Modelling historical changes in the water use efficiency of plants and ecosystems with different vegetation models

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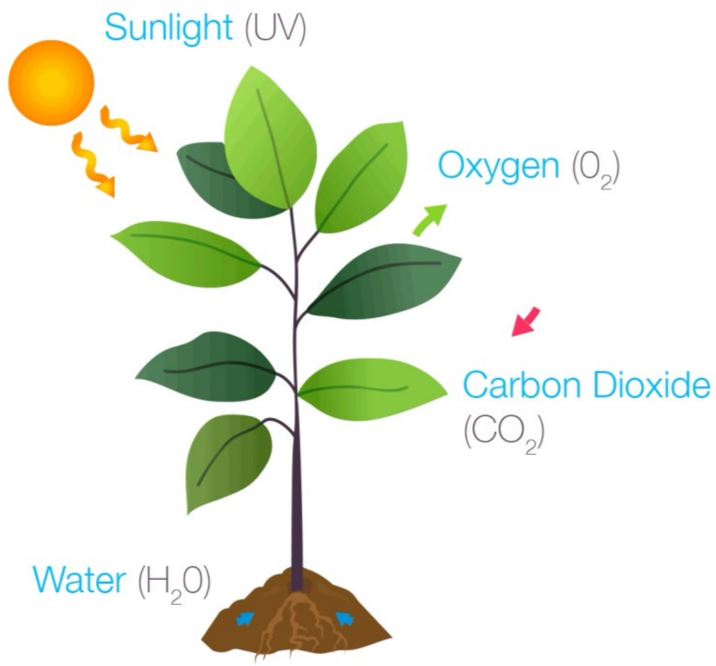
Water-use efficiency: A Carbon & Water Balance

Coupling the Carbon & Water Cycles

$$\mathbf{WUE} = \frac{CO_2}{H_2O}$$

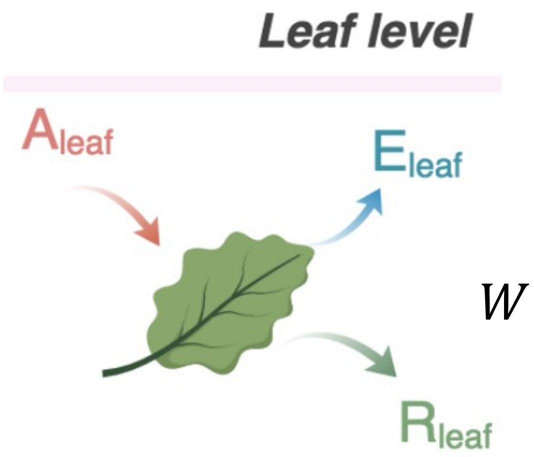


Water-use efficiency: A Carbon & Water Balance

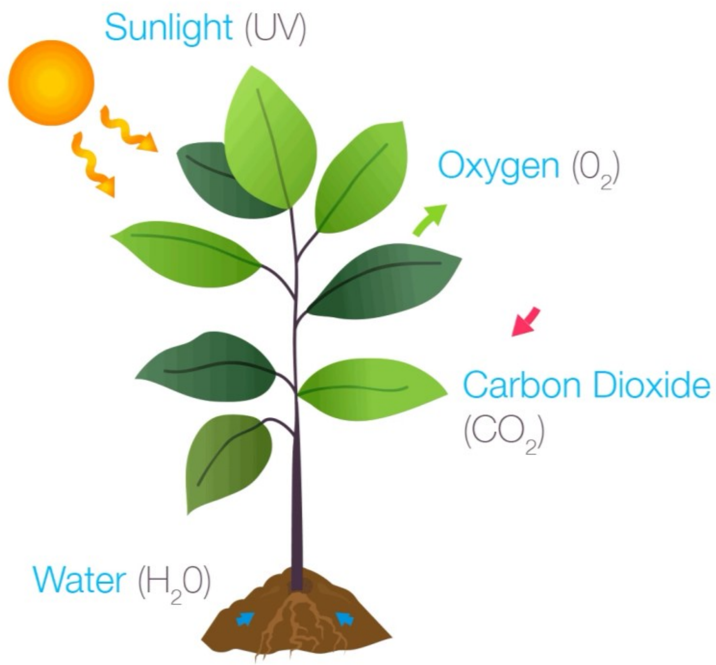
Coupling the Carbon & Water Cycles

Leaf level

$$WUE = \frac{A}{E}$$



$$WUE \approx \frac{c_a}{1.6 \cdot D} \cdot \left(1 - \frac{c_i}{c_a}\right)$$



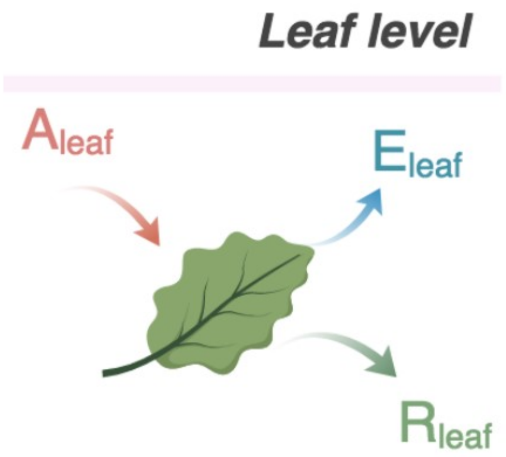
A: photoassimilation rate; E: transpiration; c_a: atmospheric CO2 concentration; c_i: intercellular CO2 concentration; D: vapour pressure deficit

