Ecosystem water use efficiency: history, applications and issues

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Outline

- Ecosystem water use efficiency (WUE): definition and keystone contributions
- Application of a simple ecosystem WUE at global scale
- A few issues
- Take-home message

A brief history of water use efficiency (60’s to 80’s)

Water use efficiency can be defined as

$\frac{A}{E_T}$ or $\frac{A}{g_s}$ at leaf scale (e_l)

$\frac{A}{E_T}$ or $\frac{A}{E}$ or $\frac{A \times D}{E}$ at ecosystem scale (e_e)

$\frac{\int A dt}{\int E dt}$ integrated over a period ($\overline{e_e}$)

Keystones in WUE (theory)

- Bierhuizen and Slayter (1965): $e_l \propto D^{-1}$

- Cowan (1977): $\lambda = \frac{\partial E}{\partial A} = \frac{\partial E / \partial g_s}{\partial A / \partial g_s}$

- Farquhar (1982) ^{13}C and leaf/ecosystem WUE:

$$\Delta_c = a\left(1 - \frac{C_i}{C_a}\right) + a_m\left(\frac{C_i}{C_a} - \frac{C_c}{C_a}\right) + b\,\frac{C_c}{C_a} - f\,\frac{\Gamma_*}{C_a};\ e_l = f\left(\Delta_c, \frac{g_s}{g_m}\right)$$

- Tanner and Sinclair (1986): scaling WUE from leaf to canopy

Theory (continued)

- Keith Mott (E control on g_s), Davis, Schulz, Passioura and Turner (soil water control on g_s)

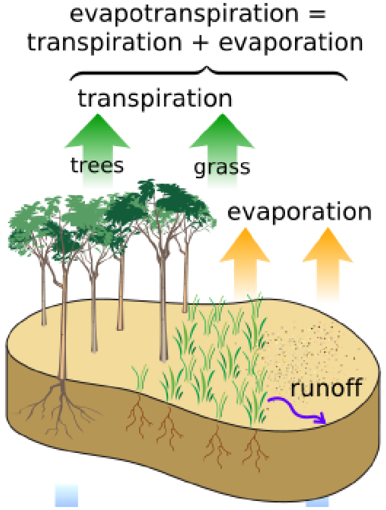
- Ball-Berry-Leuning, stomatal model: g_s depends on A_n and E

$$g_s \propto \frac{m h_s A_n}{C_s} \qquad \Longrightarrow \qquad g_s \propto \frac{A_n}{(C_s - \Gamma)\left(1 + {D_s}/{D_0}\right)}$$

- Hari (1986), Lloyd (1991); Medlyn (2011), Wolf et al. (2016):

$$g_s \propto \sqrt{D_s} \qquad \Longrightarrow \qquad g_s \propto \frac{\beta(\psi_l)}{\sqrt{(C_s - \Gamma) D_s}}$$

