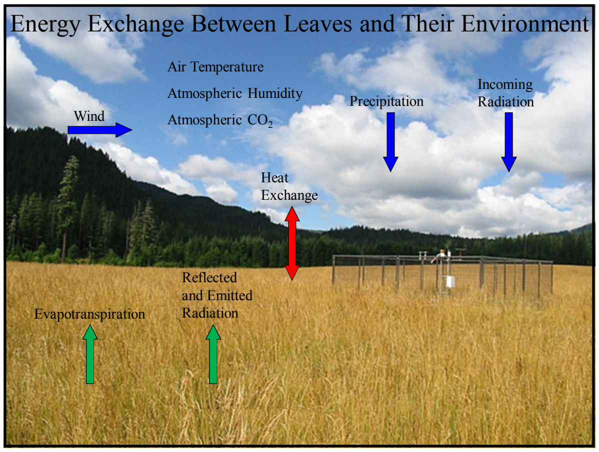


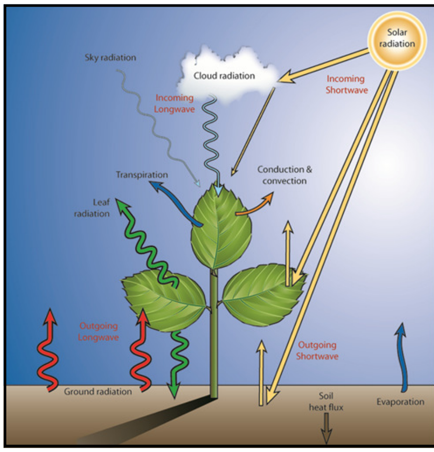
Energy exchange between leaves/plant canopies and their environment

- Leaf and canopy energy balance
- Leaf coupling factors
- Energy exchange adaptations

Leaves and plant canopies interact with their physical environment

Through energy exchange:
radiation absorption, radiation emission, heat transfer

Through mass exchange:
transpiration, photosynthesis, trace gases



Plant metabolic processes are dependent on temperature.

Leaf temperature is dependent on energy balance.

At equilibrium:
Energy in = Energy out

Plants attempt to maintain equilibrium at optimal temperature.

Leaf temperature changes until equilibrium is reached.

Incoming energy is absorbed by a surface (leaf, canopy, hillside) and converted to heat

Absorbed energy is dissipated as:

- re-radiation
- convection
- evaporation
- conduction

Typically, less than 3 % of the absorbed energy is used in photosynthesis.

Leaf energy balance: Energy in = Energy out

energy absorbed = re-radiation + convection + transpiration

$\alpha SW_{direct} + \alpha SW_{diffuse} + \alpha LW_{IR\text{-}surroundings}$

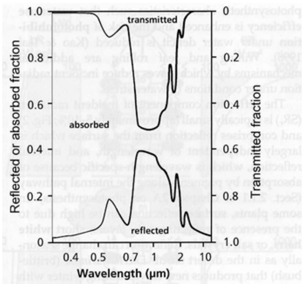
direct solar　　diffuse solar　　infrared

$SW_h \cos(i) / \sin(a)$

α = absorptivity: fraction of incident radiation absorbed

Incident radiation is absorbed, reflected, or transmitted

absorptance (α) + reflectance (ρ) + transmittance (τ) = 1

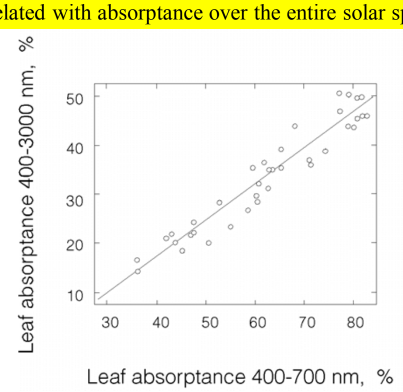


Wavelength spectrum of absorbed, transmitted, and reflected irradiance (% of total) by a leaf.