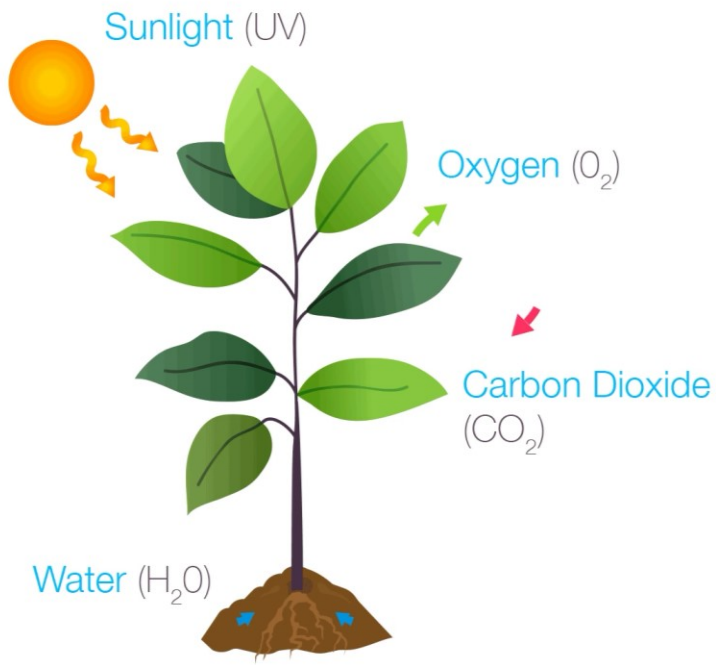
Water-use efficiency: A Carbon & Water Balance