2. WUE: An analytical WUE model (Cheng et al. 2017)



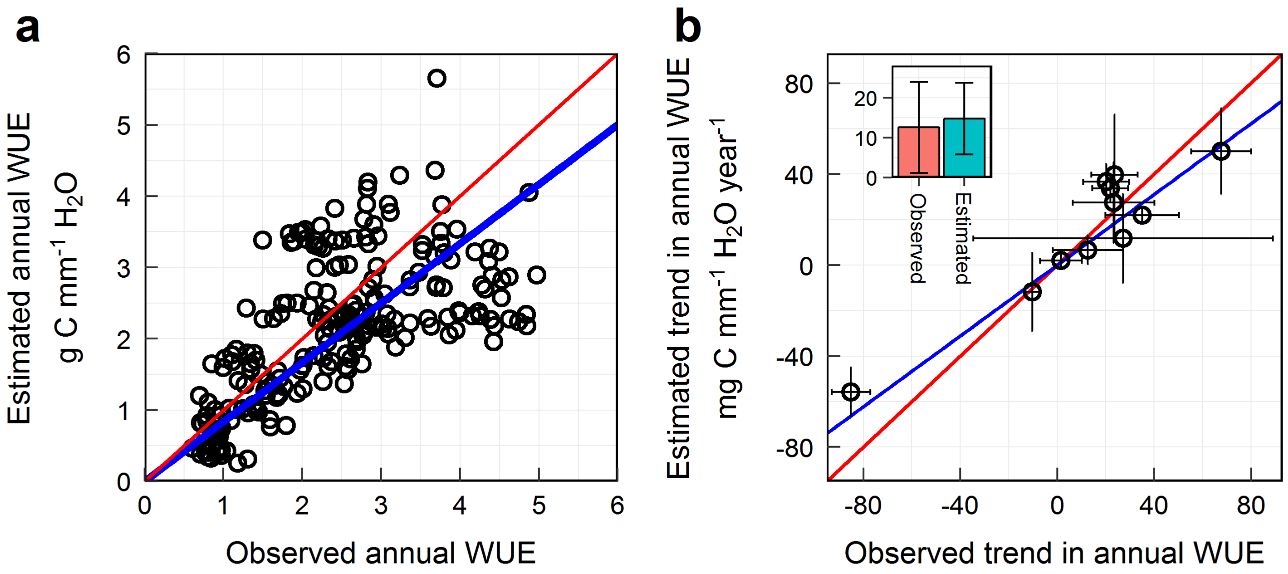
$$WUE = \frac{GPP}{E} = \frac{GPP}{E_t}\frac{E_t}{E_t + E_s}\left(1 - \frac{E_i}{E}\right)$$

$$\frac{GPP}{E_t} = \frac{\int A dt}{\int T dt} \approx WUE_l = \frac{A}{T} = \frac{C_a p_a}{1.6\left(D + g_1\sqrt{D}\right)}$$

$$E_t = (E_t + E_s)(1 - \exp(-kL))$$

$$WUE = \frac{C_a p_a}{1.6\left(D + g_1\sqrt{D}\right)}\left[1 - \exp(-kL)\right]\left(1 - f_{E_i}\right)$$

2. Model validation using EC data



- Validation of the WUE model using global FLUXNET dataset
- (a) annual WUE; (b) annual WUE trend

