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Implementing Stable Carbon Isotopes into JULES:
A novel approach for evaluating the coupled carbon and water cycles as represented in UKESM

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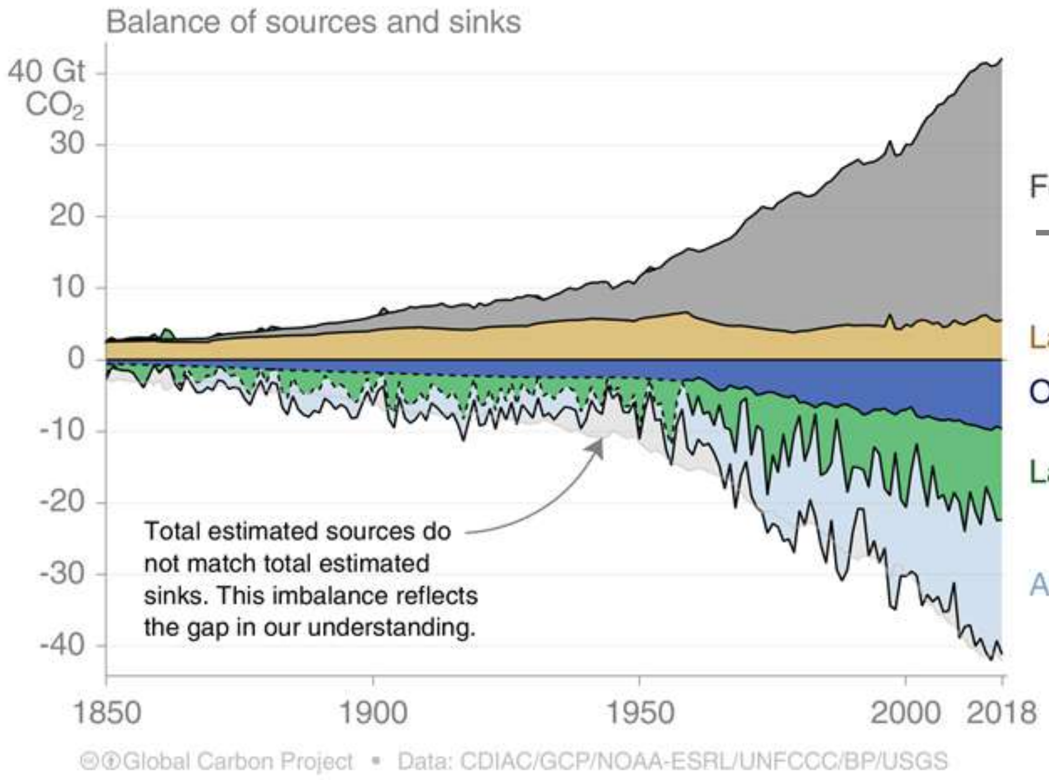
In collaboration with

Carbon isotopes: from the atmosphere to the plant

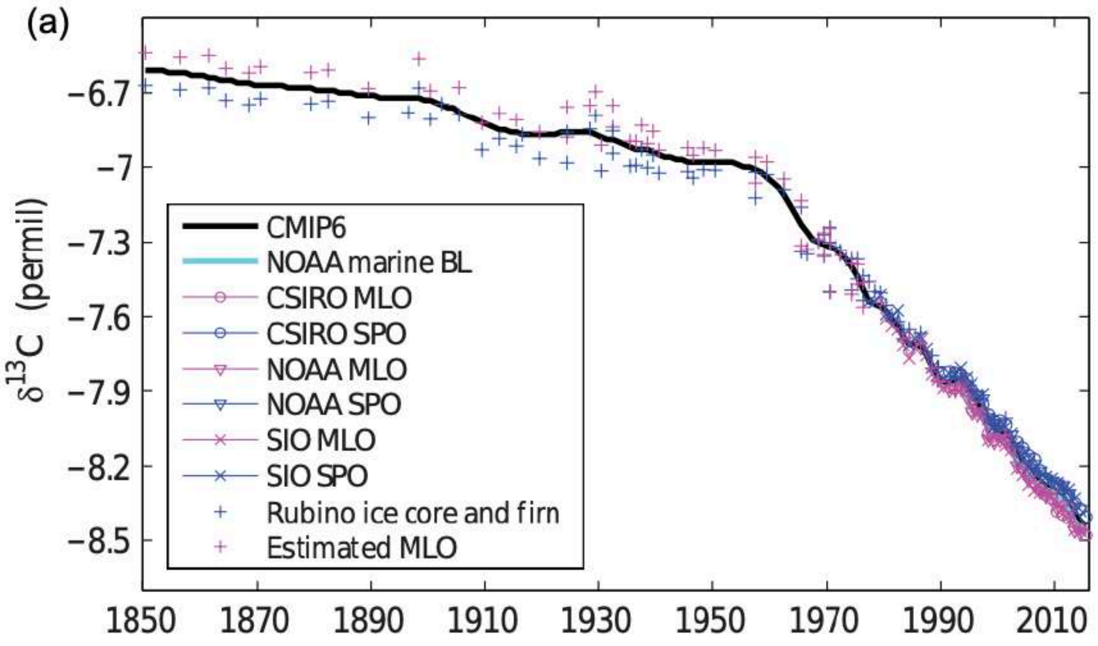


Exchanges of CO_2 between reservoirs
= 'disequilibrum fluxes'

