MAX PLANCK INSTITUTE
FOR BIOGEOCHEMISTRY

NUTRIENT CYCLE PROCESSES: WHERE ARE WE NOW & WHERE DO WE NEED TO GO?

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with input from:

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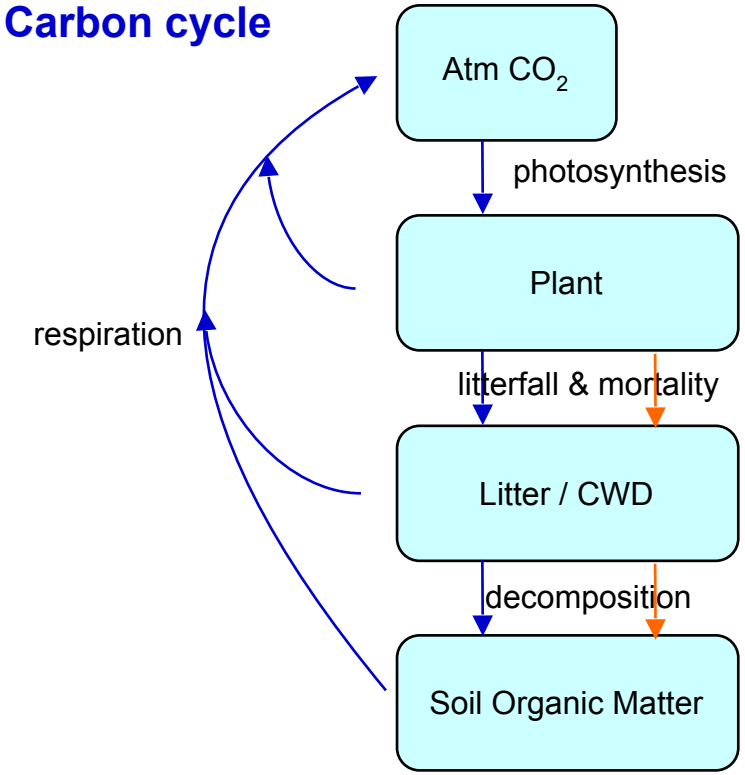
COUPLING OF TERRESTRIAL C-N-P CYCLES

Carbon cycle



Nitrogen cycle

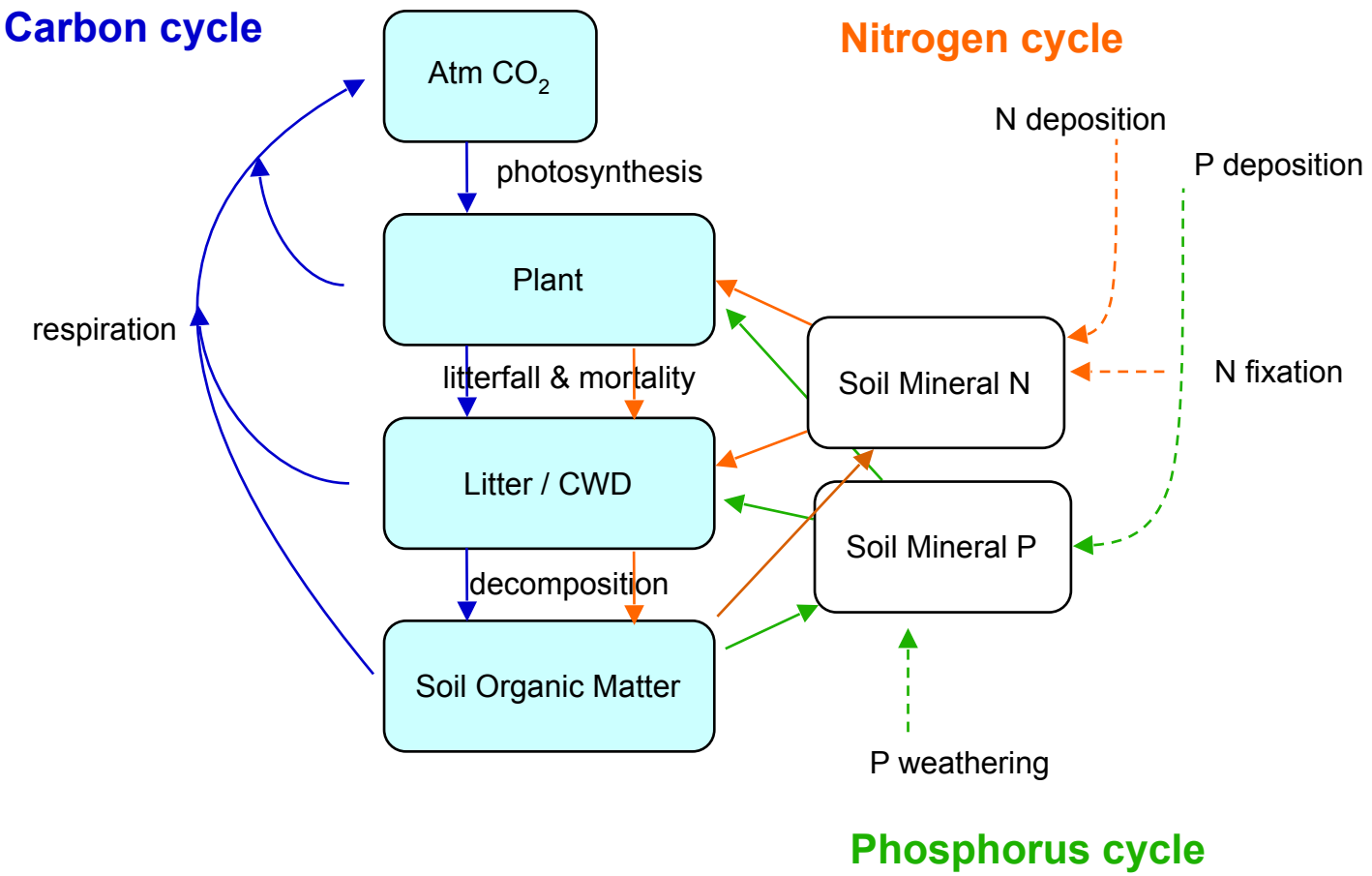
Land Biosphere C is organic:

- N needed for enzymes,
- N + P for biochemical reactions

-> constrained C:N:P stoichiometry

Phosphorus cycle

COUPLING OF TERRESTRIAL C-N-P CYCLES



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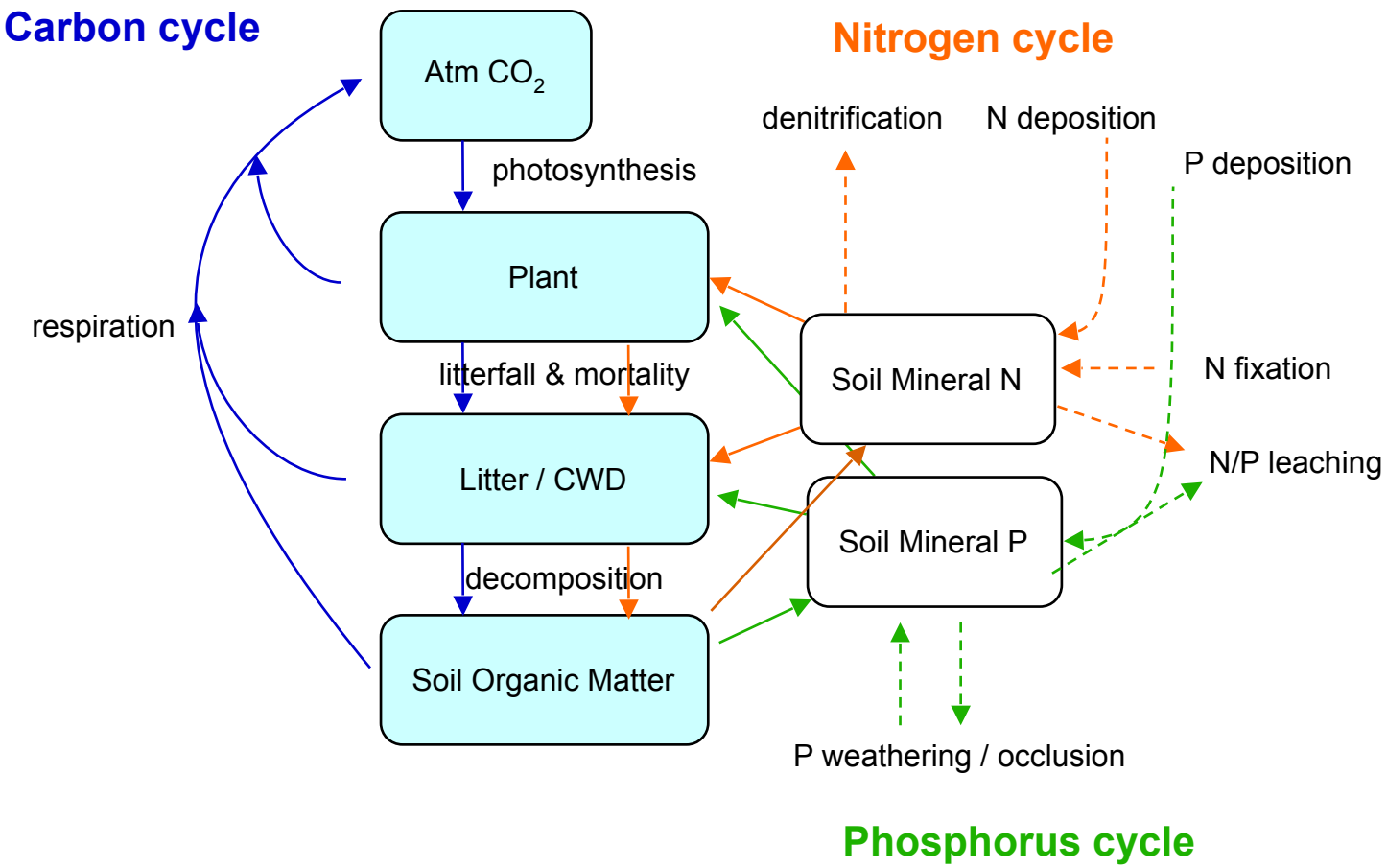
N and P are scarce in natural ecosystems

