The Abdus Salam
International Centre for Theoretical Physics

United Nations
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2237-4

Joint ICTP-IAEA Conference on Coping with Climate Change and Variability in Agriculture through Minimizing Soil Evaporation Wastage and Enhancing More Crops per Drop

9 - 13 May 2011

Evapotranspiration and Crop Water Use

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Topical Outline

- Evapotranspiration in relation to energy balance and transport
- Leaf transpiration
- Wetness of the evaporating surface—as affected by soil surface moisture, canopy cover, and stomata
- Crop coefficient for estimation of ET and crop water use, underlying determinants.

Water evapotranspired or consumed by crop fields must undergo a phase transition, from liquid to vapor.

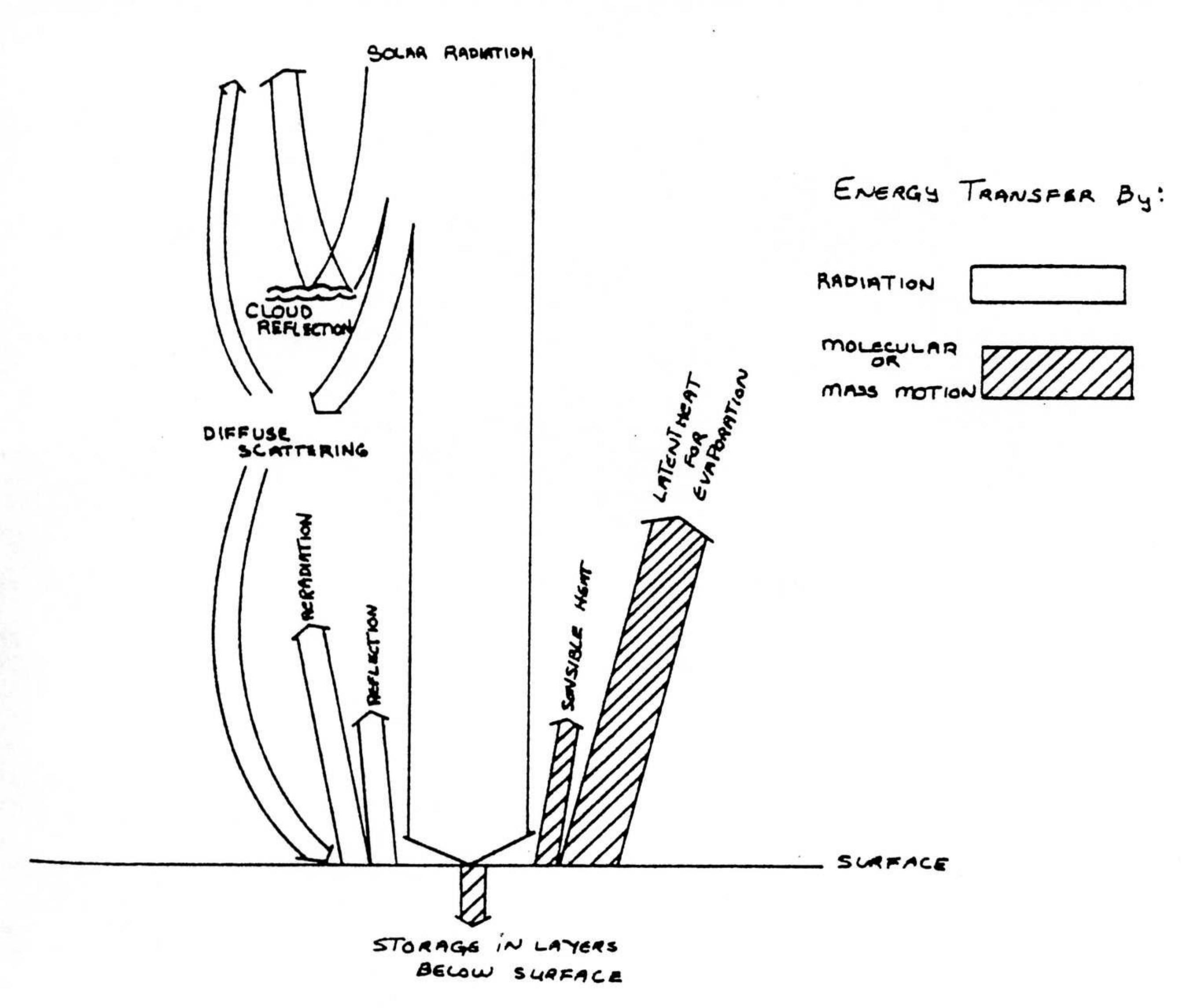
This transition requires a large amount of energy, to break the large number of hydrogen bonds in liquid water and to provide the kinetic energy associated with water molecules in the vapor phase.

The amount of energy required to evaporate one unit of water is known as latent heat of vaporization, and is represented by the symbol ℓ or L.

$\ell = 2.44\ kJ\ g^{-1}$ or $583\ cal\ g^{-1}$ at 25°C

Transpiration or evapotranspiration are dependent on energy supply

Consider first evapotranspiration and energy balance



Energy fluxes for a surface:

Net radiation R_n

Latent heat flux ℓE

Sensible heat flux H

Storage heat flux S

Incoming is positive (+)

Outgoing is negative (-)

The surface has no thickness and cannot store energy. So energy is stored in the layers below the surface

Evapotransiration is related to other energy fluxes through the energay balance relationship

Energy balance (Law of conservation of energy)

$$R_n + \ell E + H + G + M = 0$$

R_n = net radiation flux = $R_{incoming}$ - $R_{outgoing}$

ℓE = latent heat flux

ℓ = latent heat of vaporization

E = rate of evaporation

H = sensible heat flux

G = storage heat flux

M = metabolic energy flux

Incoming energy to the surface is positive

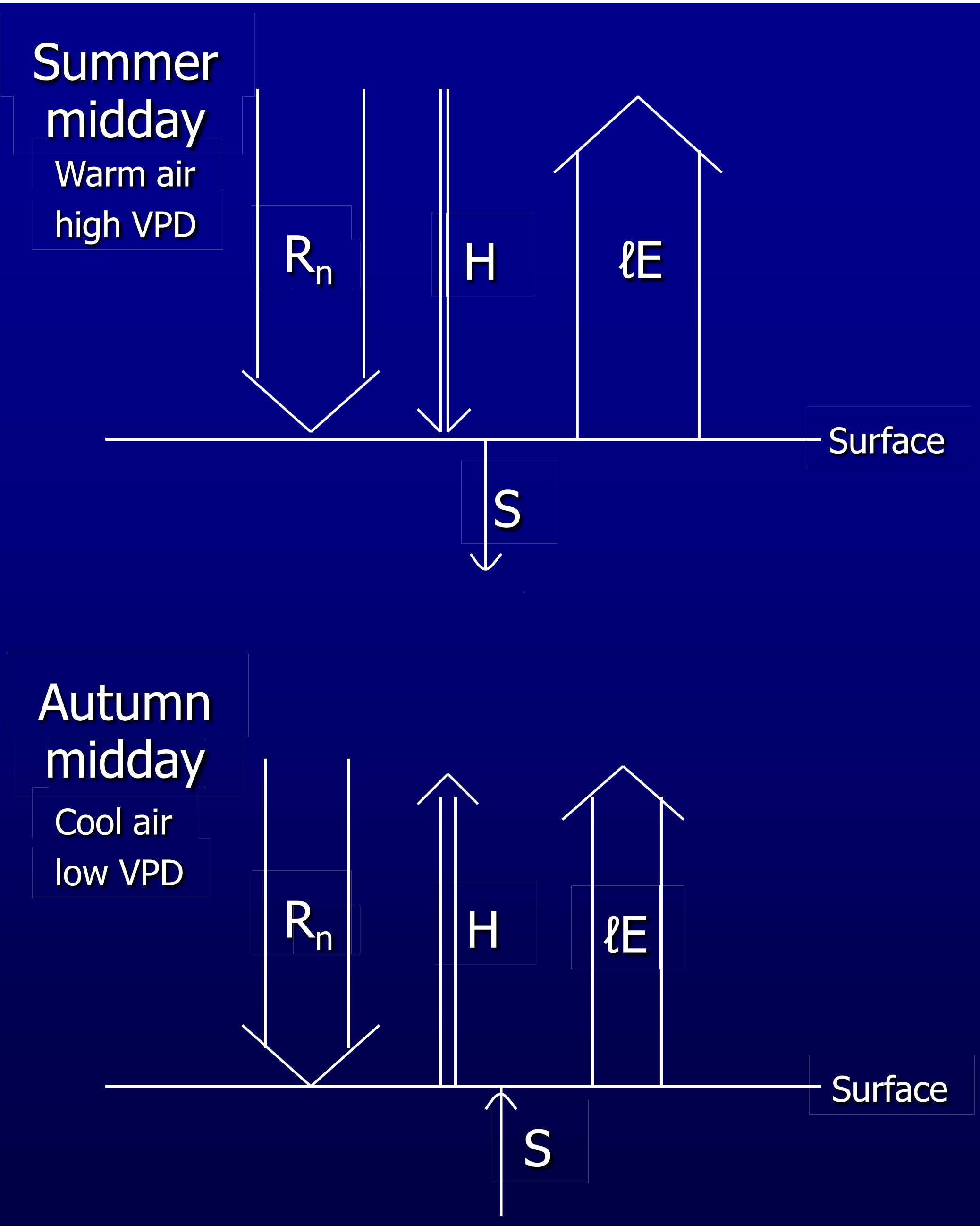
outgoing energy from the surface is negative

Metabolic energy (photosynthesis & respiration) flux is usually negligible

Averaged over 24 h or longer, G is close to zero, so:

$$E \text{ (or ET)} \approx (- R_n - H)/\ell$$

ET is equivalent to net radiation modified by sensible heat!



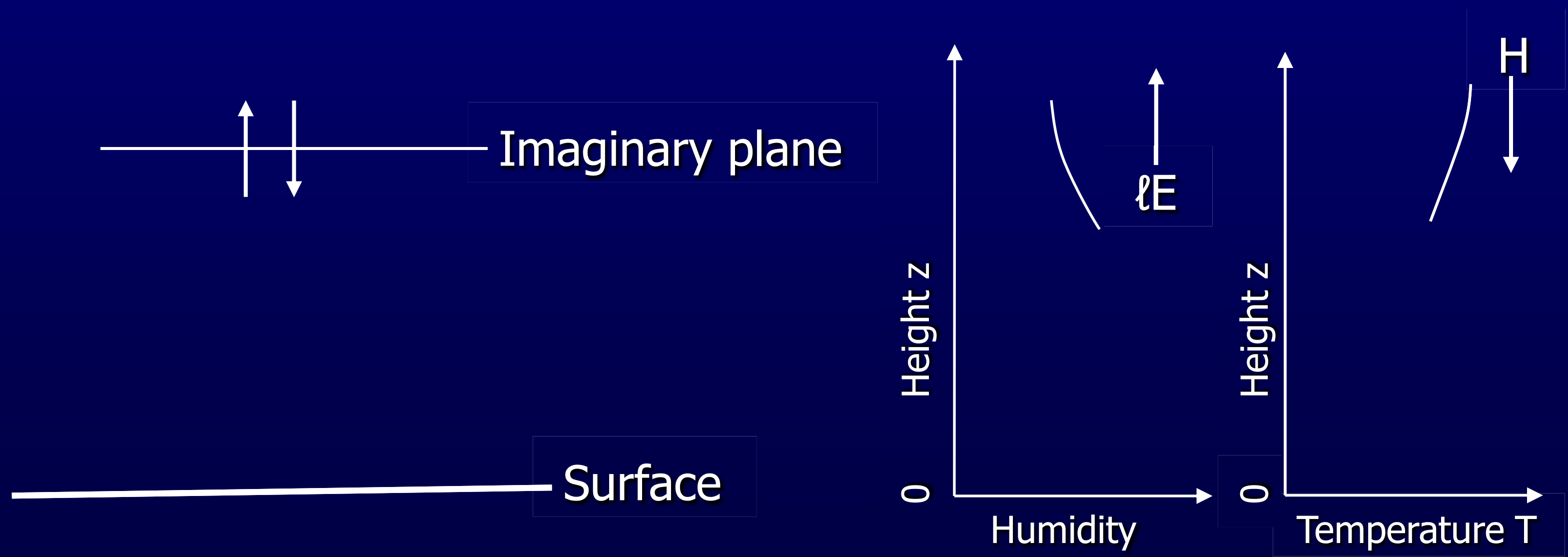
Arrow width ∝ flux magnitude

Contrasts in magnitude and direction of energy flux components between early summer and early autumn

High temperature air can supply energy to the surface, and high VPD enhances evaporation, causing ℓE to be greater than R_n.

