases with PaR



For daytime conditions of simulation stb_stn004f

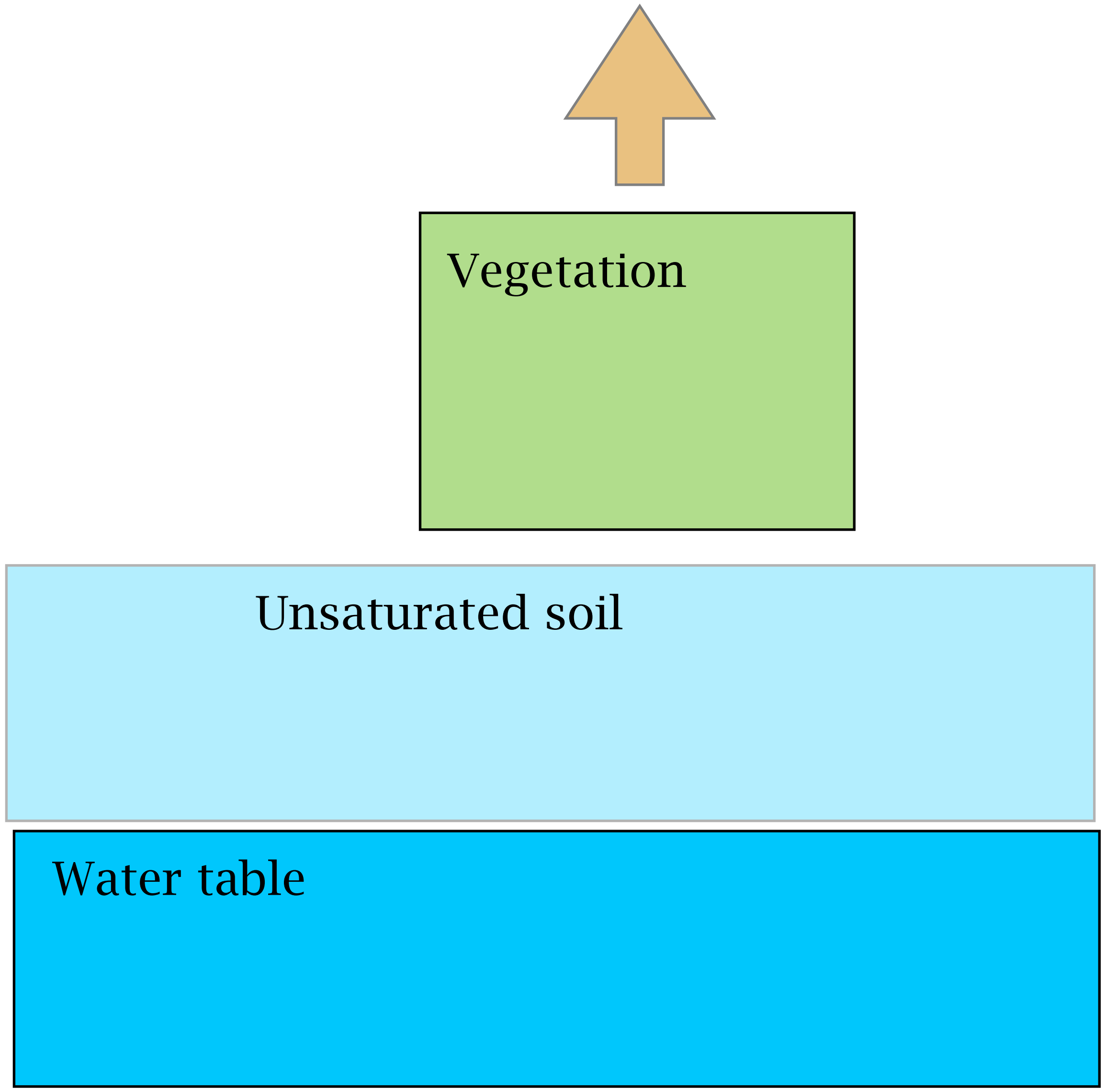
Courtesy of Giacomo Bertoldi

The physics of transpiration

evaporation from the leaves

$$\mathrm{Ev} = \; K_v \; u \; (e^*(T_s) - e(T_a))$$

$$K_v := \frac{1}{r_a} = \frac{\epsilon}{p_a \rho_v} \frac{k^2}{\log^2\left(\frac{z_m - z_d}{z_0}\right)}$$



The physics of transpiration

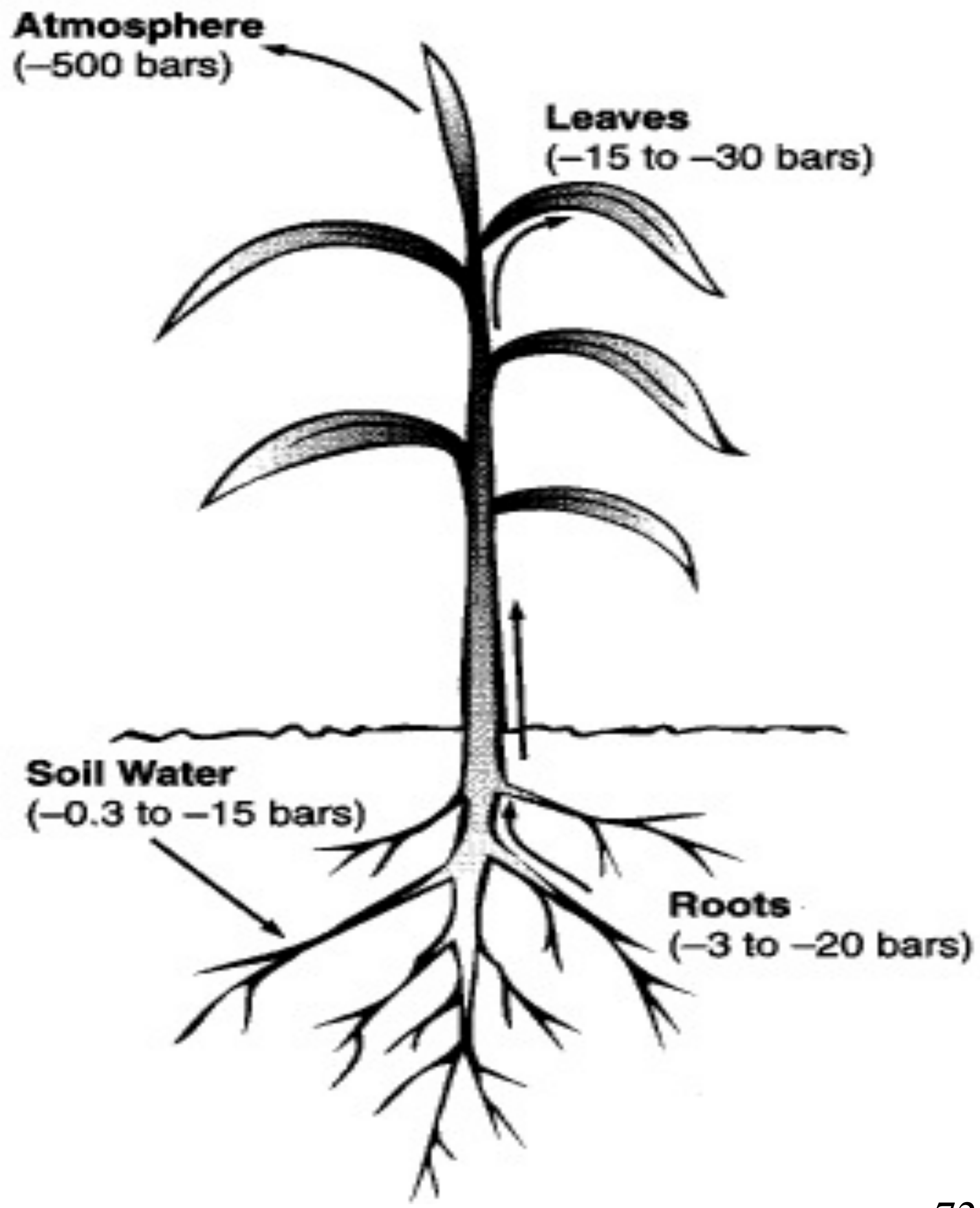
The total evapotranspiration is:

$$ET = E_v + Tr$$

Water movement in plants

http://www.ctahr.hawaii.edu/faresa/courses/nrem600/10-02%20Lecture.ppt

- The figure illustrates the differences in energy (in terms of pressure) that cause the movement of water from the soil to the atmosphere, through the plant. The water moves from a negative potential to a more negative potential in the atmosphere.



Water movement in plants

$$\vec{J}_p = -K_p\ \vec{\nabla}(z + \psi + \Pi)$$

where the hydraulic conductivity within the plant decreases, passing from the trunk to the leaves, and everything is less understood, in quantitative terms, than what happens in the soil(!).

Saturated Conductivity and Trees?

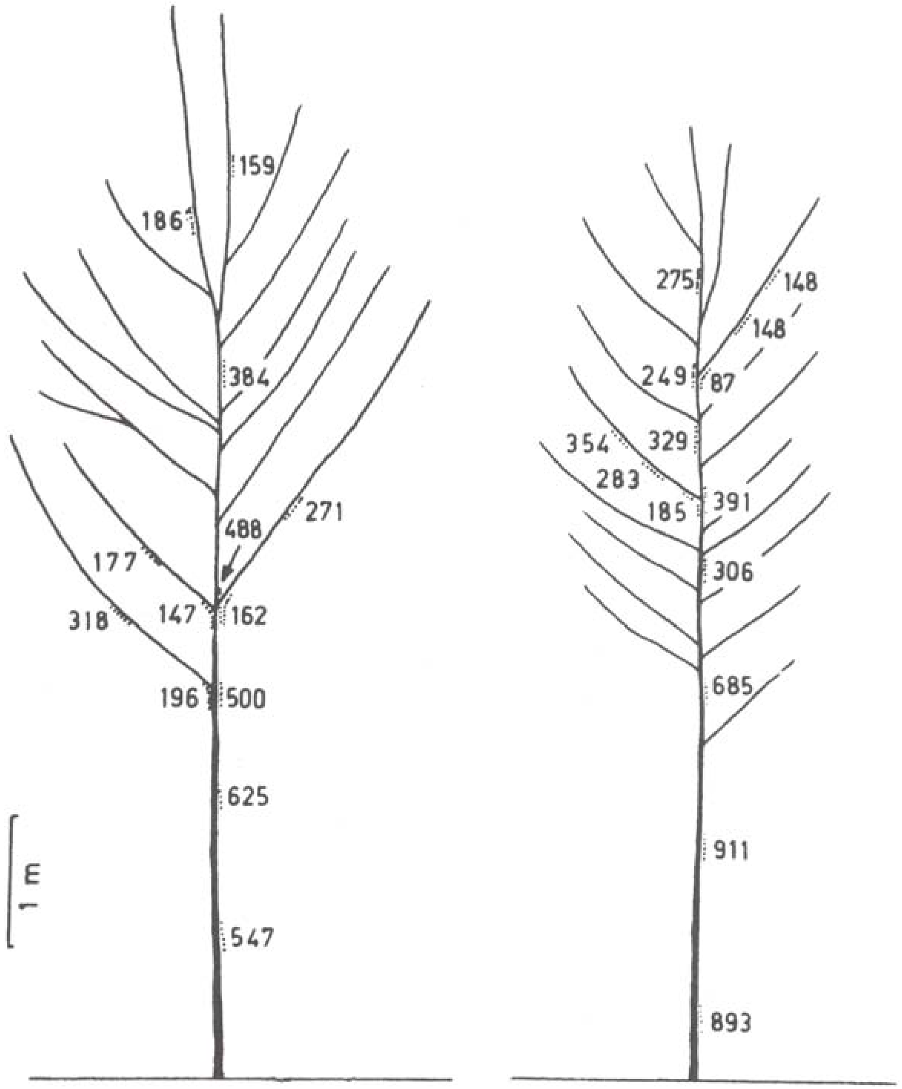


Figure 7.14 Leaf specific conductivity in microliters per hour, per gram fresh weight of leaves supplied, for two paper birch trees (*Betula papyrifera*). Conductivity decreases from lower to upper trunk and in the branches. It also is low when branches are attached to the trunk, as further indicated by the high velocity of sap flow at the point of branch attachment shown in Fig. 7.18. From Kramer (1983), after Zimmermann (1978).

Potential Evapotranspiration
PET

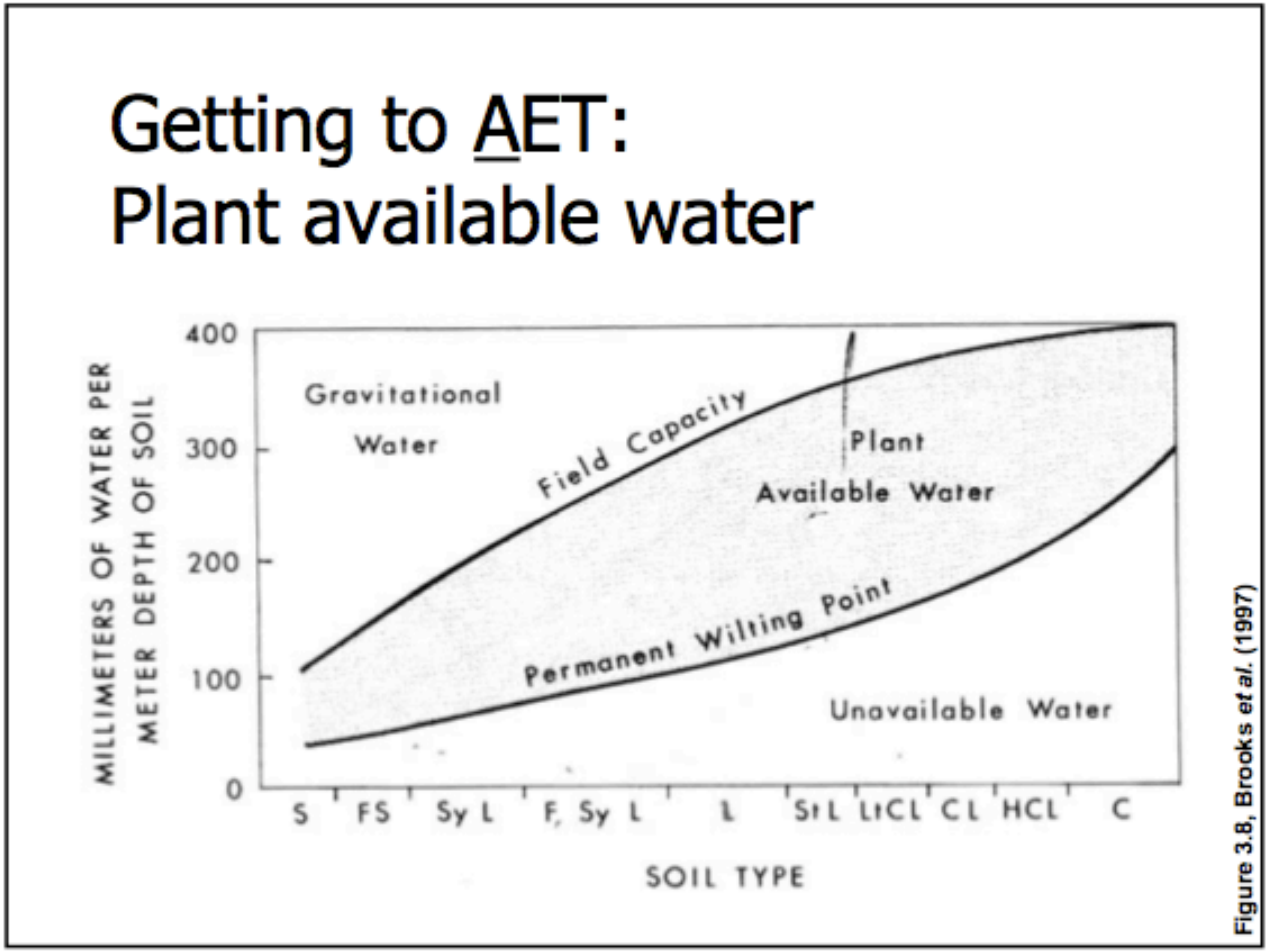
It is the evapotranspiration that occurs when water is available in the quantity and at the pressure required by the tree species in question, and assuming the physiological efficiency of the plant itself.

Actual Evapotranspiration
AET

The water that actually transpires from the plants in the effective existing conditions.