^{12}C is dominant (98.9%)
^{13}C is also stable (1.1%)
$R = {}^{13}C/{}^{12}C$

$\delta^{13}C = (R_{sample}/R_{standard} - 1) \times 1000$ ‰

The Suess effect



Graven et al. (2017) *Geosci. Model Dev.*

Carbon isotopes: from the atmosphere to the plant

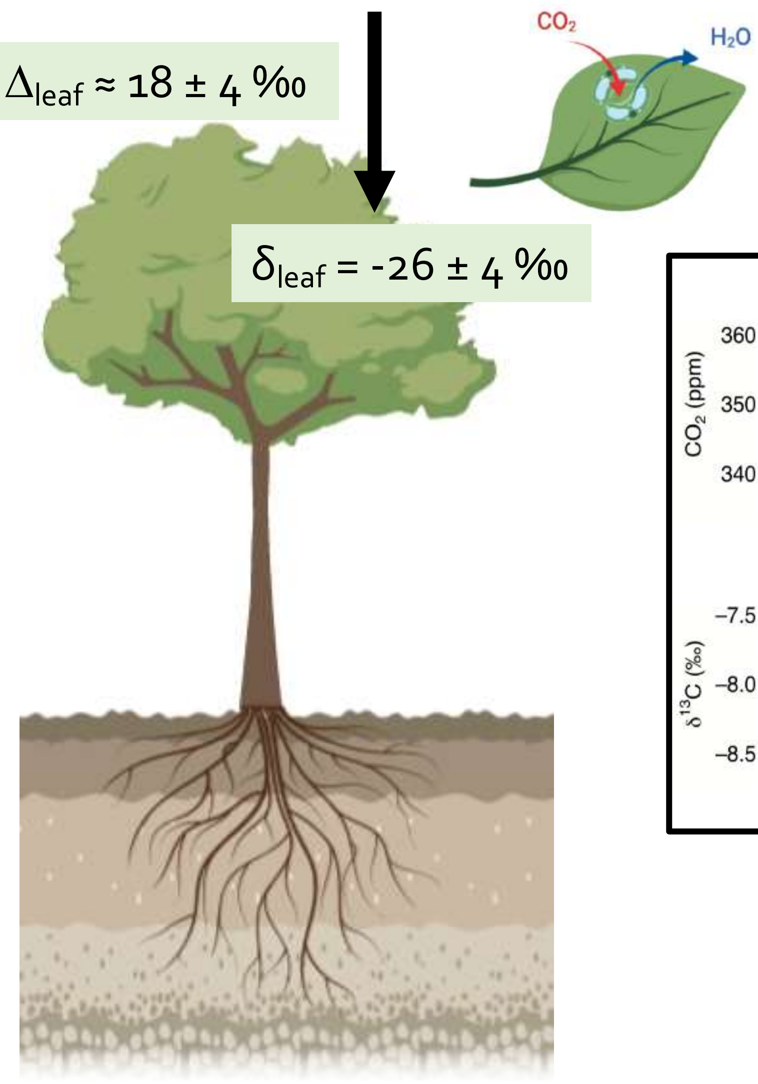
Atmospheric CO_2

δ_{atm} = -8.5 ± 0.5‰

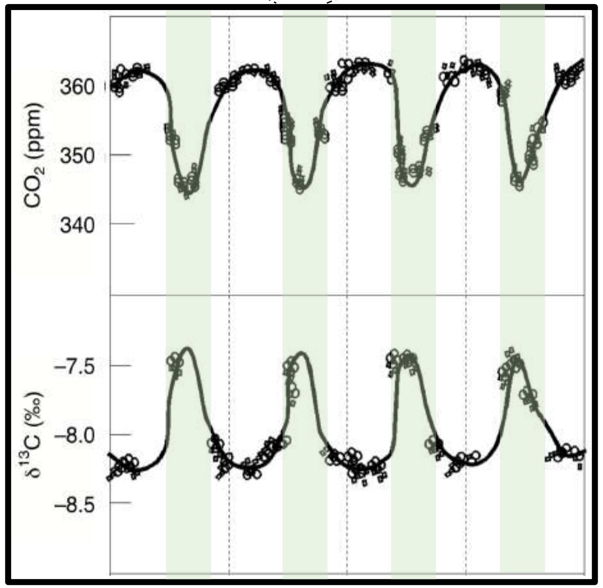
Photosynthesis

Δ_{leaf} ≈ 18 ± 4 ‰

δ_{leaf} = -26 ± 4 ‰



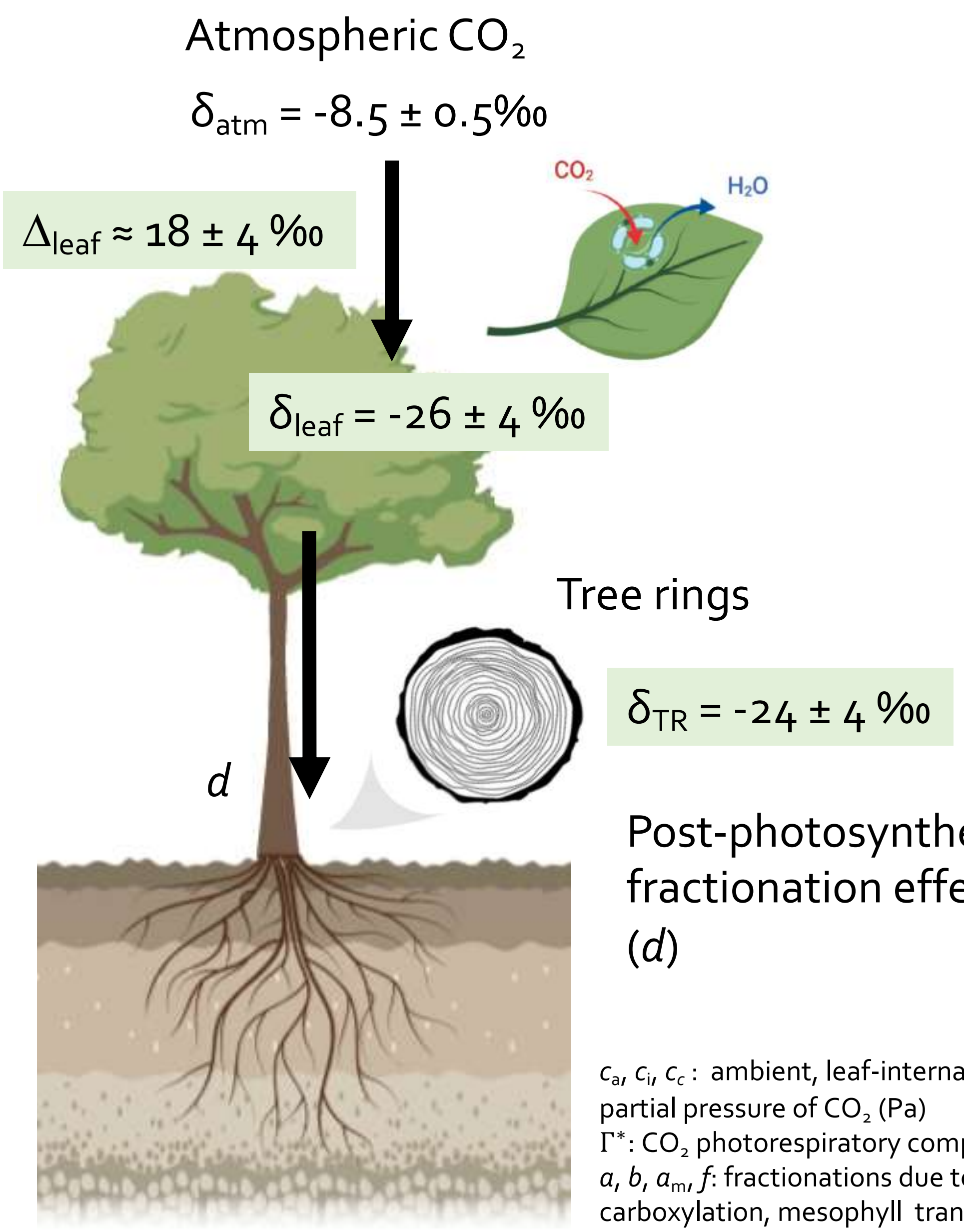
Growing season



Plants assimilate the **heavier $^{13}CO_2$ molecules less readily than $^{12}CO_2$**
→ discrimination against ^{13}C (**$\Delta^{13}C$**)

$$\delta^{13}C_{plant} \approx \delta^{13}C_{atm} - \Delta^{13}C$$

Carbon isotopes: from the atmosphere to the plant



Post-photosynthetic fractionation effects (d)

$$\delta^{13}C_{plant} \approx \delta^{13}C_{atm} - a \overbrace{- (b-a)\boxed{\frac{c_i}{c_a}} \cancel{-a_m \frac{c_i - c_c}{c_a}} \cancel{+f\frac{\Gamma^*}{c_a}}}^{\Delta^{13}C} (-d)$$

Mesophyll effect

Photorespiratory effect

= index of adjustments in stomatal conductance (g_s) and assimilation rate (*A*) to environmental changes

$\delta^{13}C_{plant}$ = *short- to long-term integrated measure* of **stomatal behavior**

→ Key variable for the study of **carbon uptake (*A*)**

→ Provides insight into leaf **water use efficiency (WUE)**

$$iWUE = \frac{A}{g_s} = \frac{c_a}{1.6}\left(1 - \frac{c_i}{c_a}\right)$$

c_a, c_i, c_c : ambient, leaf-internal and chloroplastic partial pressure of CO_2 (Pa)
Γ^*: CO_2 photorespiratory compensation point (Pa)
a, b, a_m, f: fractionations due to CO2 diffusion, carboxylation, mesophyll transfer and photorespiration

Why Modelling Stable Carbon Isotopes in models?

Formulations for $\Delta^{13}C$ already included in some vegetations models:

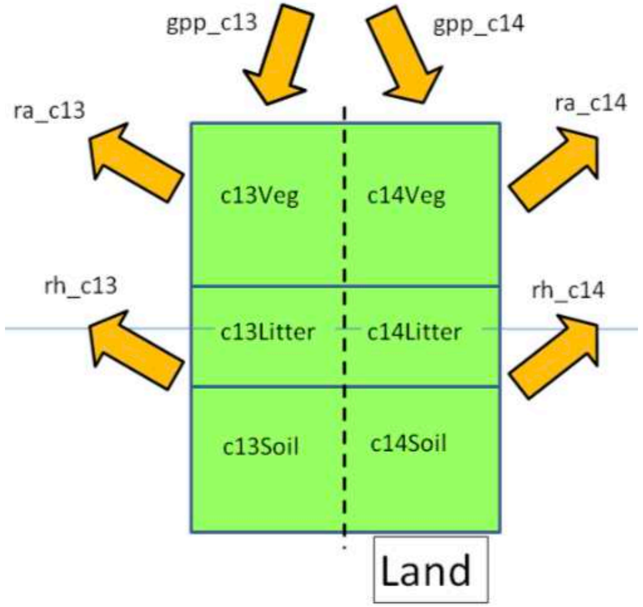
- **CLM4/5** (Saurer et al. 2014 *Glob. Change Biol.*; Raczka et al. 2016 *Biogeosc.*; Duarte et al. 2017 *Biogeosc.*; Keller et al. 2017 *Biogeosc.*)
- **LPX-Bern** (Keller et al. 2017 *Biogeosc.*)
- **LPJ** (Scholze et al. 2003 *Geophys. Res. Lett.*)
- **ORCHIDEE** (Churakova Sidorova et al. 2015 *Dendrochr.*)

To evaluate and help improving the representation of stomatal and photosynthetic behaviour + carbon allocation in vegetation models

But not fully exploited!!

