The curious case of plant responses to carbon dioxide

How does CO_2 vary over space and time?

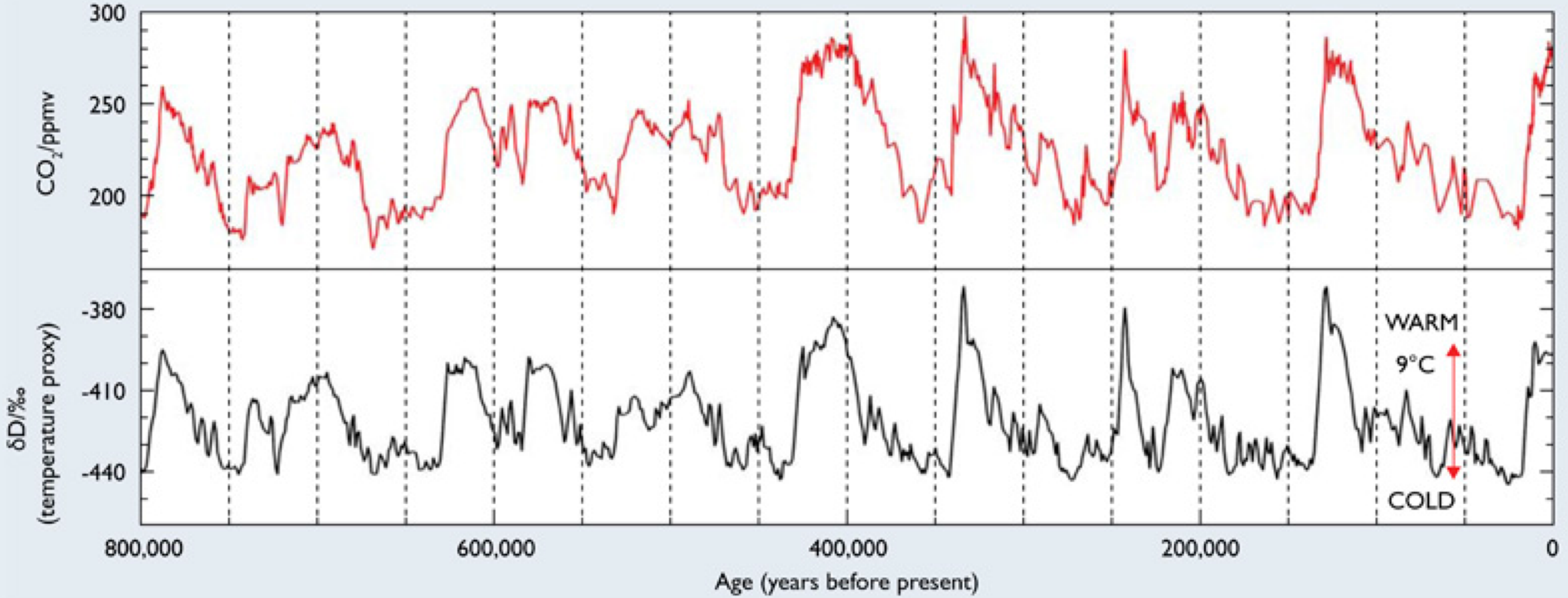
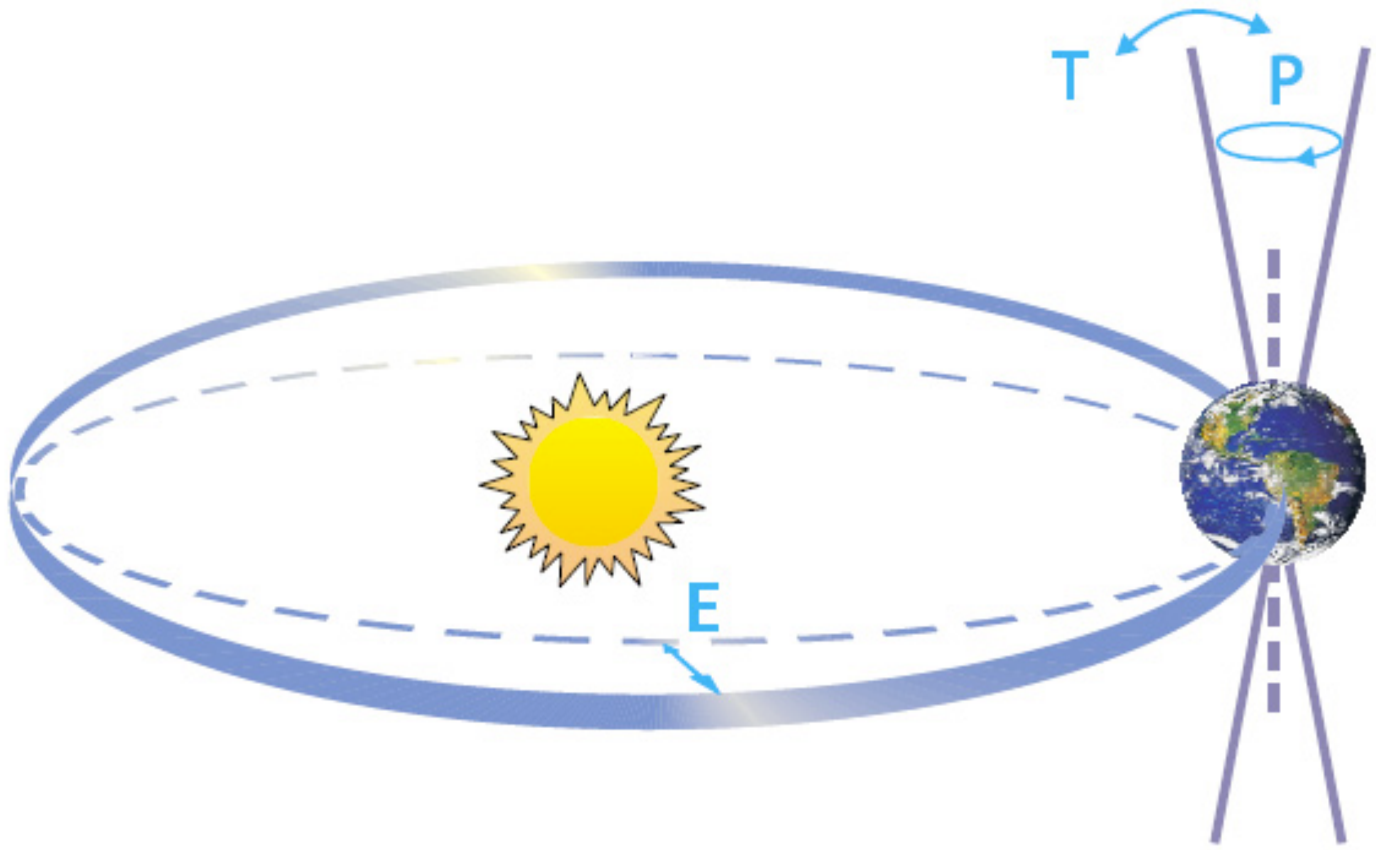


Fig. 3: Ice core data from the EPICA Dome C (Antarctica) ice core: deuterium (δD) is a proxy for local temperature; CO_2 from the ice core air[5,6]

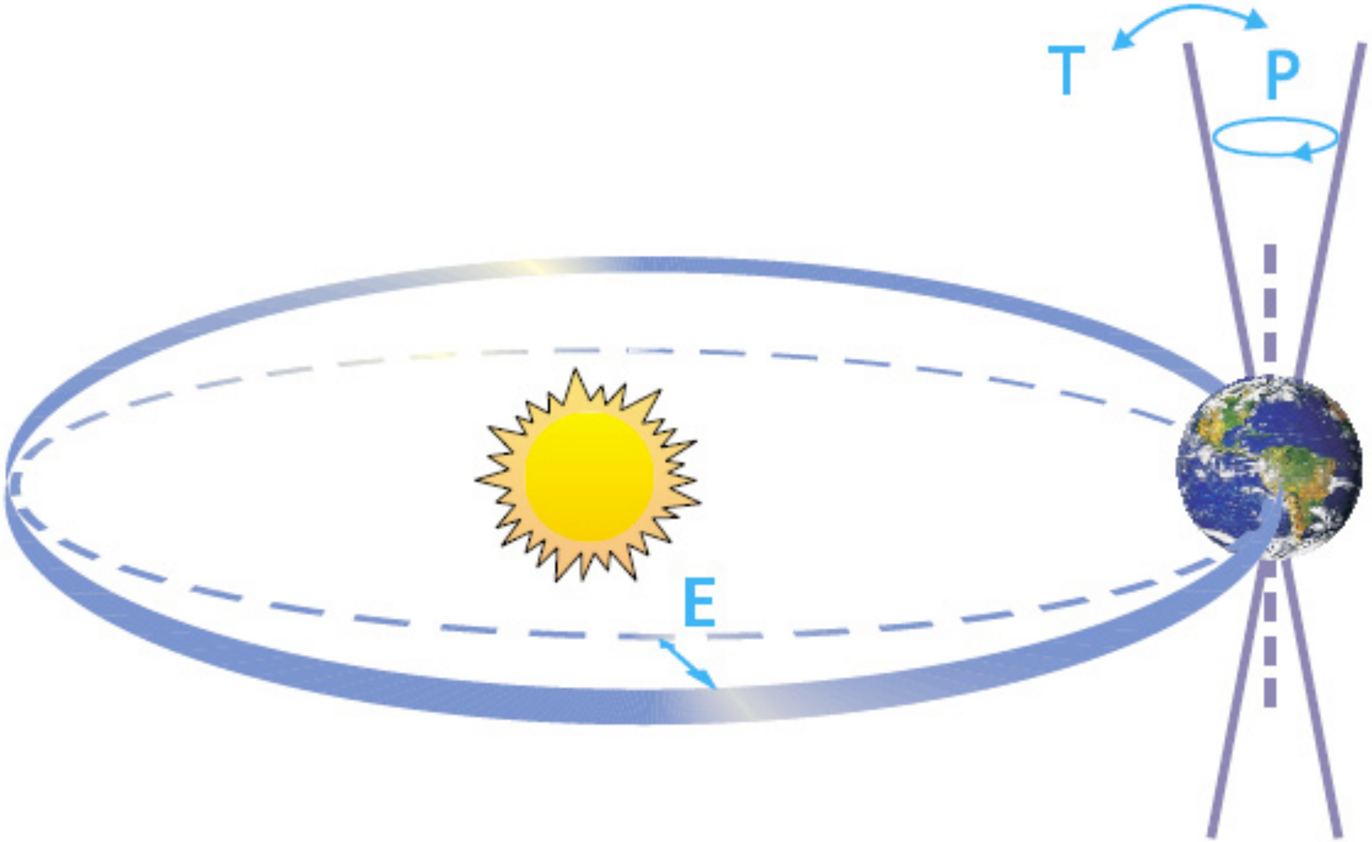
Historical rate of change: 0.002 ppm / year