Desert Tree: Low Moisture

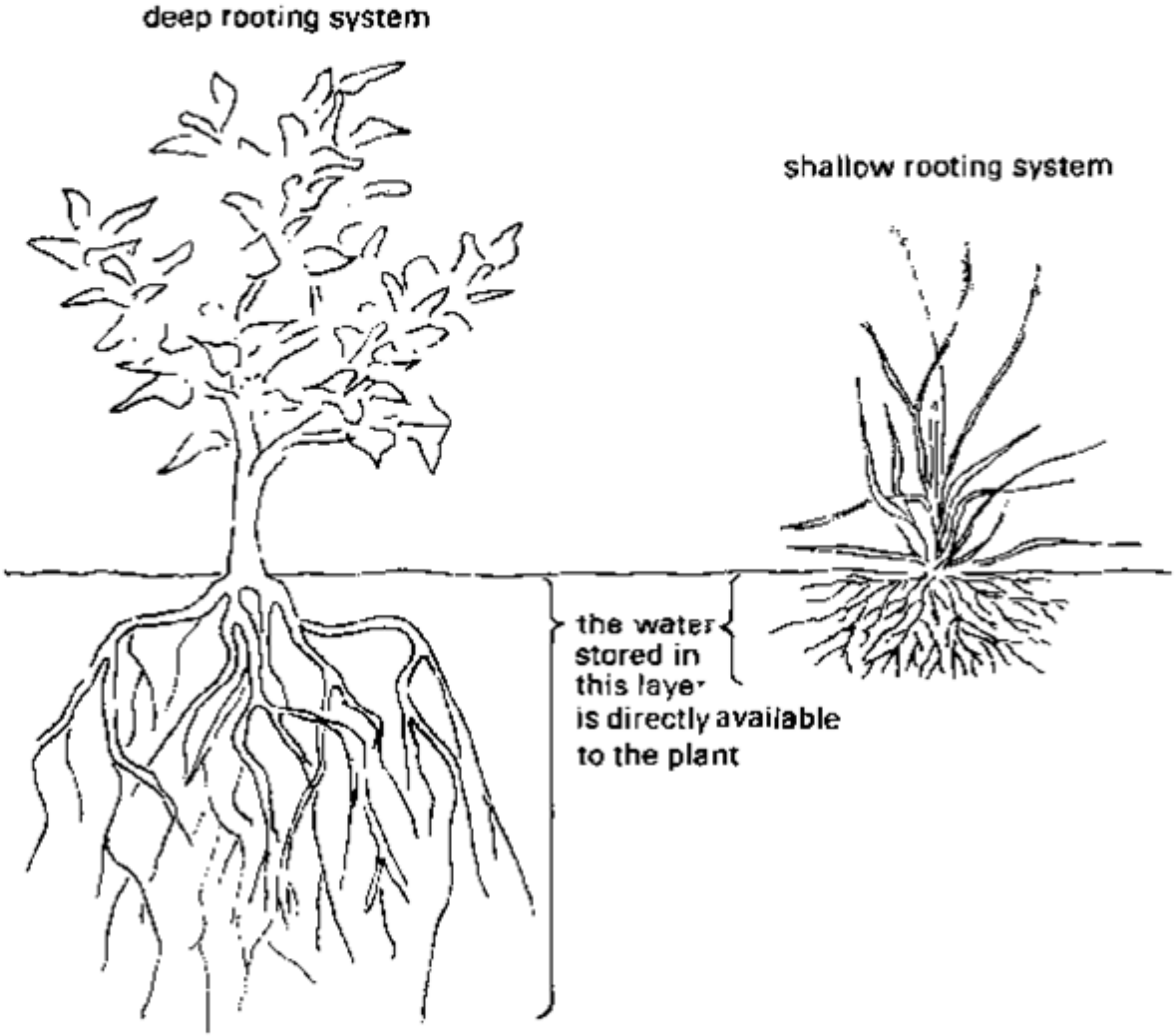
Actual Transpiration



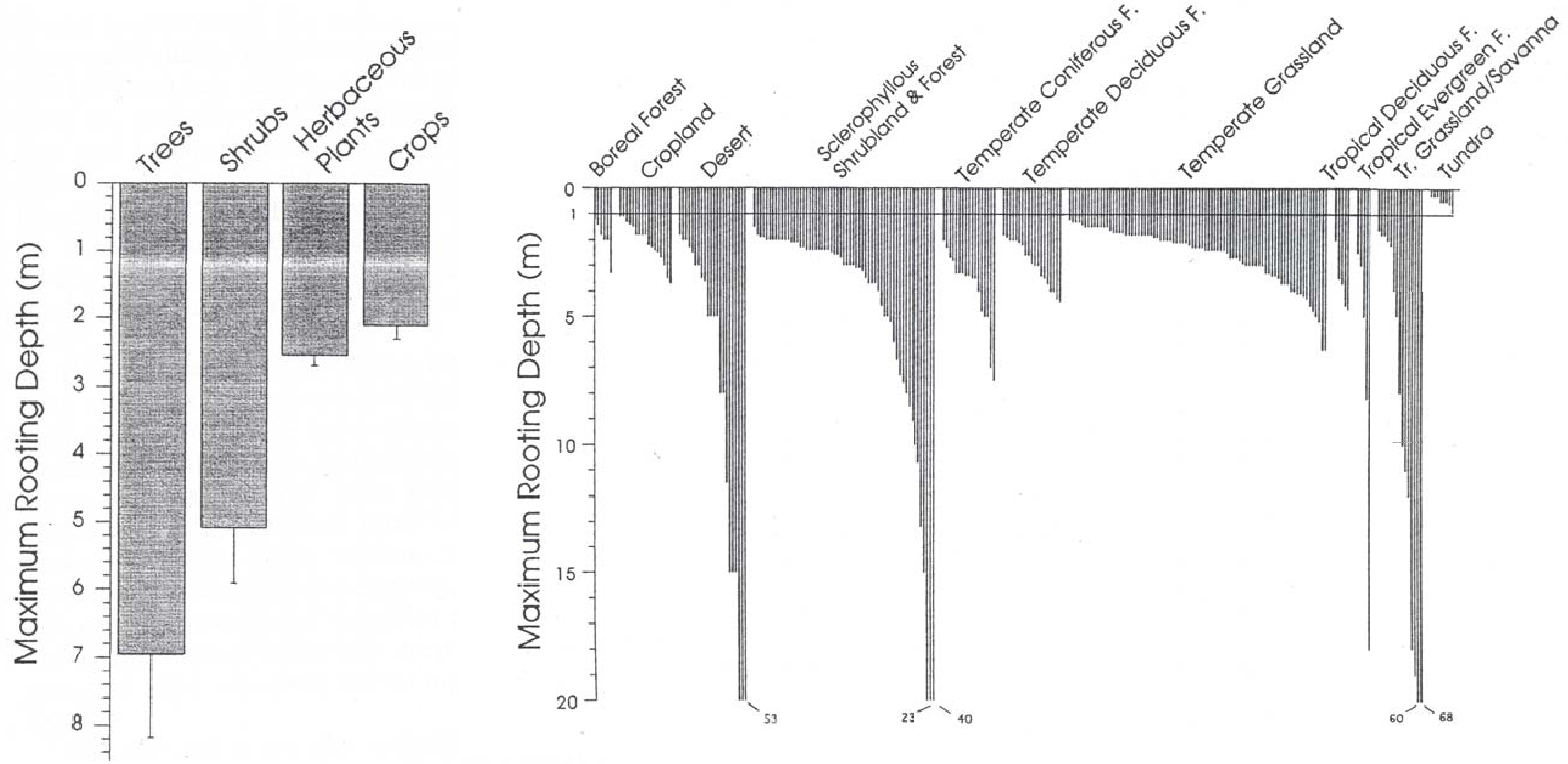
Getting to AET:
Plant available water

Figure 3.8, Brooks *et al.* (1997)

Evapotranspiration - I

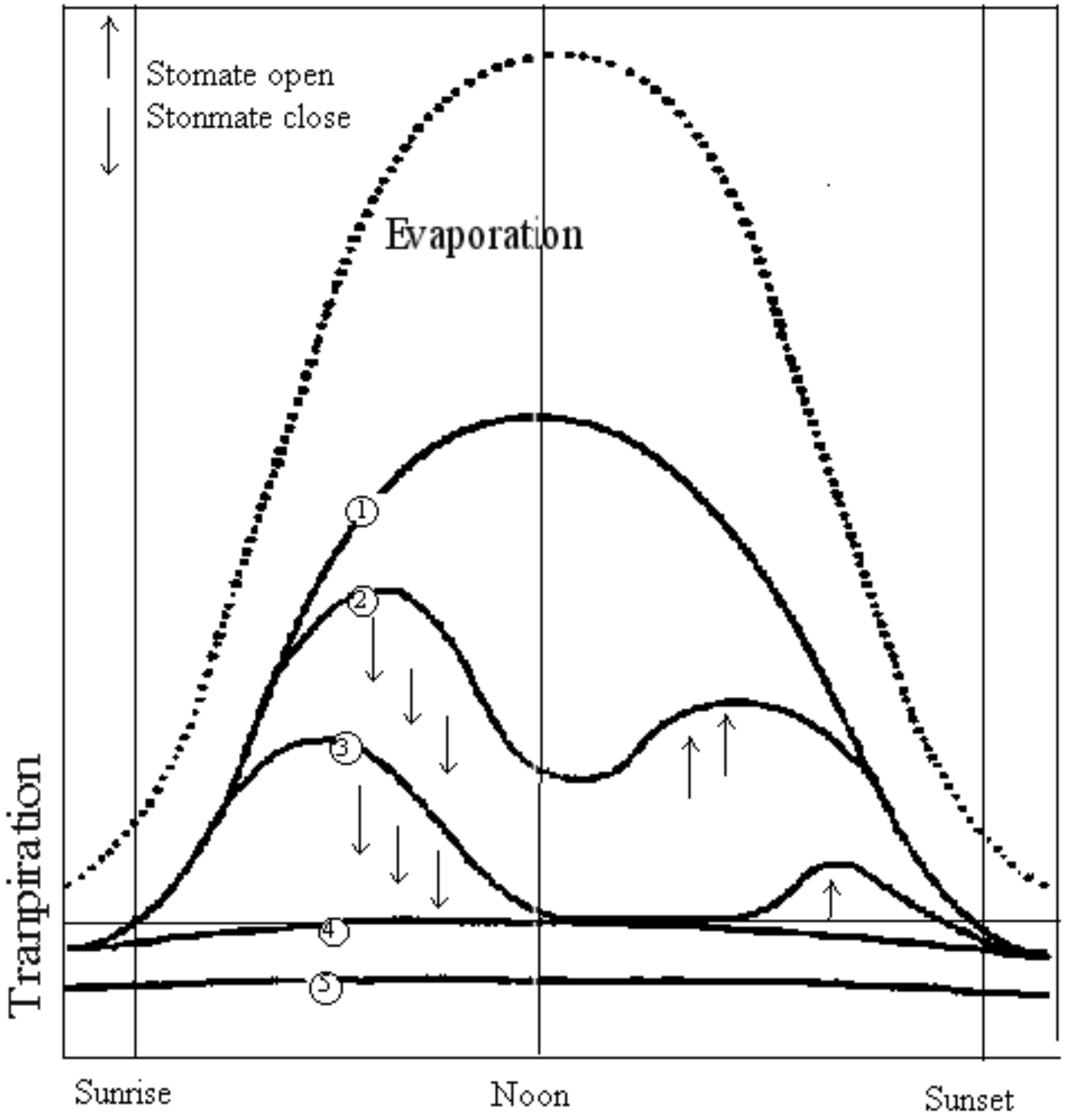


Rooting Depth



ig. 2 Mean and SE of reported maximum rooting depth (m) by ree major functional groups (trees, shrubs, and herbaceous ants) and crops

ource: Canadell, J., R.B. Jackson, J.R. Ehleringer, H.A. Mooney, O.E. Sala, and E.-D. Schulze. 1996. laximum rooting depth of vegetation types at the global scale. Oecologia 108: 583-595.



http://www.ictinternational.com.au/appnotes/ICT101.htm

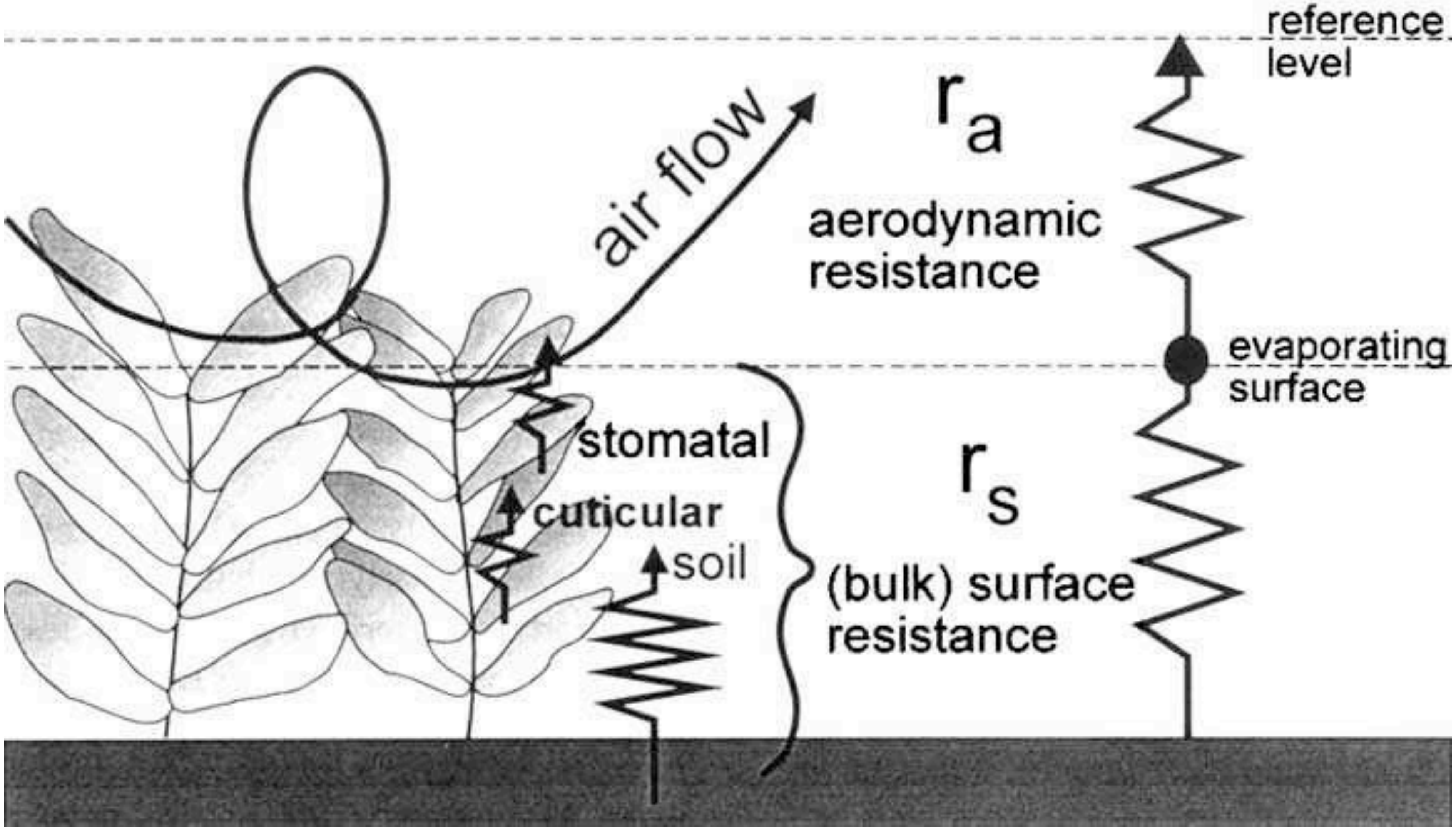
1 no water limitation stomates open
2 some water limitation midday stomatal regulation
3 severe water limitation midday stomatal closure
4 soil dry complete stomatal closure

Evapotranspiration - ET

- Hard to separate evaporative loss from transpiration loss in wilderness situations
- Look at ET (evapotranspiration)
- AET – Actual ET
- PET – Potential ET

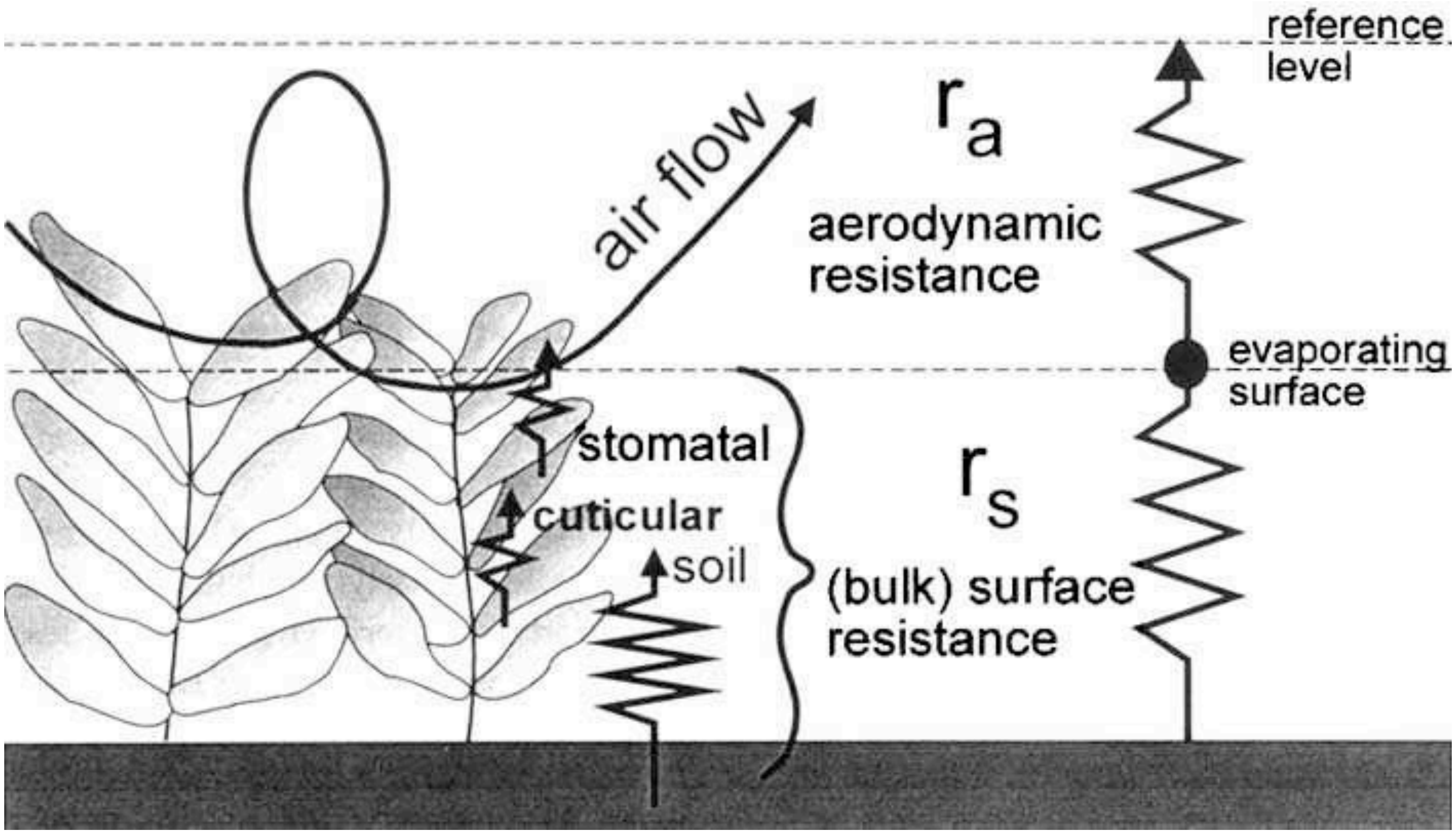
ET

$$\mathrm{ET} = -\rho_v \ \frac{1}{r}(q_r - q_0) = -\rho_v \ C \ (q_r - q_0)$$



ET

$$r = r_a \text{ Evaporation from liquid surfaces}$$
$$r = r_a + r_s \text{ Evaporation from soils}$$
$$r = r_a + r_c \text{ Transpiration from plants}$$



Transpiration

$$E = \rho \frac{1}{r_a + r_c} (q^*(T_L) - q_a)$$

$$r_c = \frac{\langle r_c \rangle}{c \, \mathrm{LAI}}$$

The LAI was first define as the total area of one side of the photosynthesising tissue per unit ground area (Watson, 1947). (Smith, 1991; Bolstad and Gower, 1990) proposed a modification to this parameter by introducing the projected leaf area. In this way the problems due to the shape of leaves and needles was reduced.