Implementation of carbon isotopes in Earth System Models recommended by the Coupled Model Intercomparison Project Phase 6 (**CMIP6**)

However, only CESM2 model (using CLM5) in CMIP6 actually modelling $\Delta^{13}C$



Jones et al. (2016) *Geosci. Model Dev.*

Implementing Stable Carbon Isotopes in JULES

JULES
Joint UK Land Environment Simulator

Develop a **new isotope modelling capability in JULES model** enabling **novel evaluation of the coupled water and carbon cycles as represented in UKESM**

1. Implement leaf-level $\Delta^{13}C$ and $\delta^{13}C_{plant}$ in JULES

2. Test different assumptions about stomatal and discrimination models using $\Delta^{13}C$ from plant materials (leaves and tree rings)

3. Evaluate implications of these assumptions at the ecosystem scale for predictions of gross primary production (GPP), evapotranspiration (ET) and inherent WUE (IWUE = GPP/G_{sw})

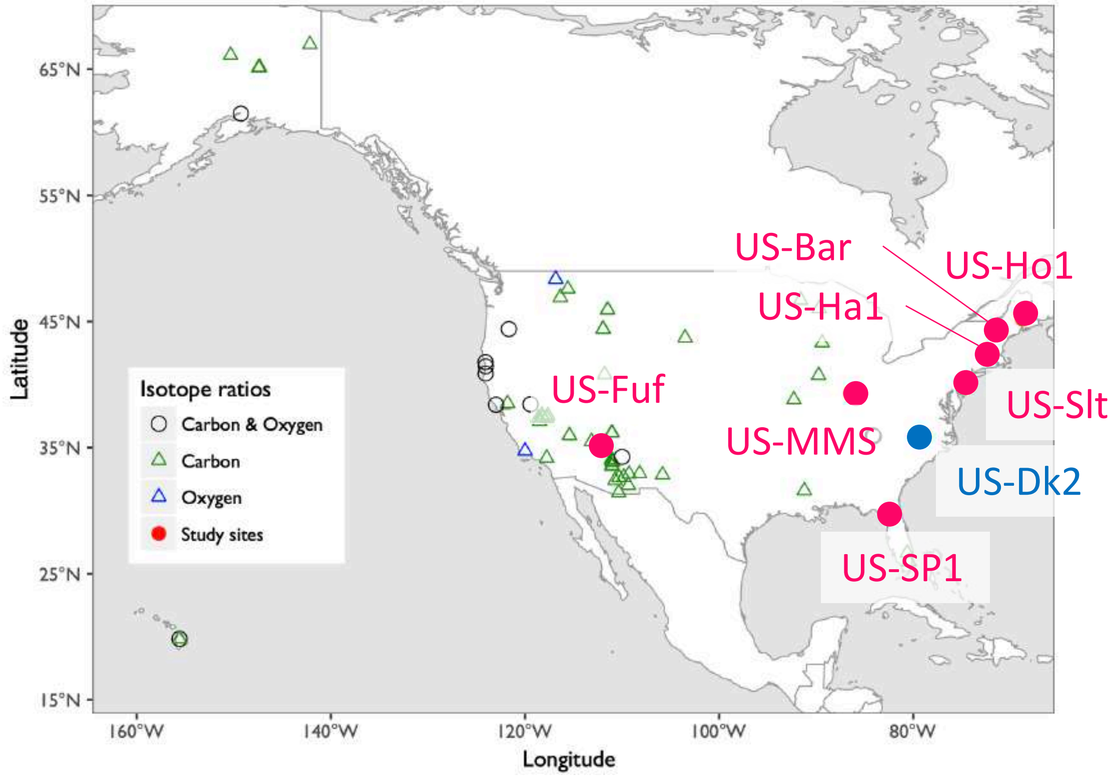
4. Assess whether the observed environmental dependencies of leaf- and ecosystem-WUE are reasonably well predicted by JULES

Eddy-covariance flux (EC-FLUX) stations

with $\delta^{13}C$ measurements from leaves and tree rings in C_3 woody plants → **test the impact of stomatal model on predicted ecosystem carbon and water fluxes**

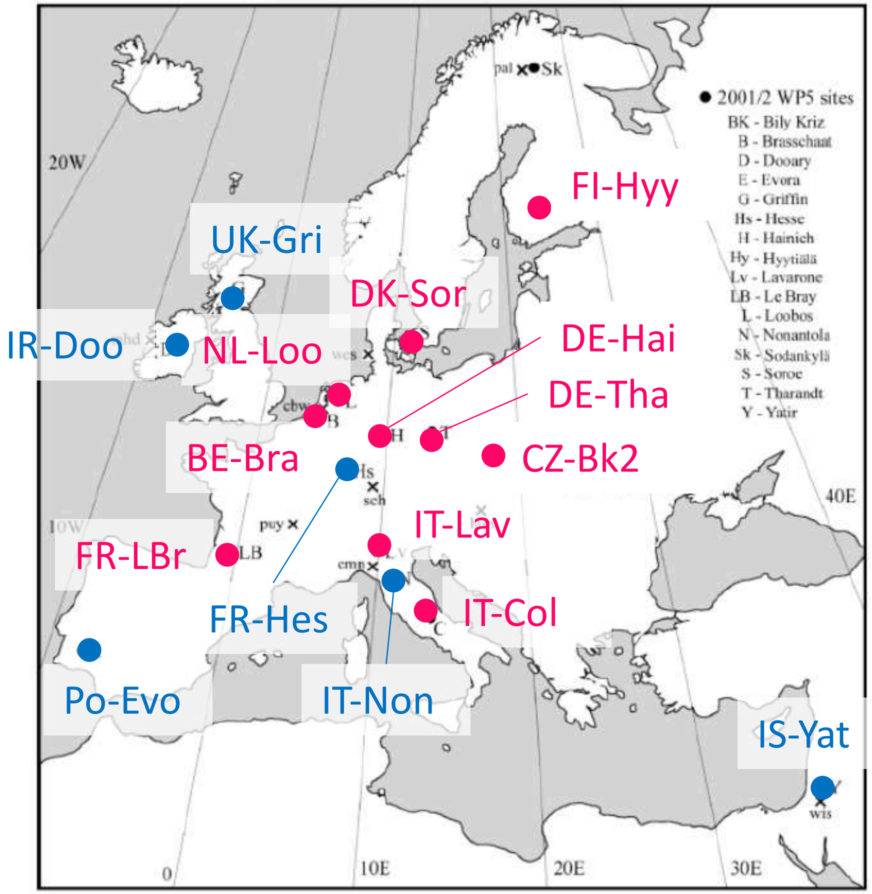
- **AmeriFLUX stations**

Guerrieri et al. (2016) *JGR- Biogeosci.* - leaves
Guerrieri et al. (2019) *PNAS* – tree rings



- **CarboEuroFLUX stations**

Hemming et al. (2005) *GCB* - leaves, stem, root, soil



Old and new JULES capability: discrimination model

Farquhar et al. (1982) *Aust. J. plant. Physiol.*

→ New implementations

$$\Delta^{13}\mathrm{C} = a + (b - a)\frac{c_i}{c_a}$$ **Simple**

$$\boxed{\Delta^{13}\mathrm{C} = a + (b - a)\frac{c_i}{c_a} - f\frac{\Gamma^*}{c_a}}$$ **Photorespiratory effect**

$$\Delta^{13}\mathrm{C} = a\frac{c_a - c_i}{c_a} + b\frac{c_c}{c_a} - f\frac{\Gamma^*}{c_a} + a_m\frac{c_i - c_c}{c_a}$$ **Photorespiratory + mesophyll effects**