Sidebar: Milankovitch cycles



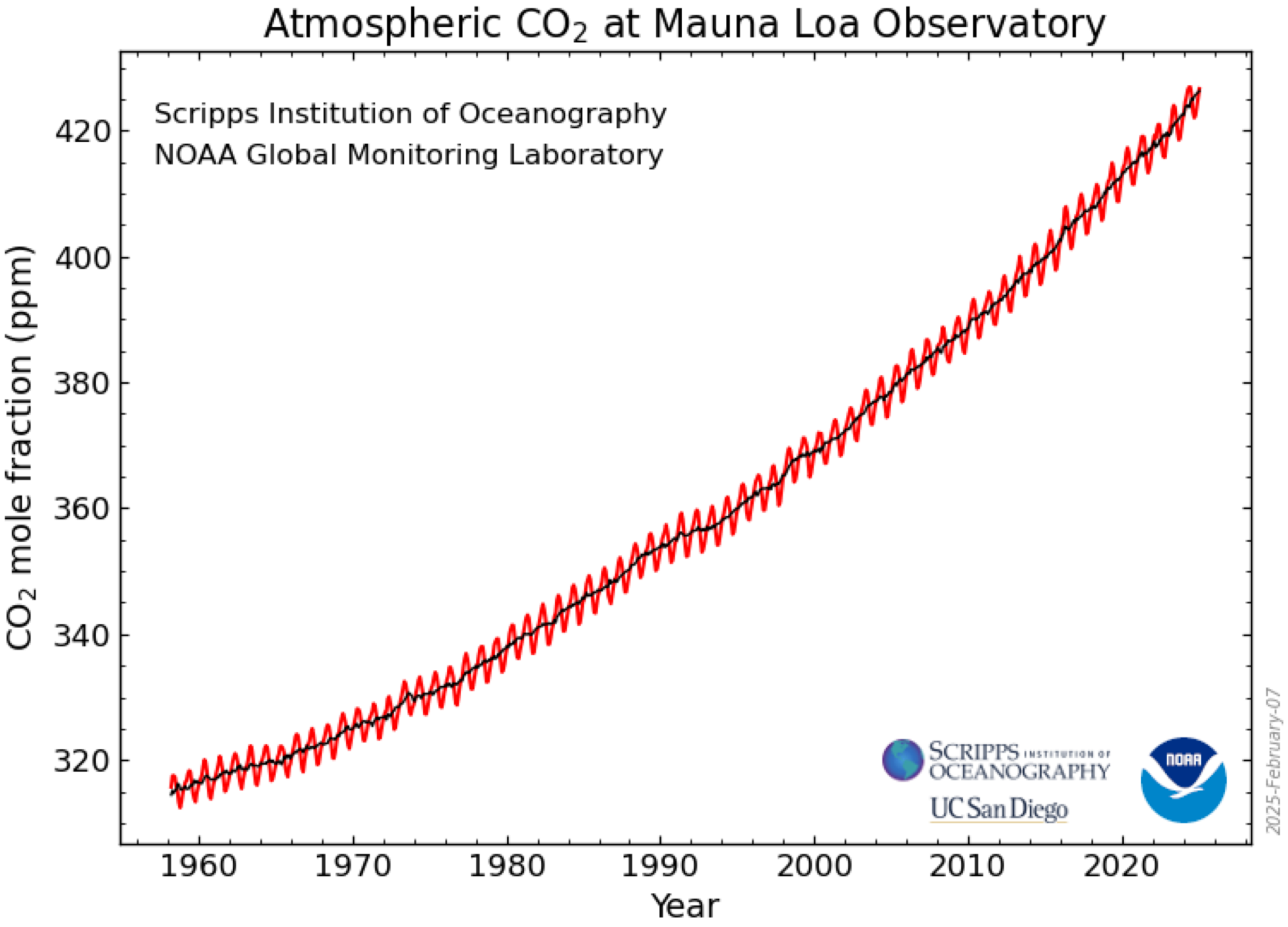
The gravitational pull from other planets causes the tilt and orbit of the Earth to change!

Sidebar: Milankovitch cycles

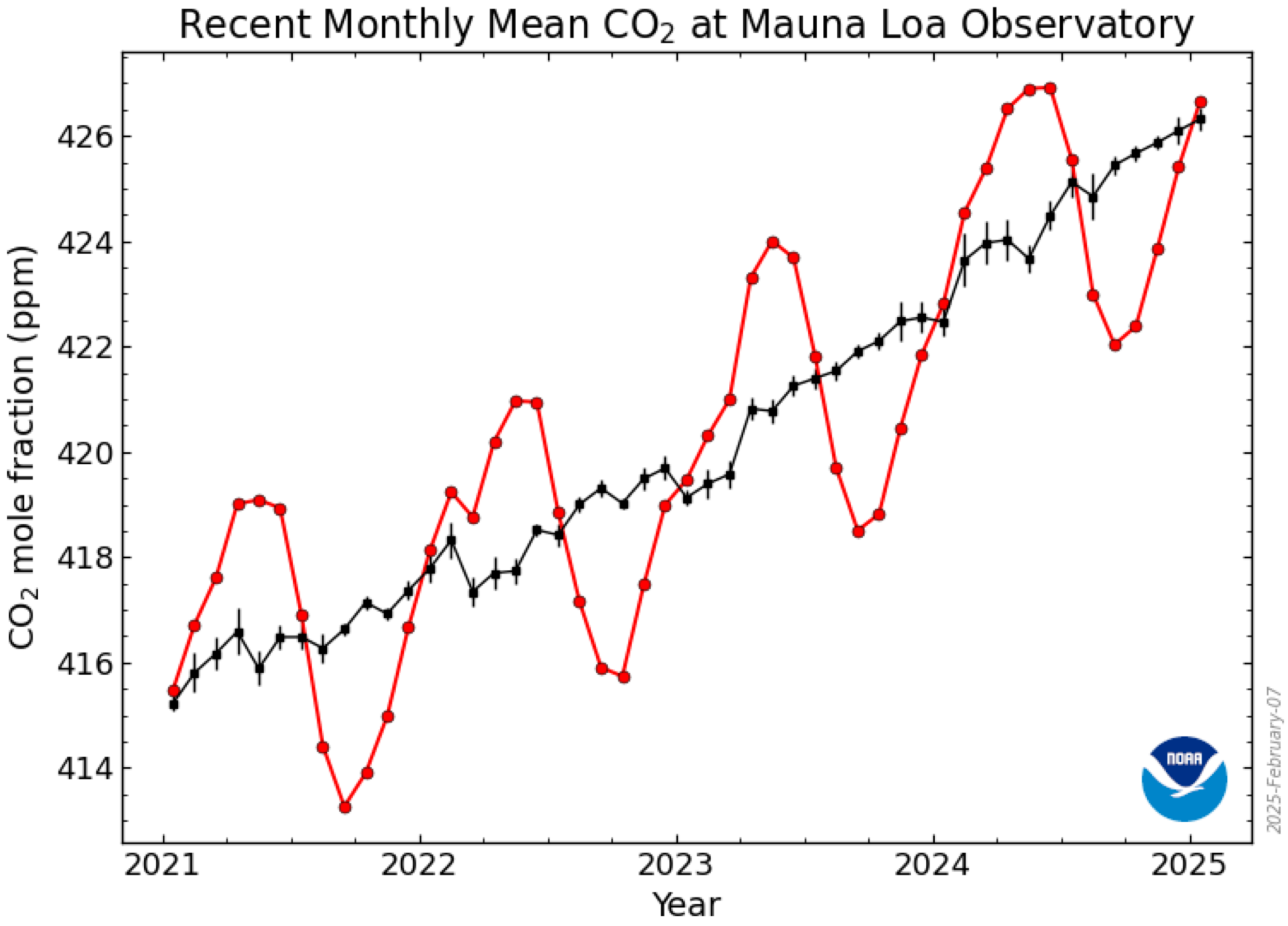


The gravitational pull from other planets causes the tilt and orbit of the Earth to change!

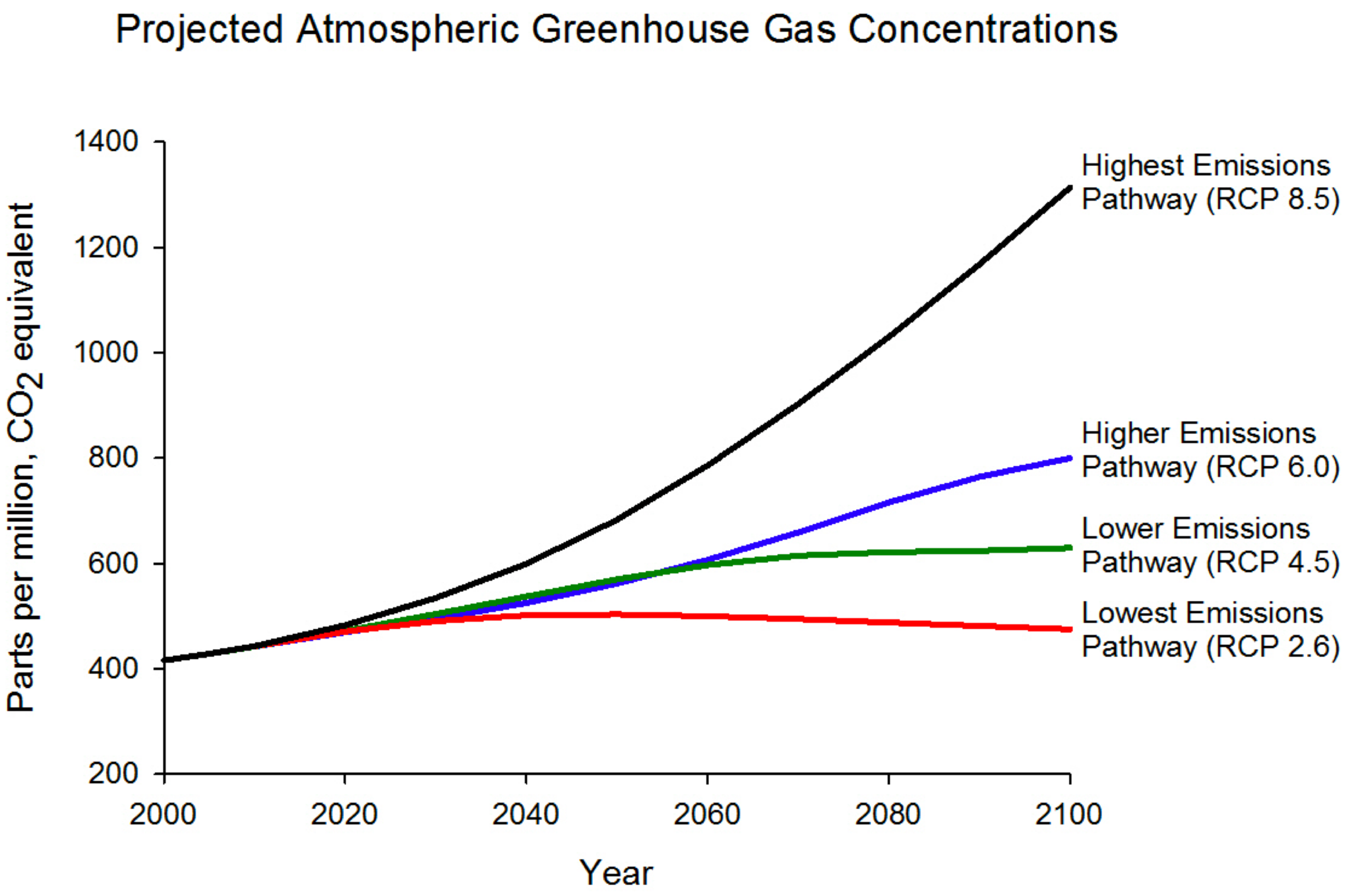
When the cycle causes long Northern hemisphere summers, we are in warm period (opposite is ice age)