Vegetation resistance

For daytime conditions of simulation stb_stn004f
Courtesy of Giacomo Bertoldi

r_c vegetation resistance

r_c =Rs /(LAI * (fS*fee*fT*fM)); (Best, 1998)

Rs minimum stomata resistance (species dependent, but constant over time)

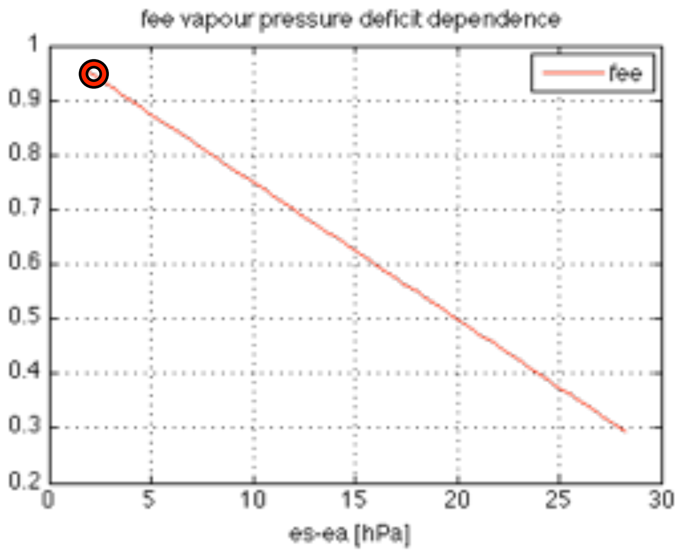
fee water vapour deficit controlling factor

fS solar radiation controlling factor

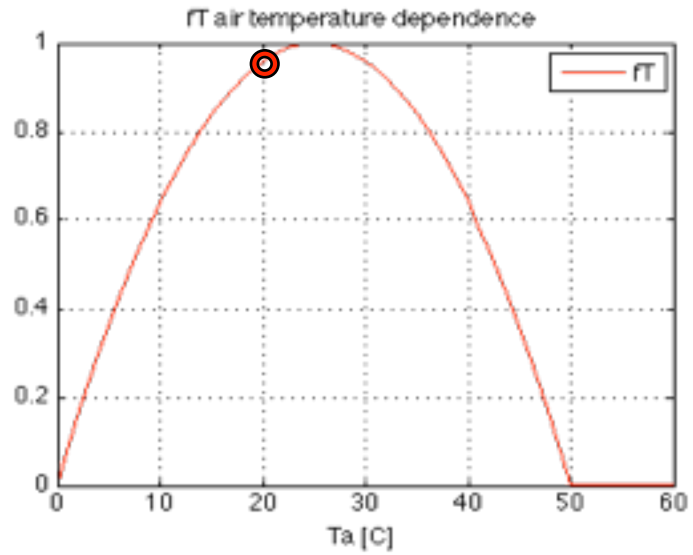
fT temperature controlling factor

Environmental dependencies of stomata conductance

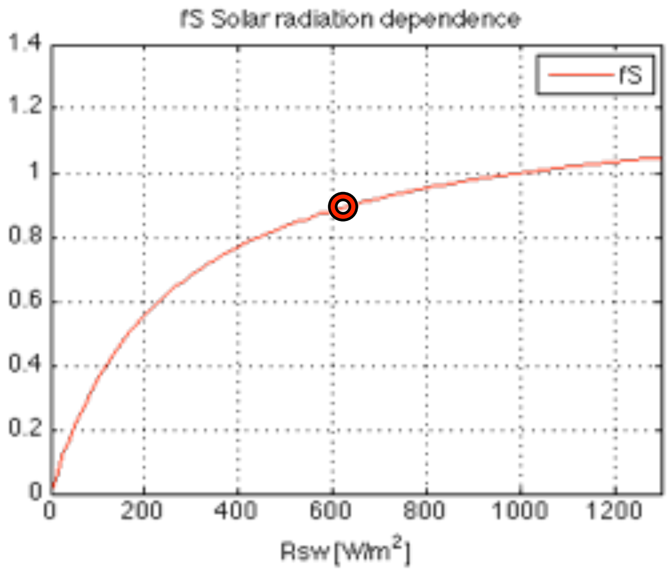
For daytime conditions of simulation stb_stn004f
Courtesy of Giacomo Bertoldi



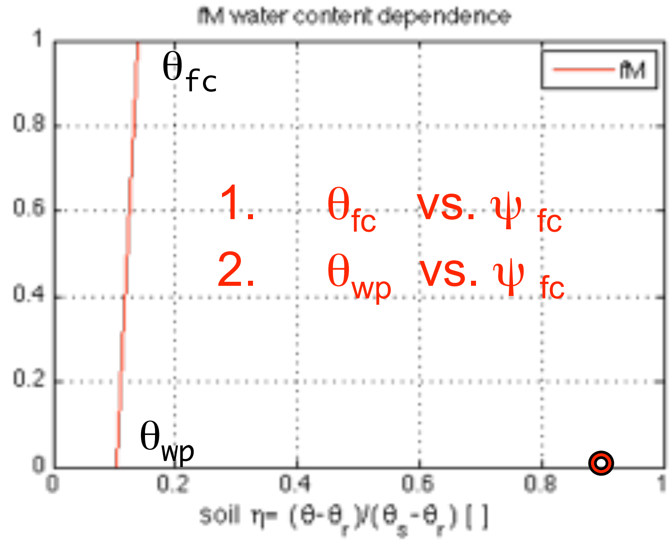
Stomata close for high vapor pressure deficit



Transpiration stop for too high and low Ta

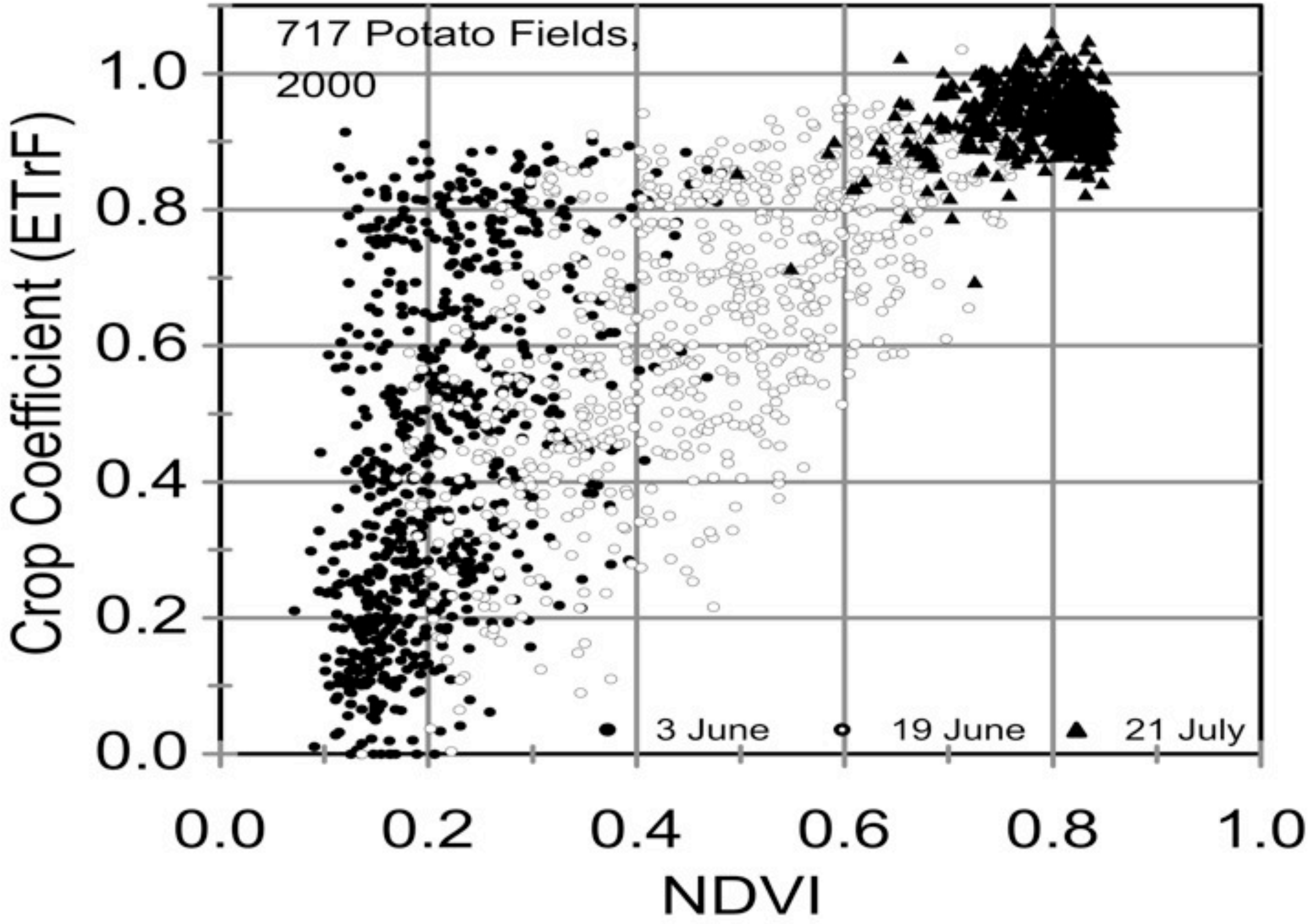


Photosynthesis increases with PaR



Transpiration is decreased below a critical water content

The LAI can be measured by satellite



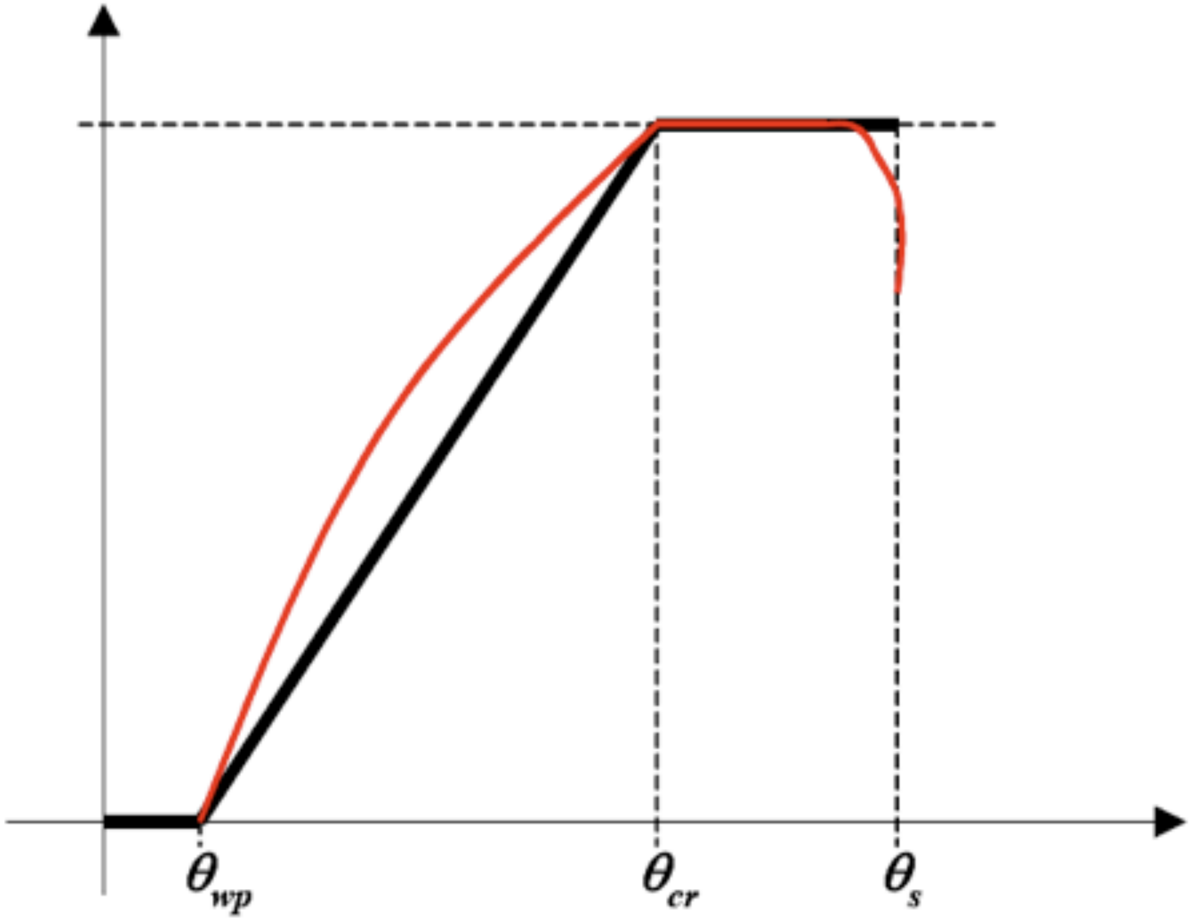
Transpiration

a simplified approach

$$\text{AET} = \beta(\theta)\ \text{ET}$$

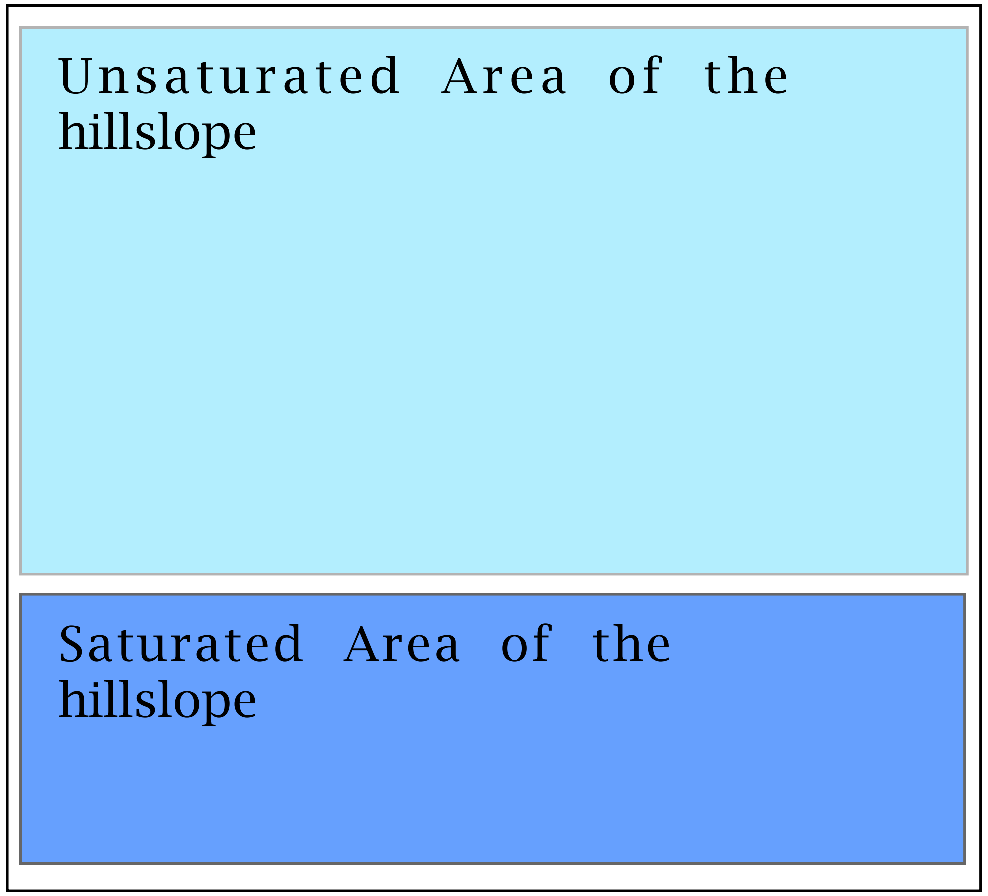
$$\beta(\theta) = \begin{cases} 0 & \theta < \theta_{wp} \\ \frac{\theta - \theta_{wp}}{\theta_{cr} - \theta_{wp}} & \theta_{wp} < \theta < \theta_{cr} \\ 1 & \theta > \theta_{cr} \end{cases}$$

Transpiration



$$\beta(\theta) = \begin{cases} 0 & \theta < \theta_{wp} \\ \frac{\theta-\theta_{wp}}{\theta_{cr}-\theta_{wp}} & \theta_{wp} < \theta < \theta_{cr} \\ 1 & \theta > \theta_{cr} \end{cases}$$

