Leaf Energy Budgets

I. *Introduction: the concept of an energy 'budget'*

A. Leaves interact with above-ground physical environment in two ways:
  1. energy exchange = light absorption, heat transfer
  2. mass exchange = transpiration (water loss), photosynthesis (CO_2 uptake), trace gas emissions (e.g. isoprene)

B. Temperatures of plants vary within single ecosystem because of differences in energy exchange characteristics or differences in height within the microclimatic profile:
  1. may result in temperature differences between plants (refer back to microclimate II lecture figures)
  2. may result in differences in rates of metabolic processes
  3. may result in variations in transpiration rates

C. When leaves are at thermal equilibrium, leaf temperature (T_l) does not change so that the rate of energy absorption by the leaf equals the rate of energy loss. The mass of the leaf can influence this. Once known, the Energy absorbed must = the energy lost as Re-radiation + Convection + Transpiration – we will review the "**terms**" of the energy balance equation first and then end by summarizing them in the full equation (see section VI below).

II. *Leaf orientation*

A. Changes in the orientation of the leaf relative to the sun (cos(i)) can affect the fraction of the direct solar radiation beam that is received by the leaf

  a. steep leaf angles (*Arctostaphylos, Simmondsia, Lomatium , Eucalyptus*)
  b. sun leaves of tree have steeper leaf angles than do the shade leaves
  c. wilting to vertical position and resulting angle change (*Helianthus, Impatiens*)
  d. leaf concavity (*Ceanothus*)
  e. leaf curling (many grasses)
  f. stem orientation - barrel cactus facing south in northern hemisphere and vice versa

B. Many of the leaf orientation characters can change under water stress (= low transpiration)

  a. increased leaf angle with water stress (*Ceanothus;* figure)
  b. paraheliotropic leaf movements (*Lupinus, Medicago, Trifolium, Macroptilion;* figures)

III. *Leaf absorptance characteristics*

A. Surface characteristics that can reduce the fraction of the incident solar radiation absorbed; reduction in absorptance is caused by an increase in reflectance

  1. hairs (*Artemisia, Encelia, Salvia*) (figure)
  2. waxes (*Eucalyptus, Dudleya*)
  3. epidermal bladders (*Atriplex*) (figure)

B. Leaf absorption of solar radiation is 400-700 nm waveband (PAR) accounts for 50% of the total solar radiation absorbed by most leaves

a typical leaf absorptance (400-700 nm) is for green leaves is 0.85 (= 85%)

hairs, waxes or epidermal bladders can reduce PAR absorptance to 0.30

C. Absorptance of solar radiation by leaves in 400-3,000 nm waveband averages 0.50 across many different leaf types (figure). Much of this absorptance is linked to water and how it absorbs in the near infrared wavebands where the leaf does not;

$$a_{400-3000} = 0.73 \bullet a_{400-700} - 0.119$$

IV. *Transpiration*

A. Leaf transpiration rate (E) can be described using an electrical resistance [Ohm's Law] analogy

$$E = (e_l - e_a) / (r_s + r_a) = (e_l - e_a) \cdot g$$

where: g = total leaf conductance to water vapor; r_s = stomatal resistance; r_a = air boundary layer resistance; $(e_l - e_a)$ = the water vapor gradient between inside the leaf (l) and the outside air near the leaf surface (a).

B. The saturated air water vapor pressure (also = leaf vapor pressure) rises exponentially with increasing temperature (figure)

C. Leaf conductance depends on density and diameter of stomatal pores (figure)

Stomatal distributions

Wild plant species in a British woodland (Salisbury, 1928, Weyers and Meidner, 1990)

Average # of Stomates per mm^2 of leaf area

life form	# of species	upper surface	lower surface
trees	26	0	223
shrubs	29	0	196
shade herbs	40	7	86
sun herbs	110	20	145

Crop species	upper surface	lower surface
Avena sativa	51	45
Hordeum vulgare	72	85
Triticum vulgare	50	40
Zea mays	98	108-200
Helianthus annuus	120	175
Medicago sativa	169	188
Nicotiana tabacum	50	190-235

Tree Species	upper surface	lower surface
Pinus strobus	28	121
Acer saccharum	66	182
Acer negundo (male)	65	189
Acer negundo (female)	59	255
Populas fremontii	26	310
Salix alba	111	128
Quercus rubra	9	144
Banksia pryinoides	22	92
Eucalyptus regnans	76	134
Eucalyptus marginata	109	105

V. *Convection*

A. Convection coefficient (h_c) is related to the resistance in the boundary layer around a leaf to the turbulent transfer of heat as,

$$h_c = c_p \rho / r_a$$

where: c_p is the volumetric heat capacity of air, ρ is the density of air and the boundary layer resistance (r_a) is a function of wind velocity (m/s), leaf width (m), and leaf shape (k_1 - a value near 4.0) as,

$$r_a = k_1 \sqrt{\text{leaf width / wind velocity}}$$

B. Boundary layer decreases with increasing wind speed (figures)

C. Boundary layer decreases also with (figures):

   1. decreased leaf size
   2. increased leaf serration
   3. increased leaf lobing
   4. compound leaves

D. Effective heat transfer across the boundary layer decreases with leaf size (figure)

E. Leaf size decreases with increasing water stress:

   1. leaf tearing (*Musa*)
   2. lobed leaves (sun x shade)
   3. pinnate and compound leaves
   4. filiform leaves
   5. seasonal leaf dimorphism (*Brassica*)

VI. *Energy budget equation*

A. As noted above in section I. We draw the abovementioned terms together in the form of the Energy Balance Equation that states, at thermal equilibrium, leaf temperature does not change and the rate of energy absorption by the leaf equals the rate of energy loss (influenced by mass). Therefore, Energy absorbed = Re-radiation + Convection + Transpiration (W m^{-2}):

$$\overbrace{a \cdot \cos(i) \cdot S_{direct} + [a \cdot S_{diffuse}] + \varepsilon \cdot R}^{\textbf{Energy in}} = \overbrace{\varepsilon \cdot \sigma \cdot (T_l+273)^4 + h_c \cdot (T_l - T_a) + k \cdot L \cdot (e_l - e_a) \cdot g_{tot}}^{\textbf{Energy out}\text{ (@ equilibrium)}}$$

<u>external parameters</u>:

S_{direct} - incident direct solar radiation on leaf (300-4,000 nm)
$S_{diffuse}$ - incident diffuse solar radiation on leaf (300-4,000 nm)
R - terrestrial infrared radiation (includes both sky and ground components) (4,000-100,000 nm)
T - temperature of leaf (T_l) and air (T_a) in °C
e - water vapor pressure of leaf (e_l) and air (e_a) (mbar)

constants:

- σ- Stephan Boltzman constant (blackbody radiation constant- see Appendix I)
- k - constant for vapor pressure to vapor density conversion (216.68)
- L - latent heat of vaporization (converts transpiration to energy units)

leaf parameters (coupling factors):

- cos(i) - cosine of leaf orientation to the sun's direct beam (last lecture)
- a - absorption coefficient to solar radiation (300-4,000 nm)
- ε - absorption coefficient to infrared radiation (4,000-100,000 nm) = emissivity (see Appendix I)
- h_c - convection coefficient (a function of leaf characteristics and wind velocity)
- gtot - total leaf conductance (stomatal and boundary)

Appendix I. Blackbody Radiation Laws

1. Any object above O° K will emit radiation

2. The amount of radiation emitted will be proportional to the fourth power of the object's temperature;

$$R_1 = \varepsilon\sigma T^4$$

R_1 = energy emitted (W m^{-2})

ε = emissivity (0.99; dimensionless)