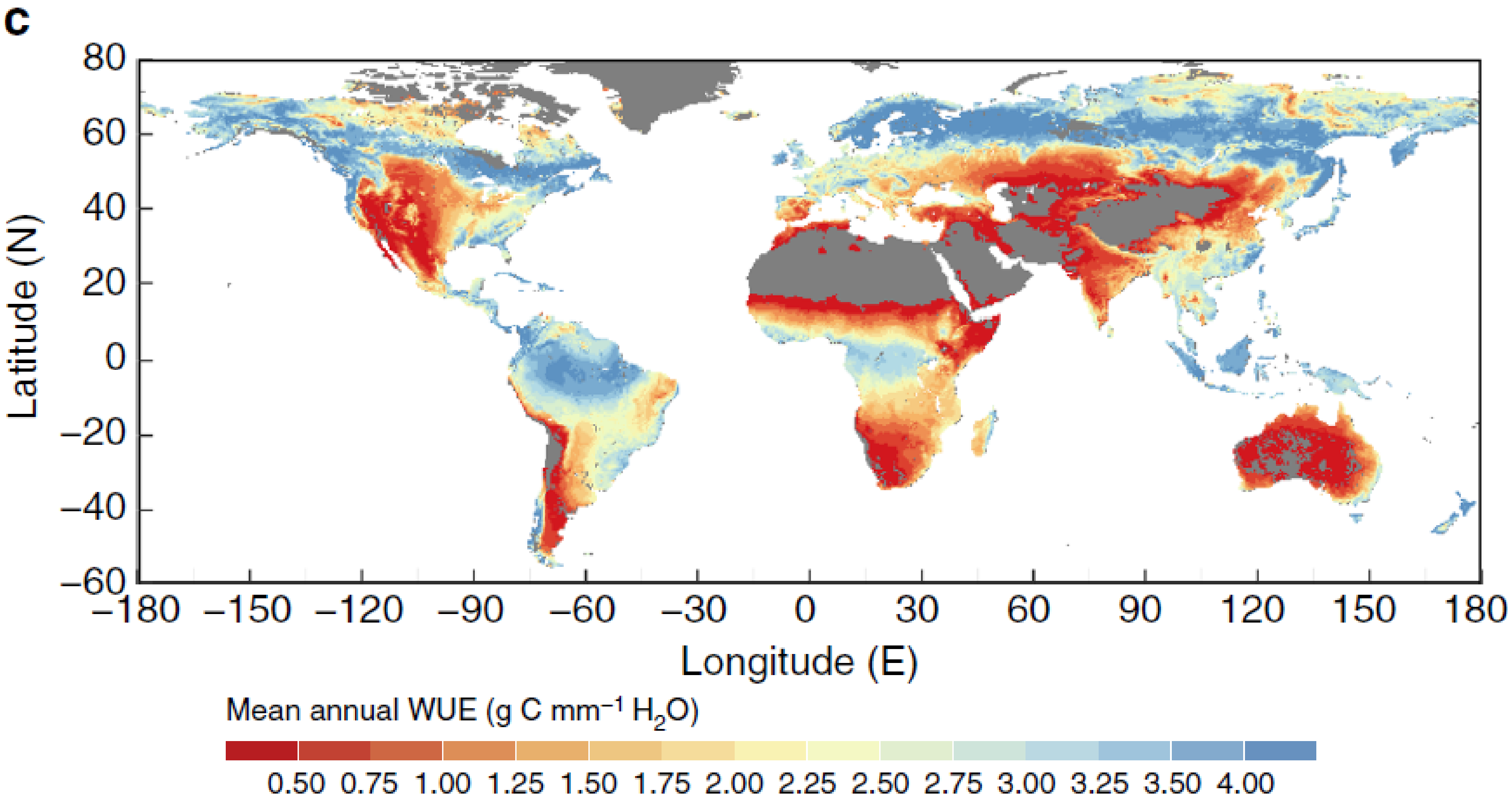
2. Ensemble global simulations

- **Study period**
  - **1982-2011, annual**
- **Spatial resolution**
  - **0.5x0.5 degree**
- **Vegetation mask**
  - **GIMMS NDVI3g > 0.1**

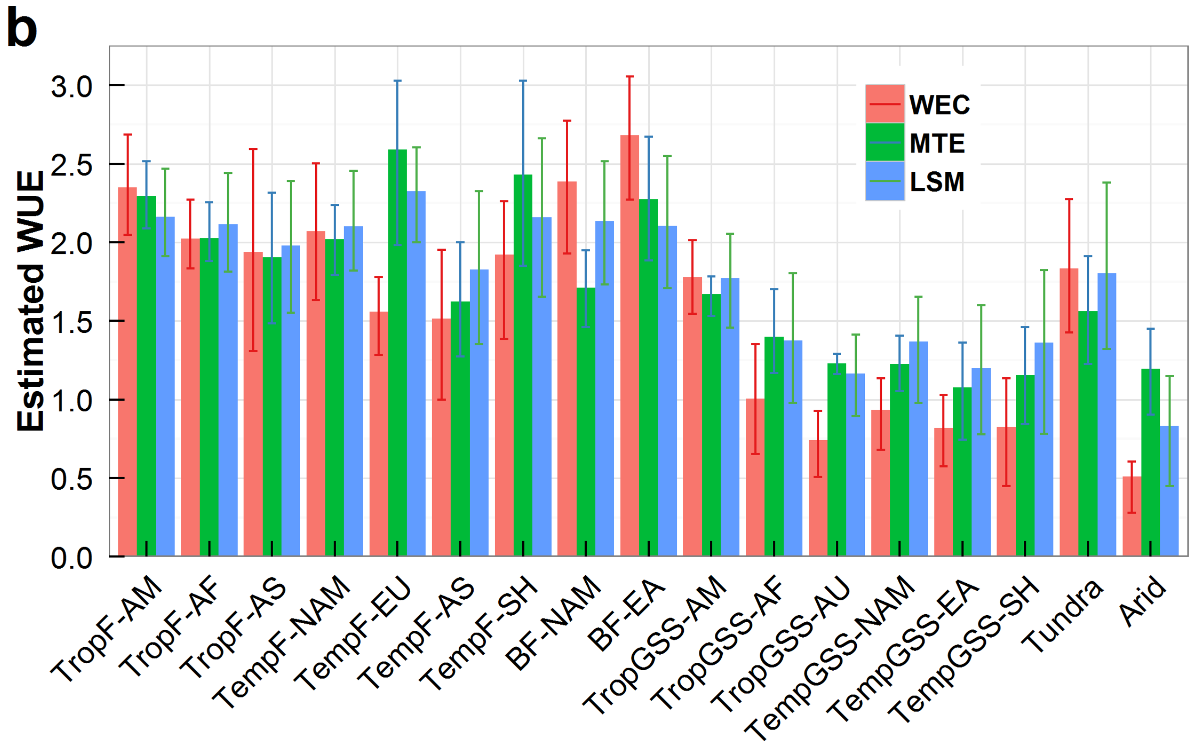
Ensemble simulations
3x2x3=18 simulations