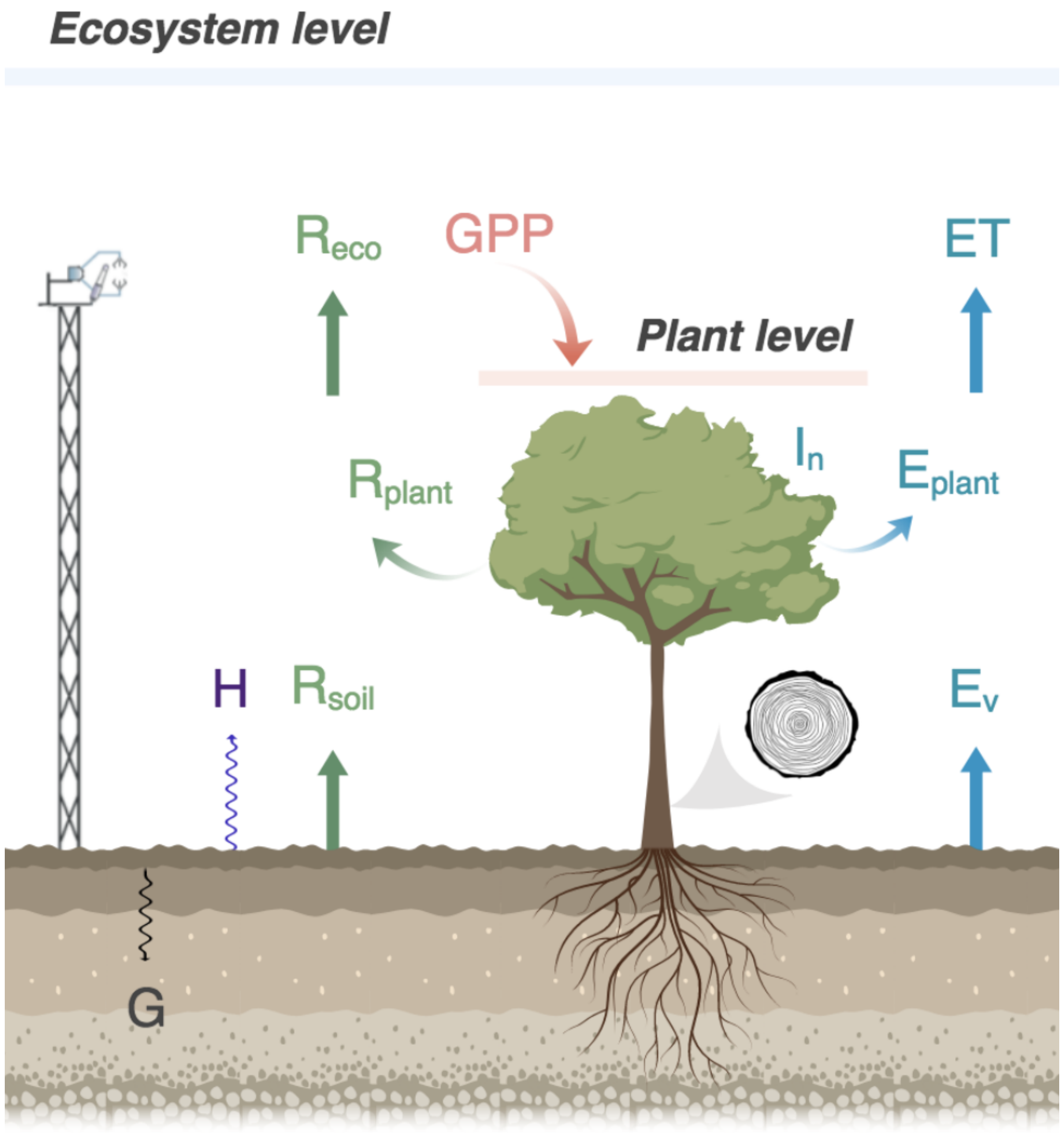
Coupling the Carbon & Water Cycles

Ecosystem level

$$\textbf{WUE} = \frac{\color{red}{\text{GPP}}}{\color{blue}{\text{ET}}}$$





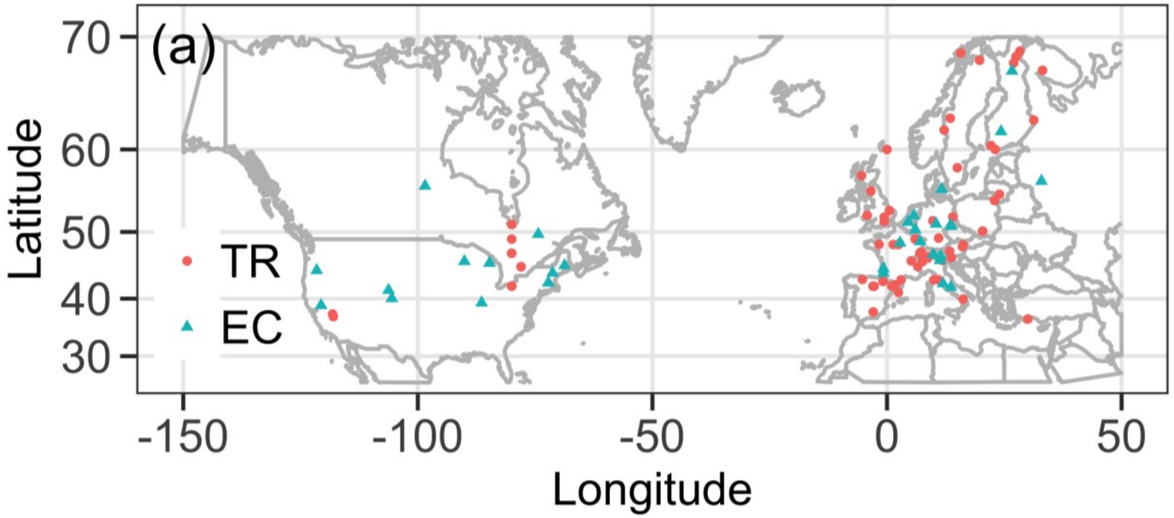


GPP: gross primary production; ET: evapotranspiration

Water-use efficiency: A Carbon & Water Balance

Coupling the Carbon & Water Cycles

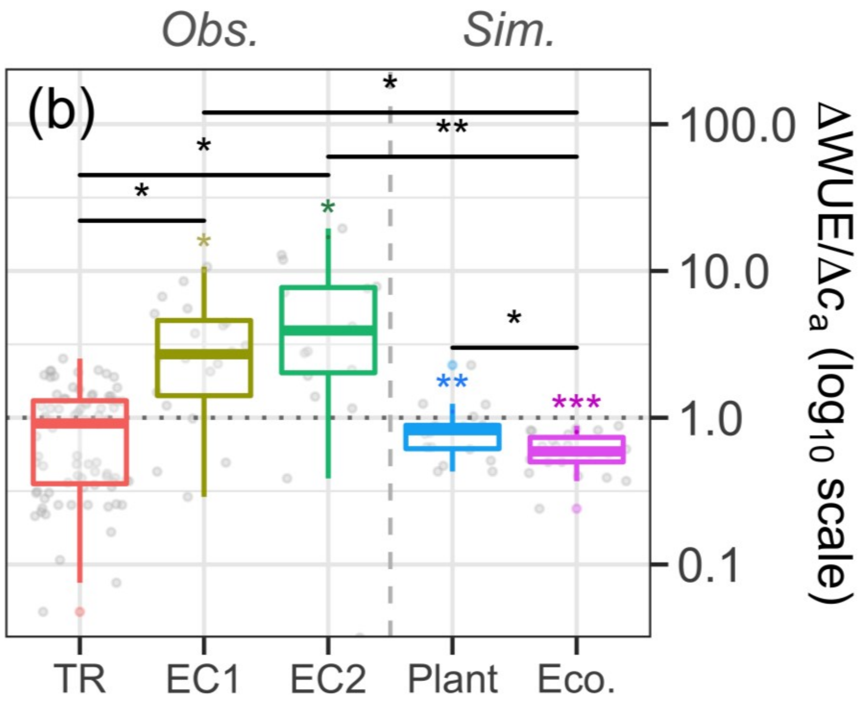
What are the relative contributions from environmental drivers?



EC: eddy-covariance flux data
TR: carbon isotopes in tree rings

→ Discrepancies in magnitude of changes in WUE between different types of observations

→ Underprediction by vegetation models



Lavergne et al. (2019) *GCB*

Driving factors: Refining Relative Contributions

Coupling the Carbon & Water Cycles

Are the dependencies of WUE on CO2 and *D* the same at leaf and ecosystem levels ?

→ Contributions from CO_2 (*a*) and *D* (*b*) to WUE

$$\mathrm{WUE_T} = \frac{c_\mathrm{a}}{1.6\,D}\left(1 - \frac{c_\mathrm{i}}{c_\mathrm{a}}\right)$$