Reflectances of different ecological surfaces in the 100 - 4,000 nm waveband (shortwave)

Surface	Reflectance (ρ)
ocean	0.05
dry sand	0.18
bare soil	0.10 - 0.15
leaves	0.18 - 0.26
pasture	0.25
forest	0.18
tundra	0.15 - 0.20
snow	0.81

Absorptance of photosynthetically active wavelengths is highly correlated with absorptance over the entire solar spectrum



Leaf energy balance: Energy in = Energy out

re-radiation: flux of emitted radiation, dependent on temperature

energy absorbed = re-radiation + convection + transpiration

$$\varepsilon\sigma(T_{leaf} + 273.15)^4$$

T_{leaf} = leaf temperature [°C]
ε = emissivity: efficiency of radiation emission
σ = Stefan-Boltzmann constant

Leaf energy balance: Energy in = Energy out

convection: sensible heat flux (H), dependent on temperature difference

energy absorbed = re-radiation + convection + transpiration

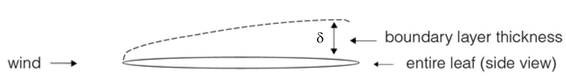
$$g_h C_p(T_{leaf} - T_{air})$$

T_{leaf} = leaf temperature [°C]
T_{air} = leaf temperature [°C]
g_h = boundary layer heat conductance [mol m^{-2} s^{-1}]
C_p = specific heat of air (29.1 J mol^{-1} °C^{-1})

A boundary layer develops as air flows across a leaf

$$g_h = 0.135(u / d)^{0.5}$$
$$\delta = 4(d / u)^{0.5}$$

δ = boundary layer thickness [mm]
d = mean leaf length [m]
u = wind speed [m s^{-1}]



Boundary layer impedes the transfer of heat, H_2O, and CO_2 between the leaf and surrounding air.

Leaf energy balance: Energy in = Energy out

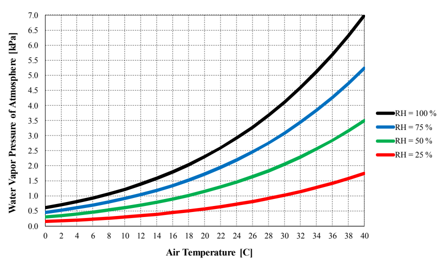
transpiration: latent heat flux (λE), dependent on water vapor difference

energy absorbed = re-radiation + convection + transpiration

$$g_{wv}\lambda(e_{leaf} - e_{air}) / P_b$$

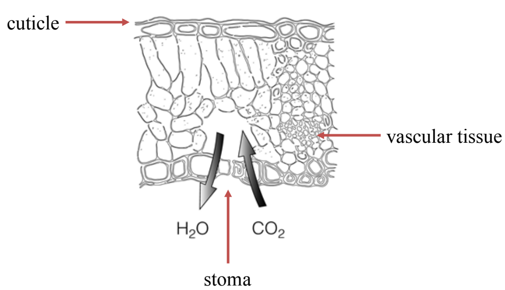
e_{leaf} = water vapor pressure inside leaf [kPa]
e_{air} = water vapor pressure of air [kPa]
g_{wv} = water vapor conductance [mol m^{-2} s^{-1}] → boundary layer and stomatal
λ = heat of vaporization (44,000 J mol^{-1} at 25 °C)
P_b = barometric pressure (101.3 kPa at sea level)

Evaporative gradient: Vapor pressure difference between leaf and air, dependent on temperature and vapor pressure



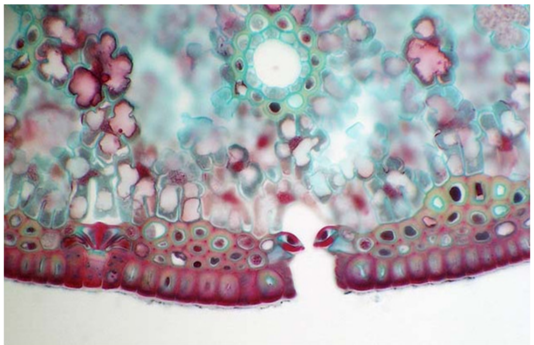
Arid conditions: evaporative gradient is typically high.
Humid conditions: evaporative gradient is typically low.

