Leaf Energy Balance, part 2

- Critical Limits on Evaporation
  - infinite surface conductance
  - infinite aerodynamic conductance
  - zero surface conductance
  - zero aerodynamic conductance
- IsoThermal Energy Balance
- Response surfaces, leaf-air temperature differences, Optimal Leaf Form, Size and Shape

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In this lecture we will use the equations to ask and answer some science questions about leaf temperature. We will manipulate the equations to see some of the limits

Well-Mixed Case, Infinite Boundary Layer Conductance

$$\lambda E = \frac{sR_n + D\rho_a C_p g_h}{(s + \gamma \frac{g_h}{g_w})}$$

$$\lambda E(g_a \to \infty) = \frac{sR_n + D\rho_a C_p \infty}{(s + \gamma(1 + \frac{\infty}{g_s}))}$$

$$\lambda E_{imposed}(g_a \to \infty) = \frac{\rho_a C_p}{\gamma} D g_s$$

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What is the limit of evaporation for a very windy condition, where ga goes to infinity?

. It is a multiplicative function of stomatal conductance times the vapor pressure deficit. This is the imposed rate of evaporation

Steps

$$\lambda E = \frac{sR_n}{(s + \gamma \frac{g_h}{g_w})} + \frac{D\rho_a C_p g_h}{(s + \gamma \frac{g_h}{g_w})}$$

Term 1

$$\frac{sR_n}{(s + \gamma(1 + \frac{\infty}{g_s}))} = 0$$

Term 2

$$\lambda E(g_h \to \infty) \sim \frac{D\rho_a C_p g_h}{(s + \gamma(1 + \frac{g_h}{g_s}))}$$

$$\frac{1}{\{\lambda E\}} \sim \frac{(s + \gamma(1 + \frac{g_h}{g_s}))}{D\rho_a C_p g_h}$$

$$\frac{s}{D\rho_a C_p \infty} + \frac{\gamma}{D\rho_a C_p \infty} + \frac{\gamma g_h}{g_s D\rho_a C_p g_h}$$

$$\frac{1}{\lambda E} \sim \frac{\gamma g_h}{g_s D\rho_a C_p g_h} = \frac{\gamma}{g_s D\rho_a C_p}$$

$$\lambda E_{imposed}(g_a \to \infty) = \frac{\rho_a C_p}{\gamma} D g_s$$

The imposed evaporation is an important concept is a closed well mixed container. In this case the rate of evaporation is imposed by the humidity of the environment and is independent of the available energy. This is the limit physiologists often experience when studying leaf evaporation in a cuvette

Still Air Case, boundary layer conductance goes to Zero

$$\lambda E(g_a \to 0) = \frac{sR_n + D\rho_a C_p 0}{(s + \gamma(1 + \frac{0}{g_s}))}$$

$$\lambda E_{eq}(g_a \to 0) = \frac{s}{s+\gamma} R_n$$ Equilibrium Evaporation

But, this Equality is physically nonsensical.

How can we expect the surface to exchange water and heat with the atmosphere if there is no transfer mechanism?

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For still air we compute LE as a function of Net radiation, assuming there are no feedbacks with leaf temperature and long wave radiation. This is physically non sensense, so we have to look back at the derivation

Equilibrium Evaporation

$$\frac{d\lambda E}{dt} = \frac{dE}{dD}\frac{dD}{dt}$$

$$\lambda E_{eq}(t \to \infty) = \frac{s}{s+\gamma} R_n$$

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Equilibrium evaporation is an important limit when feedbacks between LE and D lead to a steady state condition.

Humidity Deficit Must be Infinite in Still Air with Impending Energy

$$D(g_a \to 0) = \frac{\lambda E(s + \gamma(1 + \frac{0}{g_s}))}{\rho_a C_p 0} - sR_n = \infty$$

IsoThermal Radiation Balance $R_{n,iso} = Q - \sigma\varepsilon T_a^4$

$$R_n = Q - \sigma\varepsilon T_l^4 =$$
$$Q - (\sigma\varepsilon T_a^4 + 4\sigma\varepsilon T_a^3 (T_l - T_a)) =$$
$$R_{n,iso} - 4\sigma\varepsilon T_a^3 (T_l - T_a)$$

$$\lambda E = \frac{sR_{iso} + D\rho_a C_p (g_r + g_h)}{(s + \frac{\gamma g_r}{g_w} + \frac{\gamma g_h}{g_w})}$$

$$g_r = \frac{4\varepsilon\sigma T_a^3}{\rho C_p}$$

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As a way to deal with feedback, colleagues have developed the isothermal radiation balance, which adds a new conductance, called the radiation conductance

Alternatively Consider IsoThermal Radiation Balance

$$\lambda E(g_a \to 0) = \frac{sR_{iso} + D\rho_a C_p (g_r + 0)}{(s + \gamma(1 + \frac{g_r}{0})(1 + \frac{0}{g_s})} = \frac{[]}{\infty} = 0$$

It correctly and Physically Reveals Evaporation is Zero in Still Air

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With this form, we see that evaporation is nil in still air.

