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An observational constraint on stomatal function in forests: evaluating coupled carbon and water vapor exchange with carbon isotopes in CLM 4.5

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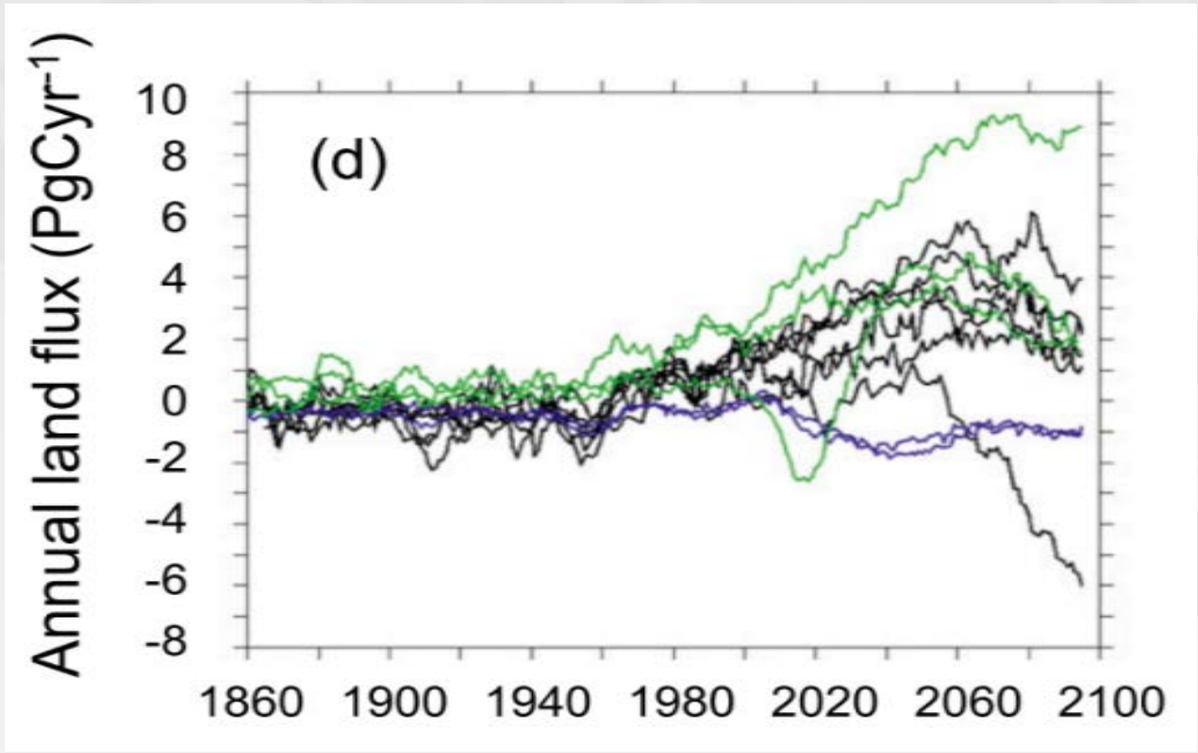
LMWG Meeting, February 10th 2016

Motivation: Stable Carbon Isotopes

- $^{13}C/^{12}C$ fractionation occurs primarily during C3 photosynthesis
- Fractionation is influenced by stomatal conductance, assimilation rate which respond to environmental conditions (stress)
- **Have potential to constrain land carbon models**, <u>improving simulation of ecosystem stomatal response and improving projections of land carbon uptake</u>



Friedlingstein et al. 2014

Objectives:

- Determine whether CLM, when calibrated to simulate Niwot Ridge fluxes and biomass, can also simulate $^{13}C/^{12}C$ at the site.

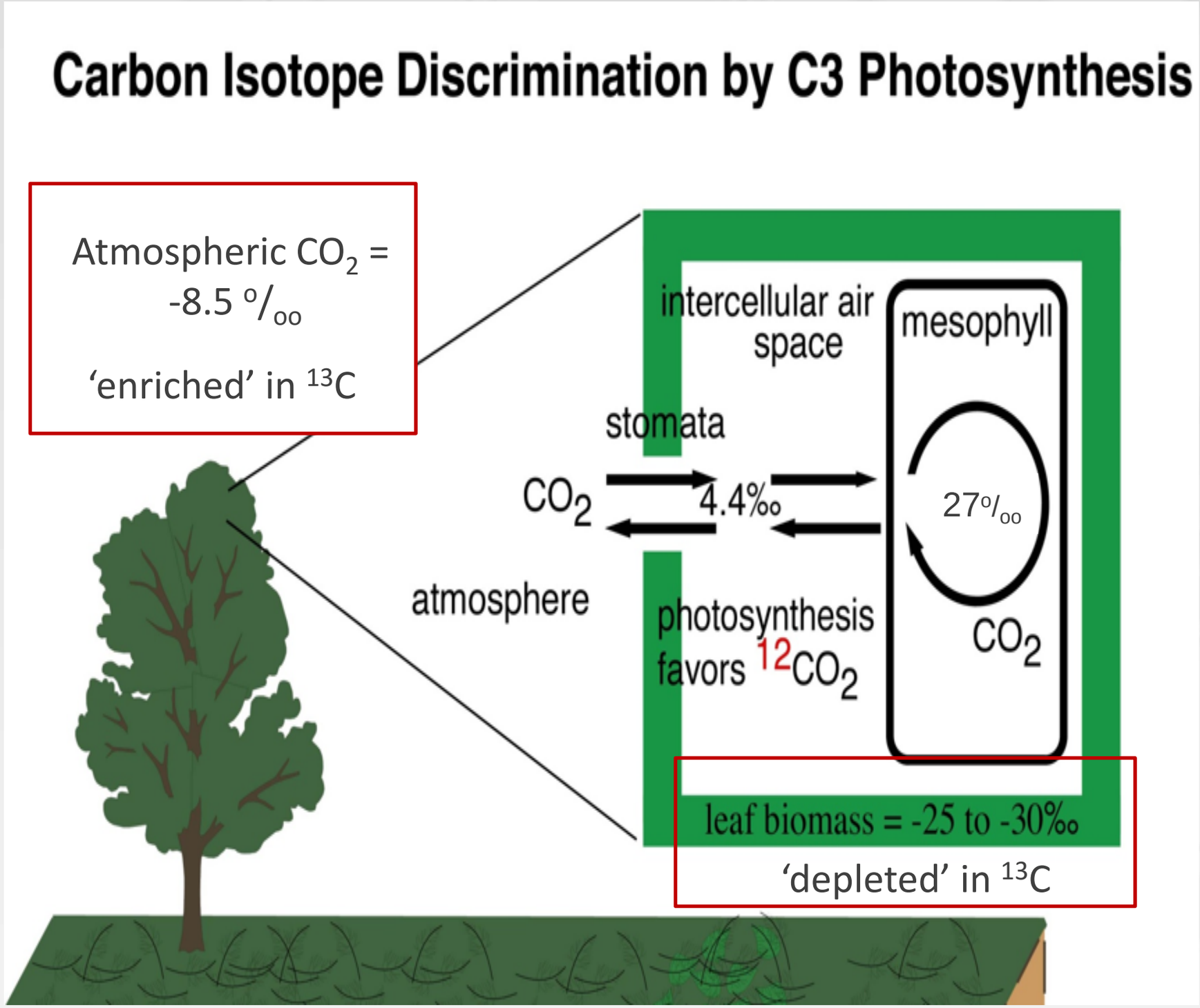
- Identify if stable carbon isotopes provide constraint to model structure and function (e.g. stomatal conductance)?

- Identify environmental drivers of multi-decadal and seasonal fractionation.

Friedlingstein et al. 2014

Photosynthetic Fractionation of ^{13}C

$$\delta^{13}C_x\ (^{o}/_{oo}) = \left(\frac{R_x}{R_{VPDB}} - 1\right) \times 1000$$



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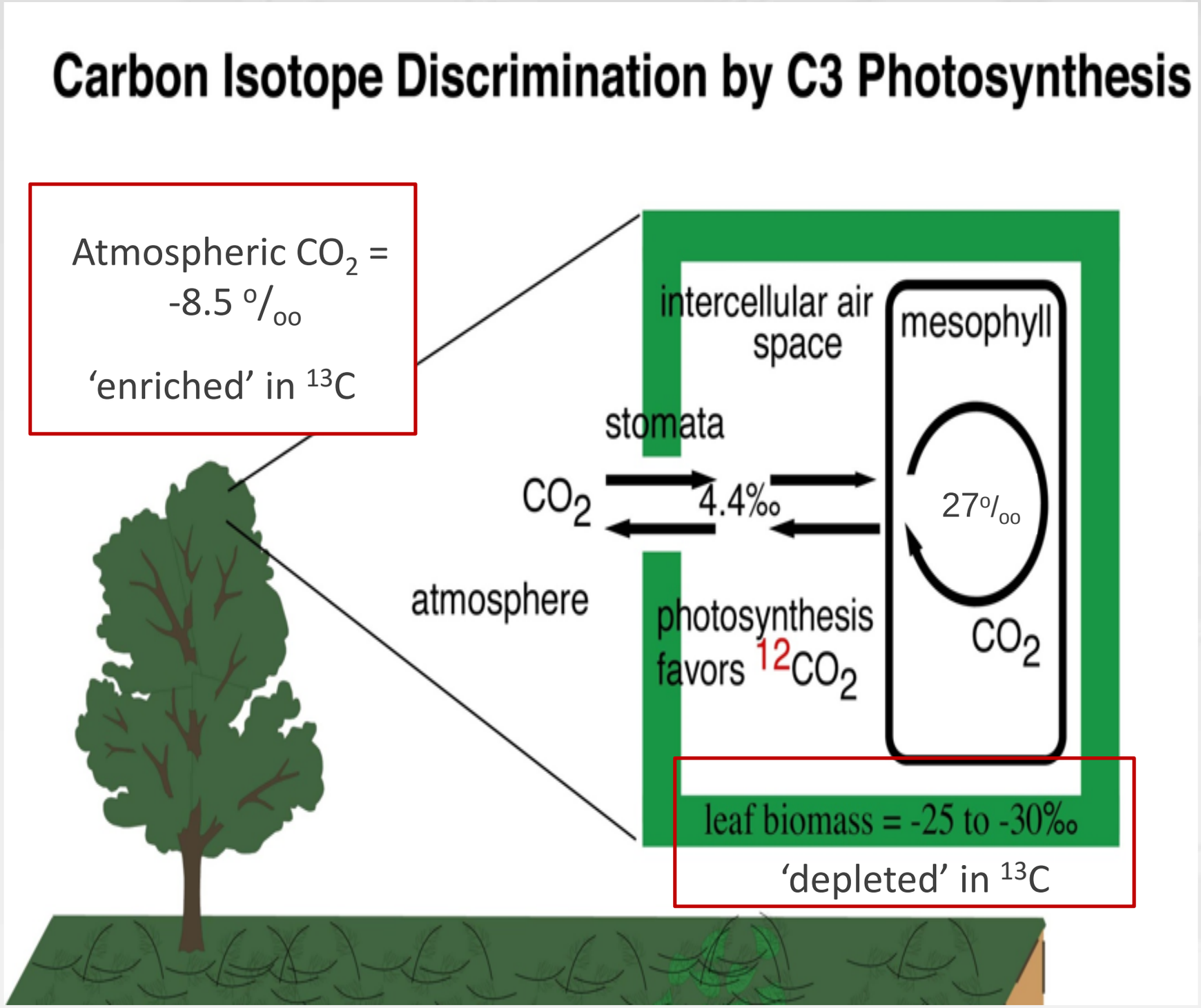
Photosynthetic Fractionation of ^{13}C



$$\delta^{13}C_x\ (^{o}/_{oo}) = \left(\frac{R_x}{R_{VPDB}} - 1\right) \times 1000$$

