

Whole Plant Energy Balance

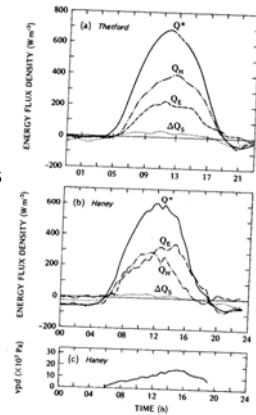
Topics to be covered this week:

1. Why it's of concern in ecophysiology
2. The Penman-Monteith Equation
3. Aerodynamic Coupling and the Omega factor
4. Energy balance of leaves vs. canopies

Whole Plant Energy Balance

Why does it concern ecophysologists?

- Transpiration of water is a large part of the plant energy budget – knowing energy budget links to plant water budget.



Whole Plant Energy Balance

Why does it concern ecophysologists?

•Stomata control transpiration – and assimilation too. Thus energy balance connects with carbon relations. The Penman-Monteith energy balance equation allows us to solve for stomatal conductance.

$$E = \frac{\{s(\Phi_n - G) + \rho_a c_p g_H \delta e\}}{\lambda[s + (\gamma g_H / g_w)]}$$



Whole Plant Energy Balance

Why does it concern ecophysologists?

- Leaf or canopy temperature depends on the overall energy balance – and numerous physiological processes depend on temperature.

Whole Plant Energy Balance

Also Important for:

Land surface energy balance/climate forcing studies

Hydrological sciences

Whole Plant Energy Balance

Finally to pique your interest:

Generally, speaking, known incoming energy to terrestrial ecosystems is not balanced by known transformations of this energy: there is a missing energy gap.



AGRICULTURAL AND FOREST METEOROLOGY

Energy balance closure at FLUXNET sites

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Abstract

A comprehensive evaluation of energy balance closure is performed across 22 sites and 50 site-years in FLUXNET, a network of eddy covariance sites measuring long-term carbon and energy fluxes in contrasting ecosystems and climates. Energy balance closure was evaluated by statistical regression of turbulent energy fluxes (sensible and latent heat (LE)) against available energy (net radiation), but the energy stored by solving for the energy balance ratio. The ratio of turbulent energy fluxes to available energy. These methods indicate a general lack of closure across sites, with a mean imbalance in the order of 20%. The imbalance was greatest in all seasons, vegetation types, and climate regimes. Long-term energy flux imbalances in temperate and arctic sites were on the order of 10% of the available energy, while in tropical sites they were on the order of 20%. A number of sites closure improved with turbulent intensity (friction velocity), but lack of total closure was still prevalent under most conditions. The imbalance was greatest during seasonal periods. The results suggest that estimates of the ratio of turbulent fluxes of sensible and LE are underestimated and/or that available energy is overestimated. The implications on average, net ecosystem CO₂ fluxes in FLUXNET are discussed in the context of the imbalance and the associated energy balance closure.

Leaf or canopy energy balance is expressed by the Penman-Monteith equation.

Penman (1948) considered energy balance on water surfaces only, and ‘fudge factors’ were applied for crop energy balance.

Later, Penman (1953) and Monteith (1965) explicitly included latent heat transfer from leaves and canopies.

Penman HL (1948) Natural evaporation from open water, bare soil and grass. Proc. Royal Soc. London A, 193: 120-145.

Penman HL (1953) The physical basis of irrigation control. Report of the 13th Intl. Hort. Congress. 2: 913-914.

Monteith JL (1965) Evaporation and Environment. Symposia of the Soc. Exp. Bio. 19:205-234.

