Leaf Energy Balance

Introduction

All organisms and objects interact with their physical environment through energy exchange processes. Metabolic functions in plants operate at optimal temperatures. For example, photosynthetic enzymes process CO2 optimally at around 30 C. If a leaf heats up past 34 C, photosynthetic enzymes can begin to denature, preventing the leaf from performing its function. Thus plants attempt to maintain an equilibrium leaf temperature to maximize their usefulness to the plant. For a leaf at equilibrium, the amount of energy that enters via solar radiation and ambient heat is equal to that that exits the leaf via heat loss, reflected light and transpired water ($Energy_{in} = Energy_{out}$). If the leaf is not at equilibrium with its environment, the temperature of the leaf will change (increase or decrease) until equilibrium is achieved. Equilibrium for leaves is usually attained in less than one minute. The energy budget equation can be expanded to:

absorbed radiation = reradiation + convection + transpiration

and, finally, for a single leaf surface we can expand the equation to:

$$a \bullet \cos(i) \bullet S_{direct} + a \bullet S_{diffuse} + \varepsilon \bullet R = \varepsilon \bullet \sigma \bullet (T_l)^4 + h_c \bullet (T_l - T_a) + L \bullet (e_l - e_a)/ r_{tot}$$

external factors:
- S_{direct} - incident direct solar radiation on leaf (300-4,000 nm) (W m^{-2})
- $S_{diffuse}$ - incident diffuse solar radiation on leaf (300-4,000 nm) (W m^{-2})
- R - terrestrial infrared radiation (includes both sky and ground components) (4,000-100,000 nm) (W m^{-2})
- T_a - temperature of air (ºK)
- T_l - temperature of leaf (ºK)
- e - water vapor density of leaf (l) and air (a) (g m^{-3})

constants:
- σ- Stephan Boltzman constant (blackbody radiation constant) (W m^{-2} $^oK^{-4}$)
- L - latent heat of vaporization (J g^{-1})

leaf parameters (coupling factors):
- cos(i) - cosine of leaf orientation to the sun's direct beam, from horizontal
- a - absorption coefficient to solar radiation (300-4,000 nm)
- ε - absorption coefficient to infrared radiation (4,000-100,000 nm) - emissivity
- h_c - convection coefficient (W m^{-2} $^oC^{-1}$)
- r_{tot} - total leaf resistance (stomatal and boundary) (s m^{-1})

Leaf coupling factors involved with absorbed radiation are the total solar leaf absorptance (a) and leaf emissivity (ε) and have been discussed in lecture. Substantial changes in emissivity do not occur among leaves. However, differences in leaf absorptance do occur among species or even within a single plant over the course of a growing season. The effects of the changes in leaf absorptance are significant in terms of affecting leaf temperature. Plants may also reduce the amount of incident radiation by changing their leaf angle.

The stomatal and boundary layer resistances serve to regulate water loss from the leaf. Stomatal resistance is a function of the aperture and density of stomatal pores. The boundary layer resistance arises because of the presence of a thin layer of still air around the leaf that increases the path of water vapor diffusion to ambient air. Note that although we typically describe gaseous movements in and out of the leaf in terms of their conductance values (e.g., leaf conductance; g), because these diffusion barriers occur in series, calculations of total conductance are simpler if we use resistances (inverse of conductance). Recall from physics that conductances are additive in parallel, whereas resistances are additive in series.

The convection coefficient (h_C) is related to the boundary layer resistance as

$$h_c = K_{air}/\delta_{bl}$$

where K_{air} is the thermal conductivity coefficient for air, i.e. the coefficient that explains how well heat travels through air. The boundary layer thickness (δ_{bl}) depends on leaf size, shape, and wind speed through the relationship,

$$\delta_{bl} = K_l \times ((w/v)^{.5})$$

where K_l is an experimentally determined leaf shape parameter (usually 4.0 for leaves), w is the leaf width (m), and v is the wind speed (m s^{-1}). The boundary layer resistance can be calculated as:

$$r_{bl} = \delta_{bl}/D_j$$

where D_j is the diffusion coefficient for H_2O vapor. This parameter serves as an estimate of mean boundary layer resistance, however the boundary layer thickness (and thus resistance) varies widely over the surface of the leaf.