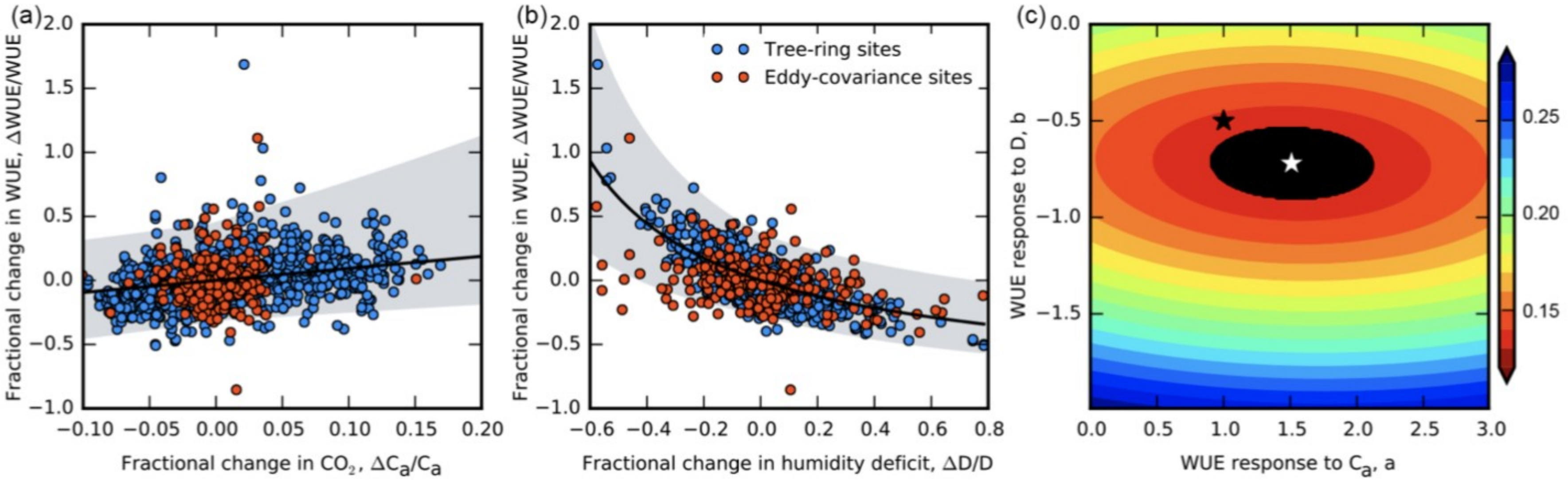
$$\ln\{1 + f\mathrm{WUE}\} = a \ln\{1 + fc_\mathrm{a}\} + b \ln\{1 + fD\}$$

Fractional changes

$$f\mathrm{X} = \frac{\mathrm{X} - \bar{\mathrm{X}}}{\bar{\mathrm{X}}}$$

Values (mean ± sd) from 31 TR and 28 EC observational series over 1900-2010:

***a* = 1.51 ± 0.57** **b = -0.72 ± 0.16**



Dekker et al. (2016) *ESD*

Driving factors: Indices for Evaluating Models?

→ Testing the performance of different types of vegetation models to predict the environmental dependencies of WUE **at the leaf and ecosystem levels**

How?

→ Estimation of contributions from CO_2 and *D* on WUE from:

1. independent networks of TR (leaf-level) and EC (ecosystem-level) observations over their common period of records (1991-2014)
2. vegetation model outputs

→ Model-data comparisons

Predicting Vegetation: different Types of Models

JULES
Joint UK Land Environment Simulator
vn4.6

- fixed land cover map
- prescribed leaf area index (LAI) → seasonal variations derived from phenology model but no year-to-year variations
- **distinction among plant functional types (PFTs) : fixed parameters defining behaviour of the vegetation**

Best et al. (2011) *Geosci. Model Dev.*
Clark et al. (2011) *Geosci. Model Dev.*

- ability of plants (within any one PFT) to acclimate or adapt to environmental changes
- stomatal limitation of photosynthesis **only driven by environmental variables**

Prentice et al. (2014)
Wang et al. (2017)
Stocker et al. (in revision)

REALM
'Re-inventing Ecosystem And Land-surface Models

P model

JULES: a Global Vegetation model

Two different model configurations for stomatal limitation of photosynthesis

vn4.6

Jacobs (1994): JAC

$$g_s = 1.6RT_{leaf}\frac{A\,\beta}{c_a - c_i}$$

$$c_i = (c_a - \Gamma^*)\frac{c_i}{c_a}\left(1 - \frac{D}{D_{crit}}\right) + \Gamma^*$$

β : soil moisture stress factor (unitless)
R: universal gas constant ($\mathrm{J\,K^{-1}\,mol^{-1}}$)
T_{leaf}: leaf surface temperature (°K)
Γ^*: CO_2 photorespiration compensation point (Pa)
A: potential leaf net assimilation rate ($\mu\mathrm{mol\,mol^{-1}}$)

Medlyn et al. (2011): MED

$$g_s \approx g_0 + \left(1 + \frac{g_1}{\sqrt{D}}\right)\frac{A}{c_a}$$

$$c_i = c_a\left(\frac{g_1}{g_1 + \sqrt{D}}\right)$$

D: leaf-to-air vapour pressure deficit (Pa)
D_{crit}: critical leaf-to-air vapour pressure deficit (Pa)
g_1: sensitivity of g_s to assimilation rate

Oliver et al. (2018) *Biogeosci.*
Best et al. (2011) *Geosci. Model Dev.*
Clark et al. (2011) *Geosci. Model Dev.*

+ Farquhar-Collatz photosynthesis model
+ canopy A (≈ GPP) estimated with big leaf approach (scaled by LAI using Beer's law)

P Model: a Simple Optimality model

Least-cost hypothesis (LC):

$$c_i = c_a \left(\frac{\xi}{\xi + \sqrt{D}} \right)$$

$$\xi = \sqrt{b} \frac{K}{1.6\eta*}$$

D: leaf-to-air vapour pressure deficit (Pa)
b: ratio of dimensionless cost factors for carboxylation and transpiration
$\eta*$: viscosity of water relative to its value at 25°C
K: effective Michaelis-Menten coefficient for Rubisco-limited photosynthesis (Pa)

Prentice et al. (2014)
Wang et al. (2017)
Stocker et al. (in revision)

Coordination hypothesis:

$$GPP = I_{abs} \cdot \phi_0 \cdot m \sqrt{[1 - (c^*/m)^{2/3}]}$$

$$m = \frac{(c_a - \Gamma^*)}{\left\{ c_a + 2\Gamma^* + 3\Gamma^* \sqrt{[1.6 \cdot \eta^* \cdot D \cdot b^{-1} \, (K + \Gamma^*)^{-1}]} \right\}}$$

φ_0 is the intrinsic quantum yield (g C / mol)
I_{abs} is the absorbed photosynthetic photon flux density (PPFD*fAPAR, mol /m²/s)
fAPAR: fraction of absorbed photosynthetically active radiation (unitless)
Γ^* is the photorespiratory compensation point (Pa)
$c^* \approx$ 0.41 is estimated from observed J_{max}:Vc_{max} ratios proportional to the unit carbon cost for the maintenance of electron transport capacity

But no explicit prediction of transpiration yet!