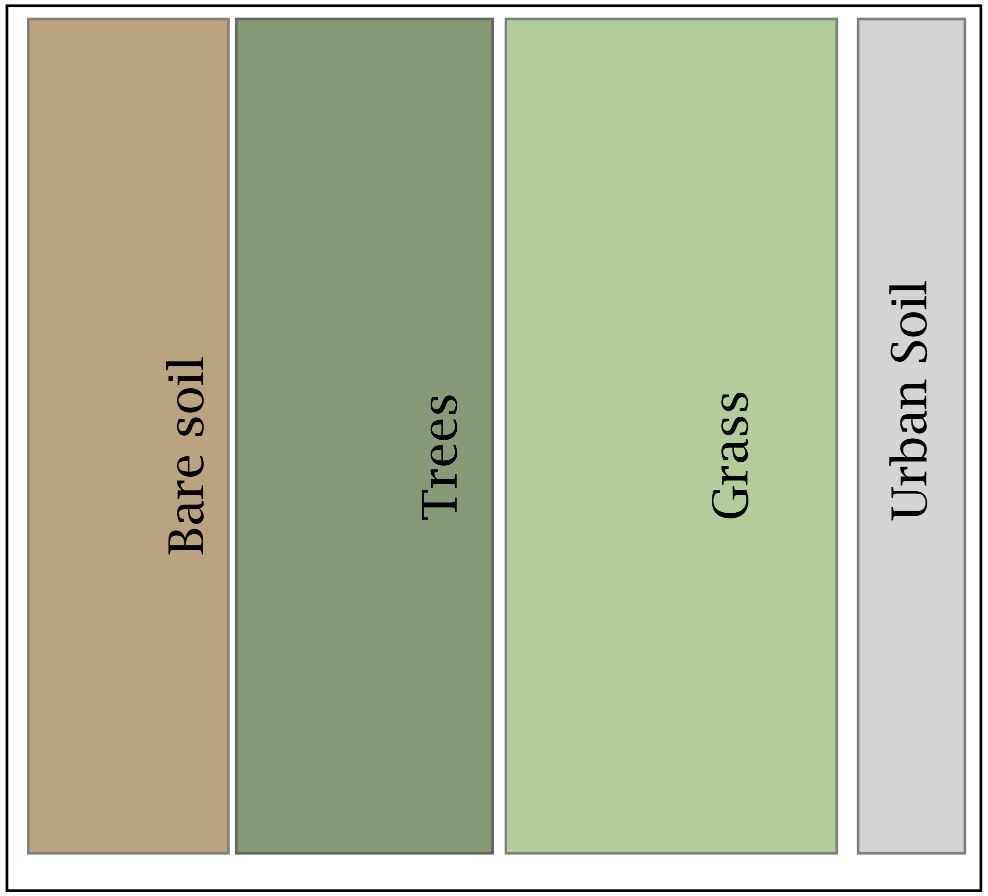
Spatial composition of ET



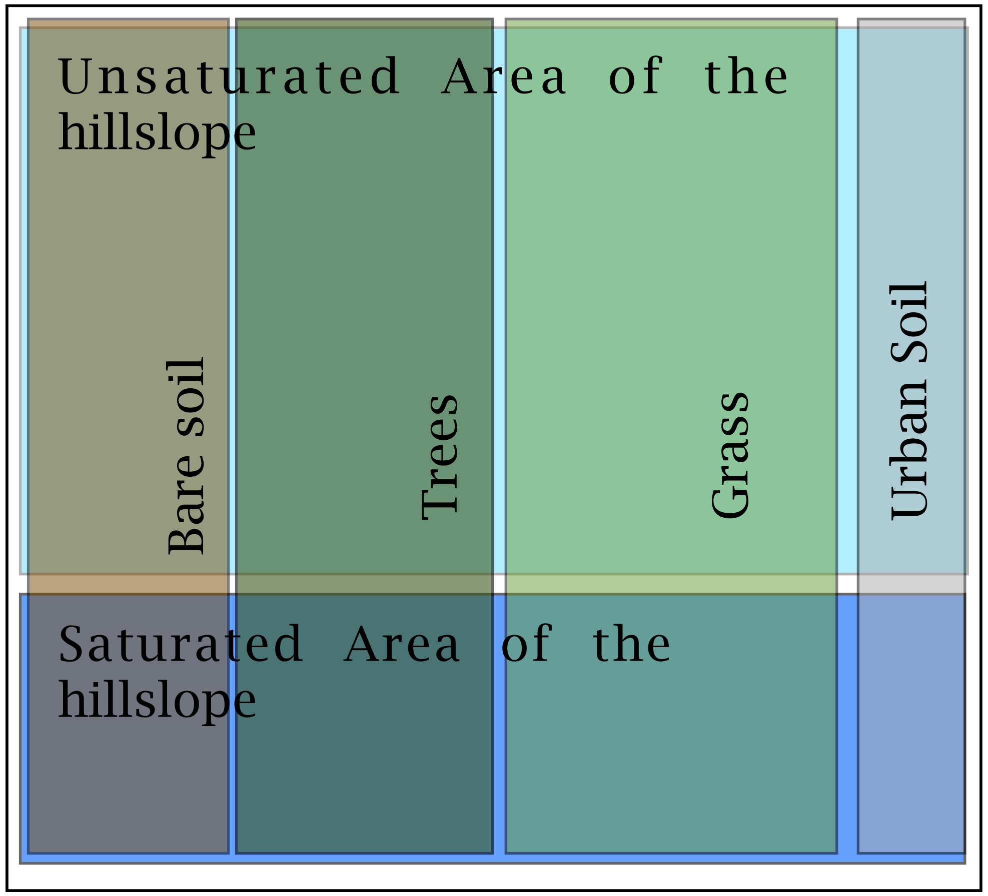
Unsaturated Area of the hillslope

Saturated Area of the hillslope

Spatial composition of ET



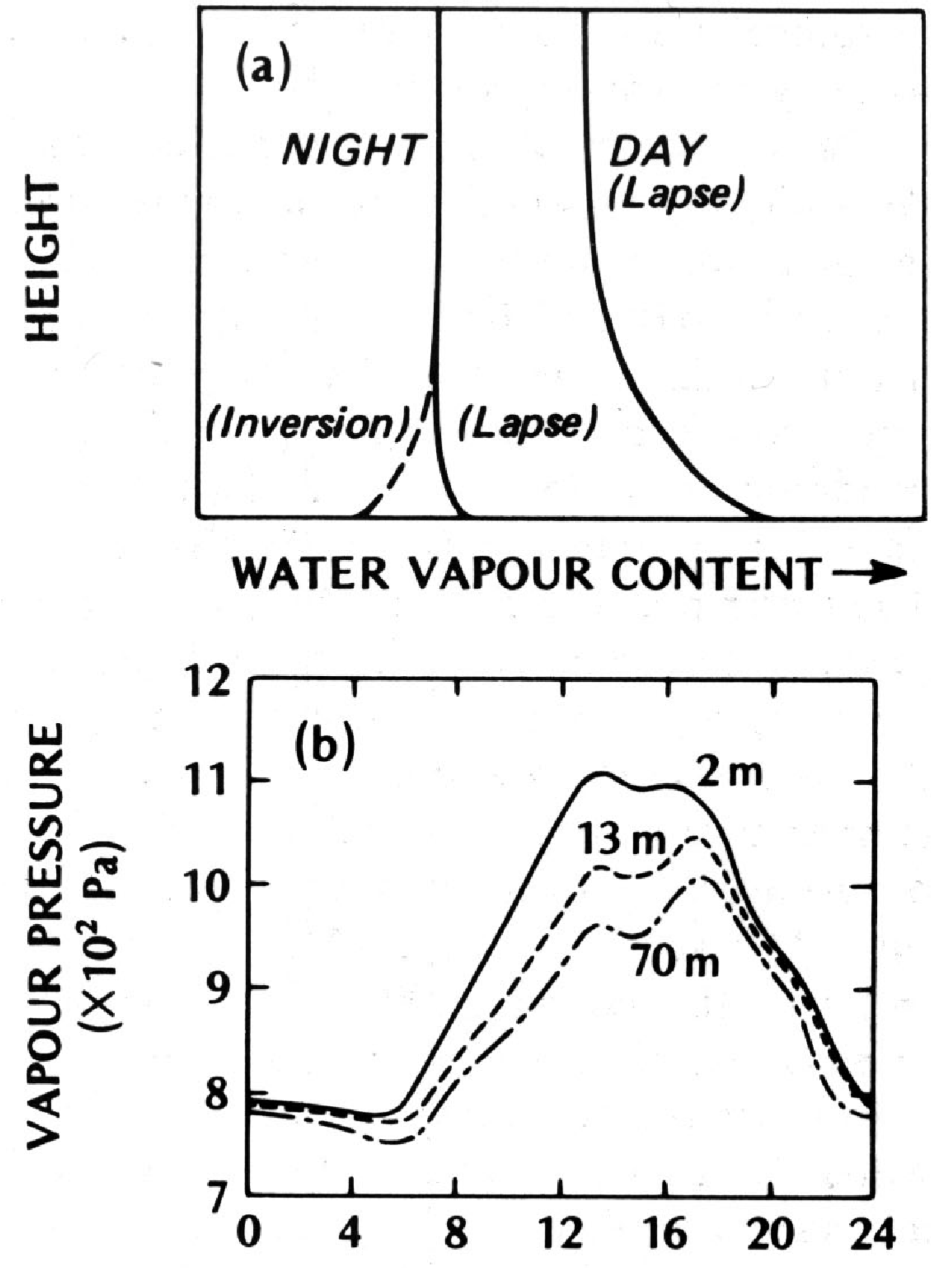
Spatial composition of ET



Soil + Water + Vegetation

$$\mathrm{ET} = E_{soil} + T_{veg} + E_{veg}$$
$$T_{veg} = T_{canopy} + T_{undergrowth}$$
$$E_{suolo} = E_{free\_soil} + E_{soil\_under\_high\_vegetation}$$

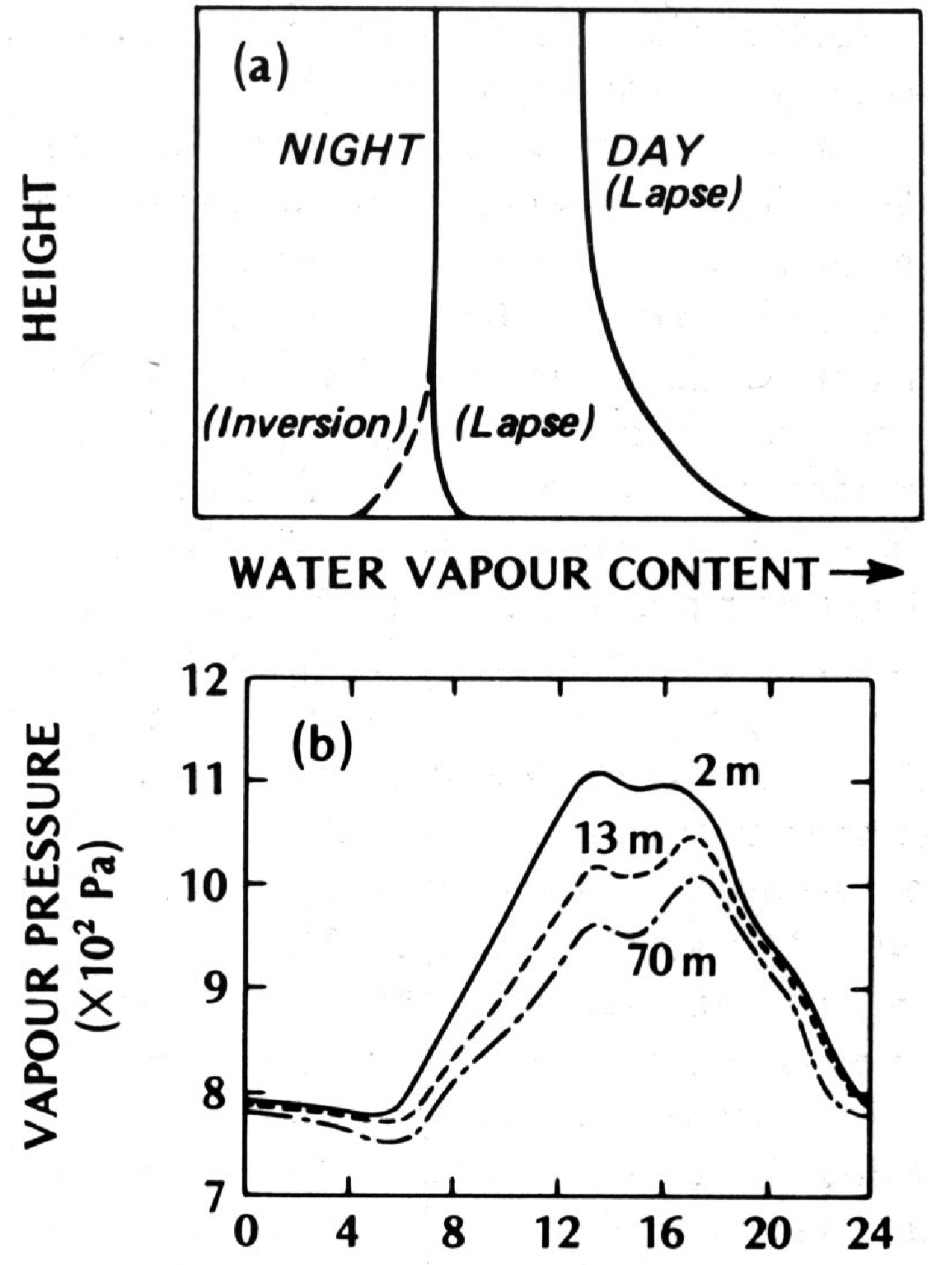
Evapotranspiration at the level of the atmospheric boundary layer



Without looking at the top figure, one could easily think that it represents temperature variation with altitude. Actually it represents the vapour content, which, like temperature, is a **passive tracer**.

Both the first and second graphs illustrate that the effects of evapotranspiration are controlled by the development of the boundary layer.

Evapotranspiration at the level of the atmospheric boundary layer



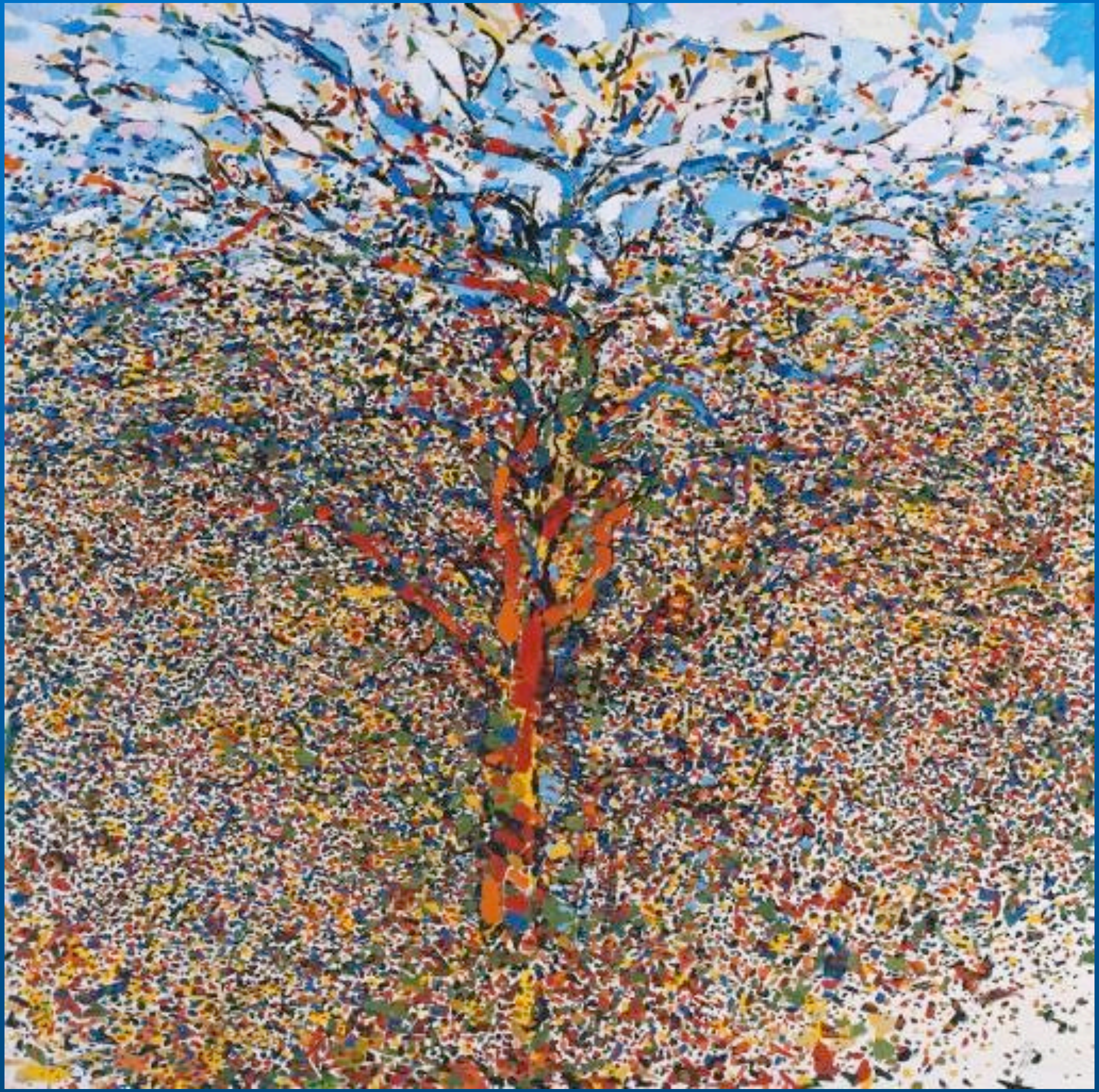
On the other hand, evaporation does contribute to controlling the temperature trend of the soil, and therefore also the development of the boundary layer.

The phenomena are inextricably tied in a non-linear way!

Mass Transfer Approach

- Apply Dalton’s law – see equations 7-18a,b
- Requires measurement of wind speed, surface vapour pressure, and air vapour pressure. None of these are commonly measured.
- Only good over short periods of time
- Gives instantaneous rate
- Ke is highly variable
- Many problems make this technique difficult to apply.

Evapotrasnpiration - II



P. Sutton, Tree, 1958 - Tate Modern

Riccardo Rigon

Summary

Alternative ET estimation methods to the one based on turbulent transfer that has been seen until now.

Evapotranspiration - II

The energy balance

$$R_n = \lambda\,\mathrm{ET} + H + G + P_S$$

The mass balance

$$\frac{dS}{dt} = P - \mathrm{ET} - R - R_G - R_S$$

Dalton’s law

(been there, done that!)

Dalton’s law on its own is not sufficient to determine evapotranspiration. In fact, the energy and mass conservation equations should also be resolved simultaneously:

$$\mathrm{E} = K_e\ V_a(e^*(T_s) - e(T_a))$$

ET

Evapotranspiration must simultaneously satisfy all three equations. The **first equation** limits ET according to the energy available in the environment. The **second** limits in relation to the water mass present in the environment. The **third** represents both the conservation of momentum (of the wind) and the maximisation of entropy (which causes the mixing of vapour in the air).

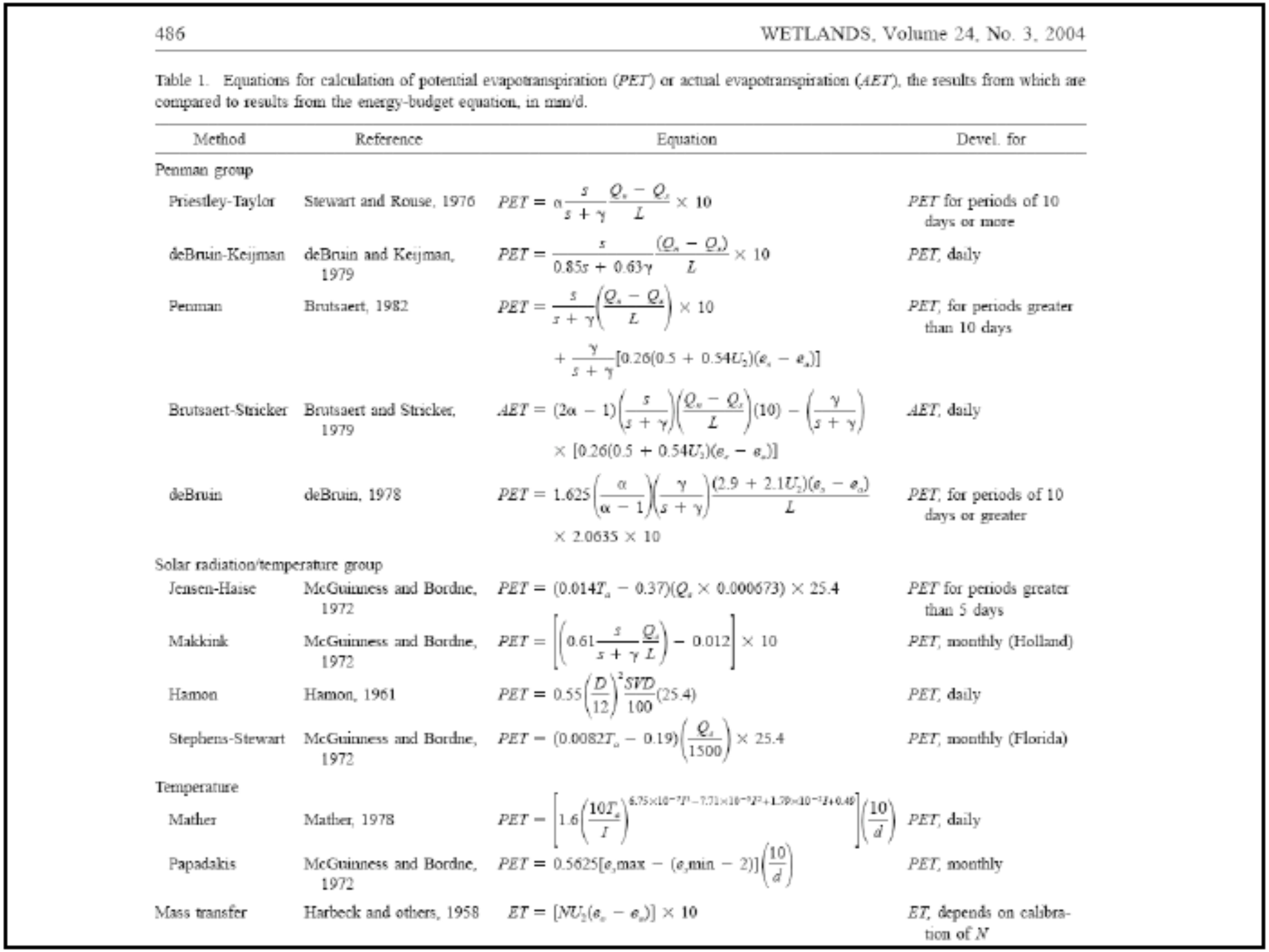
ET

- The mass conservation law is applied in the simplest models with modulating functions, which depend on the soil water content.
- It requires measurements of windspeed and vapour content at the surface and in the air, quantities which are not usually measured.
- Alternatively, these required quantities can be modelled - but that is another story!

ET: in search of simplified solutions

- Penman - Monteith (based on the energy balance)
- Priestley-Taylor (based on the radiation balance)
- Thornthwaite (based on the temperature)
- Hamon, Malstrom (based on the temperature and the vapour pressure)

Evapotranspiration - II



486 WETLANDS, Volume 24, No. 3, 2004

Table 1. Equations for calculation of potential evapotranspiration (*PET*) or actual evapotranspiration (*AET*), the results from which are compared to results from the energy-budget equation, in mm/d.