Cool air absorbs sensible heat from the surface and evaporation is reduced under low VPD, causing ℓE to be smaller than R_n.

- For a given R_n, how much energy goes to evaporate water and how much is dissipated as sensible heat?
- What is the ratio of H to ℓE? This ratio is known as Bowen ratio
- Need to look at transport of water vapor and sensible heat across an imaginary plane above and parallel to the surface
- Across this plane there must be a gradient of water vapor concentration for water vapor to move, and a gradient of temperature for sensible heat to move



Quantitatively,

Equation for vertical transport of water vapor

$$W = \rho_a K_w \frac{dq}{dz}$$

W	water vapor flux (rate/area)
P_a	air density
K_w	eddy transfer coefficient, water vapor
q	specific humidity of air
z	height above surface

Equation for vertical transport of sensible heat

$$H = c_p \rho_a K_h \frac{dT}{dz}$$

H	sensible heat flux (rate/area)
c_p	air heat capacity
K_h	eddy transfer coefficient, sensible heat
T	temperature

Transport is dependent on:

ability of pathway to conduct, K_w or K_h, and

magnitude of driving force, *dq/dz or dT/dz*

To cast both transport equation in energy terms

- assume steady state transport
- upward vertical flux W is the same as evaporation rate from surface
- W= E

For each unit of water evaporated, ℓ amount of energy is consumed, and this energy (ℓE) moves along with the vaporized water

Expressing the water flux in terms of energy (latent heat) flux:

Equation for vertical transport of latent heat

$$lE = l\rho_a K_w \frac{dq}{dz}$$

E	evaporation (rate/area)
l	*latent heat of vaporization*
P_a	air density
K_w	eddy transfer coefficient, water vapor
q	specific humidity of air
z	height above surface

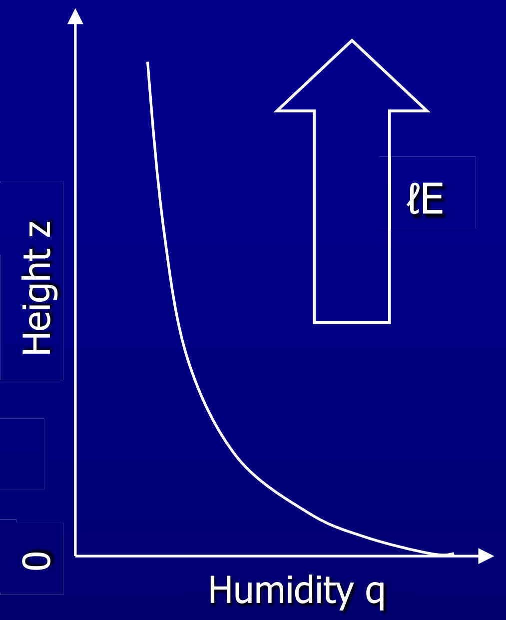
Equation for vertical transport of sensible heat

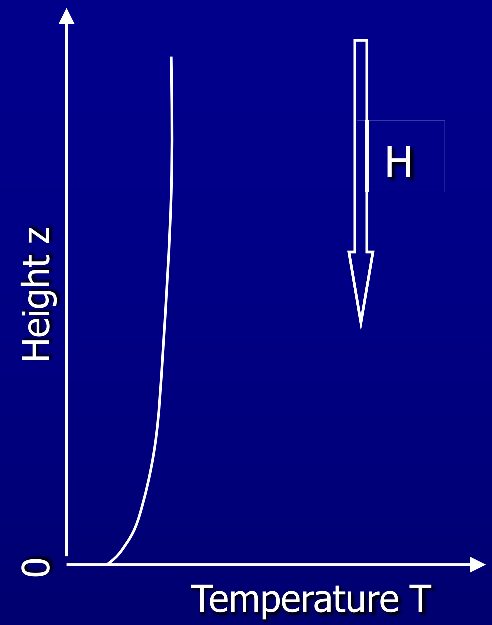
$$H = c_p \rho_a K_h \frac{dT}{dz}$$

H	sensible heat flux (rate/area)
c_p	air heat capacity
K_h	eddy transfer coefficient, sensible heat
T	temperature

Well watered field
high radiation
warm

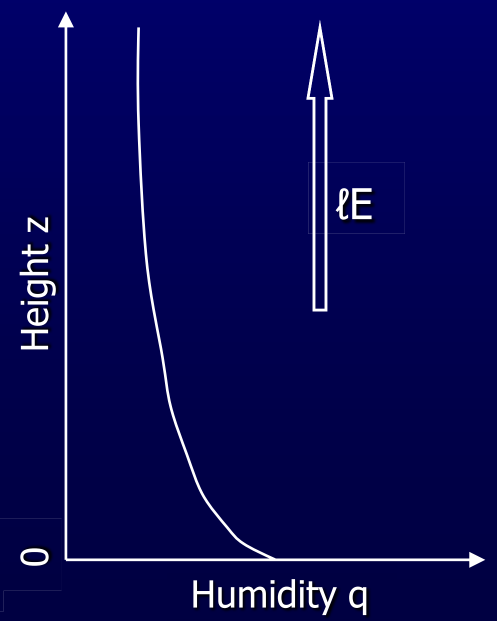
- High vapor pressure at wet surface
  - large dq/dz
  - high evaporation rate
- High evaporation cools surface to below air temp.
  - small dT/dz ↓
  - small sensible heat flux ↓

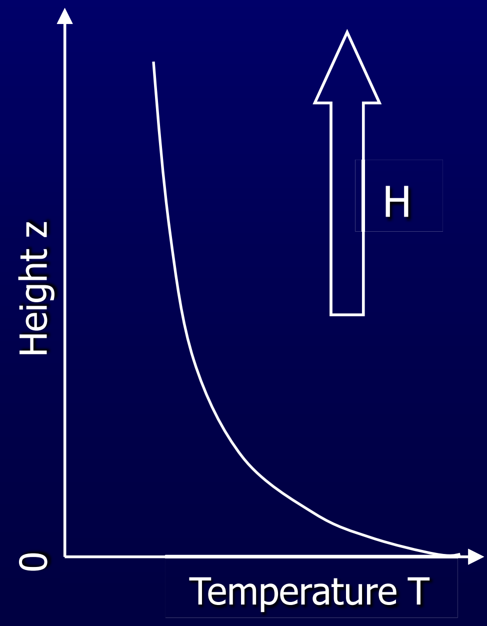




Drying field
high radiation
warm

- Low vapor pressure at surface
  - low dq/dz
  - low evaporation rate
- R_n remains high
  - surface heats up
  - large dT/dz
  - large sensible heat flux ↑





Well watered field
high radiation
warm

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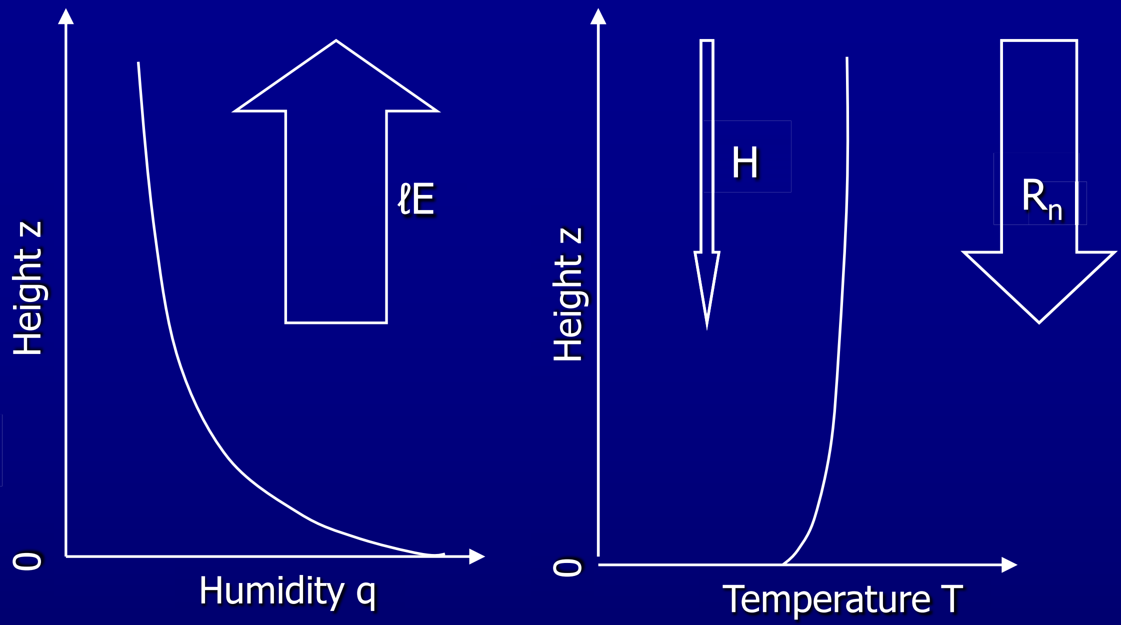
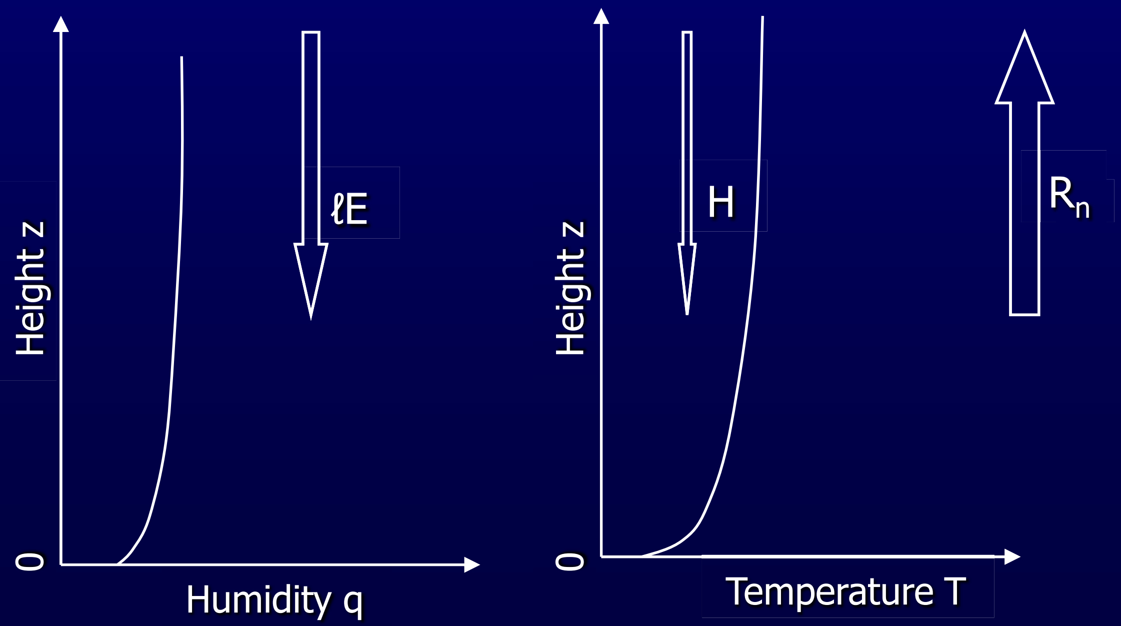