To understand the energy-exchange processes that affect leaf temperatures we will:

I. Experiment with changes in biotic and abiotic factors to observe the effects on heat transfer in leaves using liquid crystal leaf models.

II. Test these qualitative predictions with a leaf energy balance Excel spreadsheet program (Tleaf2.xls) to determine quantitatively how changes in biotic and abiotic properties affect leaf temperature.

I. Liquid Crystal Leaf Models

The purpose of this part of the lab is to make predictions based on the energy balance equation presented above as to how **three different leaf parameters** (leaf size, shape, and stomatal conductance) and **two environmental parameters** (light and wind) may interact to effect leaf temperature.

Permanent leaf models have been prepared for class use from thermosensitive liquid crystal film. The film is prepared by encapsulating cholesterol esters in sheet plastic that has a black undercoat. The liquid crystals have various melting points; each melting point denotes decreasing molecular orientation as the compound is warmed. The use of cholesterol esters, singly and in combination, gives a wide choice of temperatures at which the crystals and color changes occur.

We have cut the bonded film into leaf models of various sizes and shapes. Different models with transition temperatures ranging from 20-25, 25-30, 30-35, and 35-40º C have been mounted on wire "petioles" to permit exposure to sun and wind. The combined effects of both leaf and environmental parameters on leaf temperature are clearly mapped by the liquid crystal colors (see figures in appendix).

To determine temperature using the liquid crystal leaves: Within each temperature range the liquid crystals will exhibit the total color spectrum (see figures in Appendix). Warmer temperatures will exhibit a blue color, and cooler a red color. If the liquid crystals are black, the temperatures are too cool to exhibit a color change. If the liquid crystals are blue, then the temperature is too warm to determine the temperature of the crystals.

II. Energy Budget Analysis Using the T-leaf Program

A computer program is available to help you in an analysis of the leaf energy budget equation. The program (Tleaf2) requires that you input leaf characteristics and microclimate characteristics to compute the leaf temperature as well as the energy balance parameters. This program is useful for asking questions about the consequences of changes in individual leaf or climatic parameters on leaf temperature. The link between leaf temperature and the physical environment as shown in the energy budget equation is made by leaf coupling factors. The coupling factors are either physical properties of the leaf or parameters based on the leaf characteristics.

Assignment:

Answer **two of the hypotheticals** presented using both the liquid crystal leaves and the Tleaf2.xls program. Make extensive notes as you are performing the tests so you can write them up and individually hand them in for this week's assignment. When answering the questions you should 1) set realistic environmental parameters that fit the situations described in the hypothetical. You should describe in your written work why you chose those values 2) Answer the questions posed, explaining the mechanism by which the changes affected the leaf temperature. For example, you should describe how an increase leaf length alters leaf temperature via increases in boundary layer thickness, which in turn determines convection as well as controls heat loss via evaporation NOT just say that leaf temperature increases for longer leaves. Pay particular attention to the Calculated Leaf Parameters (δ_{bl}, r_l, r_{bl}, h_c, E etc.) and the Energy Balance Parameters (convection, conduction, evaporation) while you go through the questions. Changes in these represent the mechanisms of alterations in leaf or environmental inputs.

In your handed-in assignment, please be explicit about the hypotheses you tested and the methods you used to test them. The parameters you manipulated in Tleaf2 should be explicitly described including the values you used.