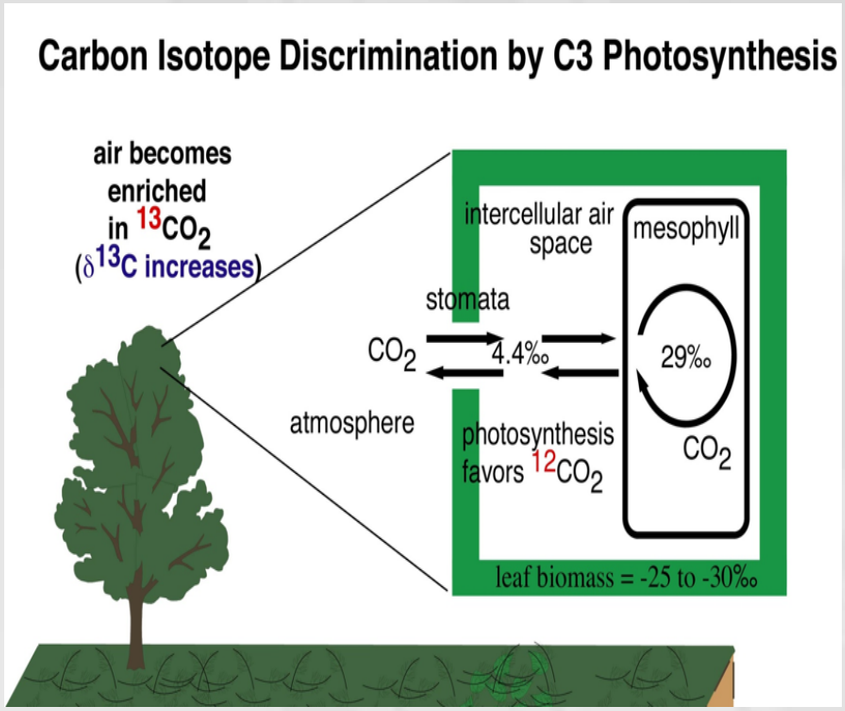
CLM uses Farquhar fractionation:

$$\alpha_{psn} = 1 + \frac{4.4 + 22.6\frac{c_i}{c_a}}{1000}$$

Environmental Drivers

- Humidity/VPD
- Light, Temp (Assim.)
- Soil moisture content
- Nutrient Limitation
- Atmospheric CO_2

Photosynthetic Fractionation of ^{13}C



CLM uses Farquhar representation:

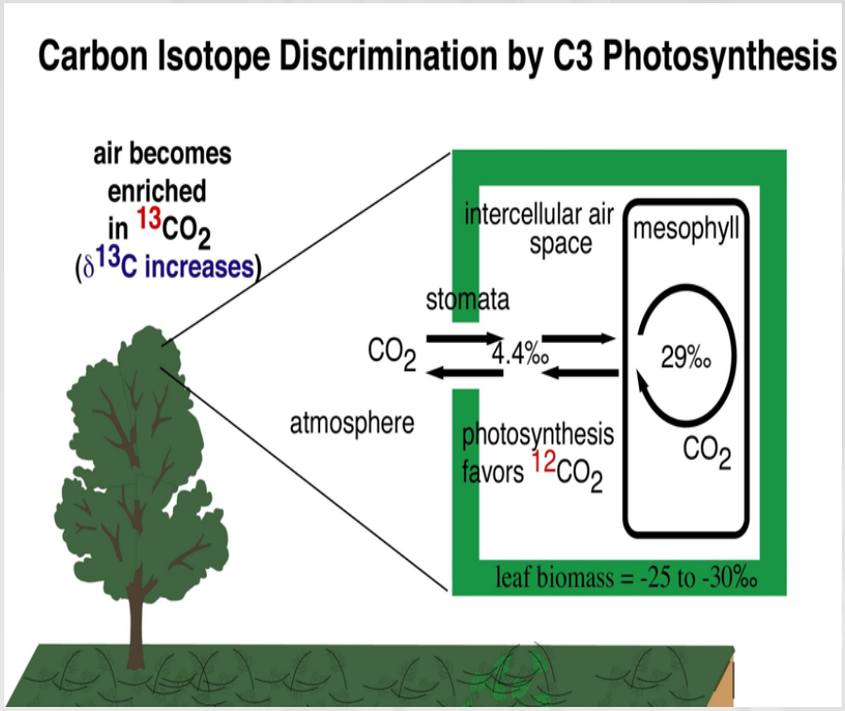
$$\frac{c_{atm}^{13}/c_{atm}^{12}}{c_{gpp}^{13}/c_{gpp}^{12}} = \alpha_{psn} = 1 + \frac{4.4 + 22.6\frac{c_i}{c_a}}{1000}$$

Intracellular leaf CO_2 defined:

$$c_i = c_a - A_n (1-d) P_{atm} \frac{(1.4g_s)+(1.6g_b)}{g_b g_s}$$

↑ photosynthesis	↑ nitrogen limitation	↑ conductances
↓ c_i	↑ c_i	↑ c_i

Photosynthetic Fractionation of ^{13}C



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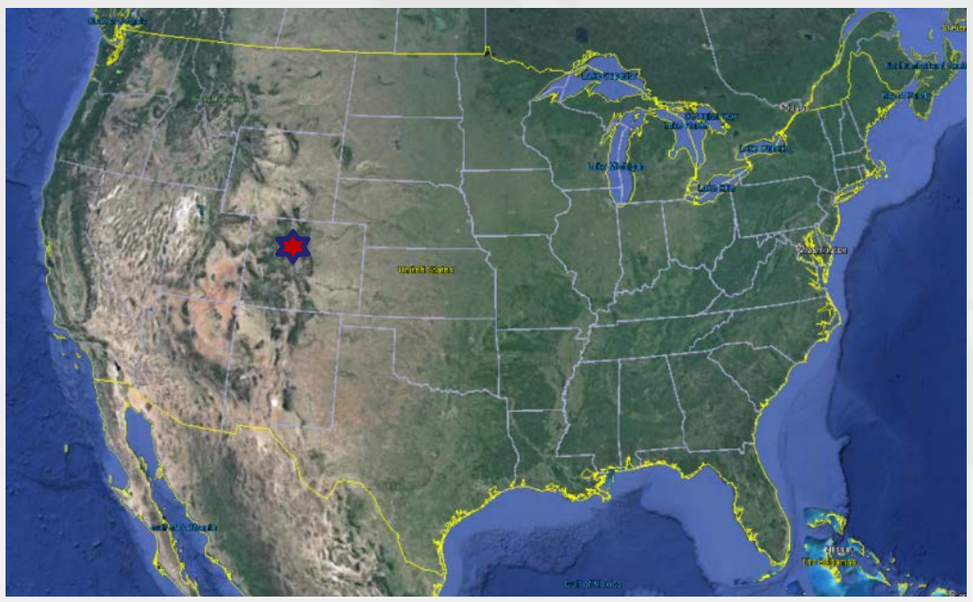
- ↑ photosynthesis → ↓ c_i
- ↑ nitrogen limitation → ↑ c_i
- ↑ conductances → ↑ c_i

Stomatal conductance (Ball-Berry) defined:

$$g_s = m\frac{A_n}{c_s/P_{atm}} h_s + b\beta_t$$

- ↑ specific humidity → ↑ c_i
- ↑ soil moisture → ↑ c_i

Site: Niwot Ridge AmeriFlux Site



Observation rich site

- LTER site: 1952- present
- Flux tower measurements (carbon, water) 1998-present
- $\delta^{13}C$ flask measurements, 1990-present
- $\delta^{13}C$ biomass measurements
- $\delta^{13}C$ high resolution, 2006-present

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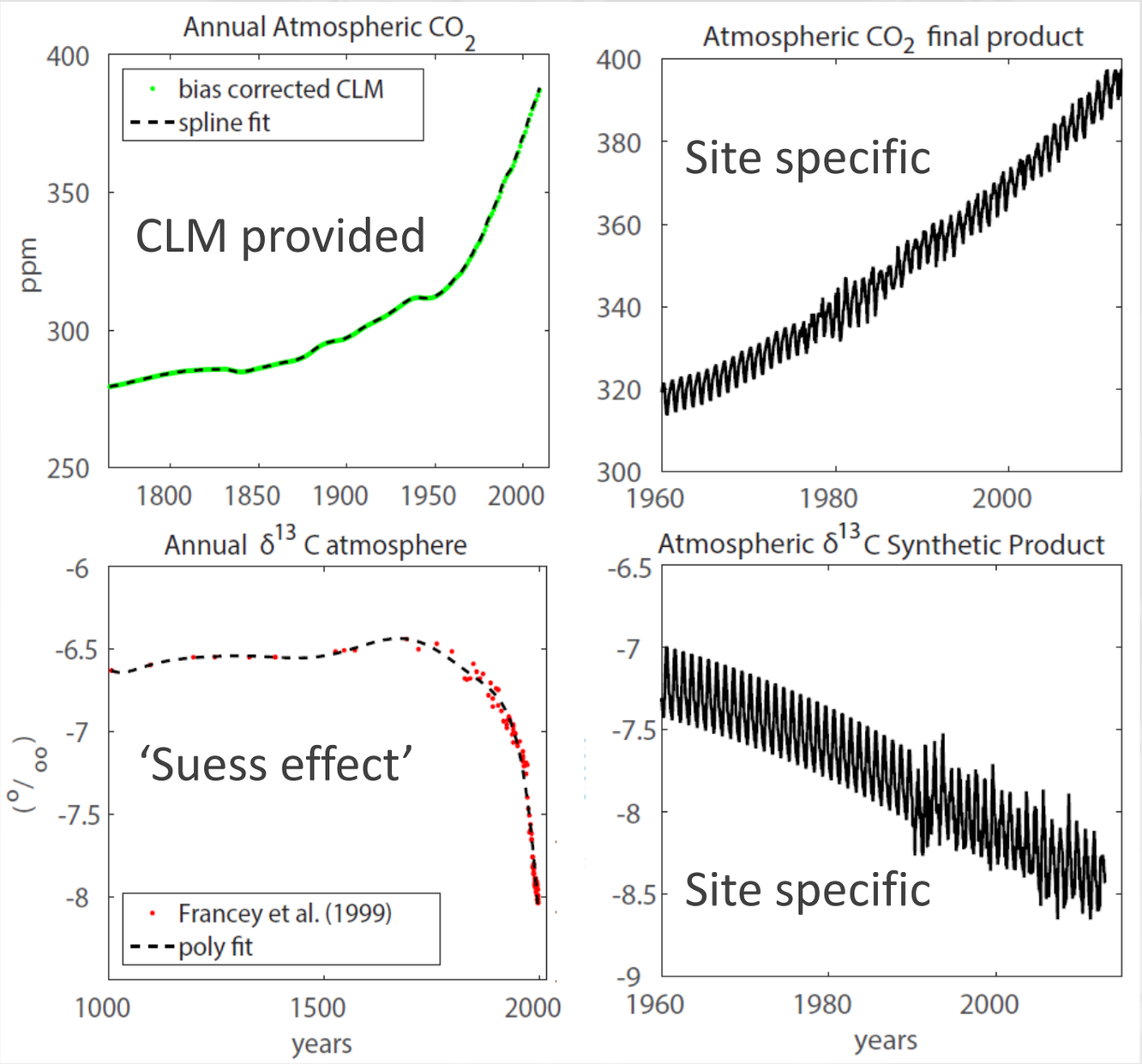
Model Setup

Atmospheric Trace Gases:



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Model Setup

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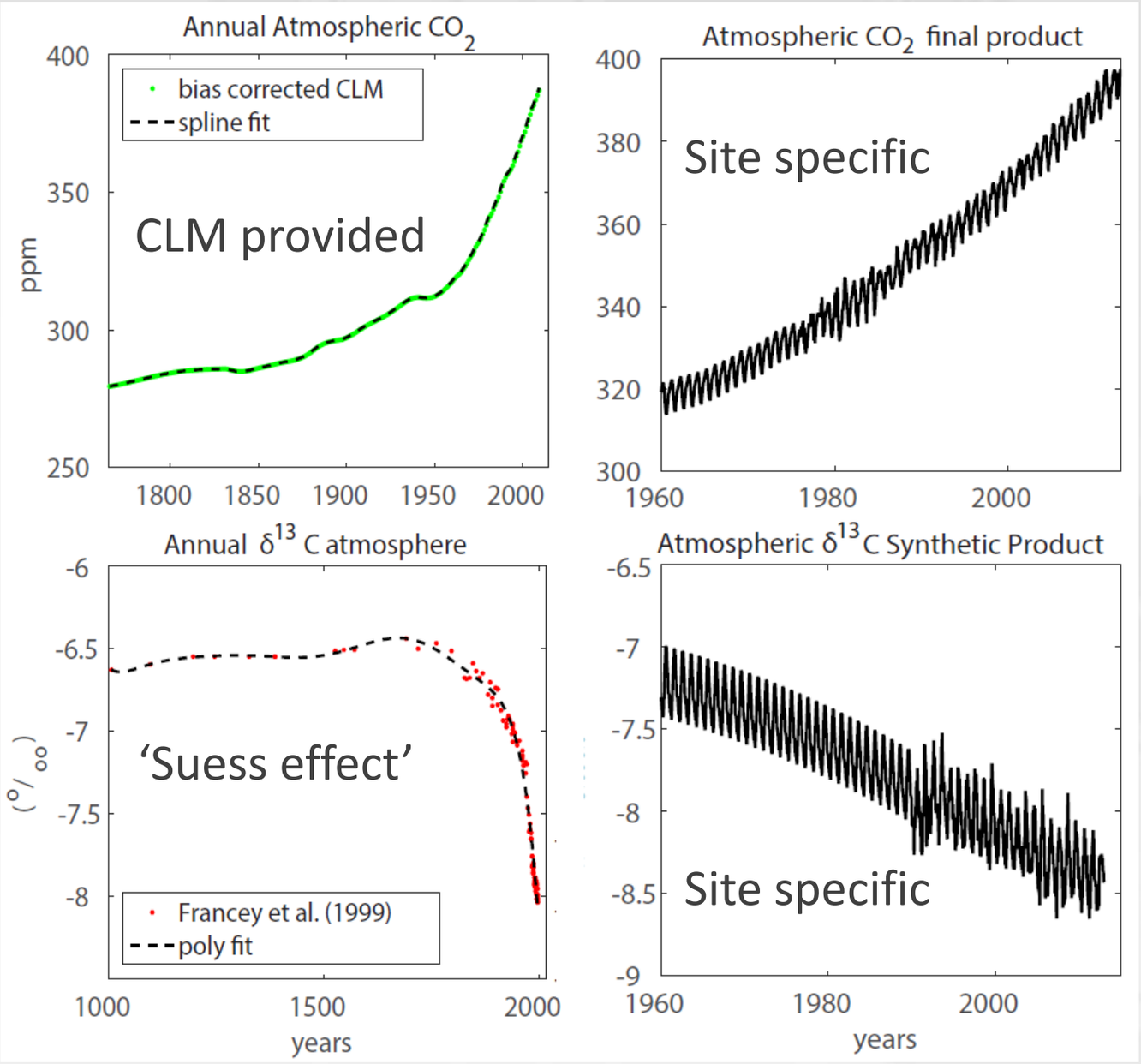

Parameter Calibration:

- ENFT default
- decomp_depth_efolding (soil decomposition)
- Seasonal-varying V_{cmax25}

Meteorology:

- 1998-2013 gap-filled flux tower
- looped during spin-up
- constant ‘climate’ w/ inter-annual variation
- Transient trace gases (1850-2013)

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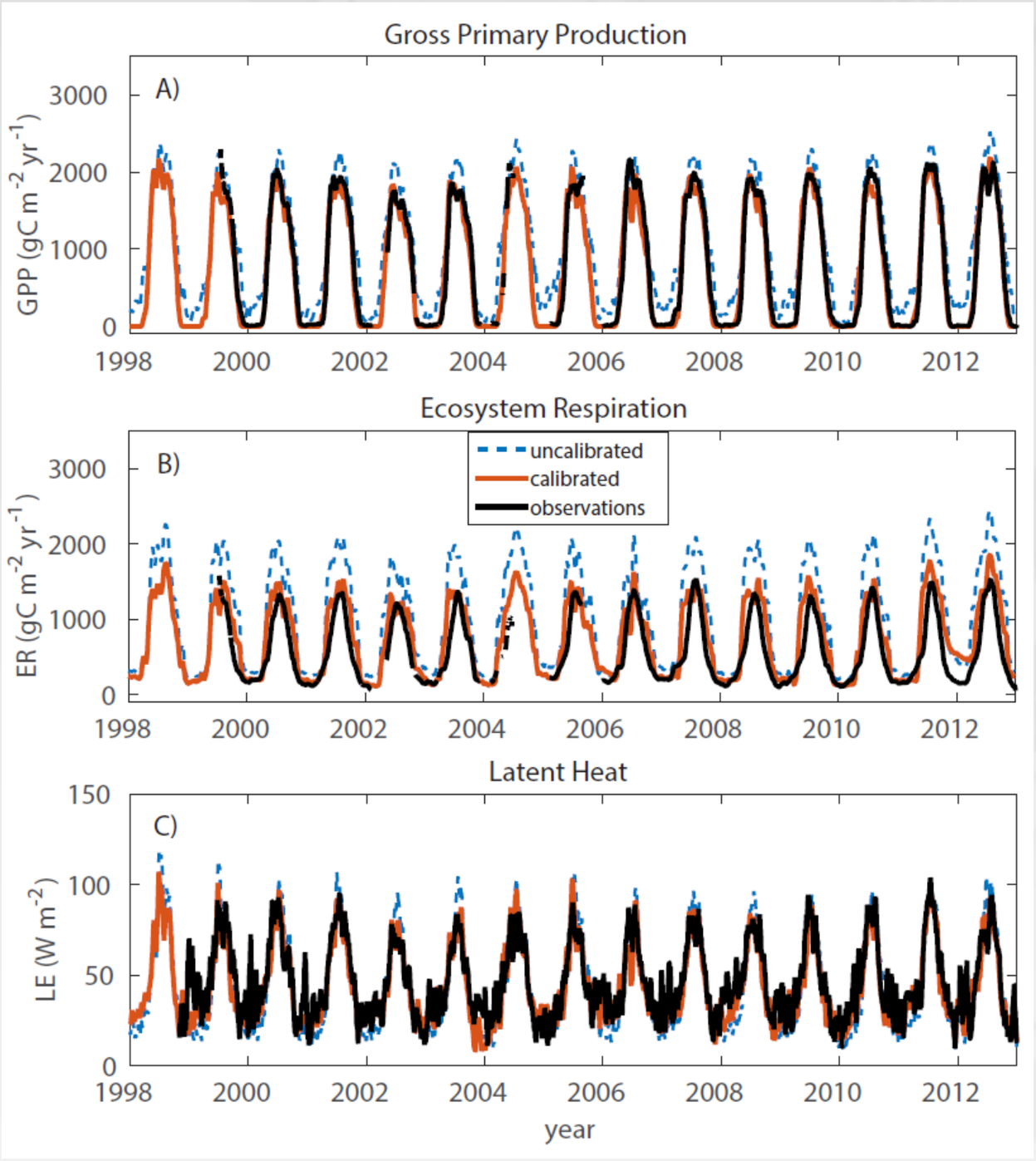
Calibrated CLM matches fluxes & biomass



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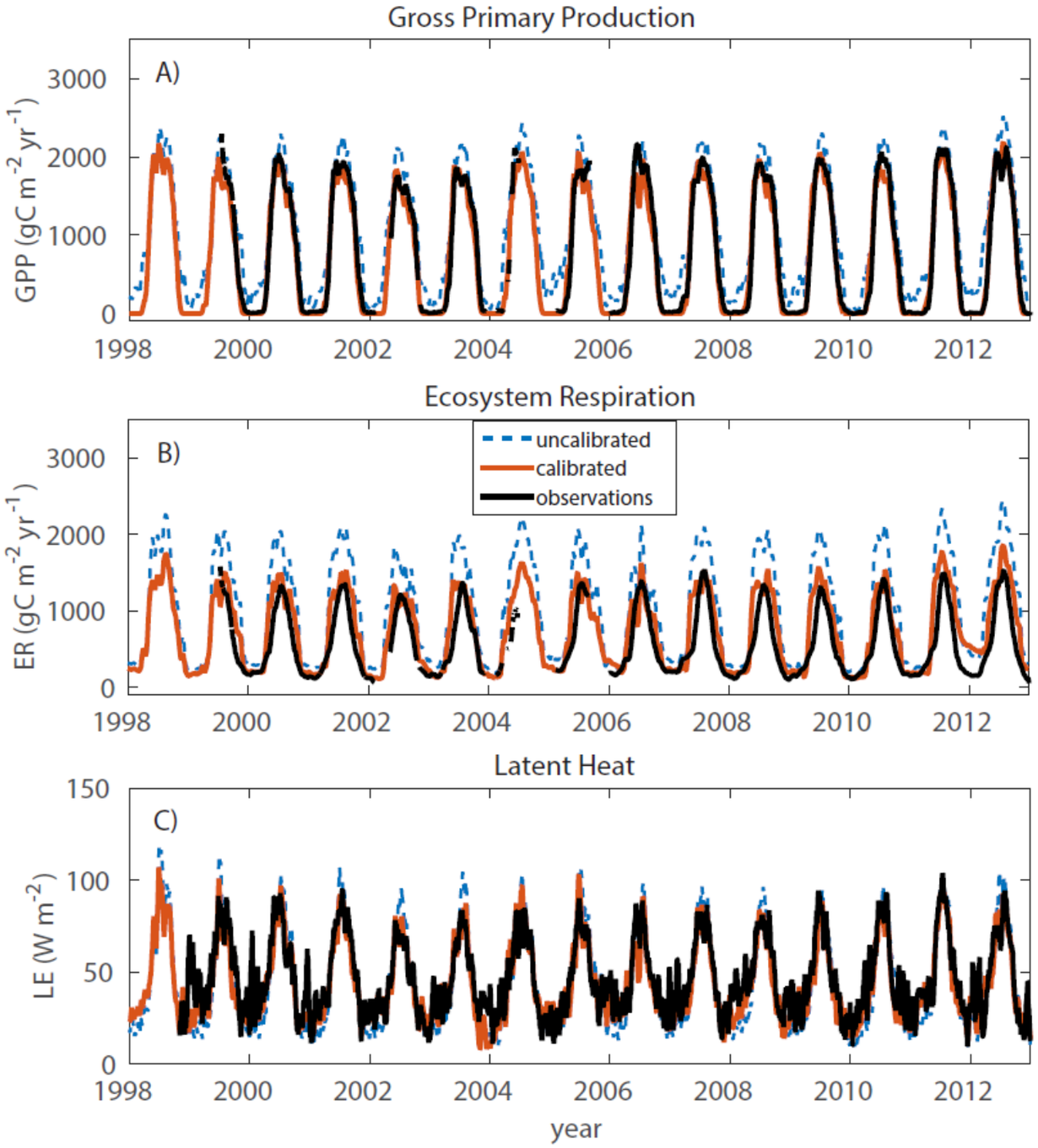