Wet Surface

$$\lambda E(g_s \to \infty) = \frac{sR_n + D\rho_a C_p g_h}{(s + \gamma(1 + \frac{g_h}{\infty}))}$$

$$\lambda E(g_s \to \infty) = \frac{sR_n + D\rho_a C_p g_h}{(s + \gamma)}$$

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What happens when a leaf is wet with rain or dew? Then the surface conductance is infinite and the rate of evaporation is limited by the net radiation and turbulent mixing.

Nocturnal Evaporation

surface conductance goes to infinity as the surface is wet with condensation

$$\lambda E = \frac{sR_{iso} + D\rho_a C_p (g_r + g_h)}{(s + \gamma(1 + \frac{g_r}{g_{av}})(1 + \frac{g_{av}}{\infty})}$$

$$\lambda E = \frac{sR_{iso} + D\rho_a C_p (g_r + g_h)}{(s + \gamma(1 + \frac{g_r}{g_{av}})}$$

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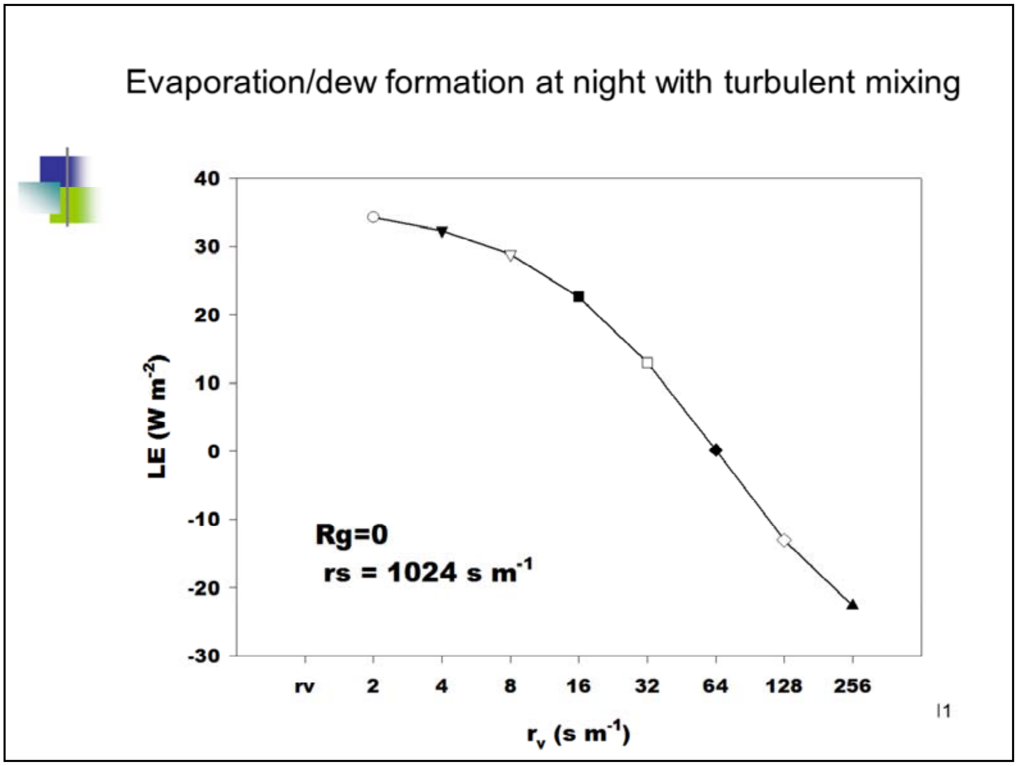
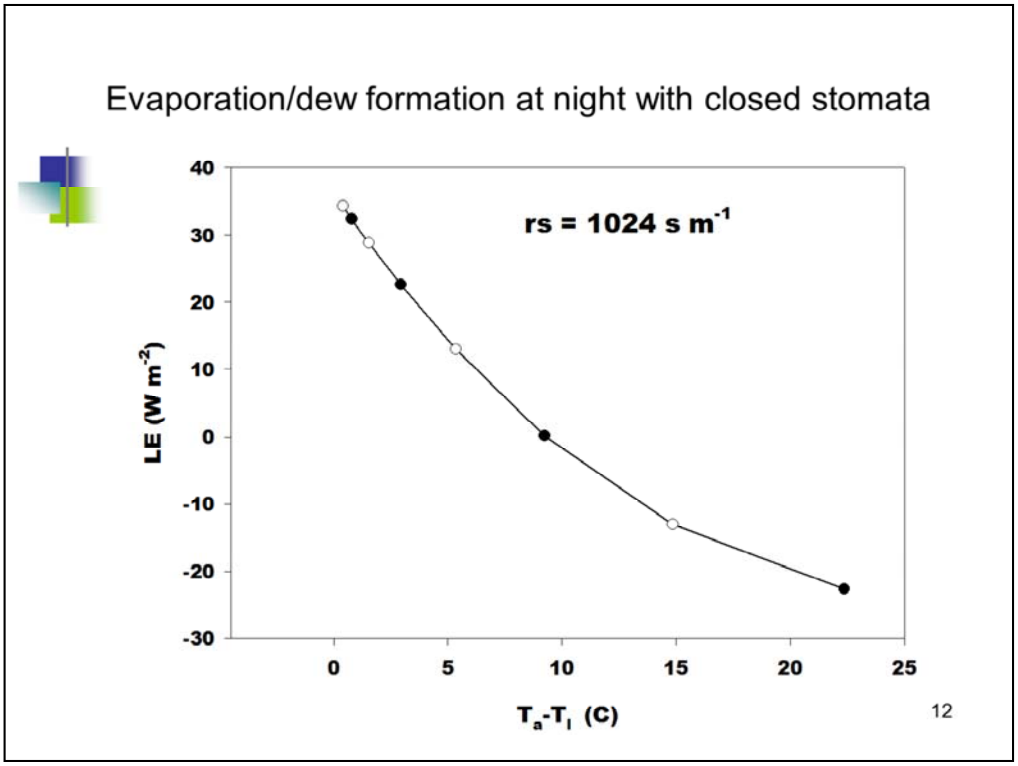
At night with dew we get this form for evaporation..version with isothermal radiation

