Physiology-based modelling of productivity and tree growth

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The least-cost hypothesis

- Plants mimimize the **sum of the unit costs** of maintaining transpiration (E) and carboxylation (V_{cmax}) capacities

- Costs are **maintenance respiration rates** per unit assimilation:
    - (*a*) active conducting tissue,
    - (*b*) Rubisco and other proteins involved in photosynthesis.

See: Wright et al. (2004) Am Nat; Prentice et al. (2014) Ecol Letters

The co-ordination hypothesis

- The Rubisco-limited and electron-transported limited **rates of photosynthesis are equal** under average daytime conditions

  - Prediction: optimal photosynthetic capacities (V_{cmax}, J_{max}) for any given environment.
  - Acclimation of V_{cmax} and J_{max} (in space and time).

See: Haxeltine & Prentice (1996) Func Ecol; Maire et al. (2012) PLOS One

P model: a universal model for GPP

A_J = assimilation rate (GPP)
I_{abs} = absorbed light

$$A_J = \varphi_0 I_{abs} m \sqrt{1 - \left(\frac{c^*}{m}\right)^{\frac{2}{3}}}$$

where

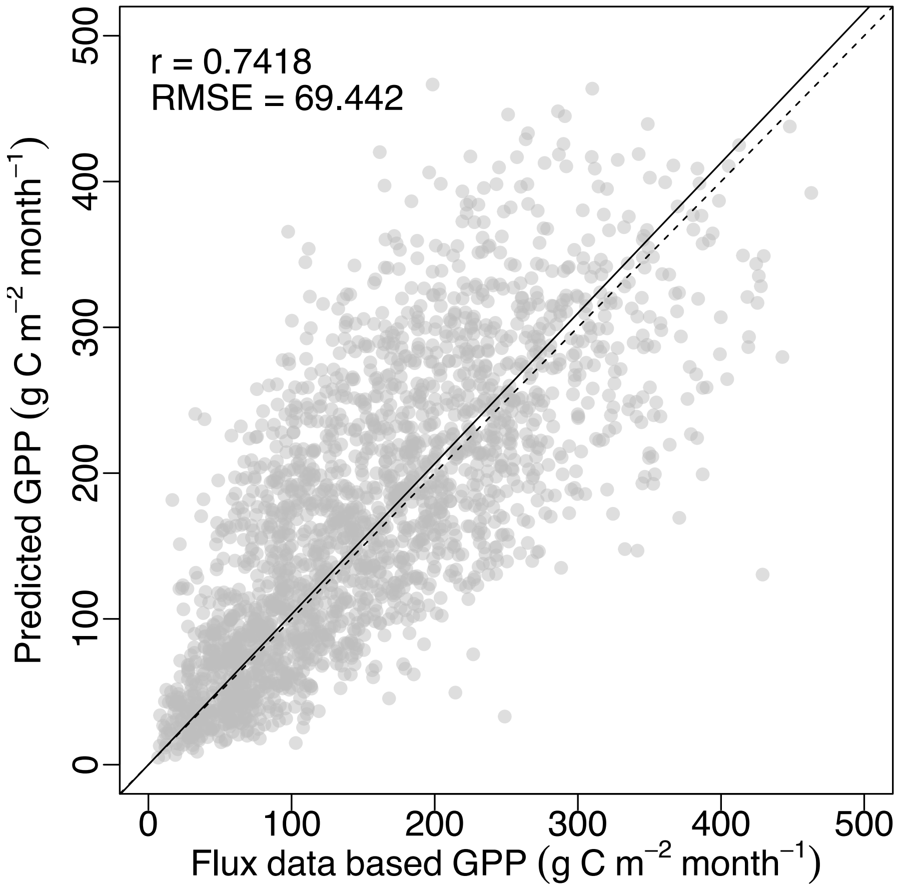
$$m = \frac{c_a - \Gamma^*}{c_a + 2\Gamma^* + 3\Gamma^* \sqrt{\frac{1.6 D \eta^*}{\beta\left(K + \Gamma^*\right)}}}$$

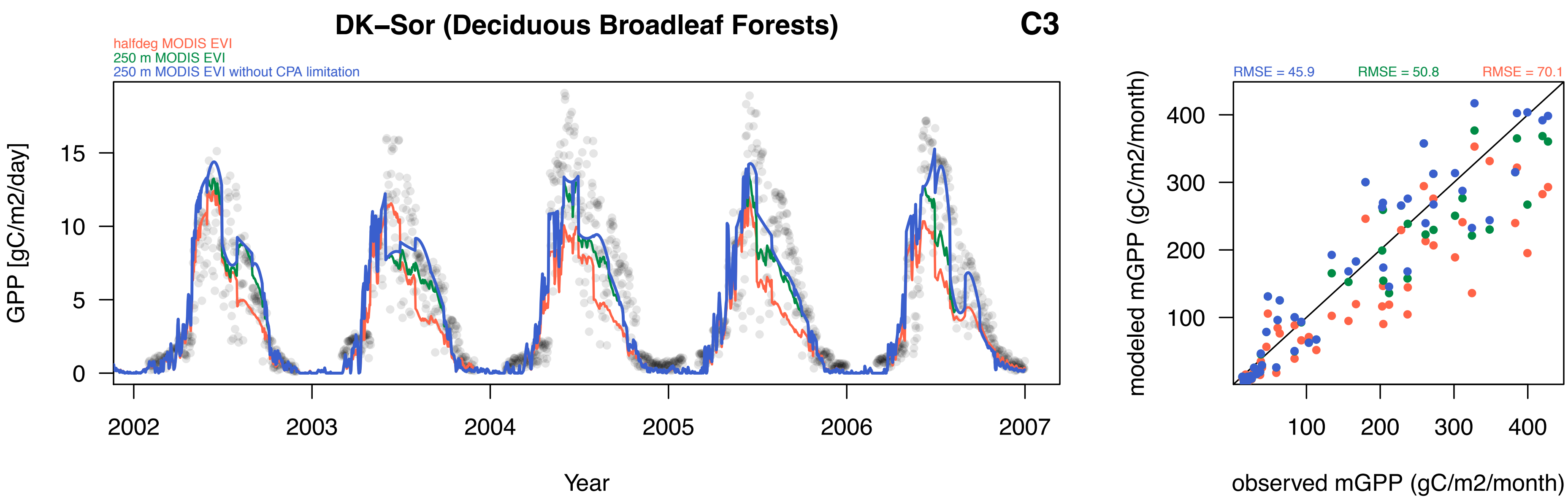
and

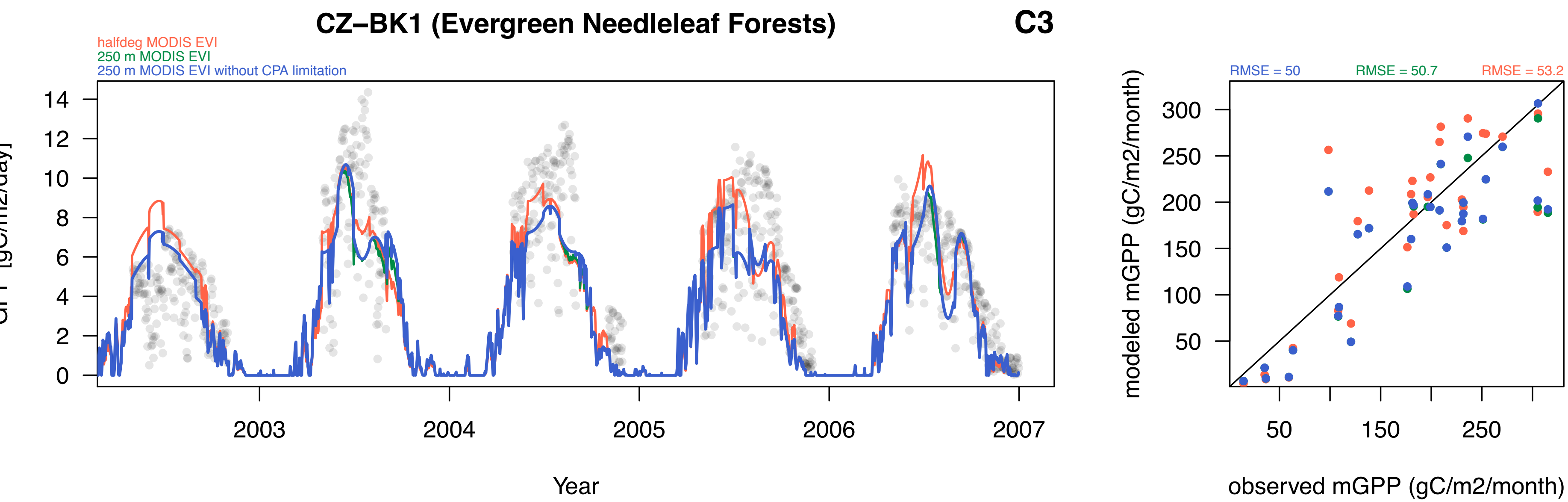
Γ^* = CO_2 compensation point (in absence of drak respiration)