Deriving the P-M equation:

1. We start with the basic energy conservation equation:

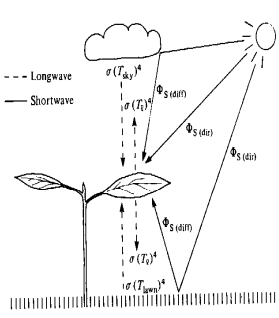
$$R_n = C + \lambda E + M + S$$

where R_n = net radiation
 C = sensible heat flux
 λE = latent heat flux
 M = biochemical energy storage
 S = physical heat storage

Let's consider each term in a bit more detail:

$$R_n = C + \lambda E + M + S$$

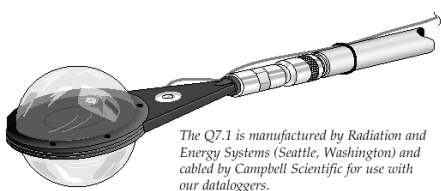
R_n = net radiation = the net of all incoming and outgoing radiation fluxes to/from leaves or canopies. A combination of shortwave and longwave radiation.



Note:

R_n is the amount of energy available to heat up leaves, evaporate water, etc., but its important to realize that plants control R_n through stomata and latent heat (transpirations) – so R_n is not exclusively a ‘meteorological’ variable.

Typical net radiometer



The Q7.1 is manufactured by Radiation and Energy Systems (Seattle, Washington) and cabled by Campbell Scientific for use with our dataloggers.

- “looks” and subtracts upward from downward radiation
- Shields prevent excessive convective cooling
- Black surfaces absorb all wavelengths, come to steady state temperature. Difference in temperature transduced into voltage and calibrated to Watts/m2.

Can also piece together net radiation from longwave and shortwave components – thermopile detectors



Infrared radiometer (longwave) W/m2



Shortwave radiometer (pyranometer) W/m2

$$R_n = C + \lambda E + M + S$$

C is sensible heat loss from leaf/canopy
Sensible means 'measurable' in terms of thermometry.

C is given by:

$$C = g_H (\rho c_p) (T_{\text{leaf}} - T_{\text{air}})$$

Where g_H is conductance to heat transfer (m s^{-1})
 ρ is density of air (kg m^{-3}) (1.2 kg/m^3 @ 25 deg C)
 c_p is specific heat capacity ($\text{J kg}^{-1} \text{K}^{-1}$) = 1012 for air

Units: (m s^{-1}) (kg m^{-3}) ($\text{J kg}^{-1} \text{K}^{-1}$) (K) = $\text{J s}^{-1} \text{m}^{-2}$ = Watts m^{-2}

$$R_n = C + \lambda E + M + S$$

$$\lambda E = \lambda g_W \Delta C_W$$

Where λ is latent heat of water ($2.4\text{-}2.5 \text{ MJ kg}^{-1}$ for $0\text{-}45 \text{ }^\circ\text{C}$)

g_W is leaf/canopy conductance to water (m s^{-1})

ΔC is water vapor concentration difference (kg m^{-3})

Units: (J kg^{-1}) (m s^{-1}) (kg m^{-3}) = $\text{J s}^{-1} \text{m}^{-2}$ = W m^{-2}

$$R_n = C + \lambda E + M + S$$

And,
$$\Delta C_W = (\rho_a M_W / M_A) \Delta e / (P - e)$$

Where ρ_a is density of air (kg m^{-3});

M_W is molecular weight of water (18 g mol^{-1})

M_A is the effective molecular weight of dry air ($\sim 29 \text{ g mol}^{-1}$)

So $M_W / M_A = 0.622$

P is atmospheric pressure ($\sim 101.3 \text{ kPa}$)

And Δe is vapor pressure difference (kPa)

Units for ΔC_W : (kg m^{-3}) (g mol^{-1}) / (g mol^{-1}) (kPa/kPa) = kg m^{-3}

Units for λE : (J/kg) (m/s) (kg/m^3) = W/m2

$$R_n = C + \lambda E + M + S$$

Thus, $\lambda E = \lambda g_W \Delta C_W$ becomes

$$\lambda E = \lambda g_W (\rho_a M_W / M_A) \Delta e / (P - e)$$

$$\text{but } (P - e) \sim P \text{ since } P \gg e$$

So,

$$\lambda E \approx \lambda g_W (\rho_a M_W / M_A) \Delta e / P, \text{ OR,}$$

$$\lambda E \approx \lambda g_W (\rho_a 0.622) (e_{s(Tl)} - e_a) / P$$

Measurement of λE and C at the canopy scale – eddy covariance technique.