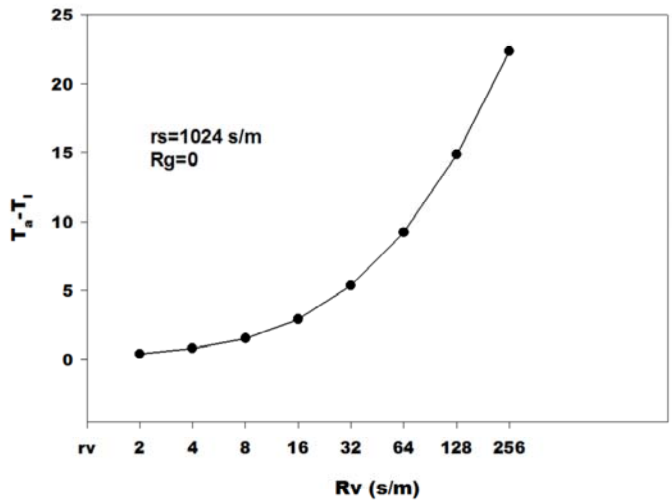


Dew formation starts when the resistance exceeds a threshold. Otherwise evaporation is promoted.



Large radiative cooling of the leaf promotes this dew deposition

Leaf-air temperatures at night with closed stomata

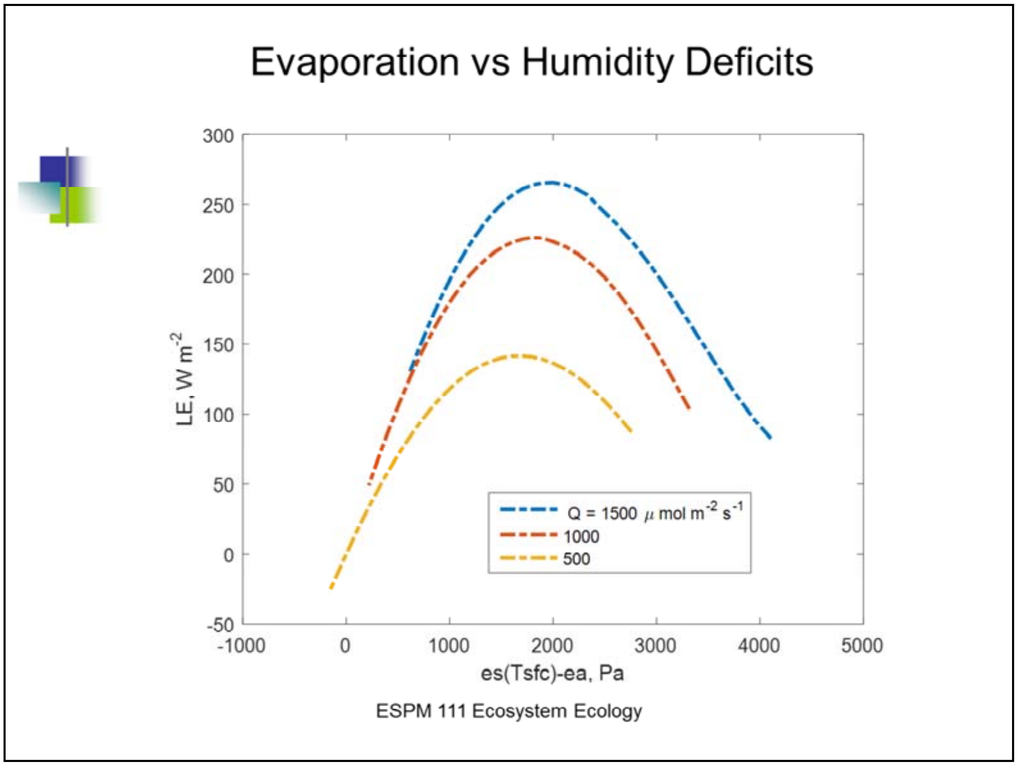


Coupling Theory

$$dE = (1-\Omega)\frac{E}{g_s}dg_s$$

$$\Omega(R_{iso}) = \frac{1+\varepsilon+\frac{g_r}{g_b}}{1+\varepsilon+\frac{g_b+g_r}{g_s}+\frac{g_r}{g_b}}$$

species	gs	D (mm)	Ω (0.2 m/s)	Ω (5 m/s)
Sitka spruce	0.07	2	0.18	0.03
Beech	0.10	40	0.50	0.10
apple	.21	60	0.50	0.11



Here we look at model computations of latent heat exchange, which is the evaporation rate (E) times the