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

In this lecture we will use the equations to ask and answer some science questions about leaf temperature

Well-Mixed Case, Infinite Boundary Layer Conductance

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

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

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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

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

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

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

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.

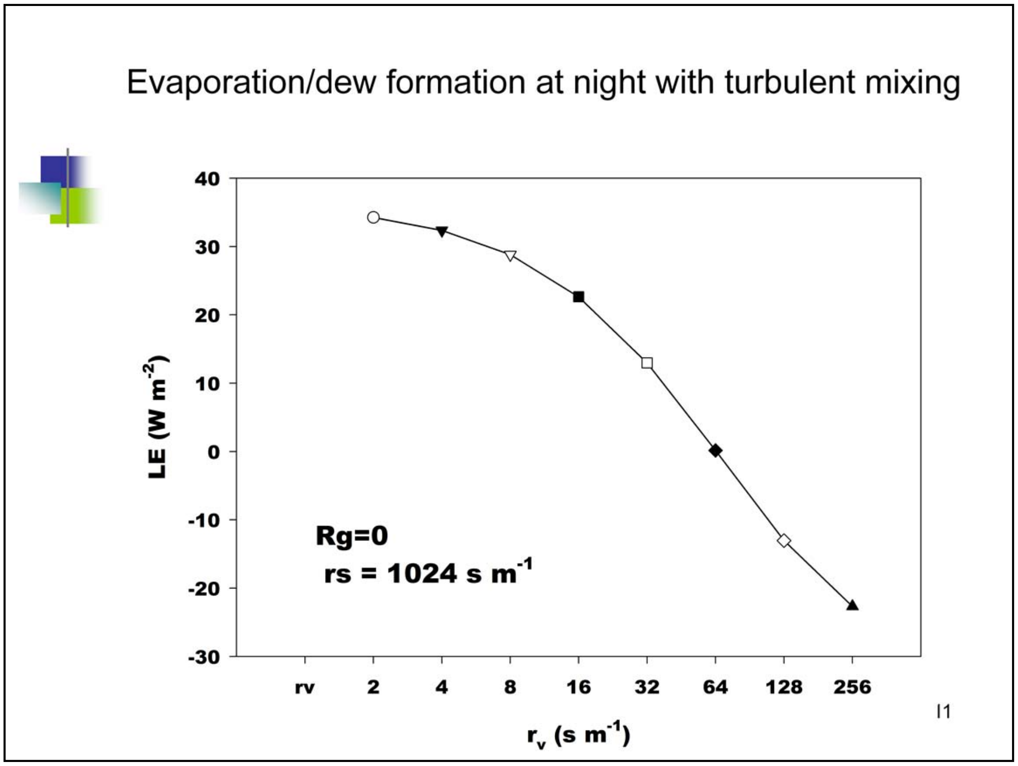
Nocturnal Evaporation

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

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

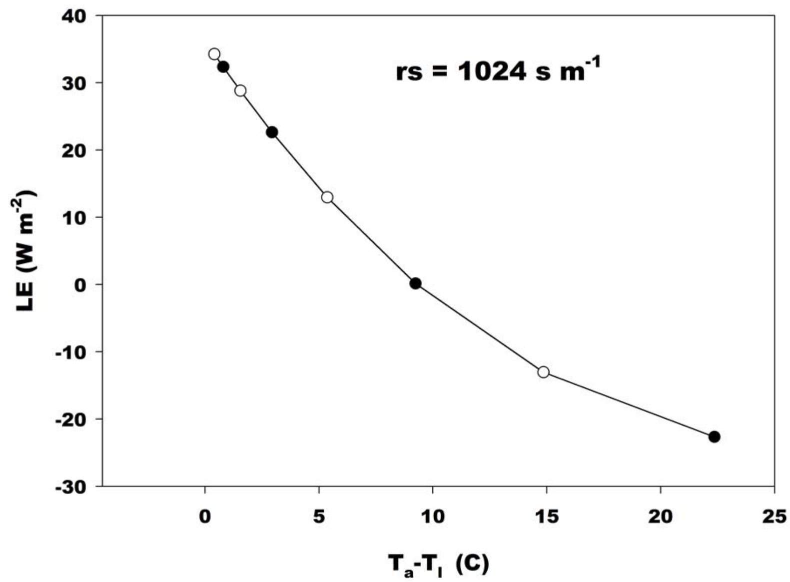
$$\lambda E = \frac{sR_{iso} + D\rho_a C_p (g_r + g_h)}{(s + \gamma(1 + \frac{g_r}{g_{av}})}$$

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.