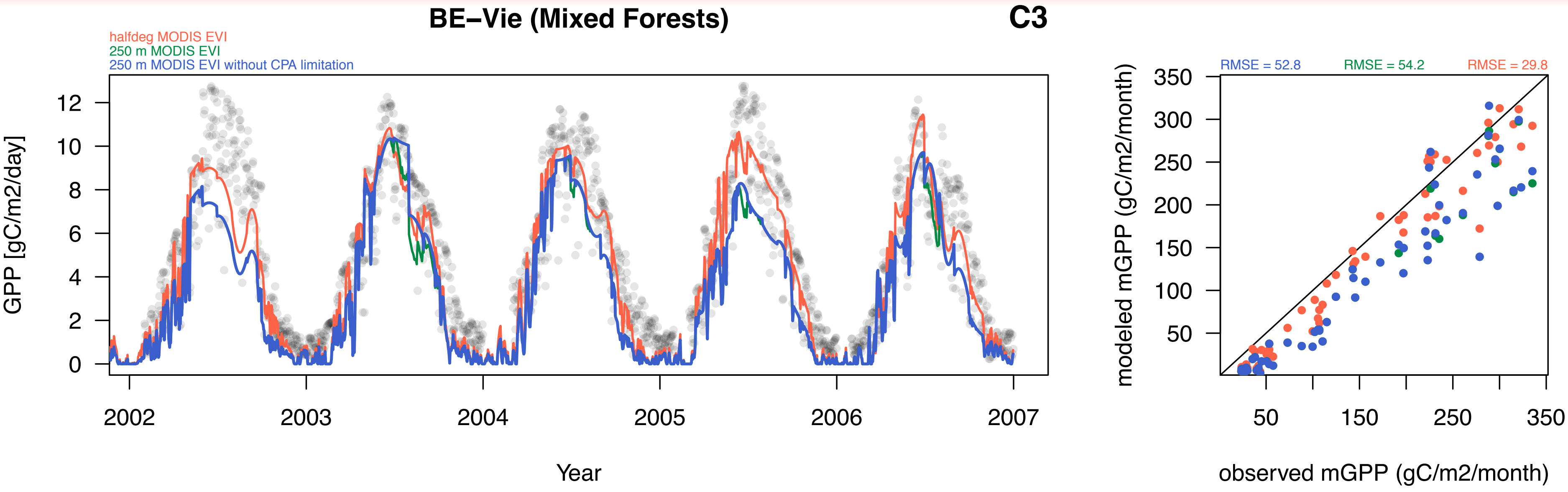
φ_0 = intrinsic quantum efficiency of photosynthesis= 0.085
c^* = cost factor for electron transport capacity = 0.41
β = b/a = ratio of cost factors for carboxylation and water transport =146

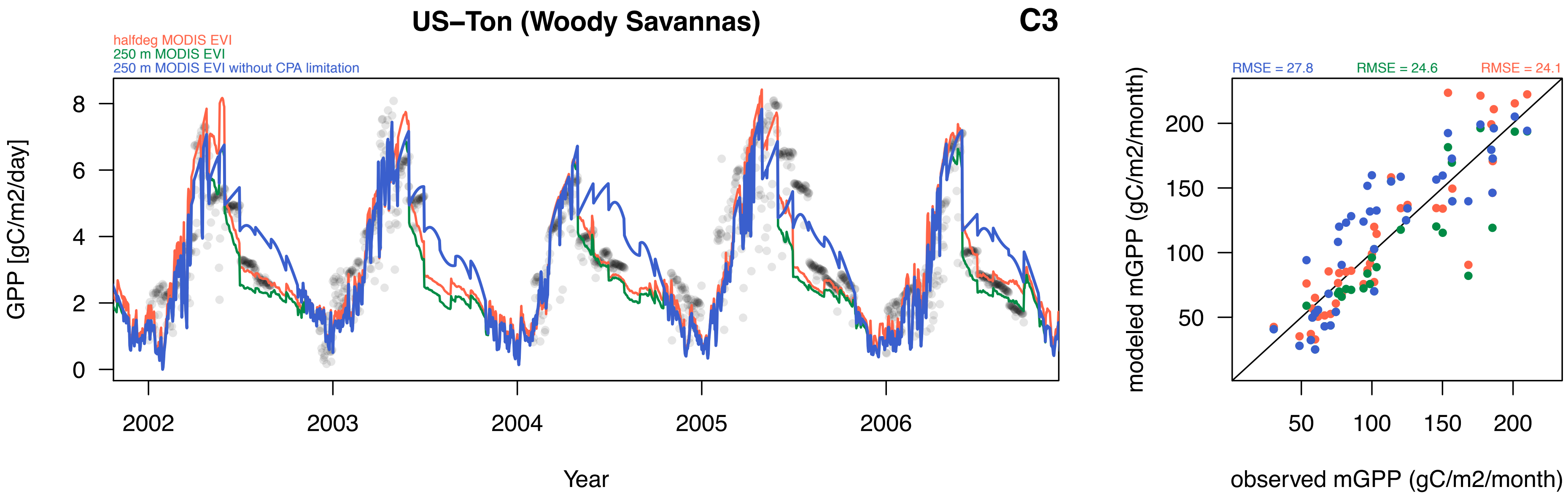
Global data-model comparison of monthly GPP

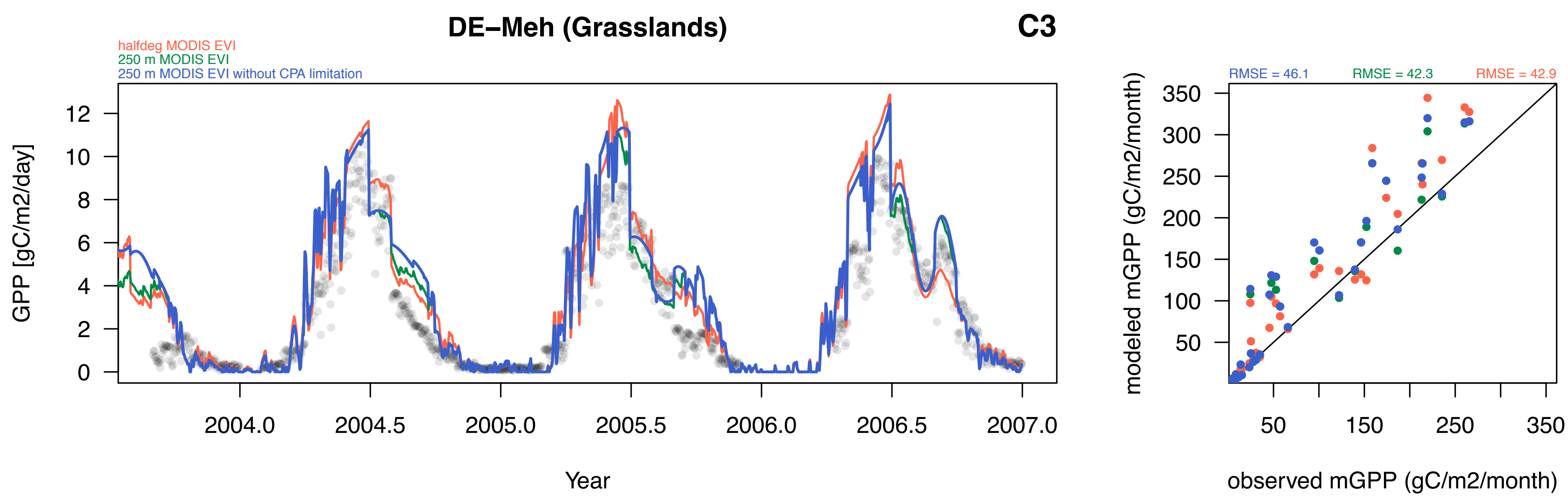



DK–Sor (Deciduous Broadleaf Forests)
C3
halfdeg MODIS EVI
250 m MODIS EVI
250 m MODIS EVI without CPA limitation
GPP [gC/m2/day]
0
5
10
15
2002
2003
2004
2005
2006
2007
Year
RMSE = 45.9
RMSE = 50.8
RMSE = 70.1
modeled mGPP (gC/m2/month)
100
200
300
400
observed mGPP (gC/m2/month)

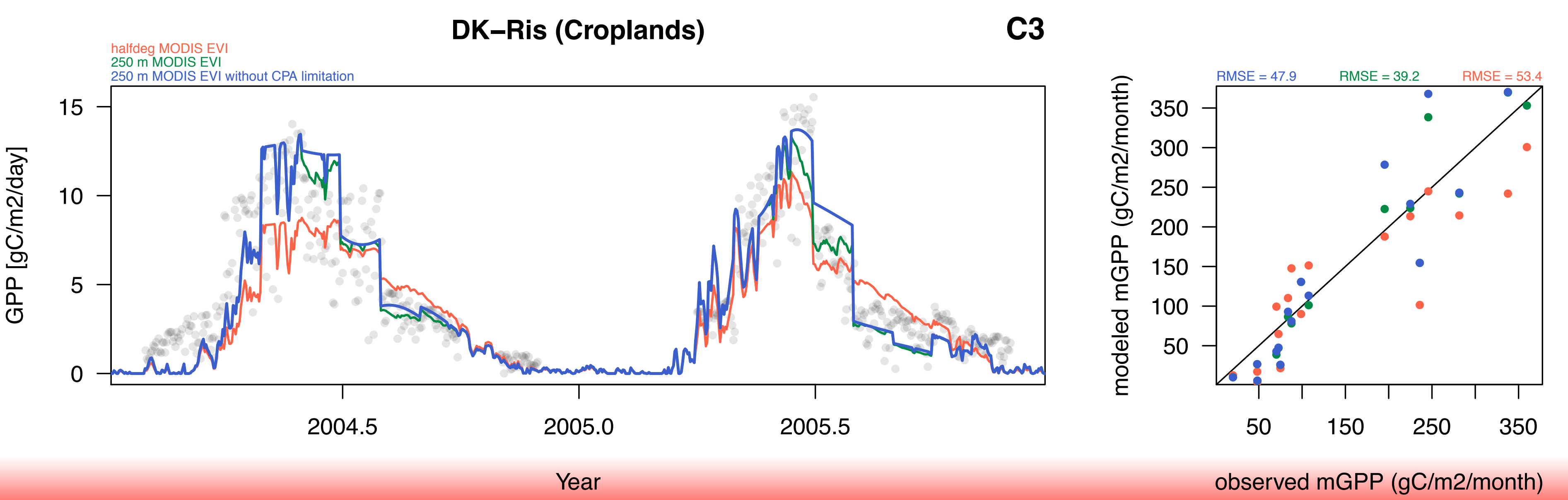

CZ–BK1 (Evergreen Needleleaf Forests)
C3
halfdeg MODIS EVI
250 m MODIS EVI
250 m MODIS EVI without CPA limitation
0
2
4
6
8
10
12
14
2003
2004
2005
2006
2007
Year
RMSE = 50
RMSE = 50.7
RMSE = 53.2
modeled mGPP (gC/m2/month)
50
100
150
200
250
300
observed mGPP (gC/m2/month)