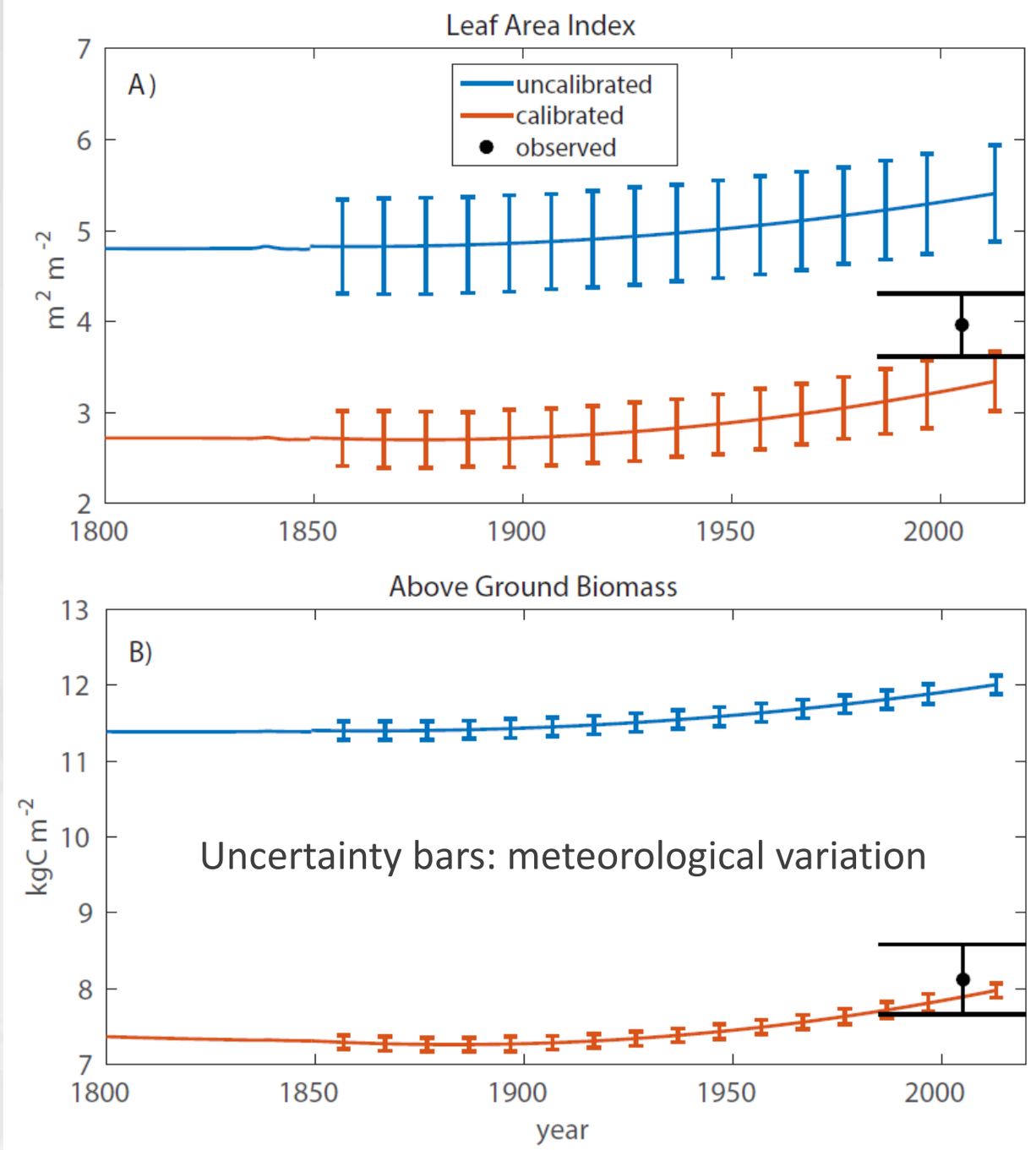

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CLM Model Formulations

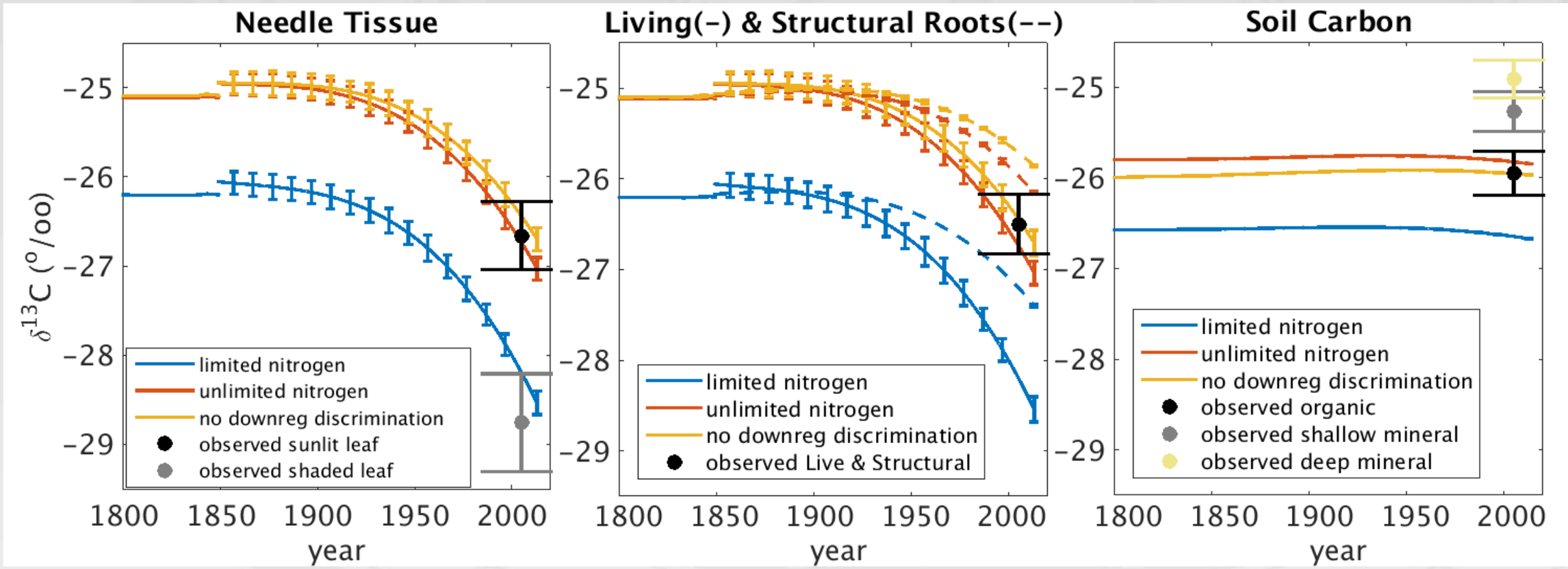
- Isotope simulations highly sensitive to type of nitrogen limitation imposed

$$d = \frac{Potential\ growth\ carbon - Actual\ growth\ carbon}{Potential\ GPP},$$

$$c_i = c_a - A_n\,(1-d)\,P_{atm}\,\frac{(1.4g_s)+(1.6g_b)}{g_b g_s}$$

	Formulation		Pre-photosynthetic nitrogen limitation (Vcmax calibration)	Post-photosynthetic nitrogen limitation (growth allocation)	Influences fractionation & c_i?
default	Limited nitrogen		Yes (weak)	Yes, $d > 0$	Yes, d is active
~foliar nitrogen model	Unlimited nitrogen		Yes (strong)	No, $d = 0$	No, $d = 0$
	No 'd' discrimination		Yes (weak)	Yes, $d > 0$	No, d turned off

CLM reproduces observed biomass $\delta^{13}C$



- Limited nitrogen simulation (post-photosynthetic nitrogen limitation) tends to underestimate $\delta^{13}C$, weaker stomatal response

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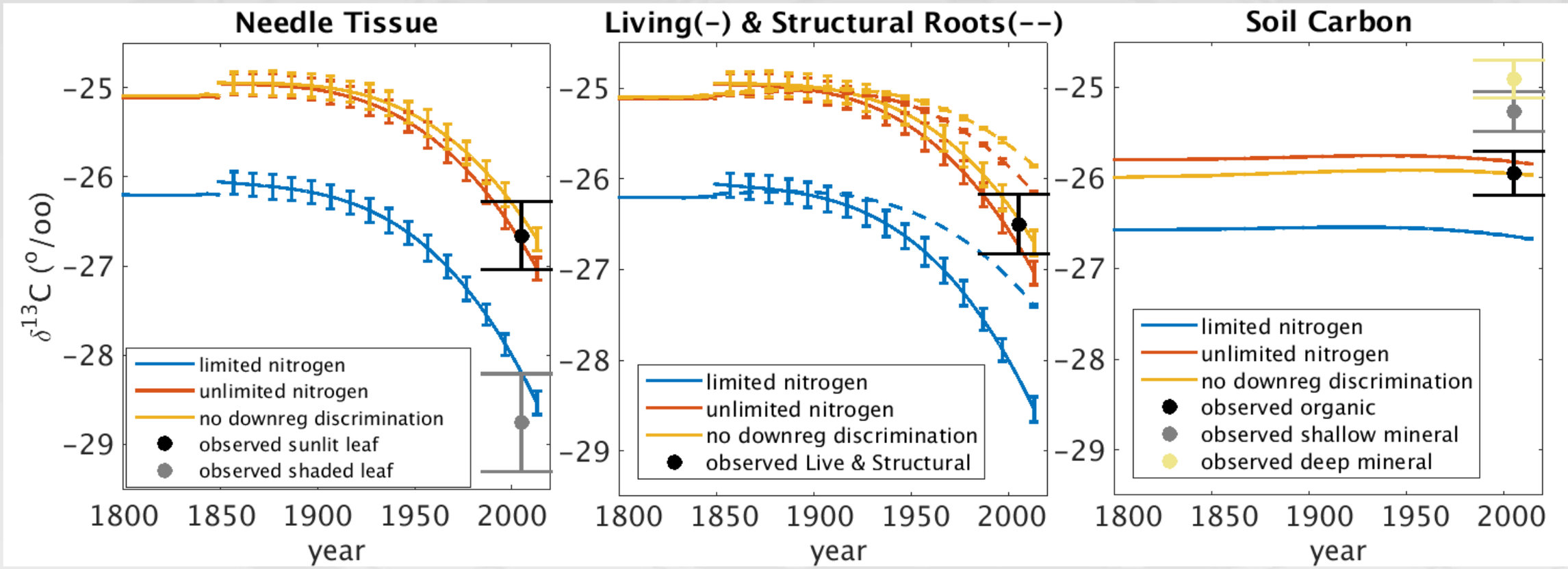

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- Decreasing $\delta^{13}C$ from combined Suess effect (70%) & increased photosynthetic discrimination (30 %)