Measurement of λE at the leaf scale – leaf cuvette/infrared gas analyzers.



$$R_n = C + \lambda E + M + S$$

M is energy stored in chemical bonds, dominated by photosynthesis and respiration, and usually $< 5\%$ of R_n . Thus, it can for most purposes be ignored in terms of the overall plant energy balance.

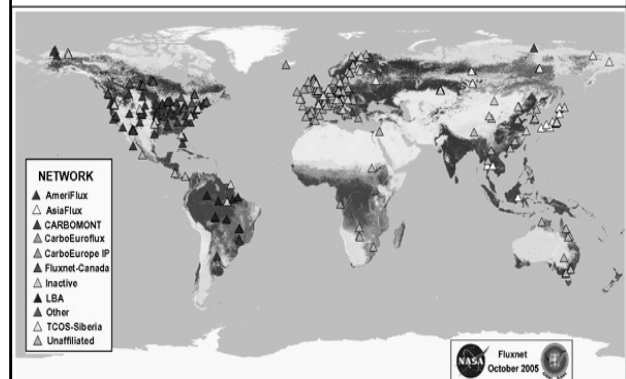
$$R_n = C + \lambda E + M + S$$

S is energy used for heating leaves, wood, soil. Generally small except for massive stems, forests, leaves, cacti.

Here we will ignore it by assuming either small plants or steady state conditions.



FluxNet: energy balance studies around the world (~350 sites currently)



Recap so far:

We've described each of the terms in:

$$R_n = C + \lambda E + M + S$$

And by ignoring the last two terms we have

$$R_n = C + \lambda E$$

$$R_n = g_H(\rho c_p)(T_{\text{leaf}} - T_{\text{air}}) + \lambda g_W(\rho_a 0.622)(e_{s(T)} - e_a)/P$$

Doesn't look very nice!

The main problem with

$$R_n = g_H(\rho c_p)(T_{\text{leaf}} - T_{\text{air}}) + \lambda g_W(\rho_a 0.622)(e_{s(T)} - e_a)/P$$

Is that it requires knowledge of T_{leaf} (or T_{canopy}) – difficult to obtain.

If we could somehow eliminate T_{leaf} from the equation life would be much easier.

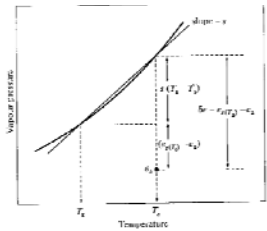
This is what Penman did.

$$R_n = g_H(\rho c_p)(T_{\text{leaf}} - T_{\text{air}}) + \lambda g_W(\rho_a 0.622)(e_{s(TI)} - e_a)/P$$

Penman made the following approximation:

$$(e_{s(TI)} - e_a) = (e_{s,Ta} - e_a) - de_s/dT * (T_a - T_{\text{leaf}})$$

Where $de_s/dT = S$ = the slope of the e_s vs. T curve.



$$R_n = g_H(\rho c_p)(T_{\text{leaf}} - T_{\text{air}}) + \lambda g_W(\rho_a 0.622)(e_{s(TI)} - e_a)/P$$

$$(e_{s(TI)} - e_a) = (e_{s,Ta} - e_a) - de_s/dT * (T_a - T_{\text{leaf}})$$

$$\text{(from last page,)} = \text{VPD} + s(T_{\text{leaf}} - T_{\text{air}})$$

VPD is just a $F(T_{\text{air}}, \text{Rel. Humidity})$ – easy to measure. S is simply a property of water vapor and can be just read off the chart.

But we still have $(T_{\text{leaf}} - T_{\text{air}})$ – which we still need to ‘get rid of’.

$$R_n = g_H(\rho_a c_p)(T_{\text{leaf}} - T_{\text{air}}) + \lambda g_W(\rho_a 0.622)(e_{s(TI)} - e_a)/P$$

Fortunately, we now have two terms in the above equation in $T_{\text{leaf}} - T_{\text{air}}$. The blue term (C) AND the yellow term (λE).