Ecological Hypotheticals (each group should choose TWO to test):

1) Todd E. Dawson needs your help. His redwood project has run into a snag and he has asked you to test some theories for him using your little cut out leaves, Tleaf2 and your wits. He is wondering what would be **the changes in the leaf energy balance of redwood leaves as you go up into a canopy**. After talking to him a bit, he reminds you that the major changes as you go up in the canopy would be increased incident radiation, increased wind and smaller leaves at the top of the canopy. How will the different outputs of the leaf energy balance (convection, conduction and transpiration) differ between leaves low in the canopy and high in the canopy? Which of the environmental changes will have the greatest effect on leaf temperature? Will leaves high in the canopy be at a higher or lower temperature than those in the low canopy? Todd promises you an A in IB 151 if you can help him out.

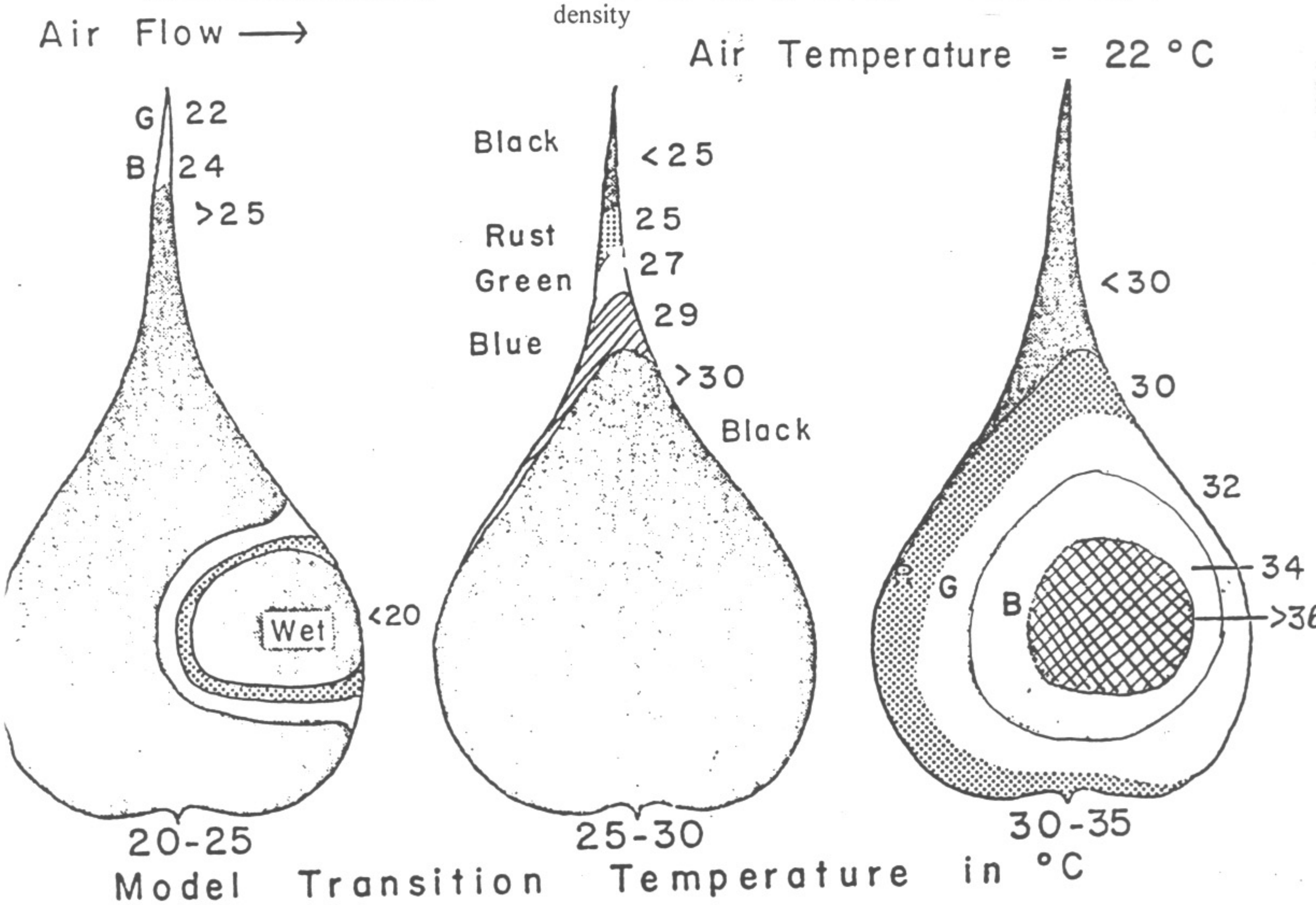
2) One day after class you notice your GSI Rafael crying in the corner. When you ask him what the problem is, he relates a sad tale concerning his doctoral dissertation. He is looking at the **correlation between leaf size and leaf resistance to water** loss in cerrado plants. He has been investigating shrubs with different leaf sizes on the same individual that paradoxically maintain the same leaf temperature. The leaves are experiencing the same environmental conditions. He thinks the difference may have something to do with stomatal resistances but doesn't know how. You offer to help him and show him the special leaves you recently acquired and the disk with the Tleaf2 program. A large smile spreads across his face and he thanks you profusely for your help.

