An Integrated Rate Methodology (IRM) for Estimating Terrestrial Water and Carbon Fluxes

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Carbon-Water Coupling

Ta

Hot desert

Tropical forest

Deciduous forest

Boreal forest

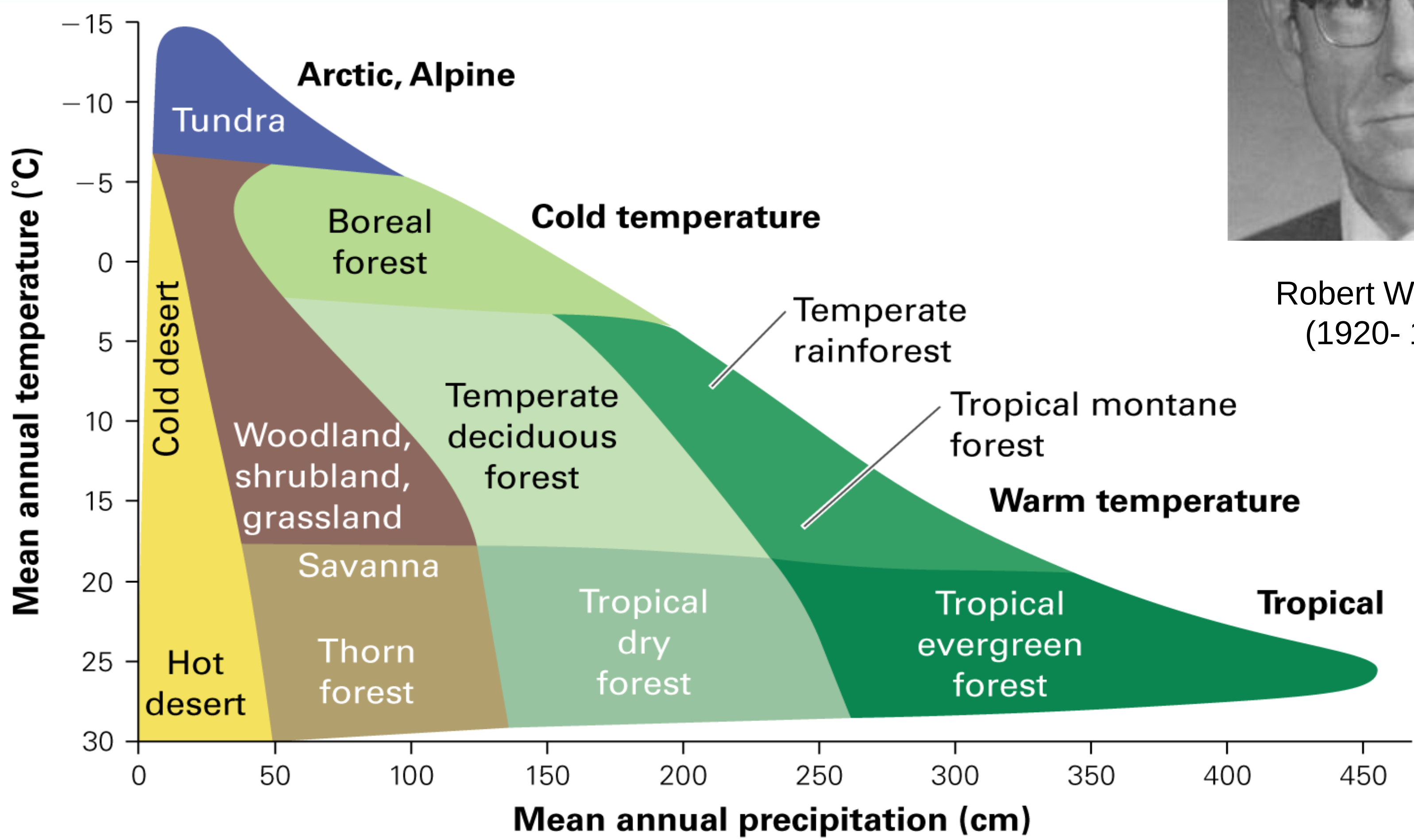
Tundra

- Key controls of terrestrial ecosystem systems?
- Interactions/feedbacks over different scales?

P

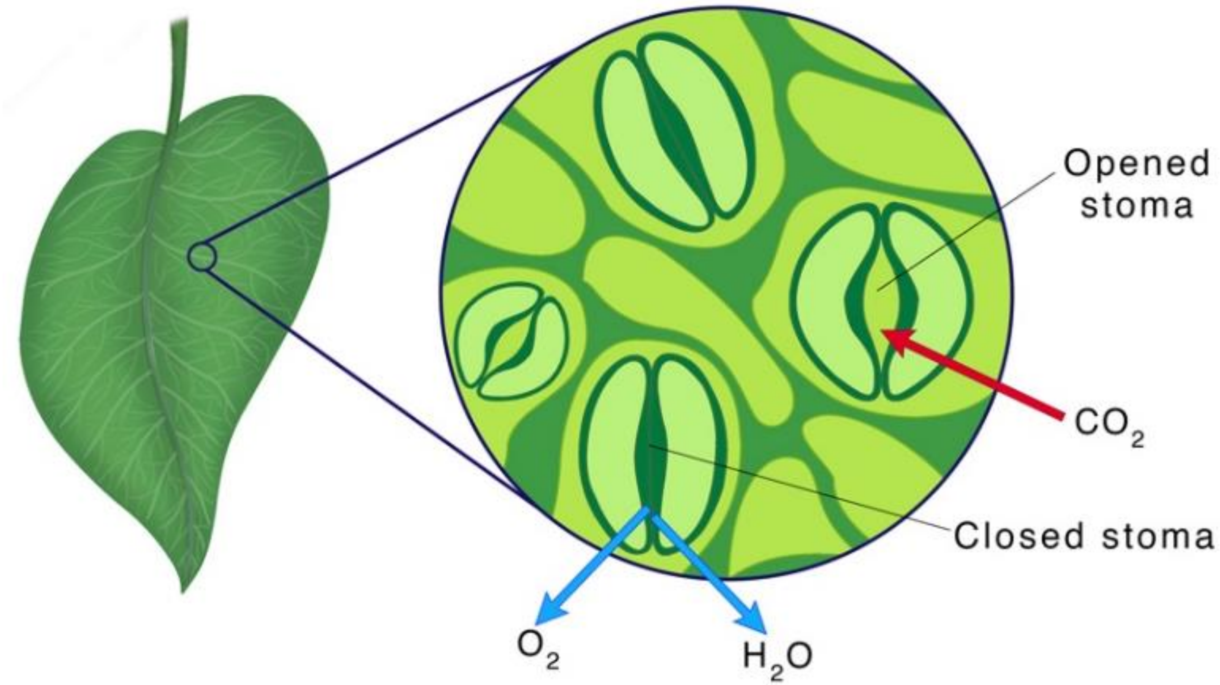
Biome and climate relationship：

Whittaker's diagram



Robert Whittaker
(1920- 1980)

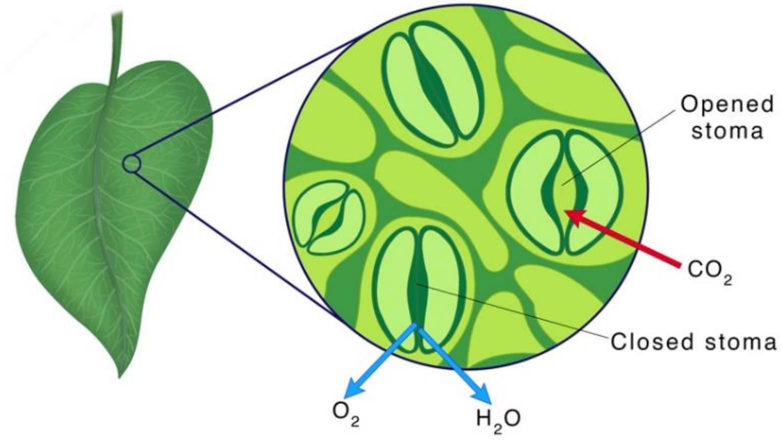
Carbon and water cycles are intrinsically coupled



Since carbon uptake and water loss occur through stomata, photosynthesis and transpiration both decline with stomatal closure.

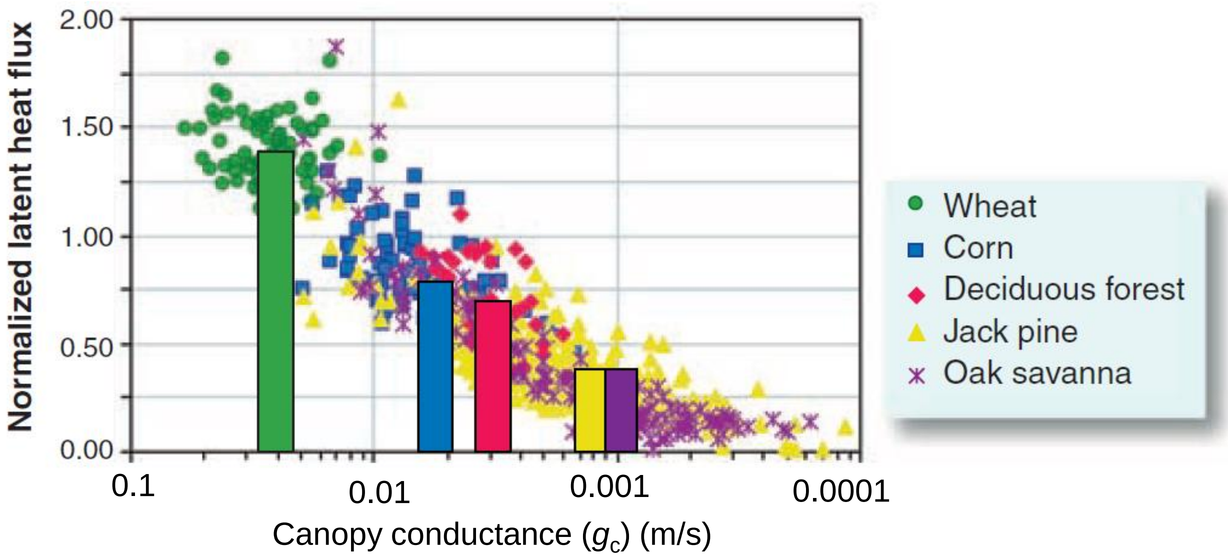
Transpiration and stomatal control

$$E = \rho g_c (q_s^* - q_s)$$

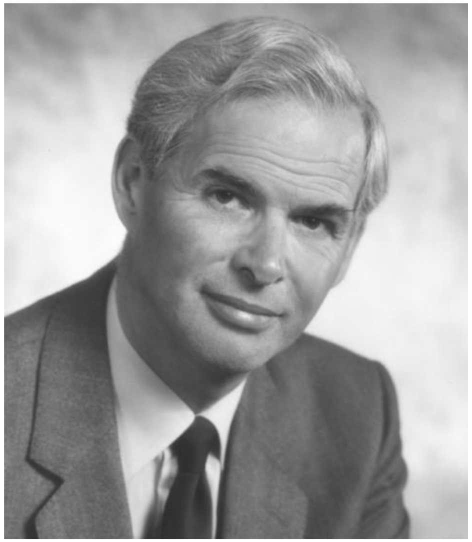


Penman-Monteith equation

$$E = \frac{\varepsilon A + \left(\rho c_p / \gamma\right) g_a D_a}{\varepsilon + 1 + g_a / g_c}$$



Bonan (2008)



John Monteith (1929-2012)

Effect of stomatal control: from leaf to region

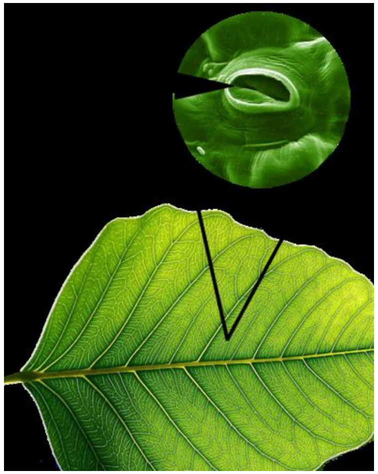
$$E = \Omega_{ci} E_{eq} + (1 - \Omega_{ci}) E_{imp} \qquad \Omega_{ci} = (\varepsilon + 1)/(\varepsilon + 1 + g_a / g_c)$$

Ω_{ci} is the decoupling factor between vegetation and atmosphere.