- high costs of biological N fixation
- P is derived from soil weathering

COUPLING OF TERRESTRIAL C-N-P CYCLES



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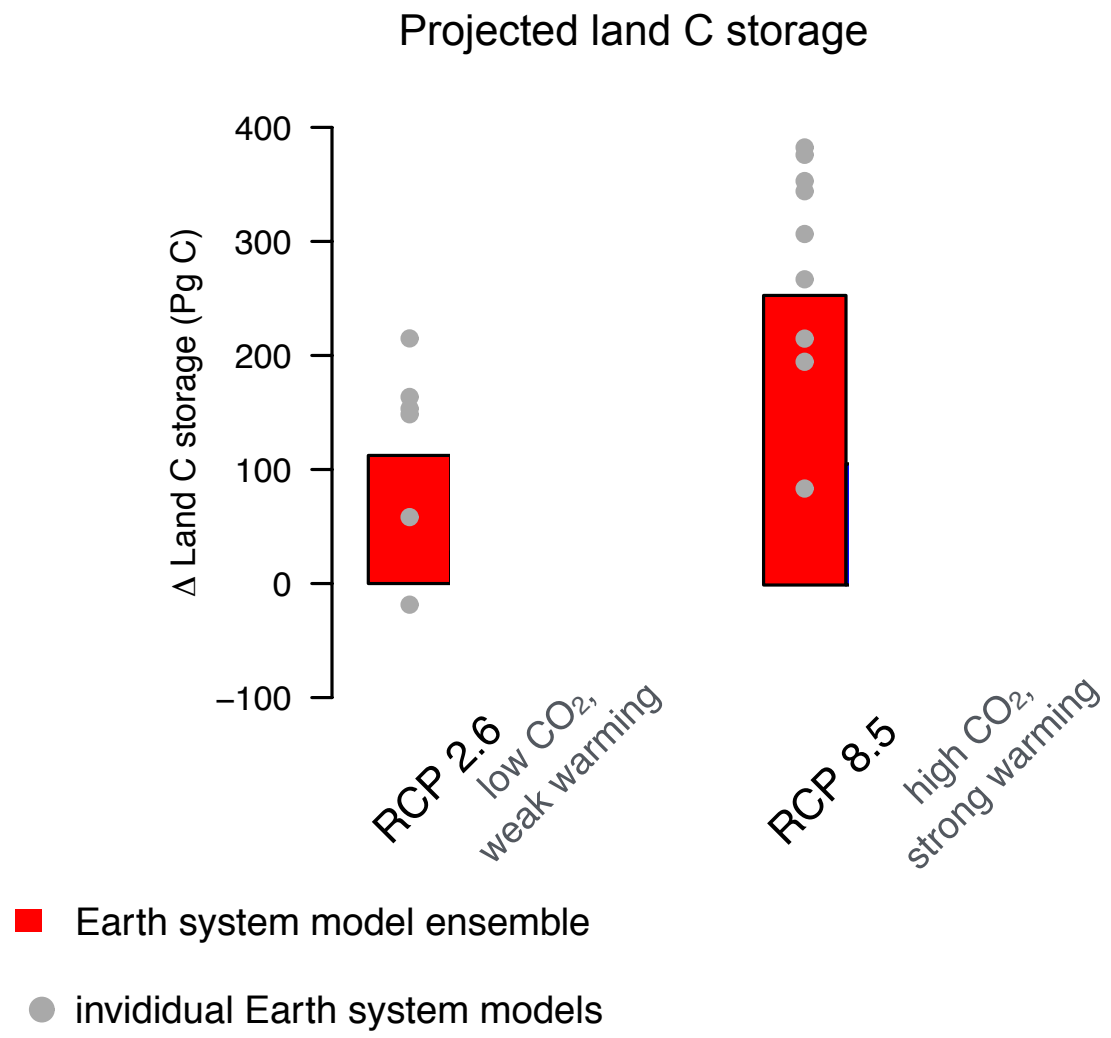
Nutrient cycle are leaky

- gaseous and leaching N losses
- P becomes gradually locked in biologically unaccessible forms.

N & P feedbacks between soil processes and vegetation growth

INFERRED N LIMITATION IN CMIP5 PROJECTIONS



Zaehle et al. 2015

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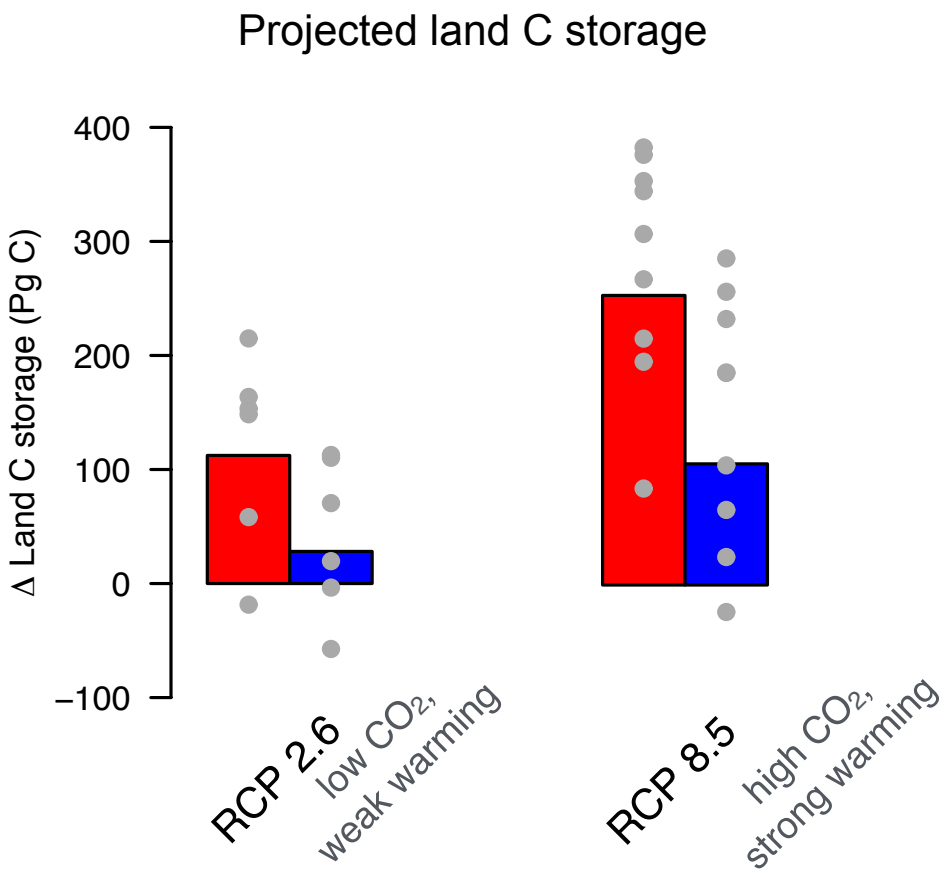
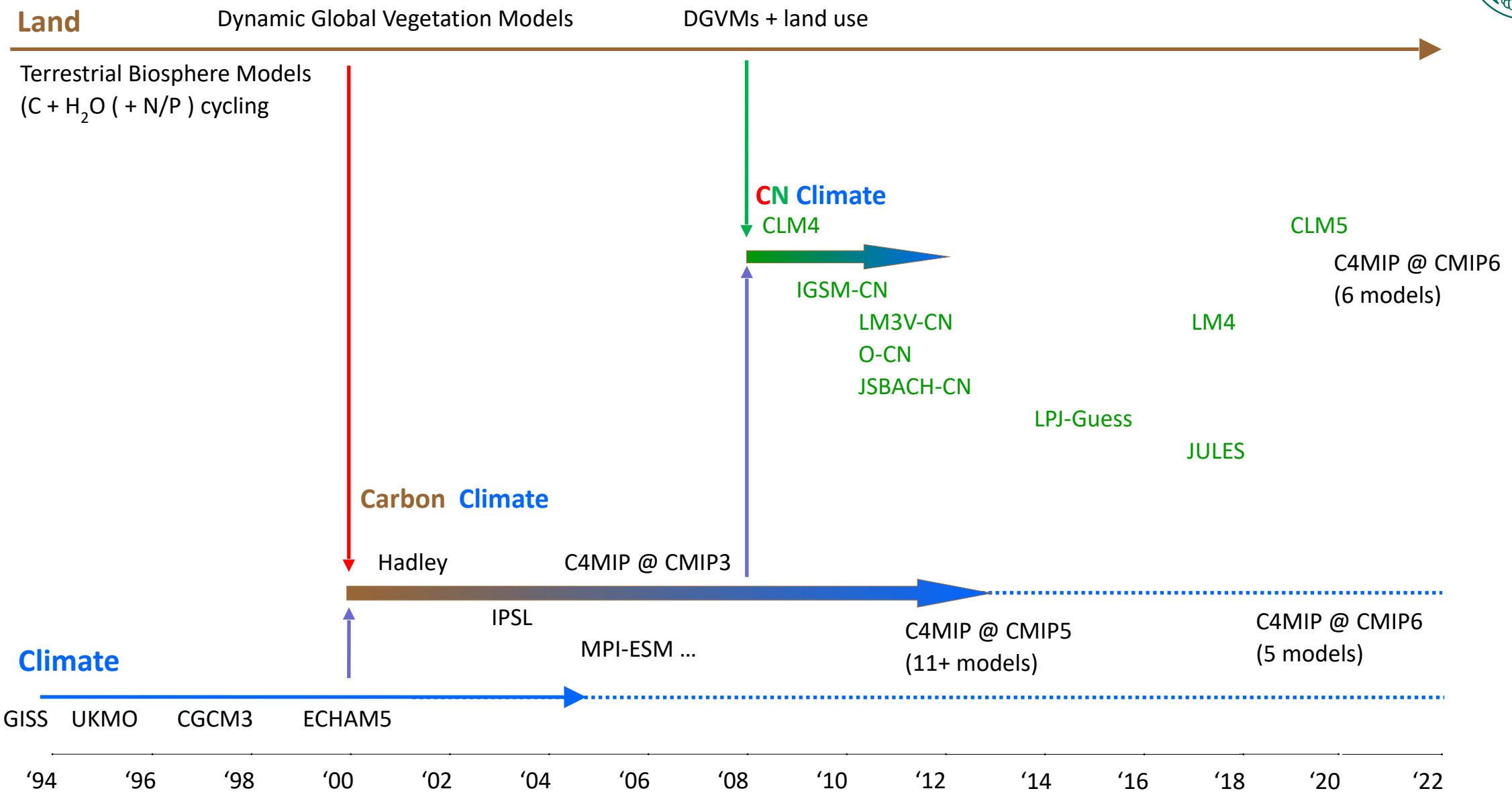