→ For this talk, I will only consider the 2nd model with photorespiratory effect

c_a, c_i, c_c : ambient, leaf-internal and chloroplastic partial pressure of CO_2 (Pa)
Γ^*: CO_2 photorespiratory compensation point (Pa)
a, b, a_m, f: fractionations due to CO2 diffusion, carboxylation, mesophyll transfer and photorespiration

Old and new JULES capability: stomatal model

Stomatal conductance for water (g_{sw}) and carbon (g_{sc}) in m s^{-1}:

$$g_{sw} = 1.6\, g_{sc} \approx 1.6\, RT\, \frac{A}{c_a - c_i}$$

- **Jacobs (1994)** ***PhD thesis***

$$\boldsymbol{c_i} = (c_a - \Gamma^*)\, f_0 \left(1 - \frac{dq}{dq_{crit}}\right) + \Gamma^*$$

- **Medlyn et al. (2011)** ***Glob. Change Biol.***

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

→ original model in JULES
Clark et al. (2011) *Geosci. Model Dev.*
Best et al. (2011) *Geosci. Model Dev.*

→ recently incorporated into JULES (vn5.5) Oliver et al. (2018) *Biogeosci.*

- **Leuning (1995)** ***Plant Cell & Env.***

$$\boldsymbol{c_i} = c_a - \frac{(c_a - \Gamma^*)}{g_1}\left(1 + \frac{D}{D_0}\right)$$

- **Prentice et al. (2014)** ***Ecol. Lett.***

$$\boldsymbol{c_i} = (c_a - \Gamma^*)\, \frac{\xi}{\xi + \sqrt{D}} + \Gamma^*$$

$$\xi = \sqrt{\left(\beta\, \frac{(K + \Gamma^*)}{1.6}\right)}$$

→ New implementations

JULES configurations

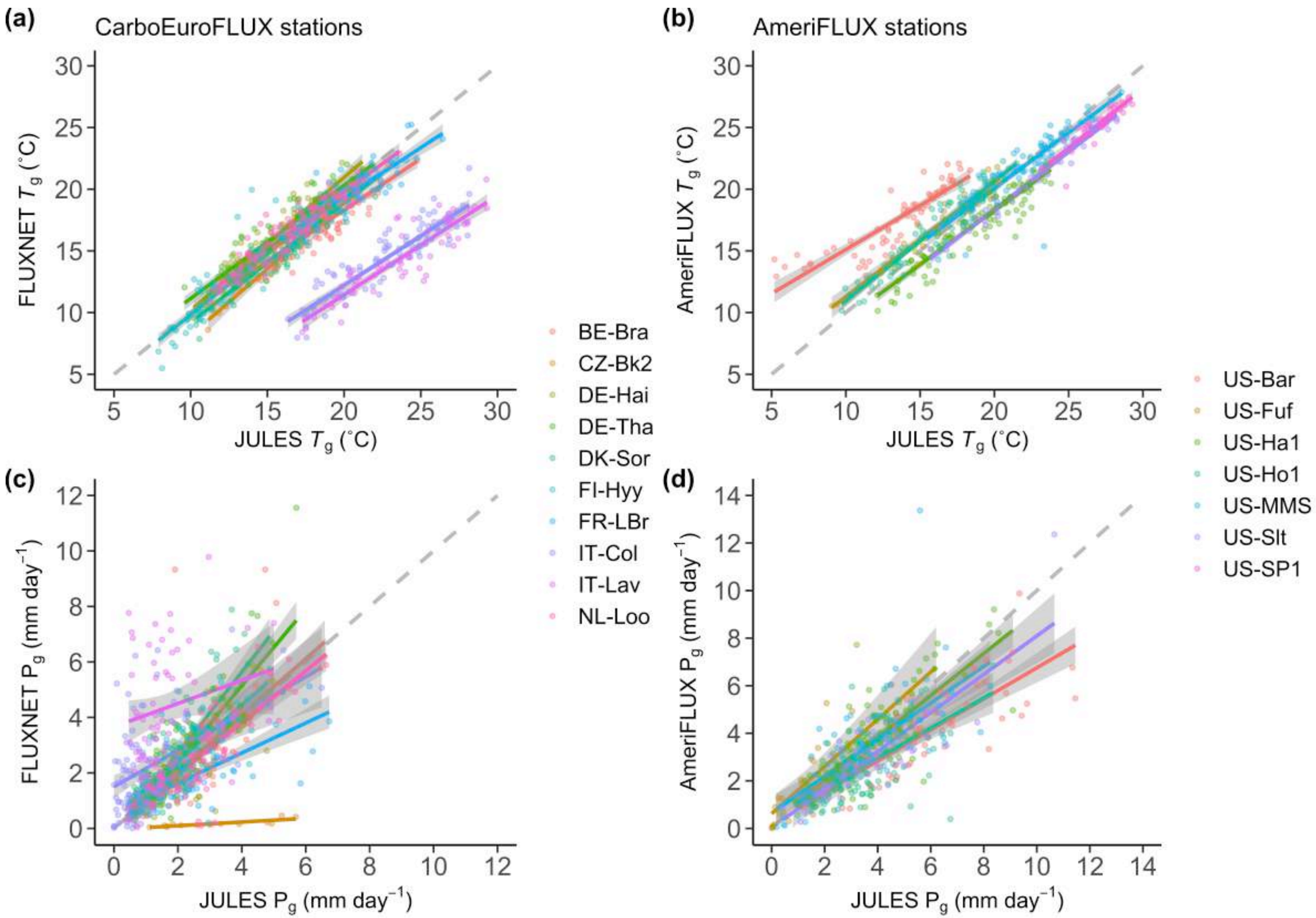
Modified JULES vn5.6 running in stand-alone on NERC JASMIN platform: **Rose suite u-bu518**

Model run at the grid scale with:
- WFDEI climate: 0.5 x 0.5 spatial resolution over 1979-2016
- Atmospheric CO_2 concentrations and $\delta^{13}CO2$ data: annual averages from NOAA ESRL and Graven et al. (2017) *Geosc. Mod. Dev.*