H_2O is inevitably lost to the atmosphere when plants open stomata to take up CO_2 for photosynthesis

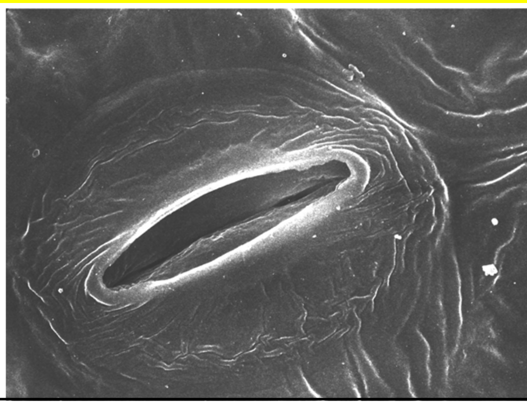


H_2O moves by diffusion from high vapor pressure to low vapor pressure (evaporative gradient).

Single stoma on pine needle



Single stoma: high or low stomatal conductance?



Plant canopy radiant energy input: Net radiation (R_n)

Net radiation: total radiation absorbed by plant canopy [W m^{-2}]:

$$R_n = (SW_i - SW_o) + (LW_i - LW_o)$$

$$R_n = (1 - \rho)SW_h + (LW_{IR\text{-}sky} - LW_{IR\text{-}surface})$$

net radiation

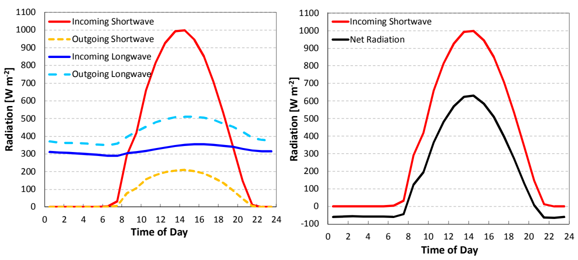
reflectance or albedo

infrared radiation from sky and surface

solar radiation incident on horizontal surface

Radiation fluxes and net radiation over a grass canopy

$$R_n = (SW_i - SW_o) + (LW_i - LW_o)$$



Energy balance: Energy in = Energy out

Net radiation must be balanced [units are W m^{-2}]:

$$R_n = H + \lambda E + G$$

soil heat flux: heat conduction into ground

latent heat flux: energy transferred to air by evaporation

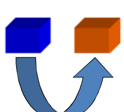
sensible heat flux: energy transferred to air by conduction/convection

Sensible heat flux

$$R_n = H + \lambda E + G$$

Energy transferred between surface and atmosphere by conduction/convection: dependent on temperature difference.

parcels of air



Typically cools canopy and warms air during day.

warm surface: vegetation, soil

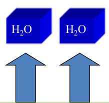
Latent heat flux

$$R_n = H + \lambda E + G$$

Energy transferred between surface and atmosphere by evaporation (or condensation): dependent on evaporative gradient.

E is evaporation and λ is the latent heat of vaporization (44,000 J mol^{-1} at 25 °C).

parcels of air



Typically cools canopy and humidifies air during day.

warm surface: vegetation, soil

Soil heat flux

$$R_n = H + \lambda E + G$$

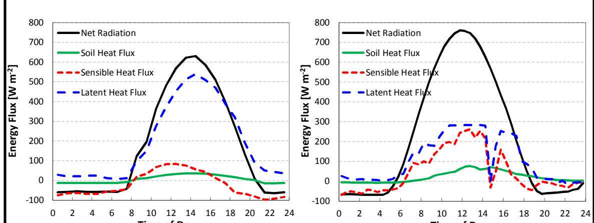
Energy transferred between soil layers, with different temperatures, by conduction.