Zaehle et al. 2015

DEVELOPMENT OF CLIMATE-BIOGEOCHEMISTRY MODELS



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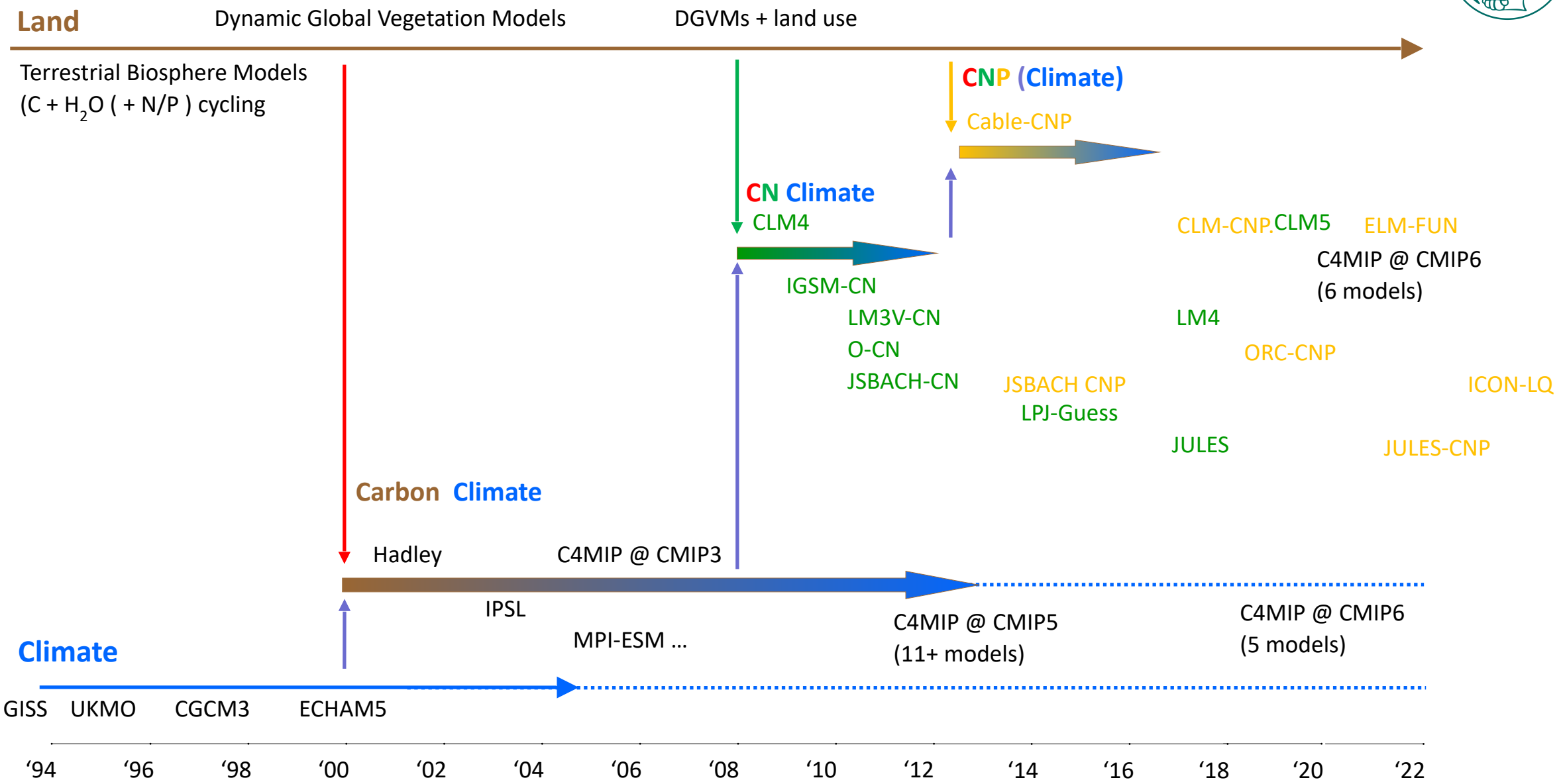
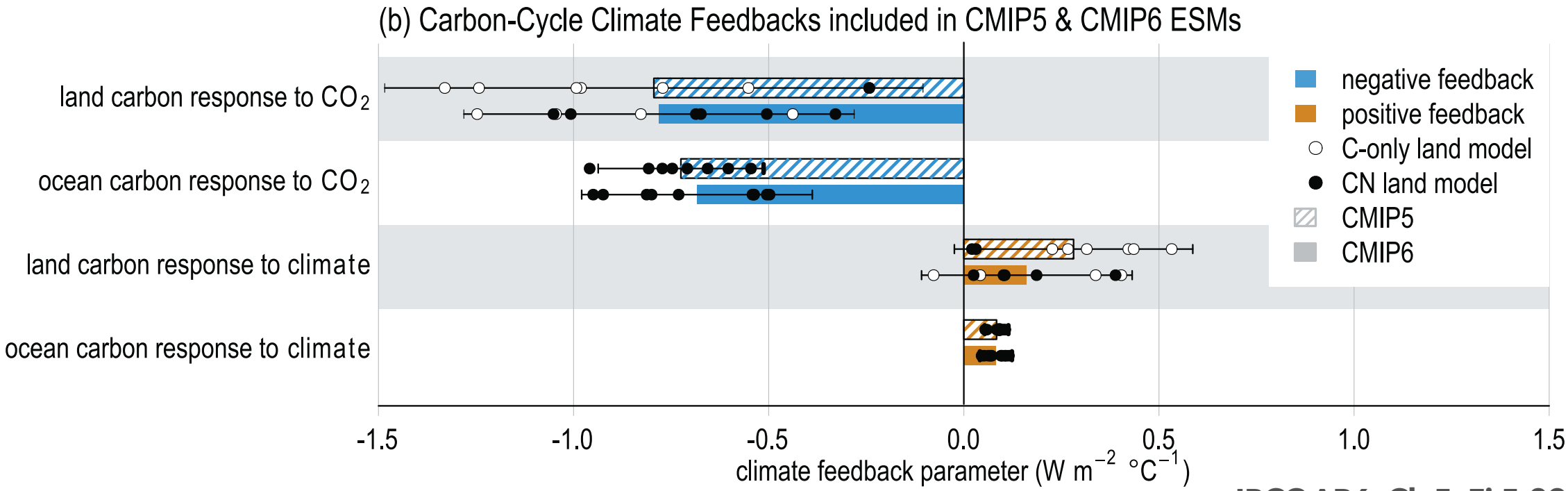