REALM
'Re-inventing Ecosystem And Land-surface Models

P model

Model-Data approach: Input Data & Parameters

Coupling the Carbon & Water Cycles

01 Vegetation models & Observations

02 Initial Results

03 Conclusion & Perspectives

04 Next steps

- WATCH-WFDEI data (Weedon et al. 2014) as input + atmospheric CO2 from Scripps

1. **leaf level:** at > 100 TR sites with carbon isotope data ($\delta^{13}C_{TR}$) compilation from Lavergne et al. (in revision)

2. **ecosystem level:** at 34 EC flux sites with > 6 years of records representing forest ecosystems (FLUXNET dataset)

→ Model-data comparisons over common 1991-2014 period: c_a increase by 43 ppm

Model	Parameter	Broadleaf	Needleleaf	References
Jacobs (JAC)	D_{crit} (kg kg^{-1})	0.09	0.06	Oliver et al. (2018)
Medlyn (MED)	g_1 (kPa$^{0.5}$)	3.22	2.22	Oliver et al. (2018)
Prentice (LC)	*b* (unitless)	146		Smith et al. (2019)

Observed Data: leaf c_i, GPP, ET, WUE & eWUE

Coupling the Carbon & Water Cycles

01 **Vegetation models & Observations**

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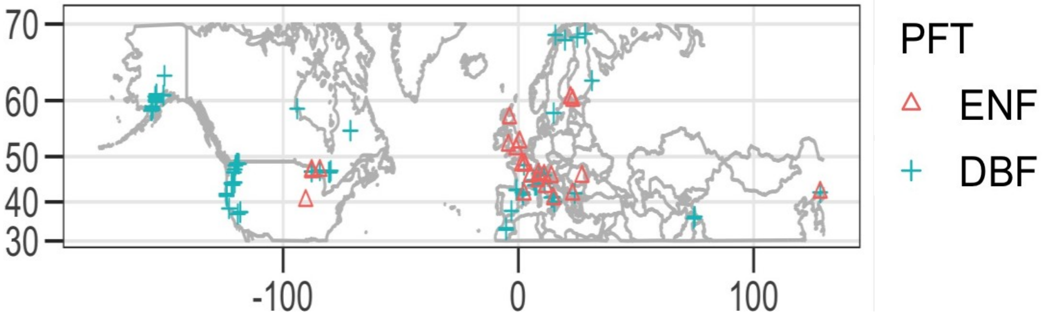
Leaf level

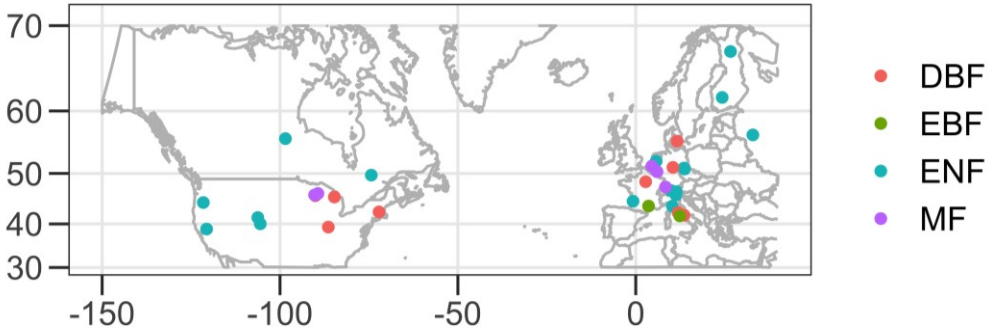


$$\frac{c_i}{c_a} = \frac{\left(\frac{\delta^{13}CO_2-(\delta^{13}C_{TR}-d)}{1+(\delta^{13}C_{TR}-d)/1000}\right)-a+f\frac{\Gamma^*}{c_a}}{b-a}$$

$$\mathrm{WUE} = \frac{c_a}{1.6 \cdot D} \cdot \left(1 - \frac{c_i}{c_a}\right)$$

$\delta^{13}CO_2$: stable carbon isotopic composition of atmospheric CO2 (‰)
Γ^*: CO_2 photorespiration compensation point (Pa)
a: fractionation due to CO2 diffusion in air = 4.4 ‰
b: fractionation due to effective Rubisco carboxylation = 30‰
f : fractionation due to photorespiration = 8‰
d: post-photosynthetic fractionations = 2.1‰

Ecosystem level



$$\mathrm{eWUE} = \frac{\mathrm{GPP}}{\mathrm{ET}} = \frac{\mathrm{GPP}}{\mathrm{LE}}\lambda_v$$