latent heat of evaporation, vs the humidity deficit between the leaf and air, so we compute es(T) as a function of the leaf temperature, Tsfc. These calculations are based on a coupled model that considers leaf energy balance and coupling between stomatal conductance and photosynthesis.

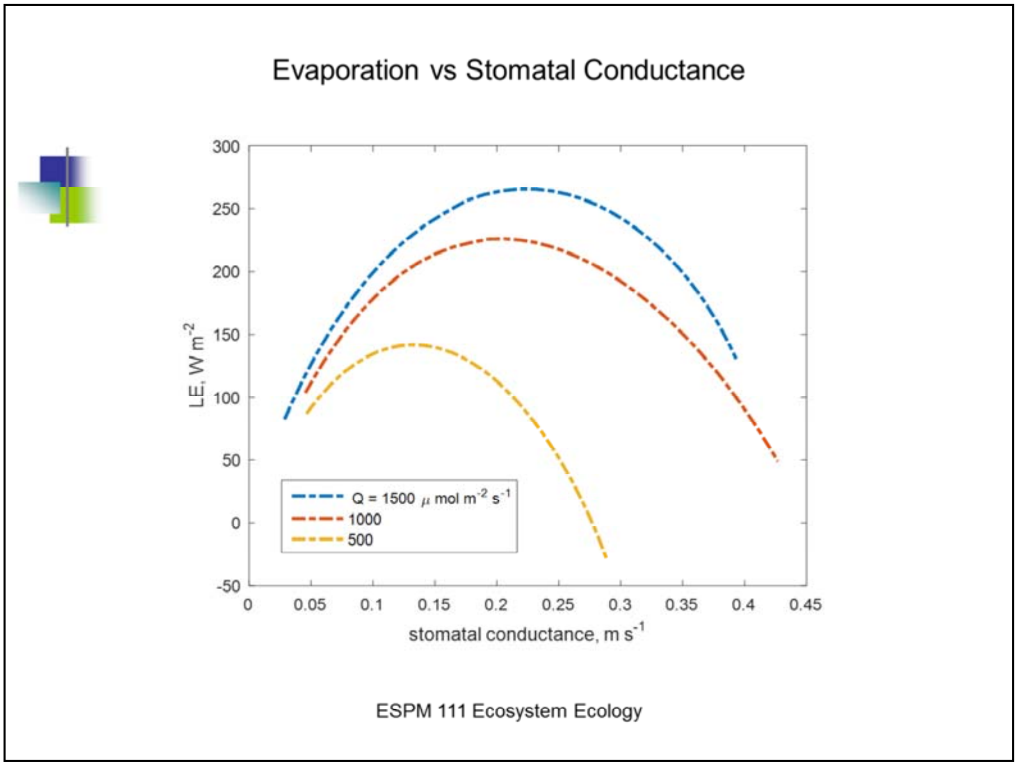
For low humidity deficits, an increase in this difference drives the potential for evaporation and rates of evaporation INCREASE. This is what one would expect simply looking at the Ohms Law analog for evaporation. But real evaporation is more complex. There are other biophysical factors that act to restrict evaporation as humidity deficits get greater and greater.