- Rate of $\delta^{13}C$ decrease depends upon turnover time of carbon pool

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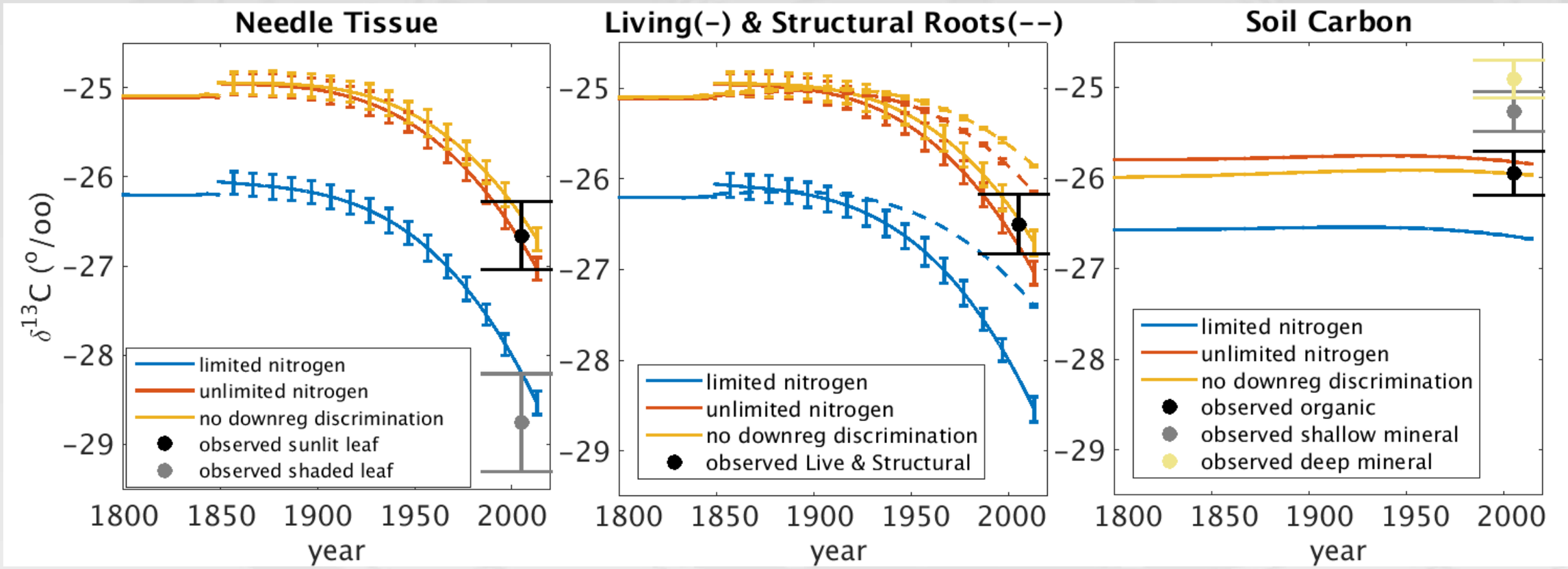

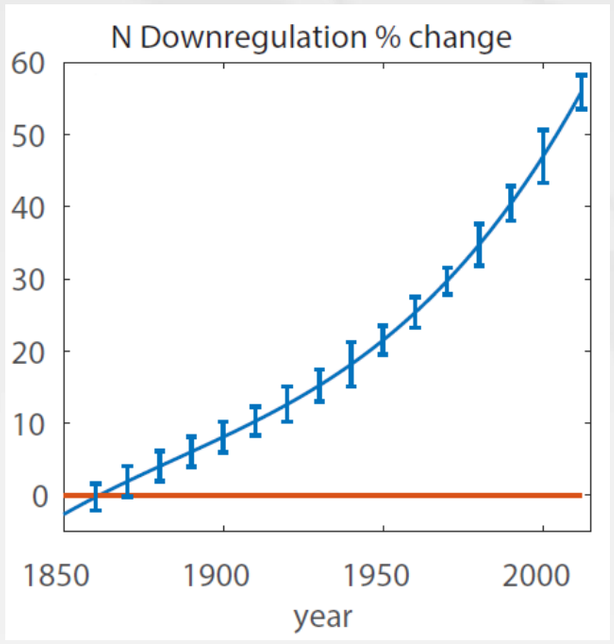

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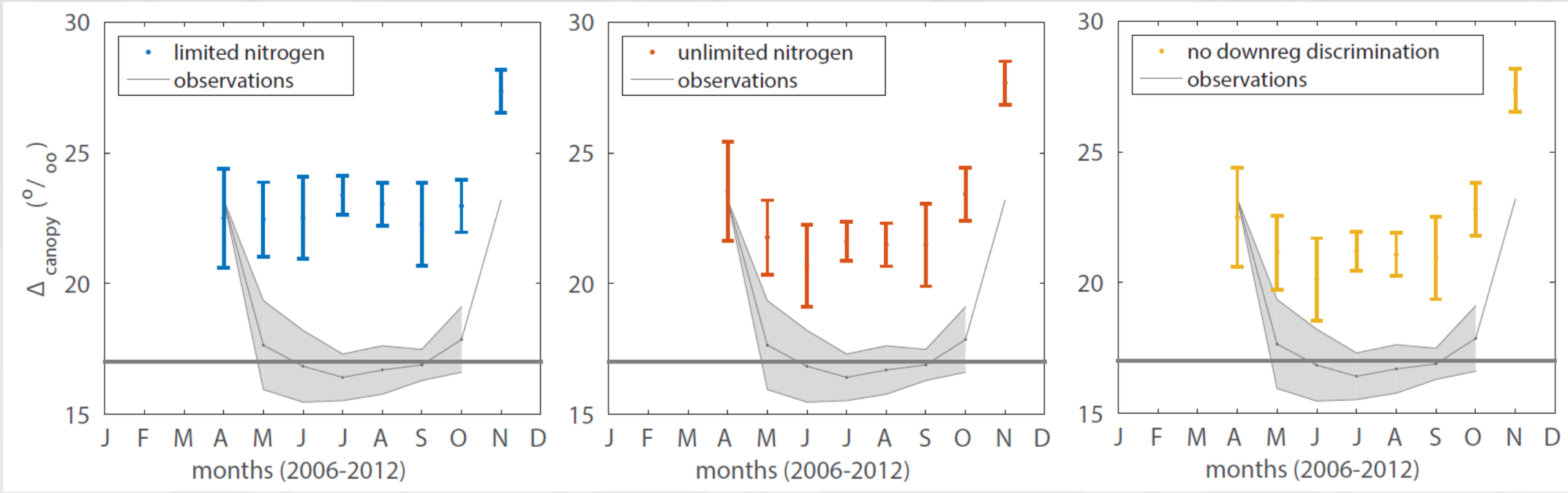
Seasonal discrimination: magnitude & pattern

$$\Delta_{canopy} = \delta^{13}_{\text{atm}} - \delta^{13}_{\text{GPP}}$$



- ‘Observations’ (grey-shade) from mixing model approach constrained by high resolution carbon flux and $\delta^{13}C$ obs. (Bowling et al. 2014)

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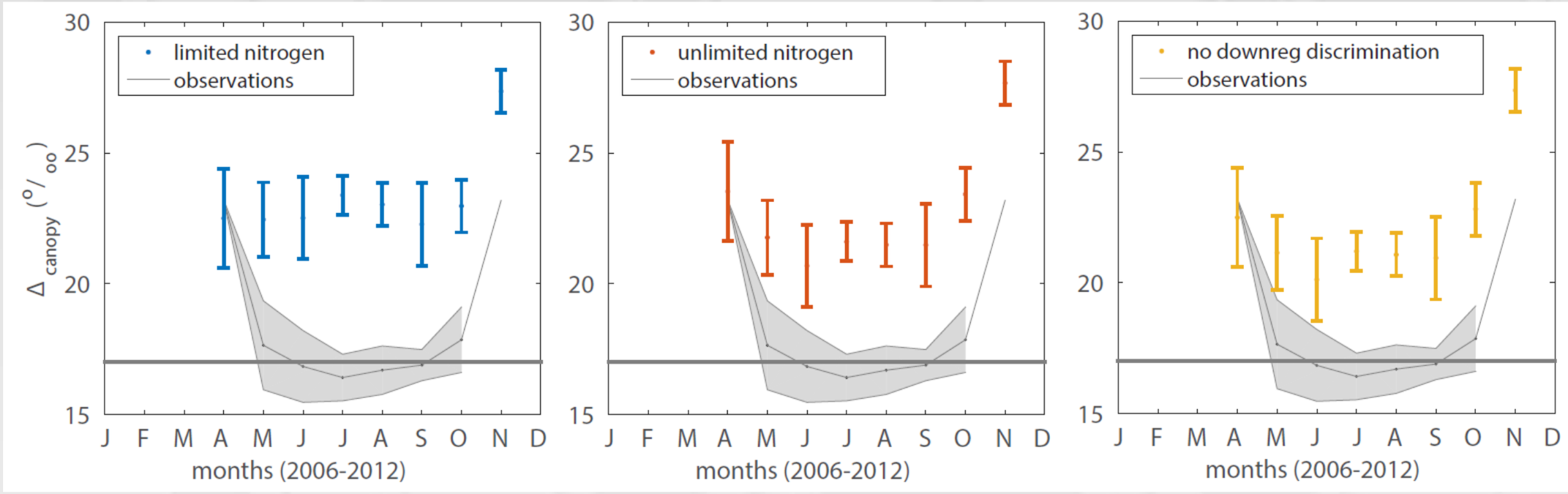

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- All formulations overestimate discrimination (yrs. 2006-2012) indicating stomatal conductance is too high (parameter, structure, VPD trend issue?)

- Perhaps the model/obs match of $\delta^{13}C$ biomass was fortuitous (compensating biases?)

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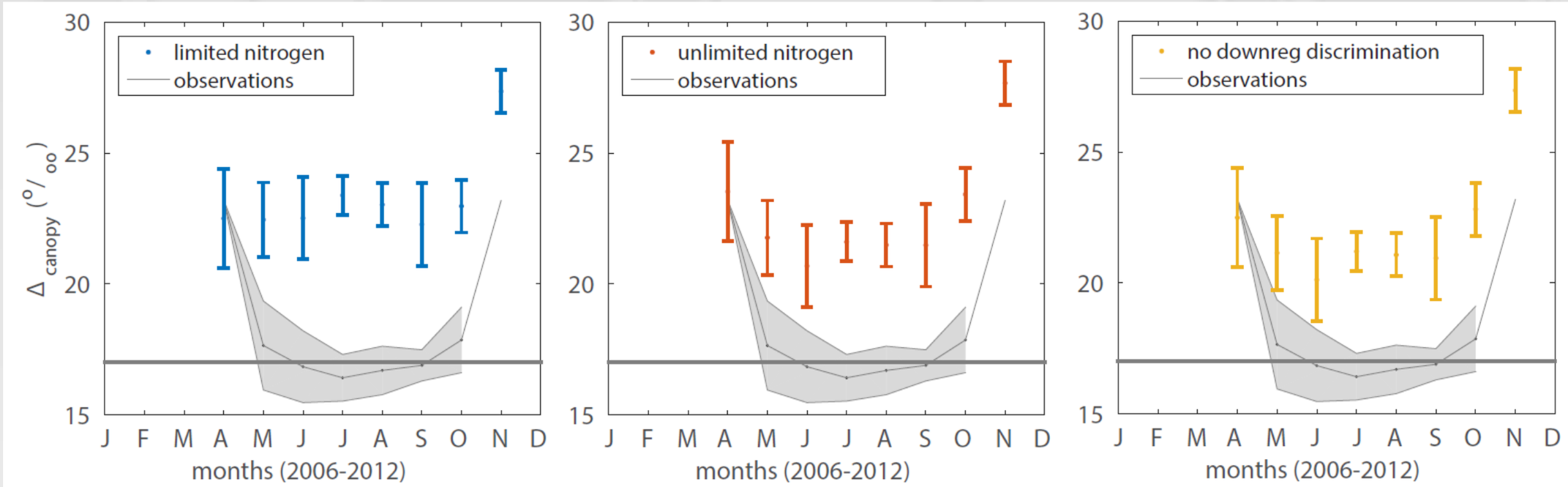

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- Limited nitrogen: no season trend

- Other formulations: Capture weaker summer discrimination

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Seasonal discrimination: magnitude & pattern