Method	Reference	Equation	Devel. for
Penman group			
Priestley-Taylor	Stewart and Rouse, 1976	$PET = \alpha \frac{s}{s+\gamma} \frac{Q_n - Q_x}{L} \times 10$	*PET* for periods of 10 days or more
deBruin-Keijman	deBruin and Keijman, 1979	$PET = \frac{s}{0.85s + 0.63\gamma} \frac{(Q_n - Q_x)}{L} \times 10$	*PET*, daily
Penman	Brutsaert, 1982	$PET = \frac{s}{s+\gamma}\left(\frac{Q_n - Q_x}{L}\right) \times 10$ $+ \frac{\gamma}{s+\gamma}[0.26(0.5 + 0.54U_2)(e_s - e_a)]$	*PET*, for periods greater than 10 days
Brutsaert-Stricker	Brutsaert and Stricker, 1979	$AET = (2\alpha - 1)\left(\frac{s}{s+\gamma}\right)\left(\frac{Q_n - Q_x}{L}\right)(10) - \left(\frac{\gamma}{s+\gamma}\right)$ $\times [0.26(0.5 + 0.54U_2)(e_s - e_a)]$	*AET*, daily
deBruin	deBruin, 1978	$PET = 1.625\left(\frac{\alpha}{\alpha - 1}\right)\left(\frac{\gamma}{s+\gamma}\right)\frac{(2.9 + 2.1U_2)(e_s - e_a)}{L}$ $\times 2.0635 \times 10$	*PET*, for periods of 10 days or greater
Solar radiation/temperature group			
Jensen-Haise	McGuinness and Bordne, 1972	$PET = (0.014T_a - 0.37)(Q_s \times 0.000673) \times 25.4$	*PET* for periods greater than 5 days
Makkink	McGuinness and Bordne, 1972	$PET = \left[\left(0.61\frac{s}{s+\gamma}\frac{Q_s}{L}\right) - 0.012\right] \times 10$	*PET*, monthly (Holland)
Hamon	Hamon, 1961	$PET = 0.55\left(\frac{D}{12}\right)^2\frac{SVD}{100}(25.4)$	*PET*, daily
Stephens-Stewart	McGuinness and Bordne, 1972	$PET = (0.0082T_a - 0.19)\left(\frac{Q_s}{1500}\right) \times 25.4$	*PET*, monthly (Florida)
Temperature			
Mather	Mather, 1978	$PET = \left[1.6\left(\frac{10T_a}{I}\right)^{6.75\times10^{-7}I^3 - 7.71\times10^{-5}I^2 + 1.79\times10^{-2}I + 0.49}\right]\left(\frac{10}{d}\right)$	*PET*, daily
Papadakis	McGuinness and Bordne, 1972	$PET = 0.5625[e_s\max - (e_s\min - 2)]\left(\frac{10}{d}\right)$	*PET*, monthly
Mass transfer	Harbeck and others, 1958	$ET = [NU_2(e_o - e_a)] \times 10$	*ET*, depends on calibration of *N*

Penman - Monteith

The first step in obtaining the Penman -Monteith equation is to approximate the saturated humidity of the soil with the saturated humidity of the air, by using a Taylor expansion of temperature:

$$q*(T_s) = q*(T_a) \; + \; (T_s - T_a) + O((T_s - T_a)^2)$$

from which:

$$\mathrm{ET} = \rho \frac{1}{r_a + r_g}(q^*(T_a) + [\frac{dq^*}{dT}]_{T=T_a}(T_s - T_a) - q_a)$$

Penman - Monteith

$$\mathrm{ET} = \rho \frac{1}{r_a + r_g} (q^*(T_a) + [\frac{dq^*}{dT}]_{T=T_a} (T_s - T_a) - q_a)$$

The derivative of the saturated specific humidity is a **Clausius-Clapeyron** relation:

$$\frac{dq^*}{dT} = \frac{\epsilon}{p} \Delta$$

$$\Delta = \frac{de^*}{dT} \qquad \Delta = \frac{25083}{(T + 273.3)^2} e^{\frac{17.3\ T}{T+273.3}} \quad \mathrm{mb}\ {}^\circ\mathrm{C}^{-1}$$

Penman - Monteith

$$\mathrm{ET} = \rho \frac{1}{r_a + r_g} (q^*(T_a) + [\frac{dq^*}{dT}]_{T=T_a} (T_s - T_a) - q_a)$$

To eliminate the soil temperature the sensible heat transfer law is used, which has a form similar to the law of latent heat transfer:

$$H = \rho \; c_p \frac{1}{r_a} (T_s - T_a)$$

Penman - Monteith

$$\mathrm{ET} = \rho \frac{1}{r_a + r_g}(q^*(T_a) + [\frac{dq^*}{dT}]_{T=T_a}(T_s - T_a) - q_a)$$

To eliminate the soil temperature the sensible heat transfer law is used, which has a form similar to the law of latent heat transfer:

$$H = \rho\ c_p \frac{1}{r_a}(T_s - T_a)$$

$$H = R_n - G - \lambda \mathrm{ET}$$

Penman - Monteith

$$\text{ET} = \rho \frac{1}{r_a + r_g}(q^*(T_a) + [\frac{dq^*}{dT}]_{T=T_a}(T_s - T_a) - q_a)$$

$$H = \rho \; c_p \frac{1}{r_a}(T_s - T_a)$$

Rather than express ET in terms of latent heat it is preferable to express it in terms of the radiative forcing by means of the stationary energy balance:

$$H = R_n - G - \lambda \text{ET}$$

Penman - Monteith

Let us also define the **psychrometric constant**:

$$\gamma \equiv \frac{p\ c_p}{\epsilon\lambda}$$

And the **humidity deficit**:

$$\delta q_a \equiv q^*(T_a) - q_a$$

Penman - Monteith

In this way we obtain:

$$\mathrm{ET} = \rho \frac{1}{r_a + r_g} \left(\delta q_a + \frac{\Delta}{\gamma} \frac{1}{\lambda \rho} r_a (R_n - G - \lambda\ \mathrm{ET}) \right)$$

and then:

$$\mathrm{ET}(1 + \frac{r_a}{r_a + r_g} \frac{\Delta}{\gamma}) = \rho \frac{1}{r_a + r_g} \left(\delta q_a + \frac{\Delta}{\gamma} \frac{1}{\lambda \rho} r_a (R_n - G) - q_a \right)$$

Penman - Monteith

Finally, there results:

$$\lambda\ \mathrm{ET} = \frac{\frac{\Delta}{\gamma}(R_n - G) + \frac{\rho\lambda}{r_a}\delta q_a}{(1 + \frac{\Delta}{\gamma} + \frac{r_g}{r_a})}$$

Penman - Monteith

$$\lambda\ \mathrm{ET} = \frac{\frac{\Delta}{\gamma}(R_n - G)}{(1 + \frac{\Delta}{\gamma} + \frac{r_g}{r_a})} + \frac{\frac{\rho\lambda}{r_a}\delta q_a}{(1 + \frac{\Delta}{\gamma} + \frac{r_g}{r_a})}$$

Penman - Monteith

$$\lambda\ \mathrm{ET} = \boxed{\frac{\frac{\Delta}{\gamma}(R_n - G)}{(1 + \frac{\Delta}{\gamma} + \frac{r_g}{r_a})}} + \frac{\frac{\rho\lambda}{r_a}\delta q_a}{(1 + \frac{\Delta}{\gamma} + \frac{r_g}{r_a})}$$

This term depends on the energy availability

Penman - Monteith

$$\lambda\ \mathrm{ET} = \boxed{\frac{\frac{\Delta}{\gamma}(R_n - G)}{(1 + \frac{\Delta}{\gamma} + \frac{r_g}{r_a})}} + \boxed{\frac{\frac{\rho\lambda}{r_a}\delta q_a}{(1 + \frac{\Delta}{\gamma} + \frac{r_g}{r_a})}}$$

This term depends on the energy availability

This term depends on the saturation deficit

Penman - Monteith: what is required to use it ?

$$\lambda \ \mathrm{ET} = \frac{\frac{\Delta}{\gamma}(R_n - G)}{(1 + \frac{\Delta}{\gamma} + \frac{r_g}{r_a})} + \frac{\frac{\rho\lambda}{r_a}\delta q_a}{(1 + \frac{\Delta}{\gamma} + \frac{r_g}{r_a})}$$

Δ the derivative of the Clausius Clapeyron law: known if air temperature is known

γ: known from the water properties and if the atmospheric pressure is known

δq_a: known if the air temperature is known (for the saturated specific humidity) and the air humidity is known

Penman - Monteith: what is required to use it ?

$$\lambda \text{ ET} = \frac{\frac{\Delta}{\gamma}(R_n - G)}{(1 + \frac{\Delta}{\gamma} + \frac{r_g}{r_a})} + \frac{\frac{\rho\lambda}{r_a}\delta q_a}{(1 + \frac{\Delta}{\gamma} + \frac{r_g}{r_a})}$$

r_a the aerodynamic resistance, known if the windspeed and the equivalent roughness of the surface (function of the height of vegetation and buildings) are known

r_g the resistance to evaporation induced by the soil: it can be estimated if the soil water content is known

r_v the resistance to transpiration by the vegetation. It is a function, in an initial approximation, of the soil water content or other, more complex, formulations linked to plant physiology and the density of the foliar apparatus

Penman - Monteith: what is required to use it ?

$$\lambda \text{ ET} = \frac{\frac{\Delta}{\gamma}(R_n - G)}{(1 + \frac{\Delta}{\gamma} + \frac{r_g}{r_a})} + \frac{\frac{\rho\lambda}{r_a}\delta q_a}{(1 + \frac{\Delta}{\gamma} + \frac{r_g}{r_a})}$$

R_n the net radiation at the surface, it requires astronomical calculations, evaluations of shading and view angle, and estimates of the attenuation of the extra-atmospheric radiation by the atmosphere.

G, the flux of heat towards the centre of the Earth, proportional to R_n and often set equal to 0 on a daily scale.

Penman - Monteith: what is required to use it ?

$$\lambda\ \mathrm{ET} = \frac{\frac{\Delta}{\gamma}(R_n - G)}{(1 + \frac{\Delta}{\gamma} + \frac{r_g}{r_a})} + \frac{\frac{\rho\lambda}{r_a}\delta q_a}{(1 + \frac{\Delta}{\gamma} + \frac{r_g}{r_a})}$$

Allen et al. (1998), FAO Irrigation and drainage Paper pp. 300, is a very precise review of how to obtain reasonable estimates of all the quantities cited, at least in the case of agricultural crops. **N.B. in order to evaluate the required quantities it is necessary to spatially extend the values of measurements obtained in single points.**

Penman - Monteith

If the soil is well irrigated or the plants do not offer resistance to transpiration, then rc = rg = 0 and the evapotranspiration is potential. There results:

$$\lambda\ \mathrm{PET} = \frac{\frac{\Delta}{\gamma}(R_n - G)}{(1+\frac{\Delta}{\gamma})} + \frac{\frac{\rho\lambda}{r_a}\delta q_a}{(1+\frac{\Delta}{\gamma})}$$

Penman - Monteith

The ratio of potential evaporation to effective evaporation (efficiency of the evaporating or transpiring surface) is then given by:

$$\beta = \frac{\lambda E}{\lambda E_p} = \frac{1 + \frac{\Delta}{\gamma}}{1 + \frac{\Delta}{\gamma} + \frac{r}{r_a}}$$

Bowen ratio

The ratio of sensible heat to latent heat is called the Bowen ration. It is expressed as:

$$\mathrm{B} = \gamma \frac{T_s - T_a}{es - ea}$$

Penman - simplified FAO version

It is a simplified formulation of the Penman equation that has been widespread. As opposed to the PM equation, it uses daily average data.

Doreenbos and Pruitt, 1977

$$ET = c\left(\frac{\Delta}{\Delta+\gamma}R_n + \frac{\gamma}{\Delta+\gamma}W_f(q_s - q)\right)$$

$$W_f = 0.27\left(1 + \frac{u_2}{100}\right)$$

Priestley- Taylor (1972)

It is a semi-empirical formulation that neglects the specific humidity deficit and the resistances, adding, however, a proportionality factor in the expression:

$$\lambda\ \mathrm{ET} = \alpha \frac{\frac{\Delta}{\gamma}(R_n - G)}{(1 + \frac{\Delta}{\gamma})}$$

Priestley- Taylor (1972)

$$\lambda \ \mathrm{ET} = \alpha \frac{\frac{\Delta}{\gamma}(R_n - G)}{(1 + \frac{\Delta}{\gamma})}$$

For its use, evidently, the estimation of the specific humidity is not required. However, there is a parameter, which is suggested as having value 1.2-1.3, that becomes a calibration parameter when this formula is used in water balance models

For the calculation of ET

one can also use the mass and energy equations

From the energy balance

Evapotranspiration - III

From the energy balance

$$\lambda\ \mathrm{ET} = Rn - H - G - P_S$$

Evapotranspiration - III

From the energy balance

$$\lambda\ \mathrm{ET} = Rn - H - G - P_S$$

From the mass balance

Evapotranspiration - III

From the energy balance

$$\lambda \, \mathrm{ET} = Rn - H - G - P_S$$

From the mass balance

$$\mathrm{ET} = \frac{dS}{dt} - P - R + R_S + R_G$$

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- It is difficult to apply in the case of vey big waterbodies

From the mass balance

$$\mathrm{ET} = \frac{dS}{dt} - P - R + R_S + R_G$$

- It is difficult to apply in the case of vey big waterbodies

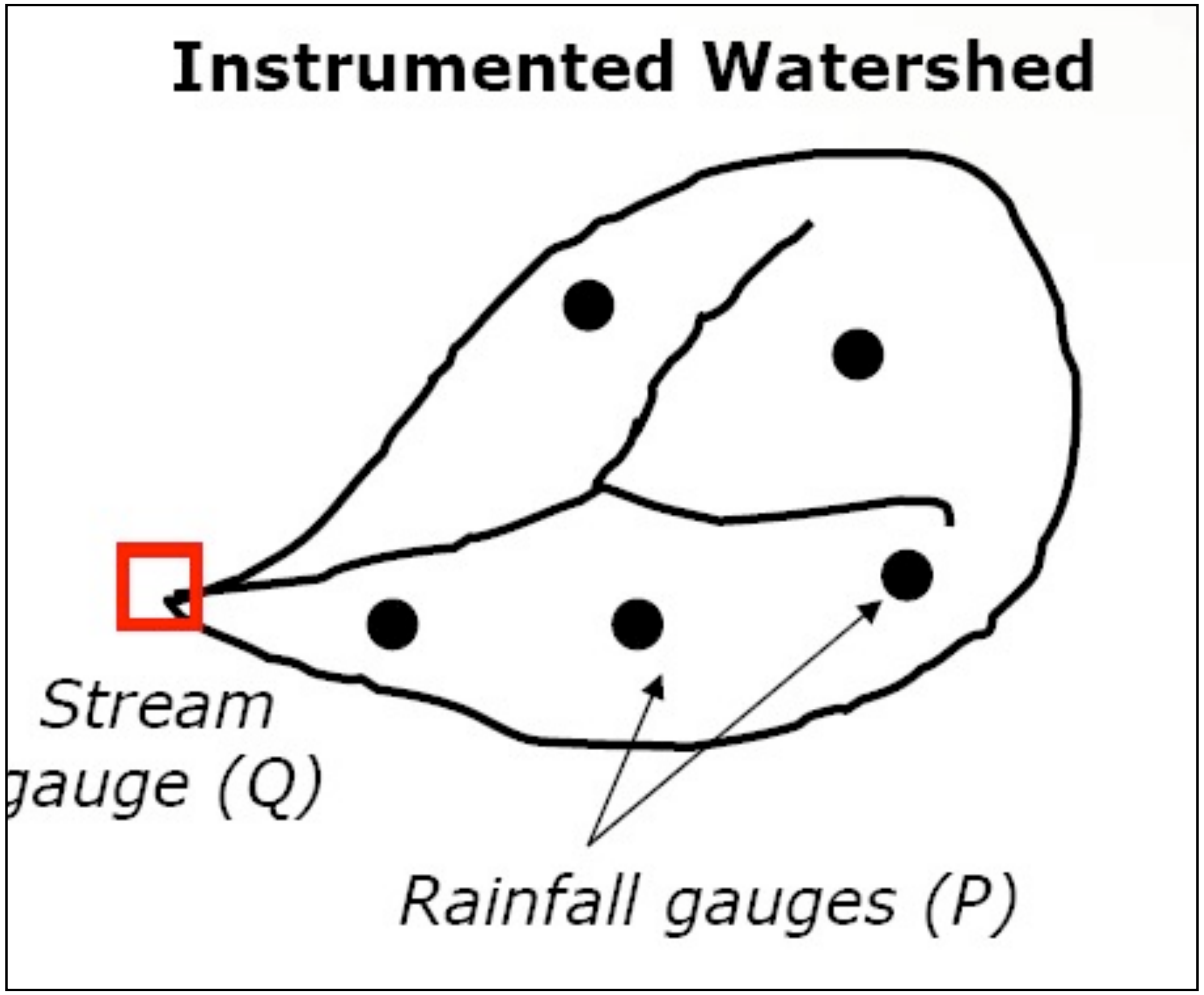
- Its reliability increases as the integration time interval increases

For waterbodies of intermediate size

Watershed water balance method applied for large regions and long time periods.

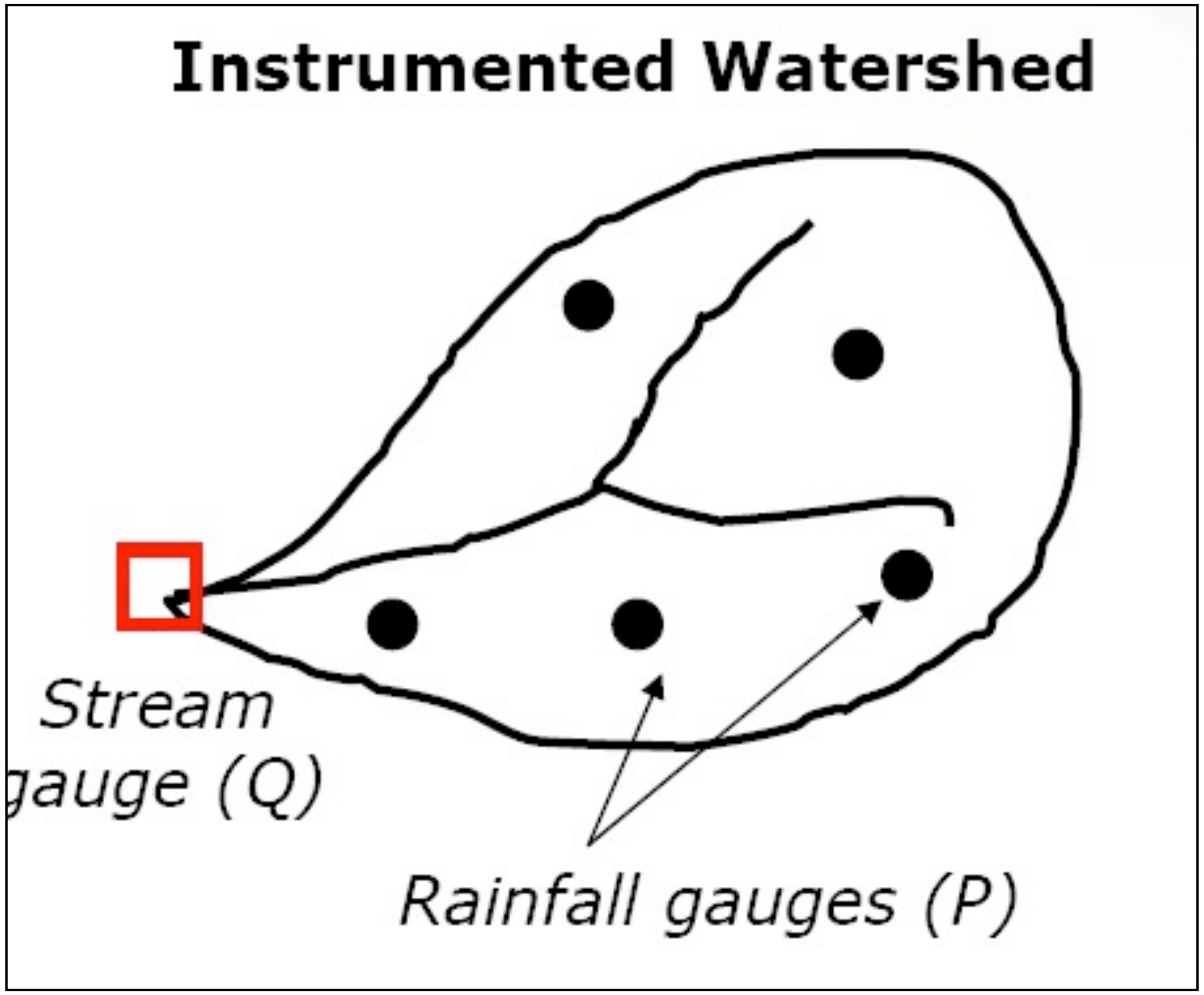
For waterbodies of intermediate size

Watershed water balance method applied for large regions and long time periods.



For waterbodies of intermediate size

Watershed water balance method applied for large regions and long time periods.