Evaporation/dew formation at night with closed stomata



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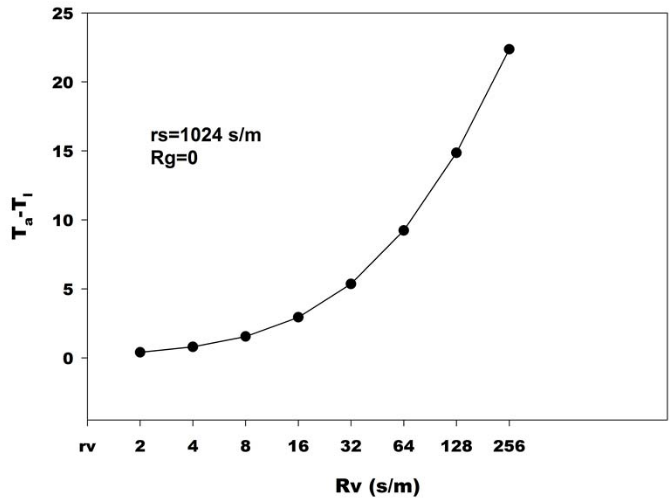
Large radiative cooling of the leaf promotes this dew deposition

Leaf-air temperatures at night with closed stomata

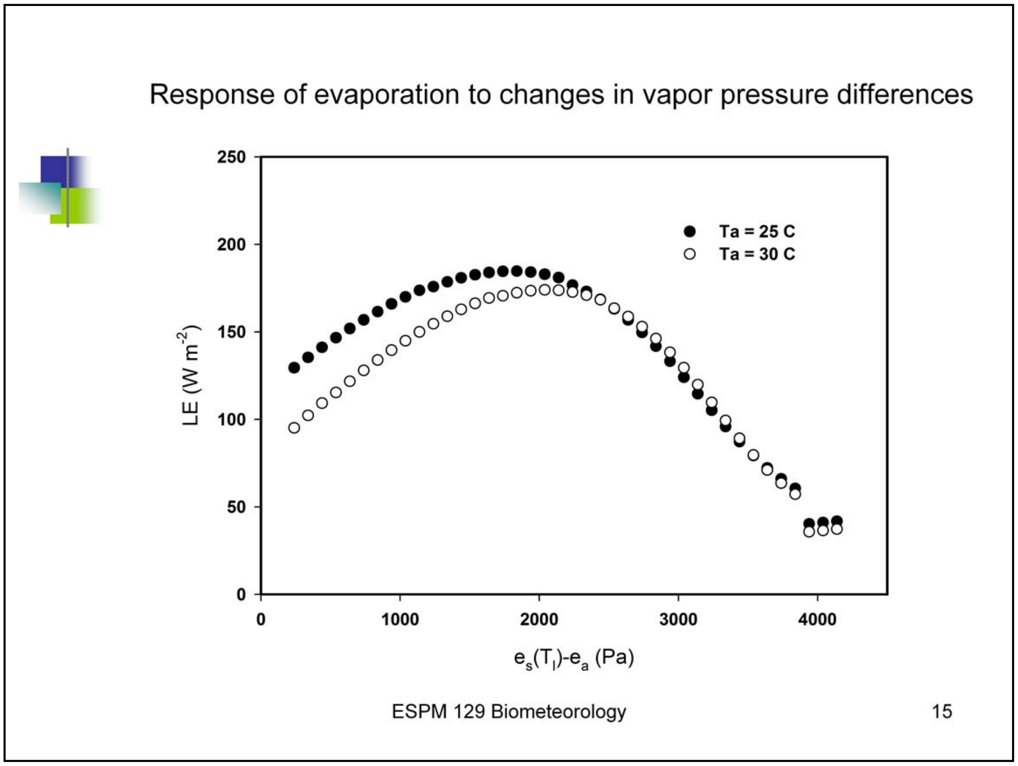


Coupling Theory

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

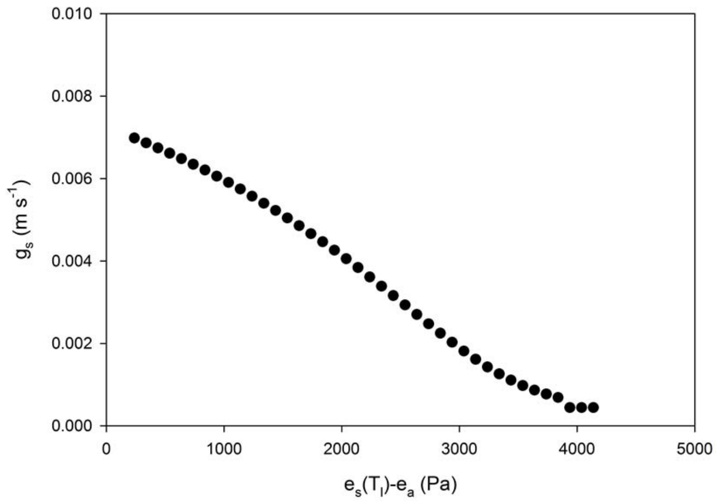
$$\Omega(R_{iso}) = \frac{1+\varepsilon+\frac{g_r}{g_b}}{1+\varepsilon+\frac{g_b+g_r}{g_s}+\frac{g_r}{g_b}}$$