3) Your GSI Neil, in a sudden career change, begins work for Chiquita growing bananas in rainforests in Hawai'i. Chiquita has hired Neil to test out his new ecologically sensitive program which involves growing **bananas in canopy gaps (high light, high air temperatures) in the rainforest**. Bananas have huge, horizontally oriented leaves (0.5 m long). Neil asks you to see whether such big leaves will exhibit leaf temperatures that are too high (> 34 ^{o}C) in the gaps. He wants to know the environmental and leaf conditions that would to make the leaves too hot? He also wants to know what the leaf temperature would be in the closed understory (cool with low light). Although you can't get hold of 0.5 m long liquid crystal leaves you can use the biggest ones you have to test this question. Neil reminds you that you can also use the Tleaf2 program to give him some hard data. Maybe he will give you some bananas in exchange for your hard work?

4) Your Australian friend comes home with you over Christmas break to meet your family for the first time. You are very nervous and hope that your parents will approve of your burgeoning relationship. But as you are chowing down on tofurkey, you hear your father asking your friend about the Australian eucalyptus forests. Hoping to impress your Dad, your Aussie friend tells him that many eucalypts have leaves that are the same size at the top and bottom of the canopy. Your friend continues that they just alter their leaf angles and leaf color to minimize the energy load at the top and maximize it at the bottom. You almost choke when your Dad asks, "**What leaf angles and absorption coefficients would allow the leaves in both the high and low canopy to maintain a maximum leaf temperature of 27 ^{o}C**?" Can you save your relationship by answering your Dad's question or will your friend be taking a slow boat back to Oz? In answering the question, first come up with realistic environmental parameters for the high and low canopy, then alter the leaf parameters and see how the energy balance parameters change and how they help maintain leaf temperature.

Appendix I:

Variable:	**Acceptable Range:**
External Factors	
Direct solar radiation (W m^{-2})	Full sun is 833, dark closed understory 250
Wind speed (m s^{-1})	0.75 m s^{-1} is considered calm (closed habitats - forests), 1.0 m s^{-1} is considered common (open habitats - grasslands, 4.0 m s^{-1} is considered windy (alpine, seashore, island habitats)
Maximum air temperature (°C)	Enter a realistic value
Minimum air temperature (°C)	Dew point, or temperature when dew forms; enter realistic value
Leaf Parameters	
Leaf Inclination	0° is horizontal, 90° is vertical
Leaf total solar absorbance (%)	60% is typical of a green leaf, 50% for a gray leaf, and 40% for a white leaf
Emissivity (ε)	How similar the leaf is to a "black body", more or less constant at 0.96
Leaf length (m)	Measured in the direction of wind for convenience
Leaf shape parameter	More or less constant at 4
Stomatal resistance (s m^{-1})	600 open stomata, high density, 5000 closed stomata, low density