σ = Stephan-Boltzman constant (5.67×10^{-8} W m^{-2} K^{-1})

T = temperature (°K)

3. Weins Displacement Law - **wavelength** (λ) of maximum emission (λ_{MAX}; in nm) is;

$$\lambda_{MAX} = 2{,}897{,}000/T$$

e.g.	sun	6000 K	480 nm
	earth	283 K	10,200 nm

4. **emissivity** (ε) is a measure of how close an object is to being a perfect blackbody. HINT: compare the ε values for polished metals to the oxidized values; an oxidized metal will have high ε because of the presence of oxygen (O_2) and the O_2 allows the bonds to rotate more freely, thereby emitting more heat at a range of wavelengths and increasing the metals ε (below):

materials	emissivity
polished aluminum	.04
polished copper	.05
silver	.02
brass	.22
copper oxide	.78
new cast iron	.65
old cast iron	.80
asbestos	.96
red brick	.93
glass	.94
water	.95
quartz	.93

materials	emissivity
soils	
sand	.93-.95
loam	.96-.98
leaves	
Gossypium hirsutum (cotton)	.96
Phaseolus vulgaris (common bean)	.94

Zea mays (corn)	.94
Acer saccharum (sugar maple)	.94
Quercus robur (English oak)	.97
Helianthus annuus (sunflower)	.97

5. Sky is **not** a perfect blackbody; its emittance is a function of gas composition within the air column;

a. CO_2 and methane are "greenhouse gases" absorbing infrared radiation

b. emittance of sky is a function of water vapor content (ξ, mbar of vapor) (Brunt, 1939):

$$\xi_{air} = 0.53 + 0.06e^{0.5}$$

c. over the range of conditions typically found, Swinbank (1963) showed that the amount of IR radiation emitted from the sky (IR_{sky}, W m^{-2}) is:

$$IR_{sky} = 1.2\sigma T^4_{air} - 171$$

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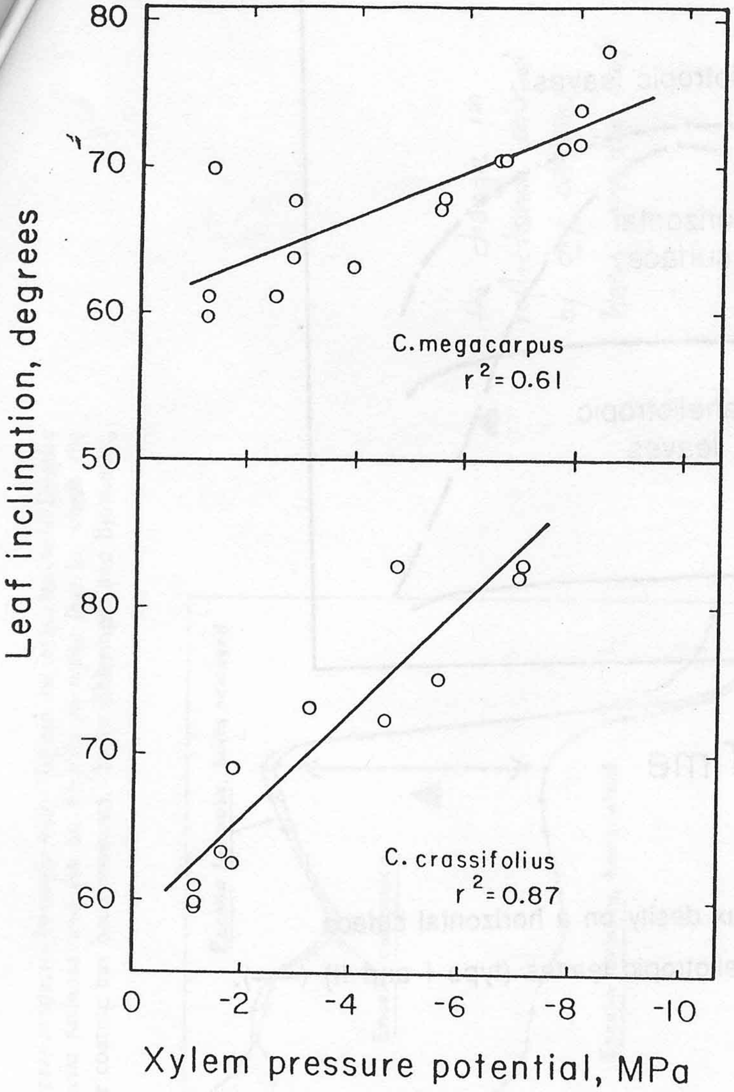
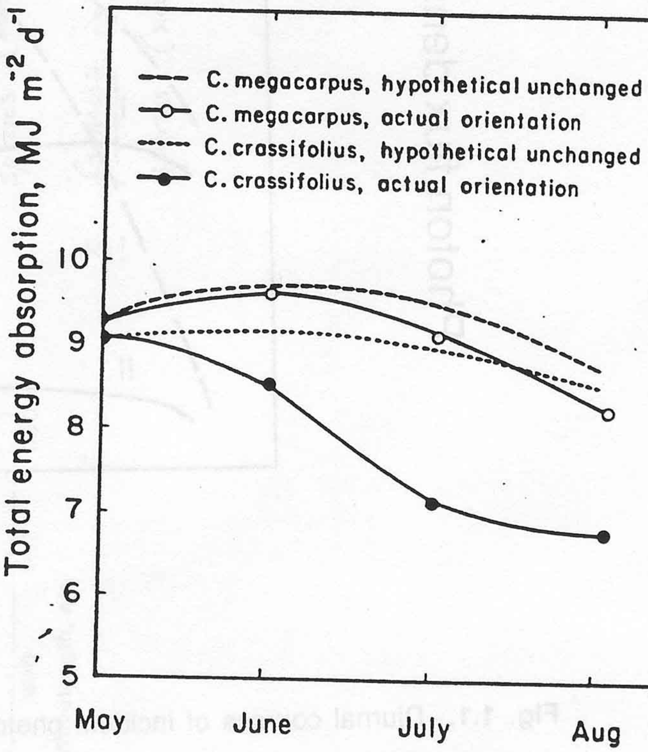
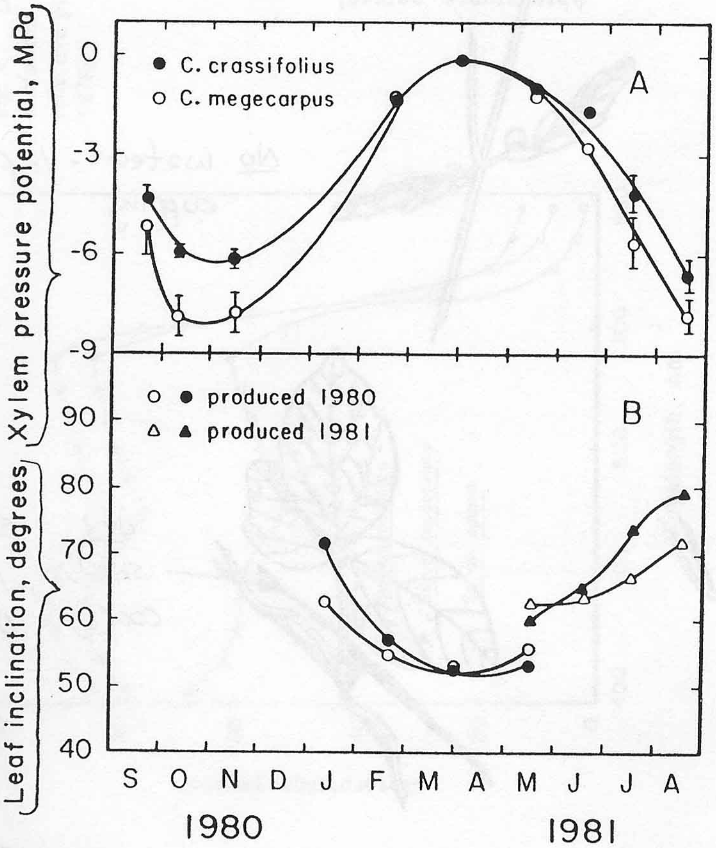