For the λE term we can replace $T_{\text{leaf}} - T_{\text{air}}$ in terms of C :

$$\lambda E = \lambda g_W(0.622 \rho_a/P)[\text{VPD} + (S C/g_H \rho_a c_p)]$$

$$= \lambda g_W(0.622 \rho_a/P)[\text{VPD} + (S (R_n - \lambda E) /g_H \rho_a c_p)]$$

Gather terms and solve for E :

Finally, going back to the overall energy balance equation: $C = R_n - \lambda E$

We obtain

$$E = \frac{SR_n + \rho_a c_p g_H \text{VPD}}{\lambda[S + (Pc_p / 0.622\lambda)g_H / g_W]}$$

This, my friends, is the Penman-Monteith equation. Note: no T_{leaf}

Let's clean up

$$E = \frac{sR_n + \rho_a c_p g_H \text{VPD}}{\lambda[s + (Pc_p / 0.622\lambda)g_H / g_W]}$$

a bit:

Let $\gamma = Pc_p / 0.622 \lambda$ (= 65-68 Pa/K from 0-50 °C)
And let D stand for VPD. Then,

$$E = \frac{sR_n + \rho_a c_p g_H D}{\lambda[s + \gamma(g_H / g_W)]}$$

$$E = \frac{sR_n + \rho_a c_p g_H D}{\lambda[s + \gamma(g_H / g_W)]}$$

Looks better, but is still limited in application:

R_n depends on $T_{\text{leaf/canopy}}$ and one would need a net radiometer for each and every vegetation plot to use this equation.

But there is another way around this...

Instead of using R_n , we can use a related variable called R_{ni} , "Isothermal Net Radiation"

R_{ni} is the net radiation that would occur if surface (leaf or canopy) temperature were the same as air temperature.

Its an artificial quantity, but useful, as we'll see.

Clearly we cant just replace R_n with R_{ni} because

$$R_{ni} = R_n + \epsilon\sigma(T_s^4 - T_a^4)$$

(I'm using $T_s = T_{leaf}$ or T_{canopy} from now on)

And this is still problematic because of T_s . But we can use a trick that ultimately gets T_s out of the way:

We substitute $T_s = T_a + \Delta T$ above to get

$$R_{ni} = R_n + \epsilon\sigma[(T_a + \Delta T)^4 - T_a^4]$$

$$= R_n + \epsilon\sigma[T_a^4 + 4T_a^3\Delta T + 6T_a^2(\Delta T)^2 + 4T_a(\Delta T)^3 + (\Delta T)^4 - T_a^4]$$

$$= R_n + \epsilon\sigma[4T_a^3\Delta T + 6T_a^2(\Delta T)^2 + 4T_a(\Delta T)^3 + (\Delta T)^4]$$

And since $T_a \gg \Delta T$, we can drop the higher order ΔT terms

So,

$$R_{ni} \cong R_n + 4\epsilon\sigma T_a^3(T_s - T_a)$$

This second term can also be expressed as $(4\epsilon\sigma T_a^3 / \rho c_p) \rho c_p (T_s - T_a)$

And now it looks very much like the term $C = g_H \rho c_p (T_s - T_a)$ for sensible heat flux.

Taking this analogy further, we can define a 'radiative conductance' as:

$$g_R = 4\epsilon\sigma T_a^3 / \rho c_p$$

So that $R_n \cong R_{ni} - g_R \rho c_p (T_s - T_a)$

We still have T_s though (recall that's what we're trying to get rid of)!

We can 'bundle' g_R in with g_H since they operate in parallel and both are associated with $T_s - T_a$. So $g_{HR} = g_H + g_R$

Thus, we can take the original PM equation:

$$E = \frac{sR_n + \rho_a c_p g_H D}{\lambda[s + \gamma(g_H / g_w)]}$$

And replace it with:

$$E = \frac{sR_{ni} + \rho_a c_p g_{RH} D}{\lambda[s + \gamma(g_{RH} / g_w)]}$$

Done!