BE−Vie (Mixed Forests)
C3
halfdeg MODIS EVI
250 m MODIS EVI
250 m MODIS EVI without CPA limitation
GPP [gC/m2/day]
Year
RMSE = 52.8
RMSE = 54.2
RMSE = 29.8
modeled mGPP (gC/m2/month)
observed mGPP (gC/m2/month)


US−Ton (Woody Savannas)
C3
halfdeg MODIS EVI
250 m MODIS EVI
250 m MODIS EVI without CPA limitation
GPP [gC/m2/day]
Year
RMSE = 27.8
RMSE = 24.6
RMSE = 24.1
modeled mGPP (gC/m2/month)
observed mGPP (gC/m2/month)

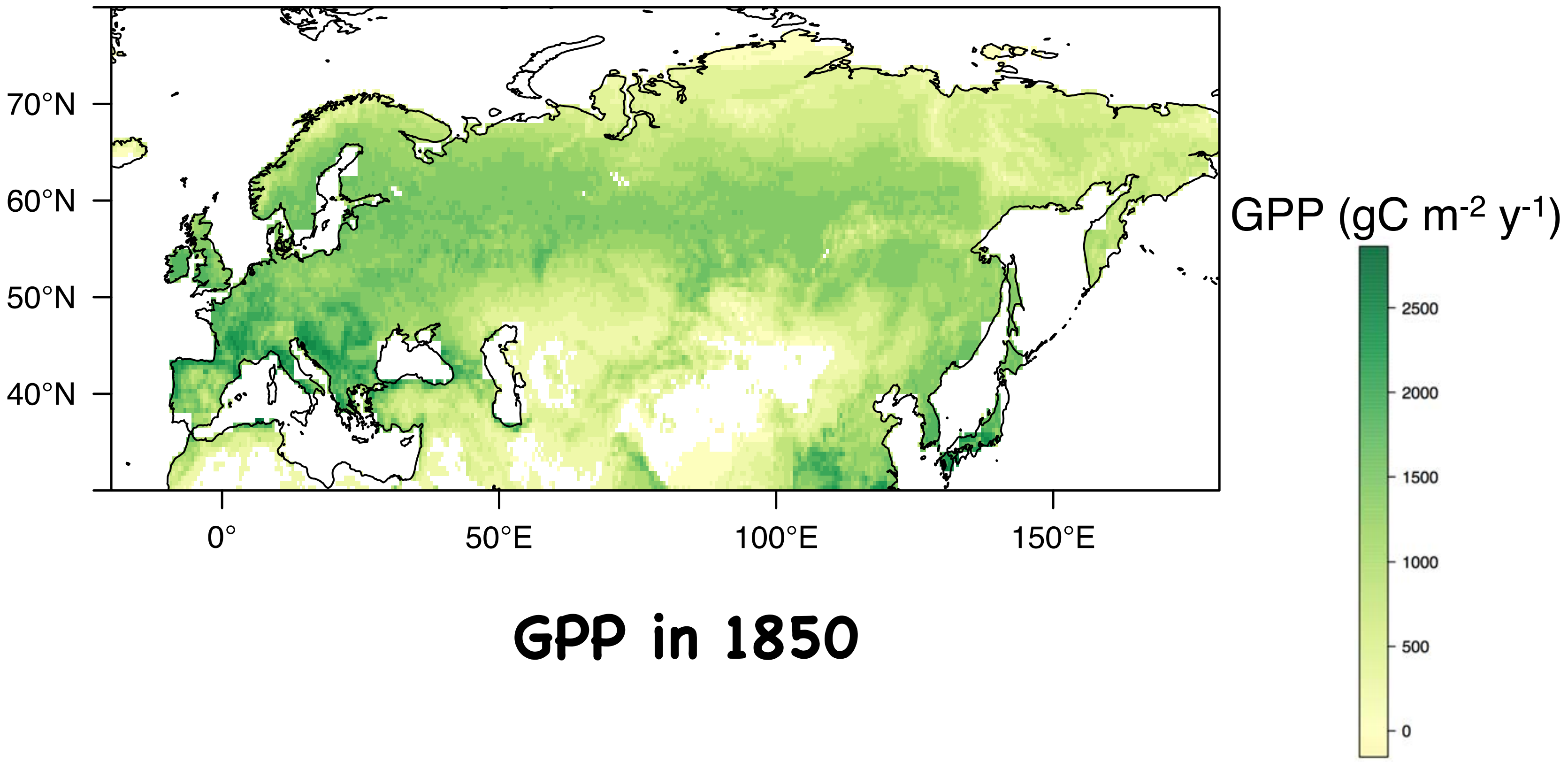


DE–Meh (Grasslands)
C3
halfdeg MODIS EVI
250 m MODIS EVI
250 m MODIS EVI without CPA limitation
GPP [gC/m2/day]
0
2
4
6
8
10
12
2004.0
2004.5
2005.0
2005.5
2006.0
2006.5
2007.0
Year
RMSE = 46.1
RMSE = 42.3
RMSE = 42.9
modeled mGPP (gC/m2/month)
50
100
150
200
250
300
350
observed mGPP (gC/m2/month)



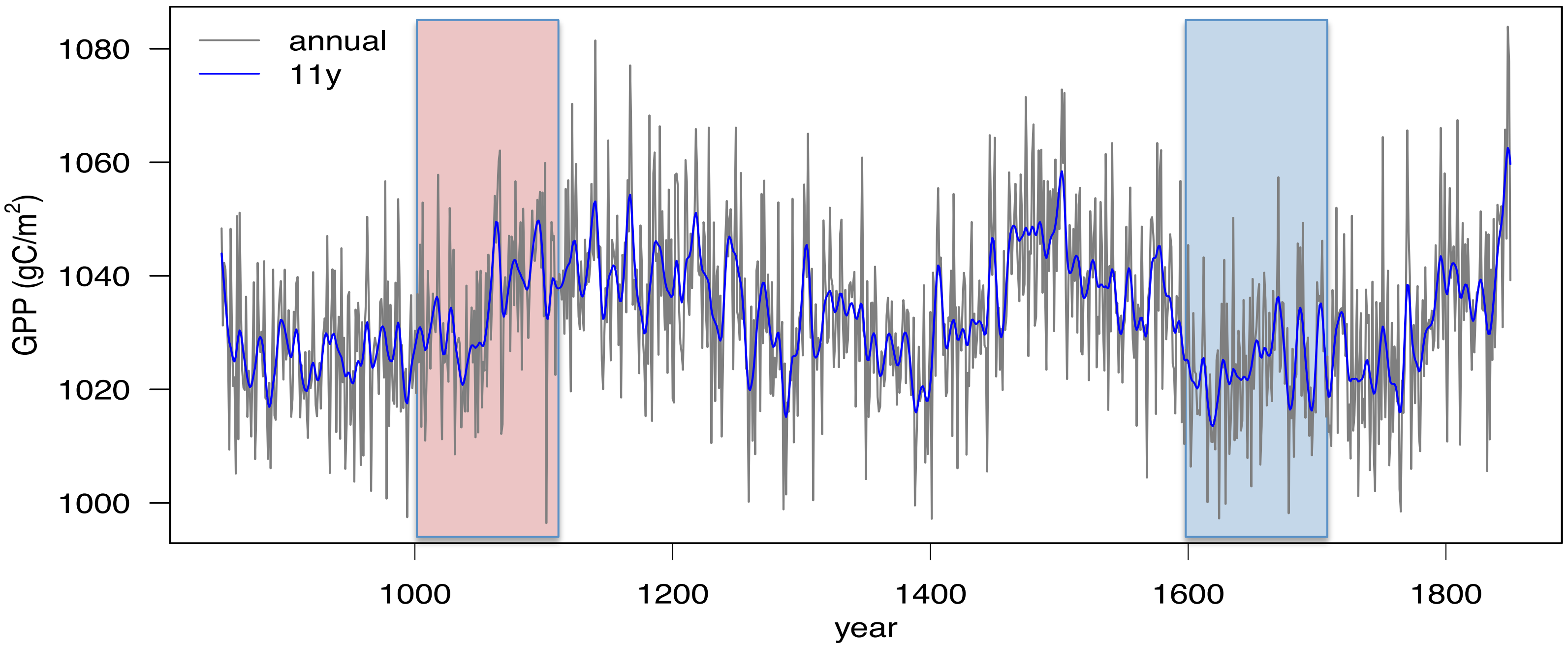
DK–Ris (Croplands)
C3
halfdeg MODIS EVI
250 m MODIS EVI
250 m MODIS EVI without CPA limitation
GPP [gC/m2/day]
0
5
10
15
2004.5
2005.0
2005.5
Year
RMSE = 47.9
RMSE = 39.2
RMSE = 53.4
modeled mGPP (gC/m2/month)
50
100
150
200
250
300
350
observed mGPP (gC/m2/month)