Ceanothus is a shrub widespread throughout California



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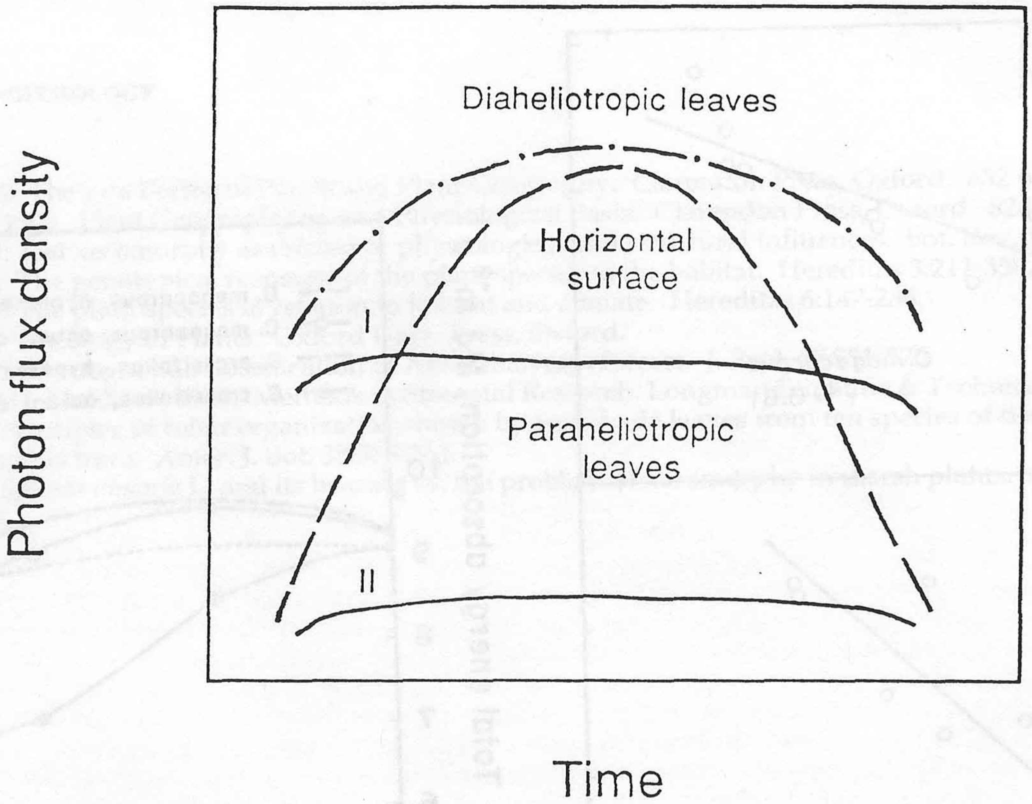
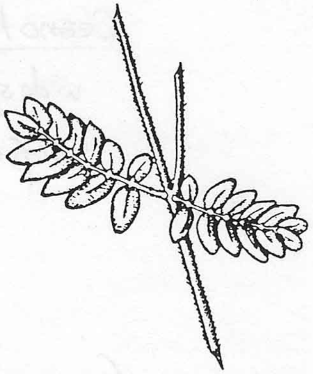
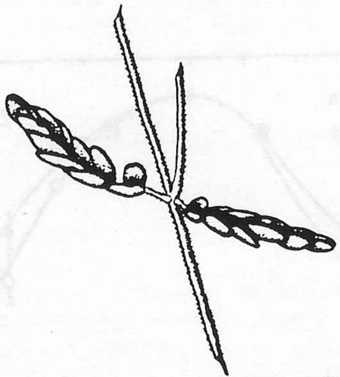


Fig. 1.1. Diurnal courses of incident photon flux desity on a horizontal suface (– –), diaheliotropic leaves (– • –), and paraheliotropic leaves (type I and II) (——).

Kalistromia (summer annual plant)

Well-watered

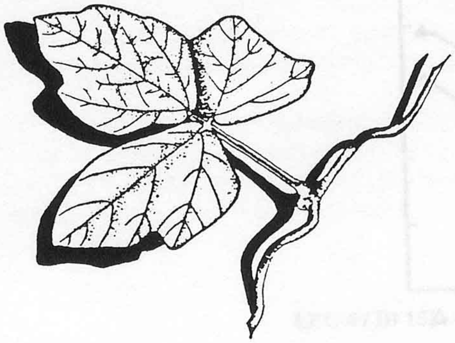


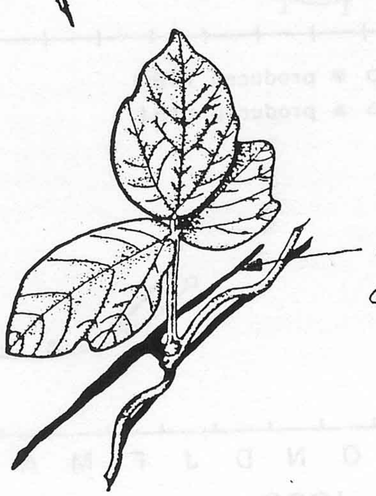


No water - leaf cupping

Macroptilion

Wet - large shadow, leaf cos(i) = 0.8, flat on ground





dry - smal shadow, leaf cos(i) = 0.11

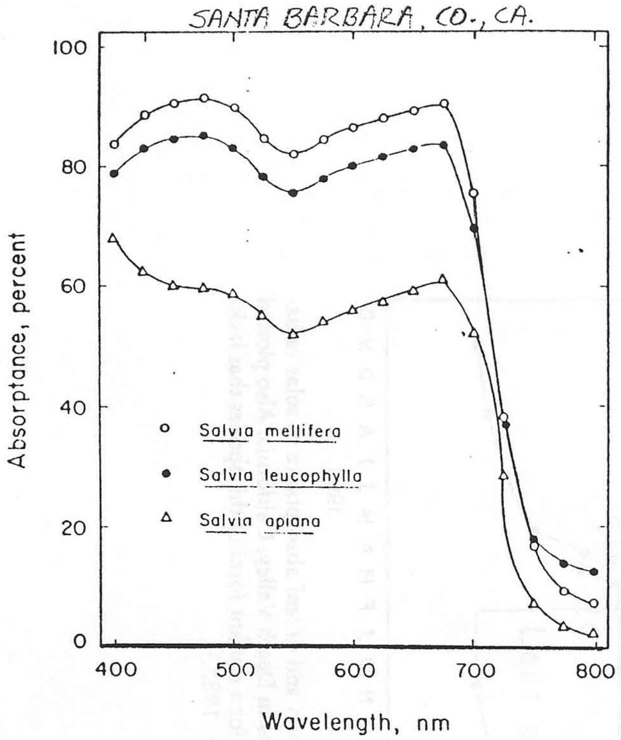
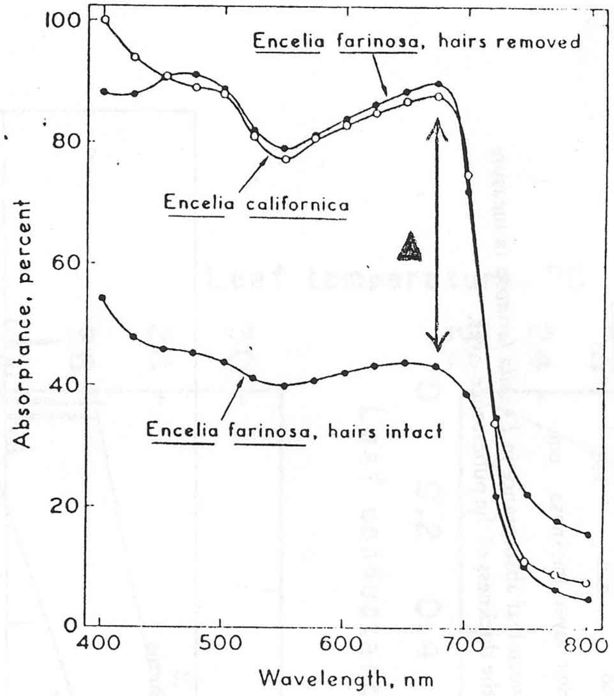