Typically warms soil during day.

warm soil surface below vegetation

cooler soil layer

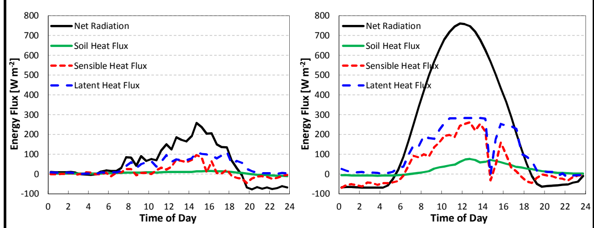
Energy balance components in a short grass canopy and pine forest



Grass

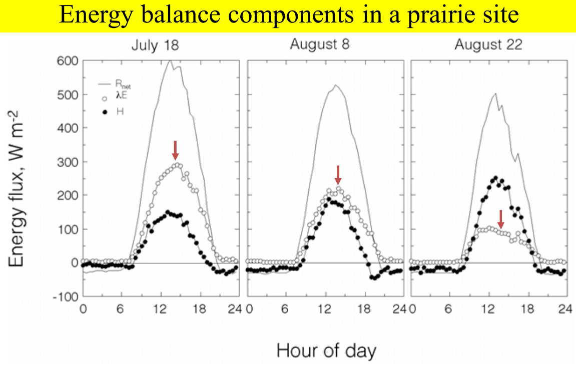
Pine forest

Energy balance components in a pine forest on clear and cloudy days



Cloudy   Clear

Energy balance components in a prairie site



Note development of drought and progressive seasonal reductions in the total solar input.

Leaf coupling factors influence the degree of energy exchange between leaf and air

Leaf coupling factors: Variables that plants can influence.

- leaf orientation
- leaf absorptance
- leaf size
- leaf shape
- leaf stomatal conductance

Typical values for two leaf coupling factors

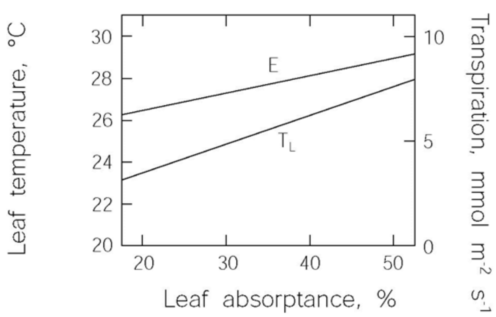
Leaf absorptance (400-4000 nm):

green leaf	50 %
white leaf	30 %

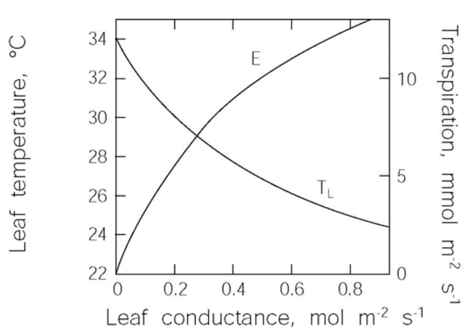
Leaf stomatal conductance:

open stomata	0.5 mol m^{-2} s^{-1}
closed stomata	< 0.05 mol m^{-2} s^{-1}

Influence of leaf absorptance on leaf temperature and transpiration



Influence of leaf stomatal conductance on leaf temperature and transpiration



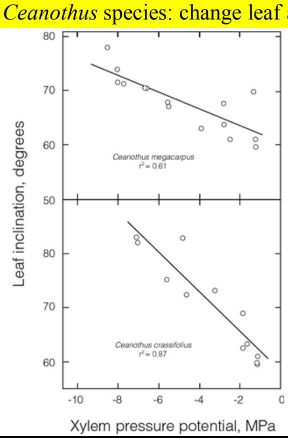
Changes in leaf orientation relative to the position of the sun strongly influence cos(i)

- Steeper angles in sun leaves than shade leaves.
- Steep leaf angles in certain species.
- Wilting to a vertical position.
- Leaf concavity.
- Leaf curling.
- Stem orientation.

Some leaf orientation characteristics change under drought stress (low water availability = low transpiration)

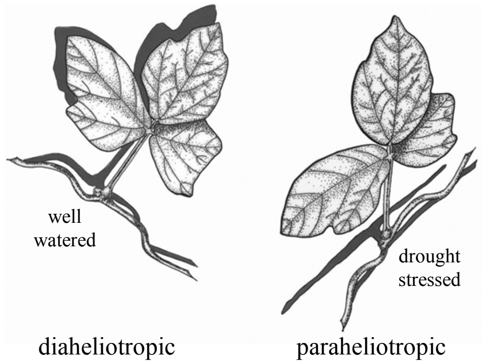
- Energy absorbed is reduced to offset reduced capacity to evaporatively cool.
- Increased leaf angle with drought stress: *Ceanothus, Lactuca*.
- Paraheliotrophic leaf movements: *Kallstromia, Lupinus, Macroptilium, Medicago*.