Clear night
Dew forming
continuously on surface

- Net radiation is outgoing (↑) removing energy
- Surface colder than air, dew point temperature reached
  - dew condenses on surface
- Condensation reduces q and create dq/dz ↓
- Condensation releases latent heat (ℓ) at surface



Bowen ratio (β) in terms of the sensible heat and latent heat transport equation

At any given height above the surface,

$$\beta = \frac{H}{lE} = \frac{\rho_a c_p K_h \, dT/dz}{l\rho_a K_w dq/dz}$$

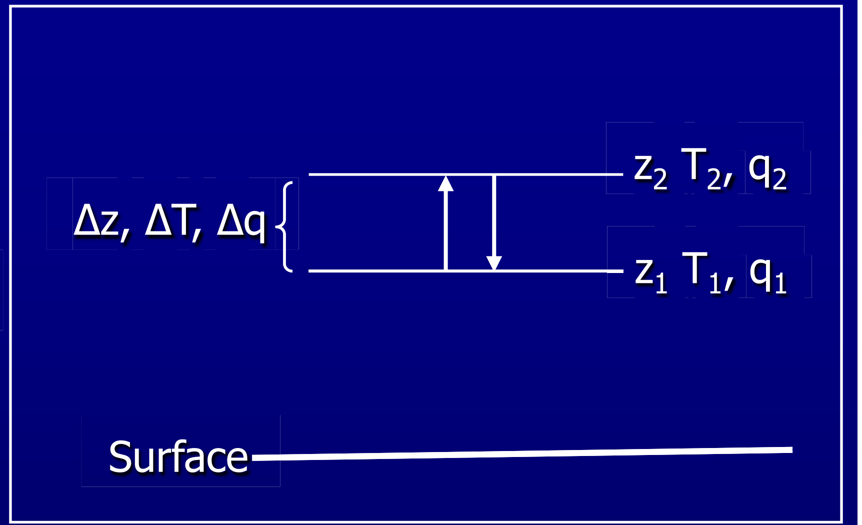
K_h and K_w are essential equal because of turbulent nature of the air. Moving "pockets" of air carries everything within it indiscriminately, whether it is water vapor, energy, or substances such as CO_2. This is known as Reynald's analogy or similarity theory. Hence,

$$\beta = \frac{H}{lE} = \frac{c_p \, dT}{l \; dq}$$

dT and *dq* are hard to determine experimentally. For practical purposes, resort to the the use of *ΔT* and *Δq*

For discrete height intervals formed by two imaginary parallel planes above the surface,

$$\beta = \frac{H}{lE} = \frac{c_p}{l}\frac{\Delta T}{\Delta q}$$



By measuring T and q at heights z_1 and z_2, *ΔT* and *Δq* between the two heights are readily determined

ΔT and *Δq* are then used to calculate *H* and *ℓE*, or the Bowen ratio (*β*)

Substituting *ℓE β* for *H* in the engergy balance equation, an expression for the the rate of evapotranspiration (*E*) is obtained in terms of *β*, R_n, *G and ℓ*

$$E = \frac{-R_n - G}{l(\beta + 1)}$$

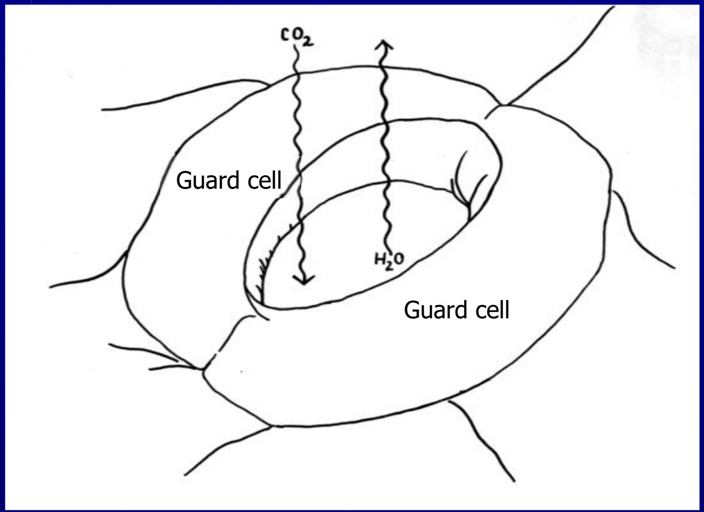
Bowen ratio/energy balance method (BRED) to determine E: measure R_n and *G*, and *T* and *q* at two heights.

Topical Outline

- Evapotranspiration in relation to energy balance and transport
- Leaf transpiration
  - Stomata as valves for passage of water vapor and CO_2
  - Resistances to water vapor and equation for transpiration
  - Leaf temperature and implicit role of energy balance

Transpiration is dependent on leaf area and the degree of stomatal opening

Stomata—microscopic valves in leaf epidermis controlling water vapor and CO_2 passage. They are formed by pairs of guard cells.



The degree of stomatal opening is measured by resistance or conductance of the leaf epidermis to water vapor diffusion, r_s or g_e

Stomata open and close in response to many environmental and plant factors. These include: light, leaf water status, extremes in leaf temperature, leaf nitrogen content, and leaf age.

Stomatal closing under low leaf water potential (Ψ) is an important response in preventing damaging dehydration of leaves. It acts as a safety valve shutting down the loss of water when water supply is insufficient.

Equations for leaf transpiration

$$T = \frac{1}{r_a + r_e}(W_i - W_a)$$

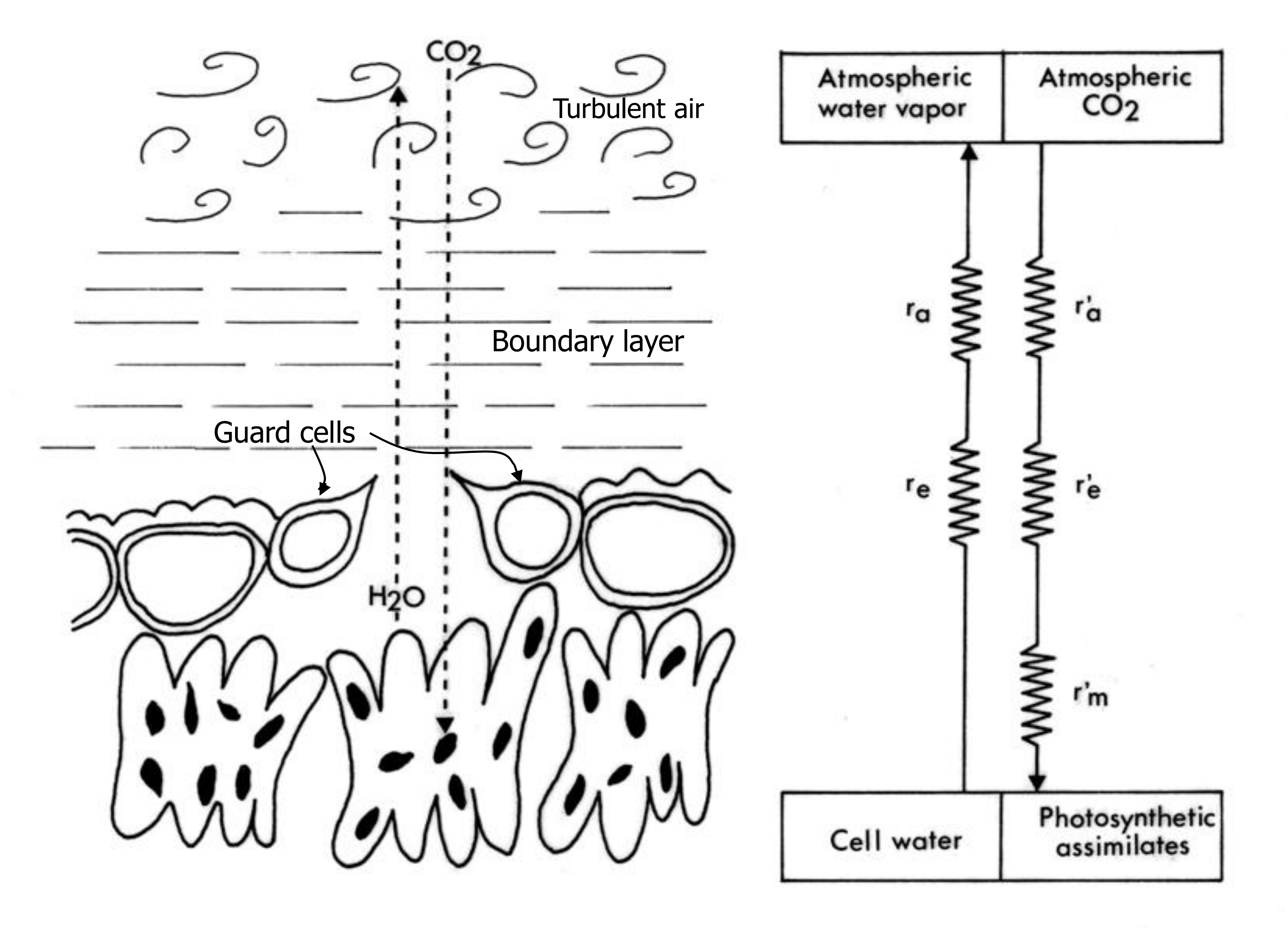
$$T = g_{total}(W_i - W_a) = \frac{g_a g_e}{g_a + g_e}(W_i - W_a)$$

T	transpiration rate (per unit leaf area per unit time)
r_a	air boundary layer resistance to water vapor
r_e	epidermal resistance to water vapor
g_a	air boundary layer conductance to water vapor
g_a	epidermal conductance to water vapor
W_i	water vapor concentration in leaf interior
W_s	water vapor concentration in the air