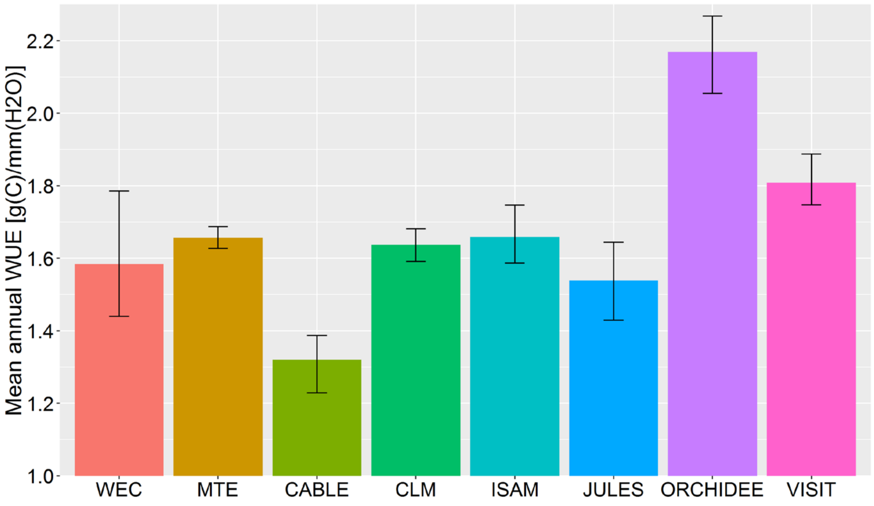
- **Global vegetation cover map**
  - **SYNMAP**
- **Vapour pressure deficit**
  - **CRU-NCEP**
  - **WATCH**
  - **PGF**
- **Leaf area index dataset**
  - **GIMMS LAI3g**
  - **GLASS**
- **Fraction of interception ratio**
  - **GLEAM-ET**
  - **CSIRO-ET**
- **Annual CO_2 concentration**
- **Global g_1 dataset**

2. Spatial variation of WUE



2. Global Water and Carbon Coupling: An analytical diagnostic WUE model – global application





Global annual WUE (Unit: g C mm^{-1} H$_2$O)