Fig. 9.7 Leaf absorptance spectra between 400–700 nm for intact leavse of *Encelia californica* and *Encelia farinosa* and for an *Encelia farinosa* leaf in which the reflective pubescence coating has been removed. (From Ehleringer and Björkman, 1978a.)



▲ = the change in reflectance caused by dry cellulose hairs on the leaf

E. californica is a coastal species (mesic)

E. farinosa is a desert species (xeric)

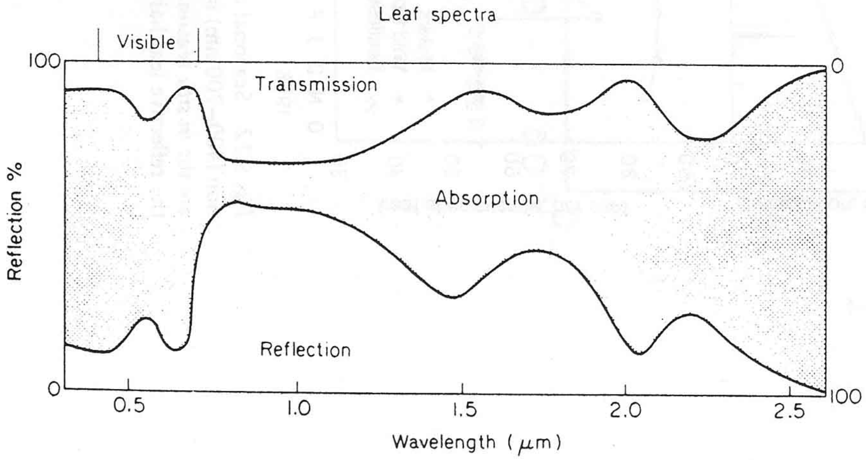


Fig. 6.5 Idealized relation between the reflectivity, transmissivity and absorptivity of a green leaf.

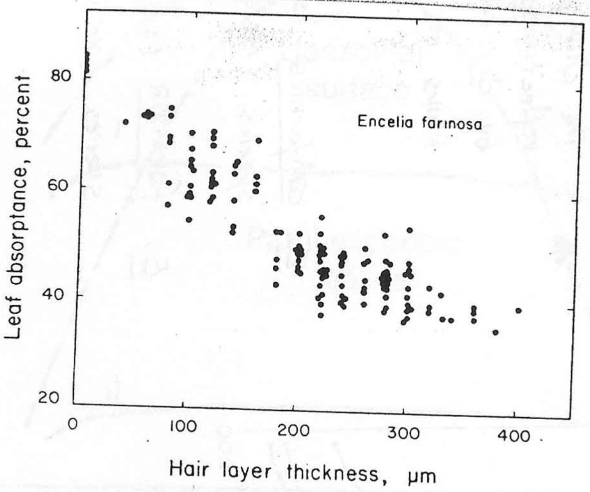


Fig. 9.9 The relationship between leaf absorptance in *Encelia farinosa* (a measure of pubescence abundance) and the thickness of the pubescence layer.

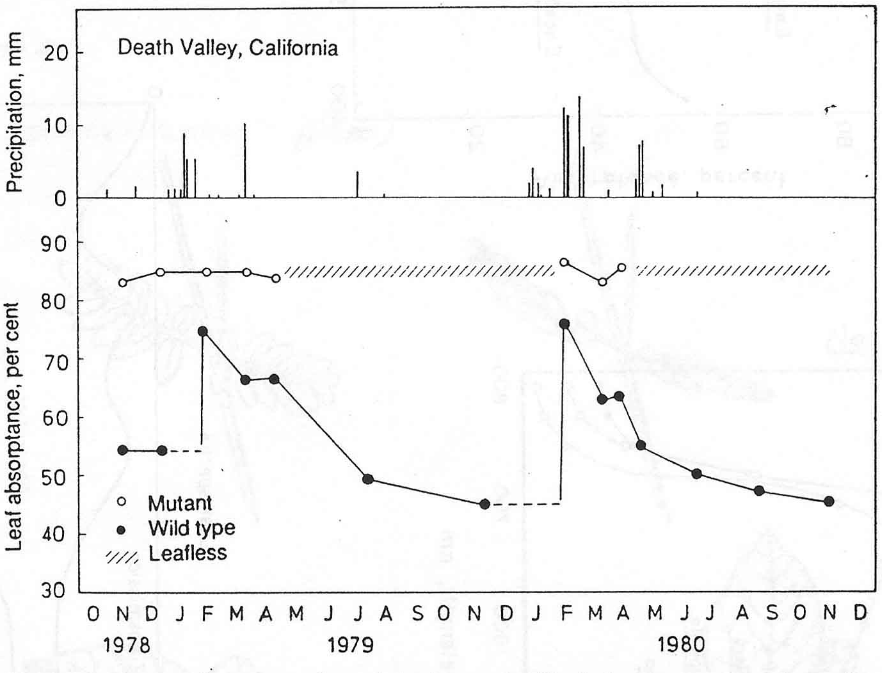
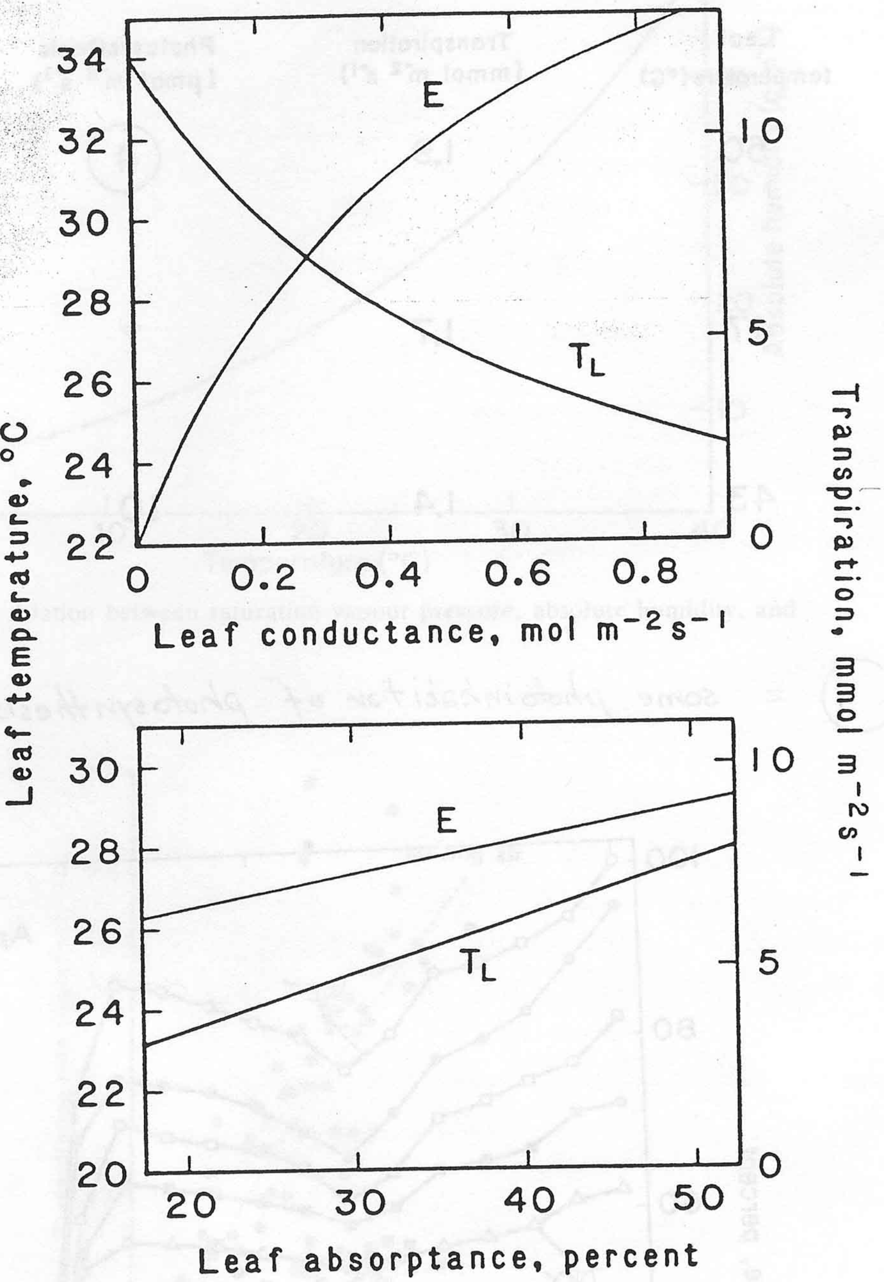