Some water goes through leaf cuticle, so r_e is made up of stomatal and cuticular resistances, connected in parallel. If stomata are quite open, $r_s \approx r_e$, and

$$T \cong \frac{1}{r_a + r_s}(W_i - W_a)$$

Water vapor and CO pathway as resistances to diffusion

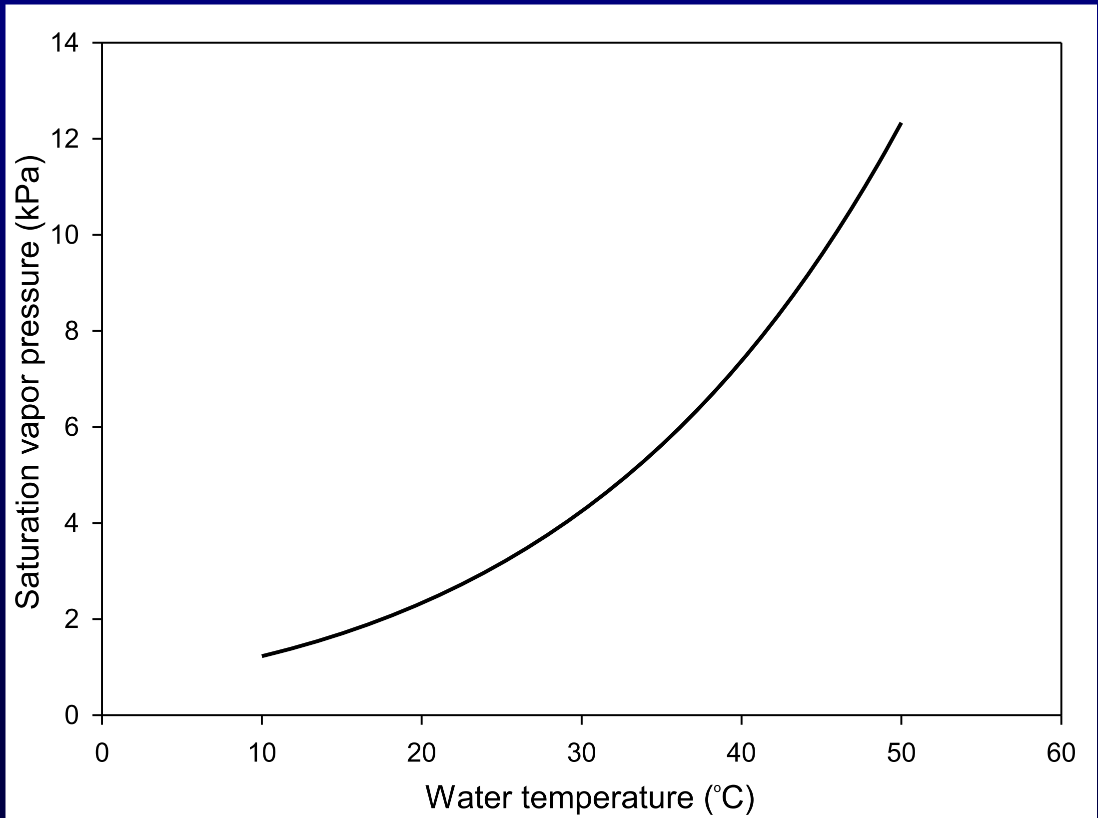


$$T \cong \frac{1}{r_a + r_s}(W_i - W_a)$$

r_a decreases with increases in wind velocity, and with decreases in leaf size

r_s decreases as stomata become more open

W_i depends essentially only on leaf temperature, increases as temperature increases

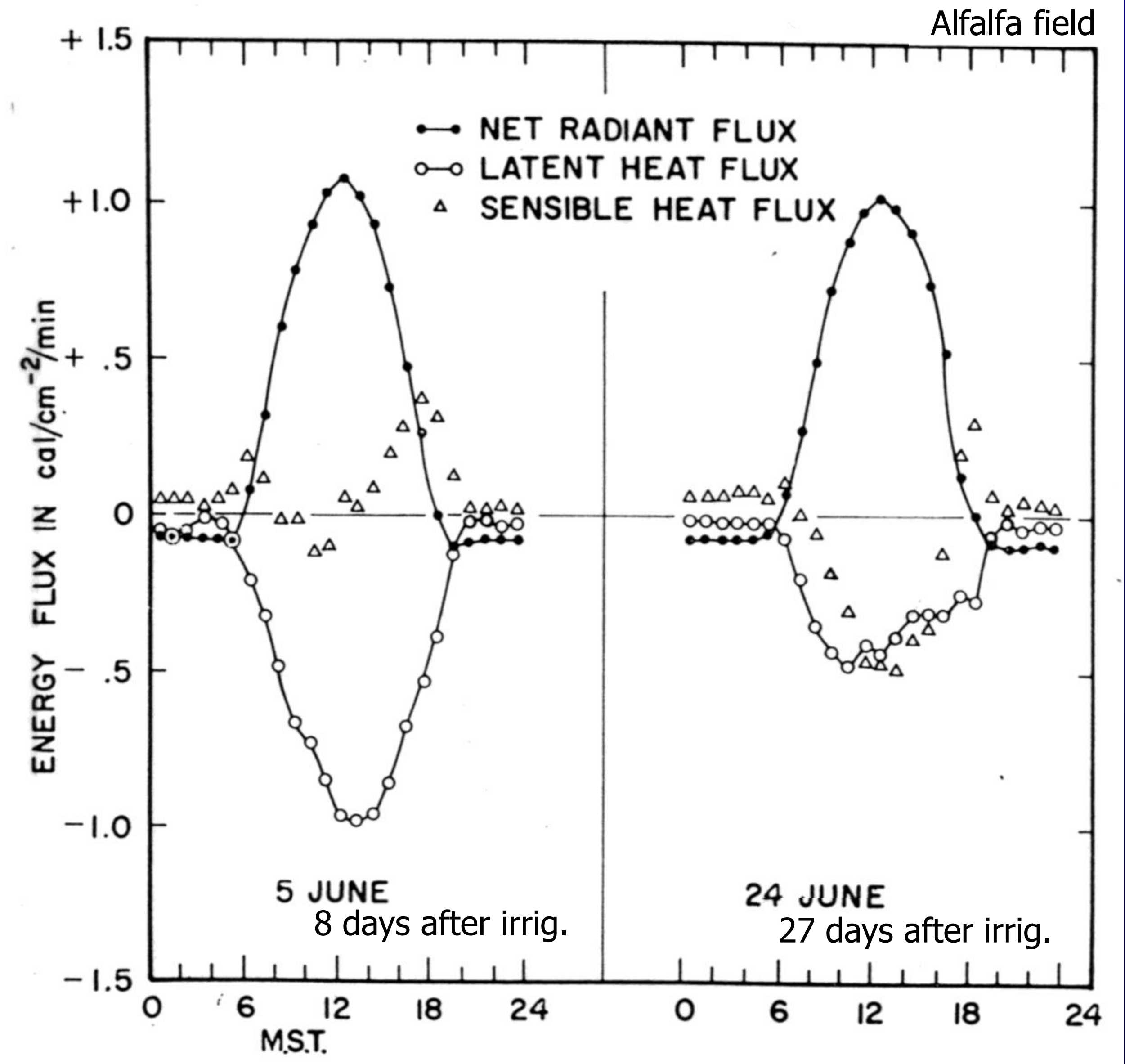


Leaf intercellular air space is essentially saturated with water vapor

Higher the leaf temperature, higher is its water temperatue, and higher is W_i

This is the link between energy balance and the transpiration equation. Any increase in energy supply or decrease in energy dissipation cause leaf temperature and ΔW to increase

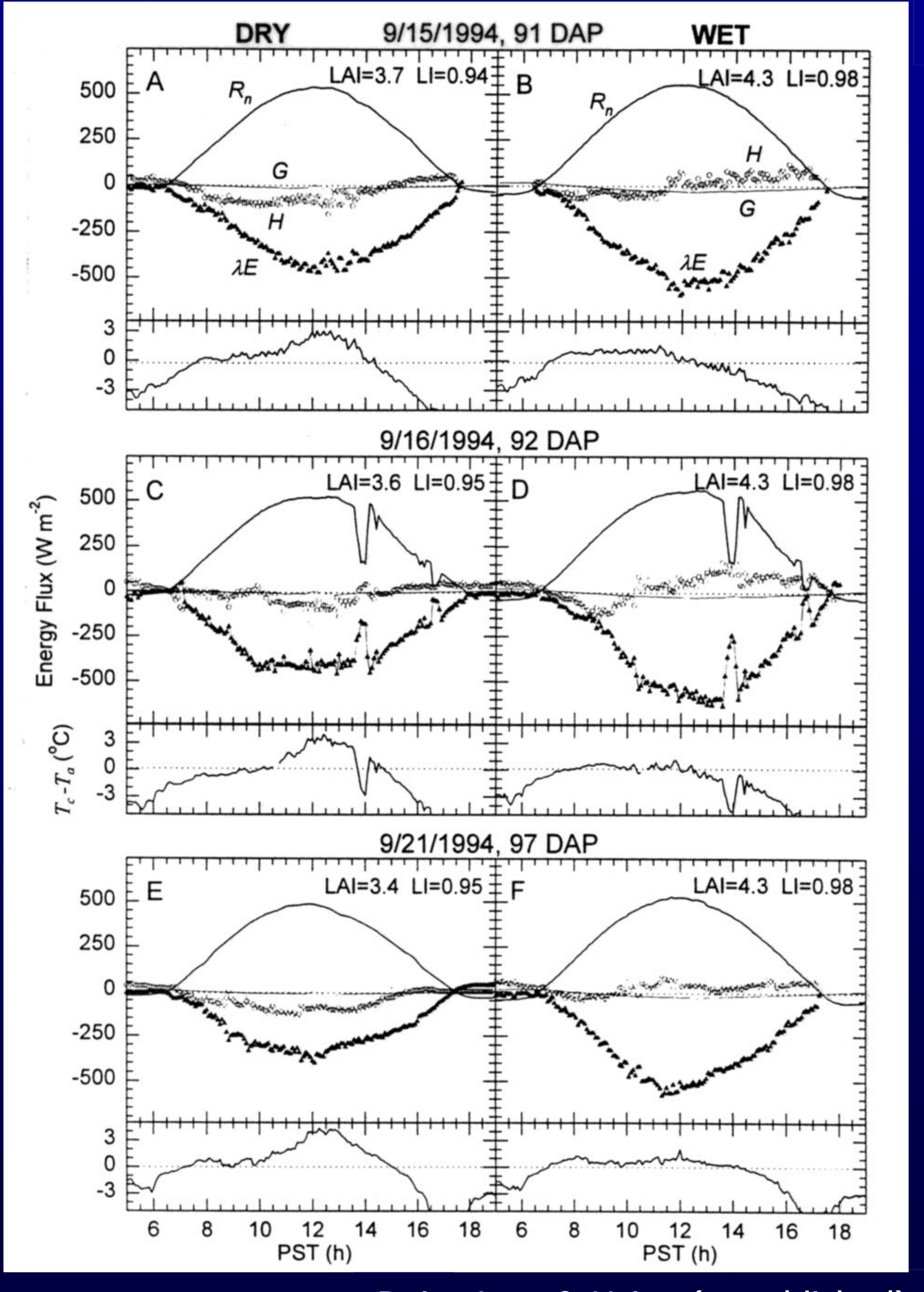
An example of water stress induced changes in latent heat flux



With water stress:

- More energy dissipated as sensible heat
- Less energy dissipated as latent heat
- Net radiation remained nearly the same

Van Bavel (1967)



Rojas-Lara & Hsiao (unpublished)