CARBON CYCLE FEEDBACKS IN CMIP6

New model structures of C-N models since CMIP5

- show attenuated carbon-cycle feedbacks,
- but with increased C-N model spread

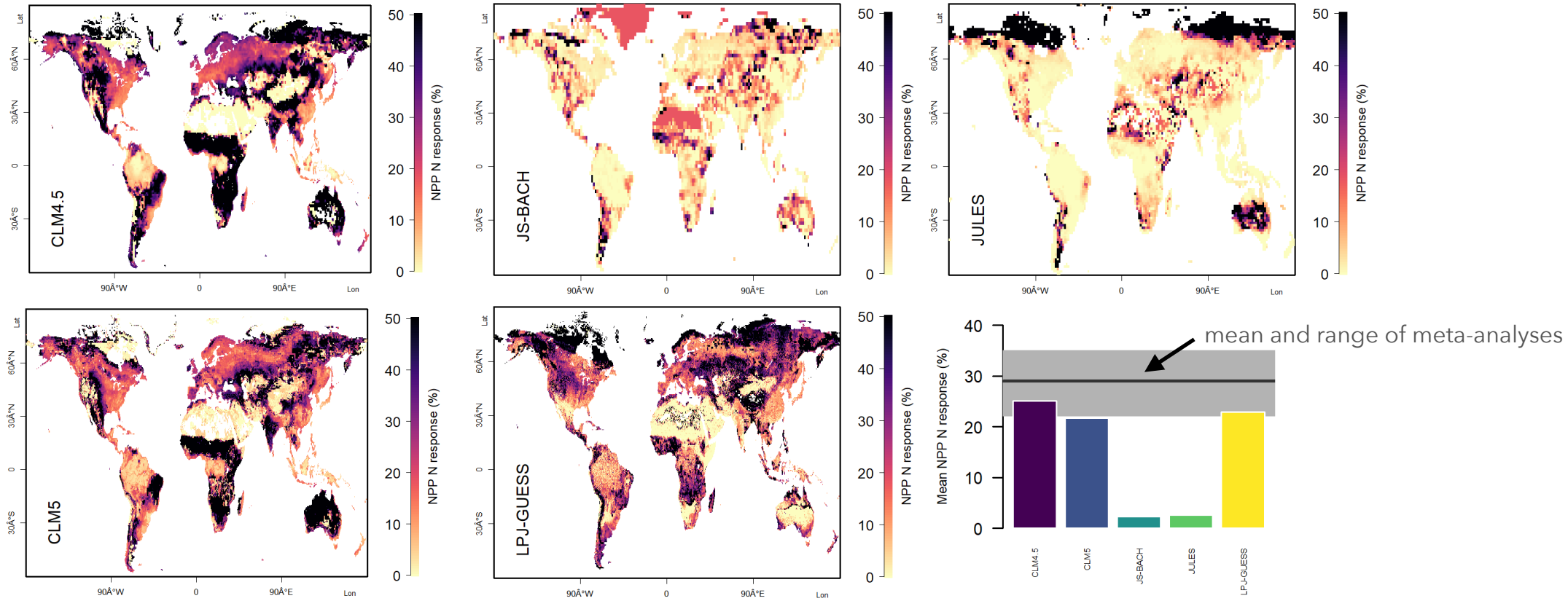


IPCC AR6, Ch 5, Fi 5.29, data from: Arora et al. 2020

LARGE DIVERGENCE IN MODEL RESPONSES

New model structures of C-N models since CMIP5

- show global carbon & nitrogen cycles generally compatible with standard C-cycle benchmarks
- but diverse responses to forcing changes (N addition, CO_2 increase…)

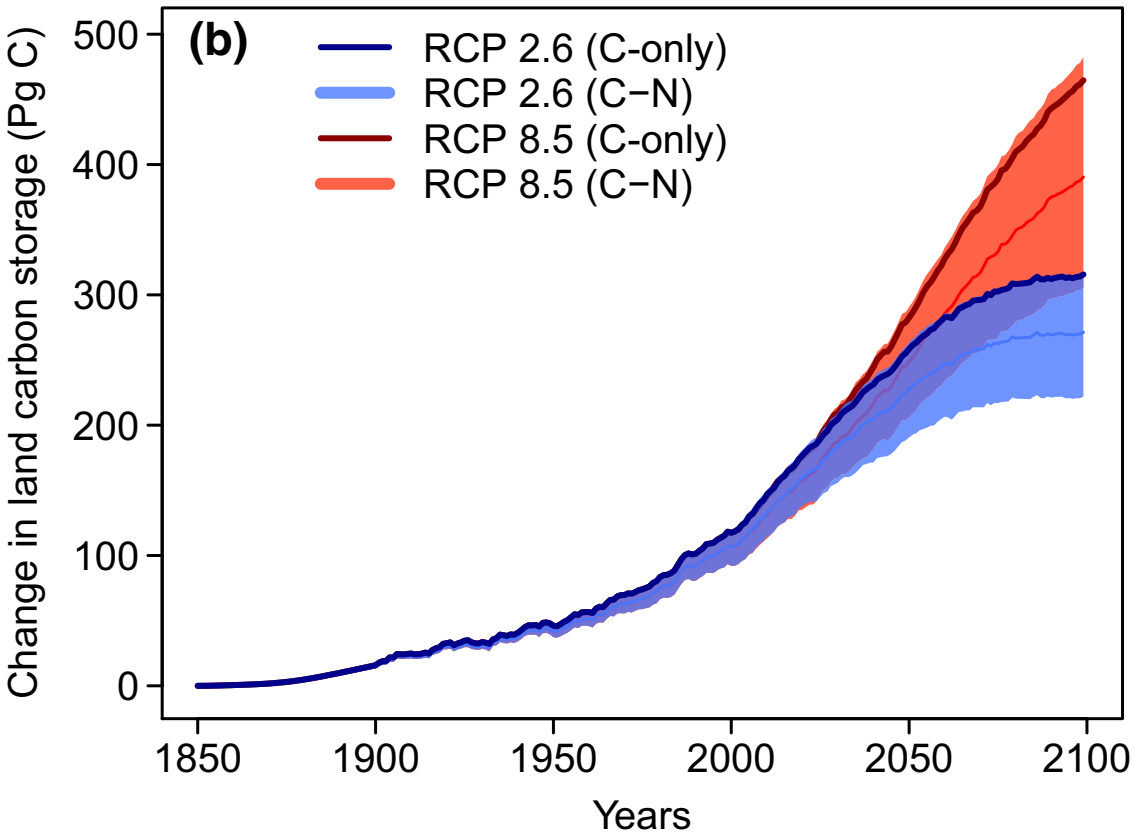


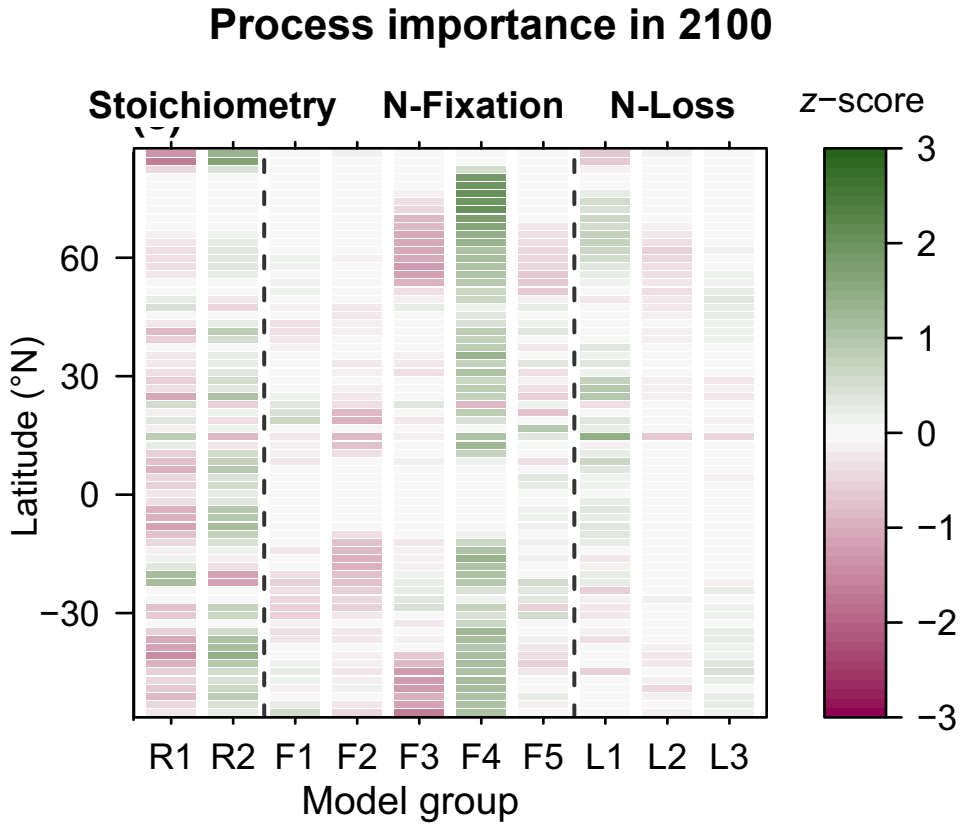
Davies-Barnard et al. 2021

EFFECT OF STRUCTURAL MODEL UNCERTAINTY

- Ensemble of opportunities rarely give good insights into underlying causes of model spread
- Modular approach needed to test multiple alternatives in a common modelling framework