Ceanothus species: change leaf angle in response to drying soil



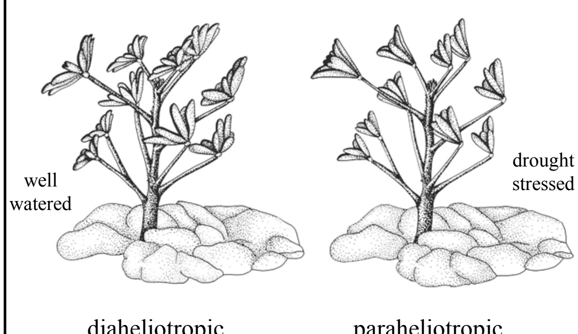
Ceanothus species have evergreen leaves and are common shrub species within the Mediterranean climate regions of southern California.

Macroptillium purpureum: herb found in subtropical regions

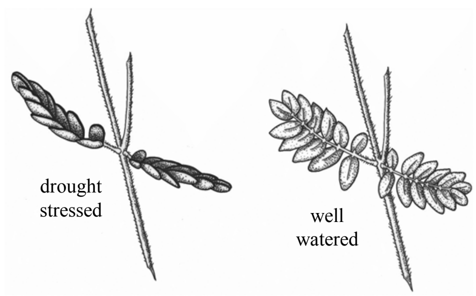


Lupinus arizonicus

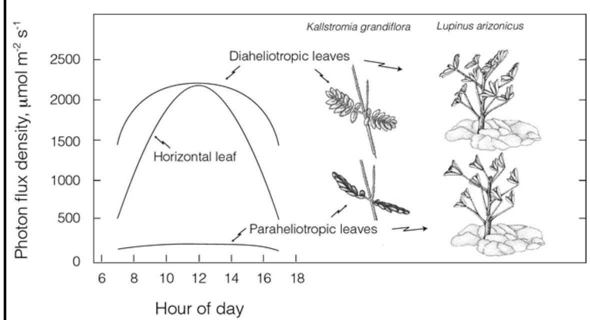
Lupinus arizonicus: C_3 annual in the Sonoran Desert