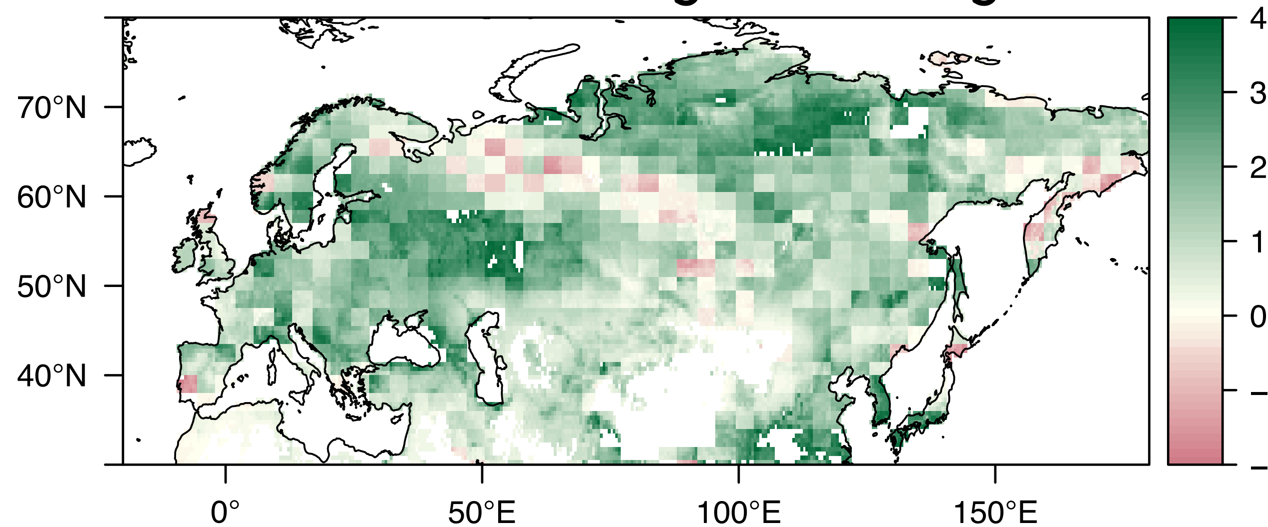
LM productivity changes



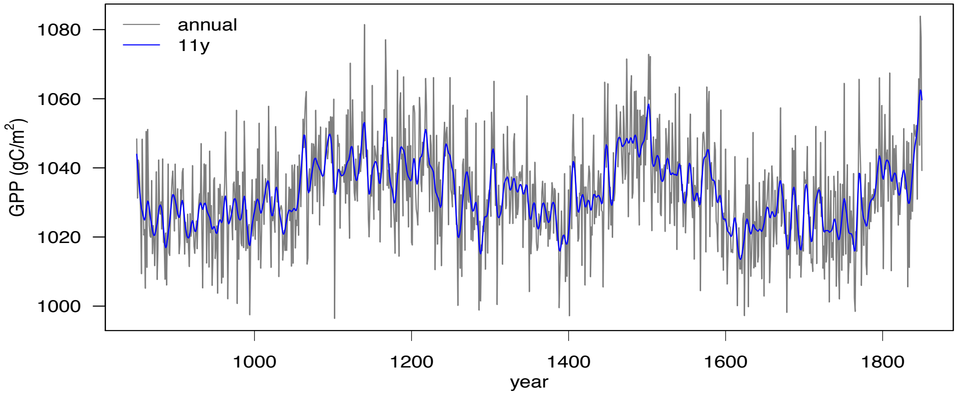
GPP in 1850

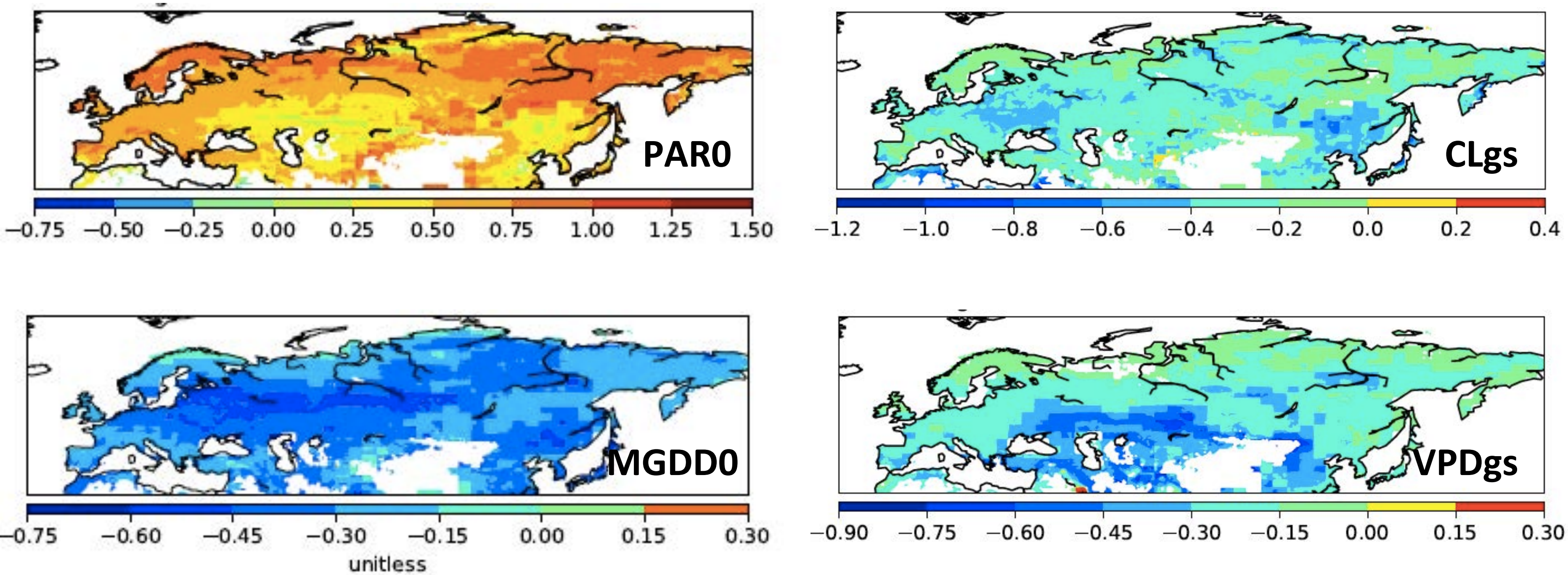
IPSL-CM5A-LR past1000



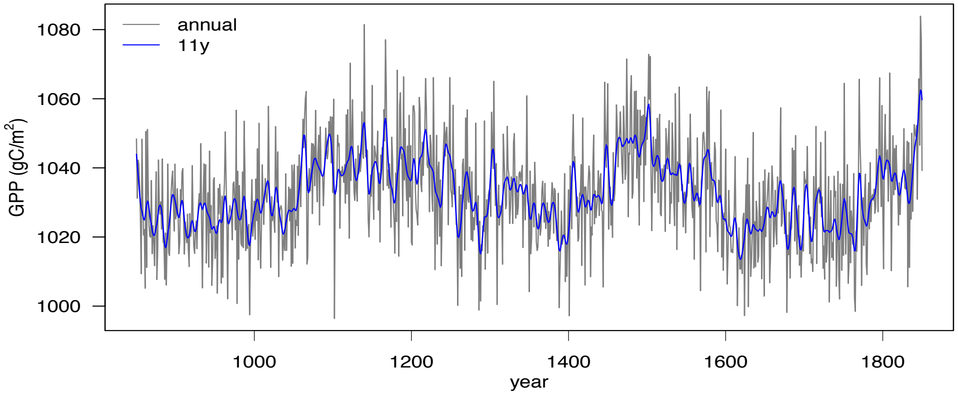


MWA-LIA change in GPP (gC m^{-2})