WEC: 1.64±0.02

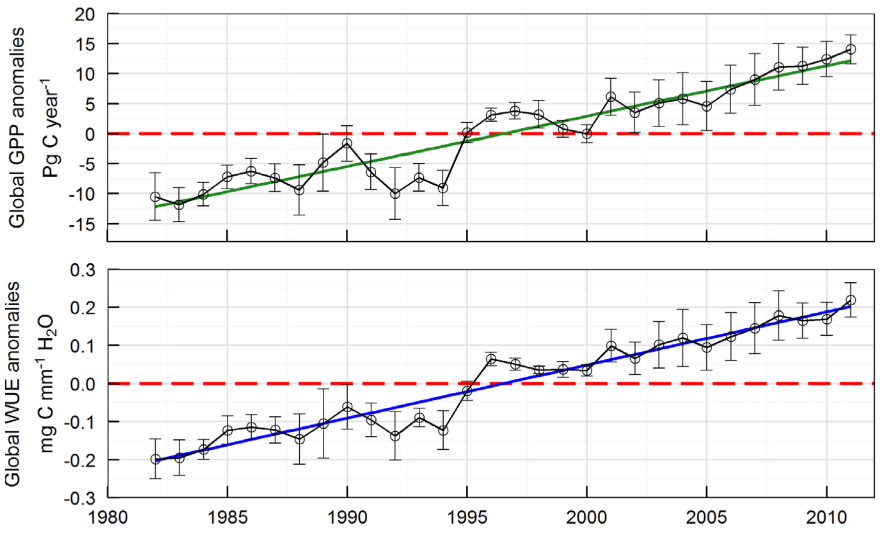
Humphrey et al. (2018): 1.0 to 1.9

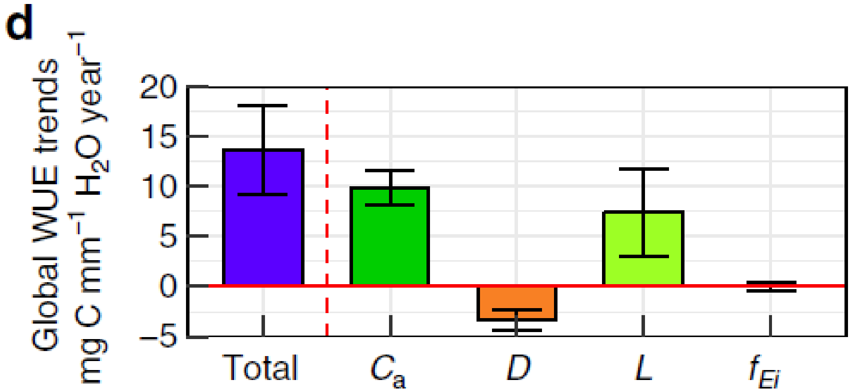
❑ WEC = this study

❑ MTE = model tree ensemble ≈ 'observation'

❑ LSM = ensemble mean from 7 LSMs

3. Trends in global WUE





Trend in global WUE

13.7±4.3 mg C/mm H_2O/year
or
21% of in 30 years

Keenan et al. (2013): 192 mg C/mm H2O/year
(with D=5 0.5 kPa)

Huang et al. (2015) 6.4 mg C/mm H2O/year

Attribution of trend global WUE

CO_2 (C_a): 77±20%
VPD (D) : -27±11%
LAI (L) : 49±16%
f_{Ei} : 0.2± 3%

While the simple model was illuminating, applications to finer scales have a few issues:

1. Control variables
2. Feedbacks on land-air exchange
3. Instantaneous vis time-averaging

Control variable

In the optimal theory of WUE (Cowan 1977), it was assumed that both E and A are regulated by stomatal conductance. This is broadly correct (not so accurate) at leaf-scale, but probably is not so correct at larger or longer time scale.

Both Priestley-Taylor equation and complementary theory have been shown to be reliable for estimating regional ET without g_s, then $\frac{\partial E}{\partial G_S} = 0$!

At a spatial scale of 1° by 1° or greater over a vegetated land surface

"Over land, as indicated as above, the sum, $\lambda E+H$ is strongly governed by the net radiation, R_t, at the earth's surface. It is equally clear that the apportionment of energy between LE and H will be governed by the dryness of the ground……"

From Priestley and Taylor 1972, MWR

Should soil moisture be included into the simple model?

Feedbacks affecting ecosystem WUE (Raupach 1998)

- Radiative feedback: outgoing LW depends on T_s. Generally small.

$$R_{net} \Rightarrow (H, LE) \Rightarrow T_s \Rightarrow R_{net}$$

- Physiological feedback: (G_s and T_s)

$$G_s \Rightarrow T_s \Rightarrow (D_s, R_{net}) \Rightarrow G_s$$

Feedbacks (2)

- Aerodynamic feedback (Garratt 1992)

$$G_a \Rightarrow (H, LE) \Rightarrow Monin - Obuklov\ L \Rightarrow G_a$$

- CBL feedback (slab model; McNaughton and Spriggs 1986)

$$\rho c_p h \frac{d\theta_m}{dt} = H + \rho c_p (\theta_s - \theta_m) \frac{dh}{dt}$$