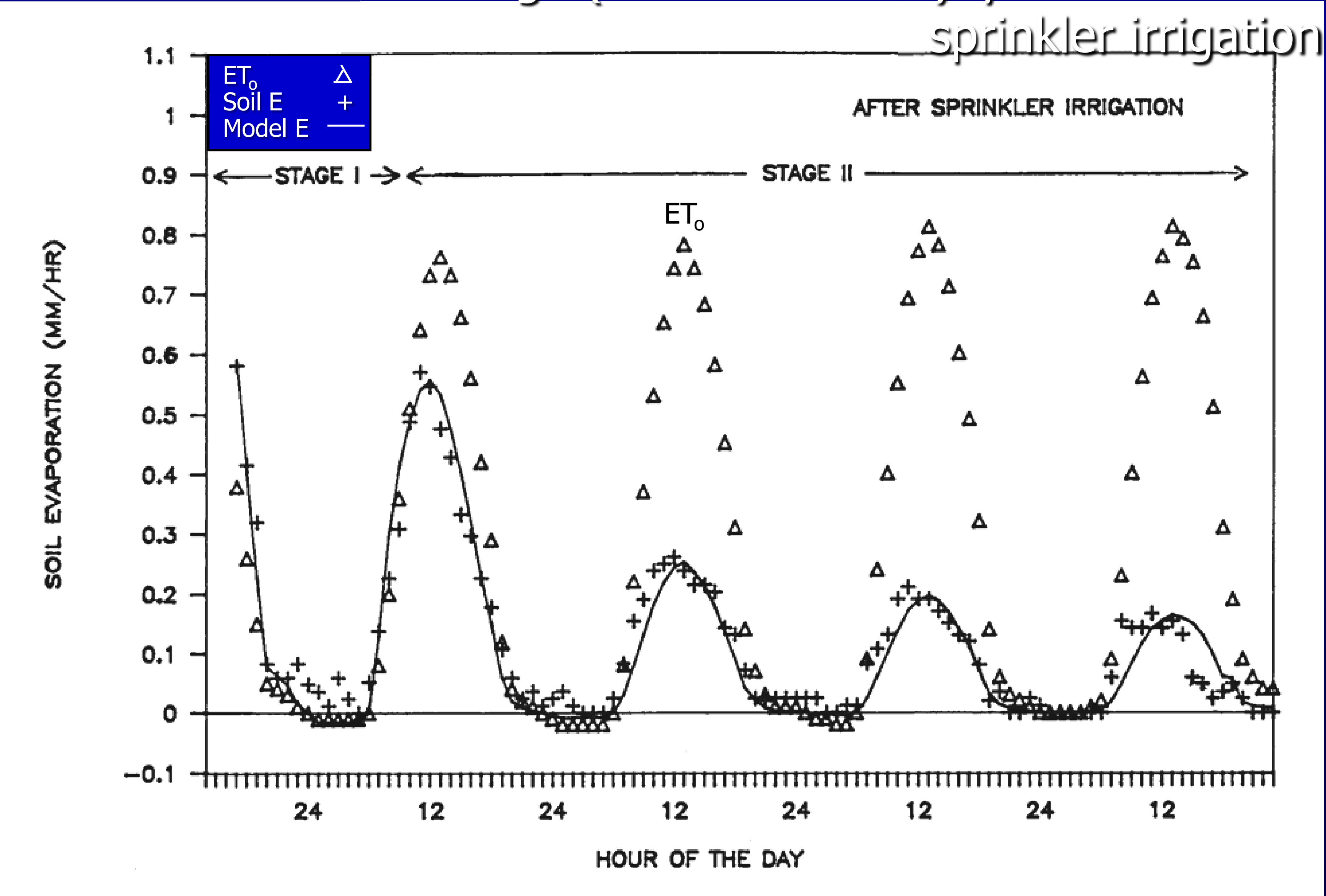
An example showing changes in partition between sensible and latent heat, and the underlying changes in leaf temperature

Soil evaporation

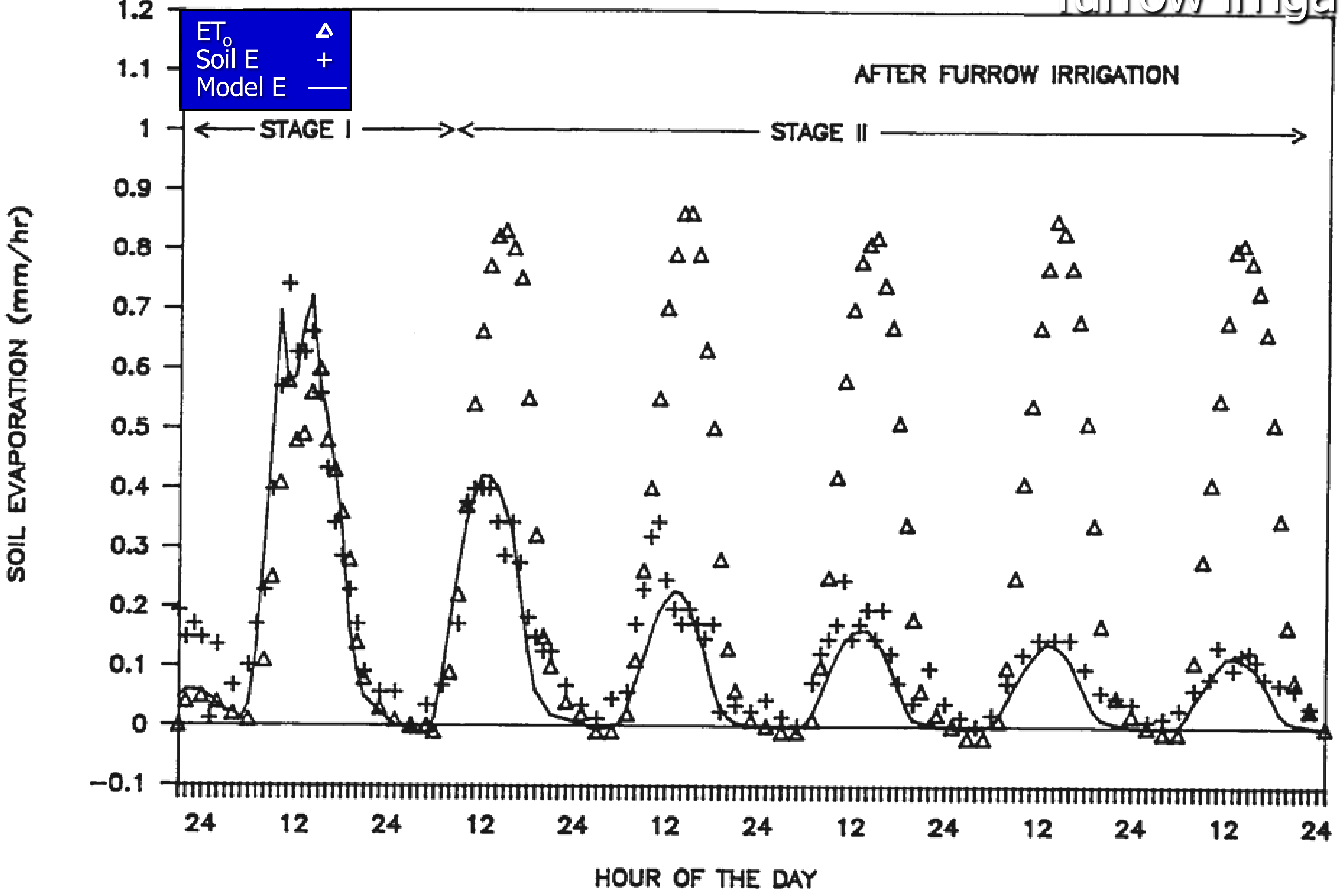
Consists of two stages, each characterized by different behavior

- Stage 1 is when the soil surface is full wet and surface soil Ψ is zero or somewhat lower. This means the absolute humidity or vapor pressure at the surface is near the same as that of water at the same temperature. Evaporation from the soil is essential the potential rate because energy supply to the surface is determining the rate and water supply to the surface is not limiting
- Stage 2 is when the soil surface begins to dry and vapor pressure at the surface begins to decrease significantly compared to vapor pressure at the surface of water at the same temperature. Evaporation at the stage declines exponentially with time

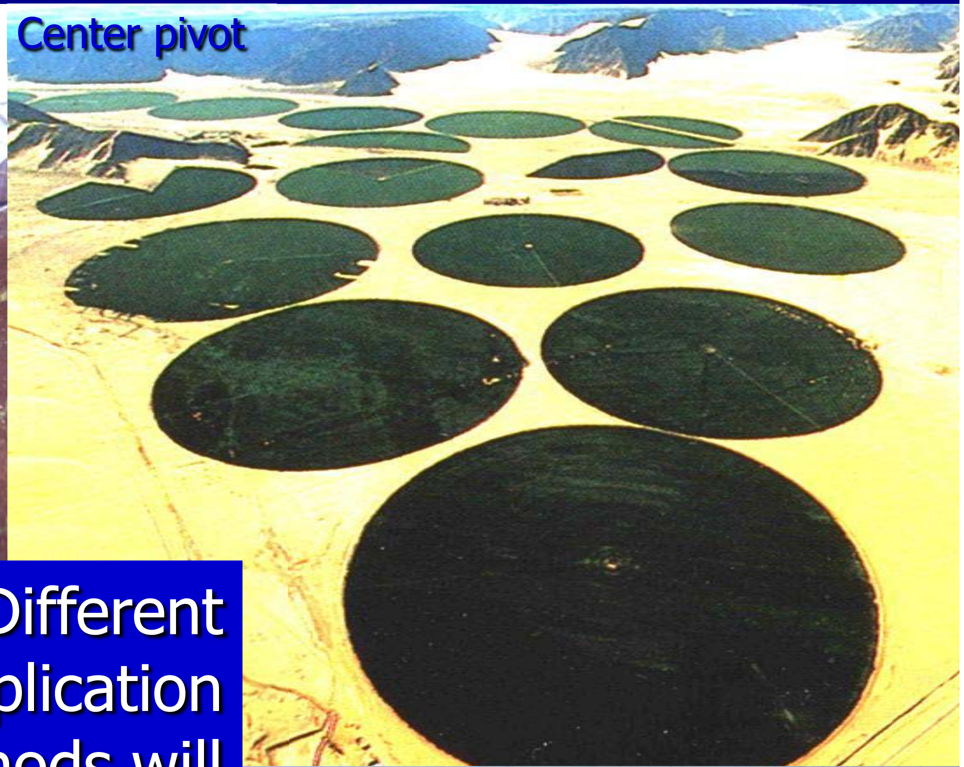
Soil (Yolo clay loam) evaporation measured hourly on large (6.1 m diameter) lysimeter after a sprinkler irrigation

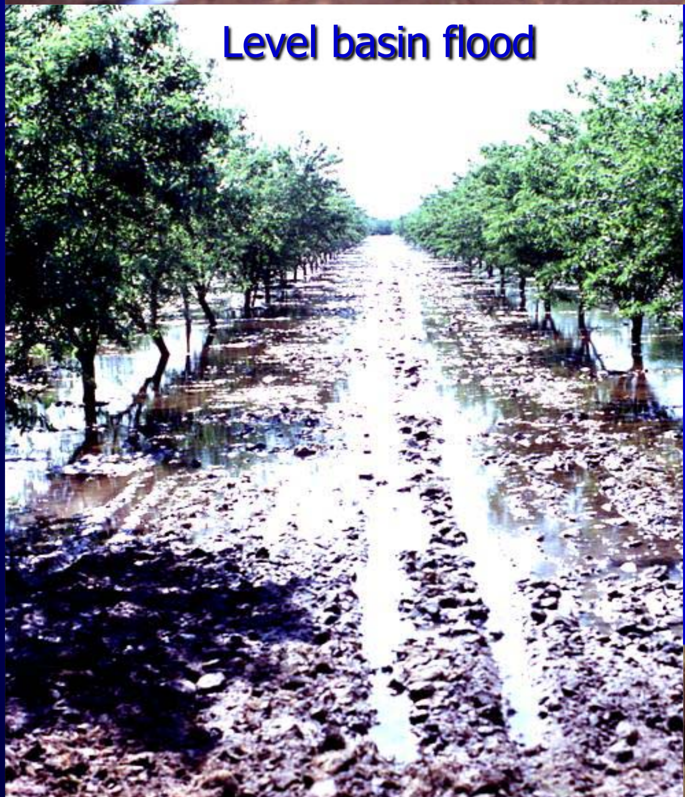


Soil (Yolo clay loam) evaporation measured hourly on large (6.1 m diameter) lysimeter after a furrow irrigation