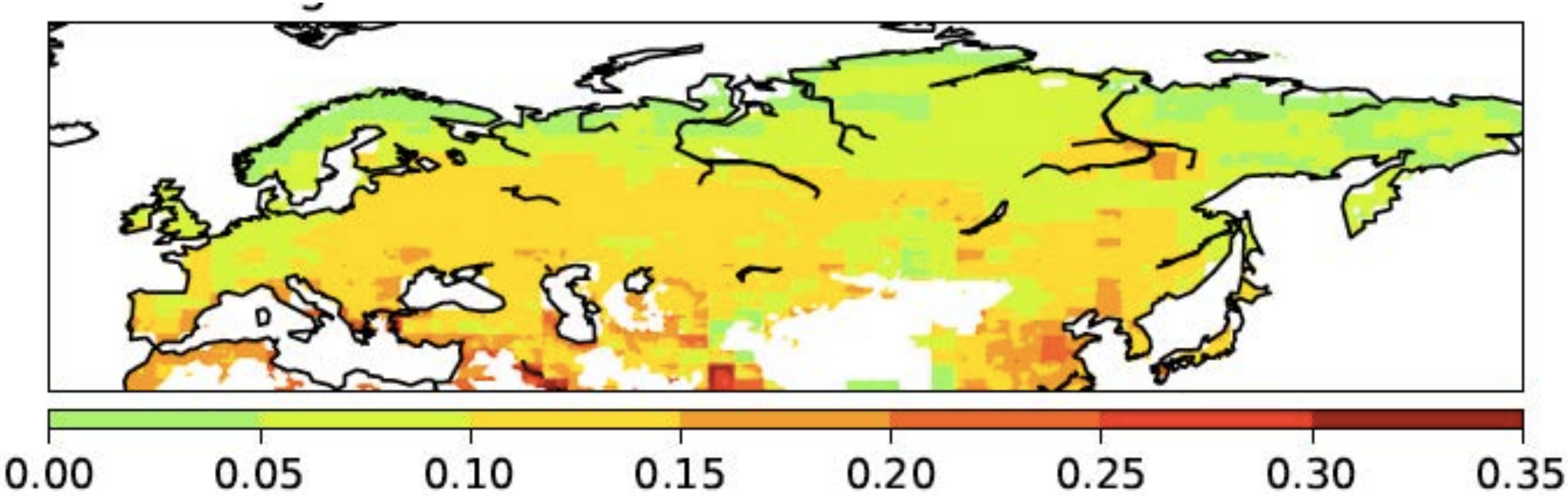




Multiple climate controls on productivity



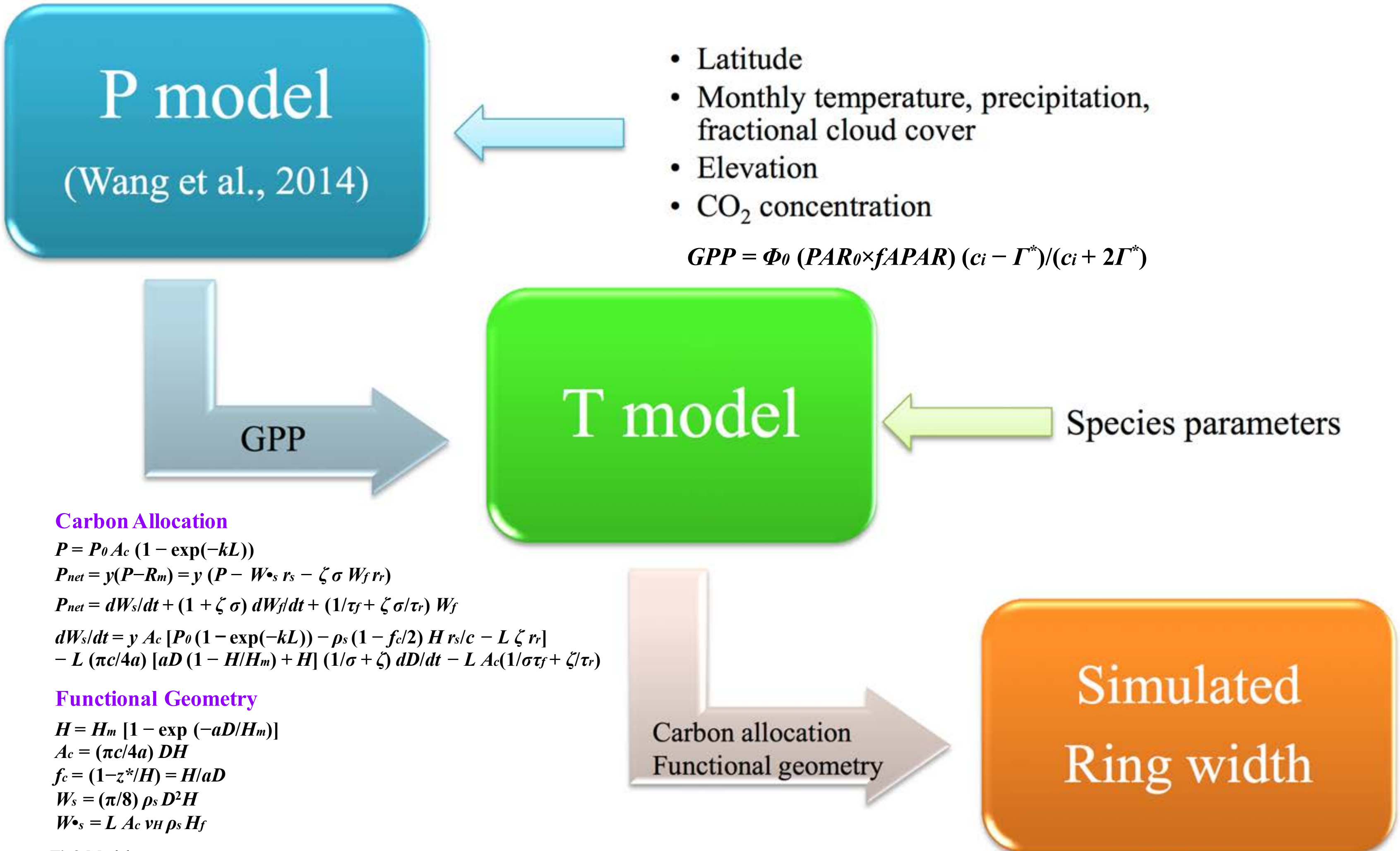
Impact of CO_2



Some false statistical modelling assumptions about trees

- Ontogenetic effects can be removed through smoothing
- A single climate factor controls growth
- Stationarity of climate control through time
- Non-climate factors (e.g. CO_2) have no influence on growth
- Stem allocation is constant proportion of total productivity

Tree growth modelling: PT model



$GPP = \Phi_0\ (PAR_0 \times fAPAR)\ (c_i - \Gamma^*)/(c_i + 2\Gamma^*)$

Carbon Allocation

$P = P_0\, A_c\, (1 - \exp(-kL))$

$P_{net} = y(P - R_m) = y\, (P - W_{\bullet s}\, r_s - \zeta\, \sigma\, W_f\, r_r)$

$P_{net} = dW_s/dt + (1 + \zeta\, \sigma)\, dW_f/dt + (1/\tau_f + \zeta\, \sigma/\tau_r)\, W_f$

$dW_s/dt = y\, A_c\, [P_0\, (1 - \exp(-kL)) - \rho_s\, (1 - f_c/2)\, H\, r_s/c - L\, \zeta\, r_r]$
$- L\, (\pi c/4a)\, [aD\, (1 - H/H_m) + H]\, (1/\sigma + \zeta)\, dD/dt - L\, A_c(1/\sigma\tau_f + \zeta/\tau_r)$

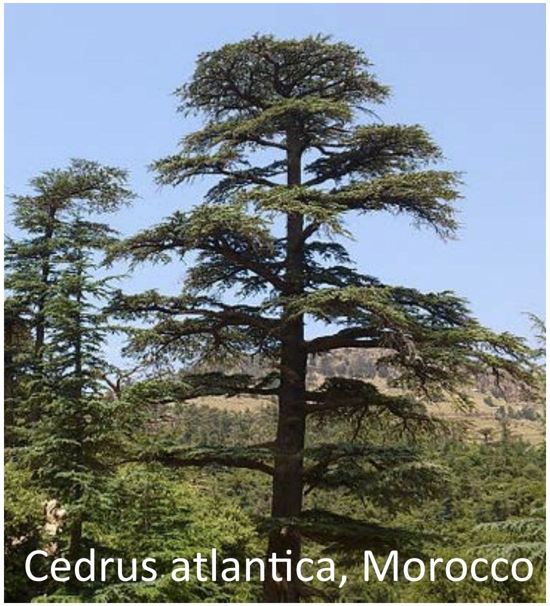
Functional Geometry

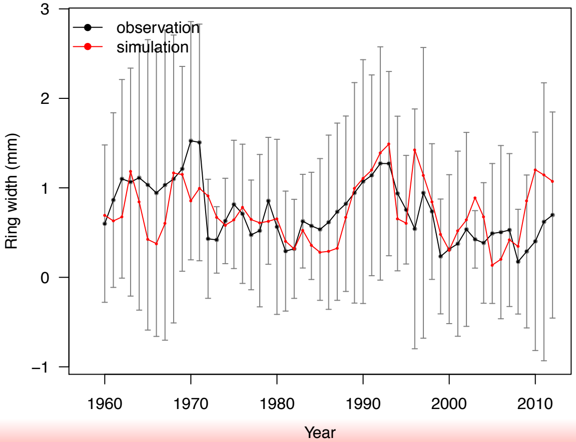
$H = H_m\, [1 - \exp\, (-aD/H_m)]$
$A_c = (\pi c/4a)\, DH$
$f_c = (1 - z^*/H) = H/aD$
$W_s = (\pi/8)\, \rho_s\, D^2 H$
$W_{\bullet s} = L\, A_c\, \nu_H\, \rho_s\, H_f$

Fig2 Model structure

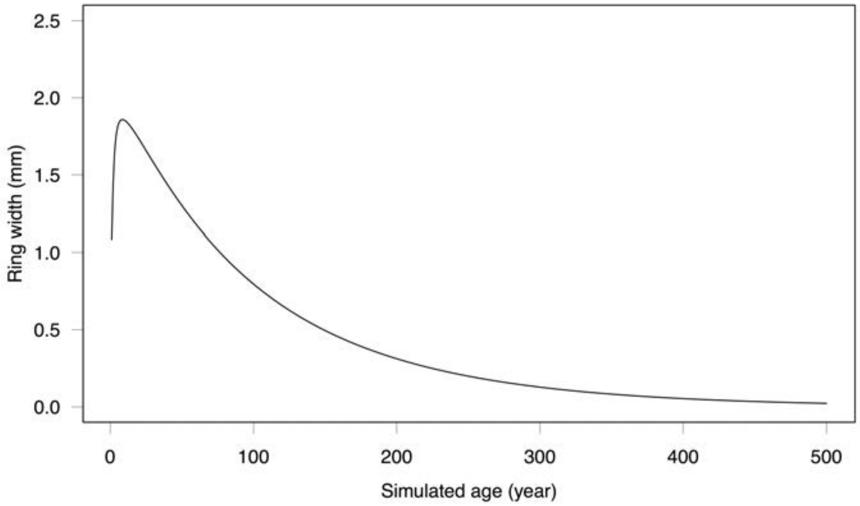
Wang et al., 2014; Biogeosci; Li et al., 2014, Biogeosci; 2016, Li et al., 2016 EcoMod

Tree growth modelling



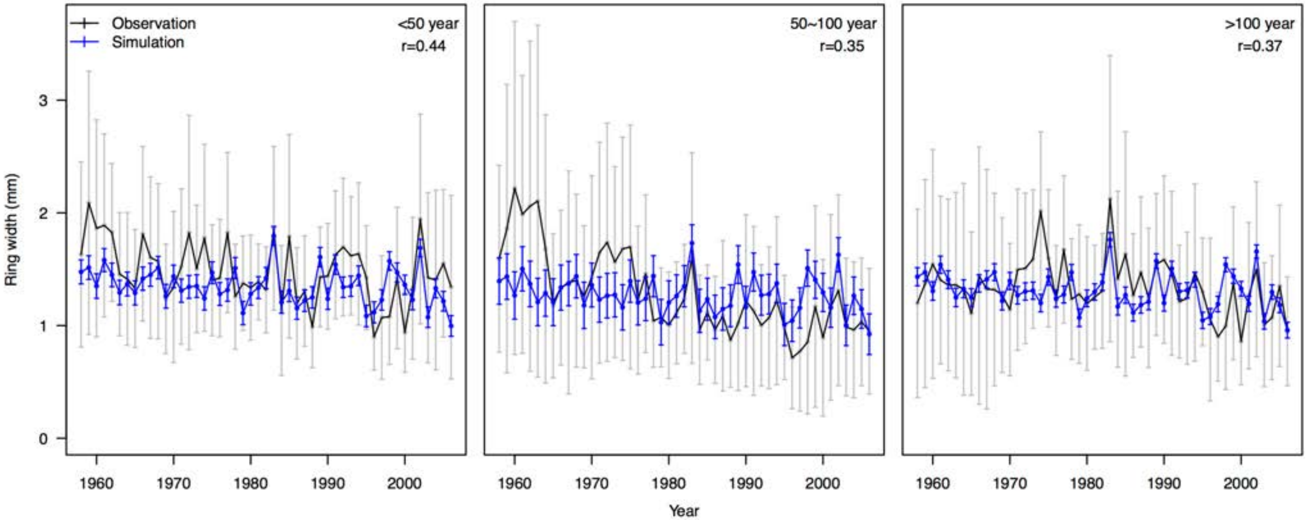


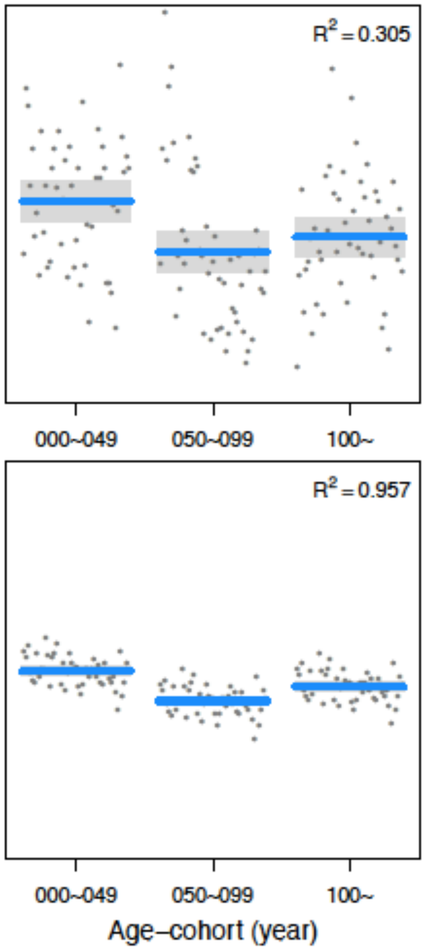
Pinus koraiensis, Changbai, China



- Initialise each simulation from the actual diameter in 1958 for each tree
- Sort the individual trees into 3 age cohorts (young, mature, and old)