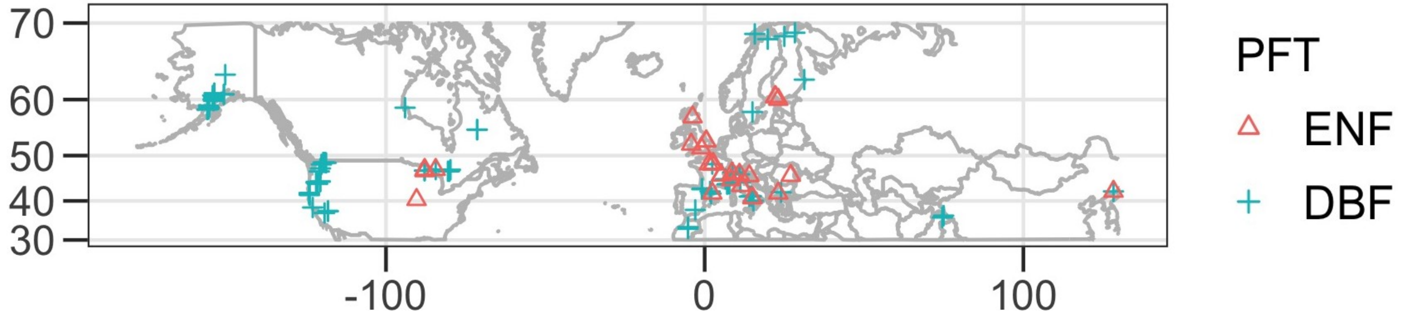
λ_v: latent heat of vaporization (kJ kg^{-1})
LE: latent heat flux (W m^{-2})

- Filtering and processing with R package bigleaf (Knauer et al. 2018 PlosOne)
- Aggregation over summer months (June-August)

TR sites: Measured *versus* Predicted leaf c_i

Leaf level

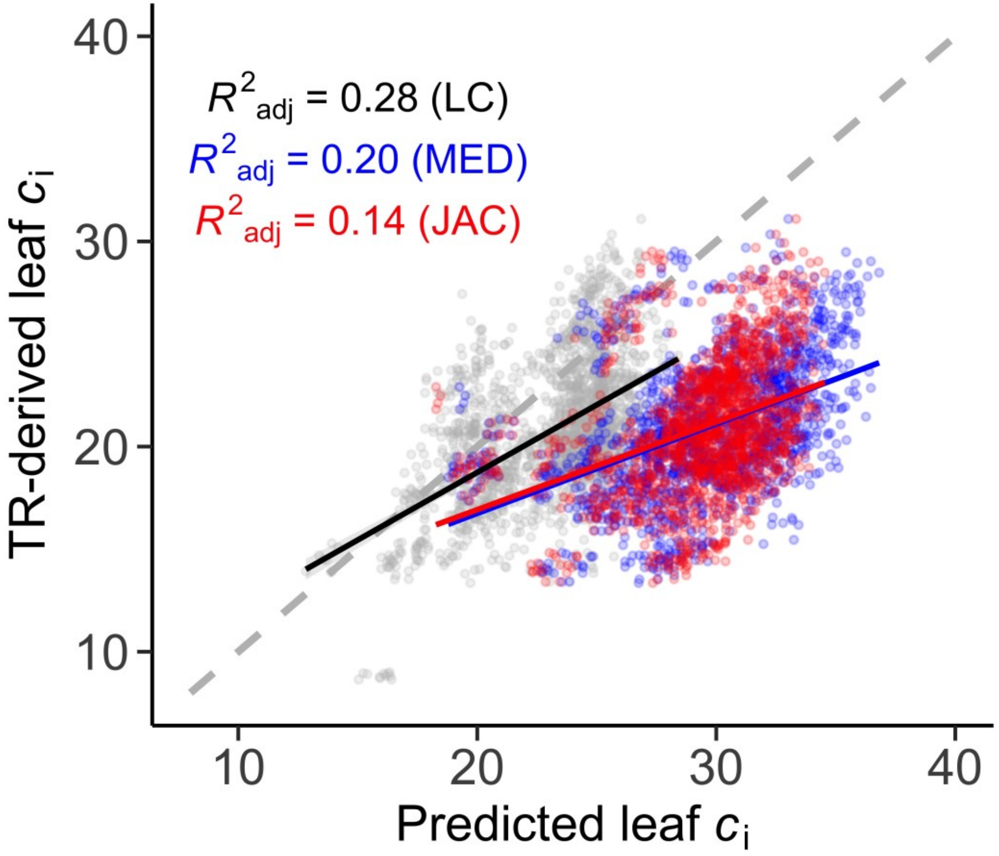
1991-2014



(JAC) $$c_i = (c_a - \Gamma^*)\frac{c_i}{c_a}\left(1 - \frac{D}{D_{crit}}\right) + \Gamma^*$$

(MED) $$c_i = c_a\left(\frac{g_1}{g_1 + \sqrt{D}}\right)$$

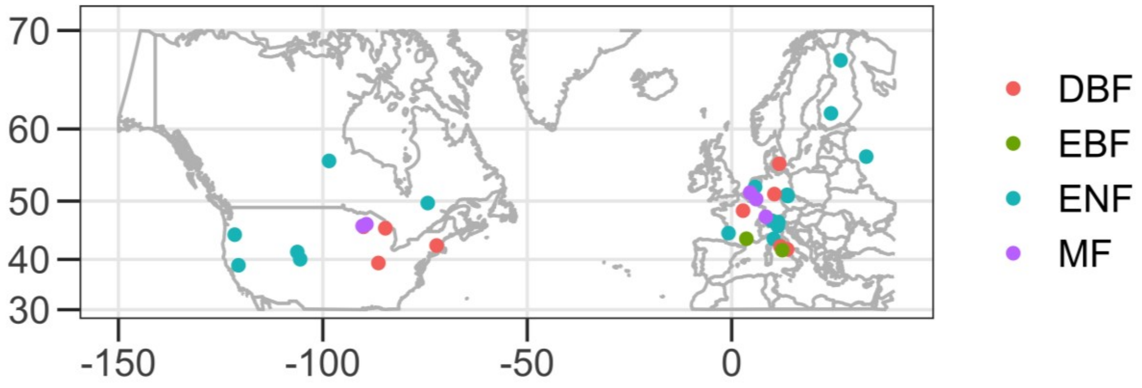
(LC) $$c_i = c_a\left(\frac{\xi}{\xi + \sqrt{D}}\right)$$