$$\rho h \frac{dq_m}{dt} = E + \rho\ (q_s - q_m) \frac{dh}{dt}$$

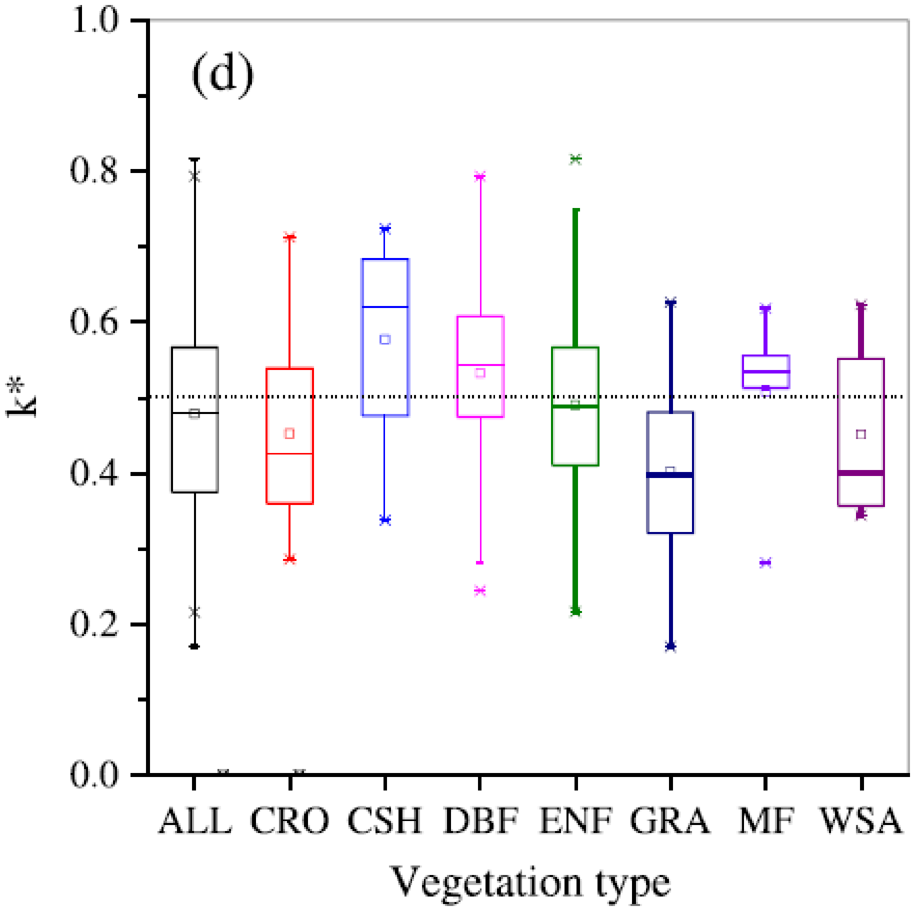
$$H + \lambda E = R_{net} - G$$

$$\frac{dh}{dt} = \frac{H + 0.07\lambda E}{\rho c_p h \gamma_v}$$

Implications on the dependence of G_s on D

$$e_l \propto D^{-0.5}$$

$$e_e \propto D^{-k^*}$$



Zhou et al. 2014, GRL

Instantaneous vis time-averaging WUE

$$\Delta_c = a\left(1 - \frac{C_i}{C_a}\right) + a_m\left(\frac{C_i}{C_a} - \frac{C_c}{C_a}\right) + b\,\frac{C_c}{C_a} - f\,\frac{\Gamma_*}{C_a}$$

$$e_l = \frac{A}{g_s} = \frac{C_a}{1.6}\left(\frac{b - \Delta_c - f\,\frac{\Gamma^*}{C_a}}{b - a + (b - a_m)\,\frac{g_s}{1.6g_m}}\right)$$

Source: Seibt U, Rajabi A, Griffiths H and Berry JA (2008). Oecologia, 155:441-454

Take-home message

At leaf- or ecosystem-scale, g_s is proportional to $1/\sqrt{D}$ if g_s dominates the variations of water loss and carbon uptake;

At global-scale, use of the simple model predicts a 20% increase in WUE, which leads to 20% increase in GPP, therefore land carbon uptake;

However, many feedbacks will affect the regional-scale WUE variations, as well as land use change;

Gs may not be the dominant control on water loss or carbon uptake at regional scale;

A disconnect between theory and interpretation of field observations.