Kallstromia grandiflora: C_4 annual in the Sonoran Desert

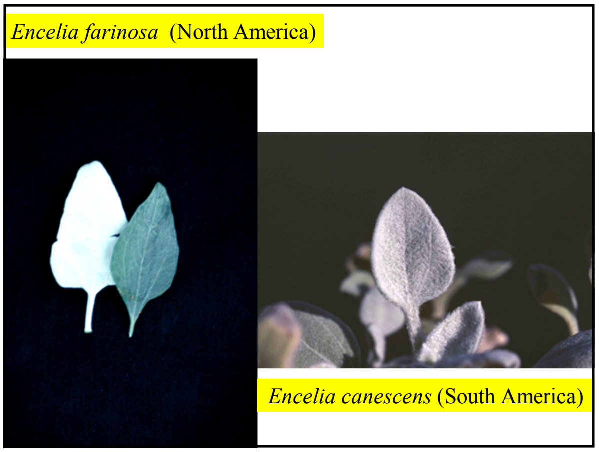


Solar radiation comparison: diaheliotropic and paraheliotropic

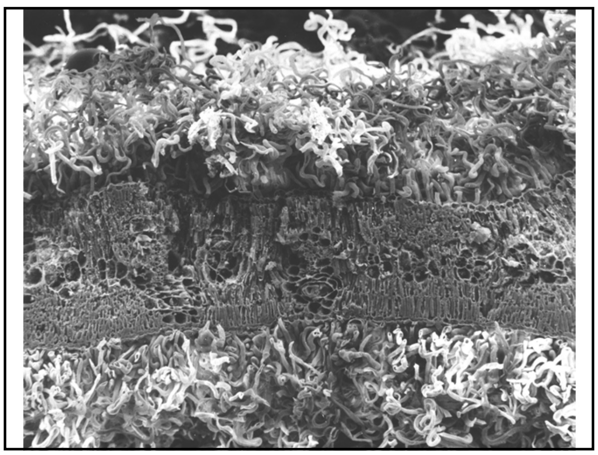


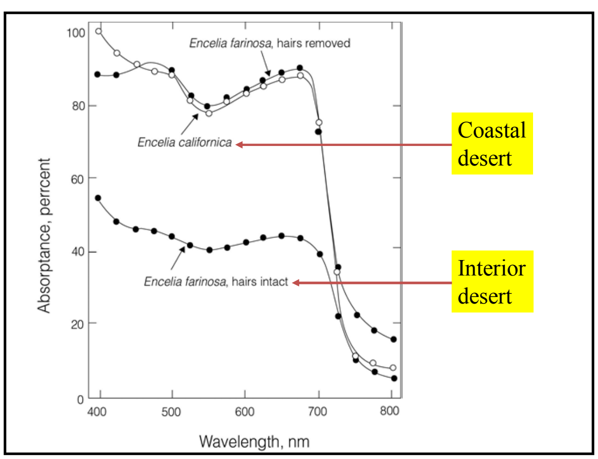
Mechanisms to reduce leaf absorptance under drought stress (low water availability = low transpiration)

- Energy absorbed is reduced to offset reduced capacity to evaporatively cool.
- Dead, air-filled epidermal hairs: *Artemisia, Encelia, Salvia.*
- Cuticular waxes: *Eucalyptus, Dudleya.*
- Epidermal salt bladders: *Atriplex.*

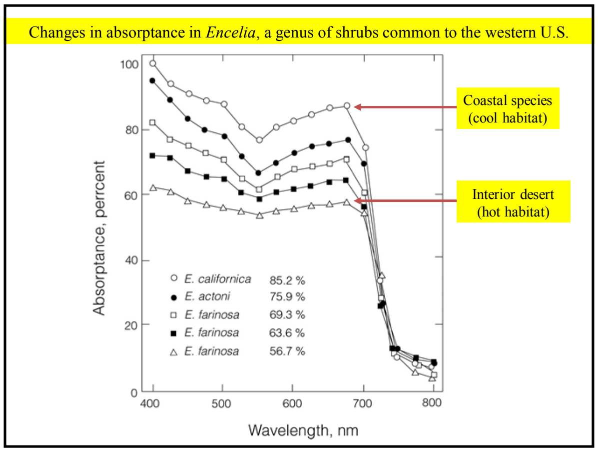


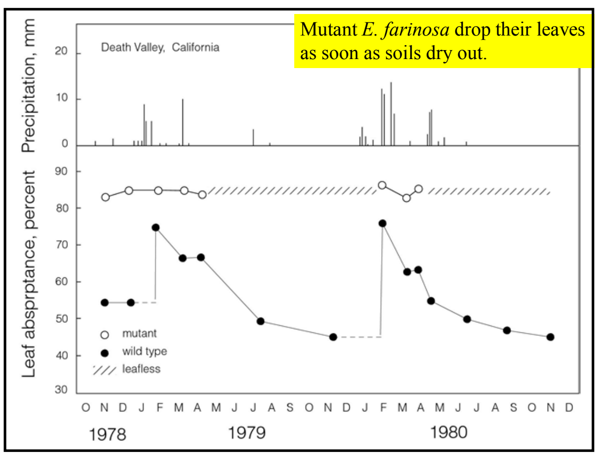
Encelia farinosa (North America)
Encelia canescens (South America)