So why is this better??

$$E = \frac{sR_{ni} + \rho_a c_p g_{RH} D}{\lambda[s + \gamma(g_{RH} / g_w)]}$$

The g_H part of g_{RH} is a f(windspeed, leaf shape, or canopy geometry) – can be modeled or measured independently

R_{ni} can be estimated simply from T_a

D is easily computed from RH and T_a

g_w can be modeled or measured with gas exchange (scaling issue...), or the whole equation can be 'inverted' to solve for g_w instead.

Now lets build upon the PM Energy Balance Equation:

Aerodynamic Coupling and the Omega factor

Example of wind chill

Aerodynamic coupling fundamentally describes how much physiological control plants have over water loss (stomata) versus how much structural (boundary layer) control plants have over water loss

This is important because it allows us to assess the importance of stomata vs. canopy structure to water and energy budgets in a broader context of plant interaction with the environment.

It can roughly be thought of as 'degree of ventilation'. Well ventilated leaves or canopies ('fractally' shaped) are highly 'coupled' to the external atmospheric envt, while poorly ventilated canopies (umbrella shaped) are 'decoupled' from the atmosphere

Well (poorly) coupled leaves/plants conduct/convect heat away efficiently (inefficiently), and therefore maintain foliage temperatures close to (not close to) bulk air temperature.

Conifers (and forest in general) are well coupled



Crops and other canopies with big leaves and/or tightly clustered foliage are poorly coupled.



Figure 4. Mature stand of *Miscanthus x giganteus* approximately 3.5 m high. Photograph taken September 1996, about 30 km south of Ulm in southern Germany, by Dr. I. Lewandowski, University of Hohenheim (Scurlock, 1998).



The relative values of g_H (or g_{RH}) and g_W are at the heart of the concept of aerodynamic coupling.

$$E = \frac{sR_n + \rho_a c_p g_H D}{\lambda[s + \gamma(g_H / g_W)]}$$

We need to step back and deconstruct g_H (or g_{RH}) and g_W first to see where the stomatal vs. boundary layer terms fall out. For simplicity, we will consider the above version of the PM equation for this purpose.

For a leaf, there is a single boundary layer conductance to heat transfer, but a series of stomatal and boundary layer conductance for H₂O (and CO₂)

So, $g_H = g_a$ and $g_W = 1/(1/g_a + 1/g_s)$

We're assuming that $g_{aH} = g_{aW} = g_a$ which is not always strictly true but doesn't matter to this discussion.

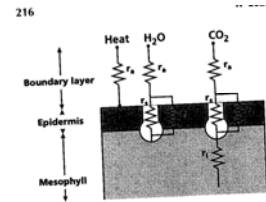


FIGURE 6. Resistances for the exchange of heat and gas between the leaf and the atmosphere. For CO₂, apart from the cuticular resistance (r_c) three resistances play a role (internal, r_s stomatal, r_b boundary layer, r_c), whereas there are only two and one for H₂O and heat exchange, respectively. Note that conductance is the inverse of resistance, $g = 1/r$ (Jones 1985). Copyright Pergamon Press.

This applies to a leaf, but for now we can consider it to apply to a canopy too – if we assume $g_a = g_{aW} = g_{aH}$ to be a 'bulk' boundary layer conductance that includes effects of all the nested boundary layers from leaf to canopy.