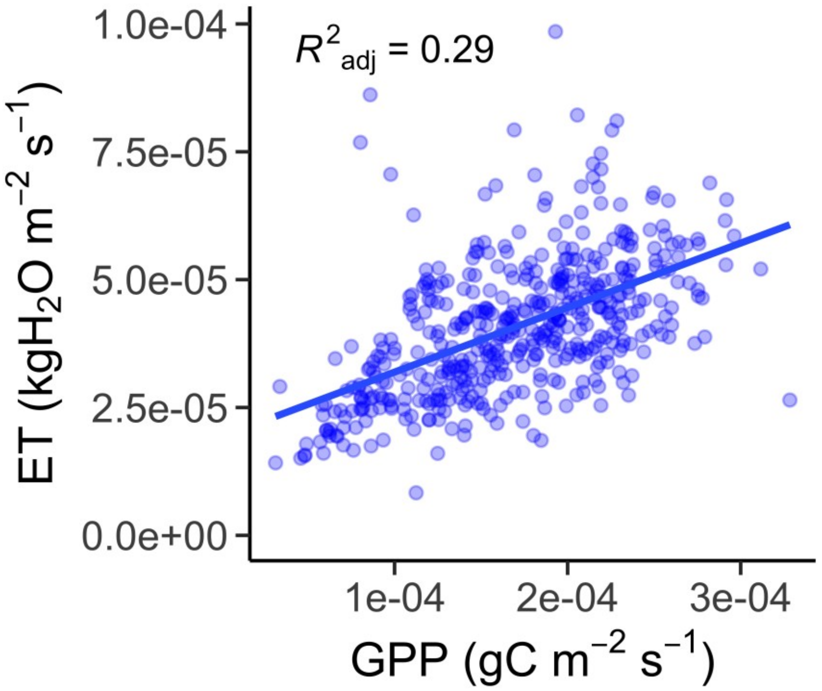
EC sites: Measured and Predicted GPP & ET