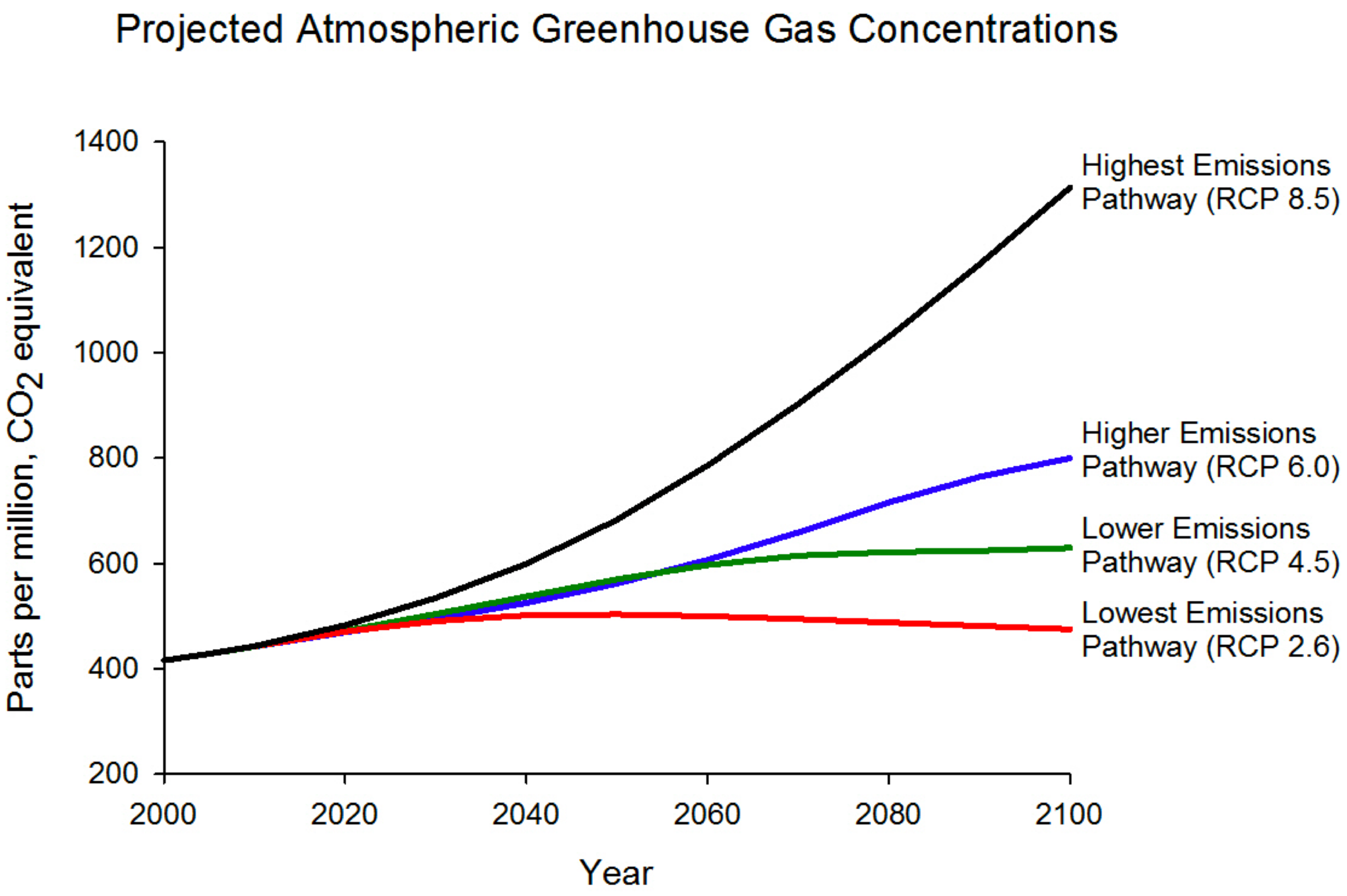
Current rate of change: 1.6 ppm / year



What causes the variations in the red line?


Projected Atmospheric Greenhouse Gas Concentrations
Parts per million, CO_2 equivalent
1400
1200
1000
800
600
400
200
2000
2020
2040
2060
2080
2100
Year
Highest Emissions Pathway (RCP 8.5)
Higher Emissions Pathway (RCP 6.0)
Lower Emissions Pathway (RCP 4.5)
Lowest Emissions Pathway (RCP 2.6)

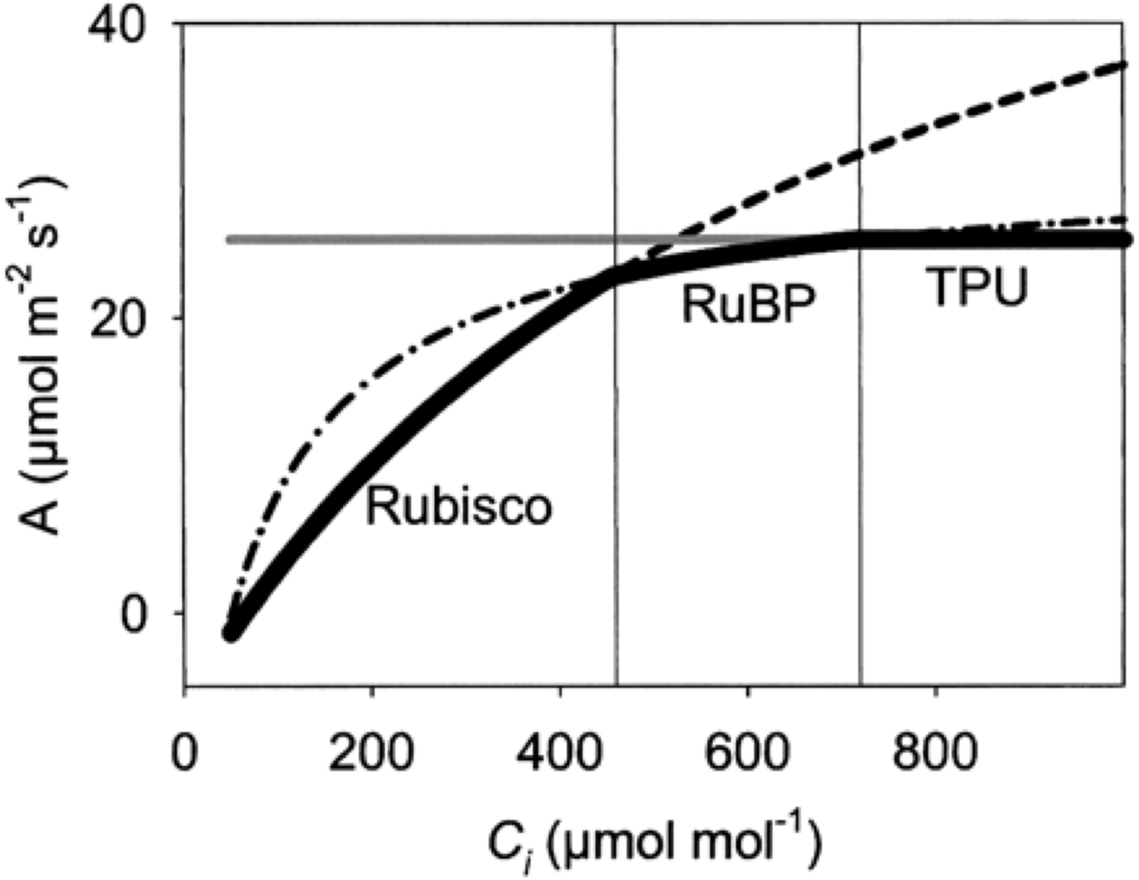
IPCC (2013)



What do you expect the plant response to be?

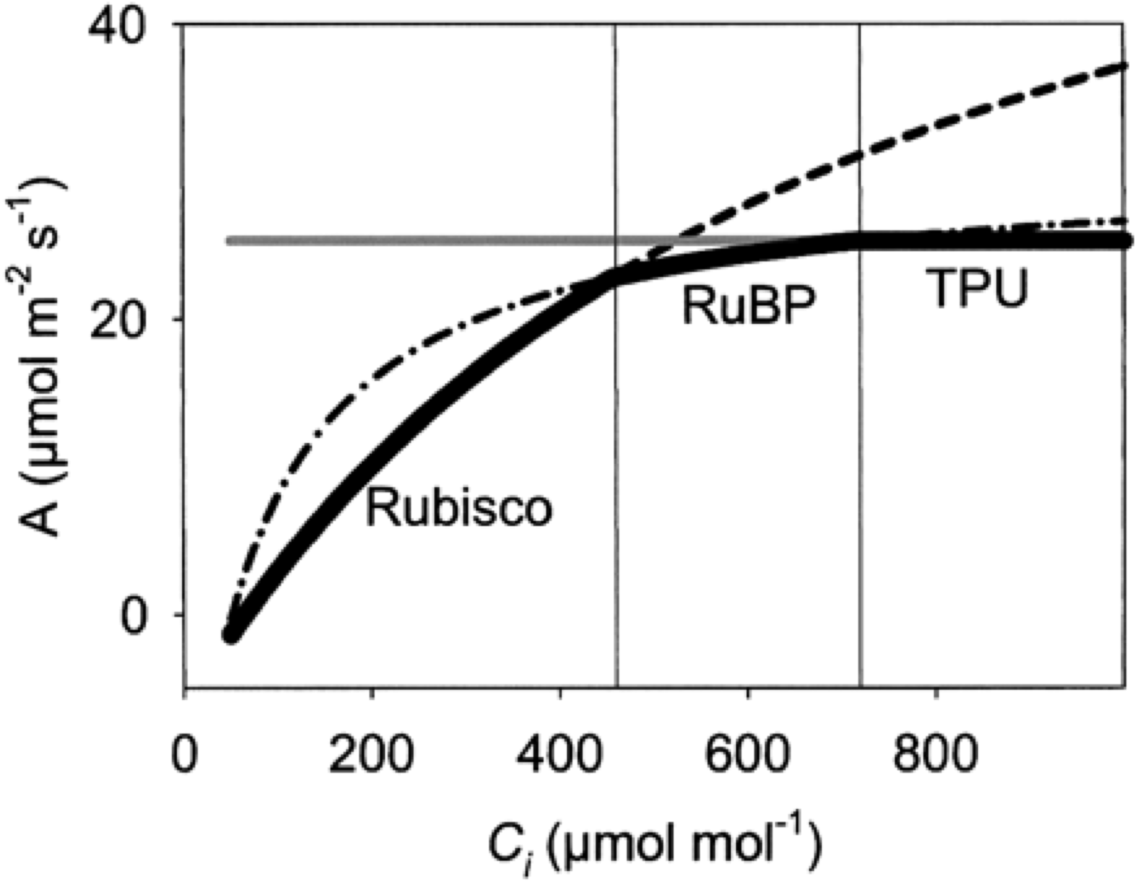
Short-term plant response to elevated CO_2: the A-Ci curve