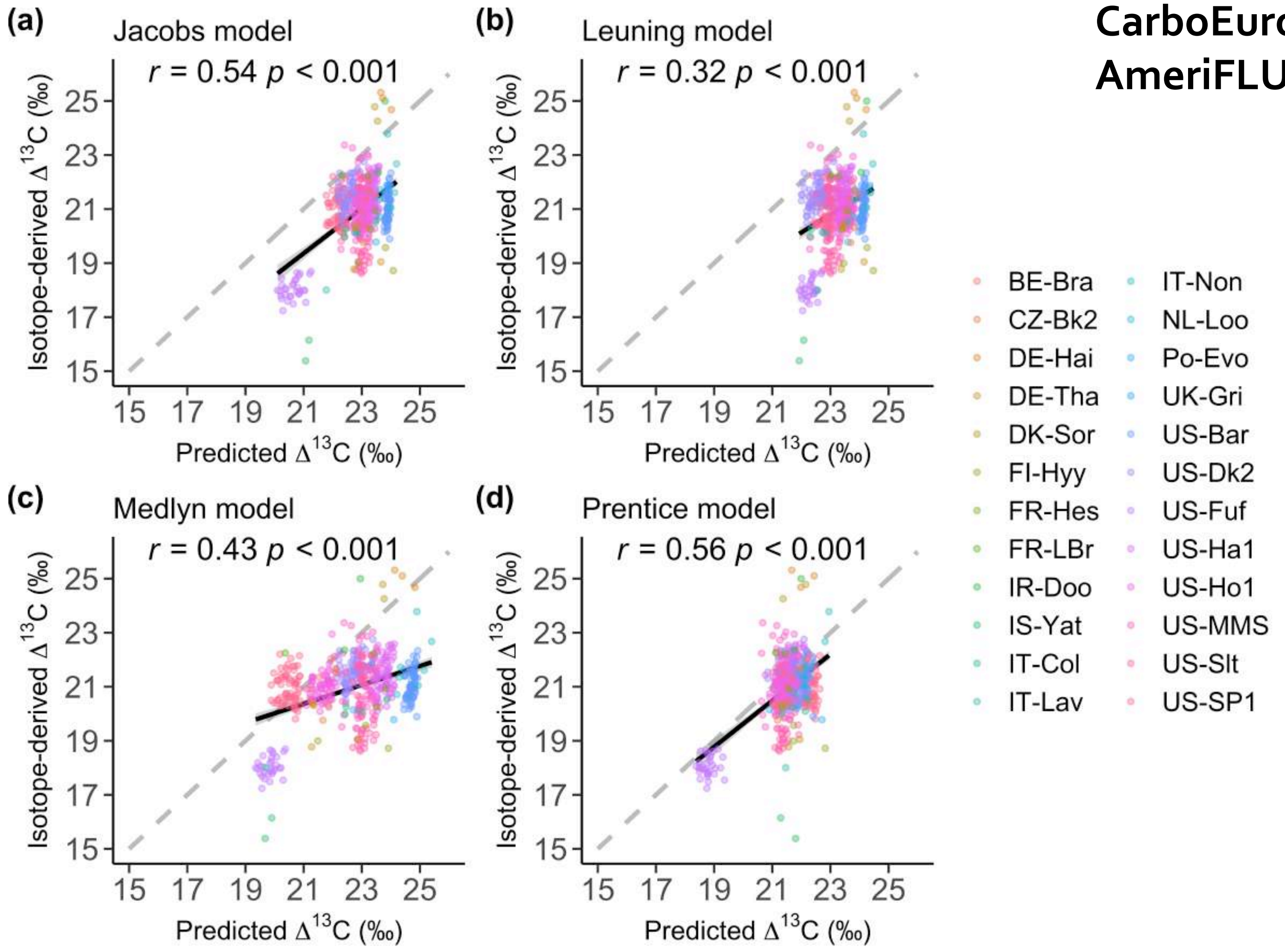
9 PFTs

- Farquhar et al. (1980) *Planta* photosynthesis model
- Phenology model: 10 days
- 14 soil layers
- 10 canopy layers