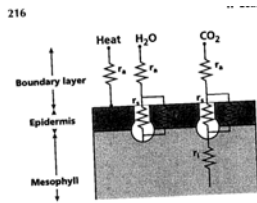


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So $g_H/g_W = g_a \times [(1/g_a) + (1/g_s)] = 1 + g_a/g_s$

And thus $E = \frac{sR_n + \rho_a c_p g_H D}{\lambda[s + \gamma(g_H / g_W)]}$

becomes

$$E = \frac{sR_n + \rho_a c_p g_a D}{\lambda[s + \gamma(1 + g_a / g_s)]}$$

Now we've more explicitly separated out the boundary layer vs. stomatal components and can consider their relative controls on E

$$E = \frac{sR_n + \rho_a c_p g_a D}{\lambda[s + \gamma(1 + g_a/g_s)]}$$

If $g_a \ll g_s$ (or $g_a \rightarrow 0$) the above equation reduces to

$$E = \frac{sR_n}{\lambda[s + \gamma]}$$

If $g_a \ll g_s$ (or $g_a \rightarrow 0$) transpiration is controlled only by net radiation, and is independent (or decoupled) from bulk atmospheric humidity (VPD)

$$E_{equilibrium} = \frac{sR_n}{\lambda[s + \gamma]}$$

Because g_a and not g_s is 'bottleneck' in overall E transport, it simply does not matter what stomates are doing!

We call this $E_{equilibrium}$ because in this case, stomata may close or open, but if they do, they will change leaf-air vapor pressure difference in such a way to maintain a constant $E_{equilibrium}$.

Now let's consider the other extreme: $g_a \gg g_s$ (or $g_a \rightarrow$ infinity)

$$E = \frac{sR_n + \rho_a c_p g_a D}{\lambda[s + \gamma(1 + g_a/g_s)]} = \frac{\frac{sR_n}{g_a} + \rho_a c_p D}{\lambda[\frac{s}{g_a} + \frac{\gamma}{g_a}(1 + g_a/g_s)]}$$

OR,

$$E = \frac{\rho_a c_p g_s D}{\lambda \gamma}$$

If $g_a \gg g_s$ (or $g_a \rightarrow$ infinity) transpiration is controlled strongly by stomata, and is directly controlled by – or coupled to – atmospheric humidity (VPD)

$$E_{imposed} = \frac{\rho_a c_p g_s D}{\lambda \gamma}$$

Because g_s and not g_a is the 'bottleneck' in overall E transport, stomates control it all

(We call this $E_{imposed}$ because ambient D is 'imposed' right at foliage surface with no intervening boundary layer of any significance)

We can see the relative sensitivity of different vegetation types to canopy (stomatal) conductance

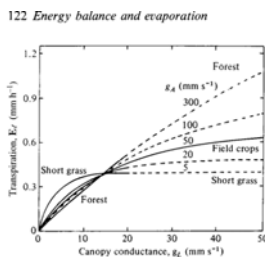


Fig. 5.6. Calculated relationships between transpiration rate and canopy conductance at different boundary layer conductances, for 400 W m^{-2} available energy, 1 kPa vapour pressure deficit and 15°C . The solid lines represent the probable range of values of canopy conductance for different crops, being up to 50 mm s^{-1} for some field crops. (After Jarvis 1981.)

Another way of looking at it...

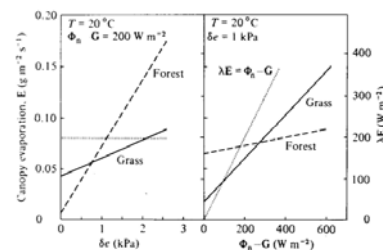


Fig. 5.7. Dependence of canopy evaporation on humidity deficit (δe) and available energy ($\Phi_a - G$) for short grass ($g_{a,0} = 10 \text{ mm s}^{-1}$) for forest ($g_{a,0} = 200 \text{ mm s}^{-1}$), with a constant physiological conductance ($g_{s,0}$) of 10 mm s^{-1} . The line where evaporation consumes all available radiant energy is shown dotted.

In general, all leaves, plants, canopies, will fall somewhere in between the two extremes of g_a and g_s described previously.