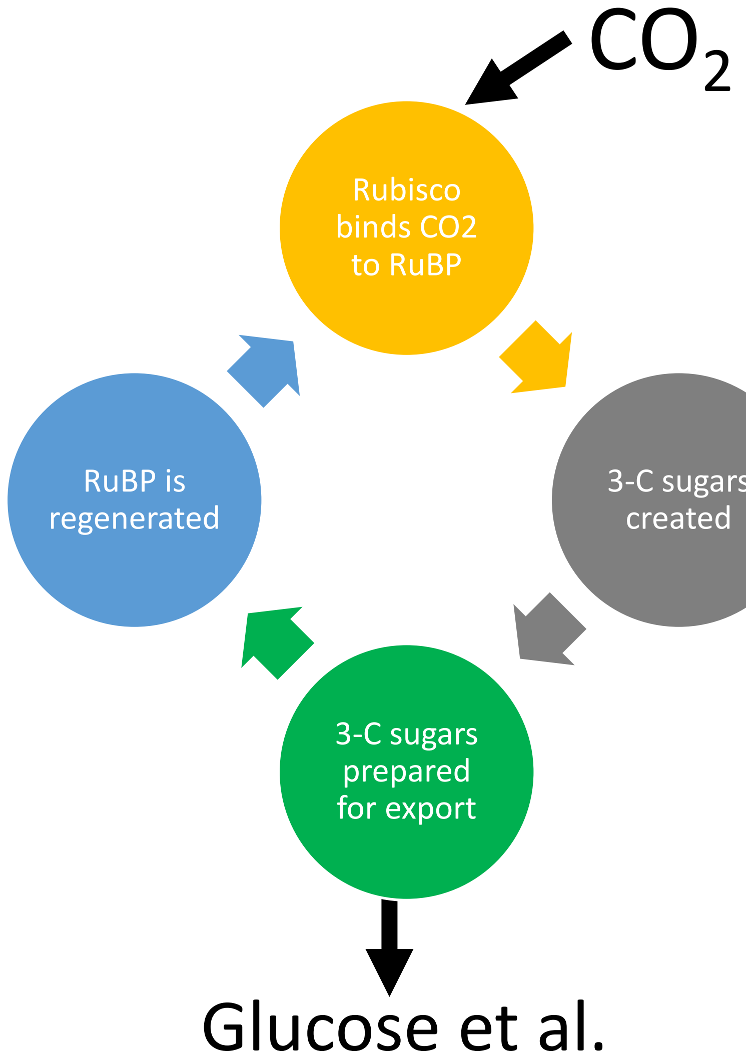
Short-term plant responses to CO2: the A-Ci curve



Long et al. (2003)

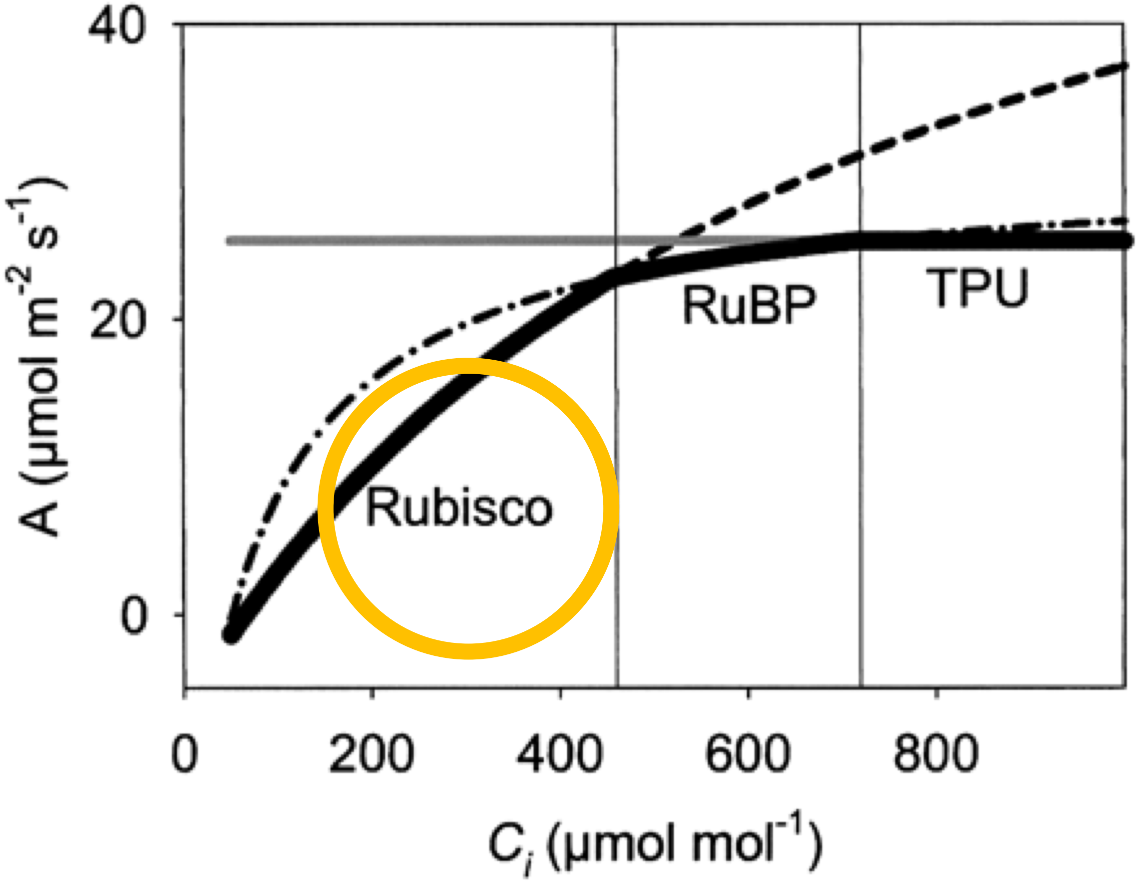
Short-term plant responses to CO2: the A-Ci curve

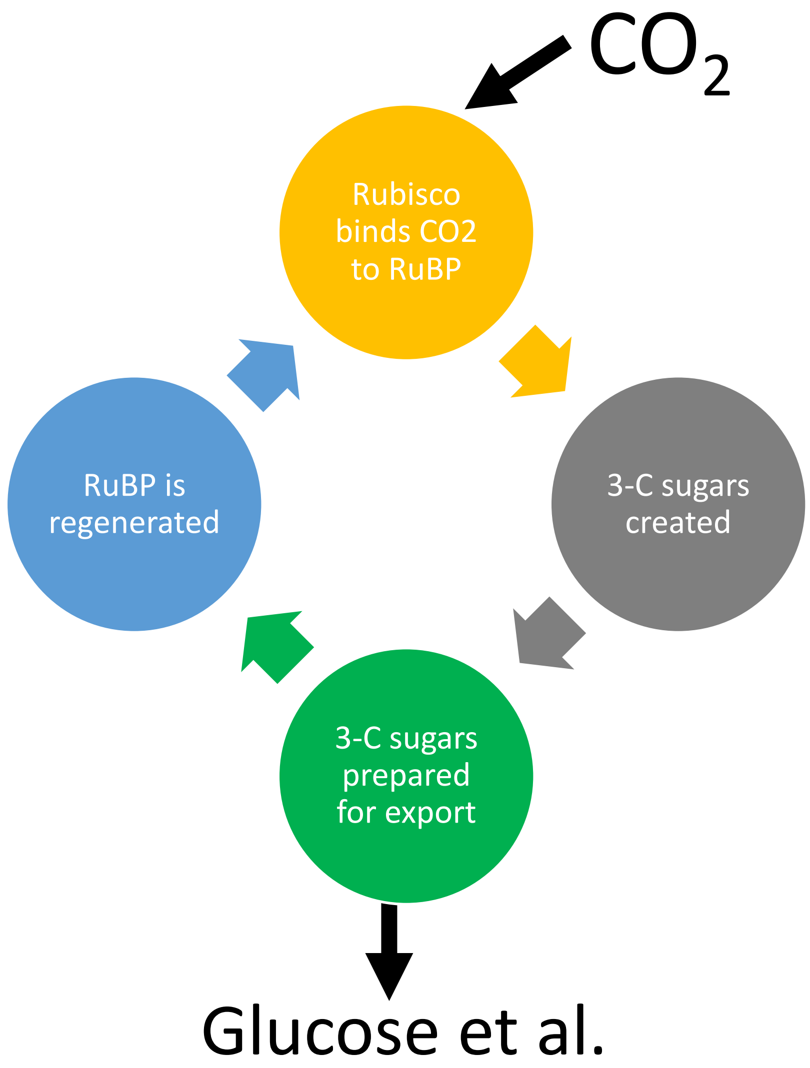




Long et al. (2003)