Ecosystem level

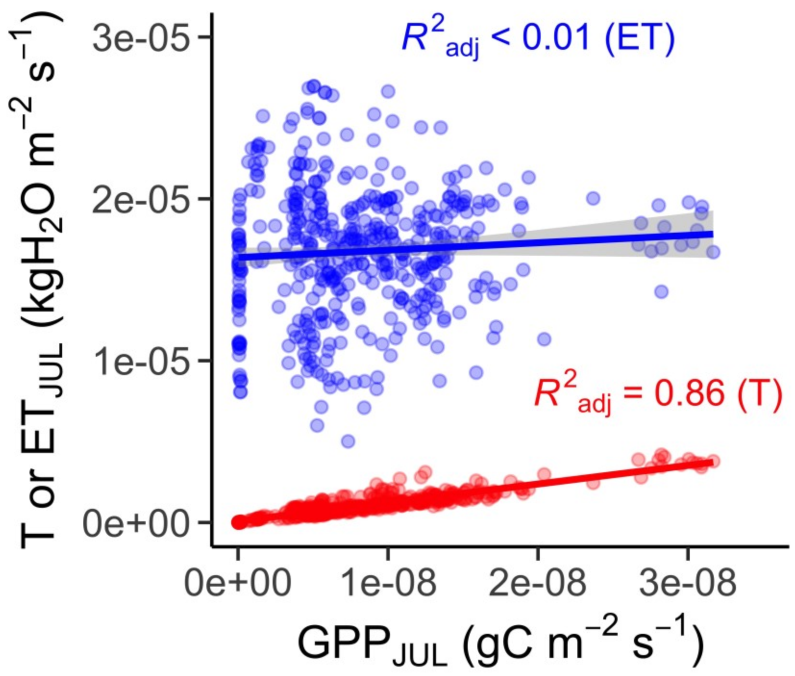
1991-2014



EC fluxes



Predictions



Drivers: Relative Contributions to WUE: obs

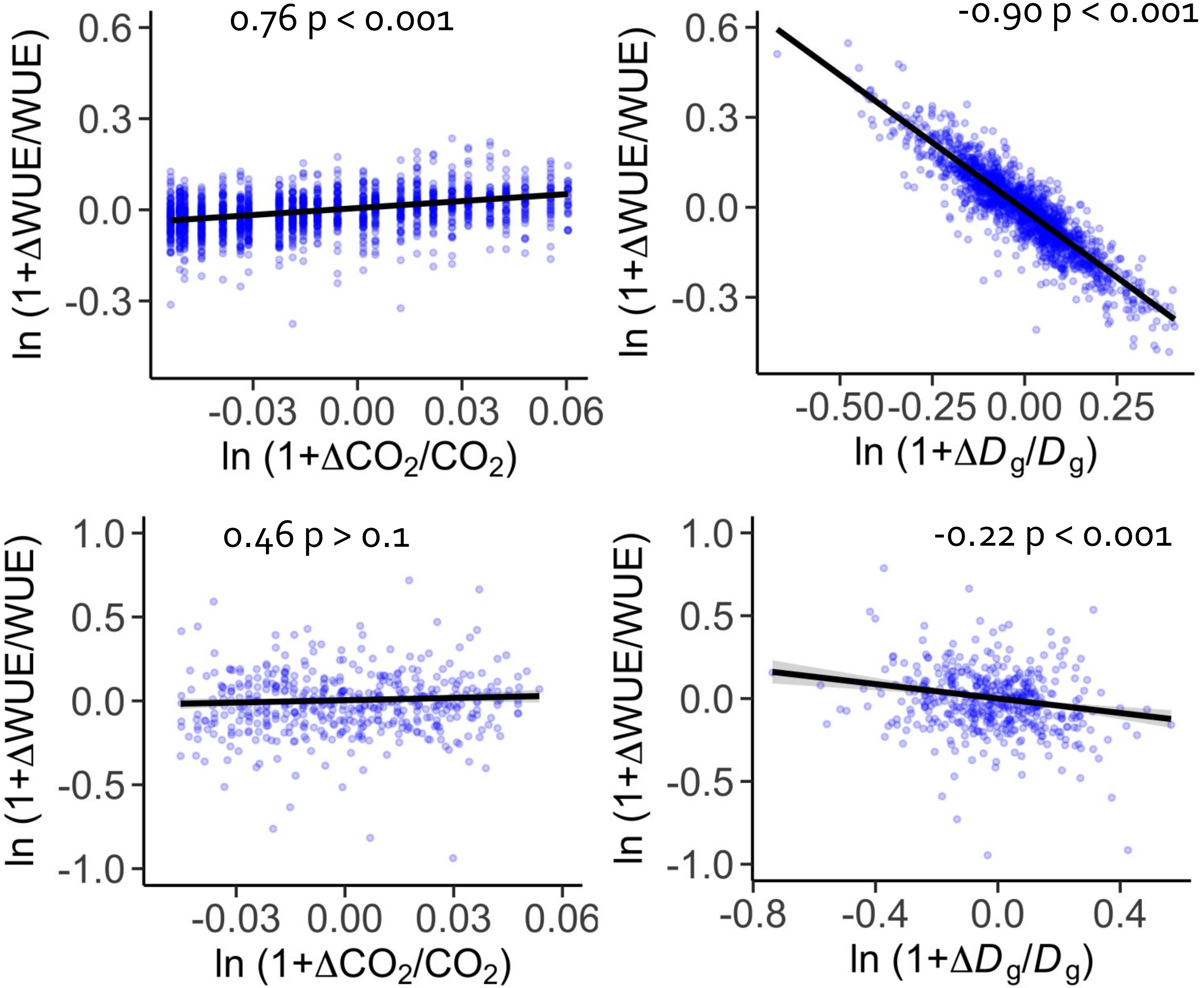
Partial residuals over 1991-2014

Leaf-level

$$\mathrm{WUE} = \frac{c_\mathrm{a}}{1.6 \cdot D} \cdot \left(1 - \frac{c_\mathrm{i}}{c_\mathrm{a}}\right)$$

Ecosystem-scale

$$\mathrm{eWUE} = \frac{\mathrm{GPP}}{\mathrm{ET}} = \frac{\mathrm{GPP}}{\mathrm{LE}} \lambda_v$$



Drivers: Relative Contributions to WUE: obs *versus* simu

Spatial scale	Type	Driver	Estimate	SE	*p* value	% of R^2 (unique)	% of R^2 (unique + common)	R^2
Leaf level	OBS-TR	CO_2	**0.76**	0.041	<0.001	3.2	0.1	**0.82**
		D	**-0.90**	0.010	<0.001	47.1	96.8	
	SIMU LC	CO_2	**1.04**	0.025	<0.001	6.3	0.9	**0.91**
		D	**-0.84**	0.006	<0.001	31.6	91.2	
	SIMU MED	CO_2	**1.17**	0.112	<0.001	4.4	0.5	**0.38**
		D	**-0.91**	0.027	<0.001	57.1	68.8	
	SIMU JAC	CO_2	**1.36**	0.110	<0.001	7.1	1.7	**0.39**
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Using ET flux	SIMU MED	CO_2	**0.29**	0.472	0.533	5.3	6.9	**<0.01**
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Coupling the Carbon & Water Cycles

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		D	**-0.10**	0.037	0.009	9.7	8.0	
	SIMU JAC	CO_2	**1.83**	0.251	<0.001	91.3	89.6	**0.10**
		D	**-0.11**	0.044	0.014	10.4	8.6	

Conclusion: Need to refine processes at ecosystem level

Leaf level: all models of stomatal limitation of photosynthesis (i.e. LC, JAC or MED) reproduce reasonably well the relative contributions from c_a and *D* to changes in leaf WUE

Ecosystem level: JULES tends to assign erroneously a positive influence of *D* to changes in eWUE when using LE flux, or overestimate the influence of CO2 when using the transpiration flux

Need to refine processes modelled at the ecosystem level → testing new formulations for GPP and ET against EC flux measurements

Implementation of transpiration in the P model done by colleagues will allow predictions of eWUE

Next steps: Planning

Coupling the Carbon & Water Cycles

RUNNING LONGER SIMULATIONS WITH JULES TO ASSESS LONG-TERM PREDICTIVE SKILLS

TESTING IMPLEMENTATION OF LC HYPOTHESIS IN JULES AND COMPARING SIMULATIONS WITH CARBON ISOTOPE DATA

IMPLEMENTATION OF CARBON ISOTOPES IN JULES

IMPROVING PREDICTIONS OF T AND GPP IN JULES?

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Coupling the Carbon & Water Cycles

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Iain Colin Prentice & Heather Graven for general discussions

FLUXNET contributors

All colleagues providing carbon isotopes data from tree rings

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github.com/Alielav
bitbucket.org/labprentice

P Model: a Simple Optimality model

Input data

Atmospheric CO2, temperature, vapour pressure deficit

Incoming shortwave radiation, fAPAR

Elevation

P model

Least-cost (LC) hypothesis

leaves minimize the summed unit costs of transpiration and carboxylation

Coordination hypothesis

photosynthesis equally limited by electron transport and carboxylation under average environmental conditions

Outputs

χ
Leaf-internal to ambient CO2 concentrations

GPP
Gross primary production

Spatial Resolution

Site
(e.g. FLUXNET, tree-ring sites)

Region
(e.g. high resolution satellite data)

Global
(e.g. MERIS, MODIS, ECMWF)

Temporal Resolution

Half-hourly to daily

Monthly

Annual

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Re-inventing Ecosystem And Land-surface Models