At intermediate humidity deficits a peak rate in evaporation is reached and then evaporation rates DECREASE with additional increases in humidity deficits. Why?

Leaves experience a Feedforward effects between Evaporation and humidity deficits. Farquhar, G.D., 1978. Feedforward Responses of Stomata to Humidity. Australian Journal of Plant Physiology, 5(6): 787-800.

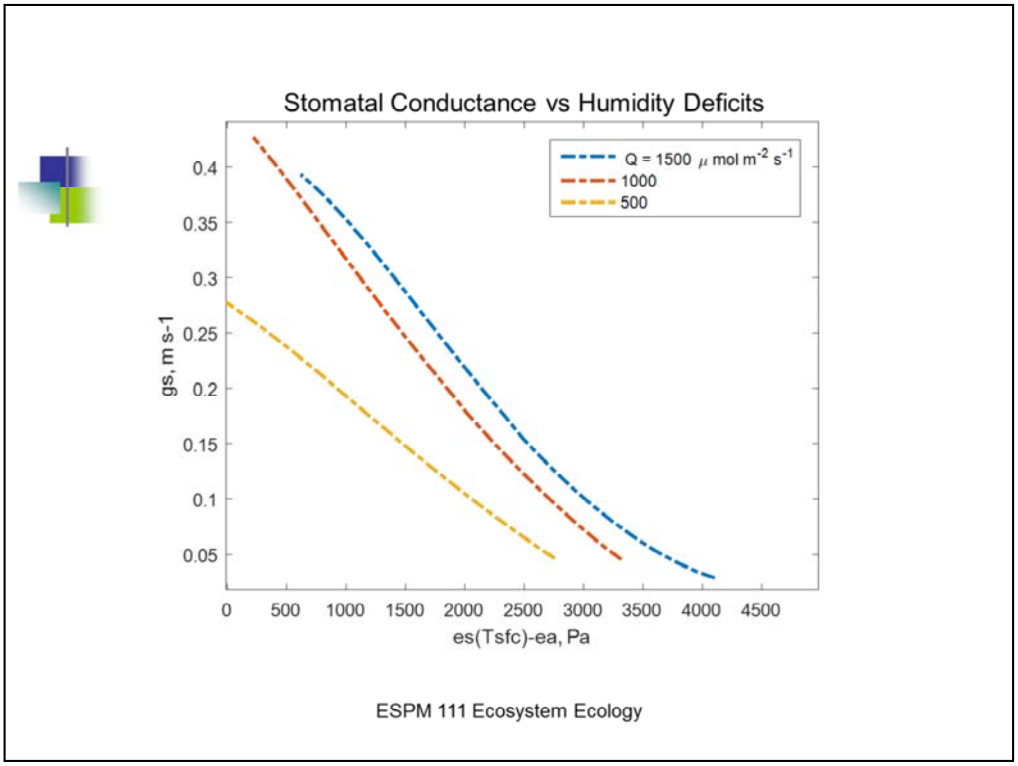
As we will see below, stomatal conductance is also a function of humidity deficits, which impacts further changes in evaporation as the air dries.