  Here: 30 alternative N cycles in the OCN framework





Meyerholt et al. 2020

INSIGHT FROM PROCESS-PERTURBATIONS

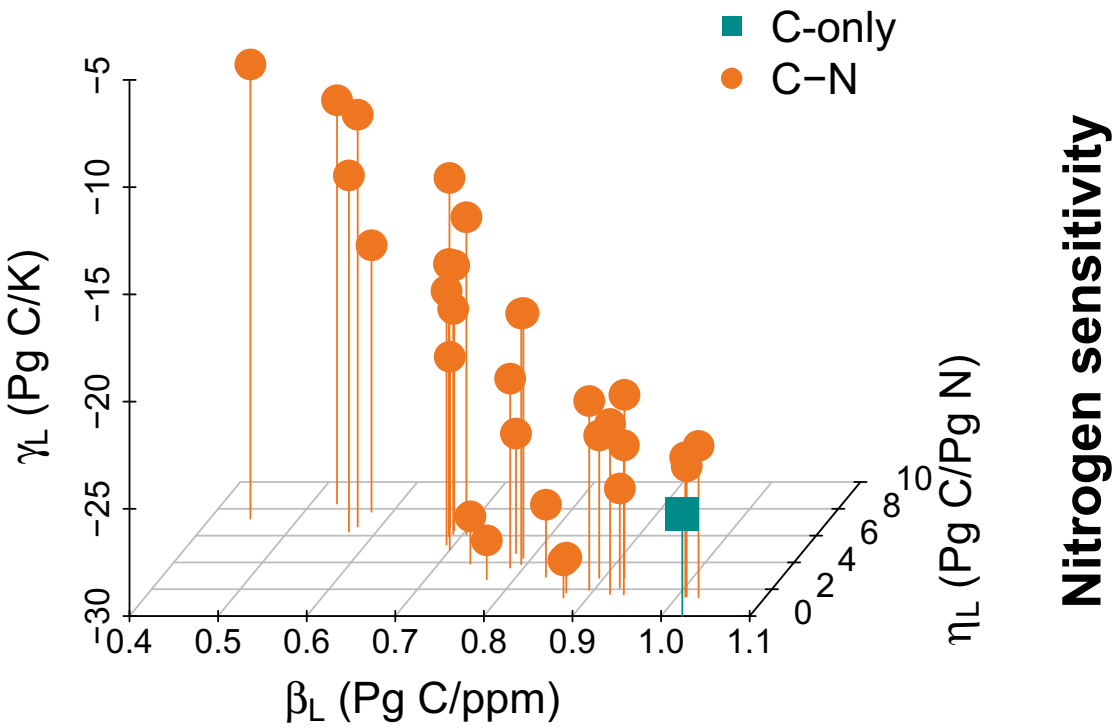
- Long-term dynamics not controlled by controls of IAV
- Clear trade-off in the magnitude of N limitation globally

Technical Challenges:

- ecosystems outside equilibrium
- computational efficiency

Interannual timescale

Climate sensitivity



Nitrogen sensitivity

Centennial timescale

CO_2 sensitivity

Meyerholt et al. 2020

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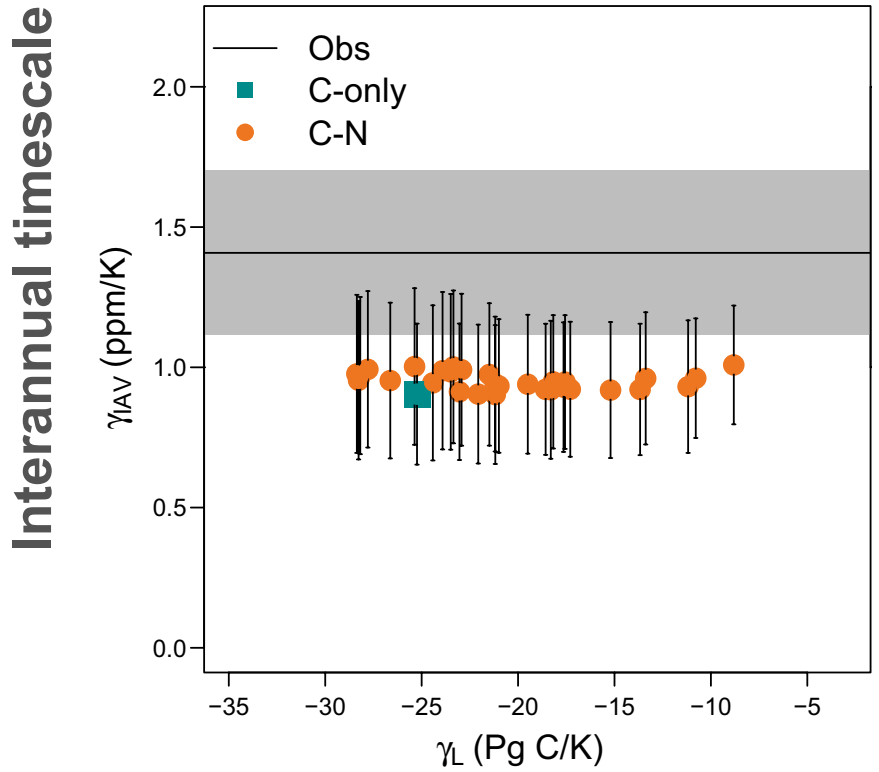
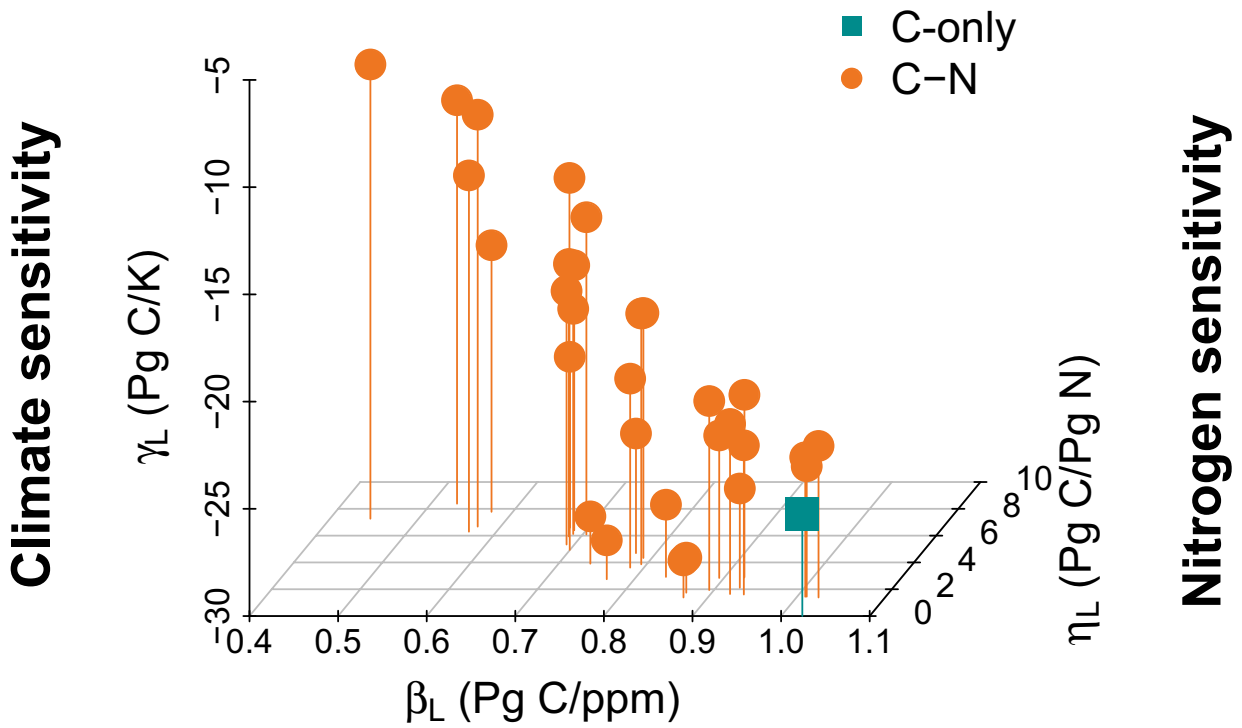