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



Evaporation is not a simple linear function of humidity deficits, because high deficits foster stomatal closure, which act to reduce evaporation

Response of stomatal conductance to humidity deficits



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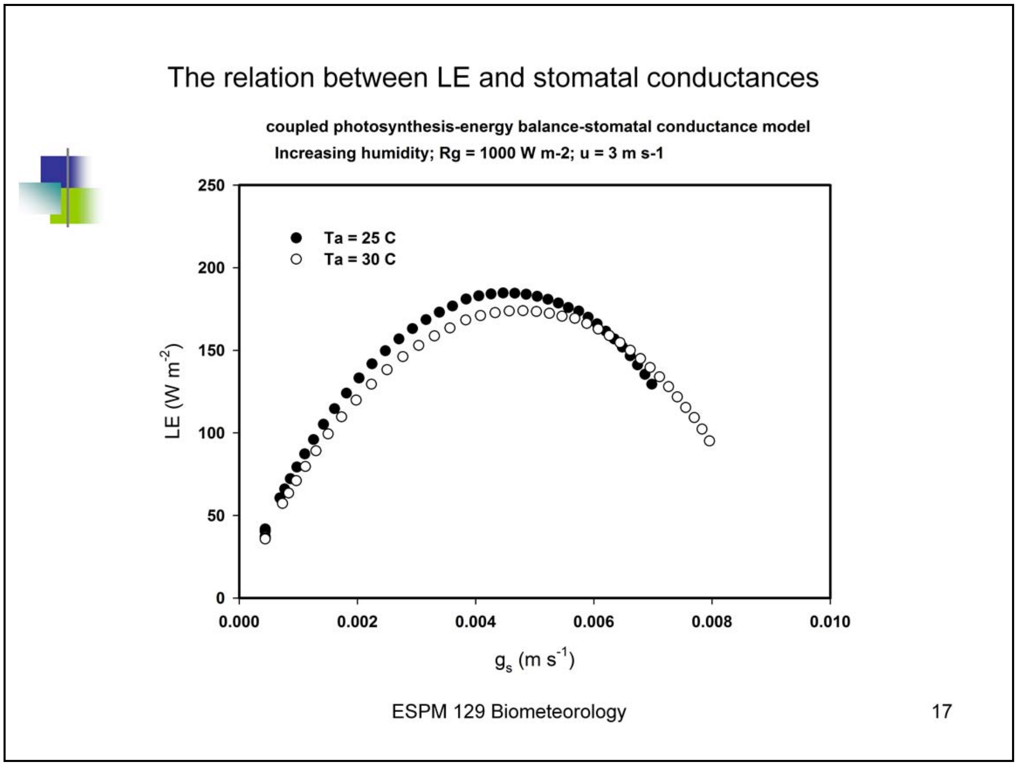
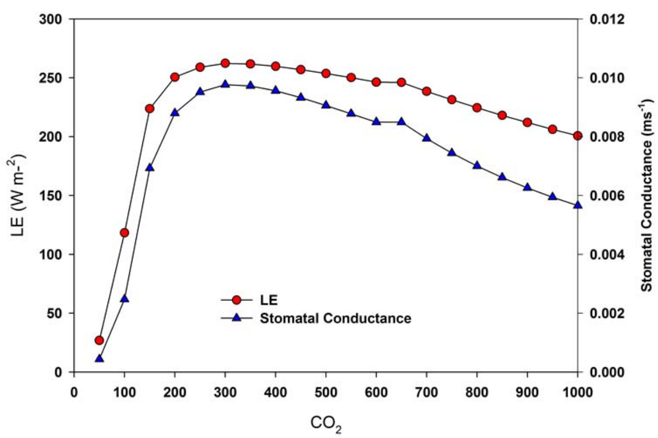
Stomatal conductance diminishes with greater humidity deficits