Fig. 9.12 Seasonal courses of precipitation and of leaf absorptance to solar radiation (400–700 nm) in leaves of *E. farinosa* in Death Valley, California. **Also plotted** are the ***in situ*** seasonal leaf absorptances for a mutant form of this species **that lacks** the reflective leaf hairs. (From Ehleringer, 1983.)


34
32
30
28
26
24
22
0
0.2
0.4
0.6
0.8
E
T_L
10
5
0
Leaf conductance, mol $m^{-2}s^{-1}$
Leaf temperature, °C
Transpiration, mmol $m^{-2}s^{-1}$
30
28
26
24
22
20
20
30
40
50
E
T_L
10
5
0
Leaf absorptance, percent

Atriplex hymenelytra summer day leaf conductance, 0.02 mol m^{-2} s^{-1}

(a species with salt bladders on leaves)

	Leaf temperature (°C)	Transpiration (mmol m^{-2} s^{-1})	Photosynthesis (μmol m^{-2} s^{-1})	WUE (μmol / mmol)
	50	1.9	④	2.1
	47	1.7	7	4.1
	43	1.4	10	7.1

○ = some photoinhabition of photosynthesis had occured

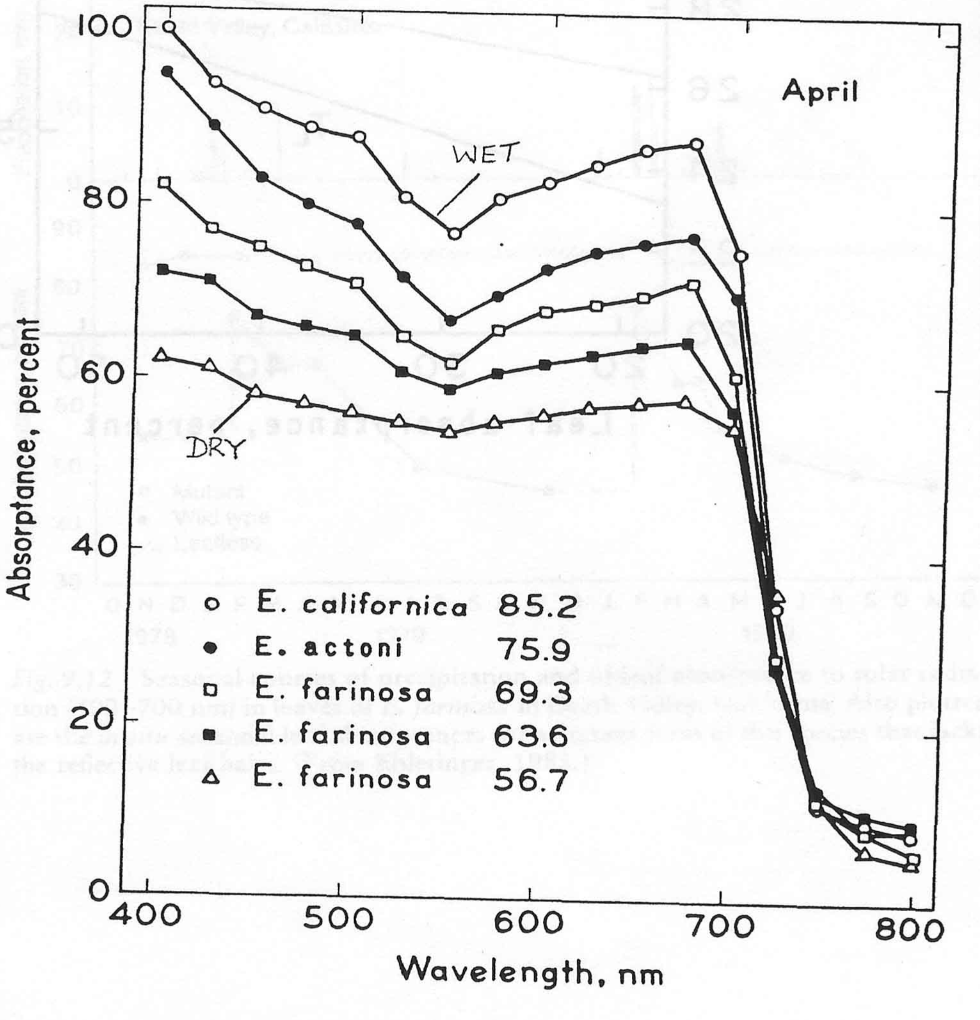


Fig. 9.11 Leaf absorptance spectra of intact leaves of *E. californica*, *E. actoni* and *E. farinosa* along an aridity gradient during April. The value adjacent to each species represents the leaf absorptance to solar radiation between 400–700 nm. (From Ehleringer, 1980.)