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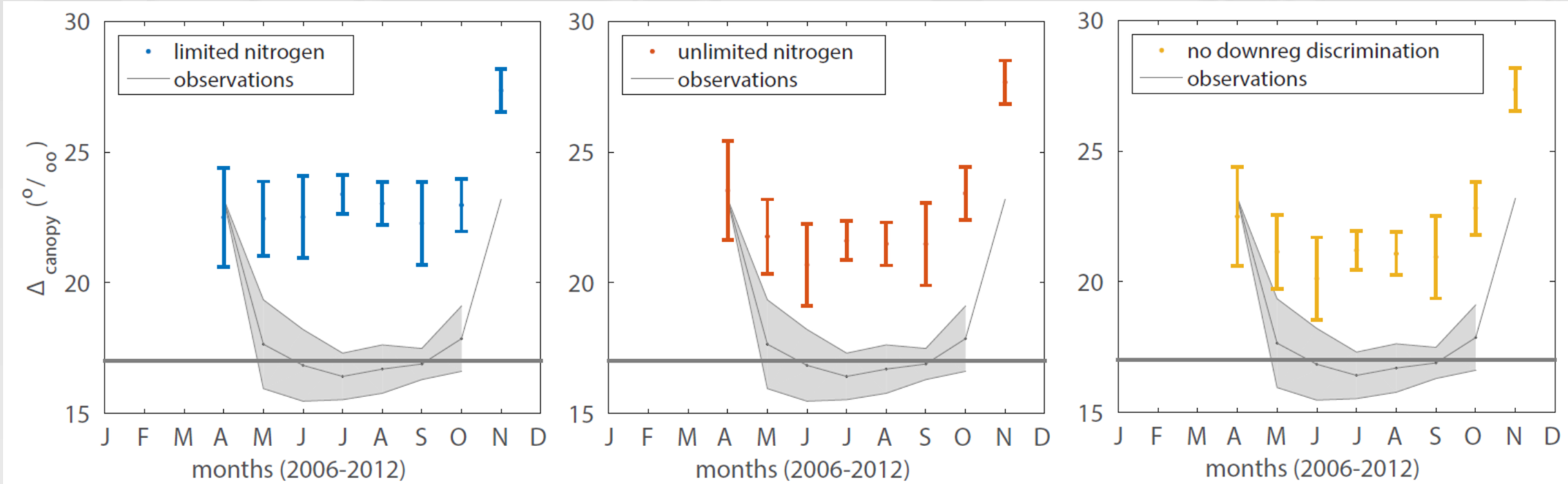
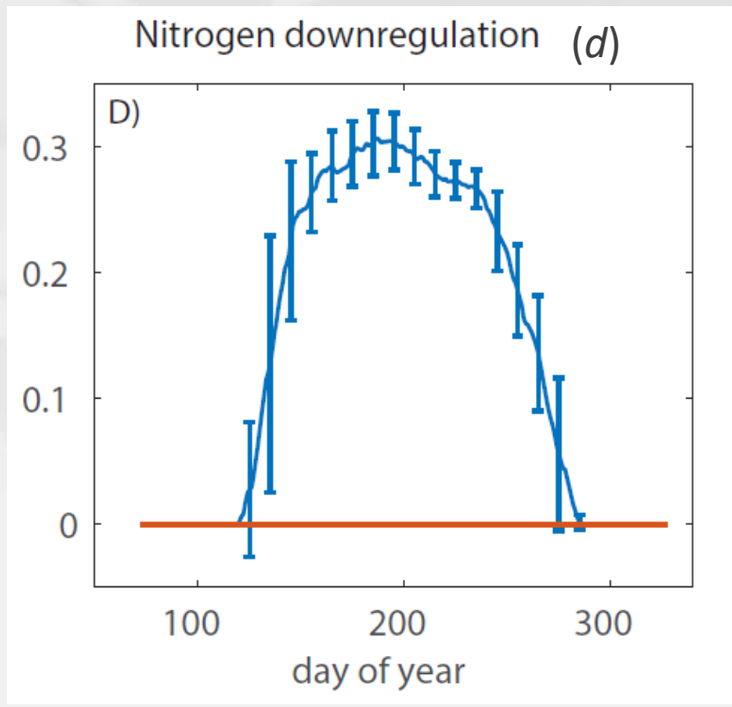
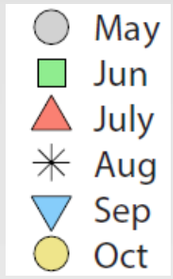




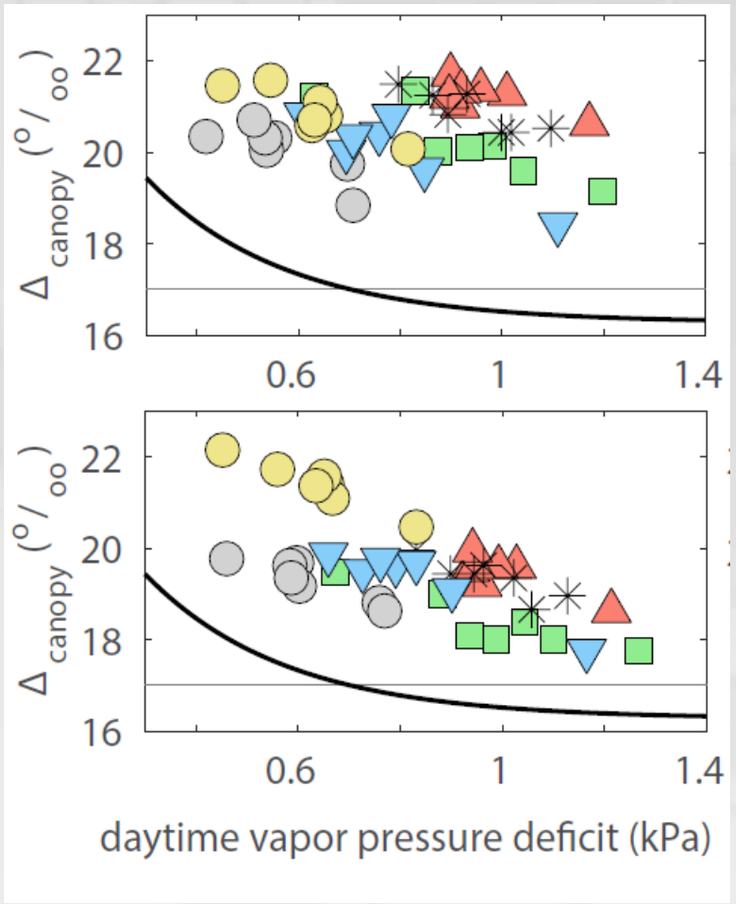
Seasonal discrimination: environmental drivers

2006-2012 monthly mean values

Limited nitrogen simulation



Unlimited nitrogen simulation



- Unlimited nitrogen formulation produces observed VPD correlation

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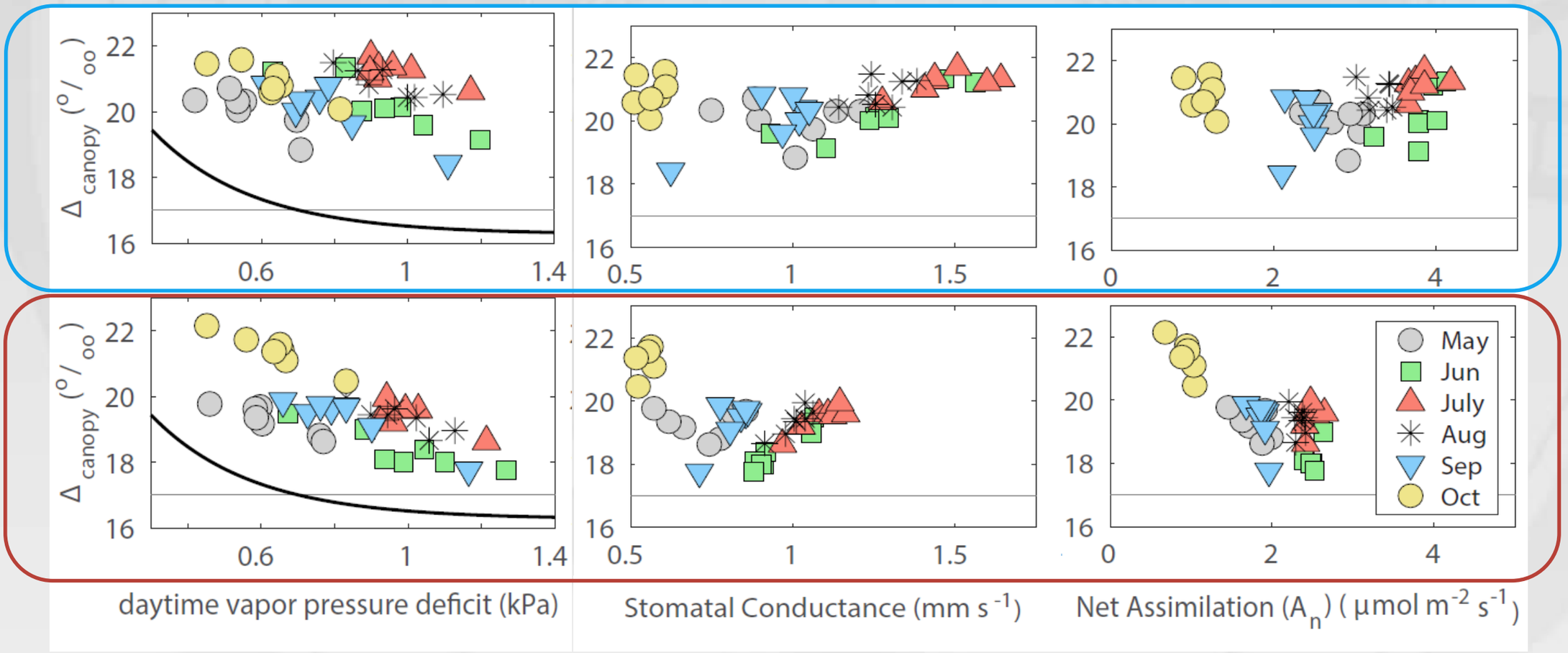
Seasonal discrimination: environmental drivers

2006-2012 monthly mean values

Limited nitrogen simulation

Unlimited nitrogen simulation



- Unlimited nitrogen formulation produces observed VPD correlation

- Net Assimilation is the primary control across season driver (spring, summer, fall)
- VPD is the primary control in summer only, inter-annual variation

Conclusions

- CLM is able to reproduce $\delta^{13}C$ in stem and biomass and the seasonal cycle in $\Delta_{canopy,}$ but only for certain model formulations
- The relative success of the 'pre-photosynthetic' formulation suggests a foliar nitrogen sub-model is worth testing in the future

Conclusions

- CLM is able to reproduce $\delta^{13}C$ in stem and biomass and the seasonal cycle in $\Delta_{canopy,}$ but only for certain model formulations
- The relative success of the 'pre-photosynthetic' formulation suggests a foliar nitrogen sub-model is worth testing in the future
- All model formulations overestimated contemporary observations of photosynthetic discrimination. Future work should identify whether this is a bias in parameterization (stomatal slope), structure (Leuning vs Ball-Berry) or multi-decadal trends in VPD (not included here).
- The model attributed most of the variation in seasonal discrimination to assimilation rate, and summer variation to VPD. Soil moisture had minimal impact.

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Acknowledgements

- This research was supported by the U.S. Department of Energy, Office of Science, Office of Biological and Environmental Research, Terrestrial Ecosystem Science Program under Award Number DE-SC0010625.

- Thank you to Sean Burns and Peter Blanken for sharing flux tower and meteorological data from Niwot Ridge.

- We thank NOAA and ESRL for providing Niwot Ridge flask data.

- The support and resources from the Center for High Performance Computing at the University of Utah are gratefully acknowledged.