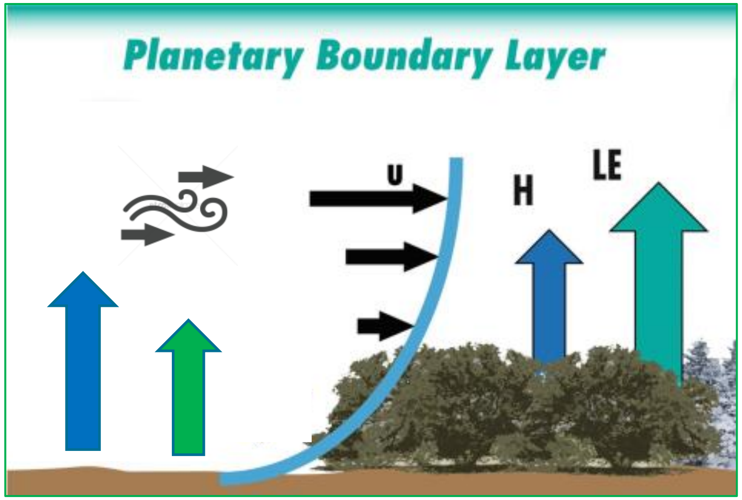
$$\frac{dE}{E} = (1 - \Omega_{ci}) \frac{dg_c}{g_c}$$

Ω_{ci} increases with spatial scale, *E* is less controlled by stomatal conductance.

much smaller change



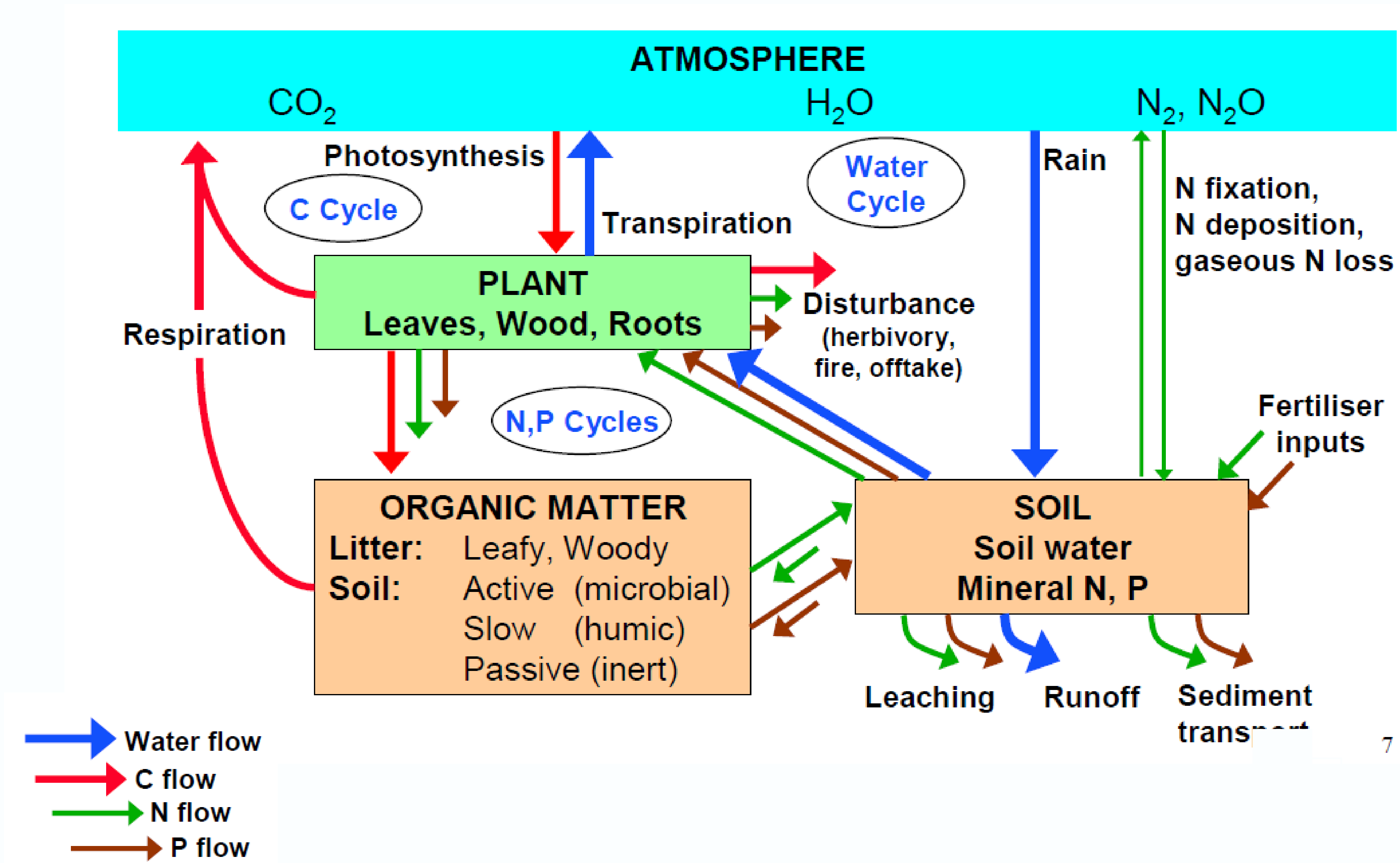
depends on Ω



equal-proportional change

Jarvis and McNaughton (1986)

Linked terrestrial water and carbon cycles



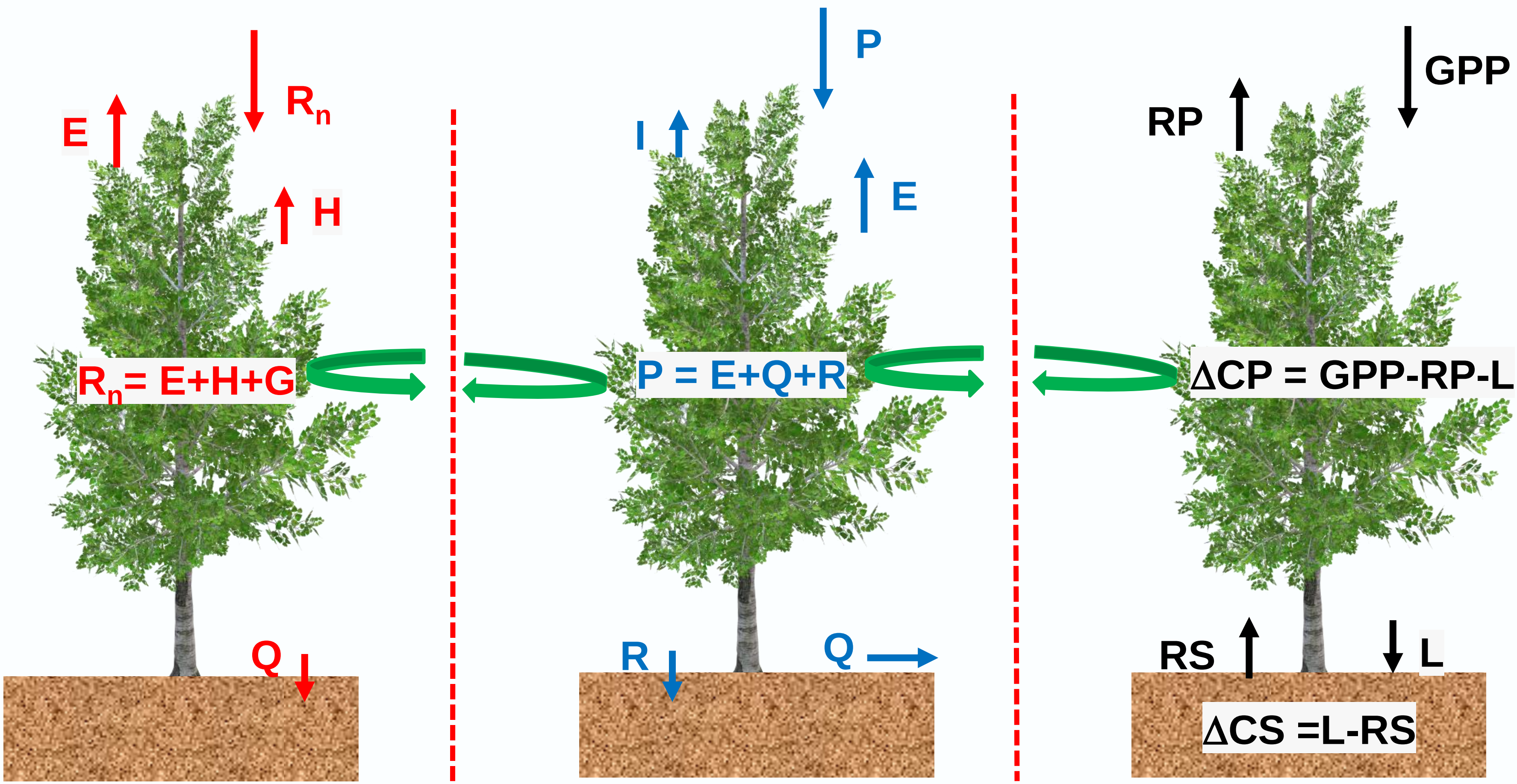
Raupach et al (2001)

Energy-Water-Carbon Coupling

Energy Balance

Water Balance

Carbon Balance



Dynamics of water-energy-carbon fluxes

Water balance： $$\frac{dS(t)}{dt} = P(t) - E(t) - Q(t) - R(t)$$

Carbon balance： $$\frac{dC_p(t)}{dt} = GPP(t) - RP(t) - L(t)$$

Energy balance: $$\frac{dW(t)}{dt} = R_n(t) - E(t) - H(t) - F_p(t)$$

We must consider the balance in the process representation so that model consistency, reliability and accuracy can be achieved.