Large lysimeter (6.1 m diameter) used to measure ET in the field in Davis





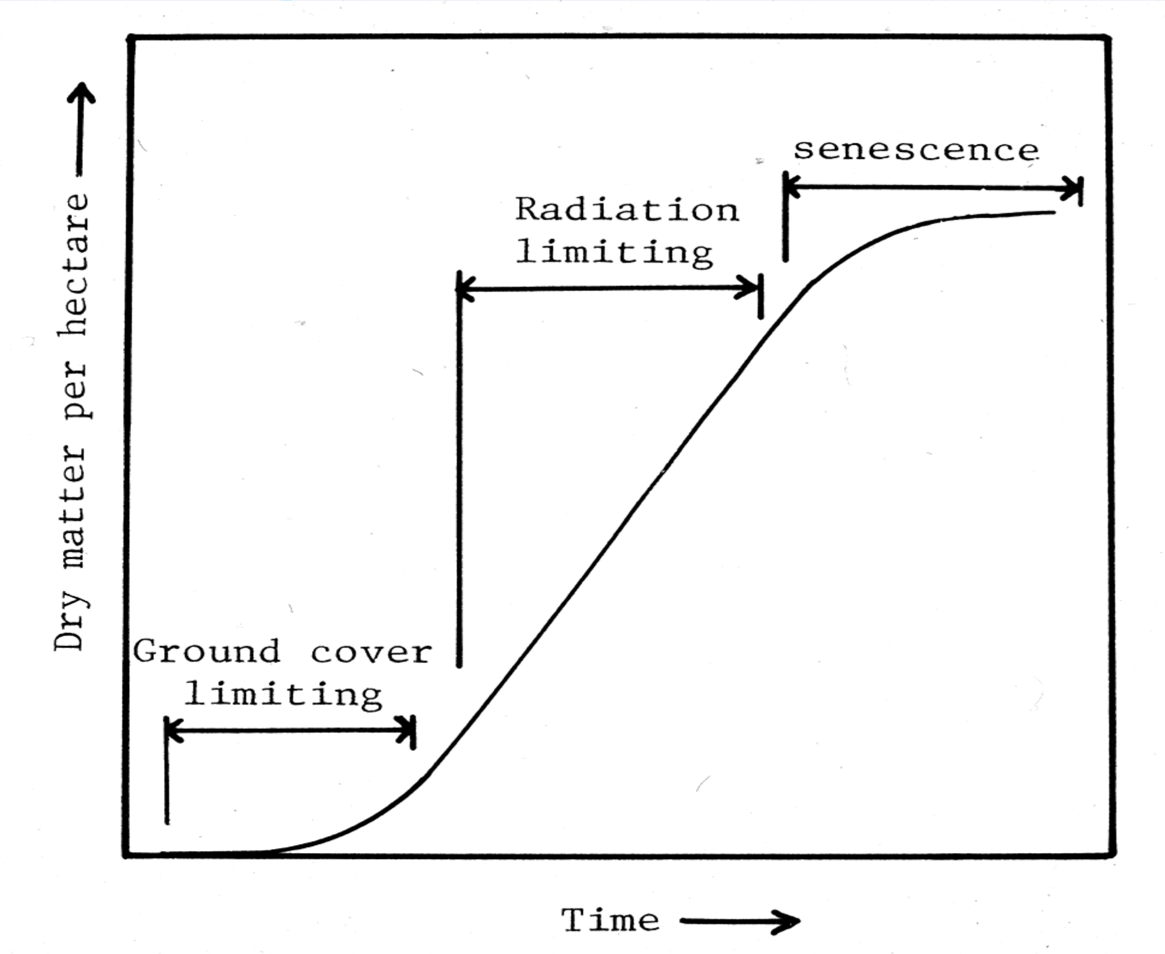
Different application methods will result in different durations of Stage 1 evaporation

$K_c = f($soil surface wetness, canopy cover extent, stomatal opening$)$

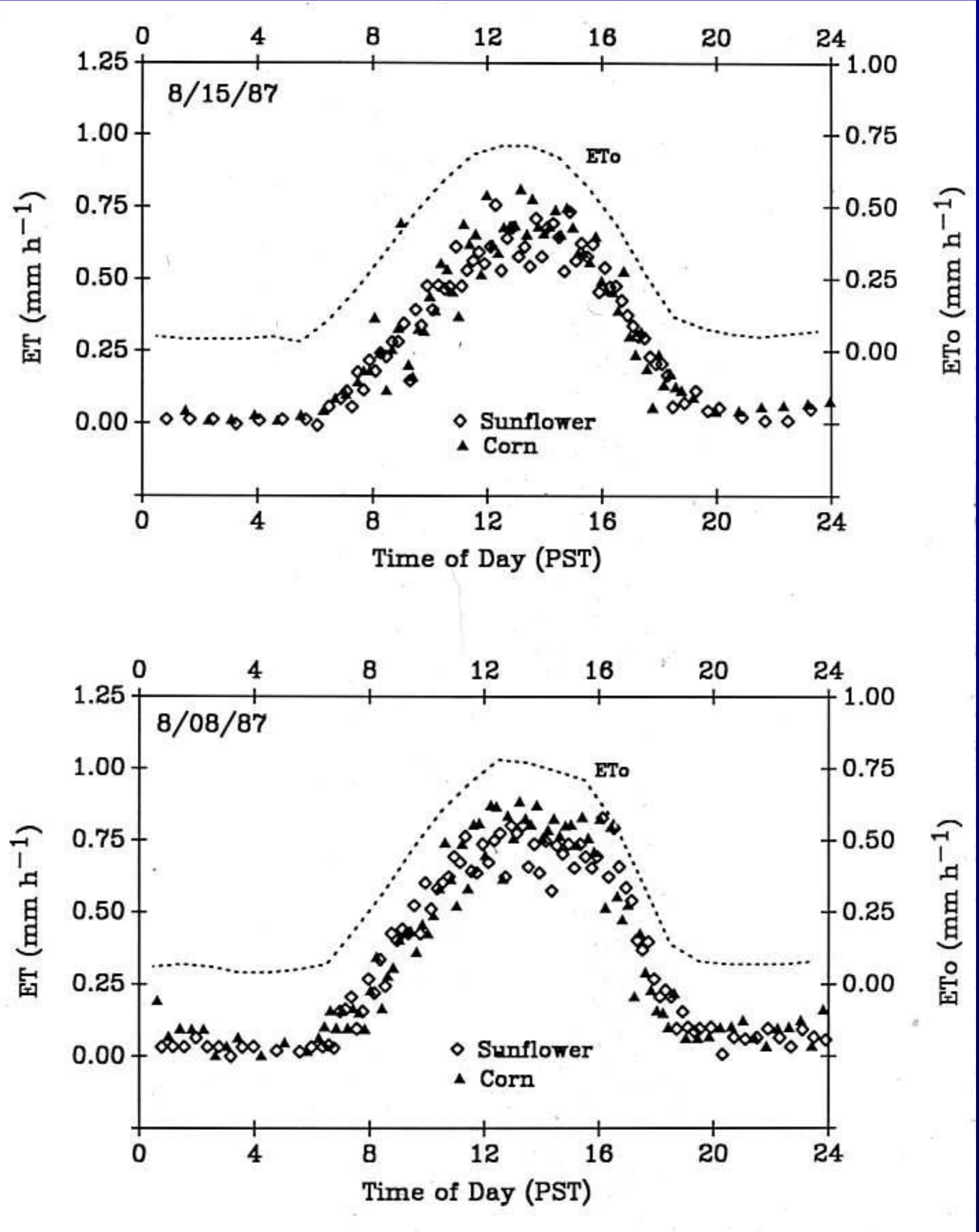
Irrigation & rainfall frequency & amount	Soil hydraulic properties	Evapor-ation rate	Plant density and pattern	Canopy growth rate	Leaf sene-scence	Water stress	Nutrient defici-ency

Three Phases of Seasonal Crop Cycle—Link between Crop Coefficient and Biomass Production Rate

Phase 1	Phase 2	Phase 3
K_c <1.0	1.0< K_c <1.2	K_c <1.0
rising	steady	falling



- The three phases of crop coefficient (K_c) correspond to the three phases of biomass production.
- The rise in K_c with time in phase 1 is mostly the result of canopy development.
- Phase 2 is reached when the canopy closes.
- The fall in K_c with time in phase 3 is the result of leaf senescence as the crop matures.



- After canopy closure, many crops have a K_c between 1.0 and 1.15 under non-stressed conditions

Transport equation for latent heat

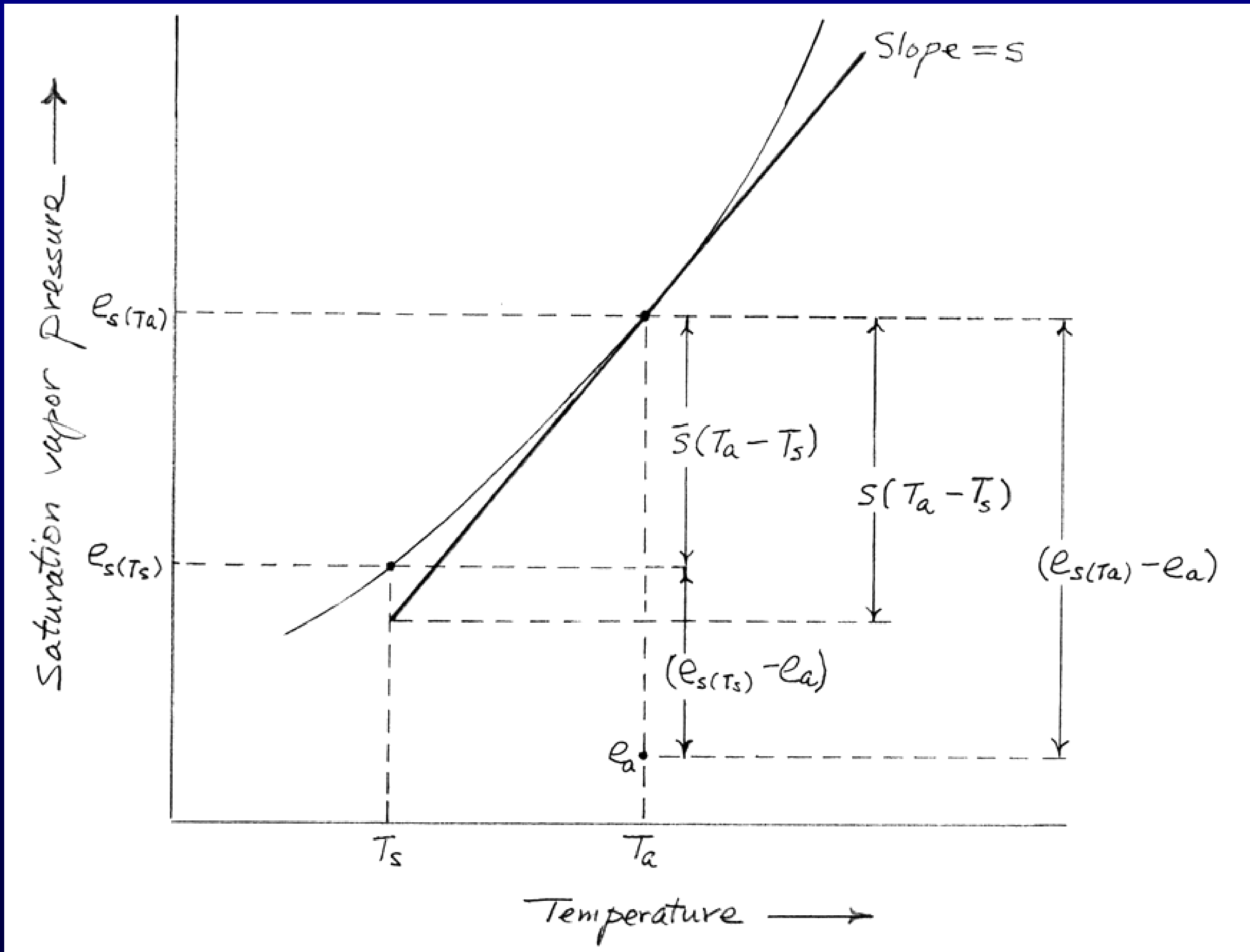
$$lE = l\rho_a K_w \frac{\Delta q}{\Delta z} = l\rho_a g_w \Delta q$$