Centennial timescale



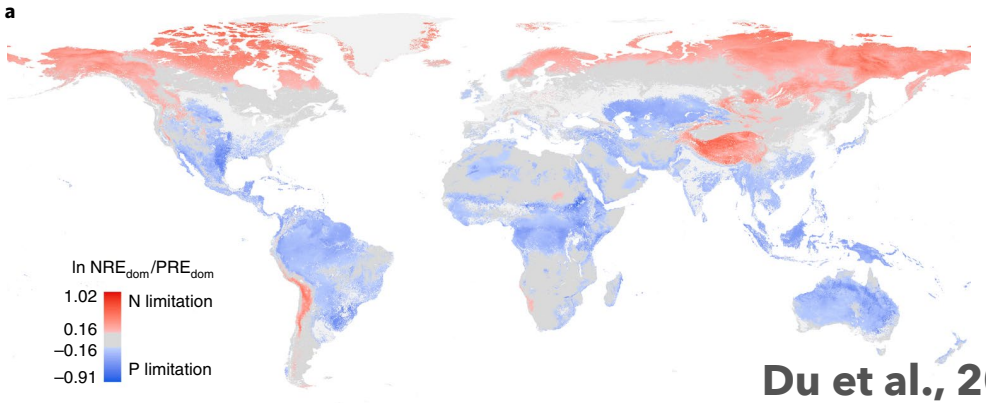
CO_2 sensitivity

Meyerholt et al. 2020

OPEN QUESTION: DISTRIBUTION OF N AND P LIMITATION

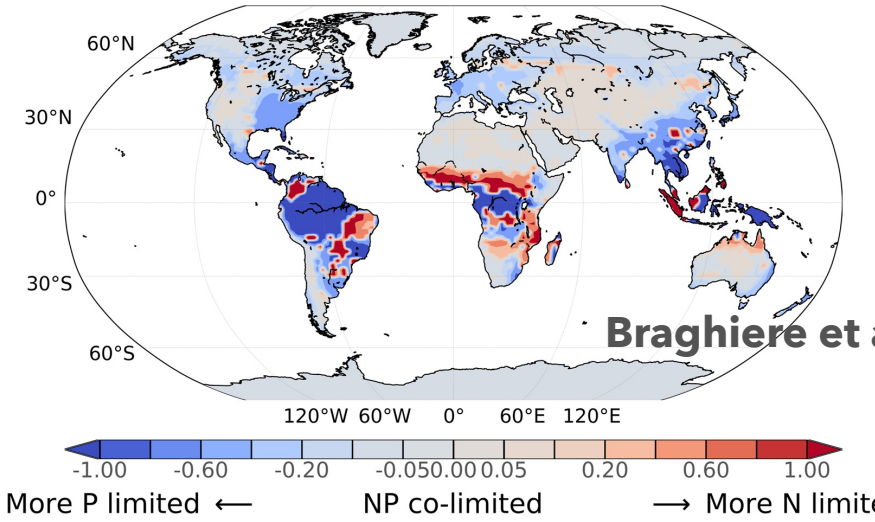
- Tremendous progress in making more realistic representations of nutrient cycle processes
- Tend to be (much) less restrictive than the first models of this kind
- Can reproduce global benchmarks similar to their C-cycle counter parts
- Have large divergence in terms of the actual effect of nutrient controls

Empirical distribution of N vs P limitation



Du et al., 2020

Model-based distribution of N vs P limitation



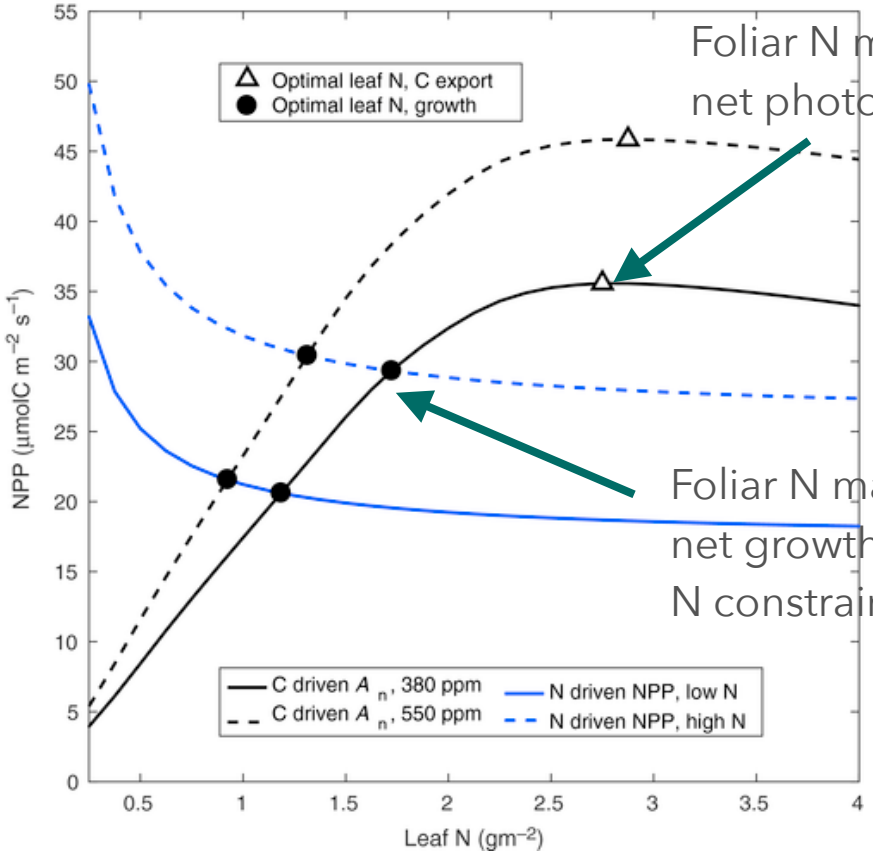
Braghiere et al. 2022

CHALLENGE: DEFINING NUTRIENT TRADE-OFFS

- How do plants adjust to changes in climate and CO_2 in terms of allocation of nutrients?
  - Important to predict spatial patterns
  - Important to predict ecosystem dynamics

- Dynamic response of plants to nutrient demand to increase below-ground carbon allocation via plant exudation and mycorrhiza vs changes vs respiration vs down regulation of photosynthesis

- Can we use optimality theory to account for these adjustments? At what time and spatial scale?



Foliar N maximising net photosynthesis

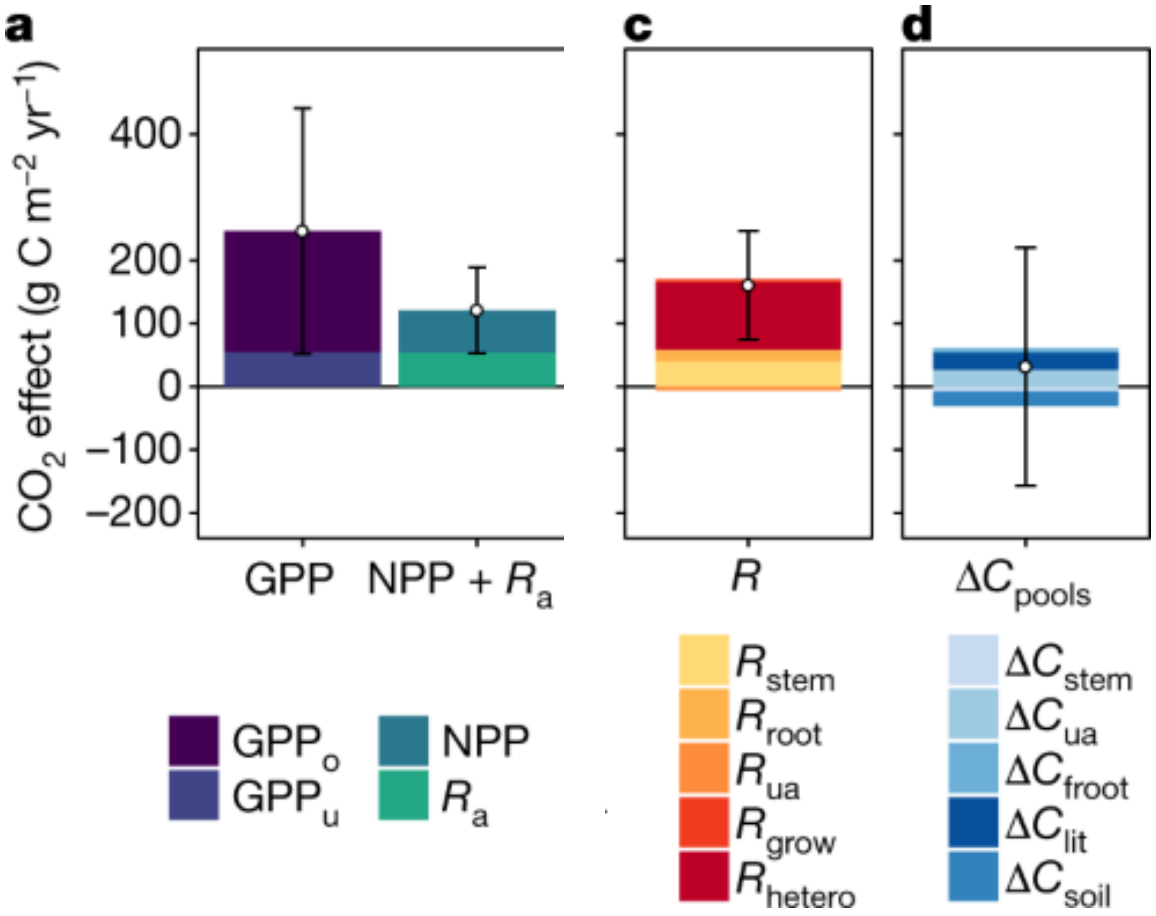
Foliar N maximising net growth under N constraints