And what is neglected in this simple scheme and model are feedbacks between the humidification of the atmosphere and its further impact on evaporation. Think is a still air with little mixing, evaporation causes the humidity of the air to increase, decreasing humidity deficits and acting to retard further changes in evaporation

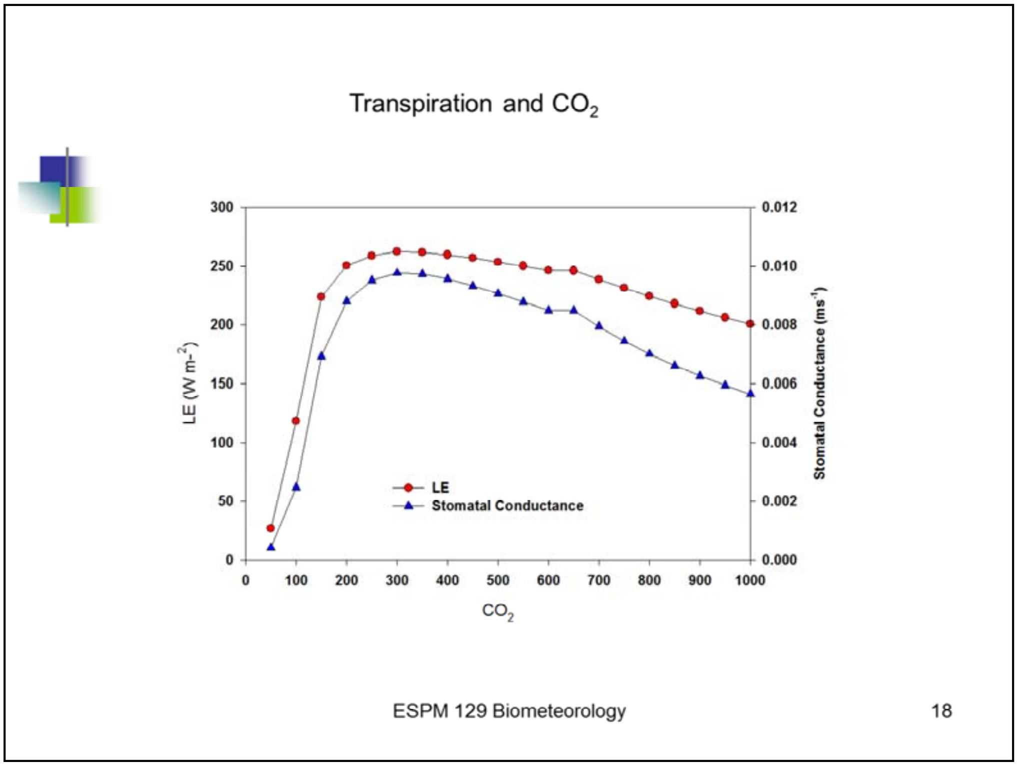


Together we can see that LE is low at highest stomatal conductances because humidity deficits are smallest and LE is low at lowest stomatal conductances because they restrict water loss. LE is optimal at intermediate humidity deficits and stomatal conductances.

These results may seem counter intuitive, but this is why we need theory and models to understand and explain the complex behavior we observe in nature. The problem I see and have is that too often this problem is tackled with over simplified models that do not consider the interactions and feedbacks (whether negative or feedforward) that we see here.

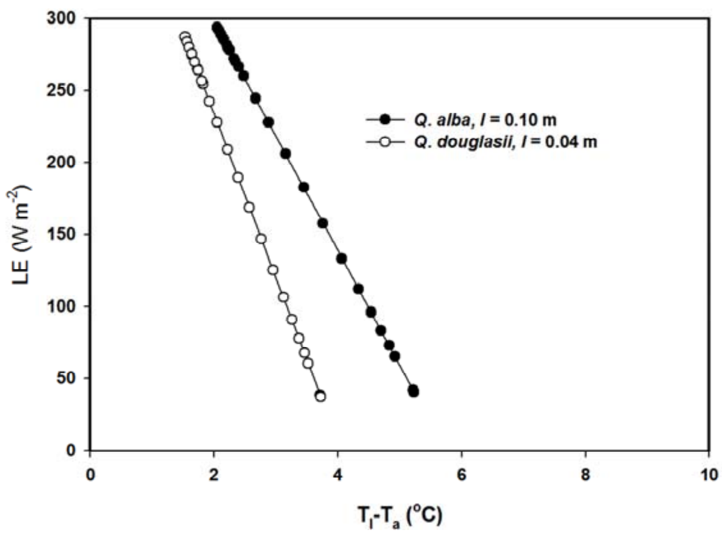


Part of the explanation for LE decreasing with increasing vapor pressure deficit, a stronger potential driver of evaporation, is because stomata conductance also decrease with increasing humidity deficits. This is because guard cells will lose water too, become flaccid and close in dry air.