If we define $\Omega = (s/\gamma + 1)/(s/\gamma + 1 + g_a/g_s)$
Which we can see has a range of 0-1

Then we can express E from the PM equation as

$$E_{total} = \Omega E_{eq} + (1 - \Omega) E_{imp} \text{ (proof not shown)}$$

The utility of Ω is that it provides us with a very easy index of stomatal vs. environmental control over transpiration

If $g_a \gg g_s$ then $\Omega = (s/\gamma + 1)/(s/\gamma + 1 + g_a/g_s) = 0$ and coupling is strong

If $g_a \ll g_s$ then $\Omega = (s/\gamma + 1)/(s/\gamma + 1 + g_a/g_s) = 1$ and coupling is weak

If $g_a \sim g_s$ then $\Omega = (s/\gamma + 1)/(s/\gamma + 1 + g_a/g_s) \sim 0.5$ and coupling is intermediary

It can be shown (see Jarvis & McNaughton 1986) that Ω may be equivalently expressed as

$$\Omega = 1 - (dE/E) / (dg_s/g_s)$$

That is, Ω is how much fractional change in E occurs with a fractional change in g_s . If a change in g_s makes zero difference to E, then stomates don't matter, boundary layers dominate, and $\Omega = 1$.

Here are some representative Ω values for leaves and crops. The boundary layers and reference location for D may be very different between leaf and canopy scales

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Table 5.3. Likely values for the decoupling coefficient (Ω) and for the sensitivity of evaporation to leaf or canopy physiological conductance ($dE/E)/(dg_s/g_s)$, for different leaves and crops (see Jarvis 1985; Jarvis & McNaughton 1986; Jones 1990)

Single leaves	Leaf width (mm)	Ω	$(dE/E)/(dg_s/g_s)$
Rhubarb	500	0.8	0.2
Cucumber	250	0.7	0.3
Beet	60	0.5	0.5
Onion	8	0.3	0.7
Asparagus	1	0.1	0.9
Open field crops	Crop height (m)	Ω	$(dE/E)/(dg_s/g_s)$
Grass	0.1	0.9	0.1
Strawberry	0.2	0.85	0.15
Tomato	0.4	0.7	0.3
Wheat	1.0	0.5	0.5
Raspberry	1.5	0.4	0.6
Citrus orchard	5.0	0.3	0.7
Forest	30	0.1	0.9
Other situations	Ω	$(dE/E)/(dg_s/g_s)$	
Uncontrolled glasshouse	0.9-1.0	0-0.1	
Lysimeters or 1 m ² plots	< 0.1	> 0.9	
Controlled environment chamber	< 0.1	> 0.9	

Values of Ω are often presented as constant, but both g_s and g_a can vary over the course of a day, and so Ω itself can vary over time

(Kostner et al. 1991)

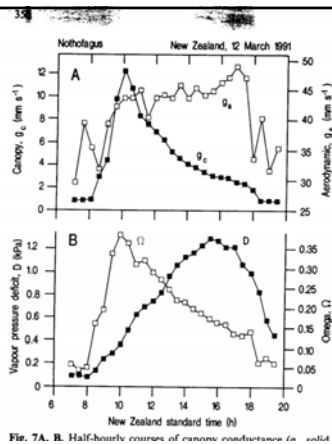


Fig. 7A, B. Half-hourly courses of canopy conductance (g_c) and decoupling coefficient (Ω) for *Nothofagus* in New Zealand on 12 March 1991.

One way to experimentally estimate Ω has been (Meinzer et al. 1997, Kostner et al.) to:

1. Use porometry to get g_s . Try to get a mean g_s for the whole branch or crown (not easy!)
2. Use sapflow on branches or crowns and compute g_w (sapflow gives E, vapor pressure difference defined across foliage to branch or canopy boundary layer)
3. Compute $g_a = 1 / (1/g_w - 1/g_s)$
4. Plug values into $\Omega = (s/\gamma + 1)/(s/\gamma + 1 + g_a/g_s)$

Two critical features of this formulation are:

- 1. It explicitly carries with it biological control of stomata (g_w).**
- 2. It can be computed without direct knowledge of leaf or canopy temperature.**

For these reasons, the PM equation is the most widely used basic energy balance formulation for vegetated surfaces.