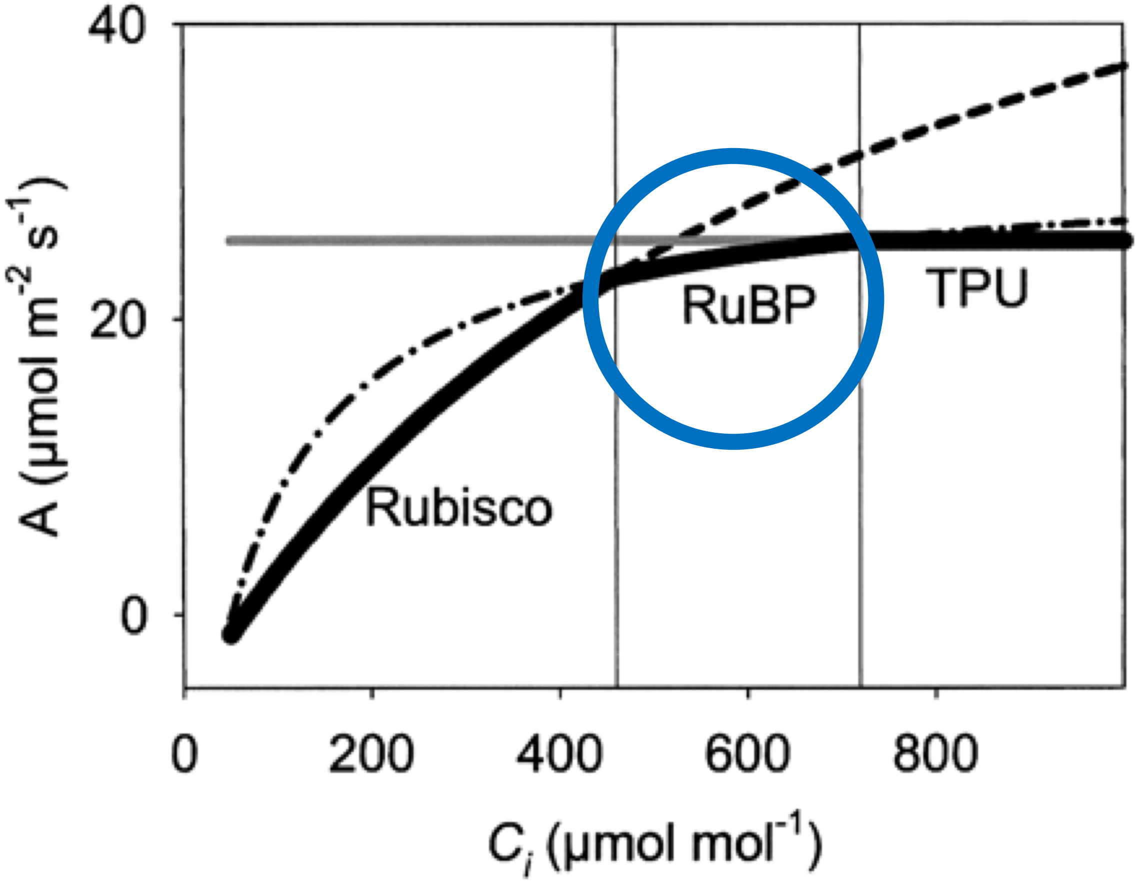
Short-term plant responses to CO2: the A-Ci curve

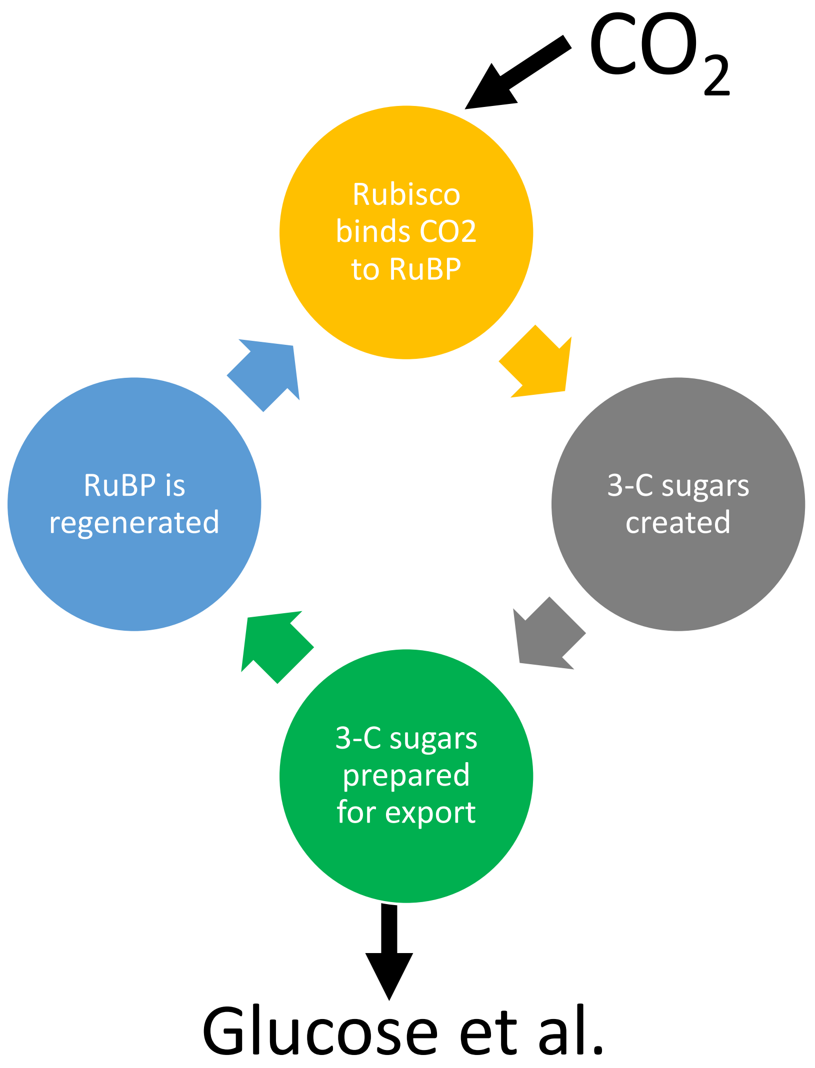




Long et al. (2003)

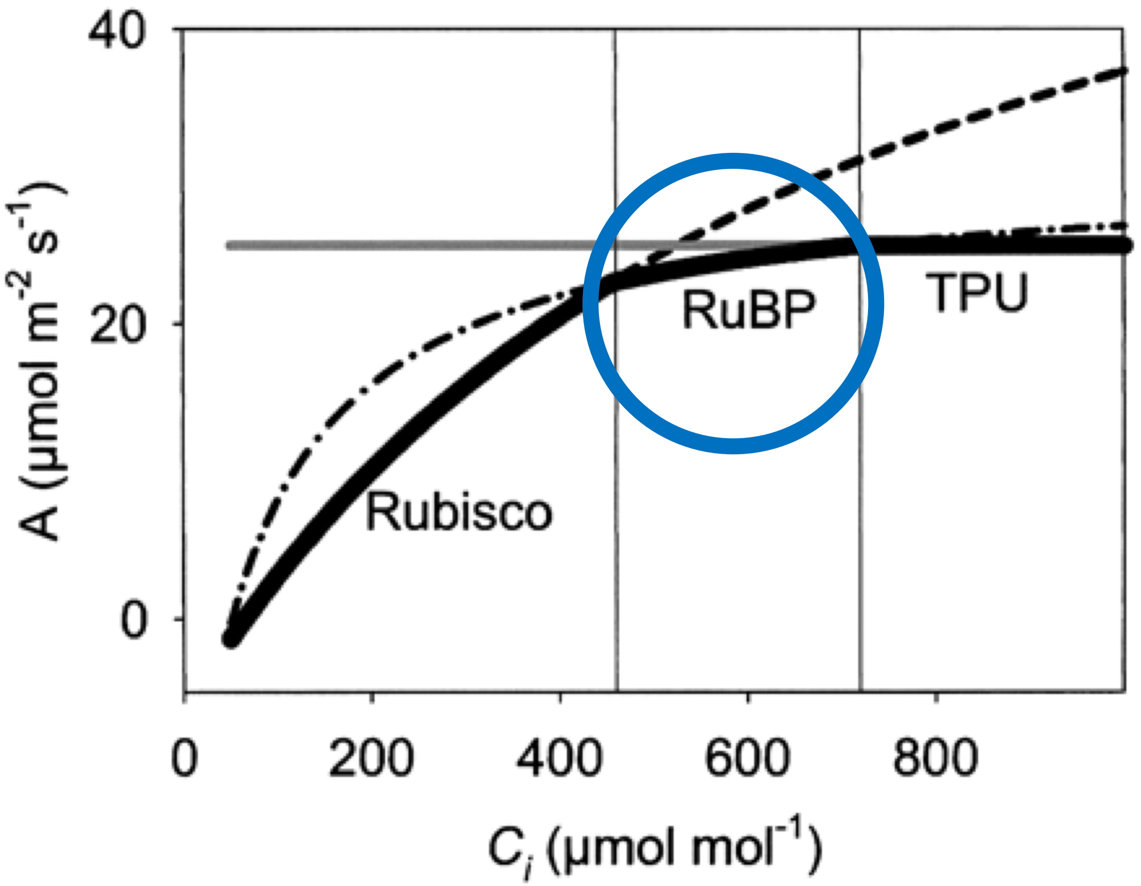
Short-term plant responses to CO2: the A-Ci curve





Long et al. (2003)

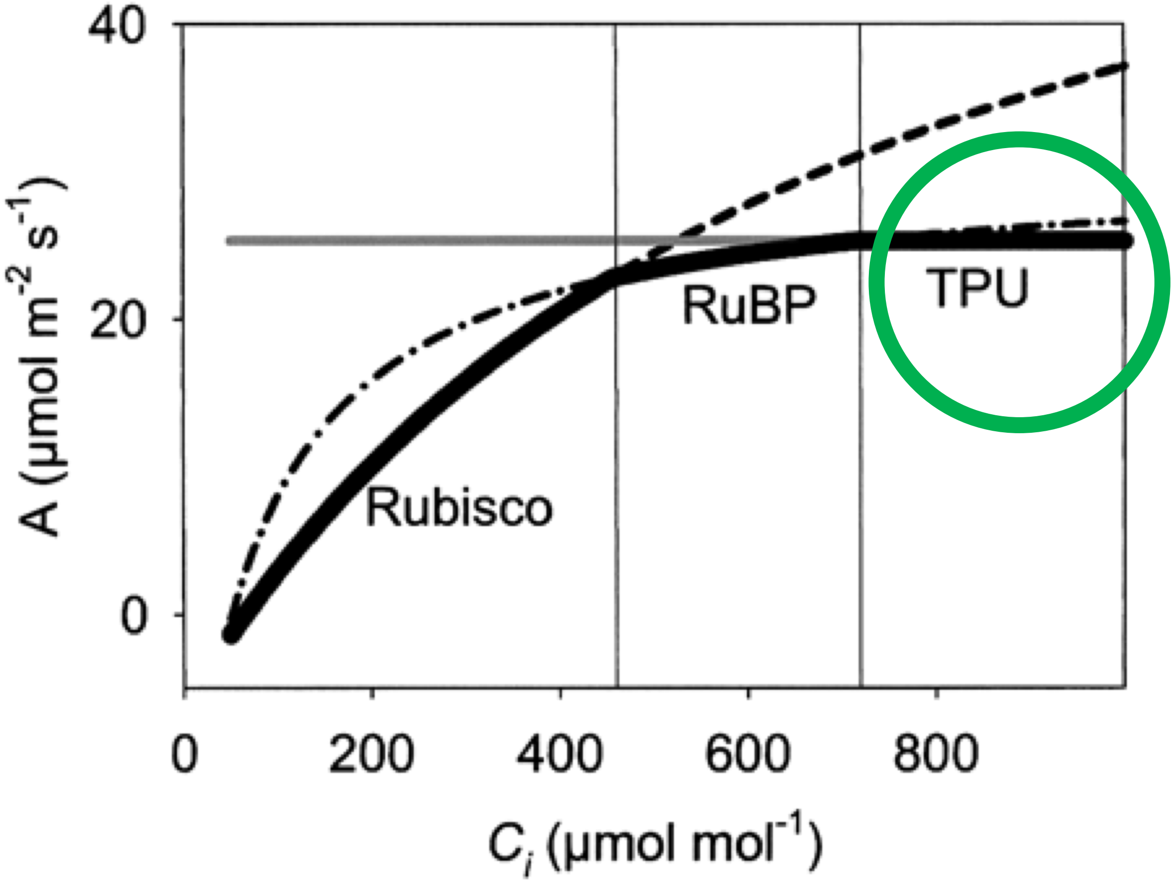
Short-term plant responses to CO2: the A-Ci curve