Supplemental Slides

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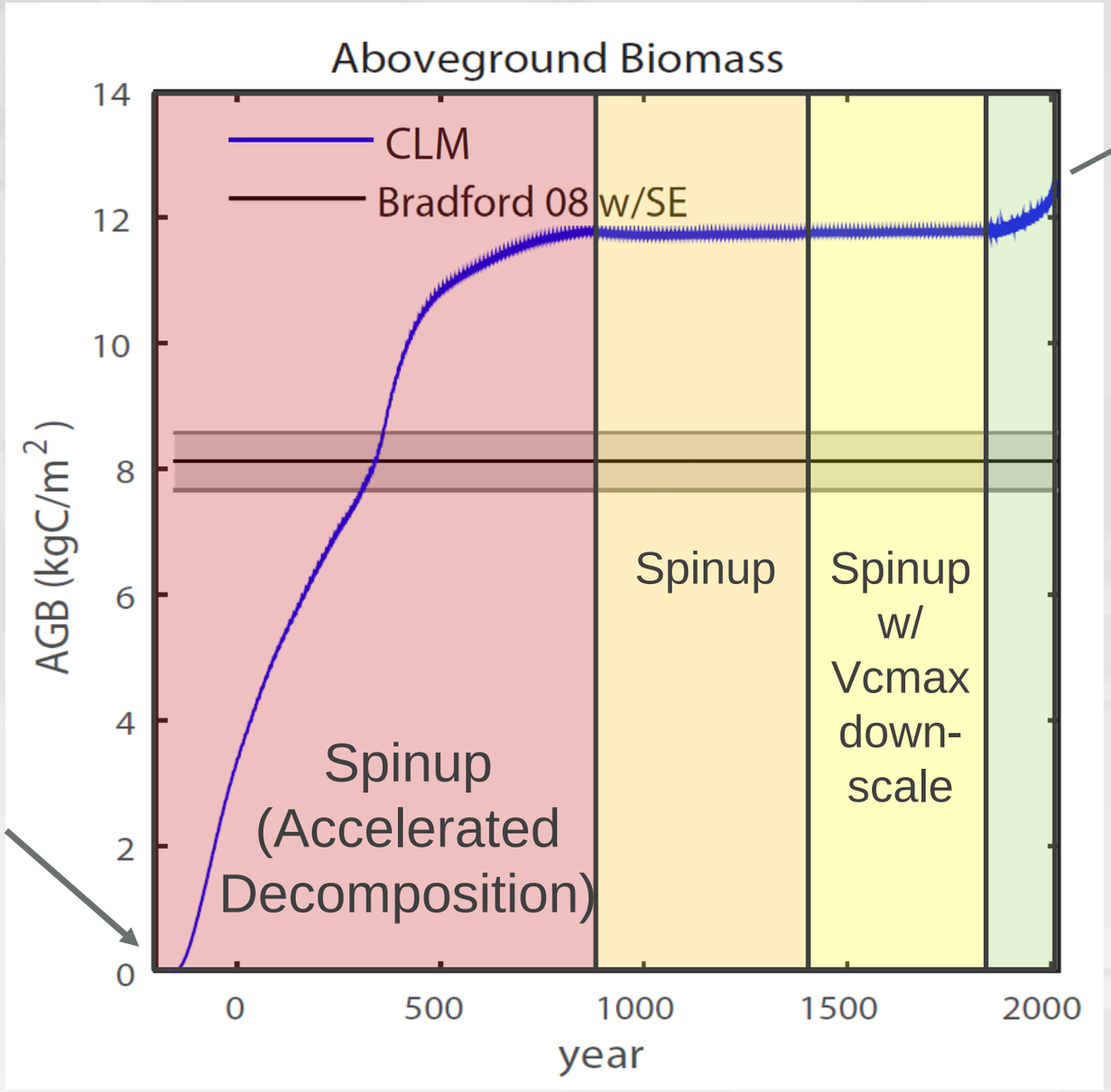
Overview

Global: Double Deconvolution method
Regional: Attribute
Local: C3/C4 plant distributions

Key Question: Is vapor pressure deficit a primary driver of carbon isotopic photosynthetic discrimination at Niwot Ridge? (Bowling VPD relationship picture…)

Methods: Initializing Niwot Ridge to present day (spin-up)

FINISH: present day (year 2013)



START: at near bare ground state

Spinup_AD: 1000 years
Looping 1998-2006 tower meteorology
Pre-industrial atm CO_2
'Fast soil carbon turnover'

Spinup: 1000 years
Same as above w/
'Normal soil carbon turnover'

Spinup w/ Vcmax : 1000 years
Same as above w/
'Vcmax seasonal downscale'

Transient: 1850-2013
Increasing atm. CO_2
Decreasing atm. $\delta^{13}C$
Nitrogen deposition'

Table 2. CLM 4.5 key parameter values for all model formulations

Parameter	Description	Value	Units
froot_leaf	new fine root C per new leaf C	0.5	gC/gC
froot_cn	fine root (C:N)	55	gC/gN
leaf_long	leaf longevity	5	years
leaf_cn	leaf (C:N)	50	gC/gN
lflitcn	leaf litter (C:N)	100	gC/gN
slatop	specific leaf area (top canopy)	0.007	m^2/gC
stem_leaf	new stem C per new leaf C	2	gC/gC
mp	stomatal slope	9	meter/sec
croot_stem	coarse root: stem allocation	0.3	gC/gC
deadwood_cn	dead wood (C:N)	500	gC/gN
livewood_cn	live wood (C:N)	50	gC/gN
flnr	fraction of leaf nitrogen within Rubisco enzyme	0.0509	gN/gN
decomp_depth_e_folding	controls soil decomposition rate with depth	20	meter

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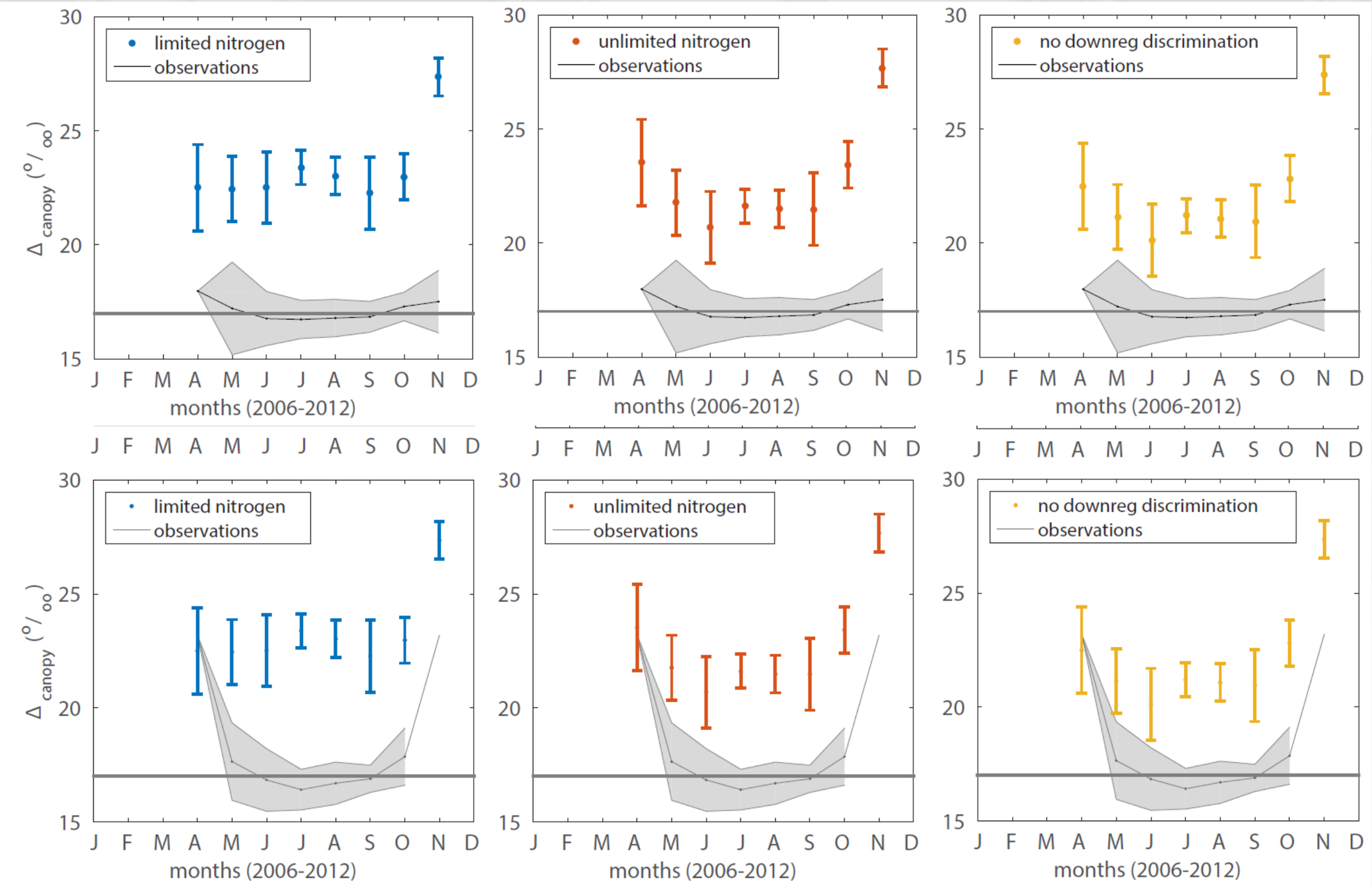
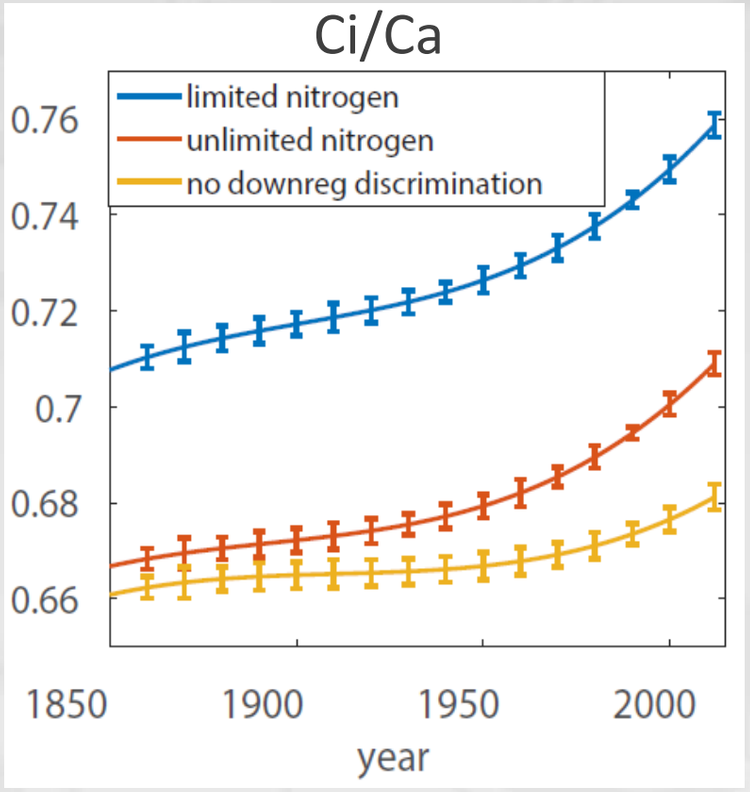
Contemporary discrimination: Reichstein- Lasslop partitioning