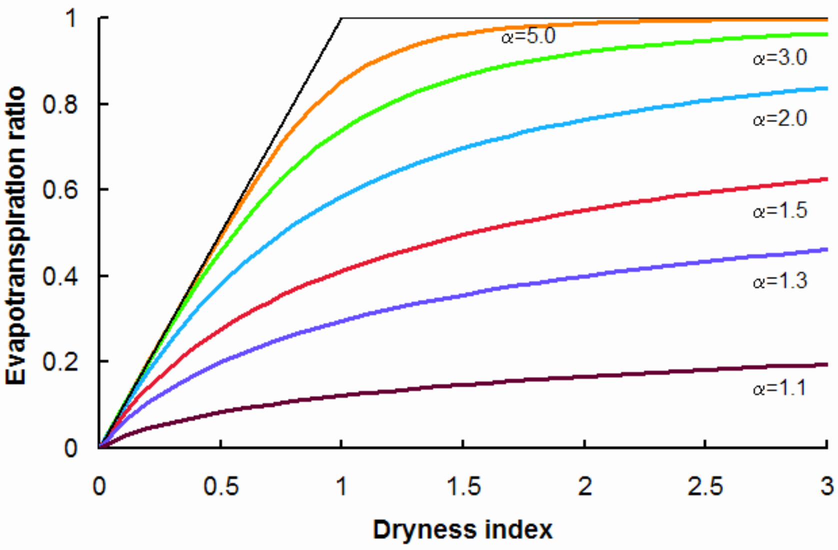
Theoretical framework: long-term average evaporation

Demand = Potential evaporation (E_0)

Supply = Precipitation (P)

$$\frac{\partial E}{\partial P} = f(E_0 - E, P)$$

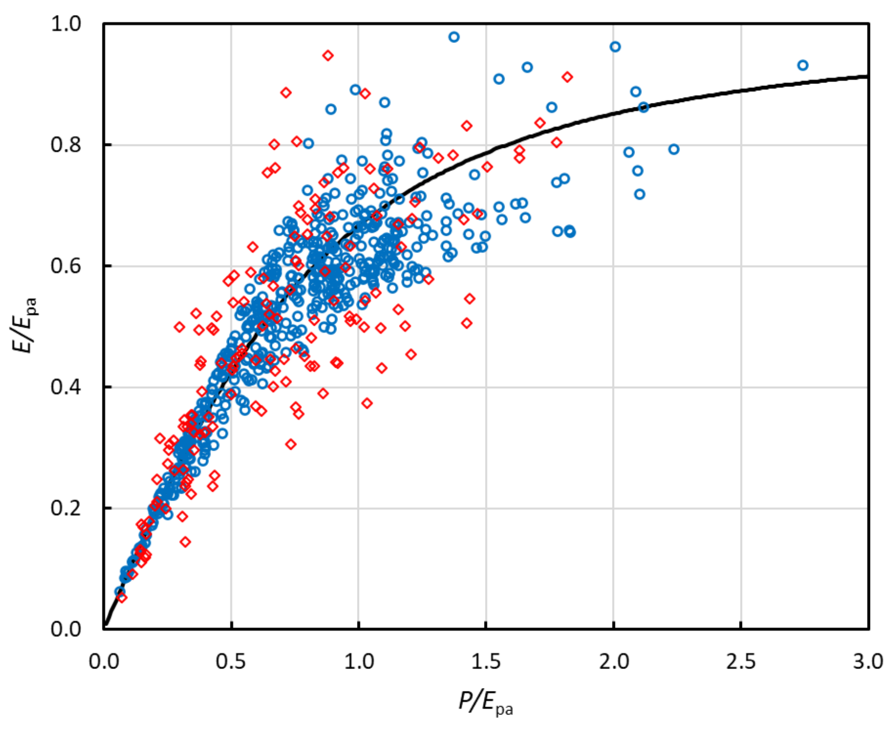
$$\frac{E}{P} = 1 + \frac{E_0}{P} - \left[1 + \left(\frac{E_0}{P}\right)^w\right]^{1/w}$$

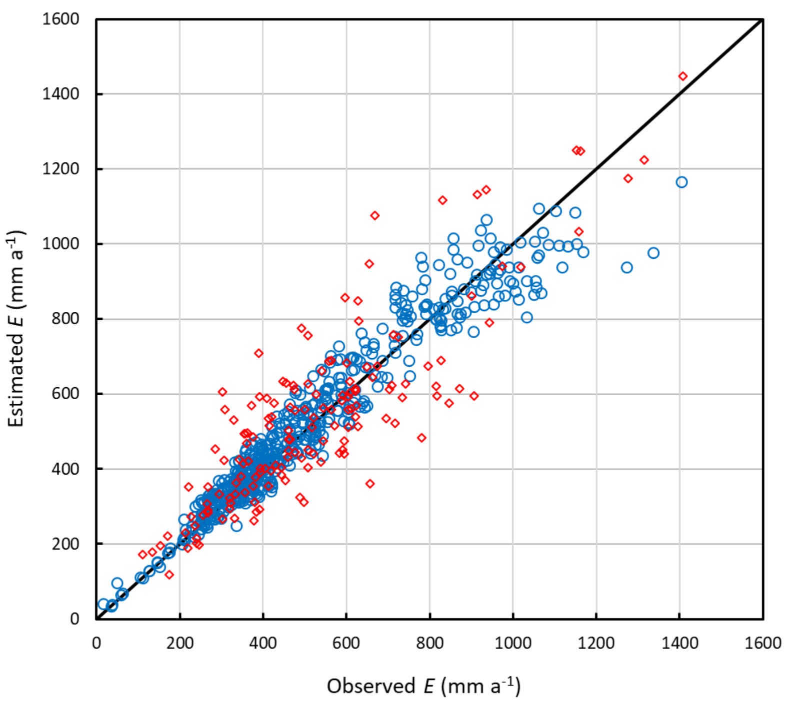


Fu (1981), Zhang et al. (2004)

Theoretical framework: long-term average evaporation

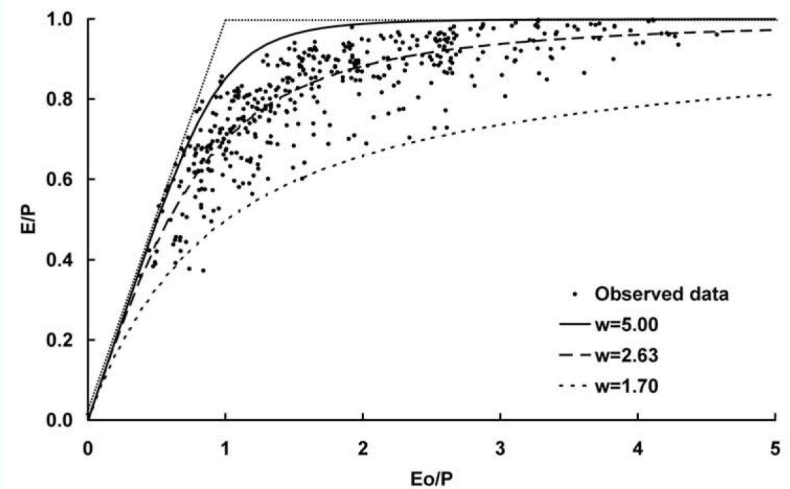
$$\frac{E}{E_{pa}} = 1 + \frac{P}{E_{pa}} - \left[1 + \left(\frac{P}{E_{pa}}\right)^{w}\right]^{1/w}$$

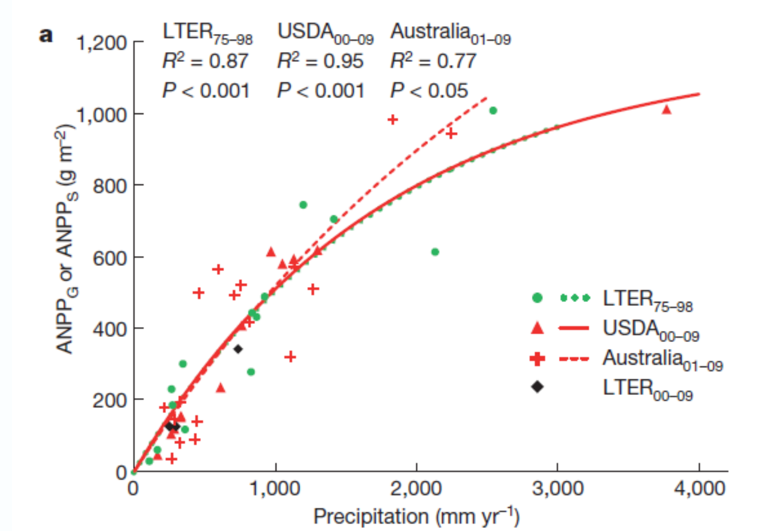


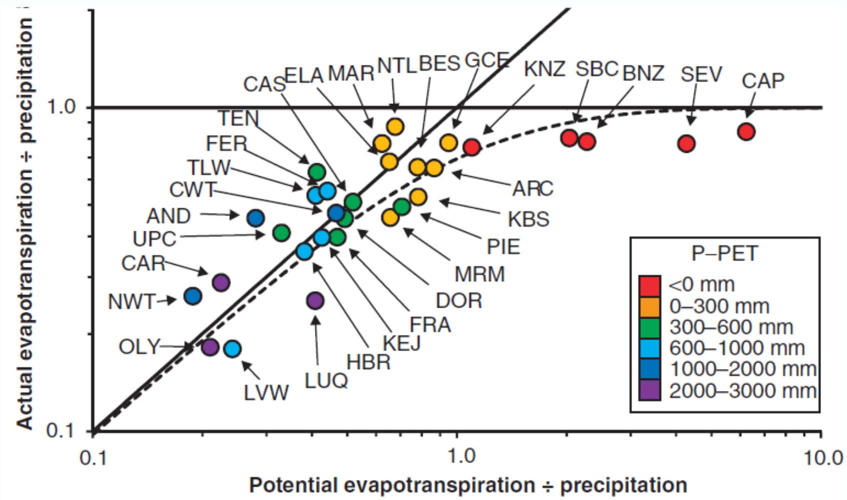


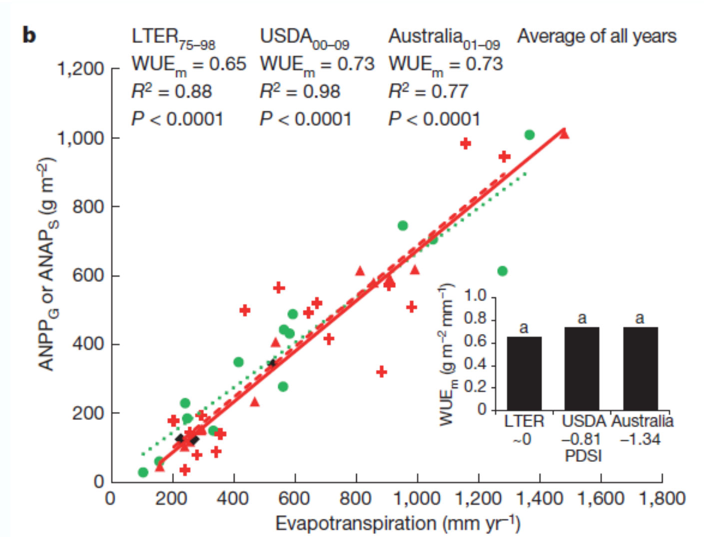
Zhang and Brutsaert (2021)

Budyko-like equation for carbon?