Acknowledgment

Material presented here benefits from the collaboration and exchange with Dr Lu Zhang of CSIRO, Professor Lei Cheng of Wuhan University. However, I am solely responsible for errors and omissions of important studies.

Afforestation reduces runoff

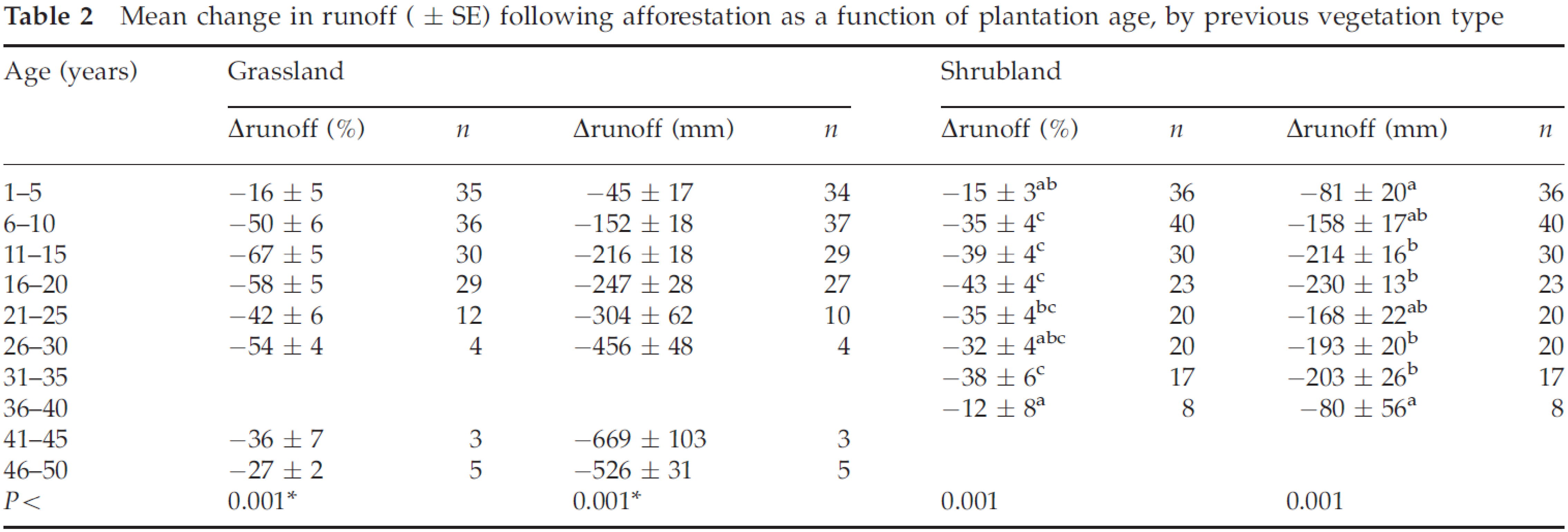
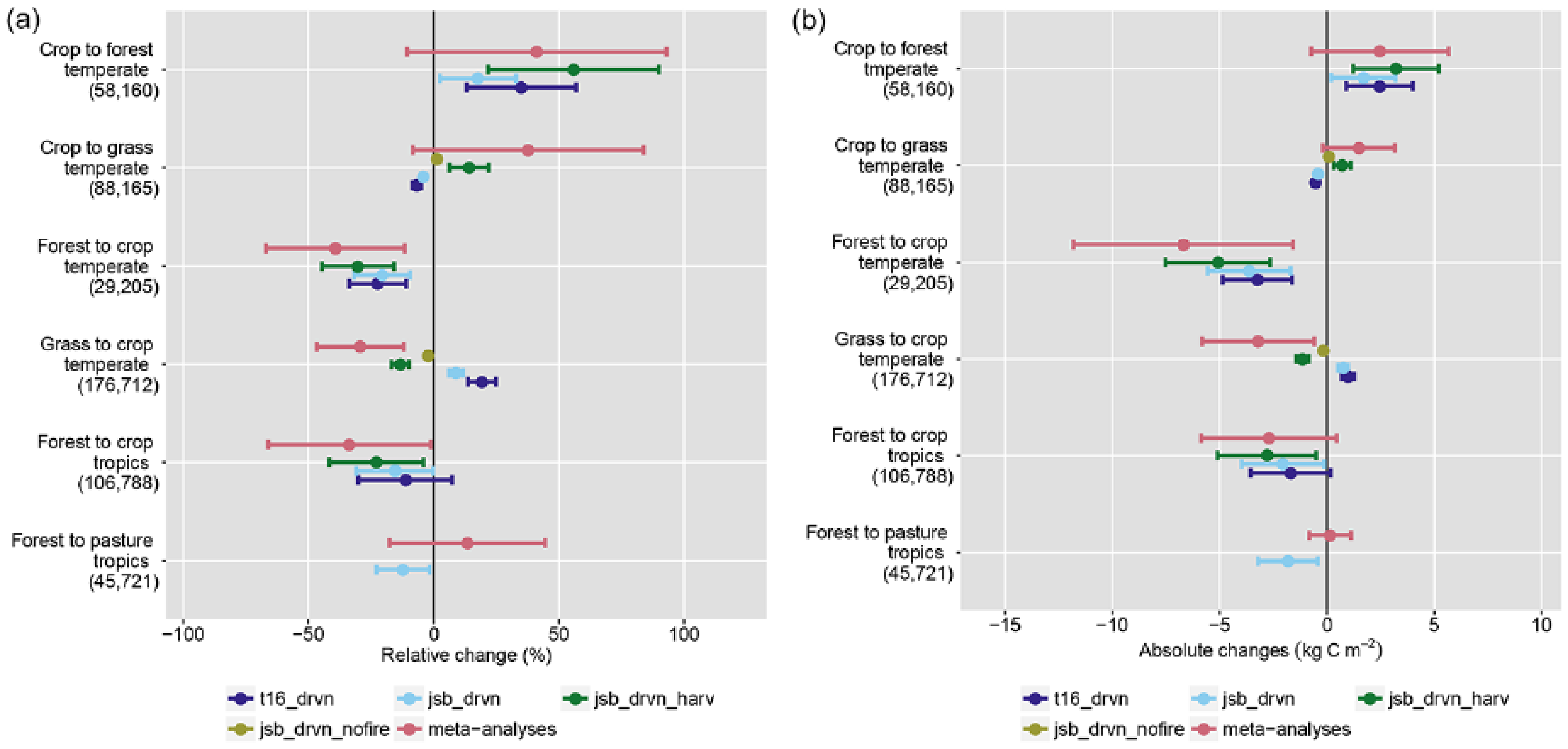