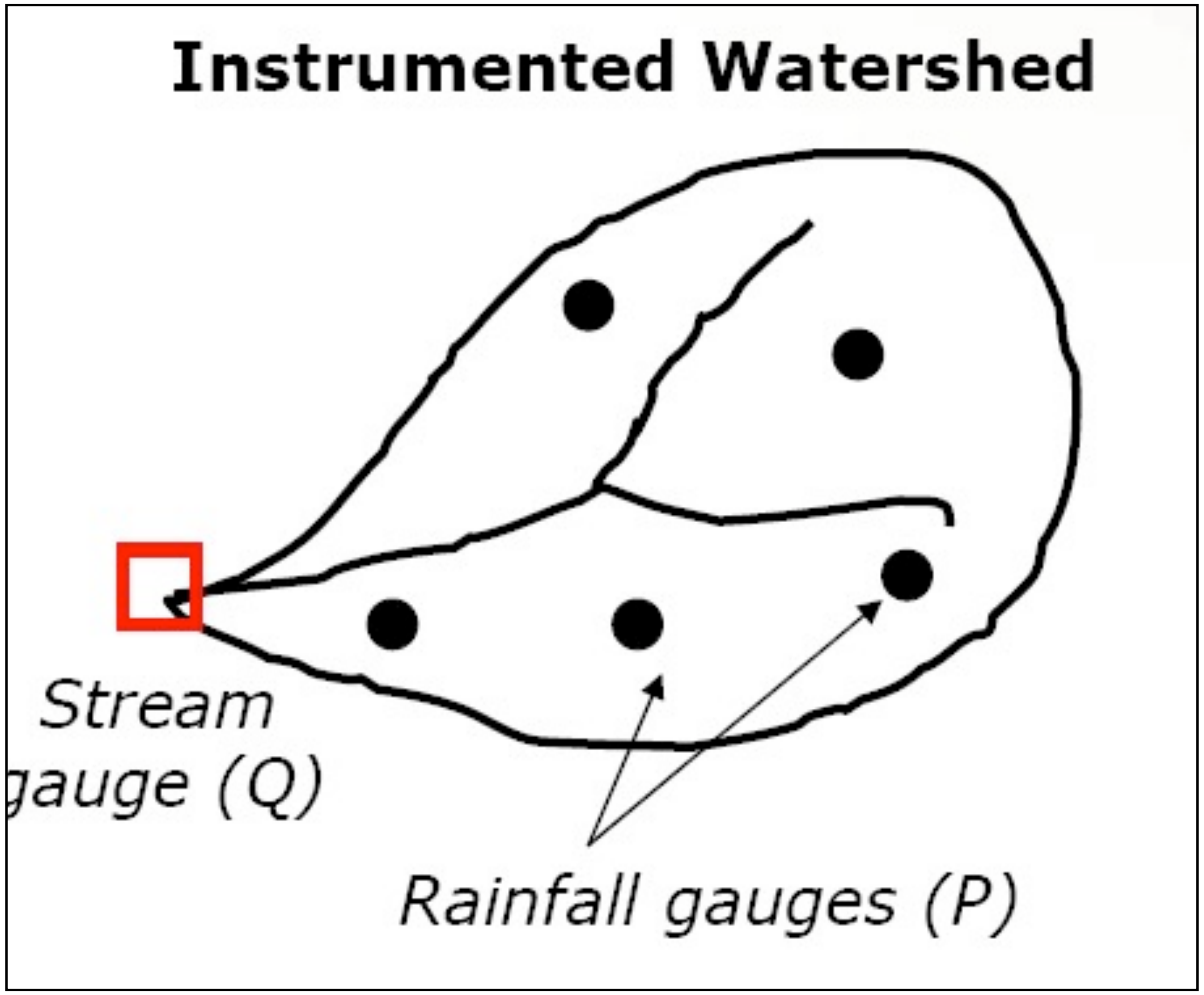
Measurement over a watershed can be used to estimate actual evaporation (ET_a) over large areas.

$$E_a = P - Q \pm \Delta G \pm \Delta\theta$$

angles in groundwater (G) and soil water (θ)

For waterbodies of intermediate size

Watershed water balance method applied for large regions and long time periods.



Measurement over a watershed can be used to estimate actual evaporation (ETa) over large areas.

$$E_a = P - Q \pm \Delta G \pm \Delta\theta$$

angles in groundwater (G) and soil water (θ)

For long-term estimates with no changes in storage (G or θ)

$$E_a = P - Q$$

From the energy balance

$$\lambda\ \mathrm{ET} = Rn - H - G - P_S$$

- It is difficult to apply but there are some interesting aspects

$$\mathrm{ET} = \frac{dS}{dt} - P - R + R_S + R_G + A_w$$

- Probably, in this case, it is necessary to also take account of energy advection

From the energy balance

Gay and Bernofer, 1991

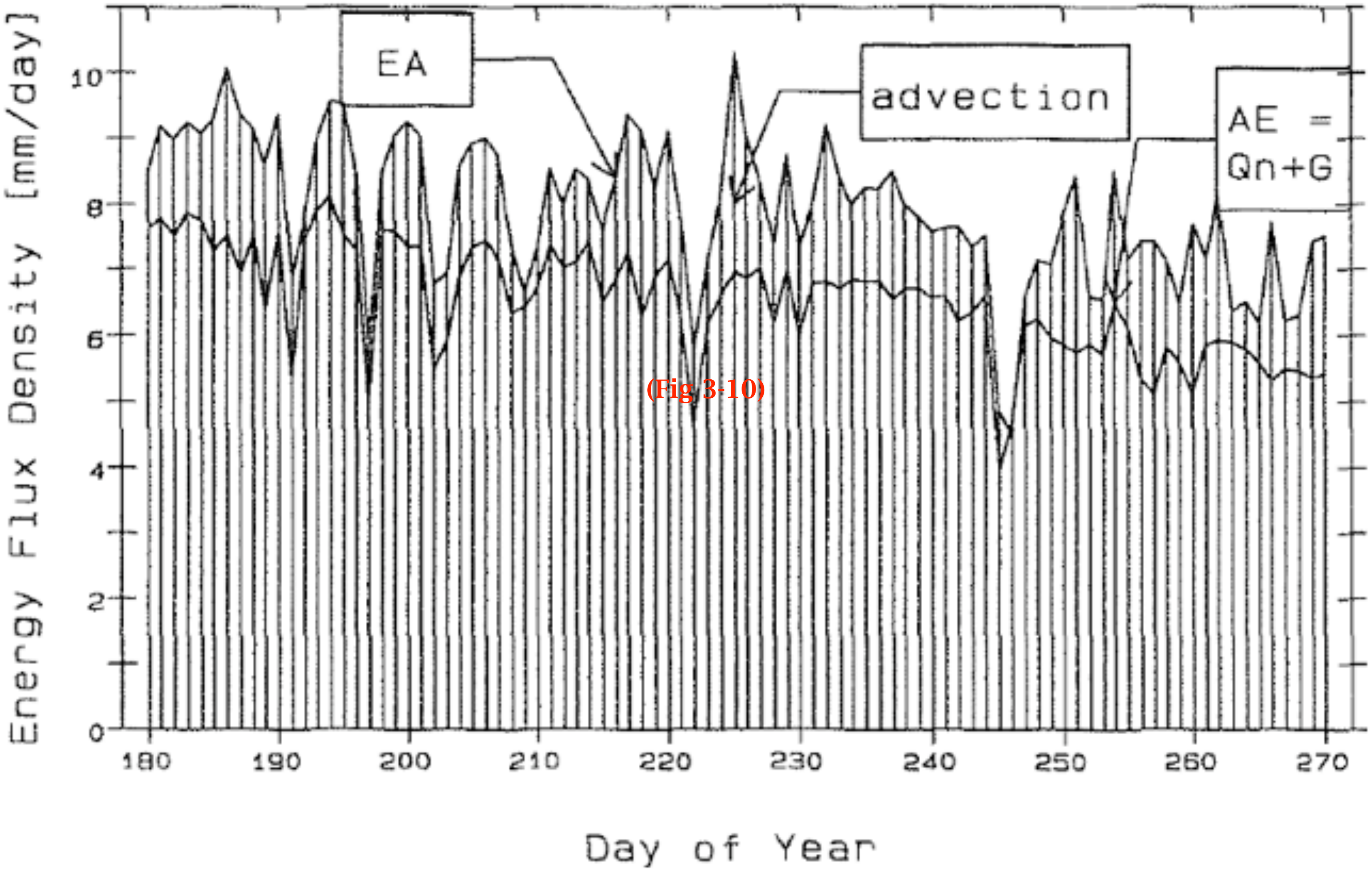
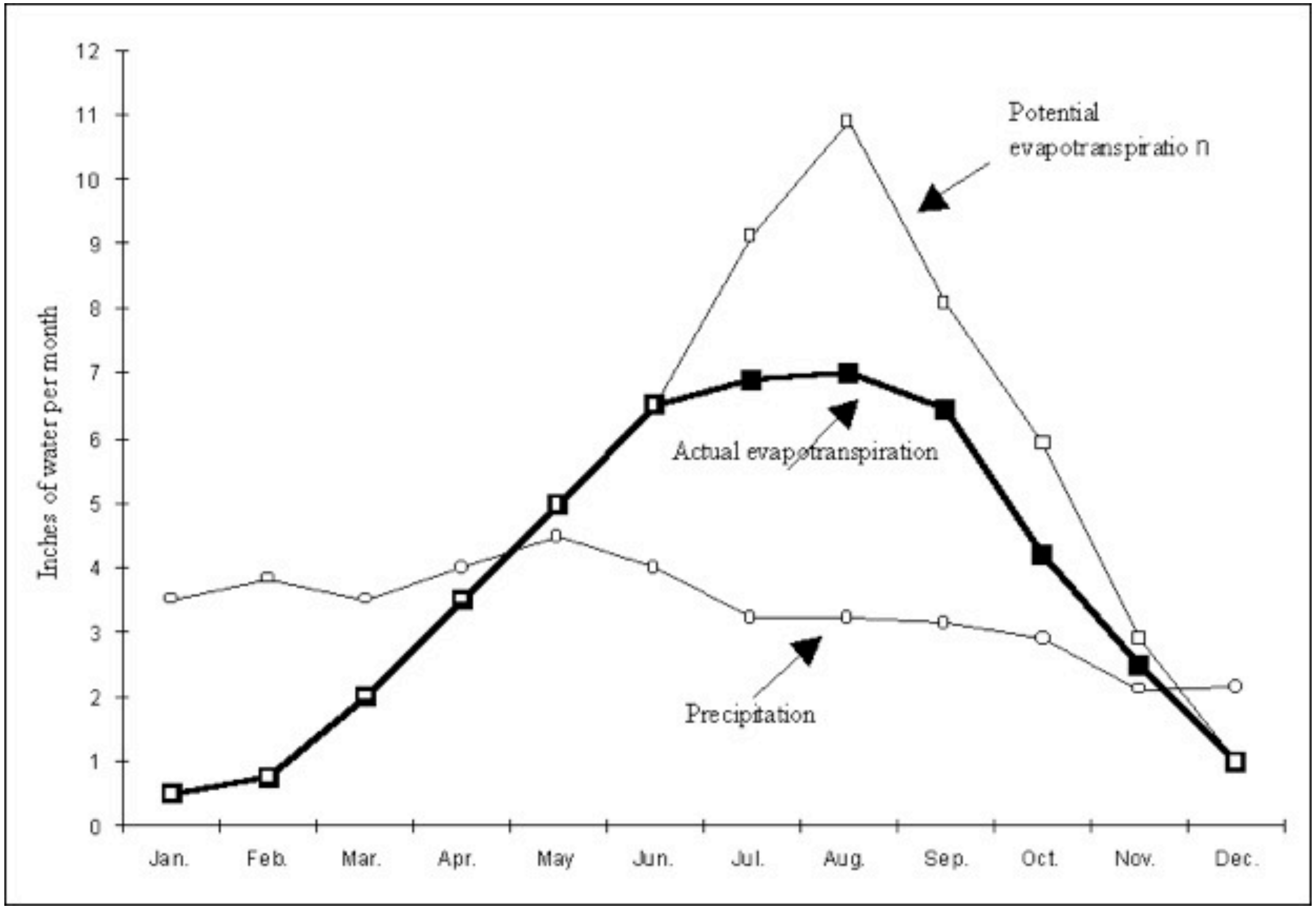


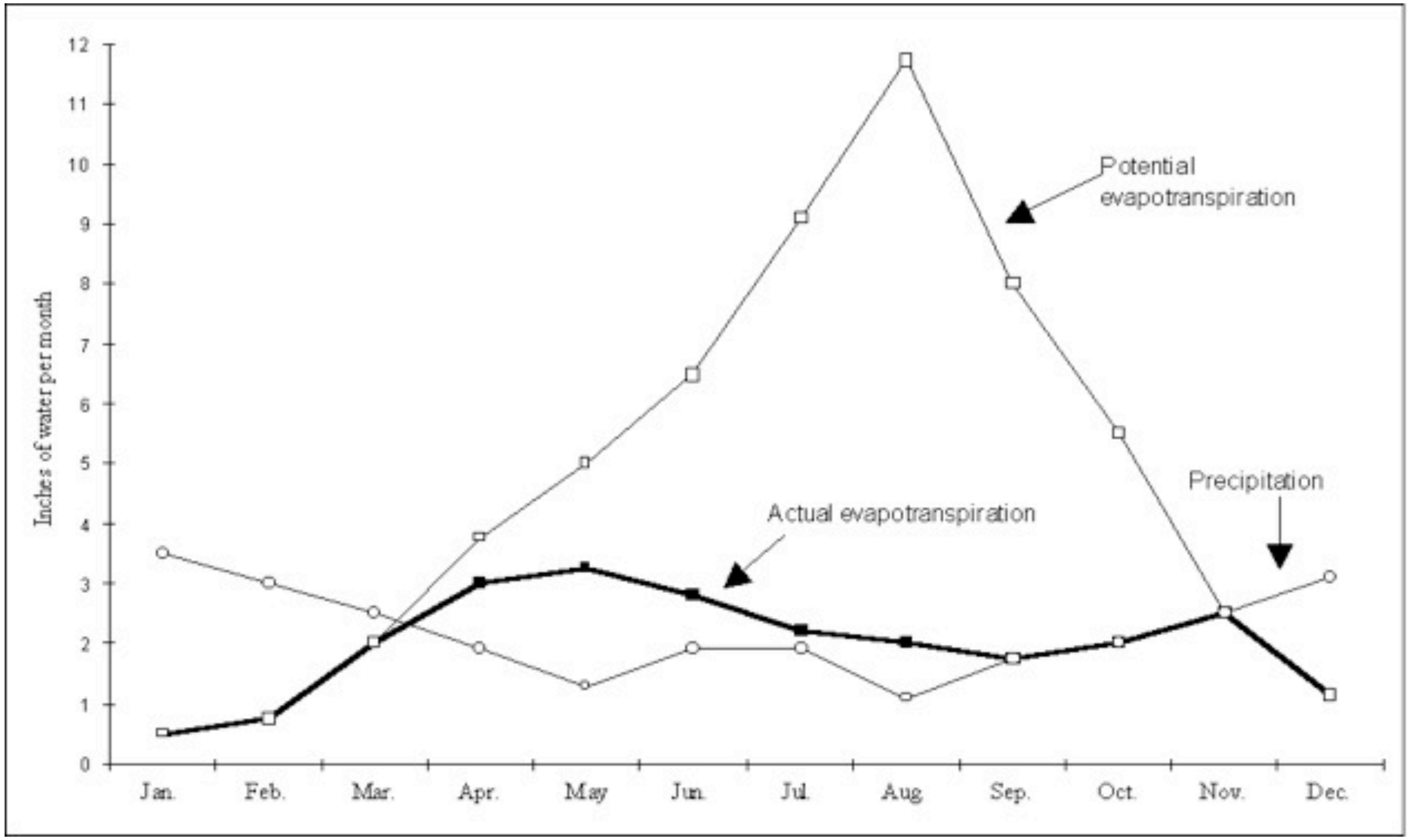
FIG. 1 E_A from drip-irrigated cotton at MAC, Maricopa, AZ. 29 June-27 September 1989.

Annual trends of ET



Soils with fine granulometry, with high possibility of storing humidity, moderately warm summers, cold winters, and constant monthly precipitations throughout the year

Annual trends of ET

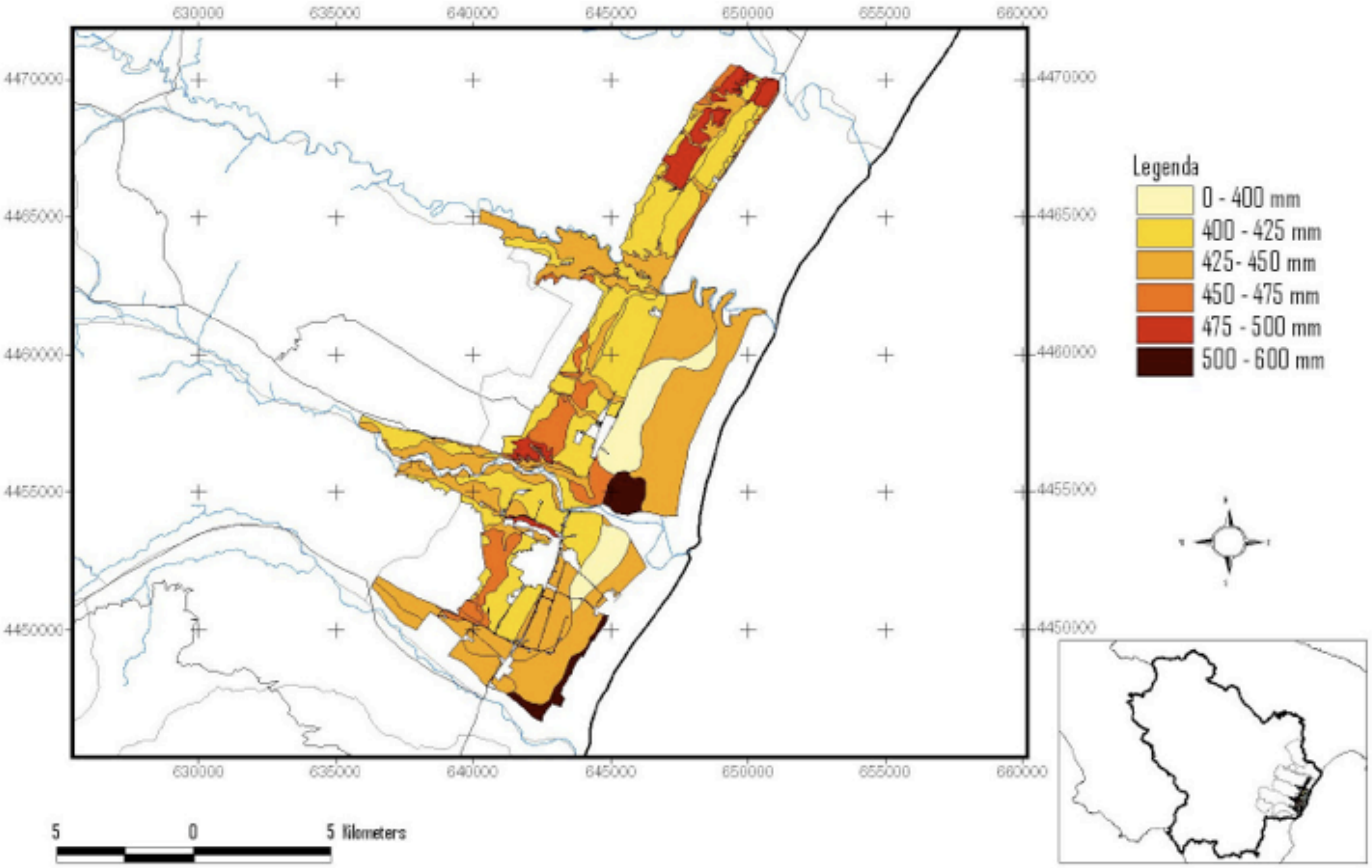


Coarse-grained soils, with limited storage capacity, dry warm summers and cold wet winters