Zhang et al (2001), Jones et al (2012)

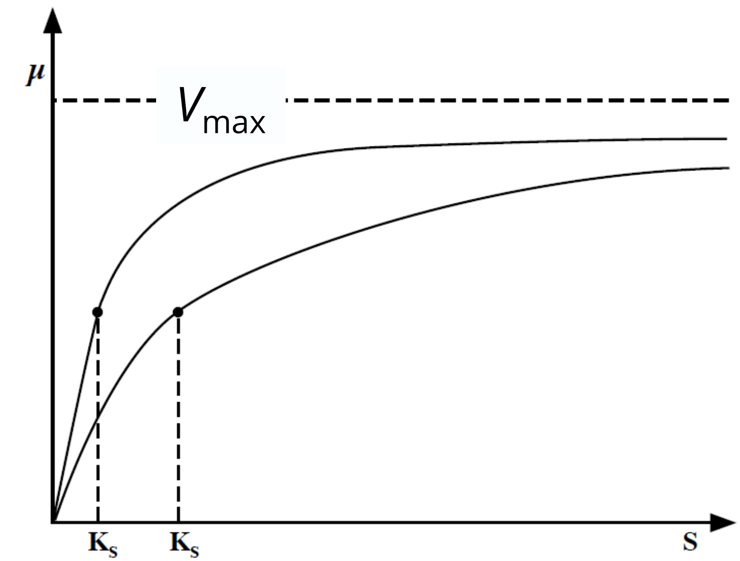
Camops et al (2013)

The Michaelis–Menten Equation

In biochemistry, the Michaelis–Menten Equation describes enzyme kinetics:

$$\mu = V_{max} \frac{S}{K_s + S}$$

Where μ is the reaction rate, and V_{max} is maximum reaction rate, S is the concentration of a substrate, K_s is the concentration of the substrate at which the reaction rate is half of V_{max}. K_s controls how fast V_{max} is approached.



Leonor Michaelis
(1875 -1949)

Maud Menten
(1879 -1960)

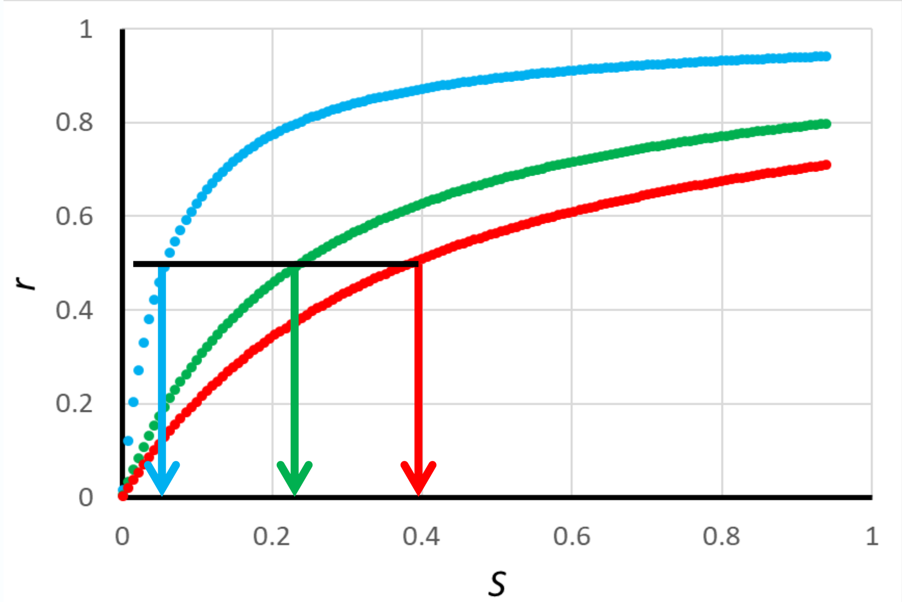
Generalized Michaelis–Menten Equation

To generalize a single substrate system to an n-substrate systems, a ratio form of the Michaelis–Menten equation is considered:

$$r = \frac{\mu}{V_{max}} = \frac{1}{1 + K_s/S}$$

The characteristics of this single substrate system:

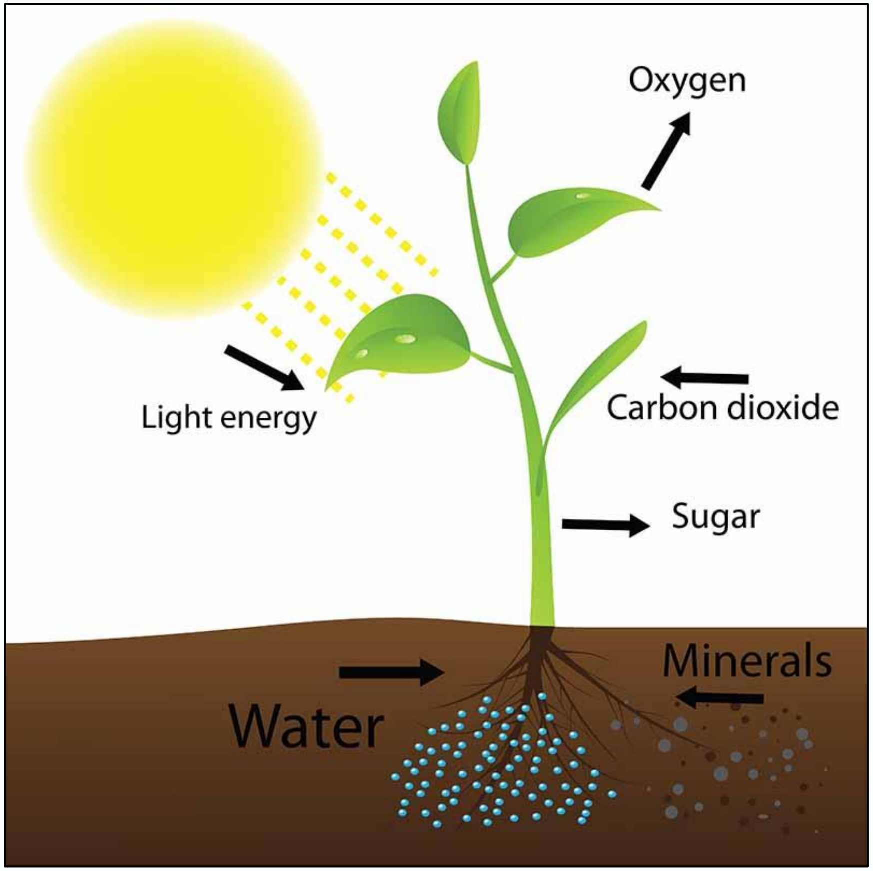
- $r = 0$ when $S = 0$
- $r = 1$ when $S \to \infty$
- $r = 1/2$ when $S = K_s$



Generalized Michaelis–Menten equation:

$$r_n = \frac{1}{1 + \sum_{i=1}^{n}\left({}^{K_{si}}/_{S_i}\right)}$$

Plant growth is fundamentally a function of available light, water, and nutrients (Wu et al., 1994).



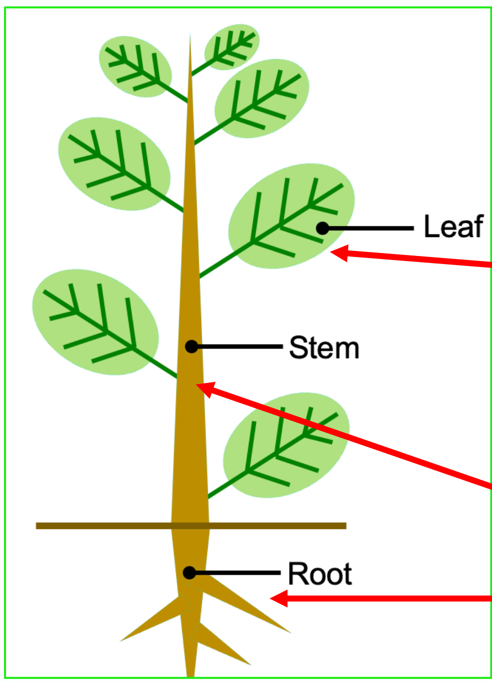
$$A = A_{max}\left[\frac{1 + W_H + W_N}{\frac{1}{m_L x_L} + \frac{W_H}{x_H} + \frac{W_N}{x_N}}\right]$$

- light: x_L
- water: x_H
- nutrients: x_N

Modelling plant growth using IRM

$$A = A_{max}\left[\frac{1 + W_H + W_N}{\frac{1}{m_L x_L} + \frac{W_H}{x_H} + \frac{W_N}{x_N}}\right]$$

where W_H and W_N are the weightings of water relative to light and nutrients, x_L, x_H, and x_N are the relative resources availabilities for light, water, and nutrient respectively, and m_L is the modifier of light availability due to temperature.



The simulated carbon (A) is partitioned to leaves, stems, and roots:

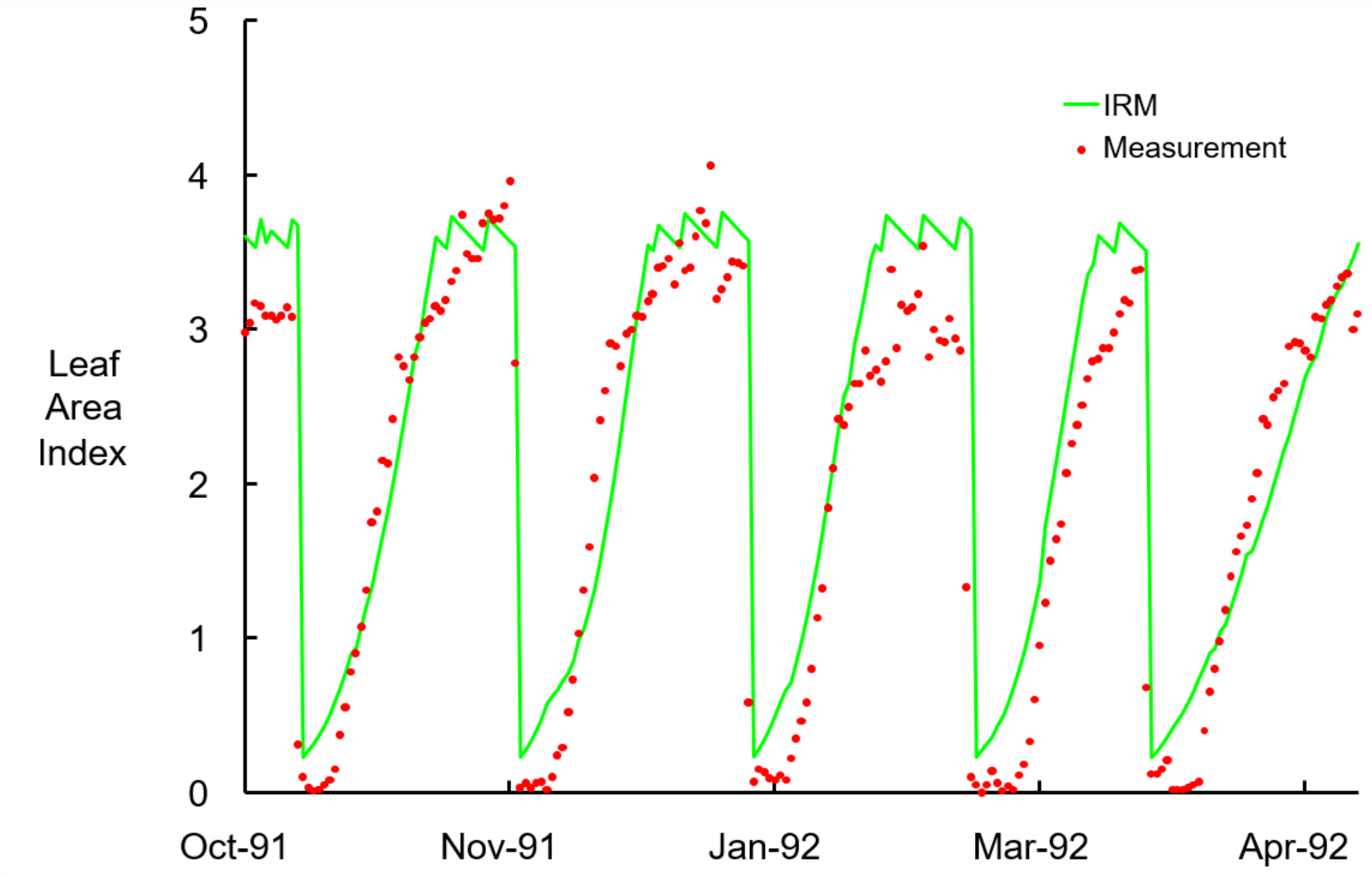
Leaf carbon

$$\Delta C_L = n_L Y_L (A - C_L R_L) - C_L M_L$$

Stem and root carbon

$$\Delta C_{S,R} = n_{S,R} Y_{S,R}\{(A - C_L R_L) - C_{S,L} R_{S,R}\} - C_{S,R} M_{S,R}$$

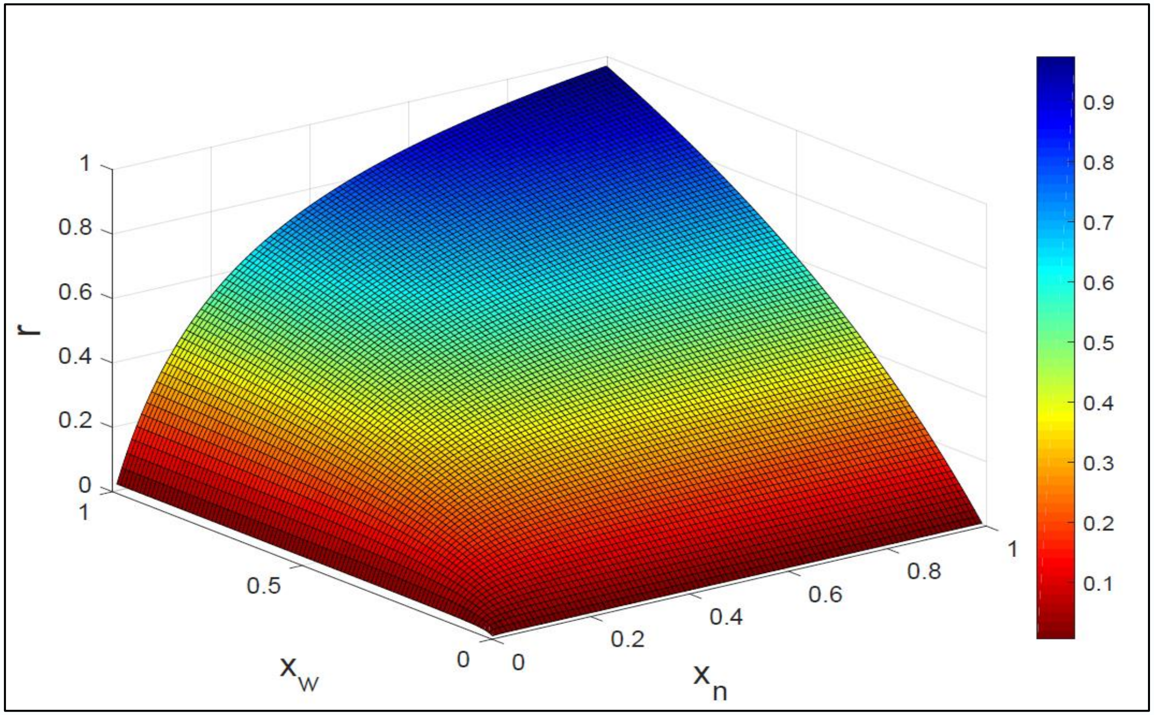
Modelling plant growth using IRM



Zhang et al., (1999)

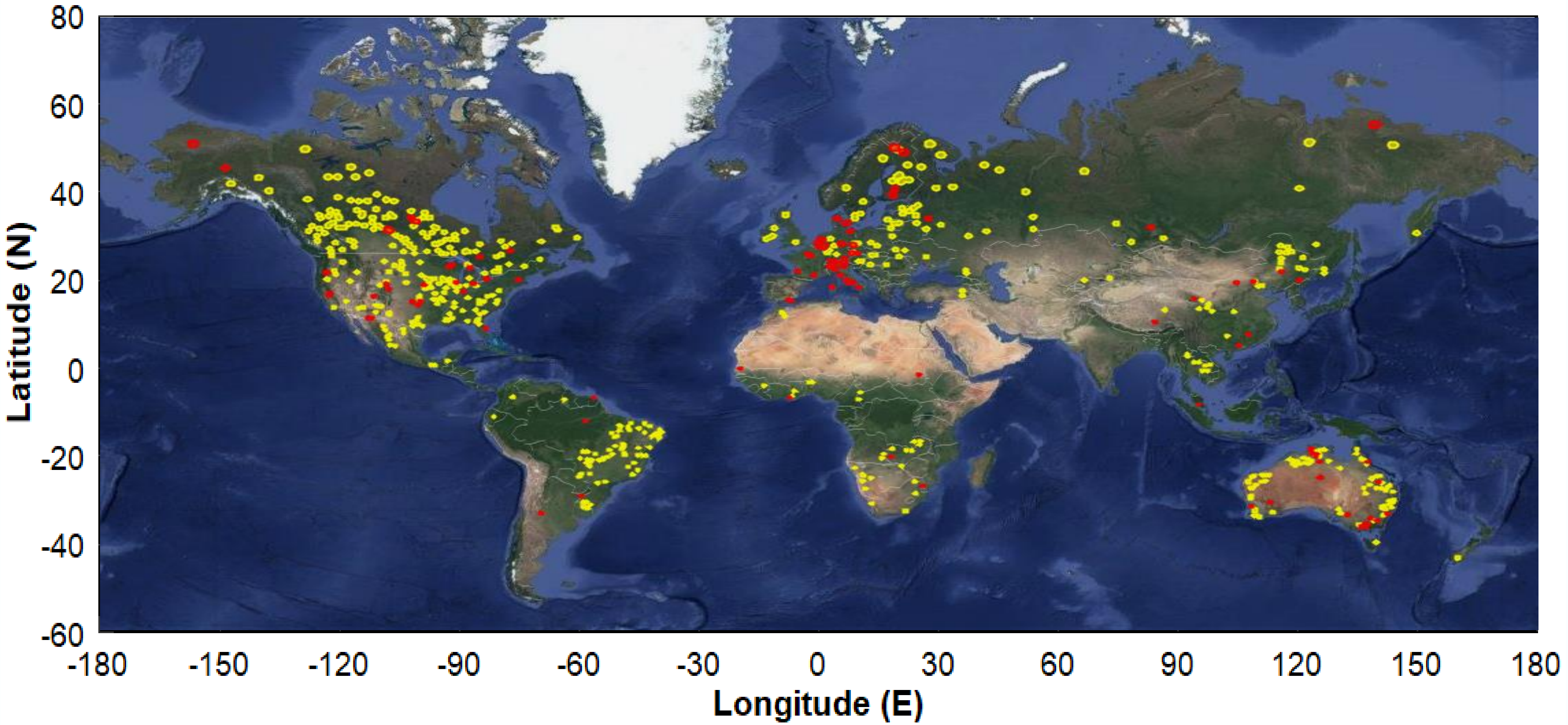
Integrated Rate Methodology (IRM) for mean annual ET and ANPP

$$Y = Y_{max}\left[\frac{1 + W_H + W_N}{\frac{1}{m_L x_L} + \frac{W_H}{x_H} + \frac{W_N}{x_N}}\right]$$



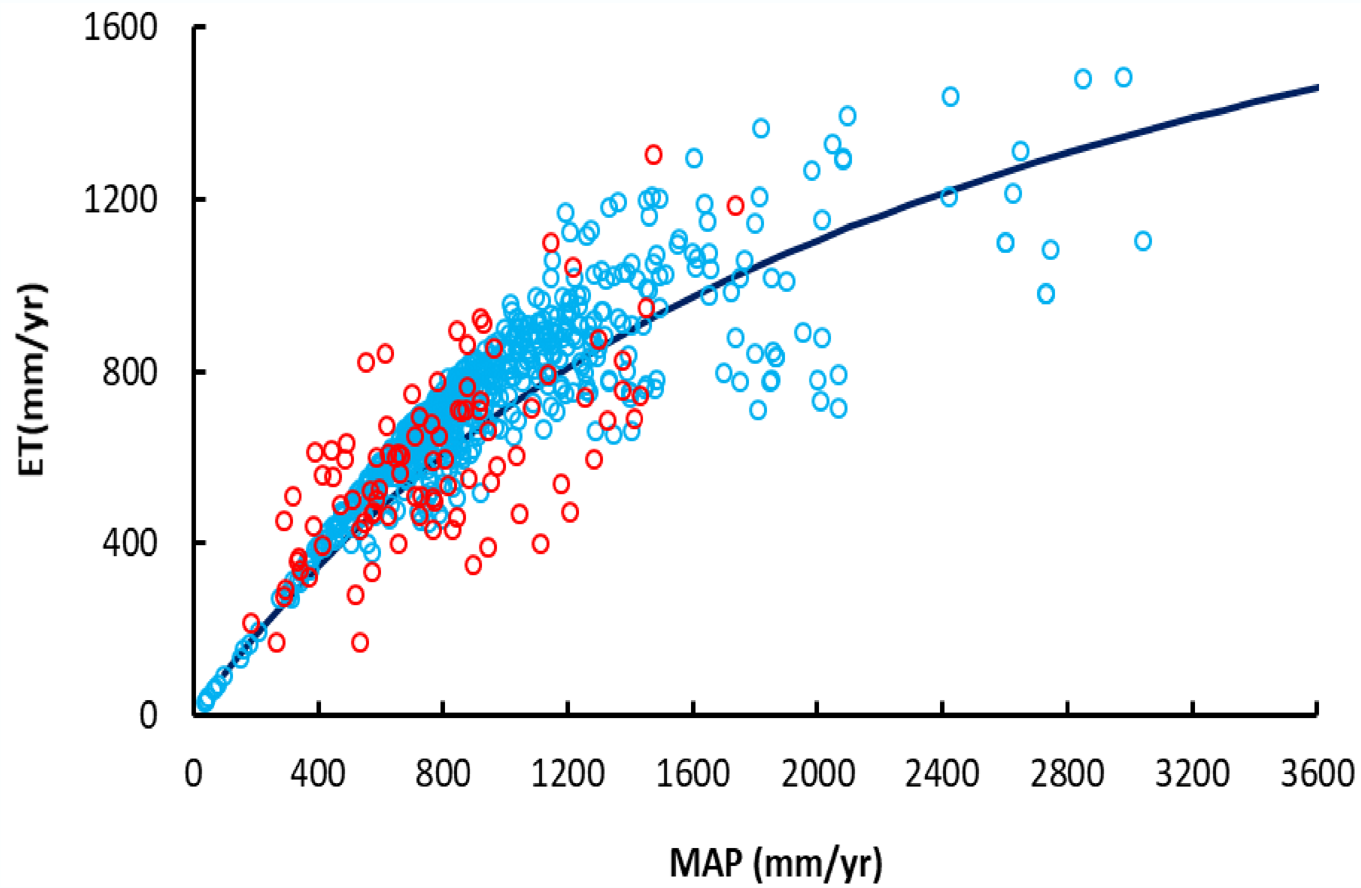
Global ET data:

- *Global catchment water balance (n=524)*
- *Global flux sites (n= 156)*

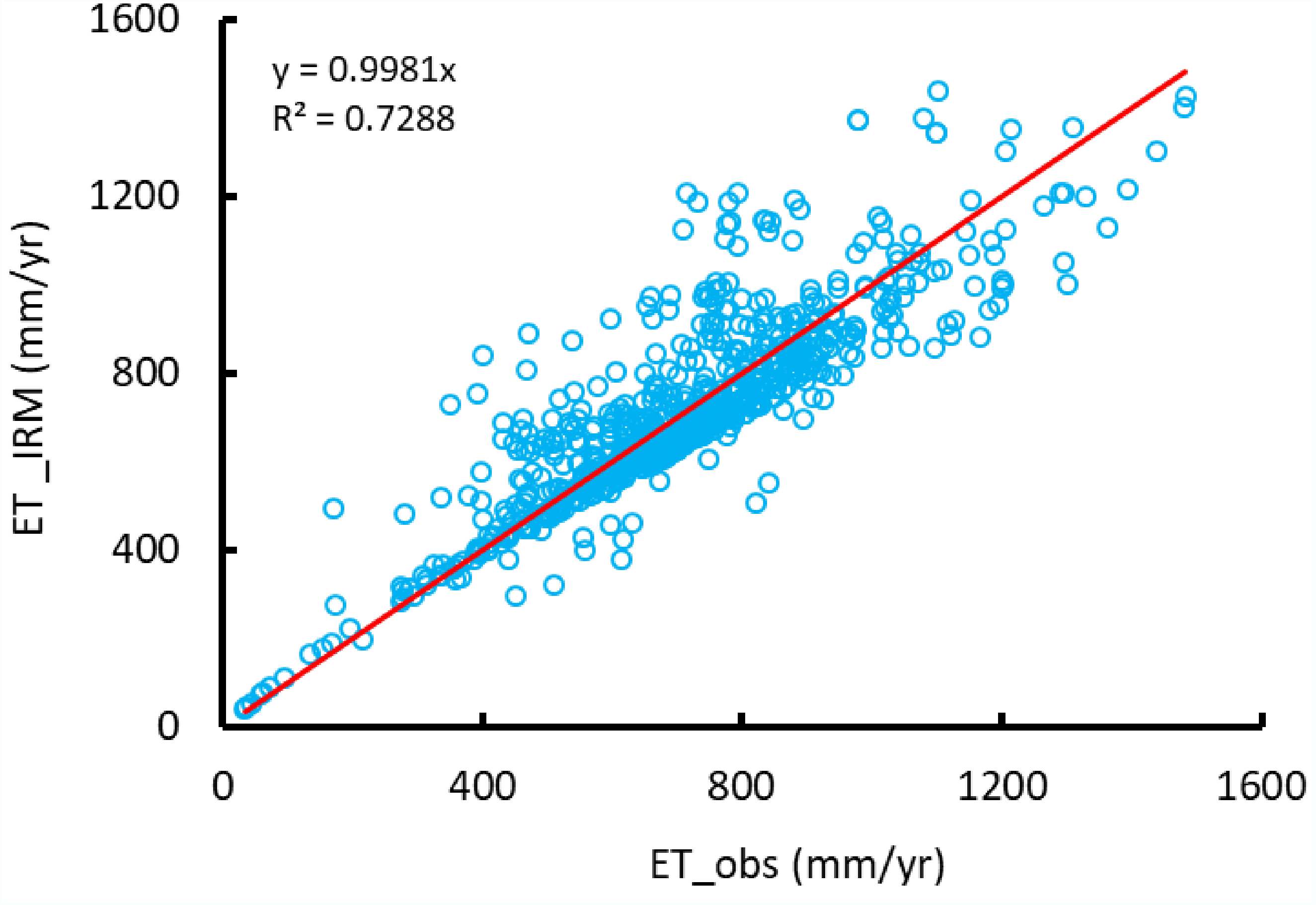


Estimation of mean annual evapotranspiration using IRM

Strong relationship between mean annual precipitation (MAP) and ET

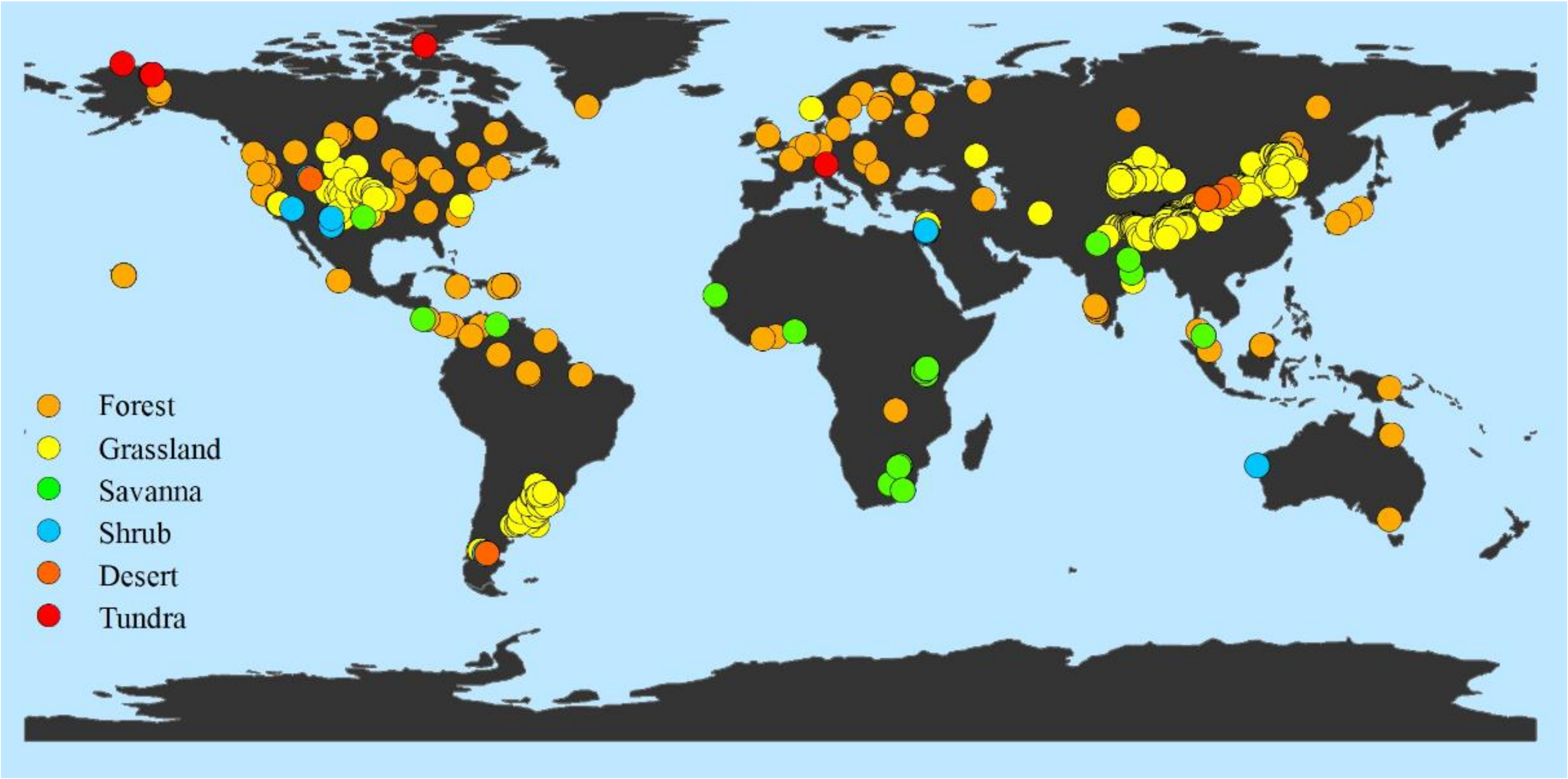


Estimation of mean annual evapotranspiration using IRM



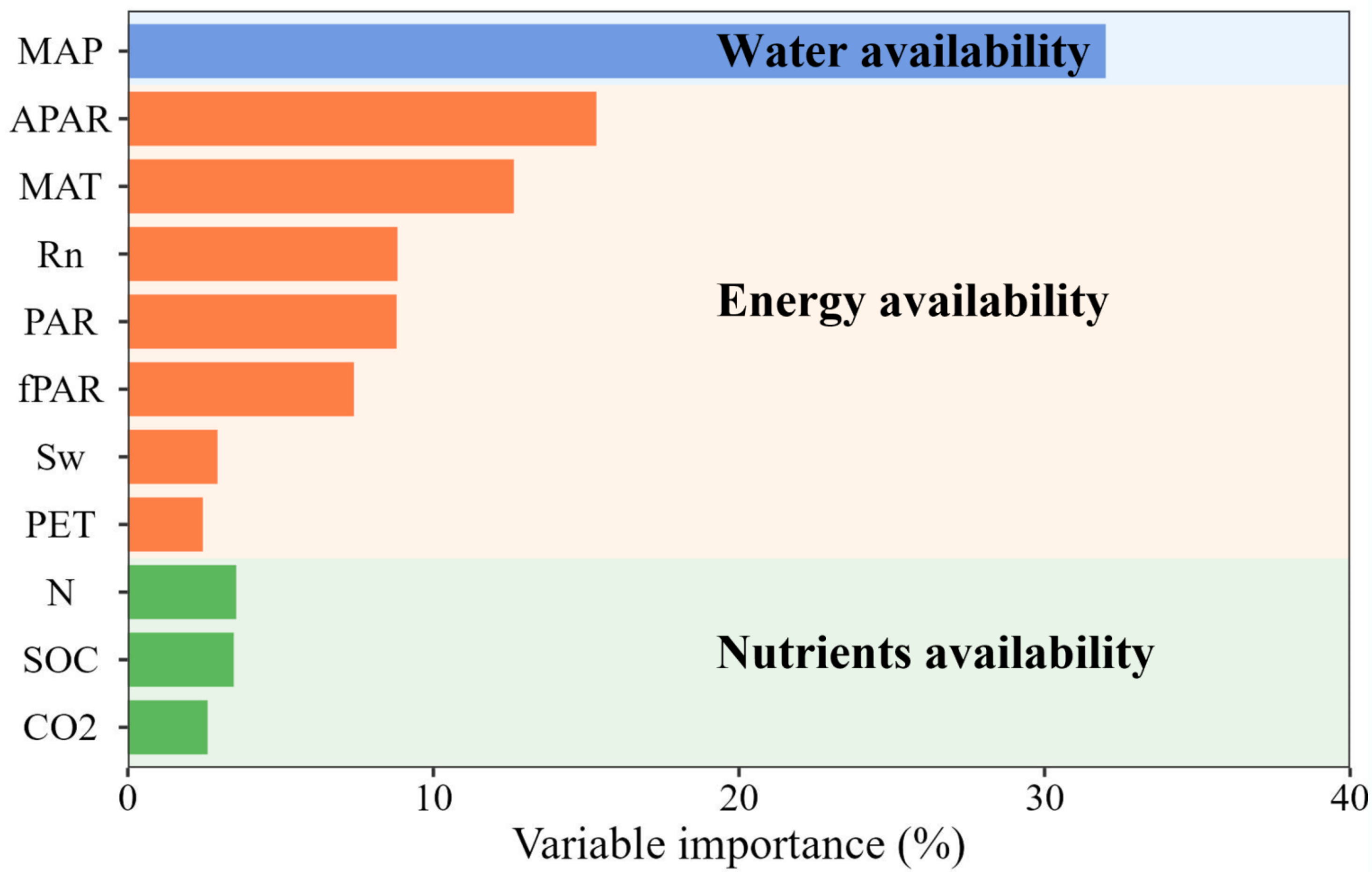