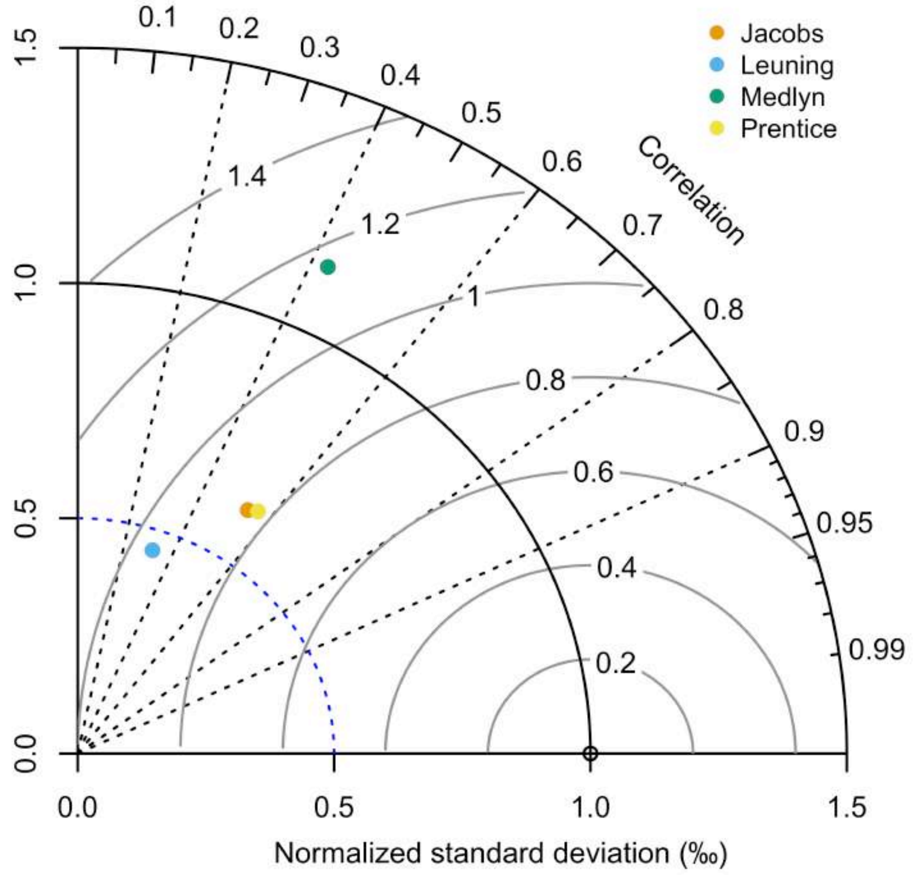
Spin up: max 3 cycles of 20 years



EC-FLUX stations: observed vs predicted Δ13C

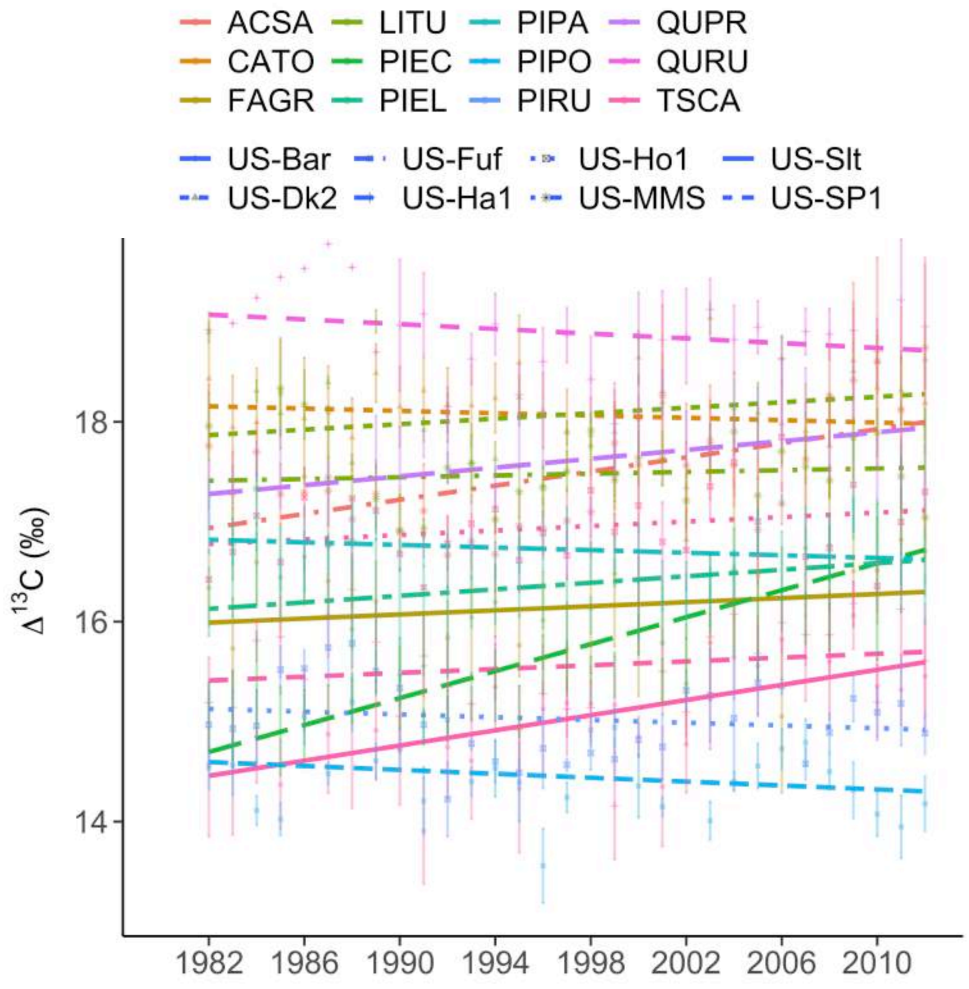


CarboEuroFLUX + AmeriFLUX stations

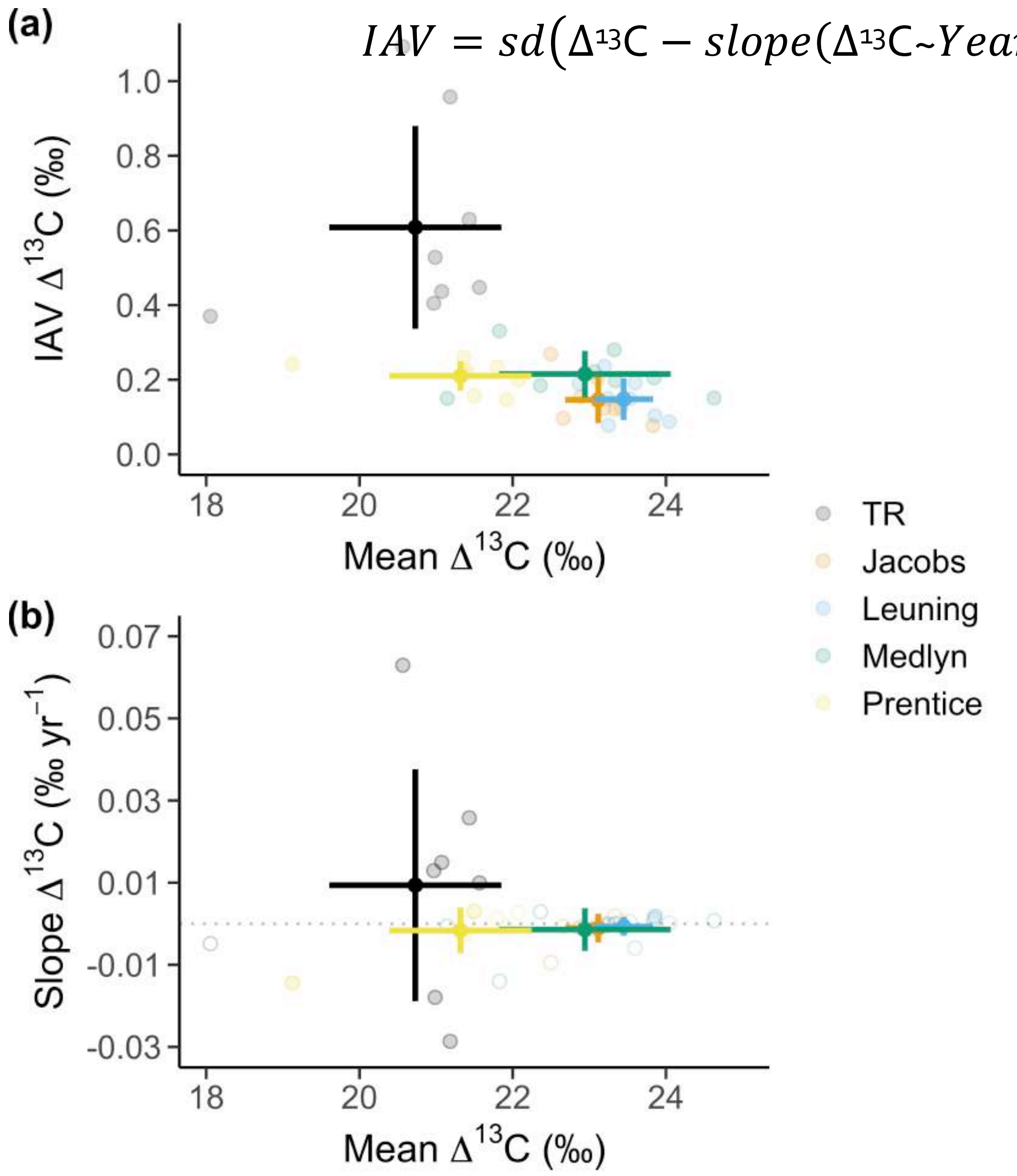


EC-FLUX stations: observed vs predicted Δ13C

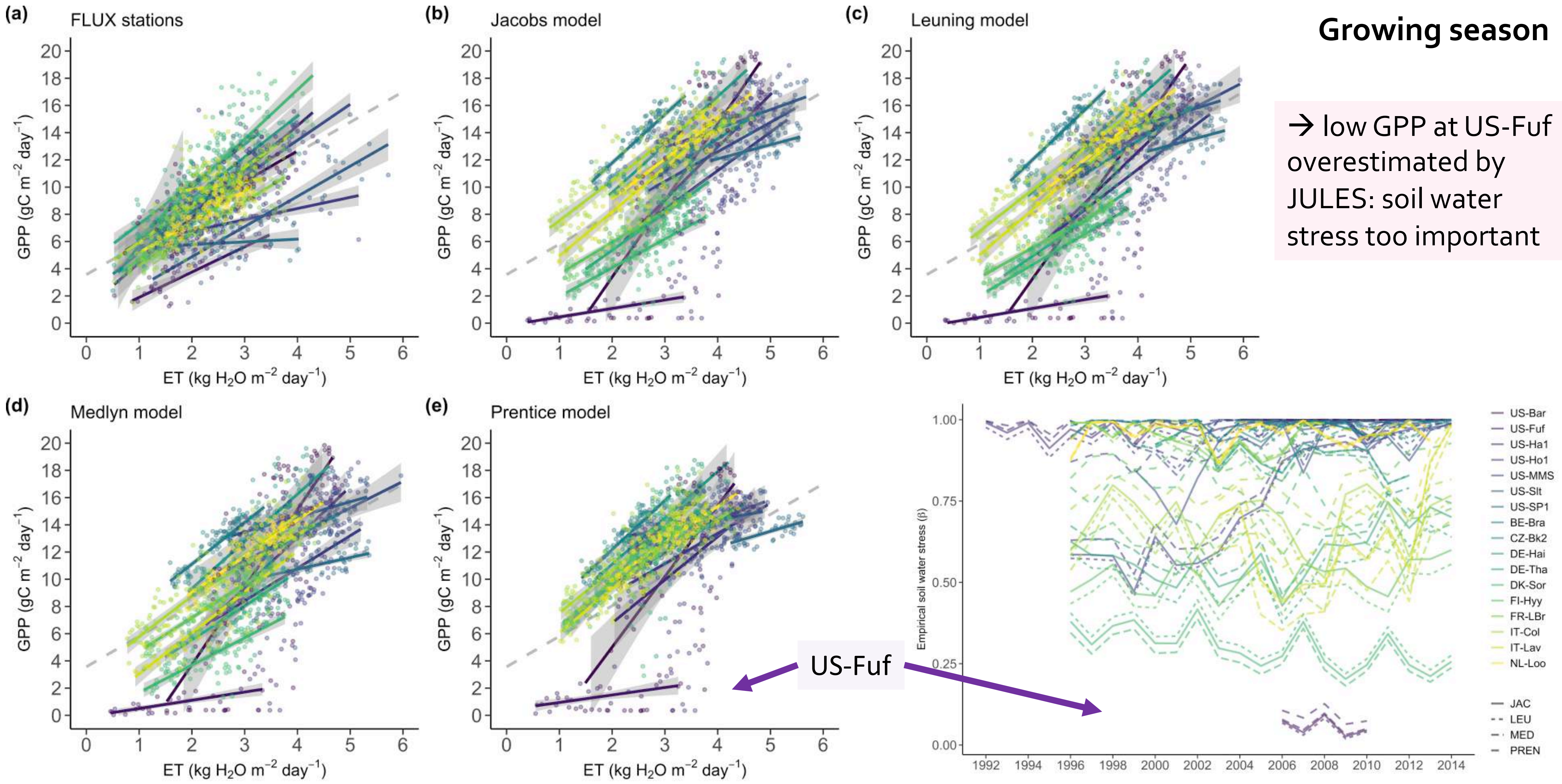
Tree-ring Δ13C timeseries at AmeriFLUX stations