Annual trends of ET

Typically, ET is at least one third of precipitations, and it equals precipitation in arid climates (PET > P). In practice, the difference P-PET can be used as an indicator of the aridity of a climate. In wet climates AET < P but it is limited by the available energy rather than the available water

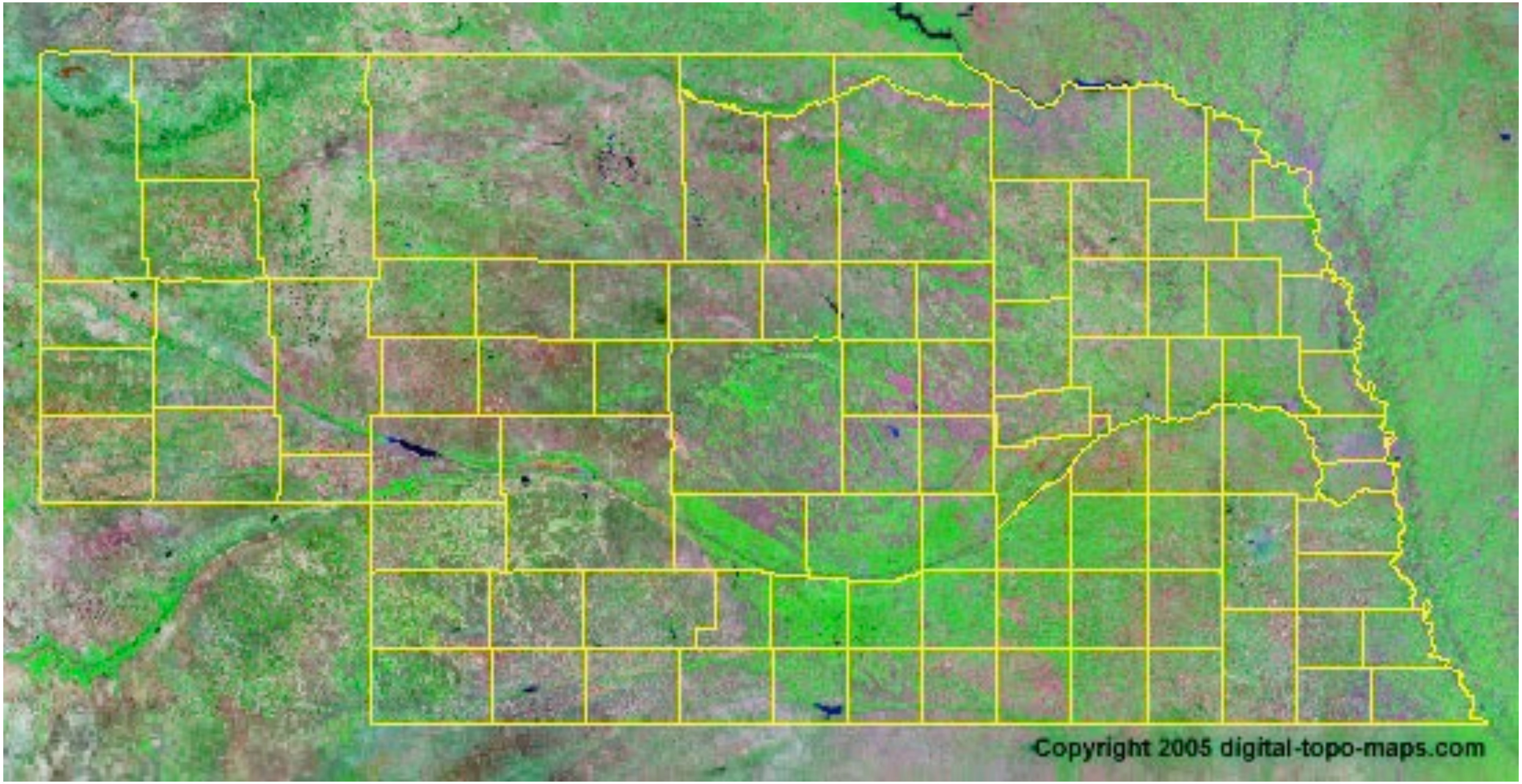
Annual trends of ET



Effective evapotranspiration map

Spatial distribution of ET

After Allen, 2007

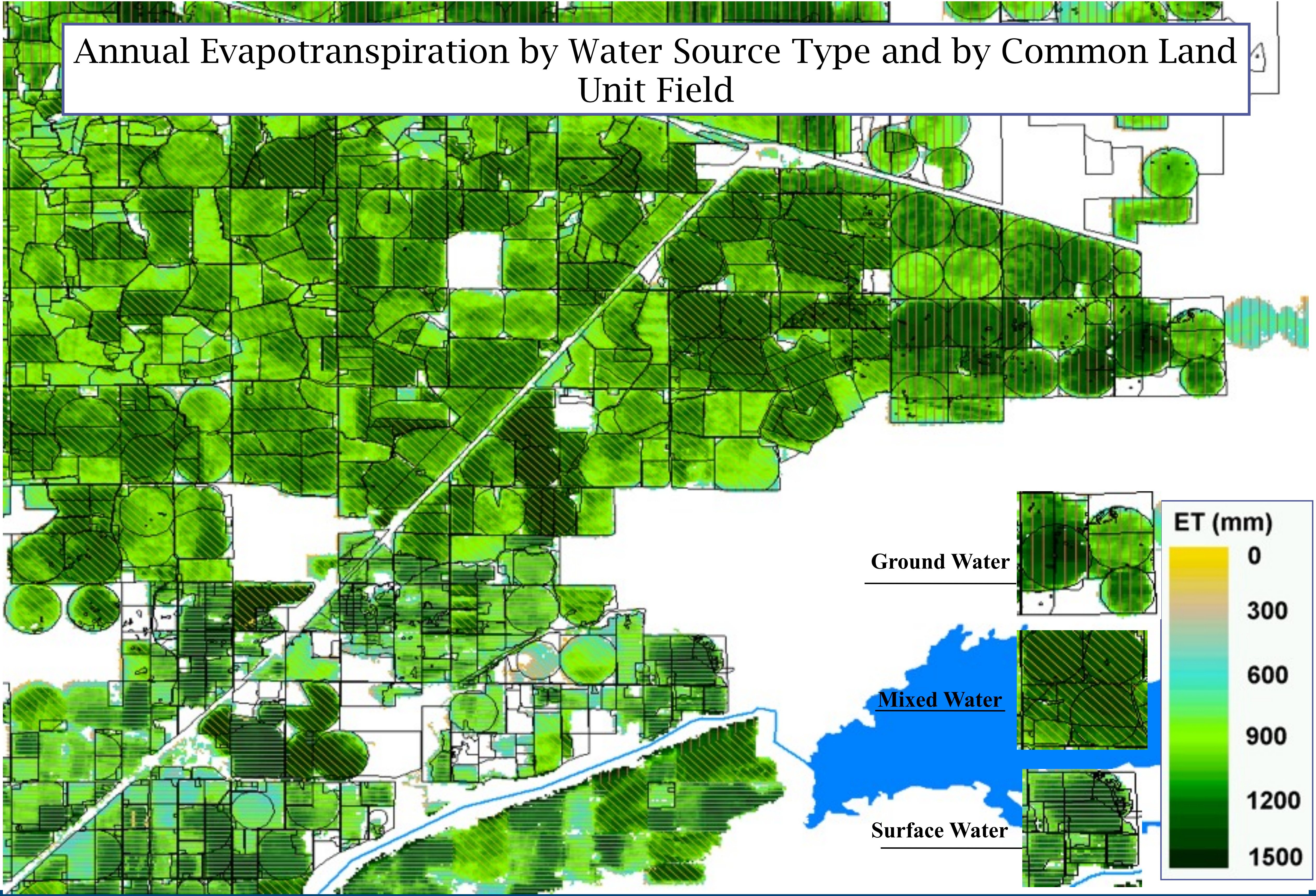


Vegetation and water content vary spatially

Spatial distribution of ET

But the various terms of the energy balance can be obtained by satellite. It is therefore possible to have maps that estimate evapotranspiration over vast areas, by processing remote-sensing images in the appropriate spectral bands.

Evapotranspiration - III

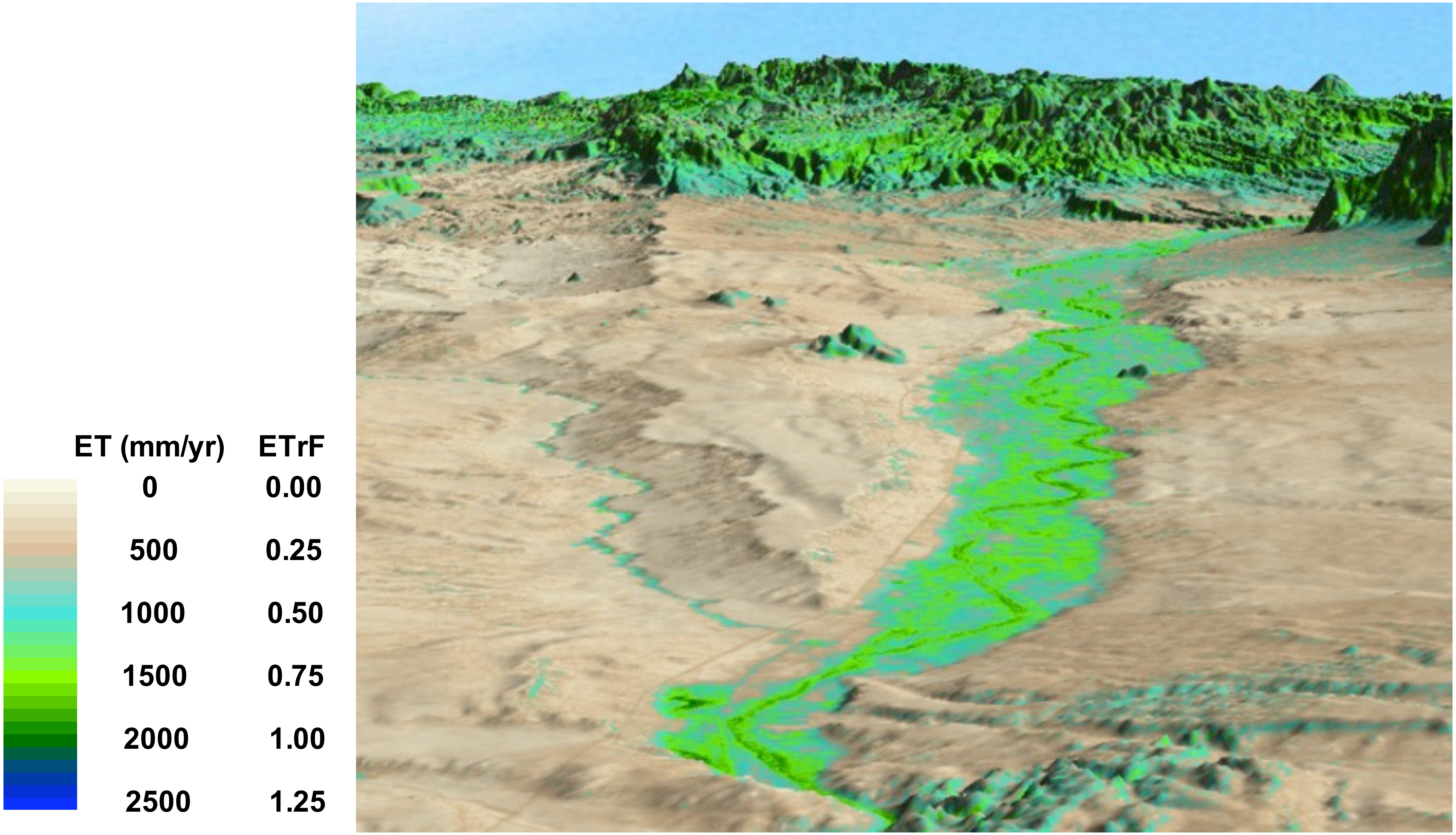


After Allen, 2007

Riccardo Rigon

Estimation of the spatial distribution of ET with the METRIC model - Middle Rio Grande, New Mexico

After Allen, 2007



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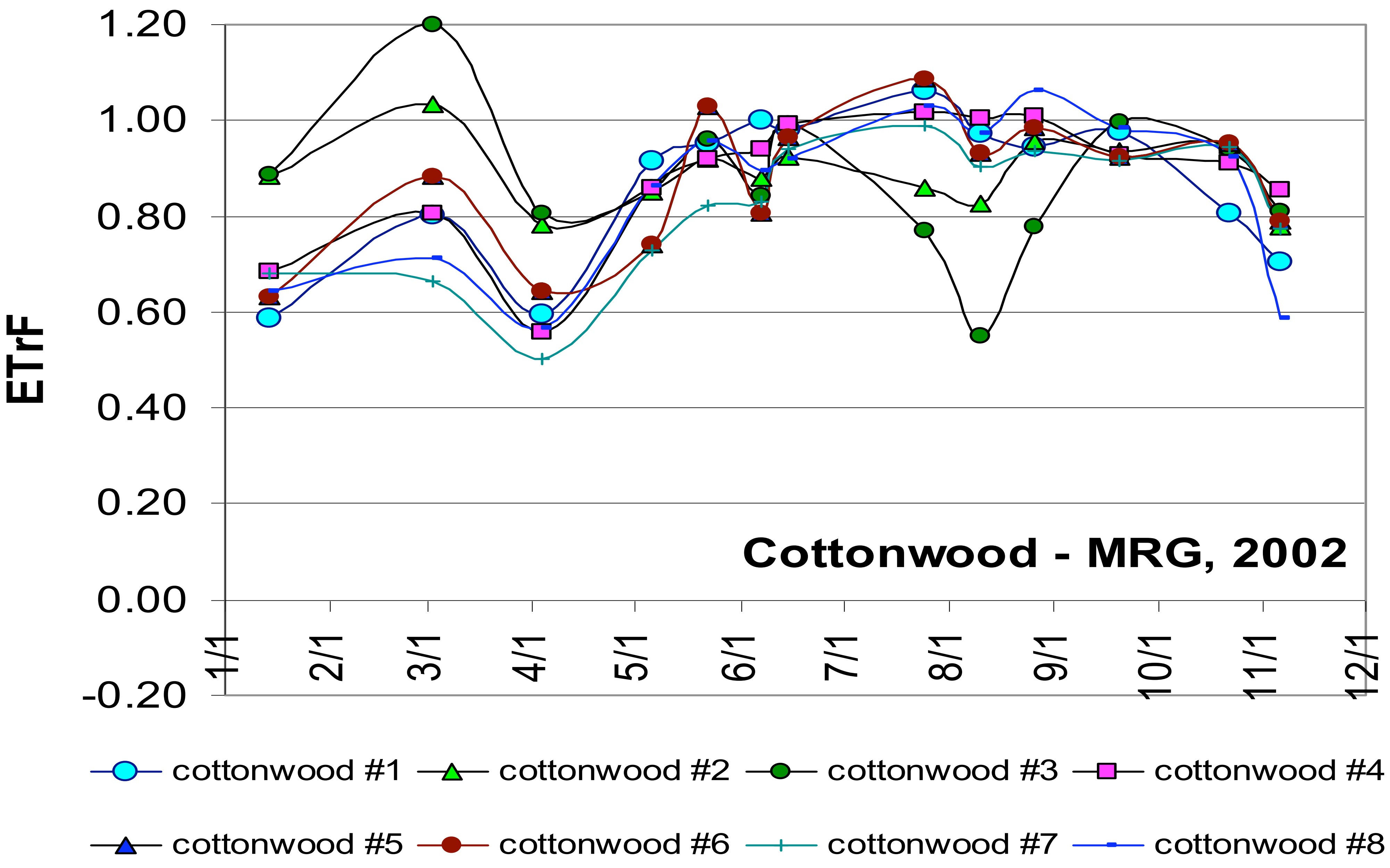

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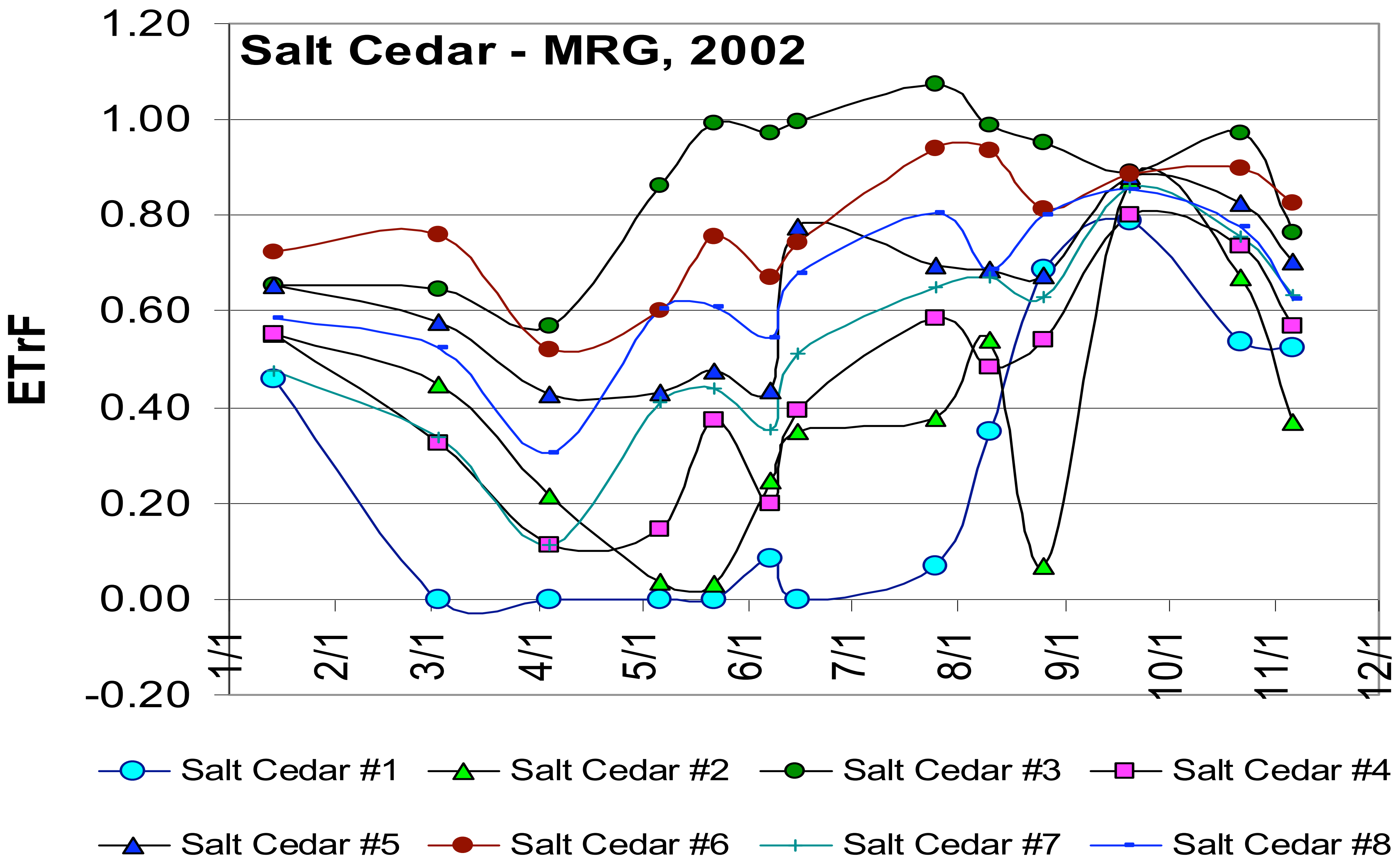