- ➢ IRM can provide accurate estimates of mean annual ET

Global ANPP data



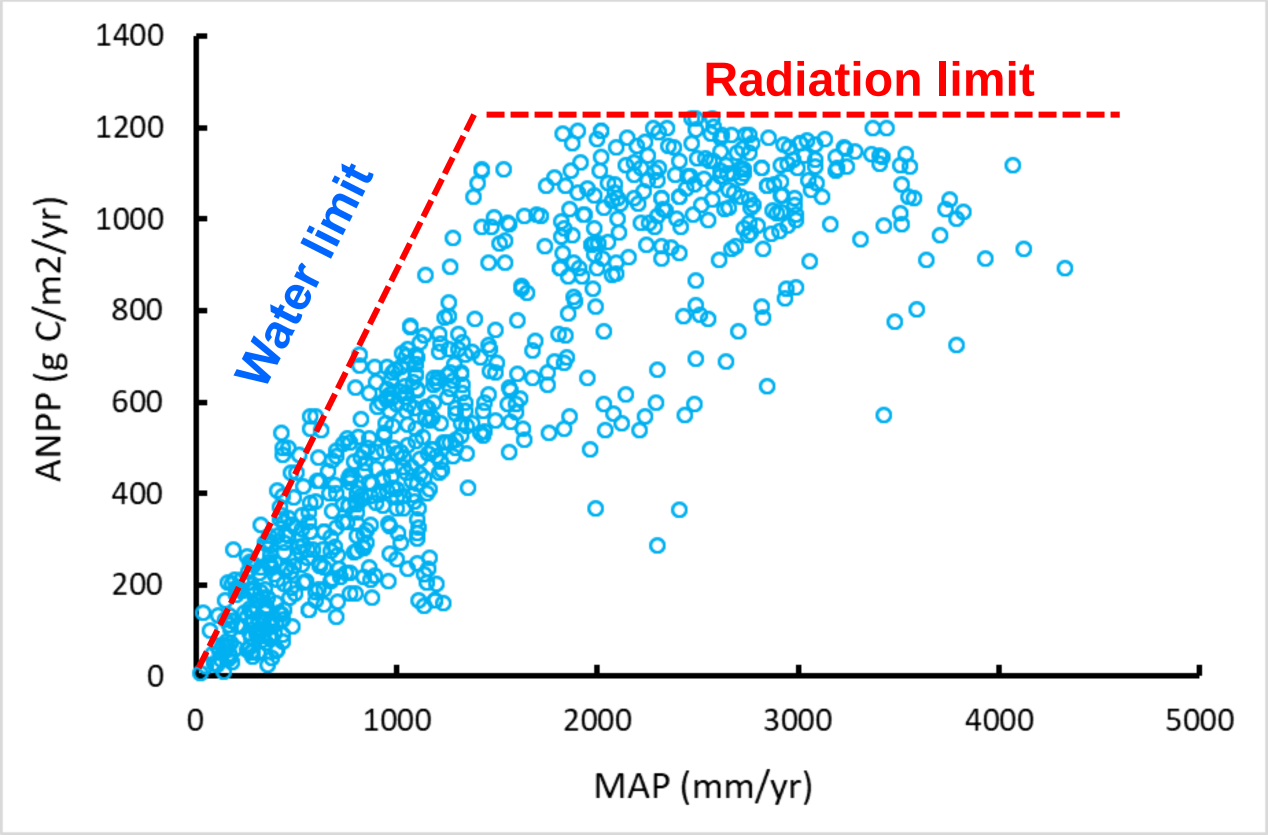
Locations of the 688 field-observed ANPP

Key controls on ANPP



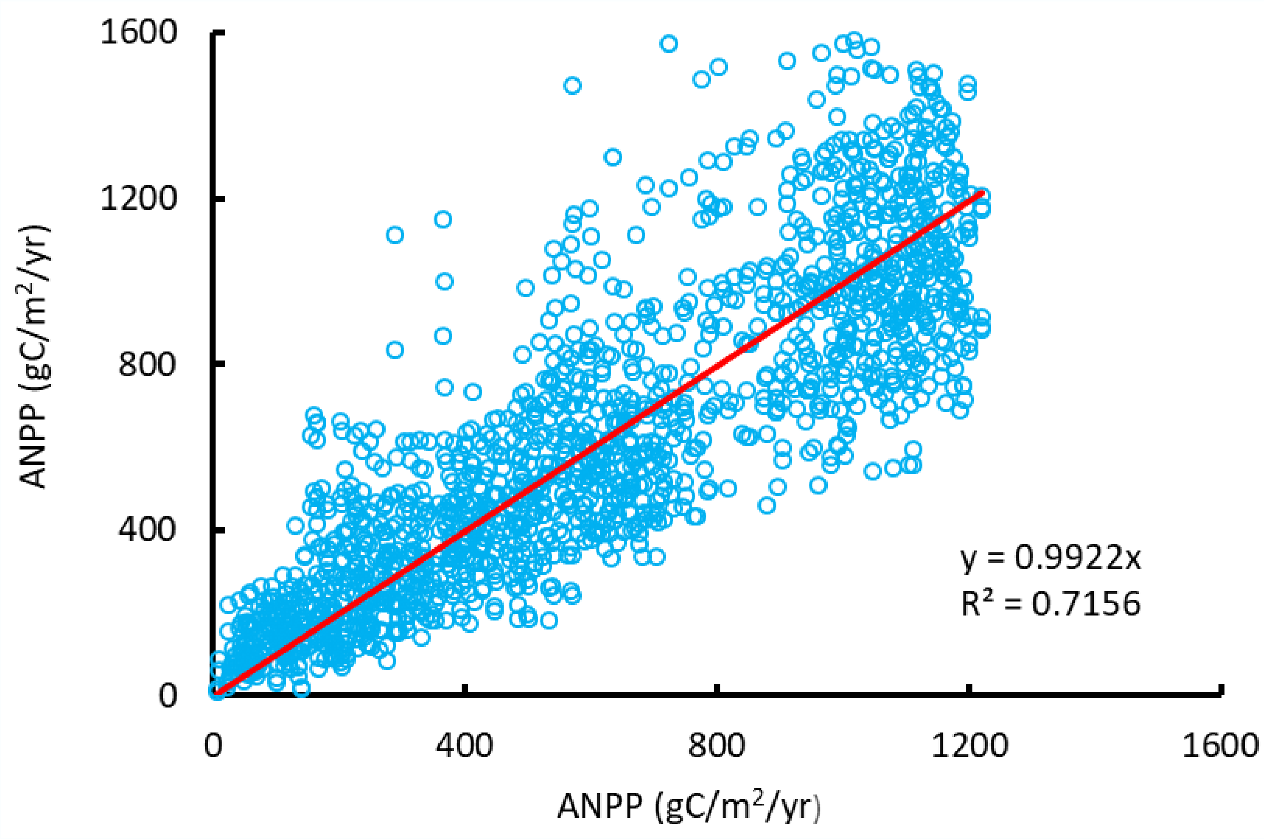
Estimation of mean annual ANPP using IRM

The Global Primary Production Data Initiative (*GPPDI*) data (1508 points)