Modelling ontogeny

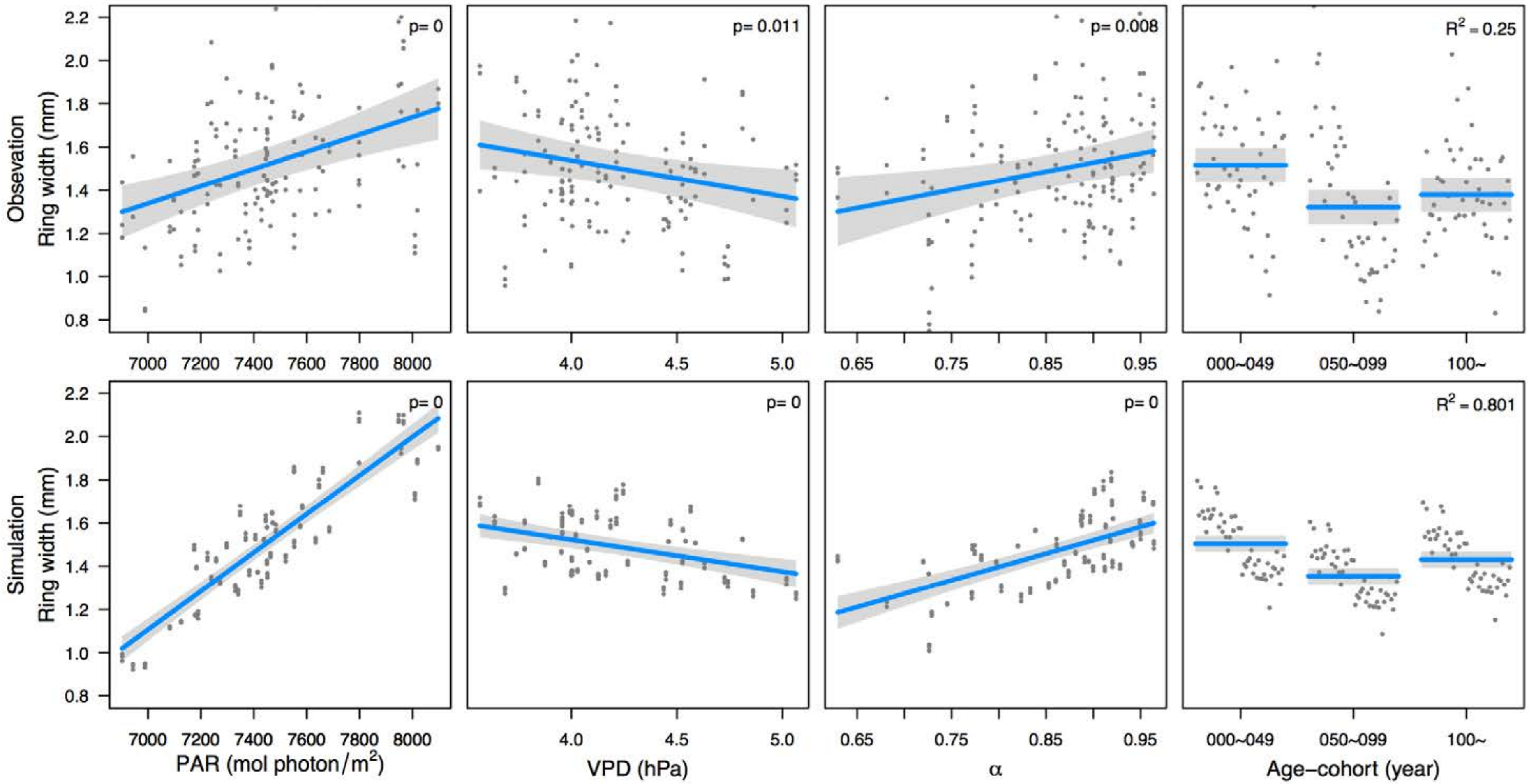




Correct simulation of
age cohorts (Changbai)