Spatial distribution of ET

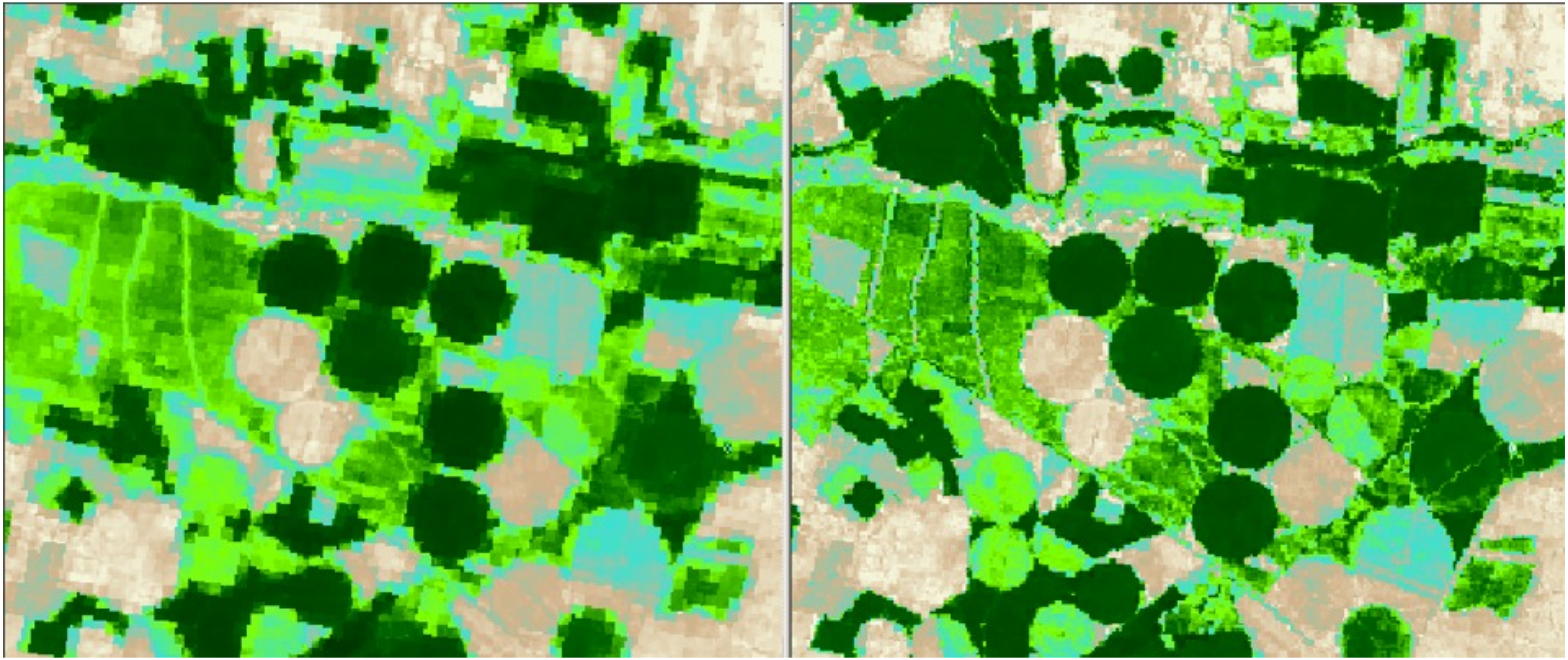
With high resolution remote-sensing systems it is practically possible to follow the transpiration trends of each single plant

Landsat 5 Thermal Band

Landsat 5 -- Albacete, Spain, 07/15/2003

ET ratio before sharpening

ET ratio after sharpening

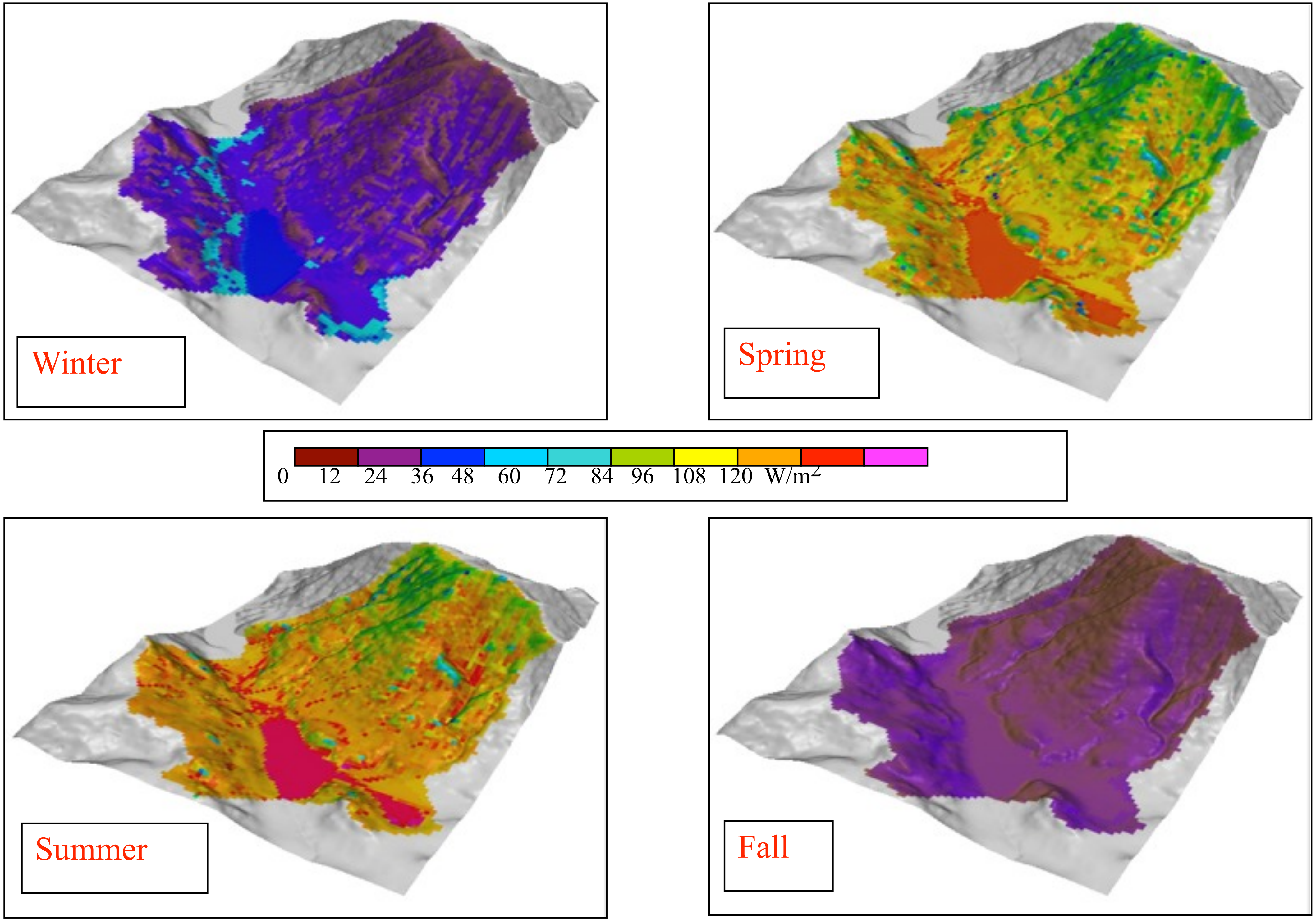


After Allen, 2007

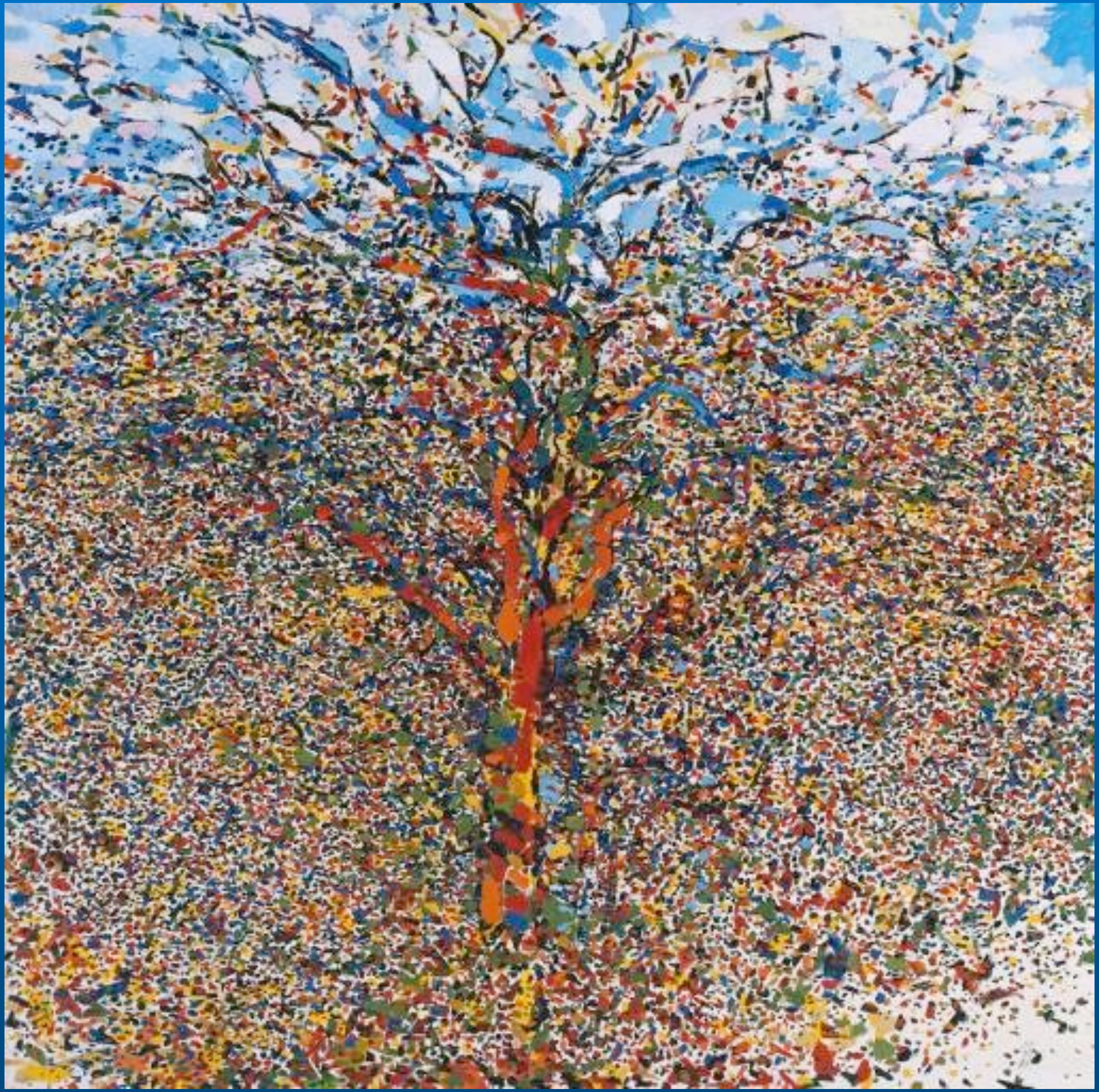
More information at:

- www.kimberly.uidaho.edu/water/ (METRIC^{tm})
- http://www.idwr.idaho.gov/gisdata/et.htm
- http://maps.idwr.idaho.gov/et/

Evapotranspiration - I



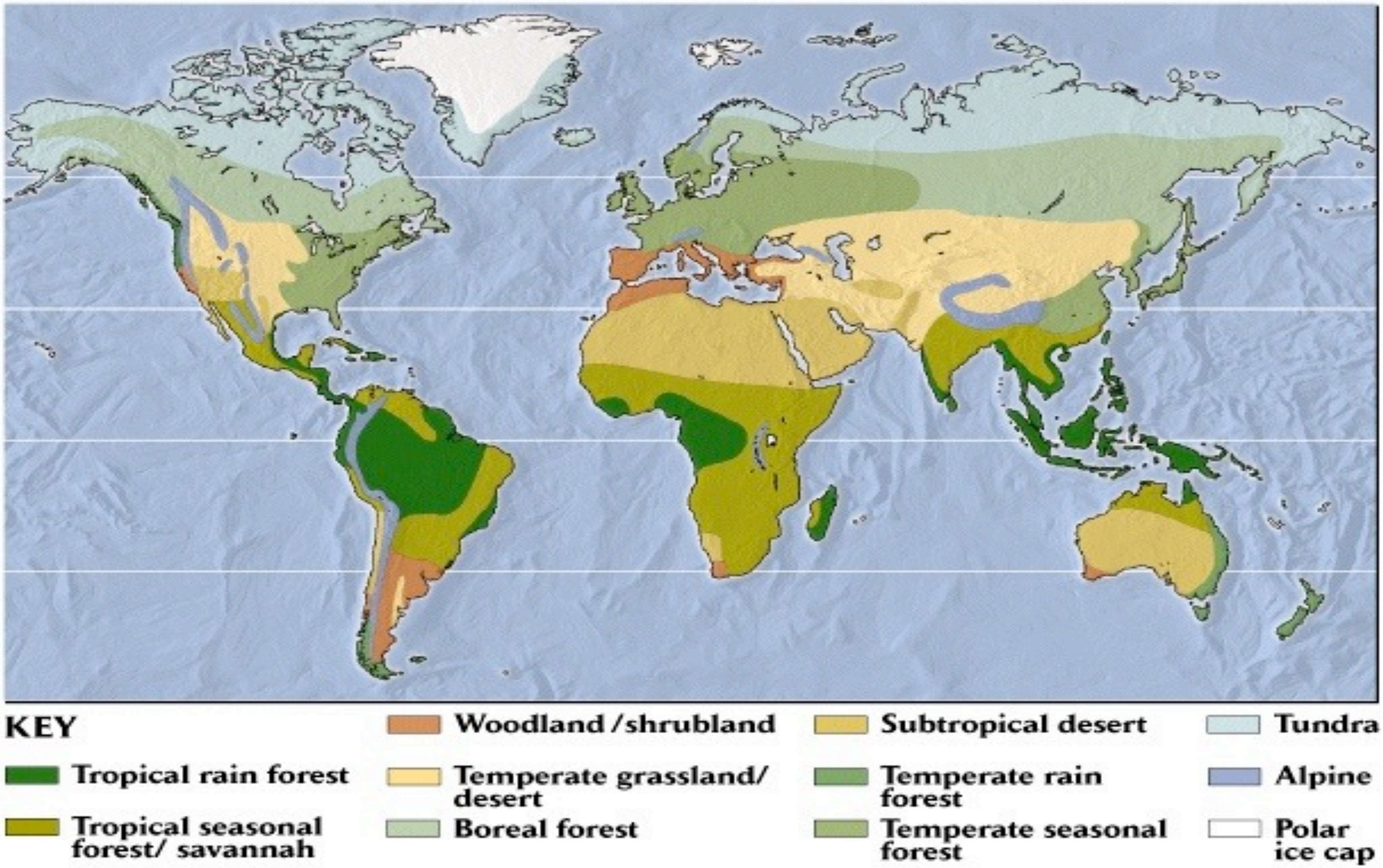
Evapotranspiration- III



P. Sutton, Tree, 1958 - Tate Modern

Riccardo Rigon

The Earth’s Biomes



What is a biome?

- A term used to describe the organisation of life?!
- A vast region of specific plants and animals that are adapted to a particular climate and physical environment
- It is not based on geography
- It does not always have a well defined boundary

What is an Ecotone?

- It is the frontier between two biomes

What defines a biome?

What defines a biome?

- **Climate at a global and regional level**

- **Physical environment**
    - Substrata

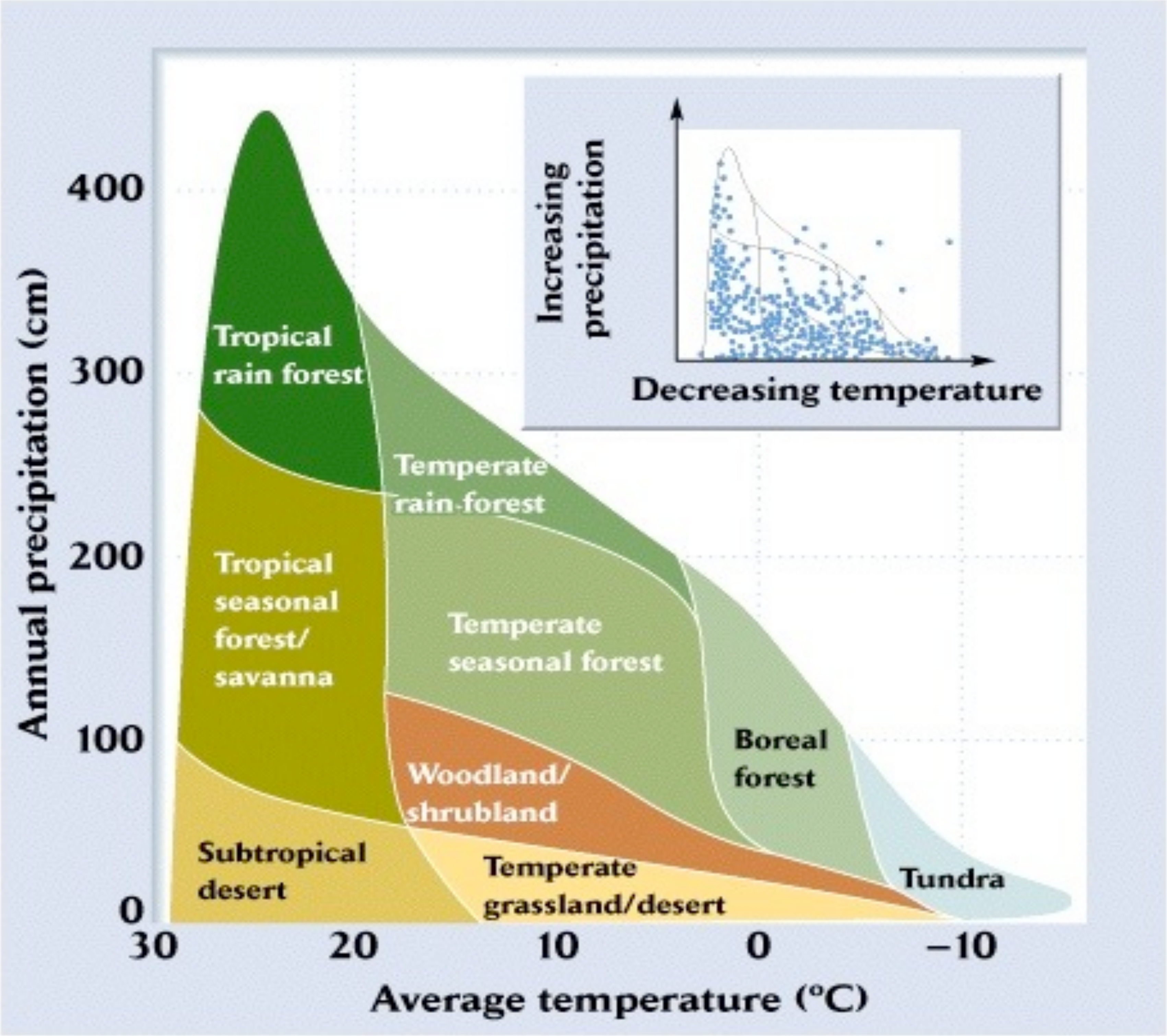
- **Human action**
    - Artificial lakes, desertification

The identification of a biome requires knowledge of …

The identification of a biome requires knowledge of …

- the climate of the region
- the position and geography of each biome
- the flora and fauna present

Effects of climate on biomes



But this is another story

G.Ulrici - Man after working on slides , 2000 ?

Thank you for your attention and patience