We can also look at how evaporation will change with increasing CO2 in a future world

Leaf Size, Temperature and Evaporation



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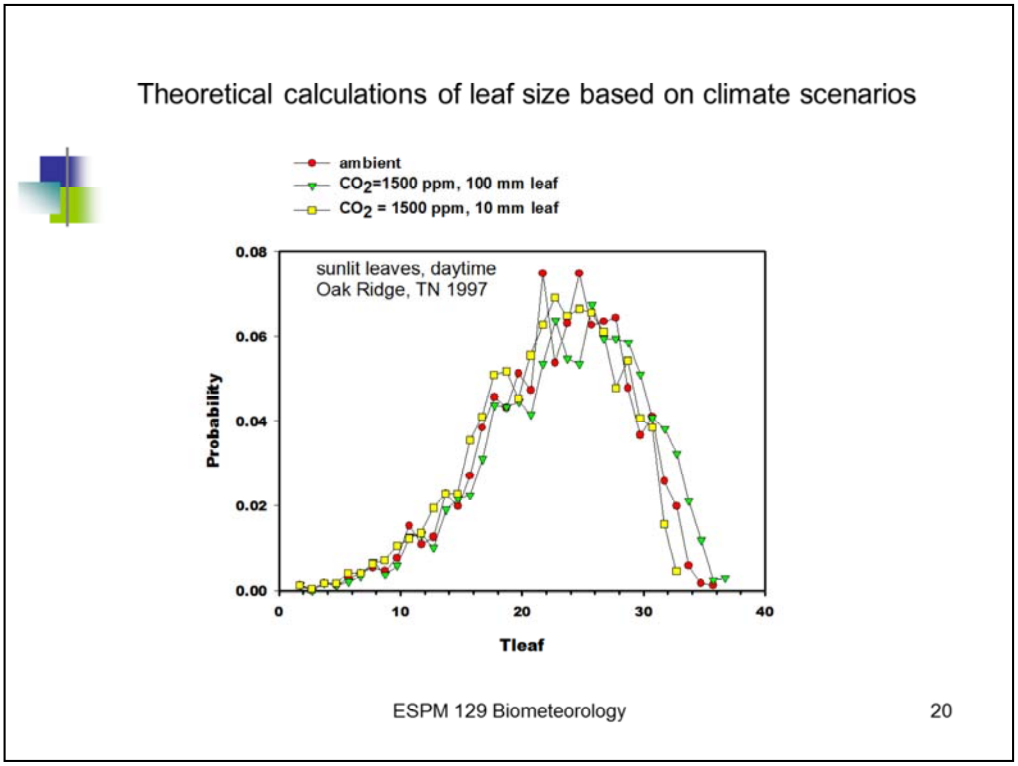
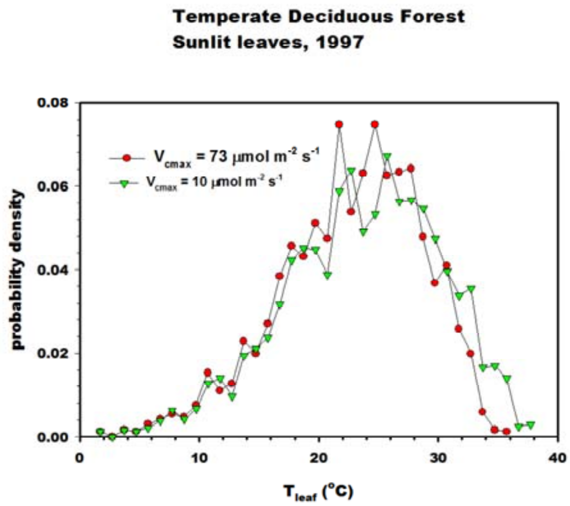
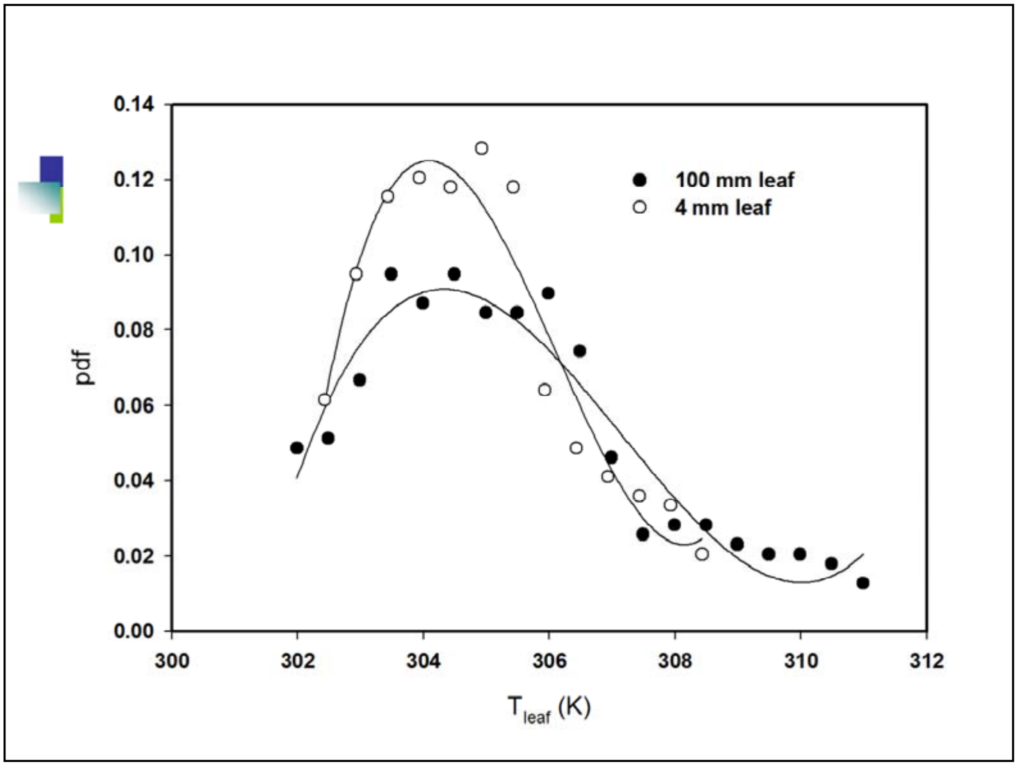