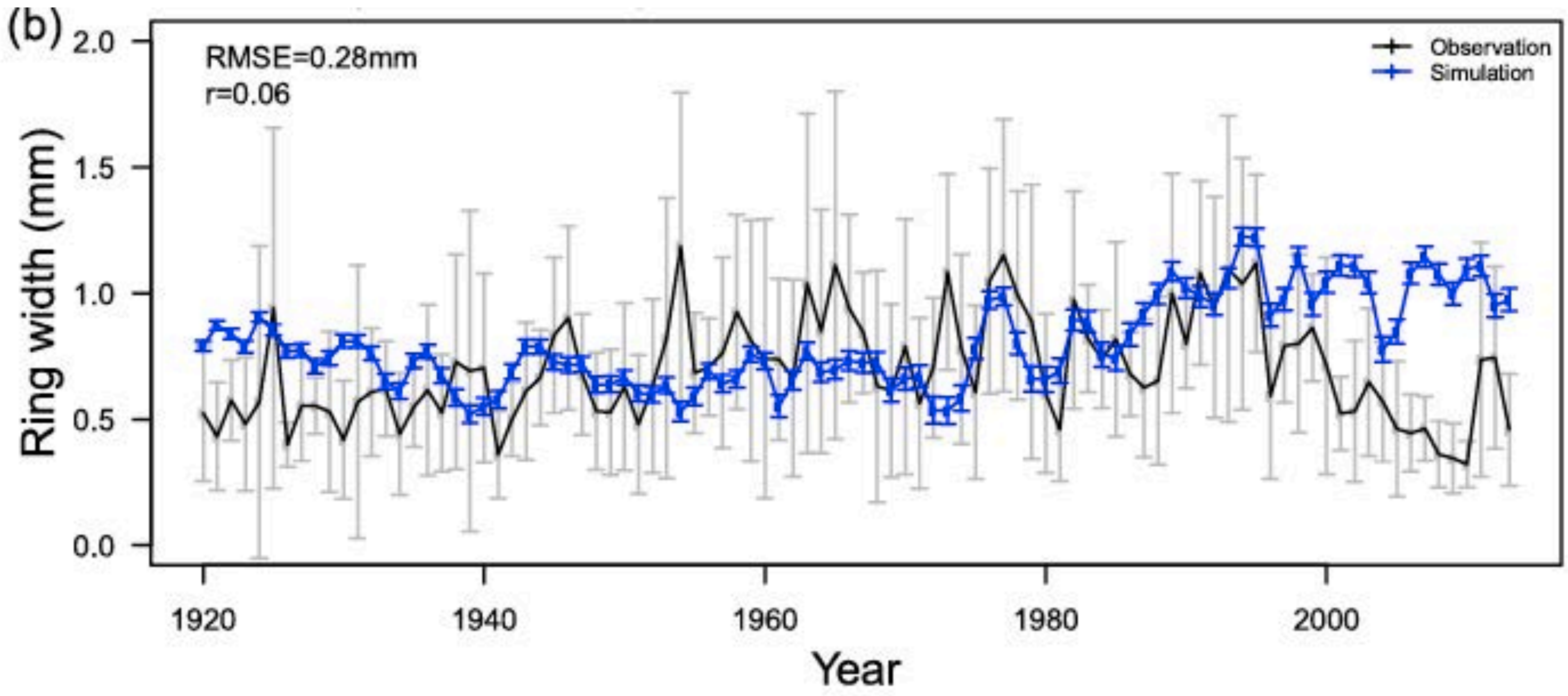
Li et al., 2014, Biogeosci

Controls on tree growth

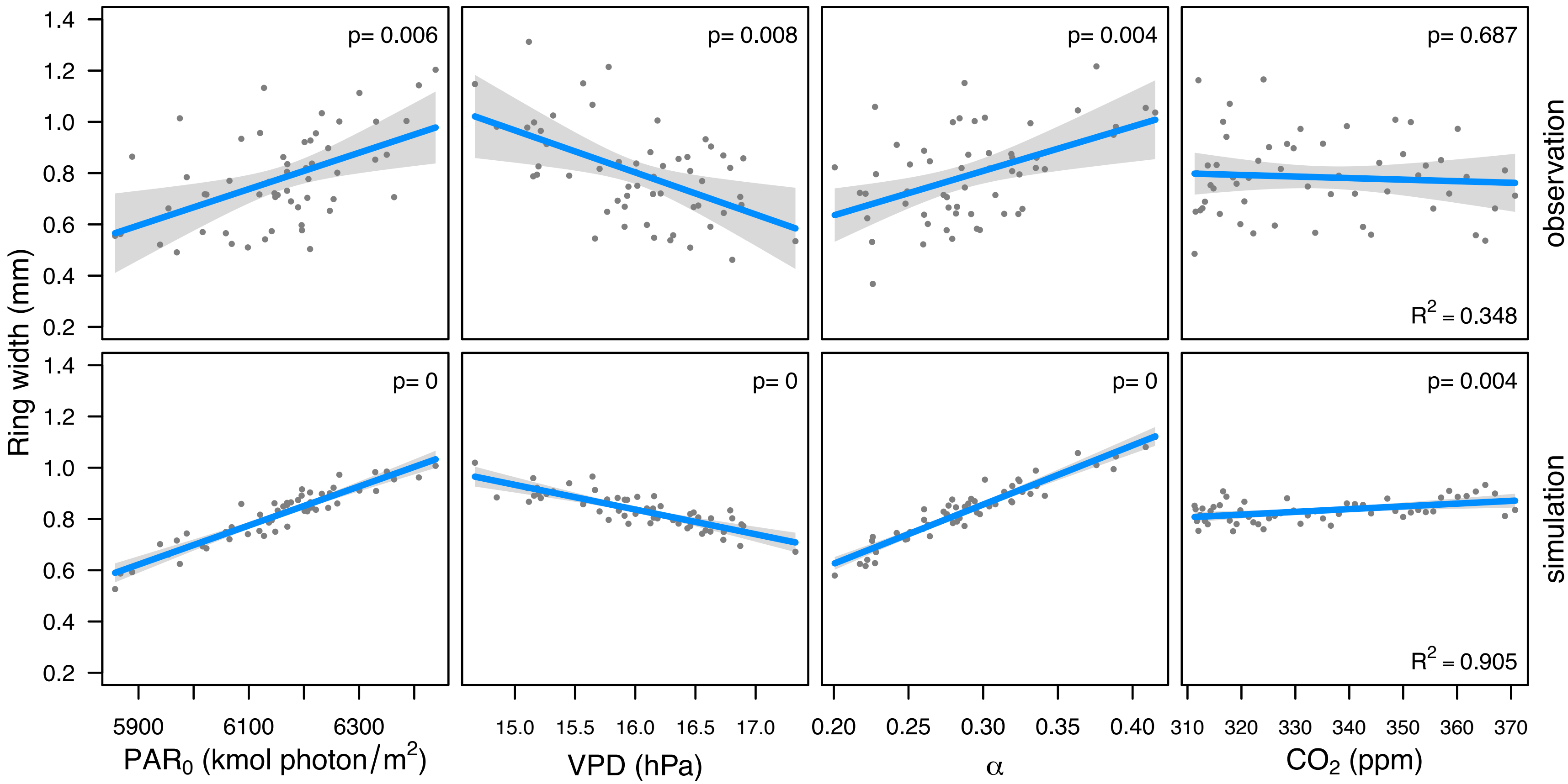


Li et al., 2014, Biogeosci

Callitris, Great Western Woodlands



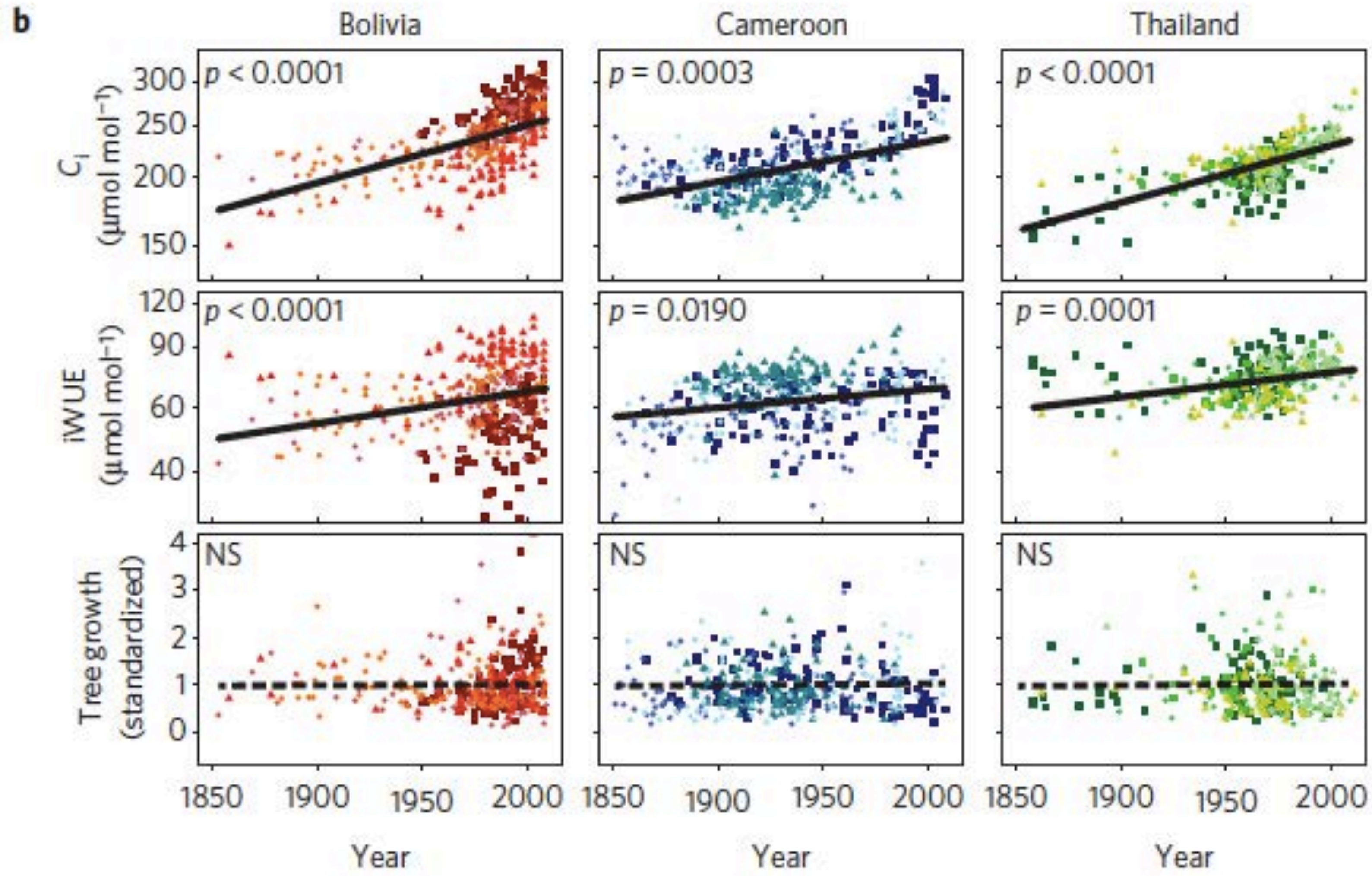
- Mean level OK; interannual variability OK
- Trend wrong



- Again, model shows same responses to climate variables as observations, ***except* [CO_2]**
- No effect from **[CO_2]** for observation, but model simulates significant [CO_2] response.