Caldararu et al. 2020

CHALLENGE: FEEDBACKS BETWEEN VEGETATION AND SOIL

- Soil C turnover responds to increased exudation & mycorrhizal growth with “priming” (enhanced decomposition)
  - This “sometimes” makes nutrients available
- Responses are vegetation/mycorrhiza/soil type specific
  - Challenging to generalise from experiments
  - Challenging to scale up
    (e.g. global distribution of mycorrhiza)
- BUT: current soil models are giving the wrong answer, simply adding microbial explicit model likely not enough

CO_2 response in a mature, P-limited Eucalyptus Forest



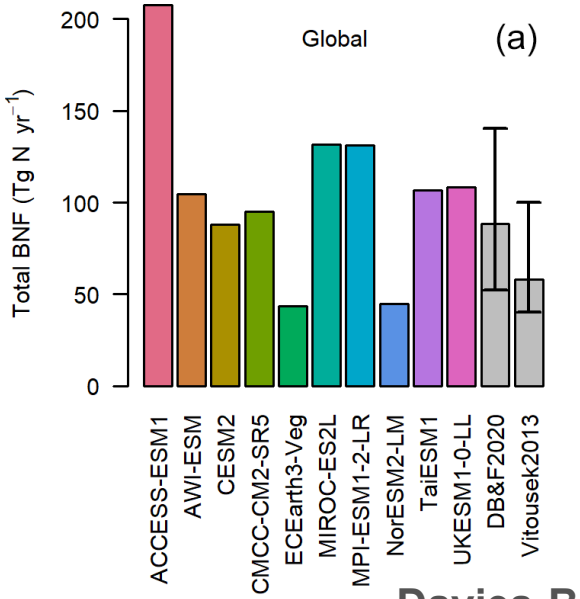
Results by : Jiang et al. 2020, Nature

CHALLENGE: CONTROLS OF NUTRIENT INPUTS

Long-term global N limitation controlled by assumptions about biological nitrogen fixation

- New data on quantifying important fixation controls (MIP by T. Bytnerowicz)
- BUT: Long-term dynamics determined by assumed cap N fixation with excess N demand (nutrient economy, vegetation composition & demography)

N fixation predicted by CMIP6 models



Davies-Barnard et al. 2022

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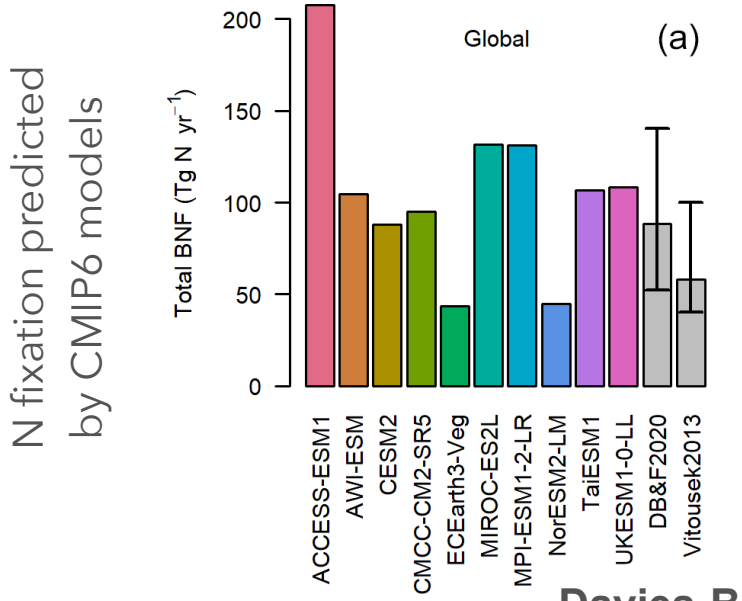
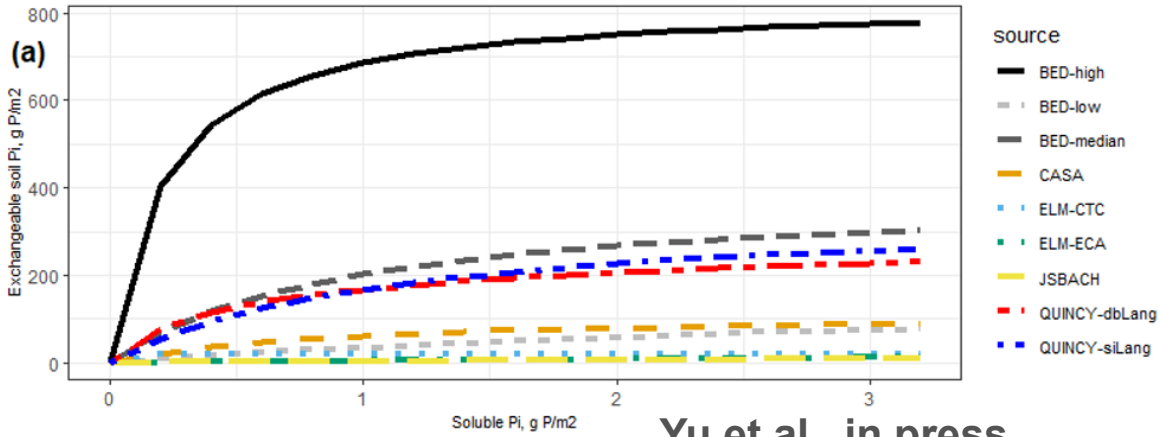


Davies-Barnard et al. 2022

Uncertainty in P availability due to exchangeability of P rather than total stock

- New data provide a better way towards representation global gradients in exchange capacity

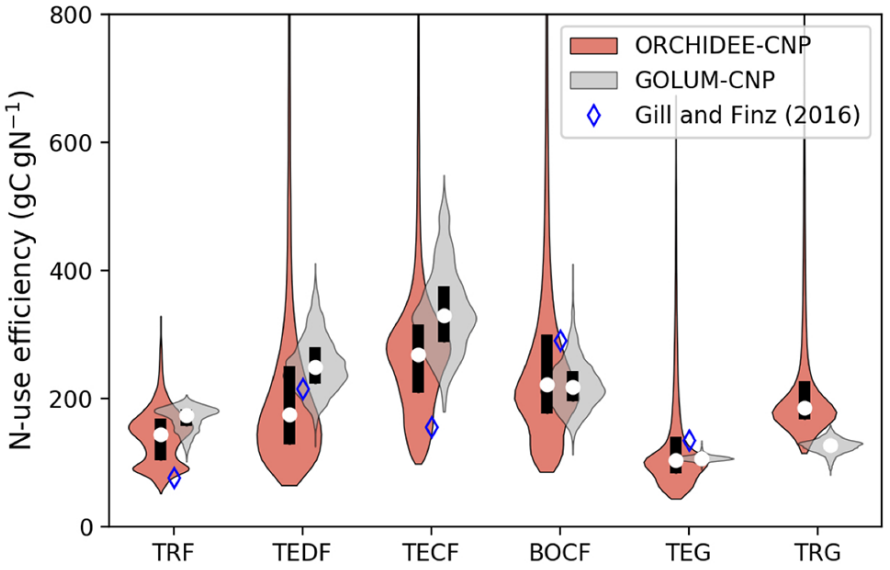
Model formulations of P sorption



Yu et al. in press

CHALLENGE: COMPREHENSIVE EVALUATION

Nutrient-specific benchmarks



Sun et al. 2021

Challenges:

- sparse nutrient cycle observations => community effort to collect relevant data would help…
- compensating model errors hamper interpretation of model biases