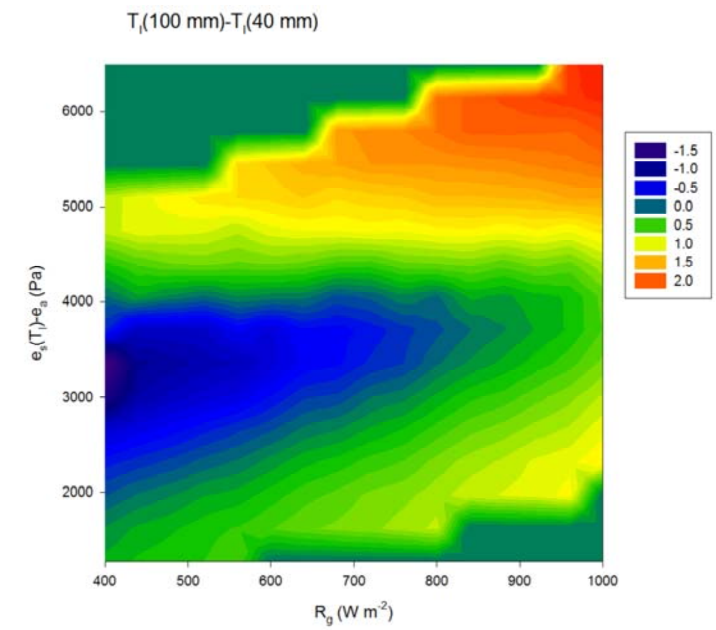
What happened in the past with high CO2 and temperatures? Having smaller leaves helps minimize exposure to lethal and debilitating temperatures.

Role of leaf photosynthetic capacity and leaf temperature





pdf
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
300
302
304
306
308
310
312
T_{leaf} (K)
100 mm leaf
4 mm leaf


T_l(100 mm)-T_l(40 mm)
6000
5000
4000
3000
2000
$e_s(T_l)$-e_a (Pa)
400
500
600
700
800
900
1000
R_g (W m^{-2})
-1.5
-1.0
-0.5
0.0
0.5
1.0
1.5
2.0

Summary

- LE imposed is defined as the limit when boundary layer conductance goes to infinity. LE is independent of the net radiation balance!
- LE goes to zero when the boundary layer conductance approaches zero, for there is no physical mechanism to transfer water from the leaf to the atmosphere
- equilibrium evaporation is independent of stomatal conductance.
  - It results from the consequence of feedbacks between surface temperature, the temperature of the air and its water holding capacity.
  - It is also identical to the derivation based on the condition when $\lambda E(Rn)$ is evaluated as *ga* goes to zero.