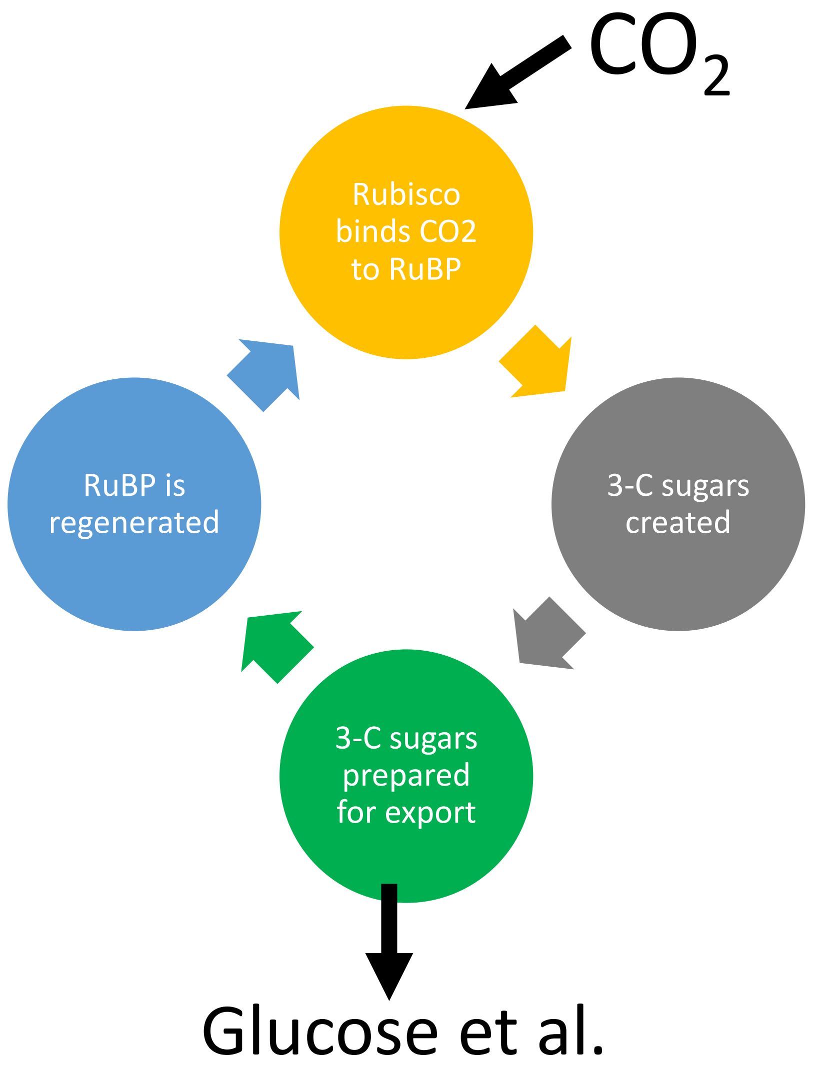


Hold on: What is strange about the RuBP regeneration response to CO_2?

Long et al. (2003)

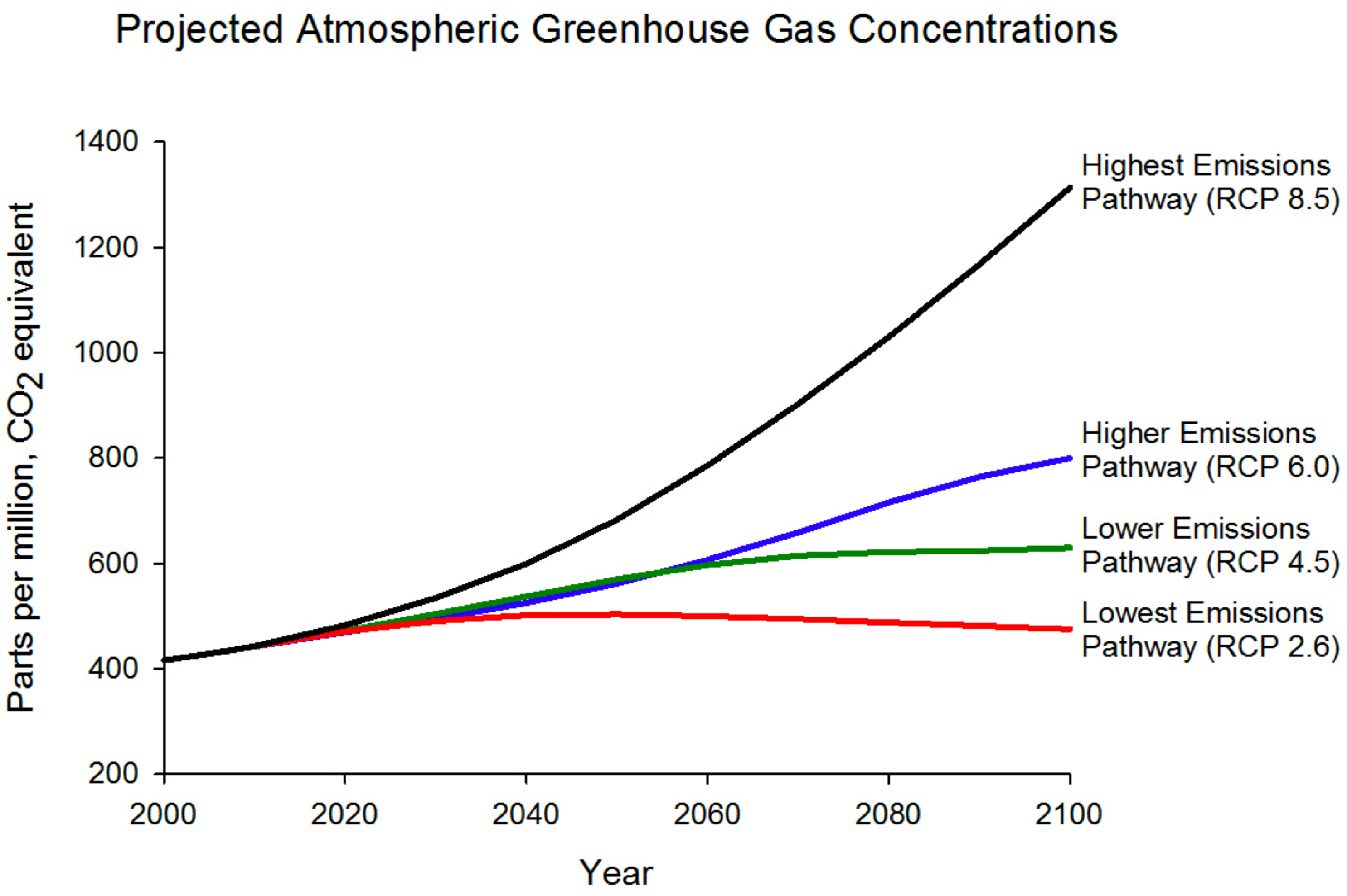
Short-term plant responses to CO2: the A-Ci curve



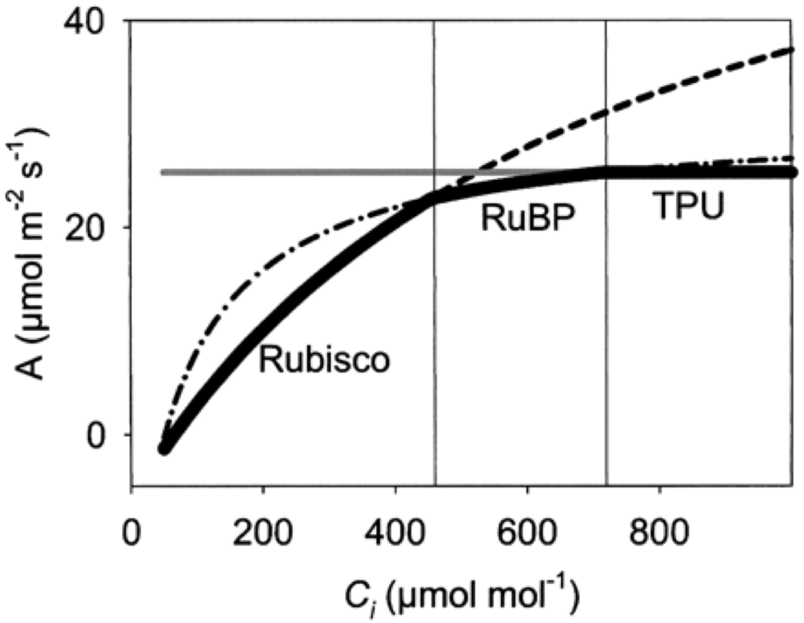


Long et al. (2003)