Table 2 Mean change in runoff (± SE) following afforestation as a function of plantation age, by previous vegetation type

Age (years)	Grassland				Shrubland			
	Δrunoff (%)	*n*	Δrunoff (mm)	*n*	Δrunoff (%)	*n*	Δrunoff (mm)	*n*
1–5	−16 ± 5	35	−45 ± 17	34	−15 ± 3^{ab}	36	−81 ± 20^{a}	36
6–10	−50 ± 6	36	−152 ± 18	37	−35 ± 4^{c}	40	−158 ± 17^{ab}	40
11–15	−67 ± 5	30	−216 ± 18	29	−39 ± 4^{c}	30	−214 ± 16^{b}	30
16–20	−58 ± 5	29	−247 ± 28	27	−43 ± 4^{c}	23	−230 ± 13^{b}	23
21–25	−42 ± 6	12	−304 ± 62	10	−35 ± 4^{bc}	20	−168 ± 22^{ab}	20
26–30	−54 ± 4	4	−456 ± 48	4	−32 ± 4^{abc}	20	−193 ± 20^{b}	20
31–35					−38 ± 6^{c}	17	−203 ± 26^{b}	17
36–40					−12 ± 8^{a}	8	−80 ± 56^{a}	8
41–45	−36 ± 7	3	−669 ± 103	3				
46–50	−27 ± 2	5	−526 ± 31	5				
$P <$	0.001*		0.001*		0.001		0.001	



Soil carbon response to land-use change: evaluation of a global vegetation model using observational meta-analyses

Sylvia S. Nyawira[1,2], Julia E. M. S. Nabel[1], Axel Don[3], Victor Brovkin[1], and Julia Pongratz[1]