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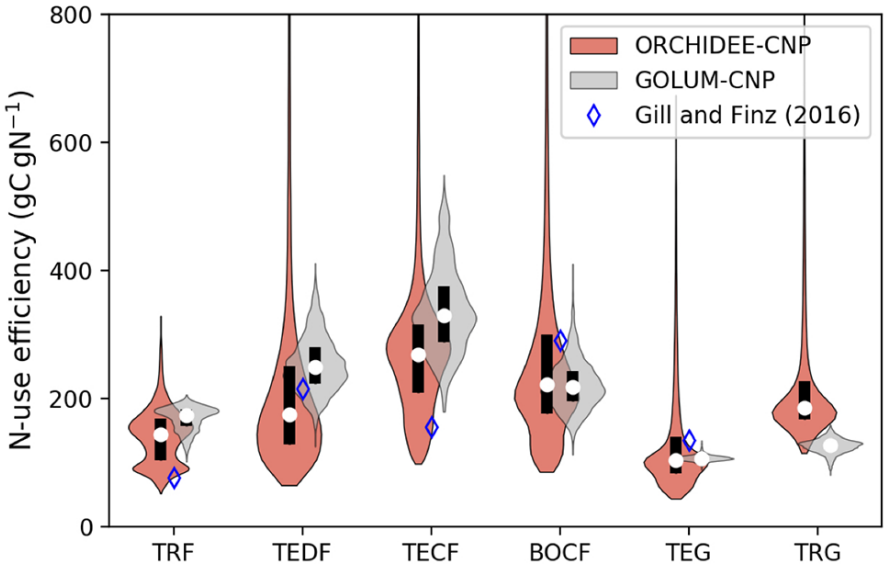
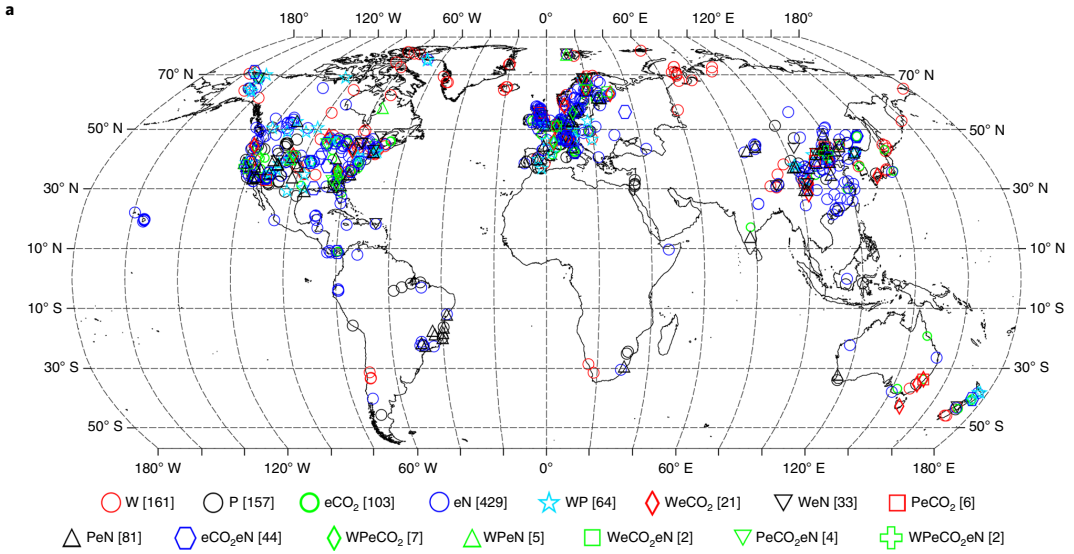


Sun et al. 2021

Manipulation experiments



Song *et al.* 2019

Challenges:

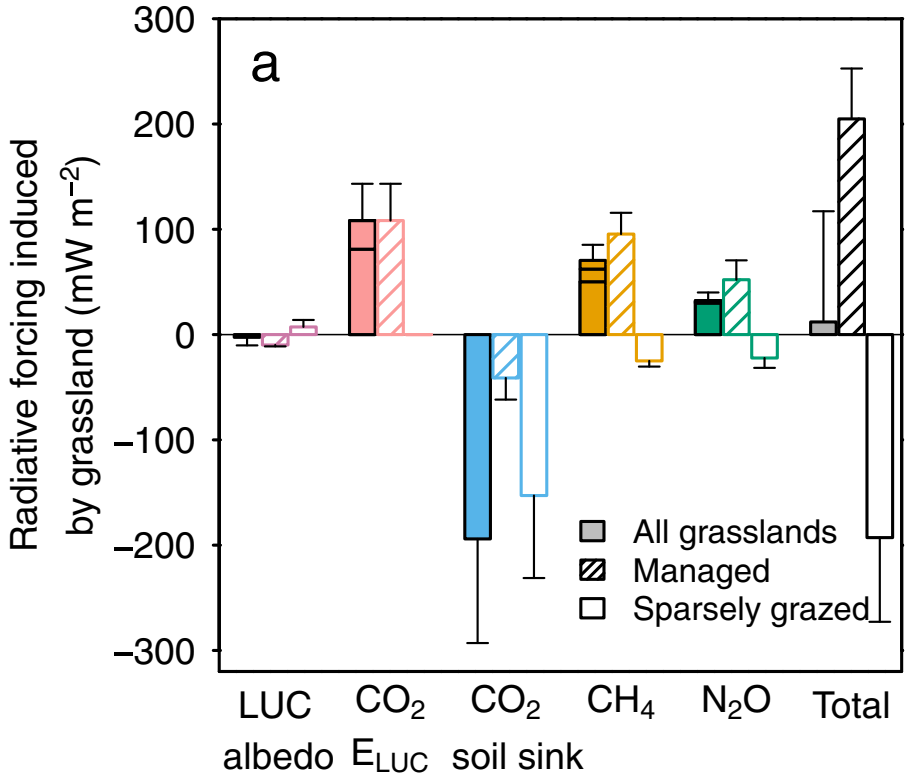
- sparse nutrient cycle observations => community effort to collect relevant data would help…
- compensating model errors hamper interpretation of model biases
- Manipulation studies: separate local from generic effects challenging?
- in long-term experiments the response almost aways depends on community dynamics

NEW RESEARCH OPPORTUNITIES

- Increased access to observations allows for better informed studies in critical regions
  - **AFEX, Amazon-FACE** deliver new resources to rethink tropical P-cycle processes
  - New insights into N dynamics in **thawing permafrost and subarctic ecosystems**

- Coupling of **N-P dynamics** to **vegetation demography** and **disturbance** regimes (fire, …)

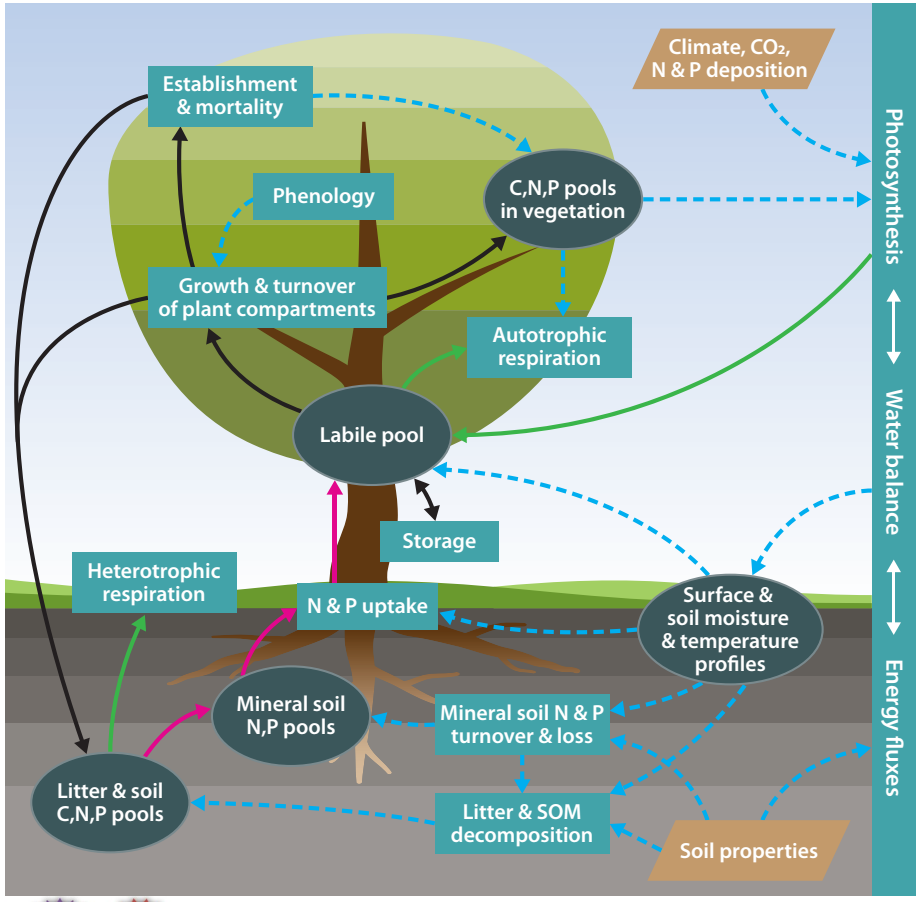
- **Trade-offs between nutrient effects on CO_2 storage and other climate drivers** (CH_4, N_2O, albedo & water flux, reactive N chemistry and aerosols)
  - Effects of land-use and management
  - Implications of CDR deployment



Chang et al. 2021

A NEW BIOSPHERE MODELLING APPROACH

- meristematic control of growth according to water/ nutrient/temperature stresses
- considerings trade-offs to make resource allocation decisions
- novel concepts for soil organic matter processes
  - vertically explicit
  - microbially explicit
  - sorption to stabilise C rather than prescribed turnover
- includes ^{13}C, ^{14}C and ^{15}N tracers to better constrain processes / improve use of manipulation experiments



Thum et al., 2019 & Yu et al. 2020

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