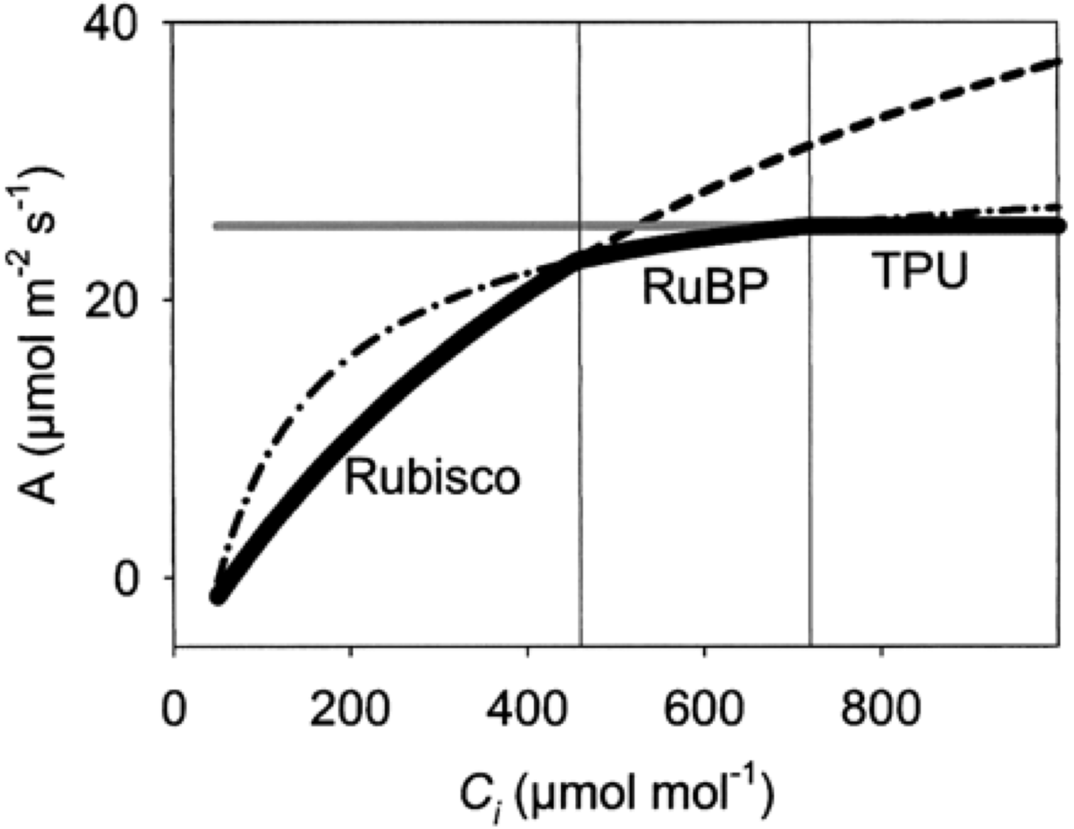
This response is relatively consistent across species and fairly easy to measure!



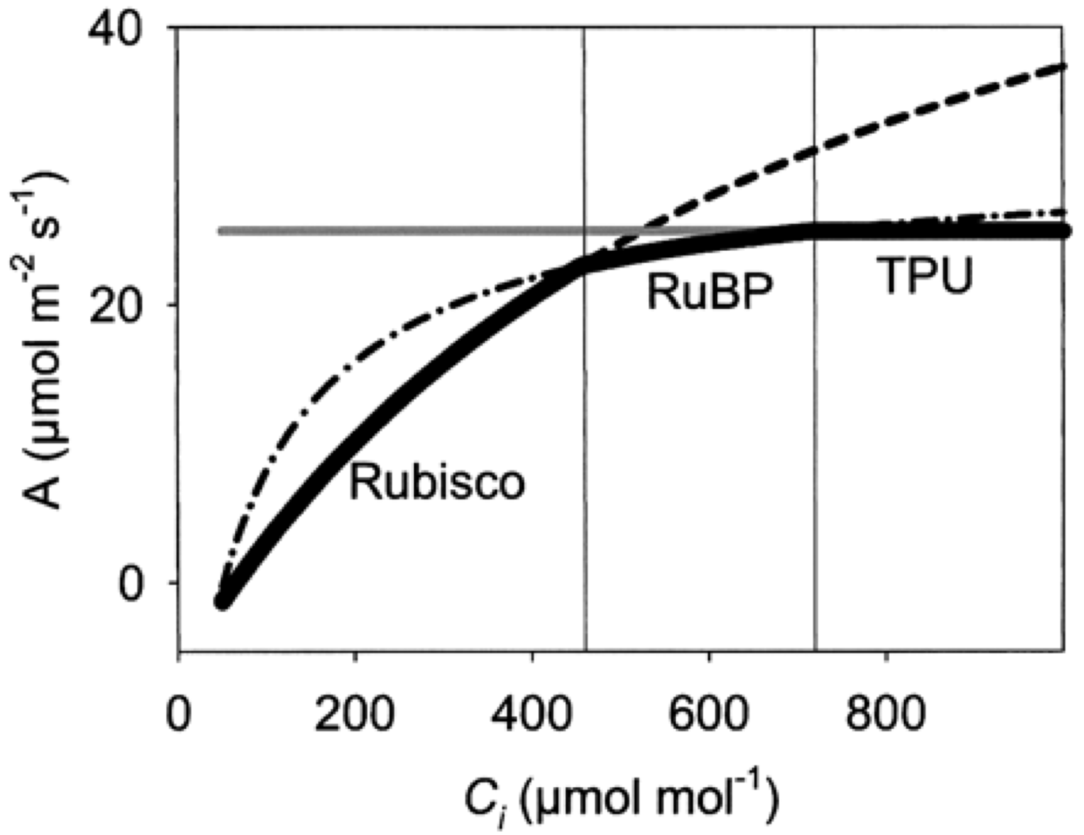
What do you expect the plant response to be?



How might the long-term response to elevated CO_2 differ?



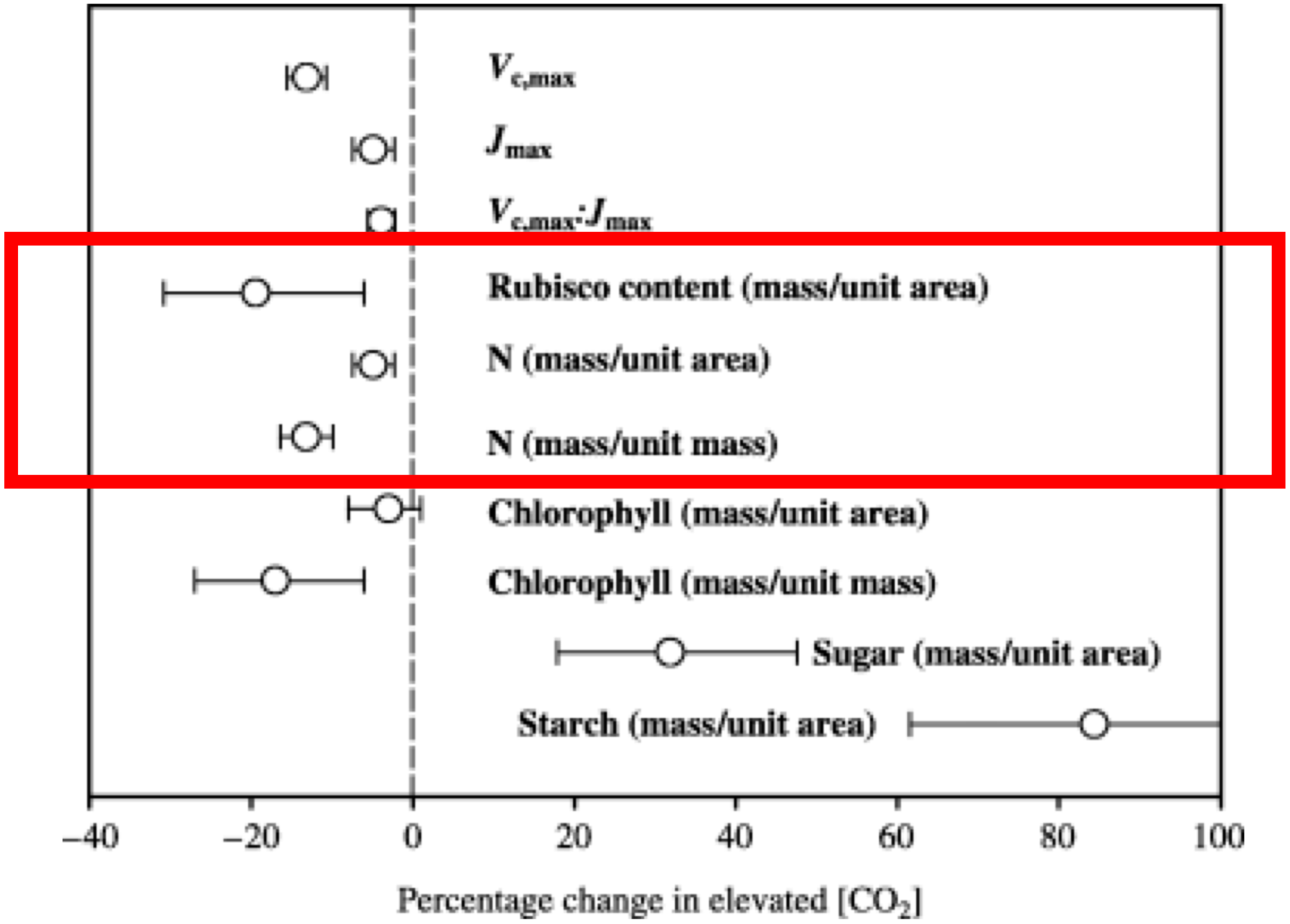
How might the long-term response to elevated CO_2 differ?