Transport equation for sensible heat

$$H = \rho_a c_p K_h \frac{\Delta T}{\Delta z} = \rho_a c_p g_h \Delta T$$

Penman's approximation of e_e (saturation vapor pressure at the surface

Measured:	e_a (air vapor pressure), T_a (air temperature)
Known:	curve of saturation v. p. vs. water temperature
Approximation:	slope of straight line (s) = average slope of curved line ($\bar{s}$)



Penman combination equation

$$lE \cong \frac{s(-R_n - G) - \rho_a c_p g_a (e_{s(T_a)} - e_a)}{s + \gamma}$$

Penman-Monteith combination equation

$$lE \cong \frac{s(-R_n - G) - \rho_a c_p g_a (e_{s(T_a)} - e_a)}{s + \gamma\left(1 + \frac{g_a}{g_c}\right)}$$

Topical Outline

- Some basics of plant-water relations
- Important responses of plants to water deficit and significance in adaptation
- Dependence of biomass production on radiation capture
- Evapotranspiration and crop water requirement
- Crop productivity as related to water supply and deficit
- Crop water use efficiency and its improvement

Response of key processes to water stress and adaptive advantage

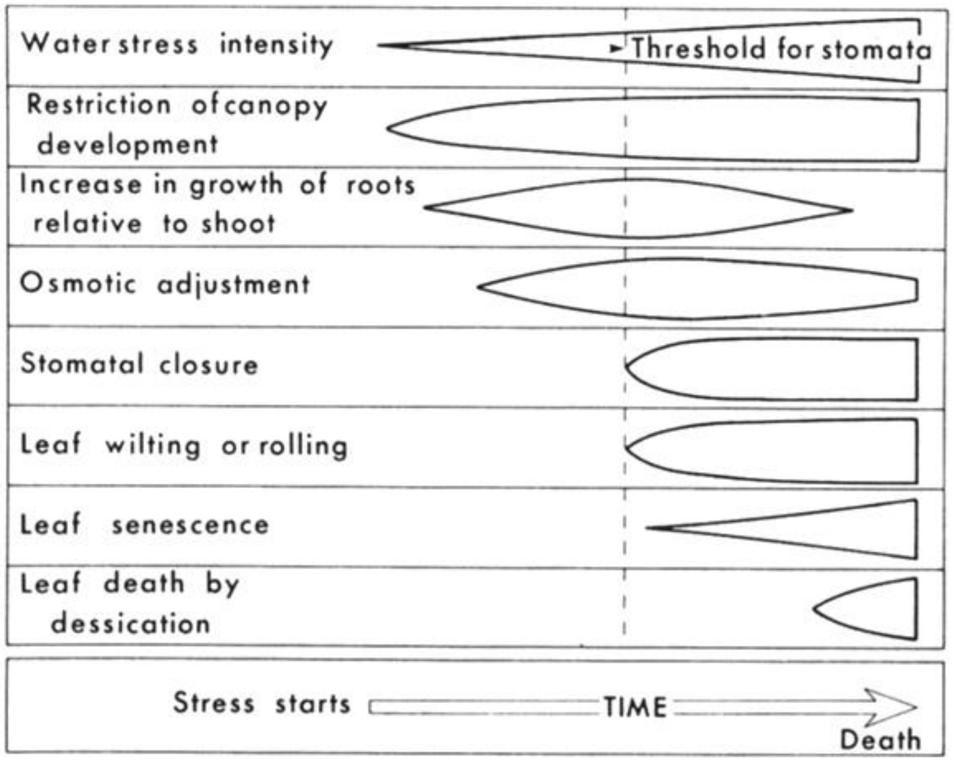
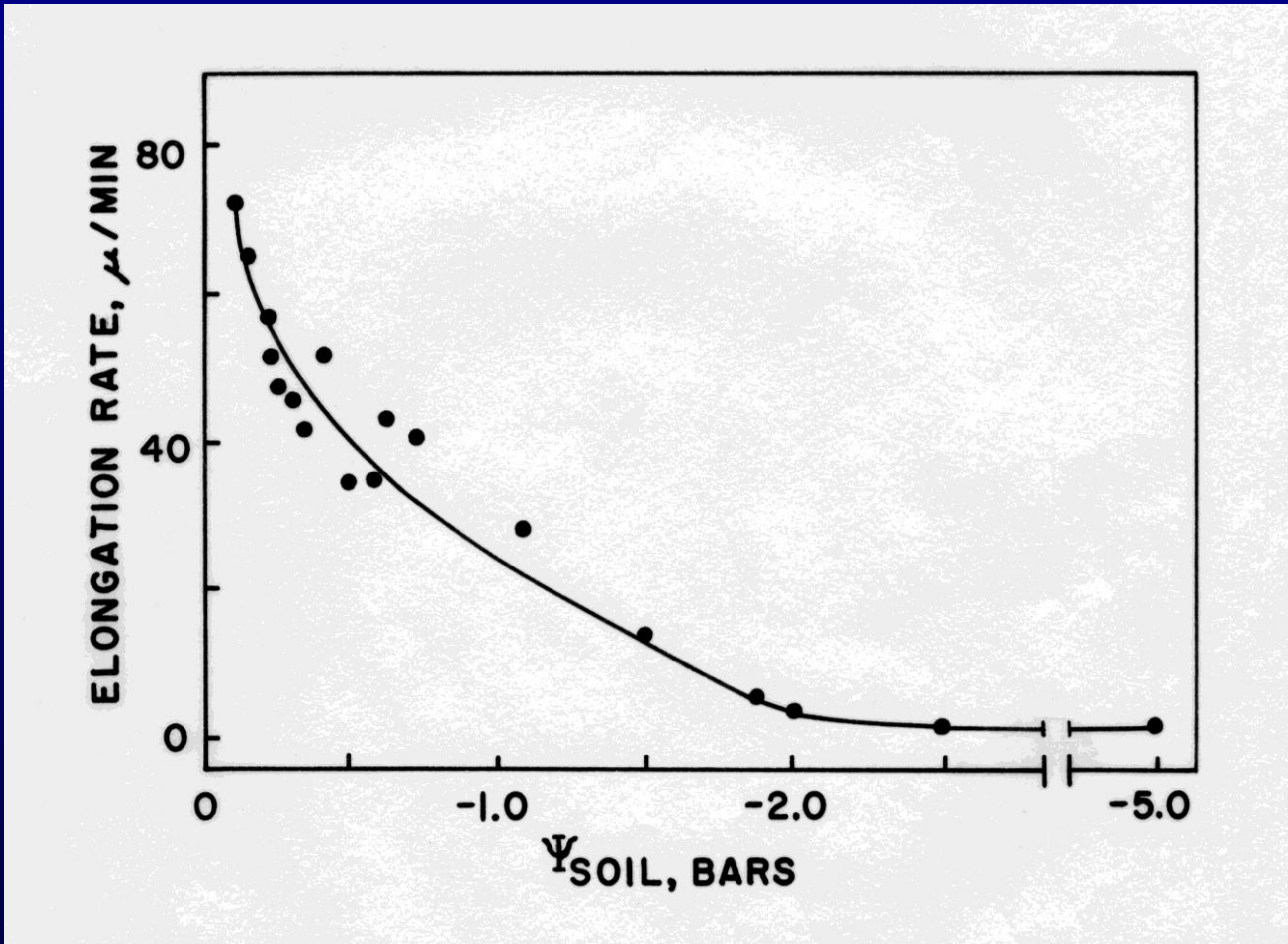


Fig. 9.7. Generalized time course of gross and adaptive changes in crop plants in response to the gradual development of water stress in the field. Width of the band at a given time represents the relative magnitude of the given response. The starting position of each band on the time scale is also indicative of the threshold water stress level for eliciting the response. Band shape reflects variations of the response with increasing stress intensity and duration. For example, preferential growth of roots relative to shoot is depicted to be nearly maximum near the threshold for stomatal closure, but declines as the soil dries out further and soil mechanical impedance rises

The earliest (first) response is the slowing of leaf growth

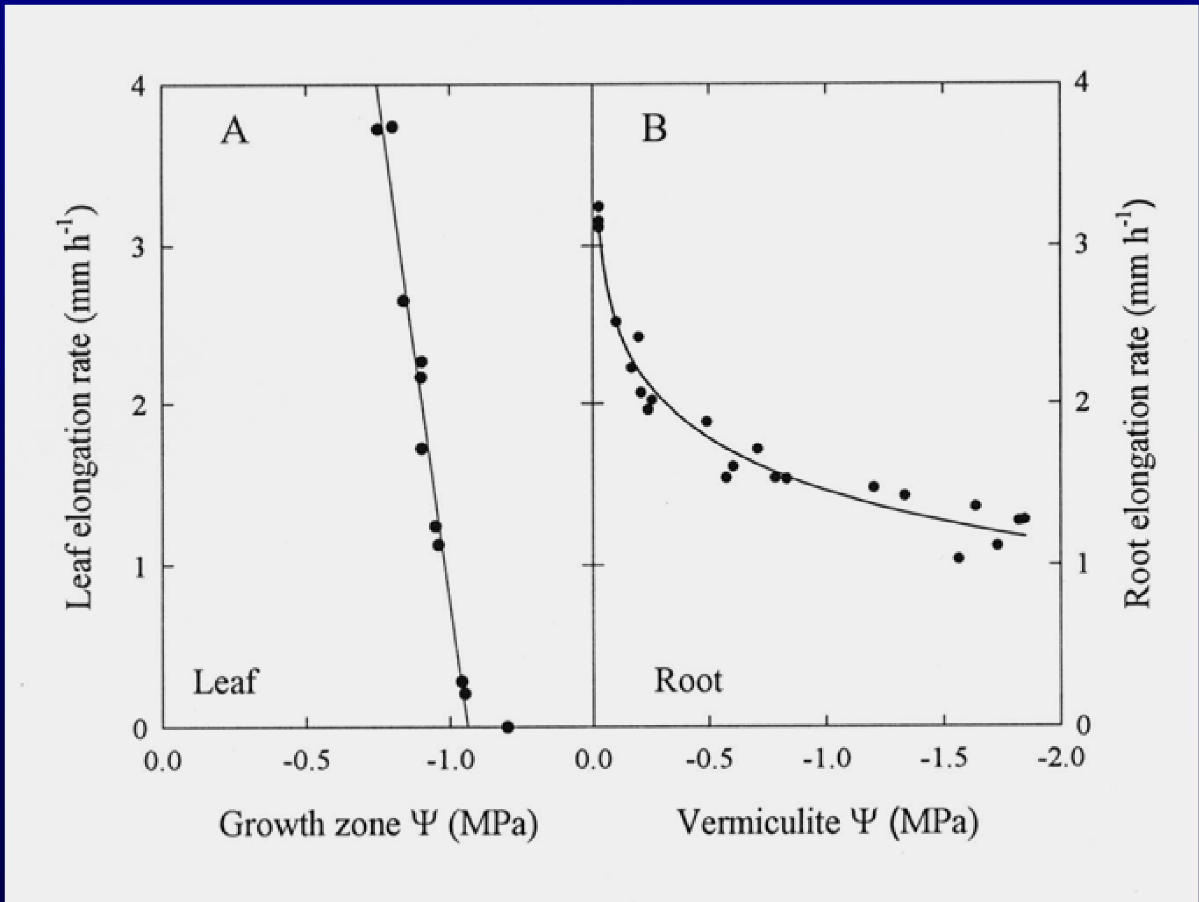


- Growth of leaves is very sensitive to water stress (deficit)
- Any reduction in soil Ψ slowed leaf growth
- Leaf growth essentially stopped when soil reached -2 bar (-0.2 MPa in this case

Maize plants growing in pots

Leaf growth is much more sensitive to water stress than root growth

As water stress develops, root growth is favored and the ratio of root/shoot increases



Maize seedlings with roots in soil or in vermiculite

Leaf growth decreased steeply as Ψ decreased, and stopped when Ψ reached -1.2 MPa (-12 bar)

Root growth was slowed but not stopped even at a medium Ψ of -1.8 MPa (-18 bar).