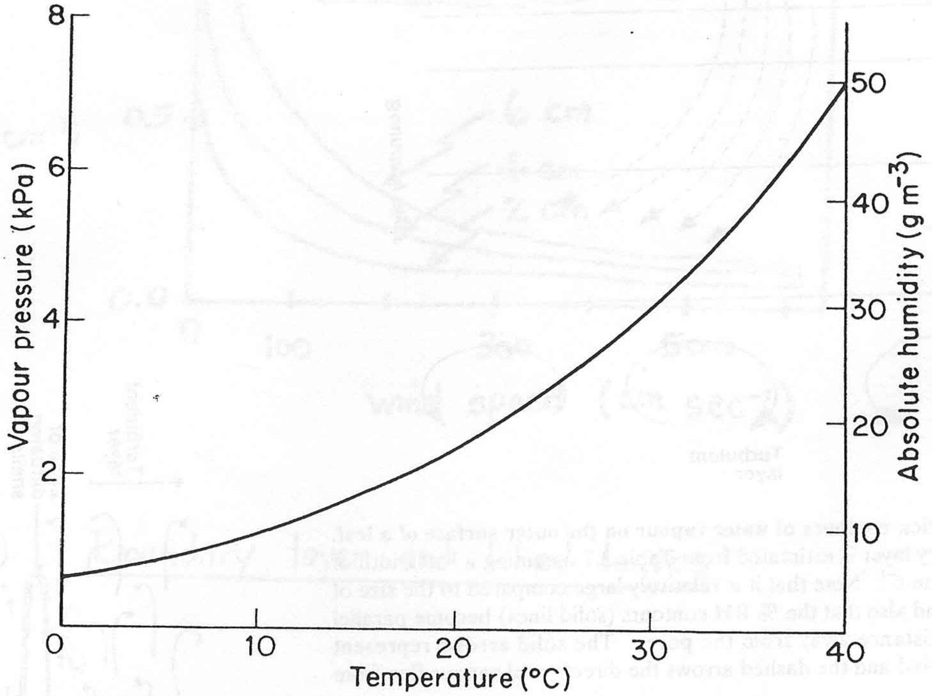


Fig. 2.1 The relation between saturation vapour pressure, absolute humidity, and temperature.

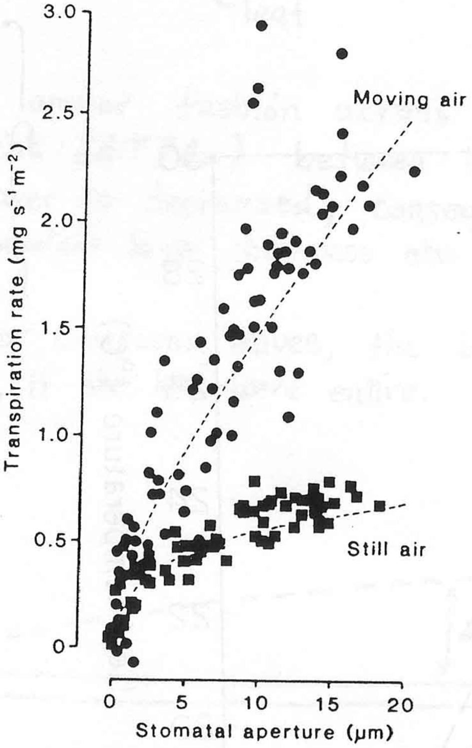


Fig. 3.5 Transpiration rate of *Tradescantia zebrina* leaves at different stomatal apertures in still and windy conditions. Adapted from Bange (1953). The data are based on gravimetric determinations of water loss over 1 - 5 min from leaf discs placed in a special holder to eliminate water loss from the edges and minimise changes in disc temperature. The VPD was 1% and the temperature 23 ± 2 °C (i.e. RH about 90 %). Stomatal apertures were estimated from 25 light microscope measurements and transpiration rates were corrected for stomatal frequency and cuticular water loss. Dashed lines are predictions based on a theoretical analysis analogous to that presented in 3.5.

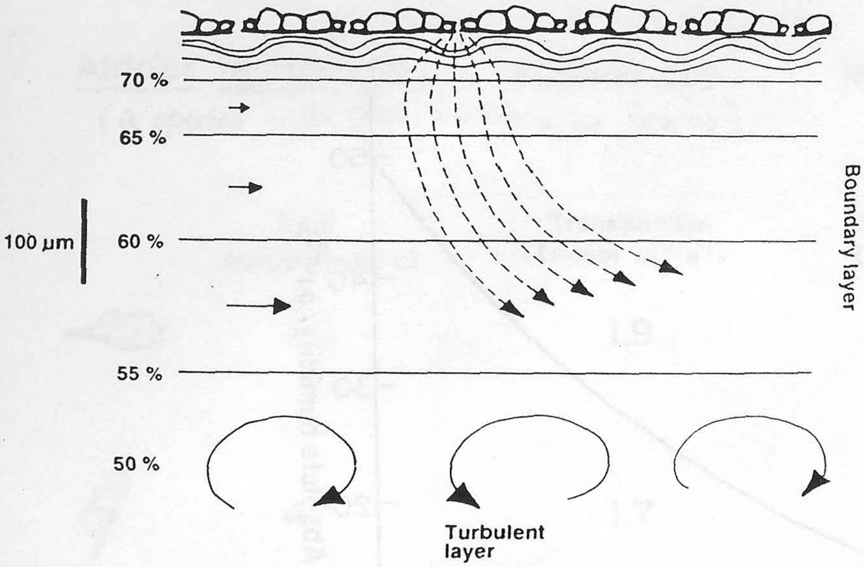


Fig. 3.3 Assumed concentration contours of water vapour on the outer surface of a leaf. The thickness of the boundary layer is estimated from Table 3.7 assuming a leaf width of 10 mm and a windspeed of 1 m s^{-1}. Note that it is relatively large compared to the size of the zone of diffusion shells and also that the % RH contours (solid lines) become parallel to the leaf surface a short distance away from the pores. The solid arrows represent direction and magnitude of wind and the dashed arrows the direction of vapour flux from one of the pores only.

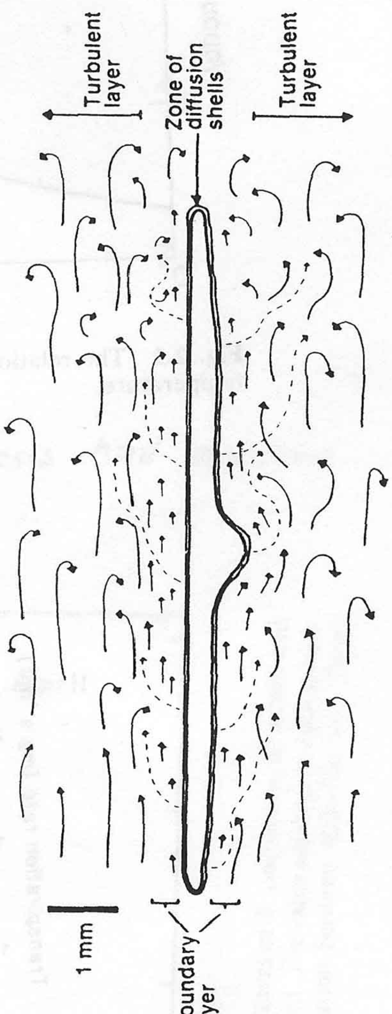


Fig. 3.4 Boundary layers and diffusion shells outside leaves. Representation of air flow pattern over a model leaf; the solid arrows indicate relative wind speed and direction and the dashed arrows the direction of vapour flux. Note laminar flow close to the leaf and turbulent regions downwind from its leading edge. Justification of scaling as in Fig. 3.3.