Together this yields a role over in LE with increasing stomatal conductance.

Transpiration and CO_2



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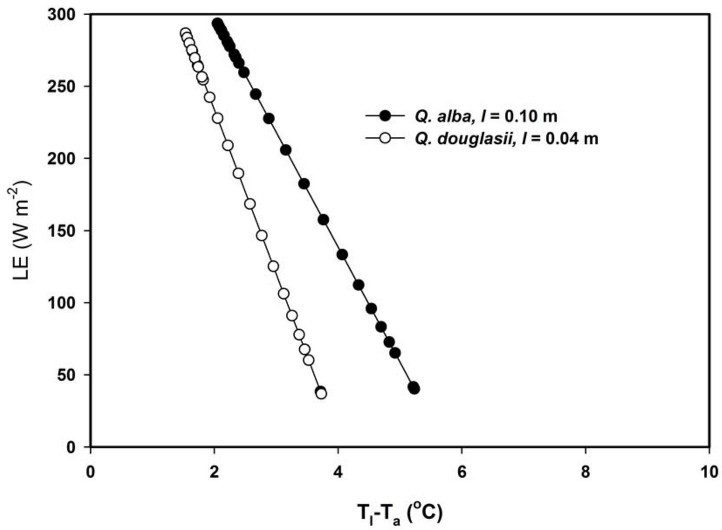
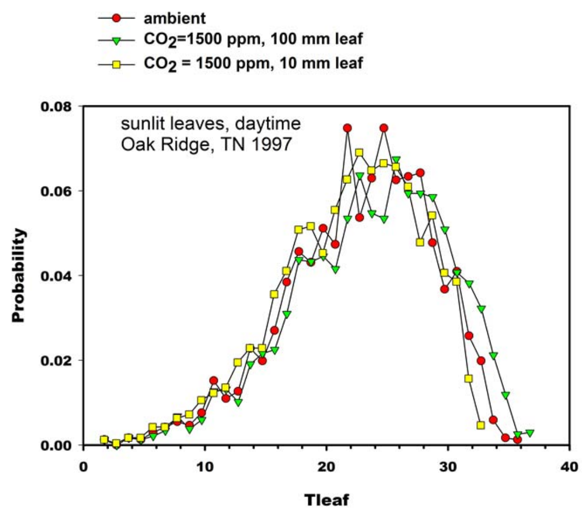
We can also look at how evaporation will change with increasing CO2 in a future world