Hence, root/shoot ratio increases with stress.

Soil water is exploited more by the plant, enhancing it water supply

Response of key processes to water stress and adaptive advantage

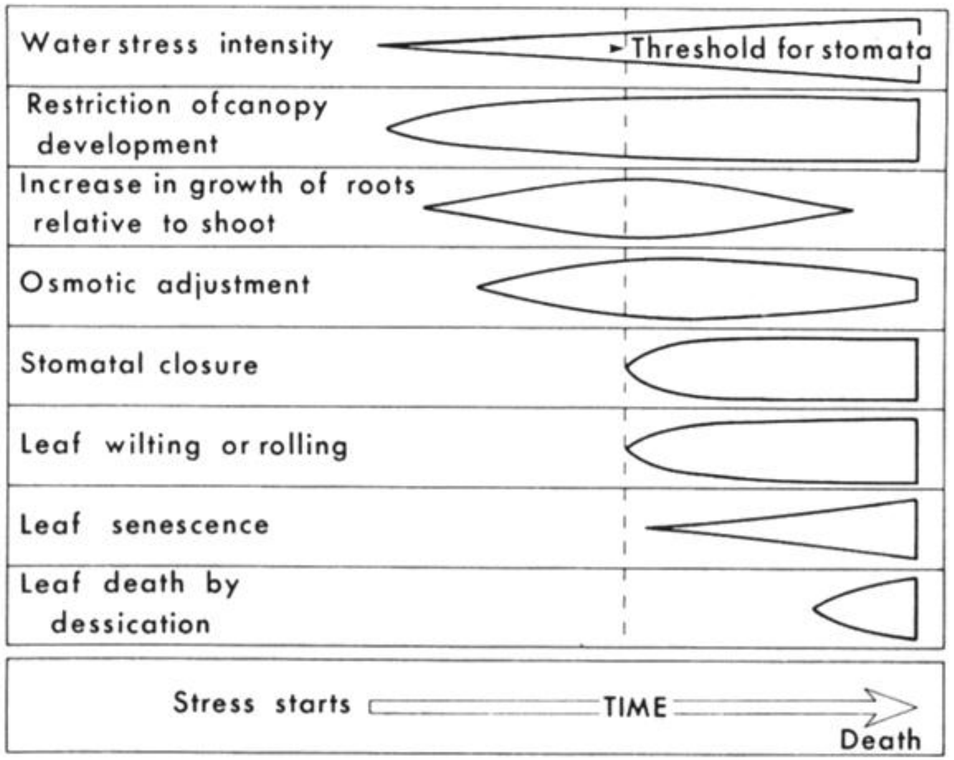
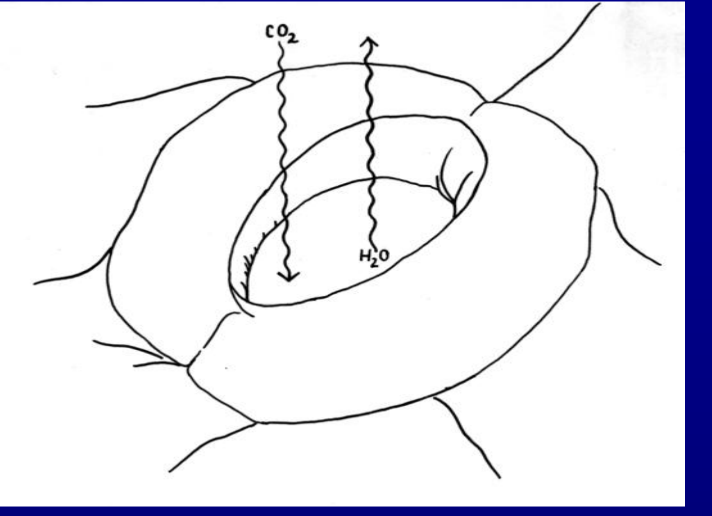
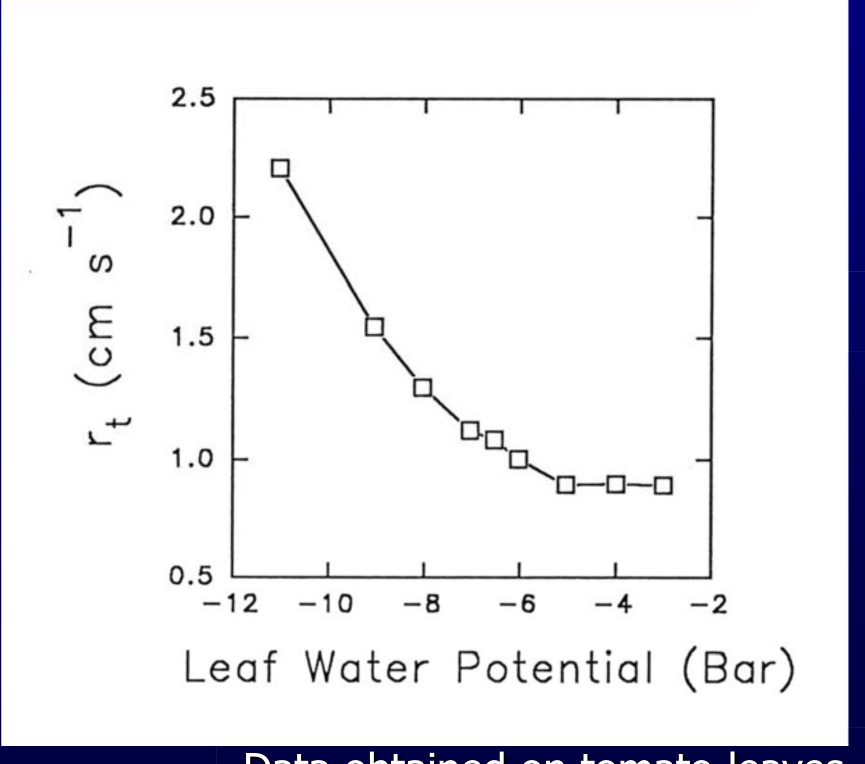


Fig. 9.7. Generalized time course of gross and adaptive changes in crop plants in response to the gradual development of water stress in the field. Width of the band at a given time represents the relative magnitude of the given response. The starting position of each band on the time scale is also indicative of the threshold water stress level for eliciting the response. Band shape reflects variations of the response with increasing stress intensity and duration. For example, preferential growth of roots relative to shoot is depicted to be nearly maximum near the threshold for stomatal closure, but declines as the soil dries out further and soil mechanical impedance rises



The degree of stomatal opening is measured by resistance of the leaf epidermis to water vapor diffusion, r_s. For the data below, $r_s \alpha r_t$ and r_t = constant + r_s.



Data obtained on tomato leaves

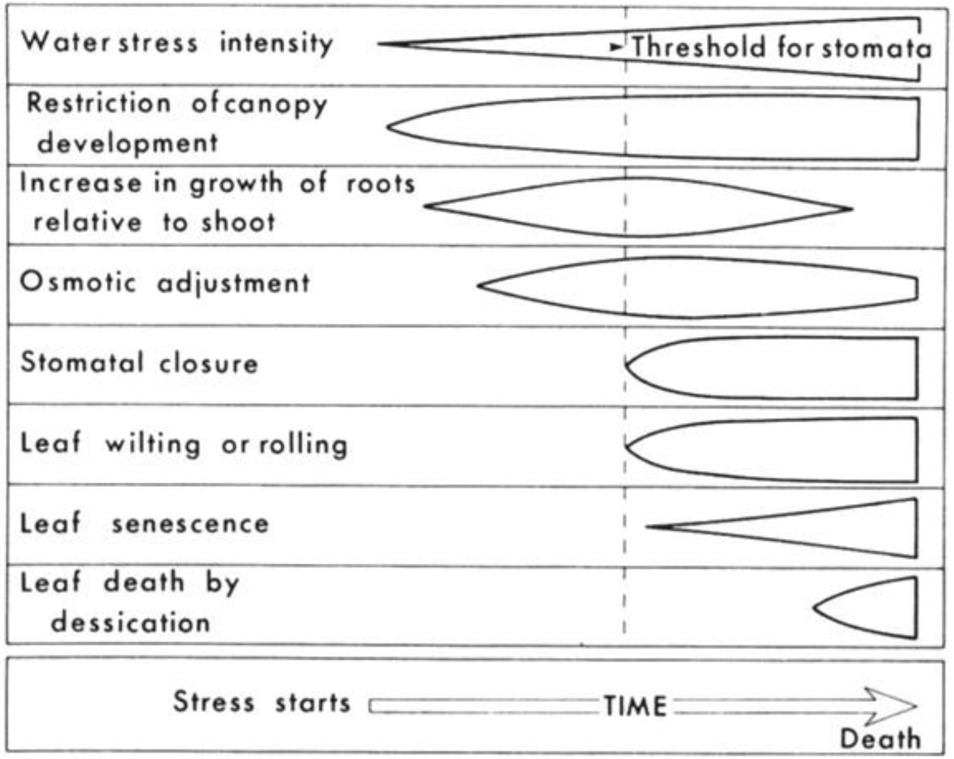
The degree of stomatal opening is partly dependent on leaf water status. Stomata begin to close as leaf water potential (Ψ) drops to some threshold value. They close more and more as leaf Ψ drops further and further.

Sunflower wilting in Southern Spain

Mild stress

Severe stress

Response of key processes to water stress and adaptive advantage



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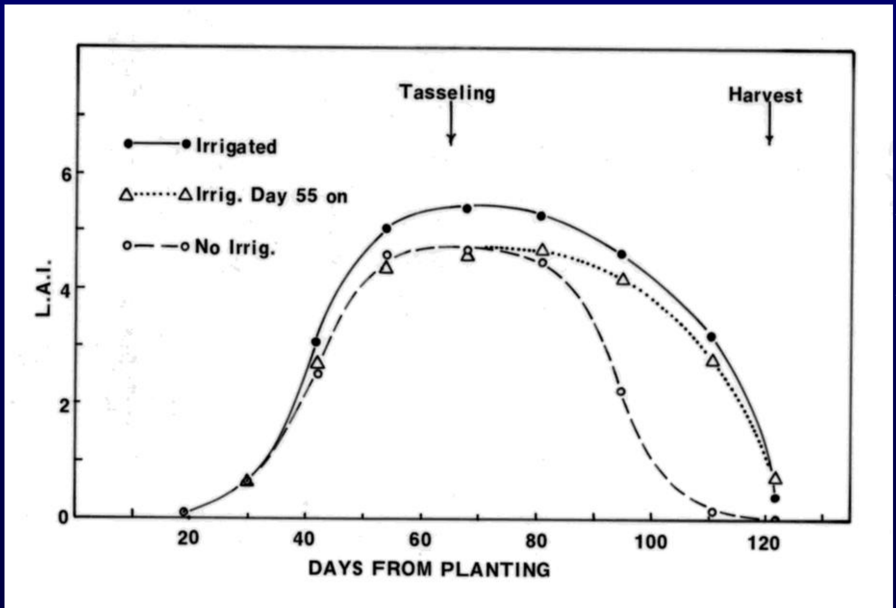
Senescence of maize leaves due to water stress

Photograph of maize taken on the same day

Well irrigated

Prolonged mild water deficit



Decline in green leaf area is accelerated under water stress. The early decline is prevented if irrigated before the decline occurs, or is stopped if irrigated after the decline begins.