Energy Balance

Plant temperature affects virtually all plant processes, so it is critical to understand the factors that affect temperature of plants.

Plant temperature is controlled by the **energy balance**, which determines the net amount of energy that is available to drive plant physical and biochemical processes (transpiration, respiration, etc.)
Radiation Basics

Electromagnetic radiation behaves as both a particle (photon) and a wave. Photons are emitted or absorbed by matter due to discreet quantum jumps in energy levels in atoms, or changes in rotational or vibrational energy levels in molecules.
Energy per photon (e) depends on the frequency of light according to Planck’s law

\[ e (J) = h \nu \]

where \( h \) is Planck’s constant (6.63 x 10^{-34} \text{ J s}) and \( \nu \) is frequency (s^{-1}).

Frequency is related to wavelength (\( \lambda \)) by the relationship

\[ \nu = \frac{c}{\lambda} \]

where \( c \) is speed of light (3 x 10^8 \text{ m s}^{-1}).

\[ e (J) = \frac{hc}{\lambda} \]

Which contains more energy, blue light or red light?
Radiant energy reaching a plant can be described as an energy flux density (irradiance) or a quantum flux density (photon irradiance).

What are the units for irradiance and photon irradiance? See page 245.

All objects emit radiation as a function of the fourth power of the surface temperature. This can be described by the Stefan-Boltzmann equation

\[ \phi = \varepsilon \sigma T^4. \]
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In this equation, \( \phi \) (W m\(^{-2}\)) is the flux density of emitted radiation, \( \varepsilon \) is emissivity, \( \sigma \) is the Stefan-Boltzmann constant \((5.67 \times 10^{-8} \text{ W m}^{-2} \text{ K}^{-4})\), and \( T \) (K) is temperature. \( \varepsilon \) is 1 for a perfect radiator, and ranges from about 0.94 to 0.99 for leaves.

What is the flux density of radiant energy emitted by a cotton leaf whose temperature is 30 C and emissivity is 0.97?

The wavelengths at which emission occurs is a function of temperature. The higher the temperature, the shorter are the wavelengths of emitted radiation.

The sun has a surface temperature of 6,000° K, and its emitted radiation is mostly shortwave (200 to 4,000 nm) with peak emission occurring at a wavelength of 480 nm, which is in the visible portion of the spectrum.
Terrestrial objects have a much lower temperature (~300°C) so they emit longwave radiation (>4,000 nm), with a peak emission occurring at about 9,800 nm.

Radiation with wavelengths less than 4,000 nm is referred to as shortwave radiation, while that with wavelengths greater than 4,000 nm is referred to as longwave radiation.

Radiation between 400 and 700 nm is visible light and is referred to as photosynthetically active radiation (PAR).
Radiation of wavelengths between 200 and 400 nm is ultraviolet radiation, most of which is absorbed by ozone in the upper atmosphere.

The major source of energy is solar radiation ($R_s$), a high percentage of which is absorbed by leaves. Solar radiation is shortwave radiation with a wavelength range of 400 to 4,000 nm. A high proportion of $R_s$ (~80% under clear skies) is direct-beam solar radiation.

Irradiance = $(A) \times \cos \alpha$
If the sun is 30° above the horizon, and the irradiance (A) measured perpendicular to the solar beam is 1000 W m⁻², what is the irradiance upon a horizontal soybean leaf?

\[ \alpha \]

\[ \text{Leaf} \]
In addition to the sun, leaves receive shortwave radiation from the sky. This is solar radiation that is scattered by particles in the atmosphere, and reaches the leaf as blue skylight.

Leaves also receive shortwave radiation that is reflected from surrounding leaves and soil, or transmitted through surrounding leaves.
Leaves receive longwave (thermal) radiation emitted from the sky, surrounding leaves and soil.

The leaf emits longwave radiation from both surfaces as a function of the fourth power of leaf temperature.

The net radiation ($Q^*$) is the total amount of short and longwave irradiance from all sources that is absorbed by the leaf, minus longwave radiation emitted by the leaf.
Net radiation is positive during the day.

At night, there is no shortwave component from the sun and sky.
so that \( Q^* \) is negative.

Measurements at noon show that a soybean leaf is absorbing 700 W m\(^{-2}\) of shortwave radiation and 300 W m\(^{-2}\) of atmospheric longwave radiation, and emitting 400 W m\(^{-2}\) of longwave radiation. What is the net radiation of the leaf?

Leaves can dissipate or gain energy by convective transfer of sensible heat (\( Q_H \)). If the leaf is warmer than the air, \( Q_H \) will be directed away from the leaf.
Why is it called sensible heat?

If the leaf is cooler than the air, \( Q_H \) will be directed toward the leaf. This is common during hot, dry afternoons when the leaf is cooled by evaporation, and at night.
Surrounding the leaf is a layer of still air called the laminar boundary layer. The boundary layer is an impediment to heat transfer. The thicker the layer, the lower is the heat flux.

Boundary layer thickness decreases as wind speed increases. Thus, wind enhances heat transport. Boundary layer thickness increases as leaf size increases.

Convective heat transfer is governed by Fick's law

\[ Q_H (W m^{-2}) = -C_p (T_L - T_a)/\theta_h \]

where \( Q_H \) is the convective heat flux density, \( \theta_h \) (s m\(^{-1}\)) is the boundary layer resistance for heat transfer, \( C_p \) (1200 J m\(^{-3}\) K\(^{-1}\)) is specific heat of air, and \( T_L \) and \( T_a \) are leaf and air temperature, respectively, in °K. Boundary layer resistance decreases as wind speed increases, and increases as leaf size increases.
Latent heat flux ($Q_e$) is a major component of the leaf energy balance. It is the heat contained in the water vapor that diffuses from the leaf interior to the atmosphere.

Why is it called latent heat?

Key Point:

It takes a lot of energy (~2450 J per gram of water, 44 kJ per mole) to convert water from a liquid to a vapor. This means that 1 g of water vapor carries with it 2450 J of energy when it leaves the leaf. 1 mole of water vapor carries 44,000 J of energy.

Transport of latent heat is the main way that leaves get rid of excess energy.
Water vapor must diffuse through the stomatal opening as well as through the boundary layer.

The driving force for $Q_E$ is the difference in water vapor concentration between the leaf interior and the air.

Diffusion of $Q_E$ is governed by Fick’s law

$$Q_E = -\lambda (C_{wv(leaf)} - C_{wv(air)})/(r_b + r_s),$$

where $\lambda$ is the latent heat of vaporization (44 kJ mol$^{-1}$, 2450 J g$^{-1}$), and $r_b$ and $r_s$ are boundary and stomatal resistances to water vapor diffusion.

Later, we will examine water vapor diffusion through leaves in more detail.
Leaves generate a small amount of metabolic energy ($M$).

$Q^* + Q_H + Q_E + M = 0$

$Q^* (+)$  $Q_H(+ or -)$  $Q_E (-)$

Leaves is usually small, so we can neglect it.

$Q^* + Q_H + Q_E + M = 0$

$Q^* (+)$  $Q_H(+ or -)$  $Q_E (-)$

Thus, the energy balance for a leaf consists of the sum of net radiation, sensible heat flux and latent heat flux.
KEY POINT:
The amount of water used by a plant is controlled by net radiation ($Q^*$), and how it is partitioned between latent ($Q_E$) and sensible heat ($Q_H$). $Q_E$ cannot exceed the sum of $Q^*$ and $Q_H$!!! Plants are not suction pumps, using as much water as they please.

Ecosystem Energy Balance

$$Q^* + Q_G + Q_E + Q_H = 0$$