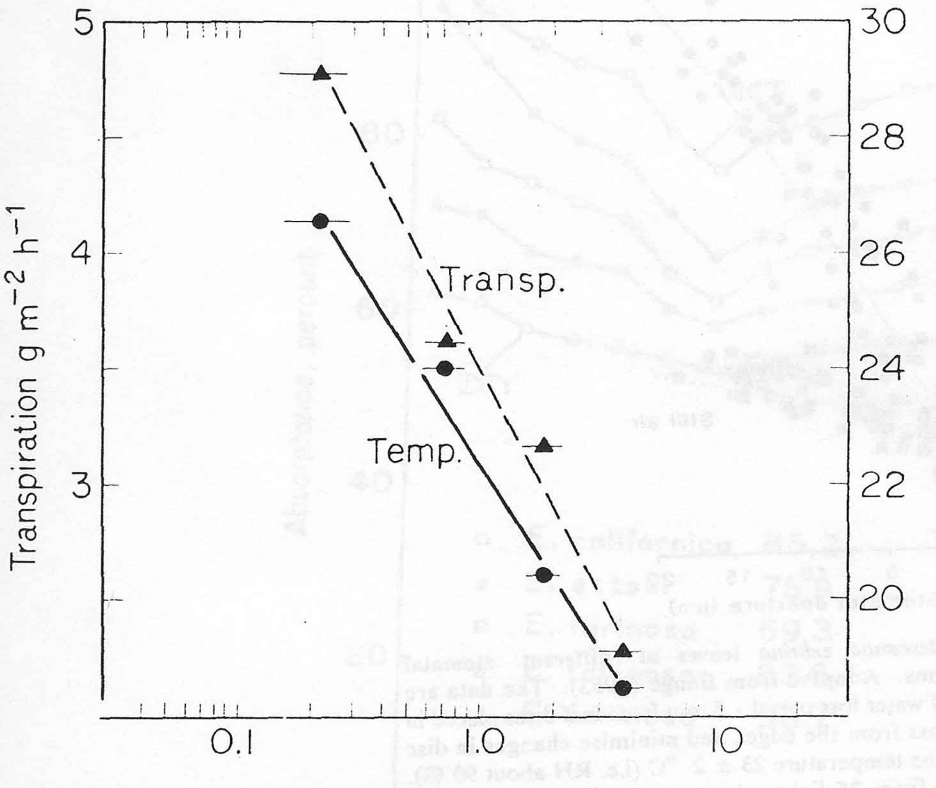
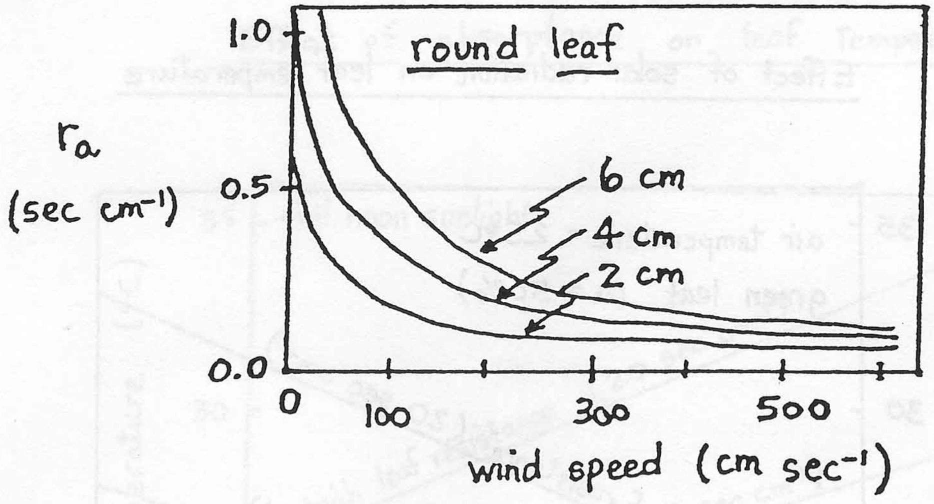
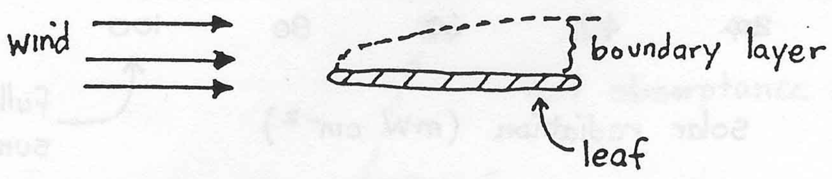


Fig. 11.5 The change of transpiration rate and leaf temperature with windspeed for a *Xanthium* leaf exposed to radiation of 700 W m^{-2} at an air temperature of 15°C and 95% relative humidity (from Mellor *et al.*, 1964).