Leaf Size, Temperature and Evaporation



Theoretical calculations of leaf size based on climate scenarios



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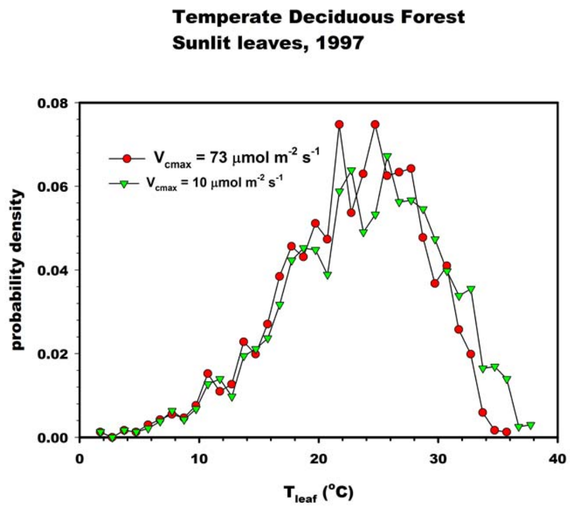
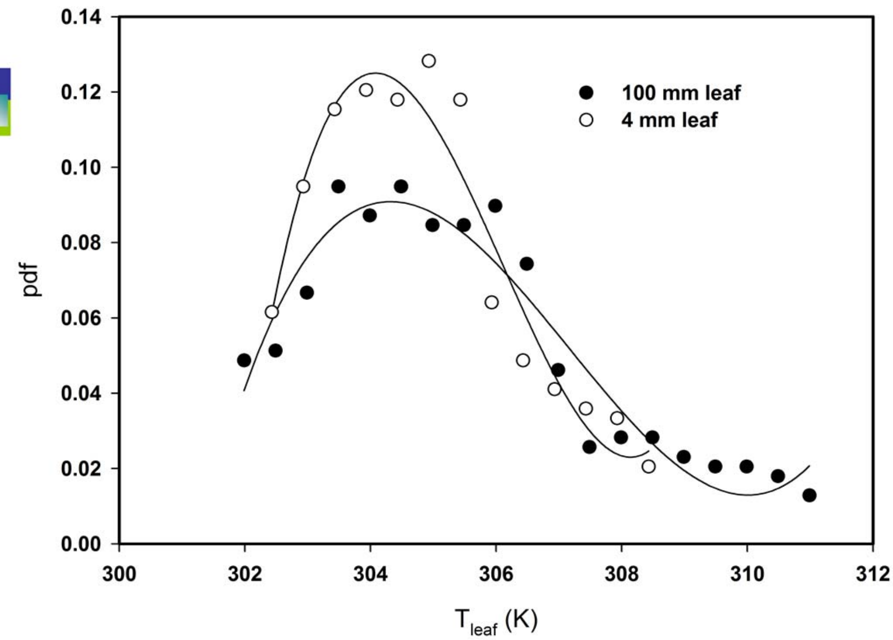
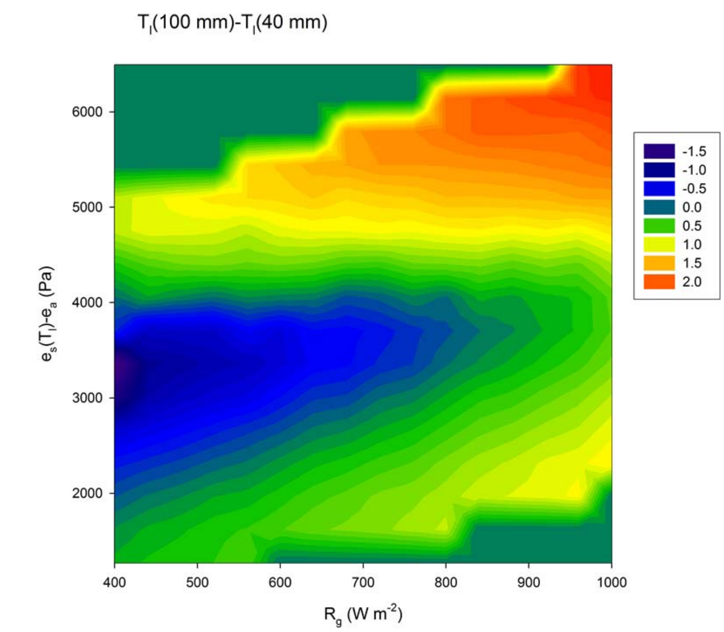
What happened in the past with high CO2 and temperatures? Having smaller leaves helps minimize exposure to lethal and debilitating temperatures.

Role of leaf photosynthetic capacity and leaf temperature





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



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.