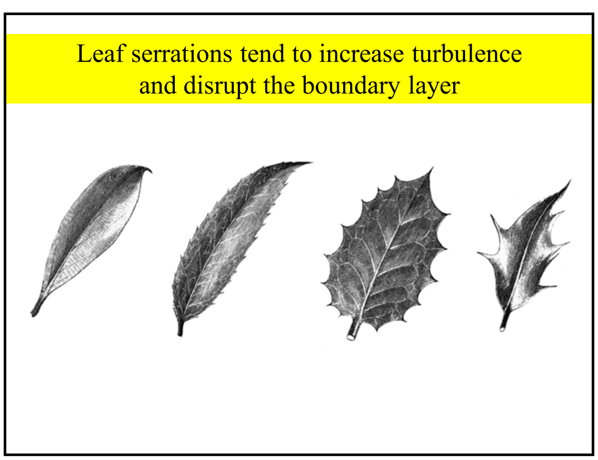




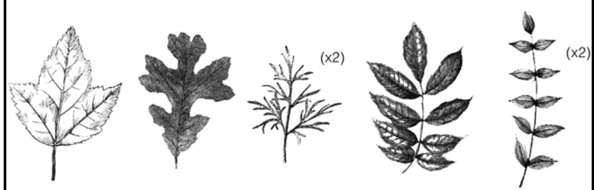
Encelia farinosa, hairs removed
Encelia californica
Encelia farinosa, hairs intact
Coastal desert
Interior desert
Absorptance, perrcent
Wavelength, nm
0
20
40
60
80
100
400
500
600
700
800


Changes in absorptance in Encelia, a genus of shrubs common to the western U.S.
Coastal species
(cool habitat)
Interior desert
(hot habitat)
Absorptance, percent
Wavelength, nm
100
80
60
40
20
0
400
500
600
700
800
E. californica 85.2 %
E. actoni 75.9 %
E. farinosa 69.3 %
E. farinosa 63.6 %
E. farinosa 56.7 %


Mutant E. farinosa drop their leaves as soon as soils dry out.
Death Valley, California
Precipitation, mm
Leaf absprptance, percent
mutant
wild type
leafless
O N D J F M A M J J A S O N D J F M A M J J A S O N D
1978
1979
1980

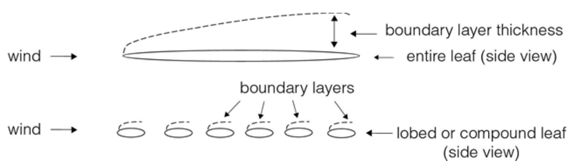

Leaf serrations tend to increase turbulence
and disrupt the boundary layer

Leaf lobing and compound leaves are quite common in plants of arid regions



Lobing is usually more developed in sun leaves than in shade leaves.

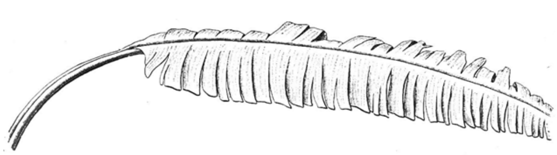
Leaf lobing and serrations interrupt the developing boundary layer, increases convective heat transfer



$$\delta = 4(d / u)^{0.5}$$

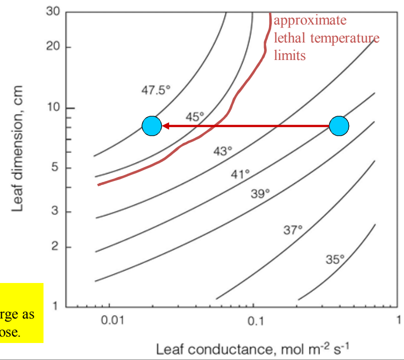
$$g_h = 0.135(u / d)^{0.5}$$

Banana leaves tear during water stress periods and during the dry season



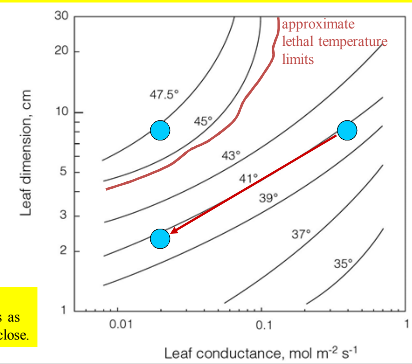
Leaf tearing occurs along senescent zones.

Banana leaf temperatures depend on both how large the leaf is and how wide open the stomata are



Leaf size remains large as stomata close.

Banana leaf temperatures depend on both how large the leaf is and how wide open the stomata are



Leaf size decreases as stomata close.