TLEAF2.xls

External Factors

S_{dir}	W m^{-2}	200 - 1000	900.00
v	s m^{-1}	0.75 -4.0	0.75
T_a	°C	10 -30	25.00
Tmin	°C	0 - 25	10.00
S_{dif}	W m^{-2}		*100.00*
e_l	g m^{-3}		*30.52*
e_a	g m^{-3}		*23.0954*
R	W m^{-2}		*810.00*
Δ	Kpa °C^{-1}		*0.19*

Leaf Parameters

i	°	0 - 90	0.00
a	%	0.4 - 0.6	0.50
ε	none	0.96 - 0.97	0.96
w	m	0.03 - 0.5	0.50
K_l	none	4 - 6	4.00
r_{st}	s m^{-1}	600 - 5000	5000.00
r_c	s m^{-1}		*2500.00*
r_{ias}	s m^{-1}		*25.00*

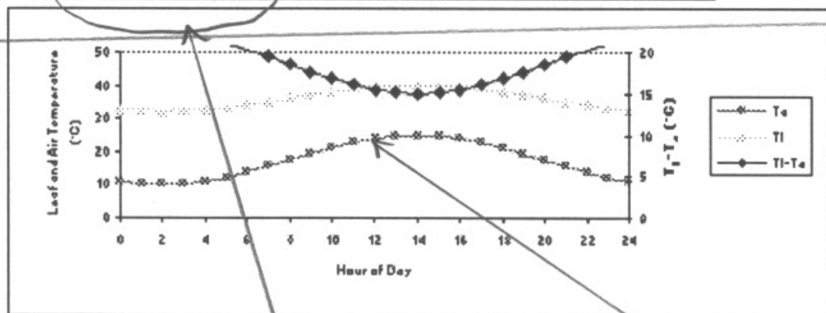
Constants

σ	W m^{-2} °K^{-4}	*5.67E-08*
L	J g^{-1}	*2450.00*
D_j	$m^2 s^{-1}$	*2.42E-05*
K^{air}	W m^{-1} °C^{-1}	*0.0259*

energy in			=	**energy out**		
direct	**$a \times \cos(i) \times S_{dir}$**	450.00 W m^{-2}		**conduction**	**$\varepsilon \times \sigma \times (T_l)^4$**	1044.29 W m^{-2}
+				**+**		
diffuse	**$a \times S_{dif}$**	50.00 W m^{-2}	=	**convection**	**$h_c \times (T_l - T_a)$**	237.21 W m^{-2}
+				**+**		
long-wave radiation	**$\varepsilon \times R$**	777.60 W m^{-2}		**transpiration**	**L×E**	14.39 W m^{-2}
TOTAL IN		1277.60		**TOTAL OUT**		1295.89

Calculated Leaf Parameters

δ_{bl} =	**$K_l \times ((w/v)^{\wedge}.5)$**	**3.27**	mm
r_{bl} =	**δ_{bl}/D_j**	**134.96**	s m^{-1}
h_c =	**K_{air}/δ_{bl}**	**7.93**	W m^{-2} °C^{-1}
r_l =	**$(r_{ias} + r_{st})(r_c)$ / $(r_c + r_{ias} + r_s)$**	**1669.44**	s m^{-1}
E =	**$(e_l - e_a)/(rl+rbl)$**	**0.23**	mmol m^{-2} s^{-2}
T_{leaf} (°C) =	**39.96**	**T_{air} (°C) =**	**25.00**



environmental parameters to change

energy balance parameters, pay attention to how they respond

leaf parameters to change

do not change but pay attention to how they respond

generally acceptable range for that parameter

LEAF TEMPERATURE

daily time course graph with air temp., leaf temp. and the difference between the two

units

do not change things in grey boxes

put cursor over symbol to see name