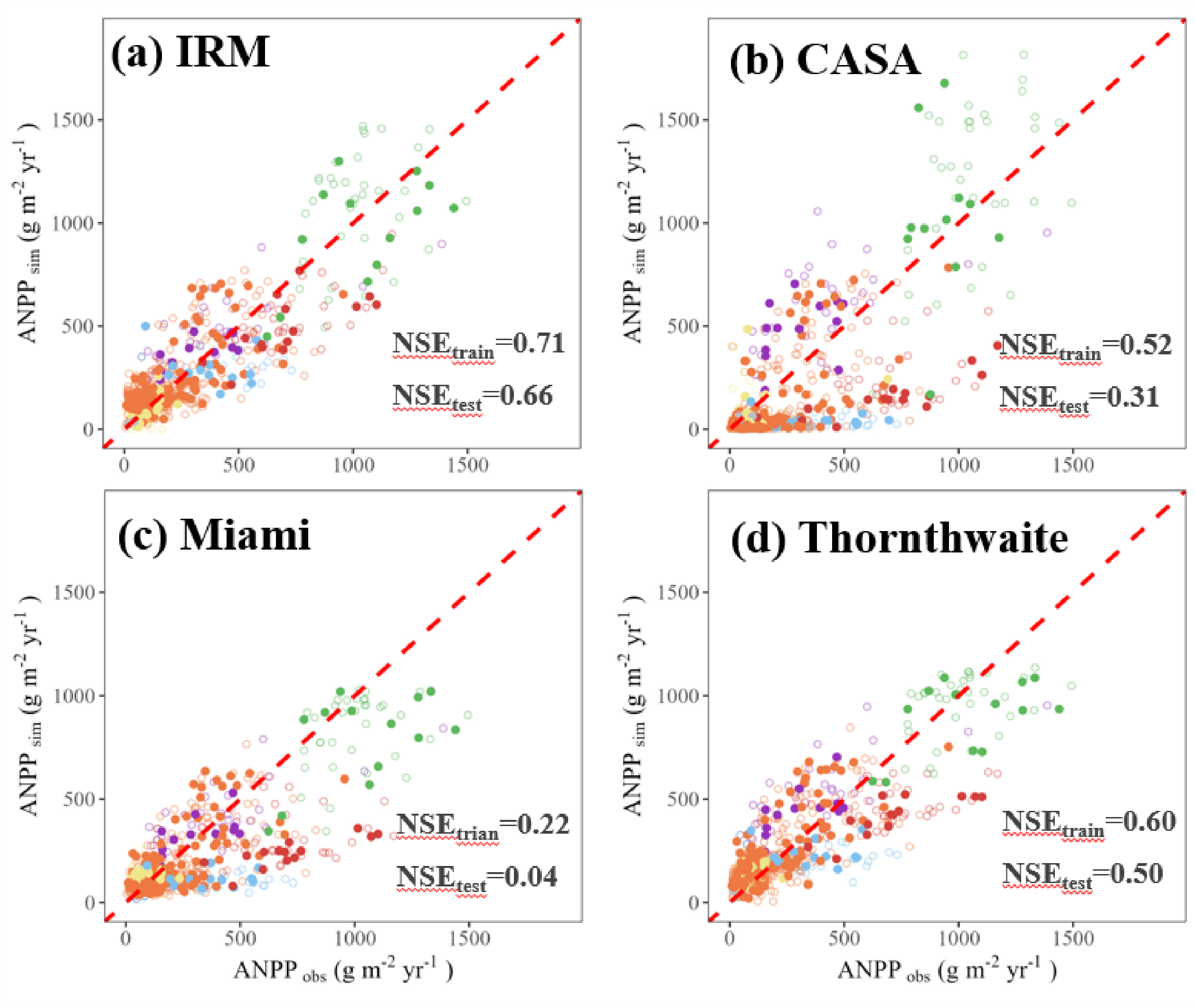
➢ AMP and ANPP exhibits relationship similar to the Budyko curve

Estimation of mean annual ANPP using IRM



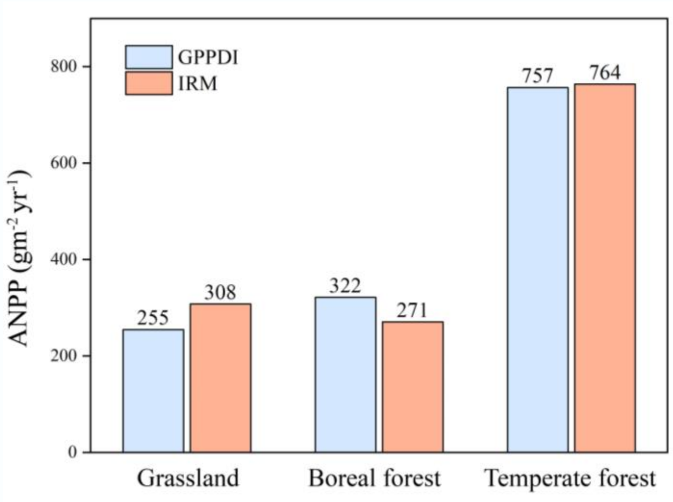
- ➢ IRM can provide reasonable estimates of mean annual ANPP

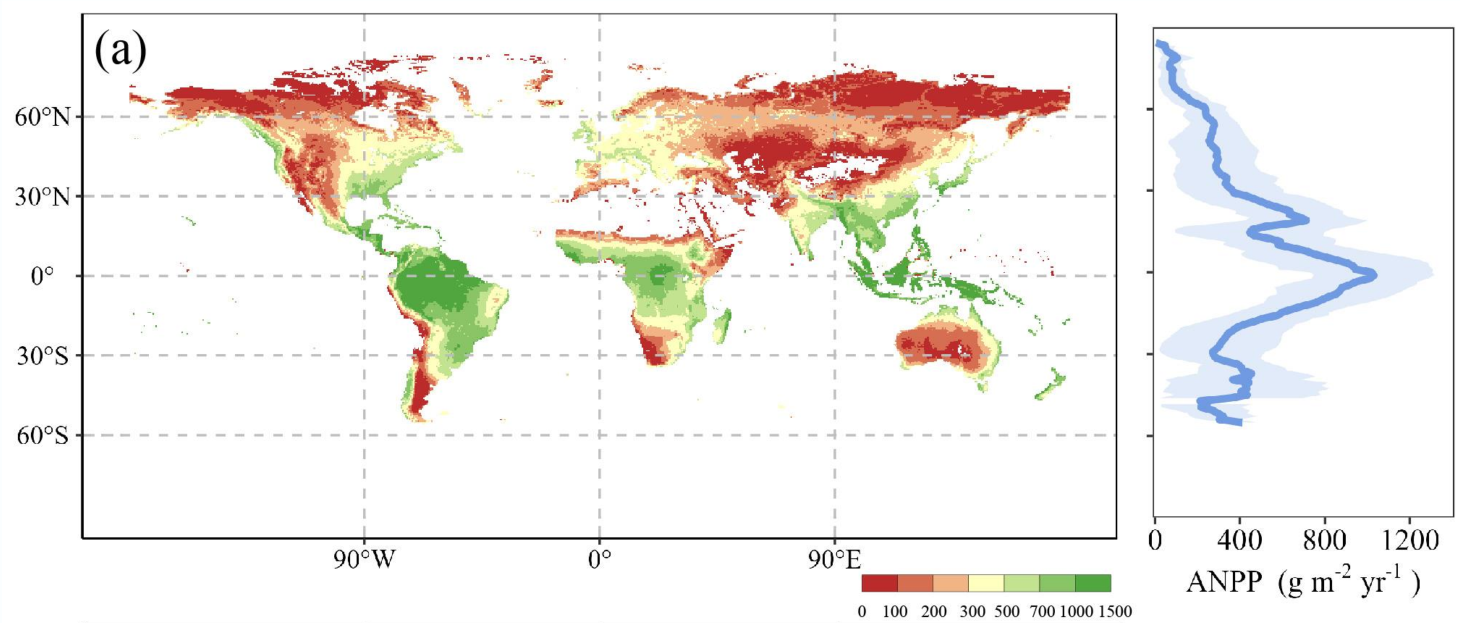
Estimation of mean annual ANPP using IRM



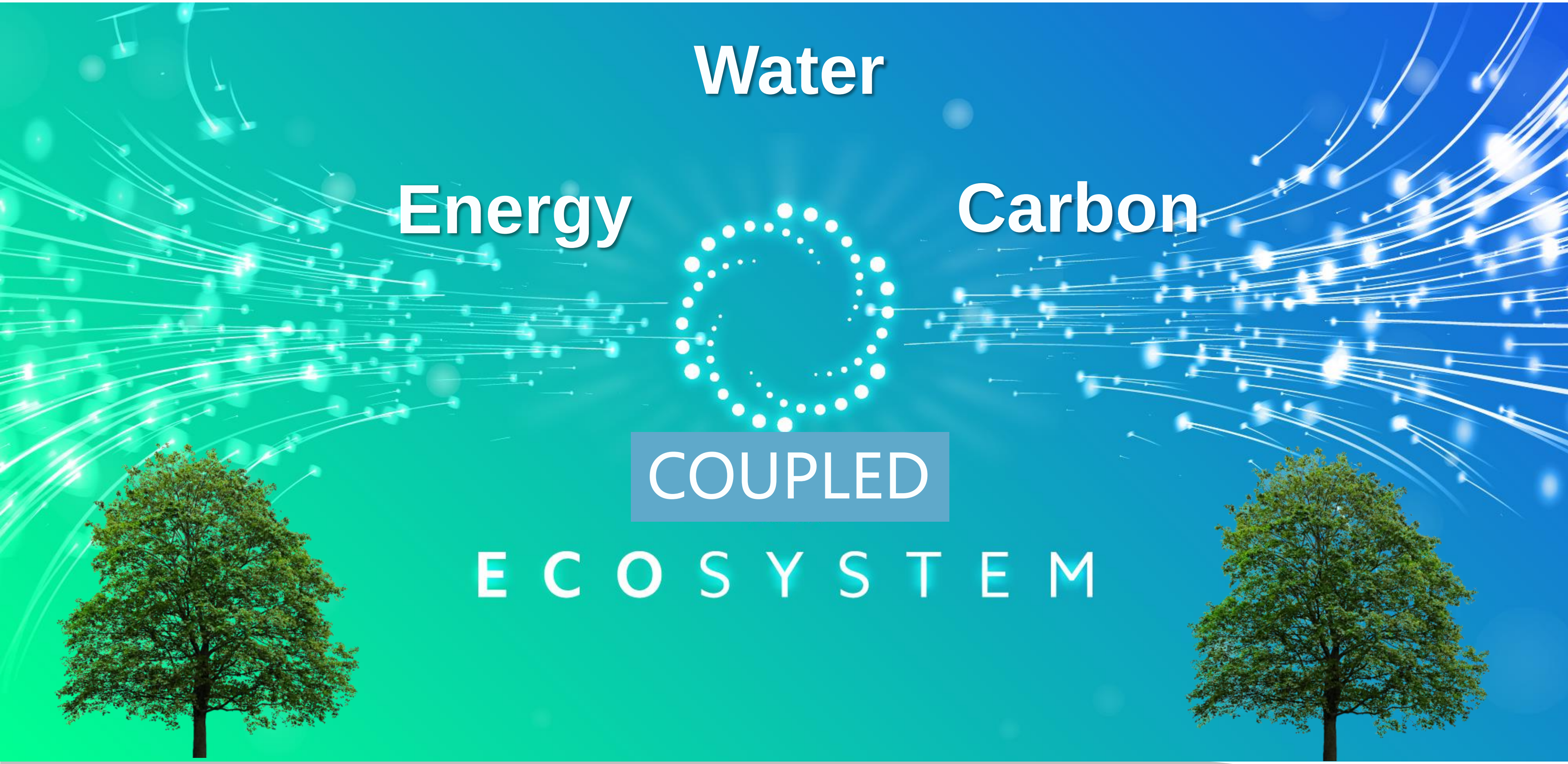
- IRM can provide reasonable estimates of mean annual ANPP

Estimation of global ANPP





IRM is a useful tool for modelling carbon & water fluxes



Summary

- Carbon and water coupling is important for ecohydrology and ecosystem services.
- Dominant controls of ecosystem water and carbon balance include precipitation and radiation.
- The integrated rate methodology (IRM) can be used to estimate mean annual ET and ANPP.
- Uncertainties in the ET and ANPP estimates include temperature and age effects.
- Further studies will be conducted to examine sensitivity parameters in the IRM and their effects on water and carbon modelling.

Thank you！