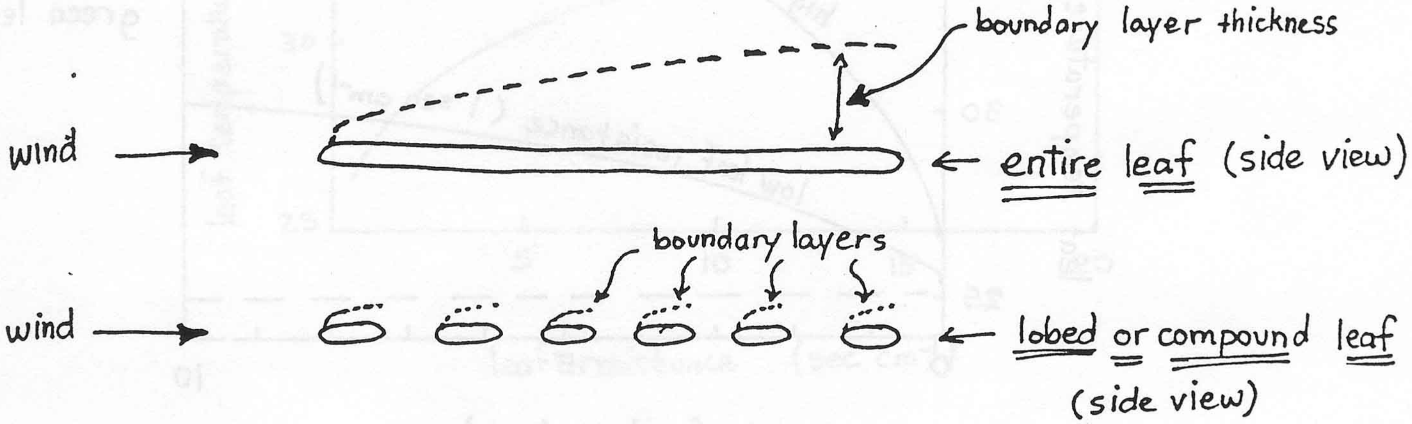


Boundary layer and lobed leaves



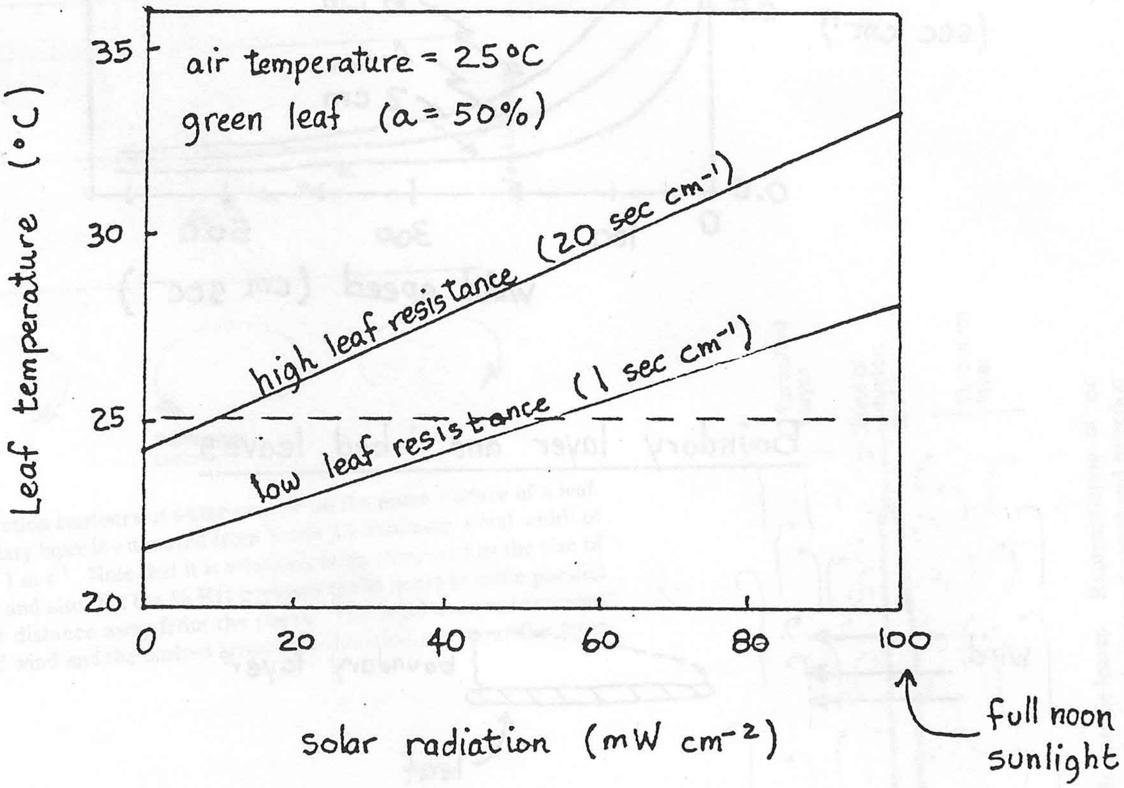
As air moves in laminar fashion across the leaf, the temperature gradient (dT/dx) between leaf and the air in the boundary layer is decreased; consequently heat exchange is decreased. Boundary layer thickness also increases across the leaf.

By having lobed or compound leaves, the boundary layer never attains the size it would if the leaf were entire.

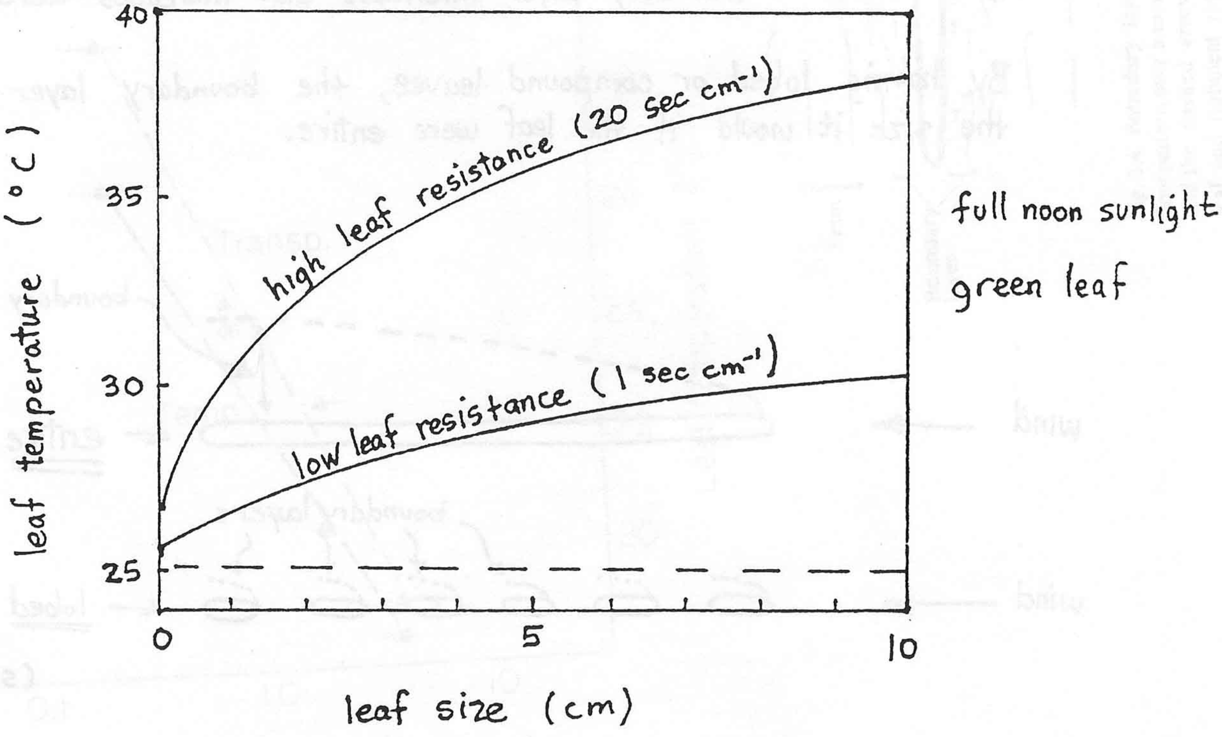


A lobed or compound leaf is a better heat exchanger than is an entire leaf.

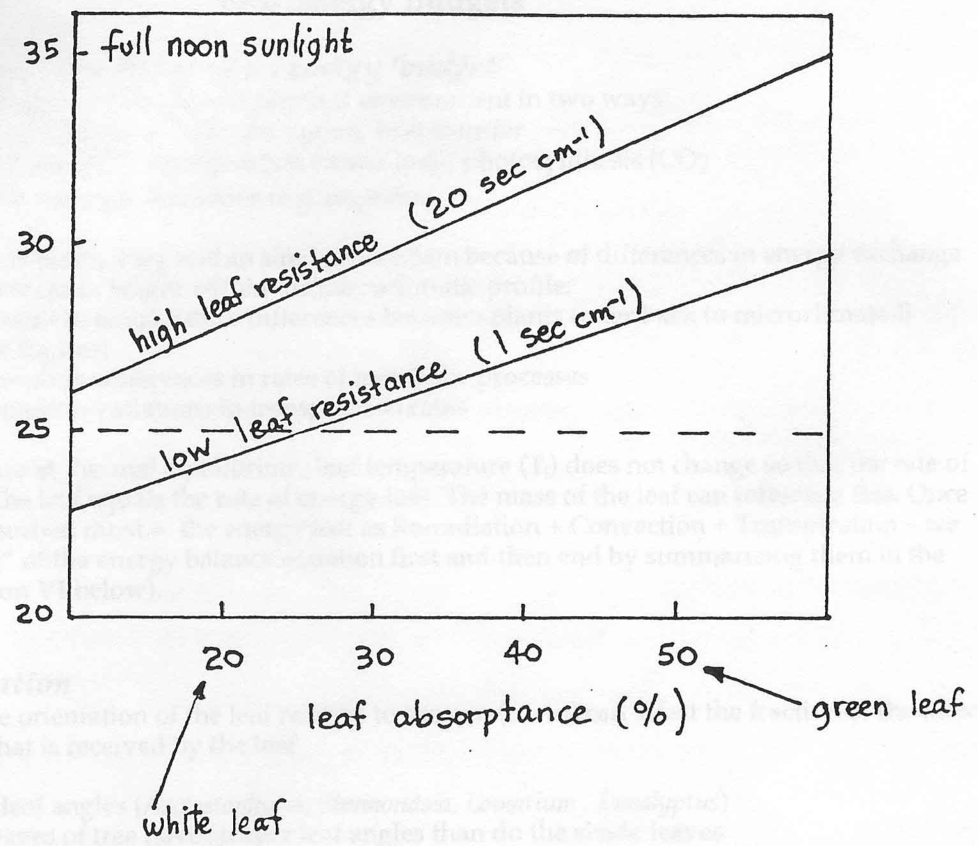
Effect of solar radiation on leaf temperature



Effect of leaf size on leaf temperature



Effect of absorptance on leaf temperature



Effect of leaf resistance on leaf temperature