$IAV = sd(\Delta^{13}C - slope(\Delta^{13}C \sim Year))$



EC-FLUX stations: observed/predicted GPP vs ET

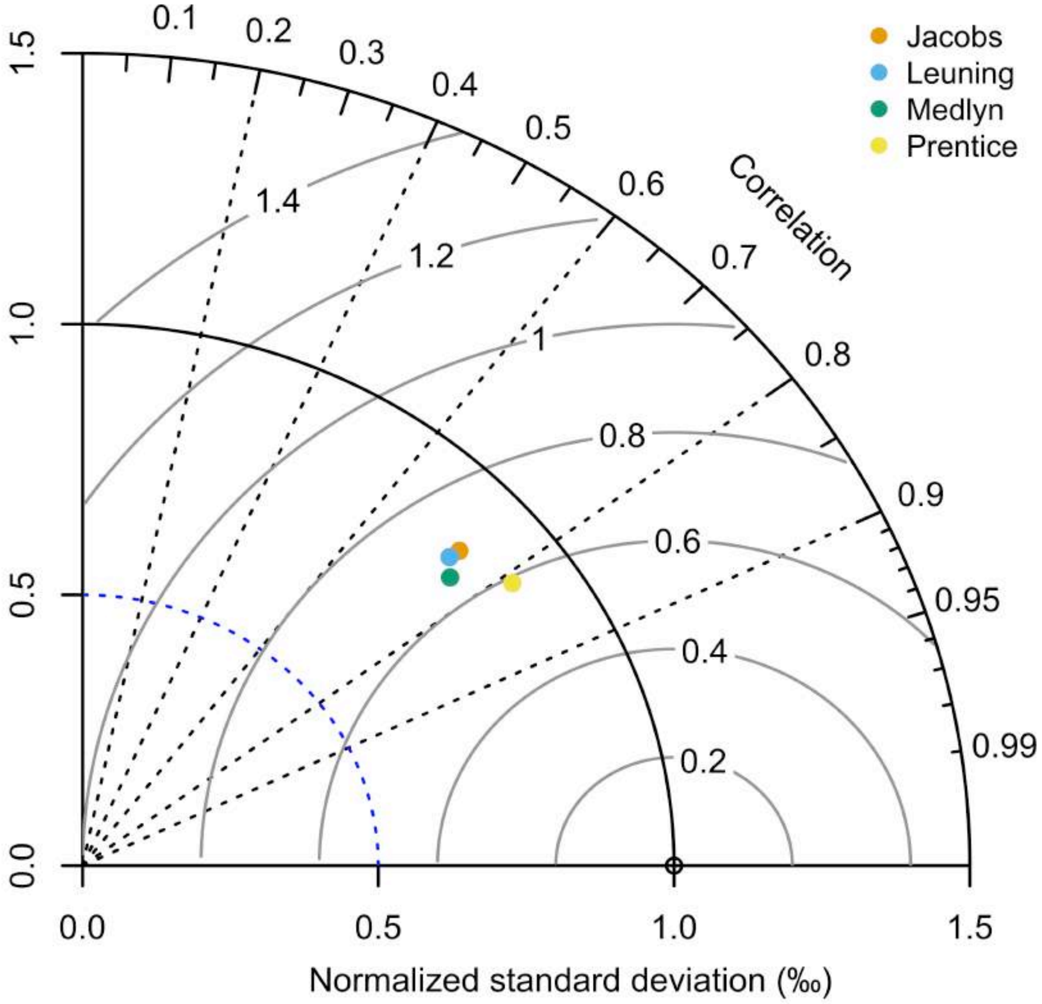


Growing season

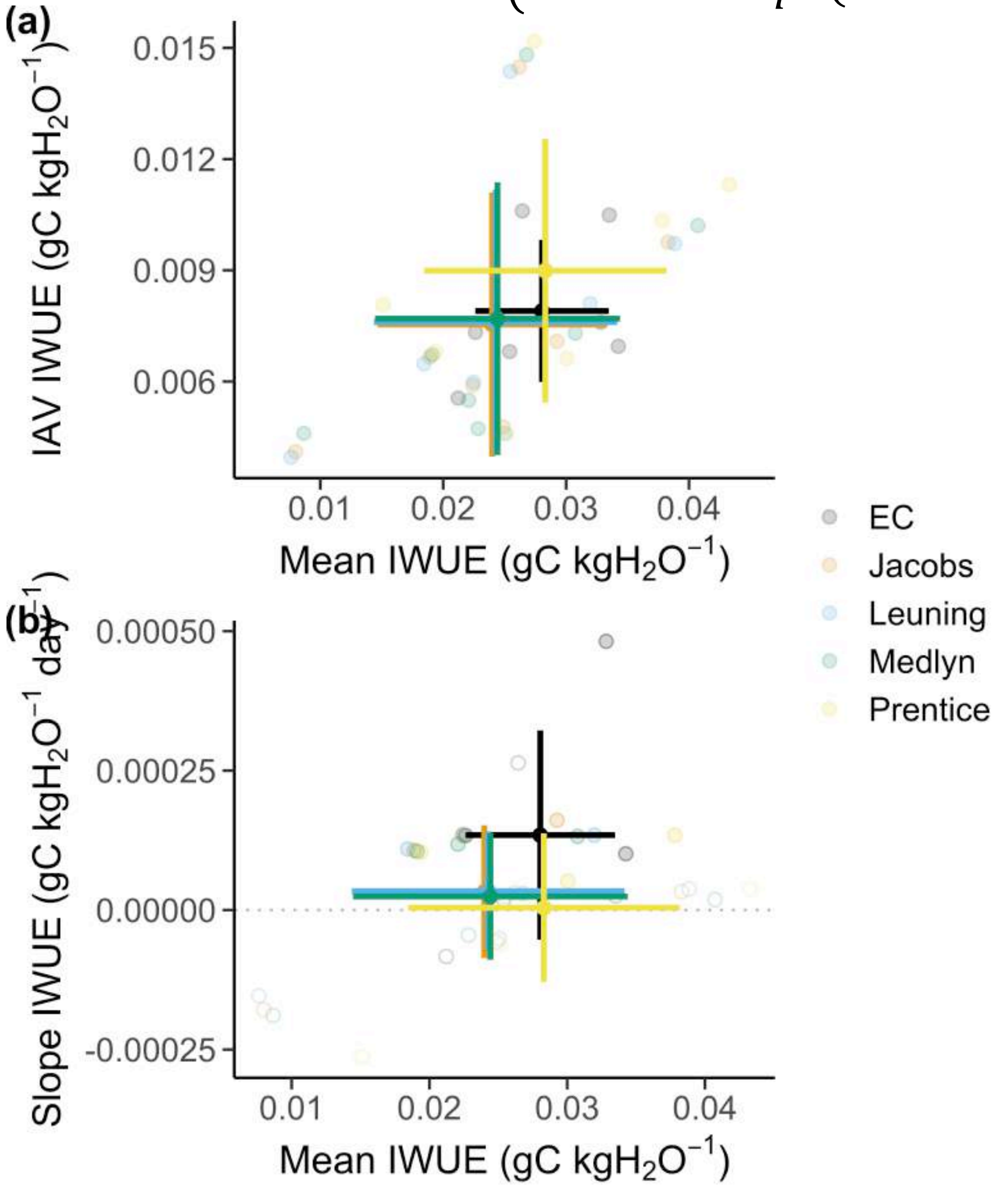
→ low GPP at US-Fuf overestimated by JULES: soil water stress too important