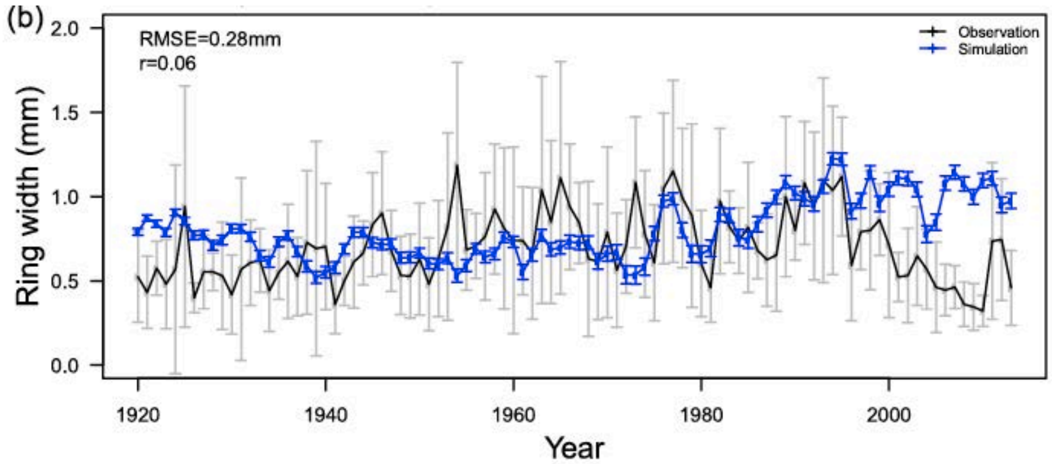
Li et al.,(2016) ECOMOD

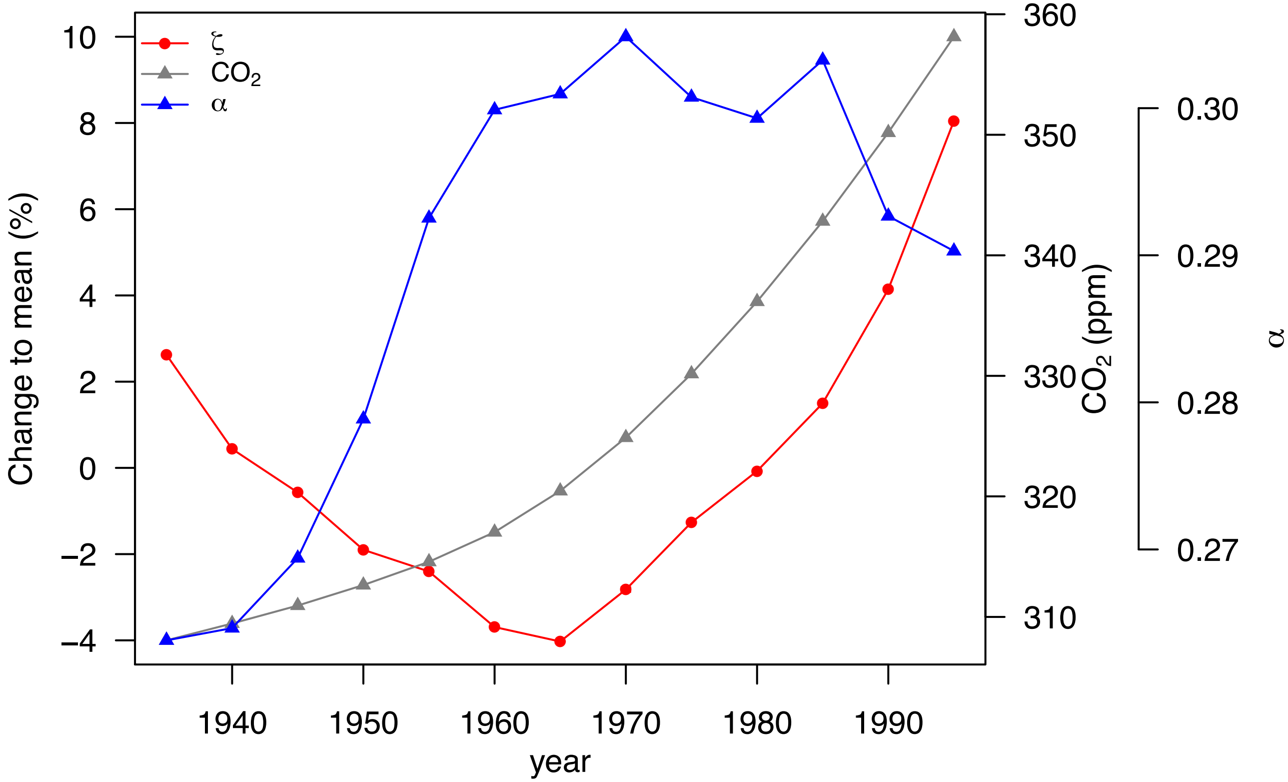
CO_2 impact



Van der Sleen et al. (2014) Nature Geosci

Allocation





Variance partitioning

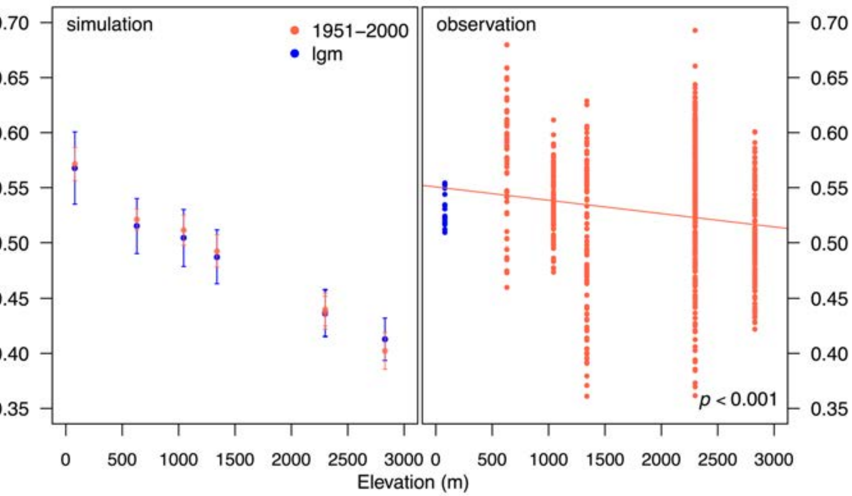
- CO_2: 70%
- Soil moisture: 30%

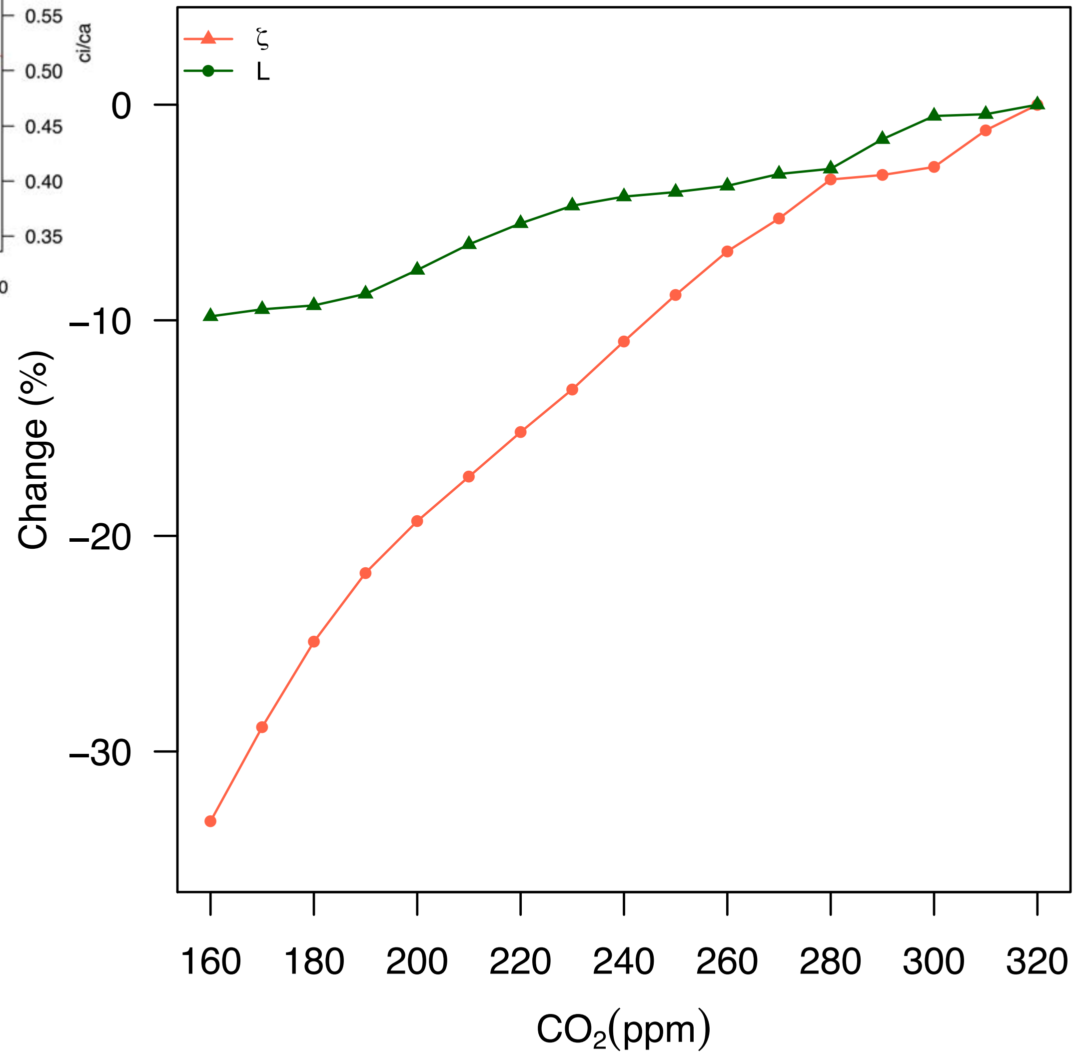
Trees at the LGM

Glacial *Juniperus* from La Brea Tar Pits

- glacial c_i/c_a is similar to today
- c_i = 100~120 ppm, **STARVATION** level
- BUT glacial **growth** (ring width) is **similar** to today

Li et al., 2017, Nature Scientific Reports





Changes in allocation to leaves and roots **are required** to maintain tree growth under LGM climate

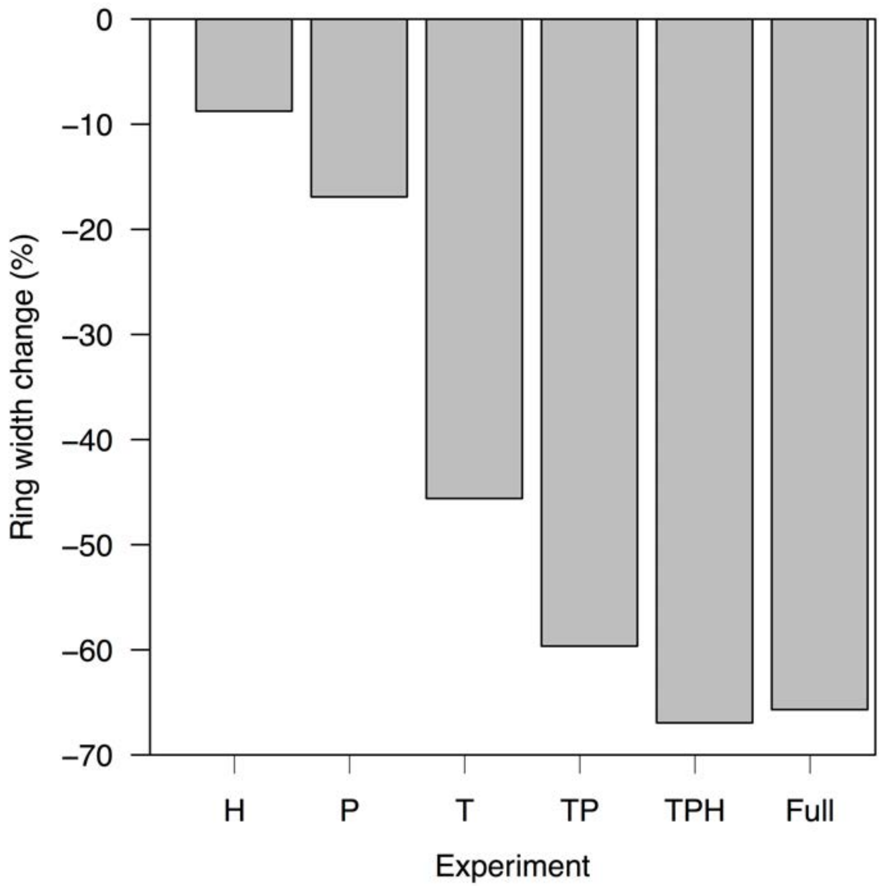
Climate cooler and wetter

- Cooler = lower photorespiration + less drought
- Wetter = less drought

Biggest effect from

temperature: -46%;

Precipitation effect: -17%



Take-home messages

- Assumptions of statistical reconstruction techniques violated under changing climate (past and future); but we can use knowledge about the biology
- Plants are clever: optimise performance to maximise growth (on both short and long-time scales): optimal resource allocation theory is biological "law of thermodynamics"
- Trees aren't foresters: optimising stem growth instead of leaves/roots is not a sensible option; changes in allocation important
- The way forward: explicit modelling of productivity and tree growth