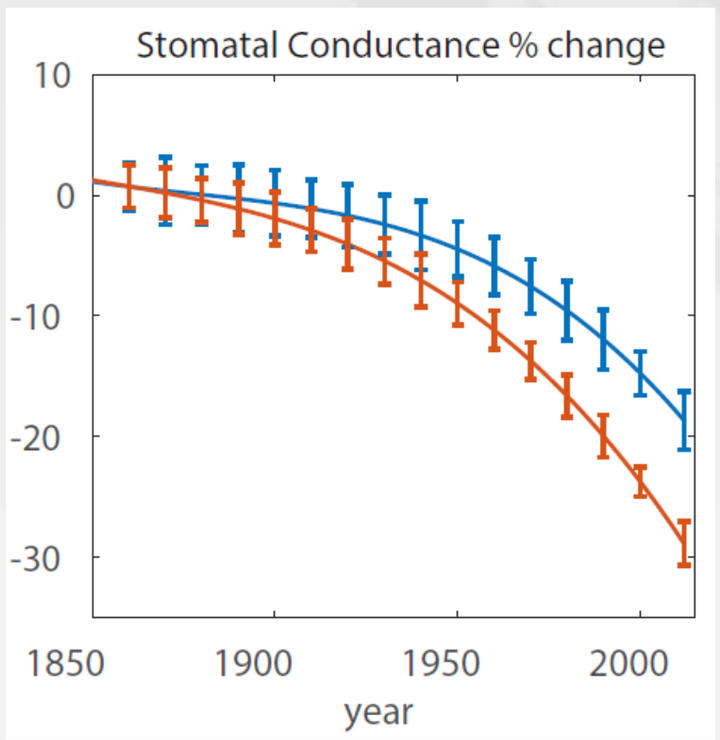


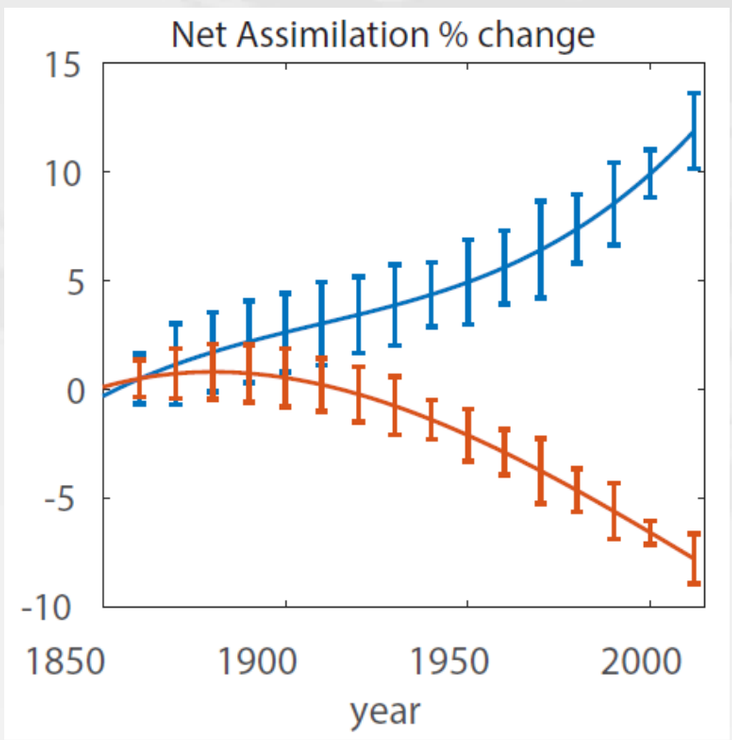
CLM response to CO_2 fertilization

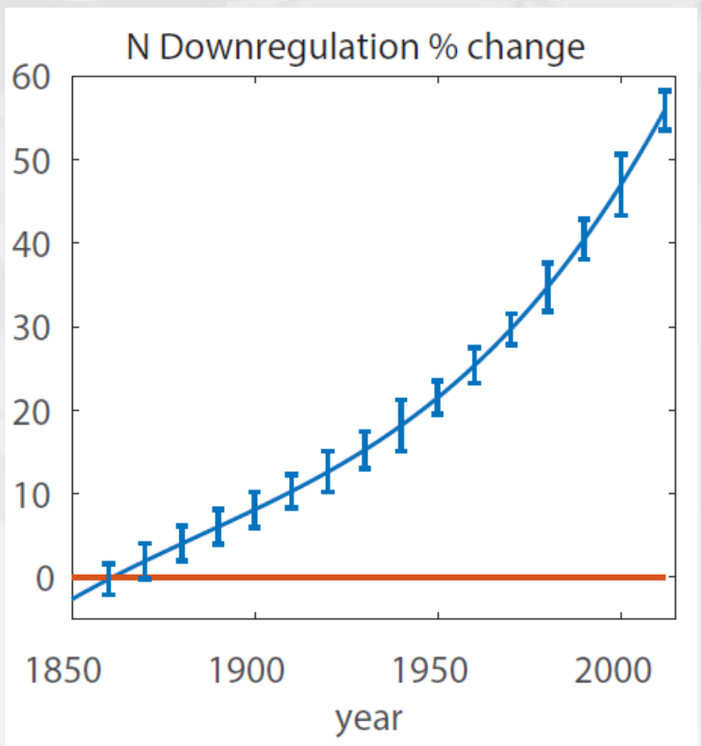


- In general, theory and observations suggests vegetation should maintain Ci/Ca (Franks et al. 2015)

- CLM simulates a 'weak/moderate' stomatal response







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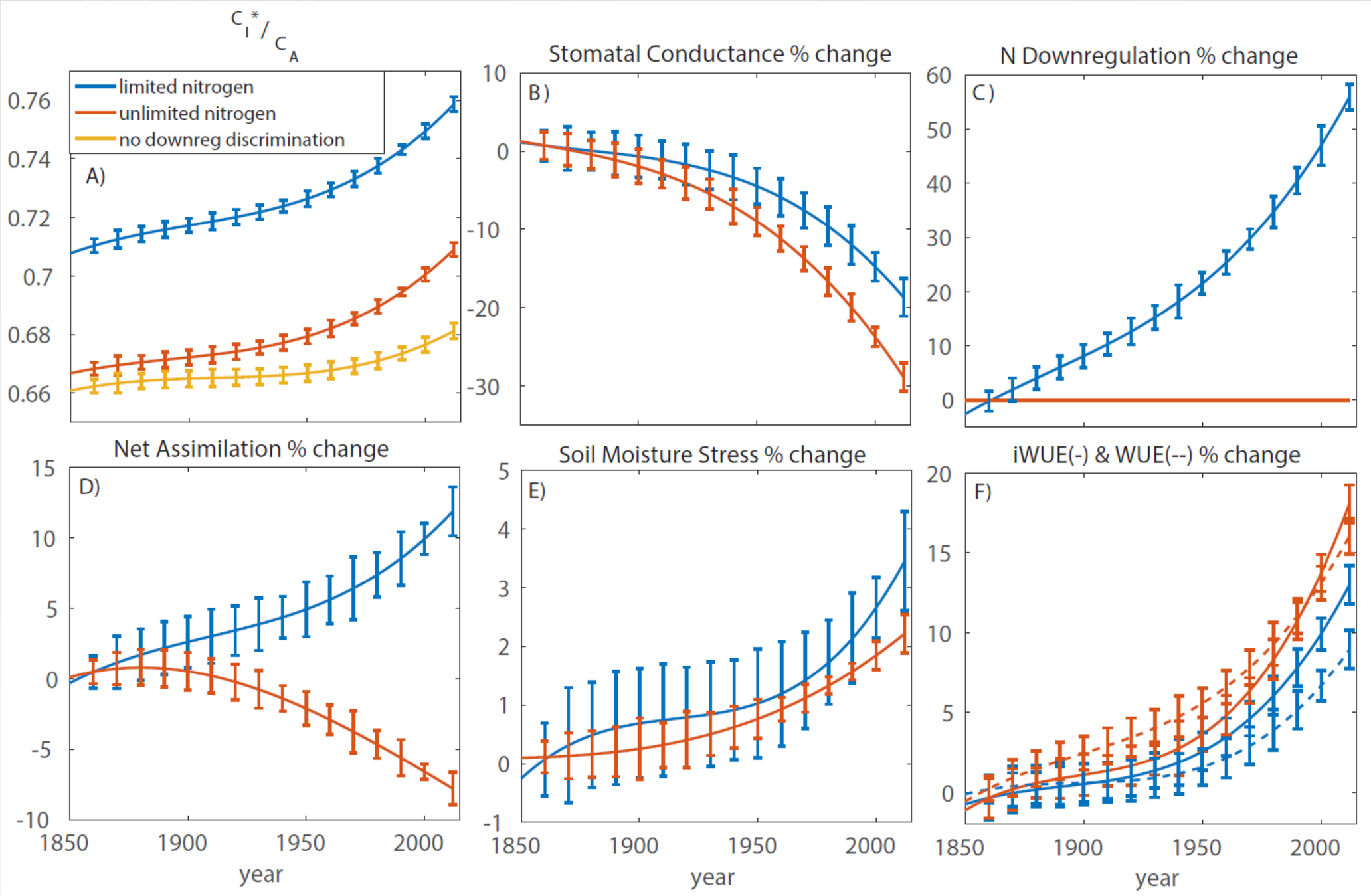
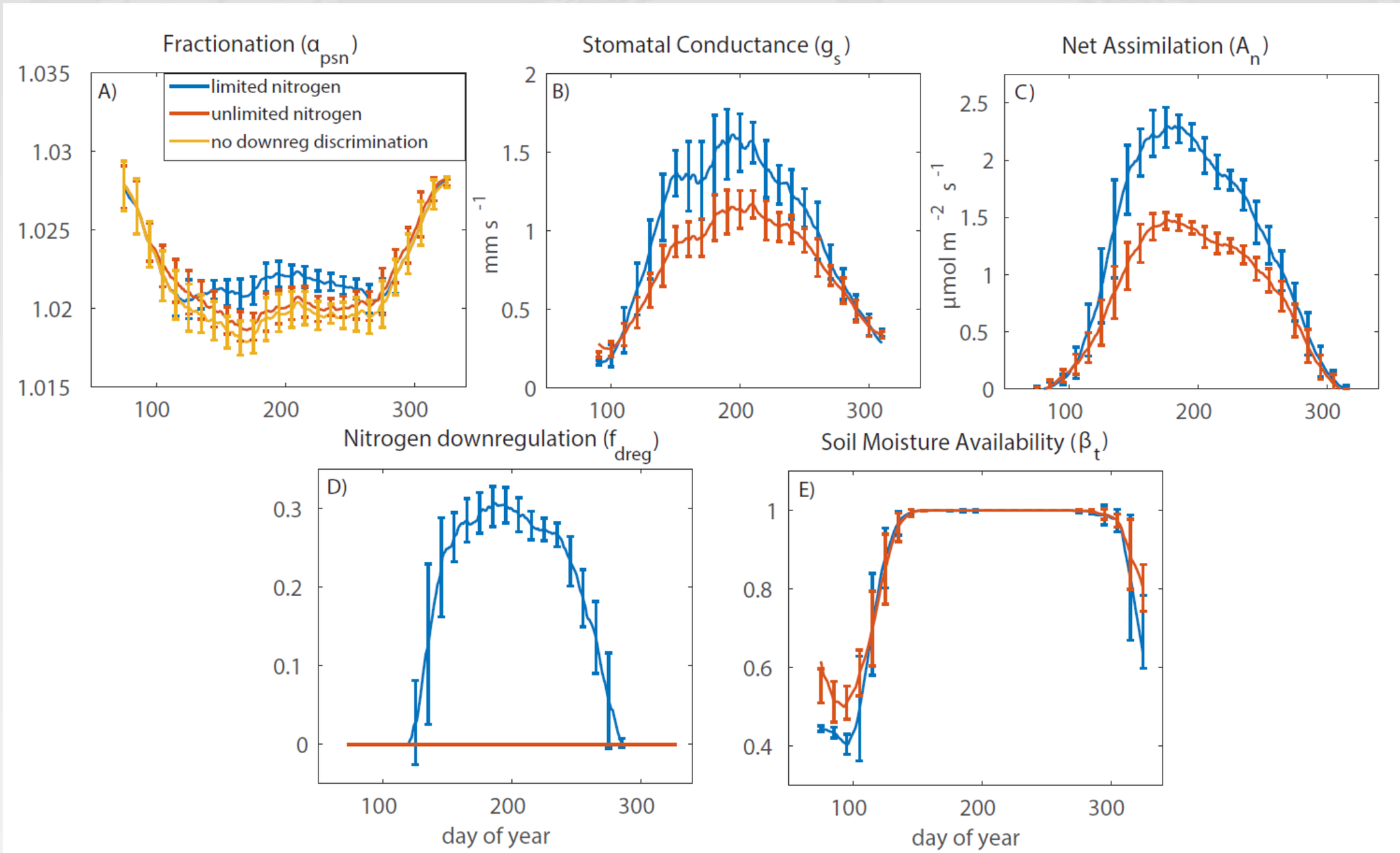


Seasonal environmental drivers



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Discrimination: Leaf VPD and RH