EC-FLUX stations: observed vs predicted WUE

IWUE = GPP/G_{sw} ≈ GPP/ET*VPD/P_{atm}



$$IAV = sd\big(IWUE - slope(IWUE \sim Year)\big)$$

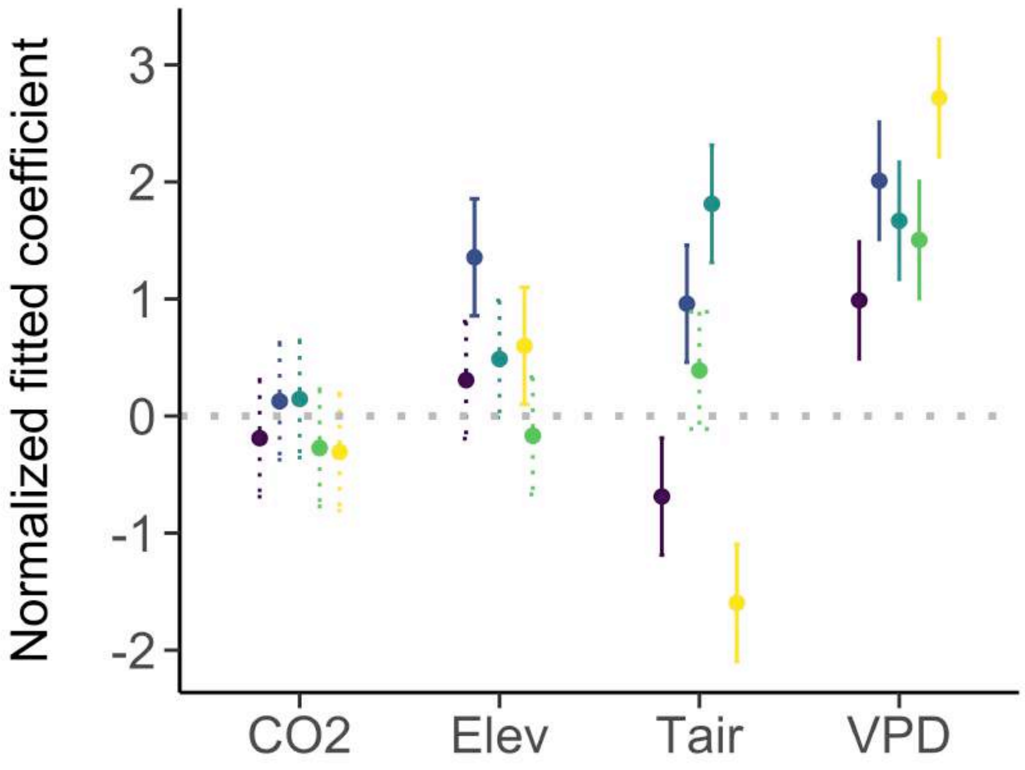


EC-FLUX stations: relative environmental dependencies

Growing season

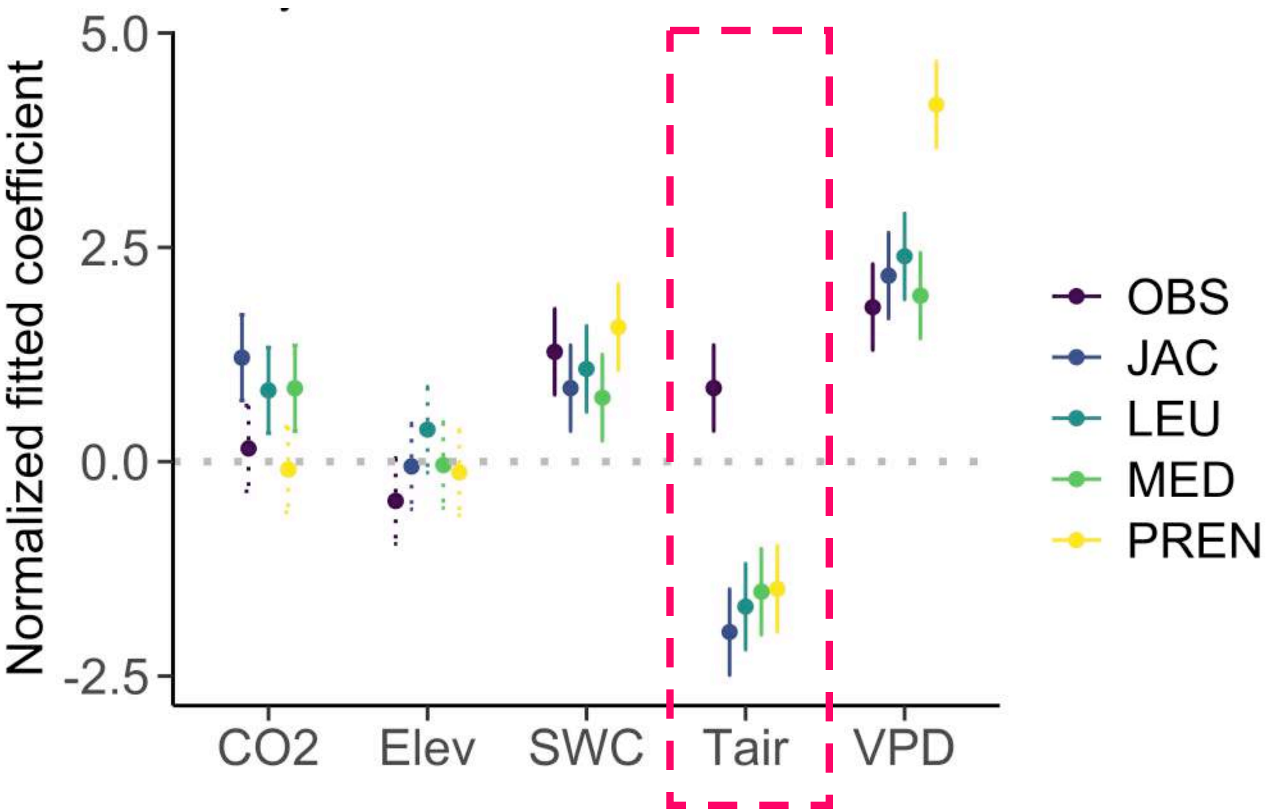
Leaf-level

iWUE = A/g_{sw} = $c_a/1.6*(1-c_i/c_a)$



Ecosystem-level

IWUE = $GPP/G_{sw} \approx GPP/ET*VPD/P_{atm}$



→ High T_{air} decreases leaf iWUE but increases ecosystem IWUE: not reproduced by JULES

Conclusions

- At leaf scale, **Prentice and Jacobs models** better predicting $\Delta^{13}C$ as inferred from plant materials of C_3 woody plants
- Observed $\Delta^{13}C$ increases, but predicted $\Delta^{13}C$ stay constant

- At the ecosystem scale, IWUE better predicted by **Prentice model**
- Observed IWUE increases, but predicted IWUE stay constant

- Predictive skills of JULES at leaf and ecosystem-scales vary across sites
- **Not all** environmental dependencies accurately predicted by JULES

Model limitations:
- Temporal resolution of dataset: only a few years!
- No post-photosynthetic isotopic fractionation and carbon allocation effect on $\delta^{13}C$ included in JULES yet!!

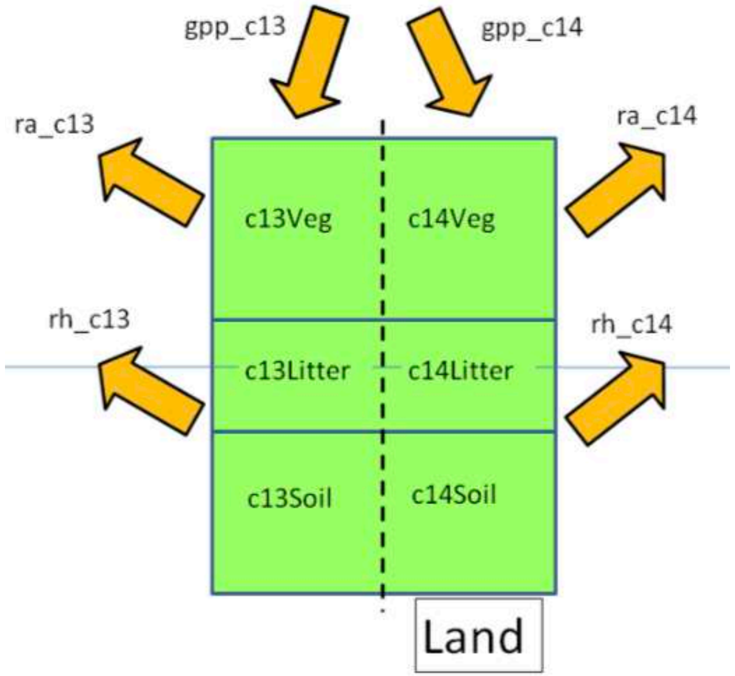
Future work

Implementing carbon fluxes (CF) and stocks (CS) of ^{13}C and ^{12}C in different carbon pools:

as recommended by CMIP6

$$CF_{13C} = \begin{cases} CF_{totC}\dfrac{CS_{13C}}{CS_{totC}} f_{frac} & for\ CS_{totC} \neq 0 \\ 0 & for\ CS_{totC} = 0 \end{cases}$$

- if $f_{frac} = 1$ (no fractionation), CF_{13C} and CF_{totC} simple proportion to CS_{13C} and CS_{totC}
- if $f_{frac} < 1$, discrimination against the heavier isotope (^{13}C)
- if $f_{frac} > 1$, preference for heavier isotope



Jones et al. (2016)
Geosci. Model Dev.