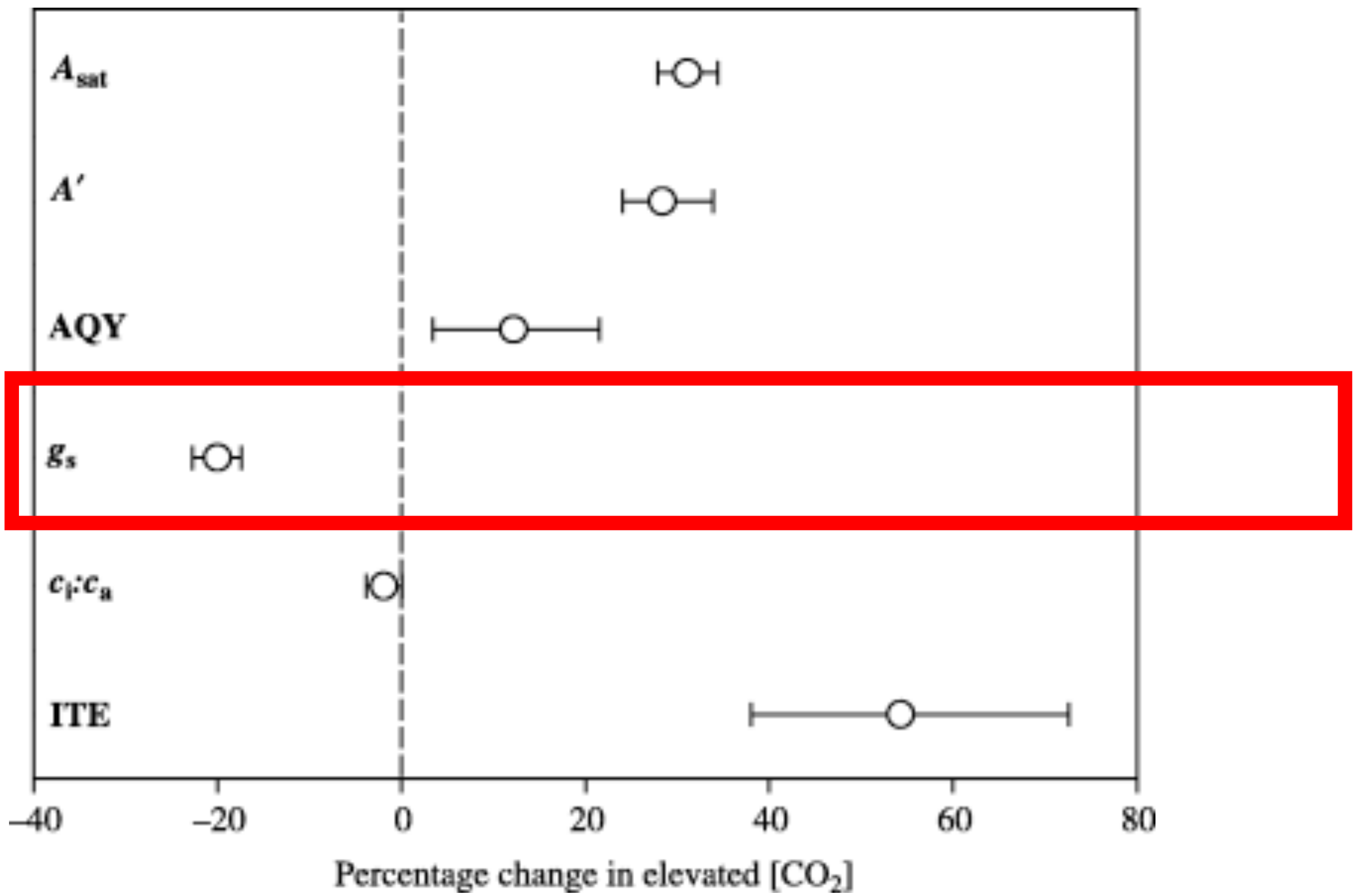
Things to consider:

- Each component represents a within leaf investment
- Plants generally aim for efficiency
- RuBP regeneration is principally determined by light availability
- Rubisco is an expensive enzyme (lots of N)
- It's costly to use water

Free Air CO_2 enrichment (FACE) experiments



Ainsworth and Long (2005)



Ainsworth and Long (2005)

What does this mean for the whole plant?

What does this mean for the whole ecosystem?

No cover image available

Volume 54, Issue 8
August 2004

Article Contents

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JOURNAL ARTICLE

Progressive Nitrogen Limitation of Ecosystem Responses to Rising Atmospheric Carbon Dioxide

Yiqi Luo, Bo Su, William S. Currie, Jeffrey S. Dukes, Adrien Finzi, Ueli Hartwig, Bruce Hungate, Ross E. McMurtrie, Ram Oren, William J. Parton ... Show more

Author Notes

BioScience, Volume 54, Issue 8, August 2004, Pages 731–739,
https://doi.org/10.1641/0006-3568(2004)054[0731:PNLOER]2.0.CO;2
Published: 01 August 2004

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Abstract

A highly controversial issue in global biogeochemistry is the regulation of terrestrial carbon (C) sequestration by soil nitrogen (N) availability. This controversy translates into great uncertainty in predicting future global terrestrial C sequestration. We propose a new framework that centers on the concept of progressive N limitation (PNL) for studying the interactions between

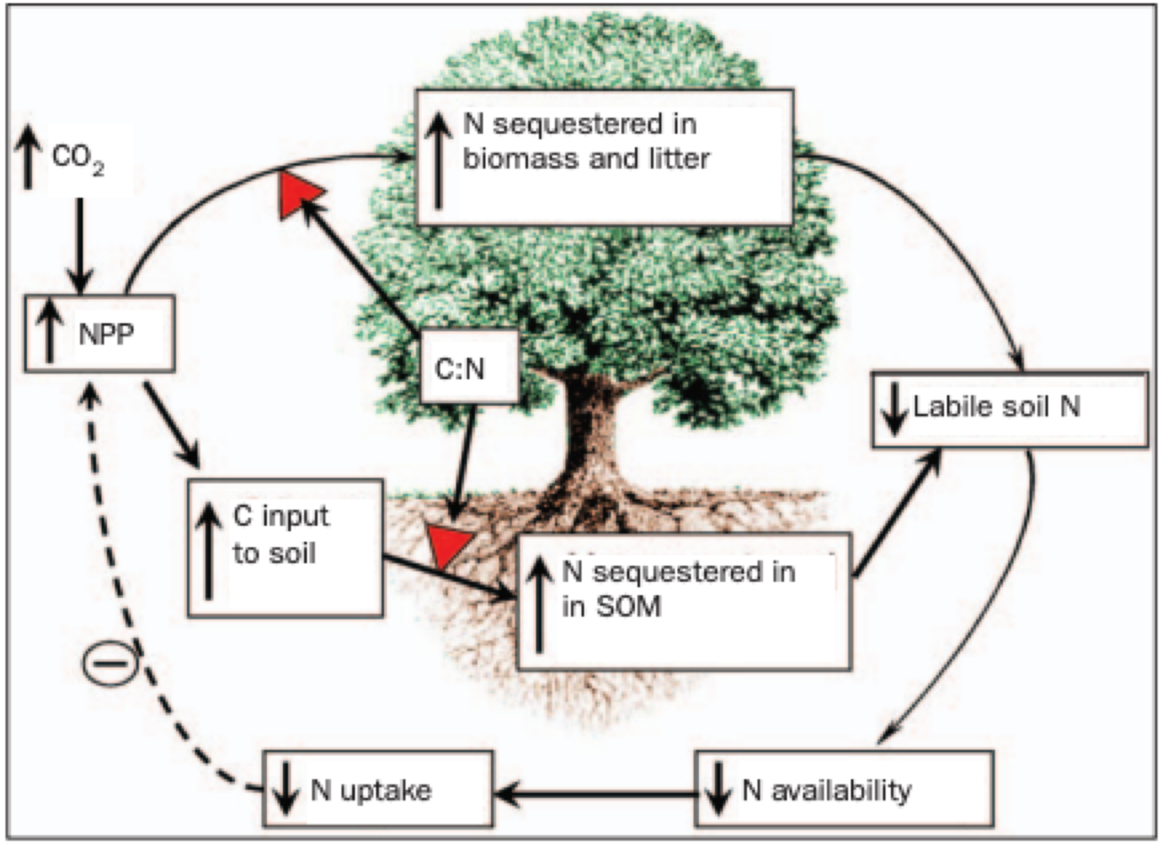


Figure 1. Two sets of feedback processes to elevated carbon dioxide (CO_2) leading to progressive nitrogen (N) limitation. In the upper pathway, the initial productivity response to elevated CO_2 results in N sequestration in plant biomass and litter pools, slowing N release to labile soil N. In the lower pathway, increased net primary production (NPP) in response to elevated CO_2 increases carbon (C) input to soil (increased exudation, root growth and death, and aboveground litterfall), leading to increased N sequestration in soil organic matter (SOM). This N sequestration reduces N availability to plants and subsequent plant N uptake. Flexible C:N ratios in ecosystem organic matter pools can modify both pathways. Flexible soil C:N pools could allow increased C storage without restricting short- to medium-term N availability. A flexible plant C:N ratio could temporally decrease N demand.

Luo et al. (2004)

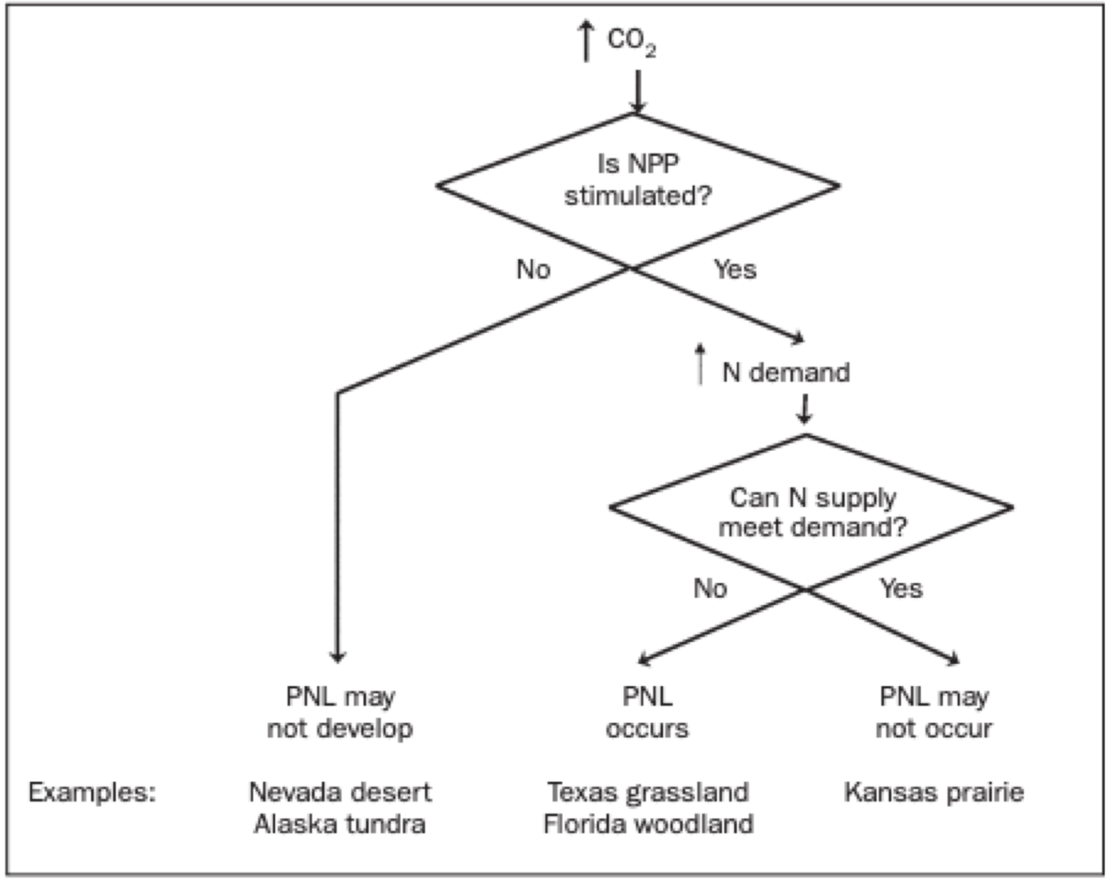
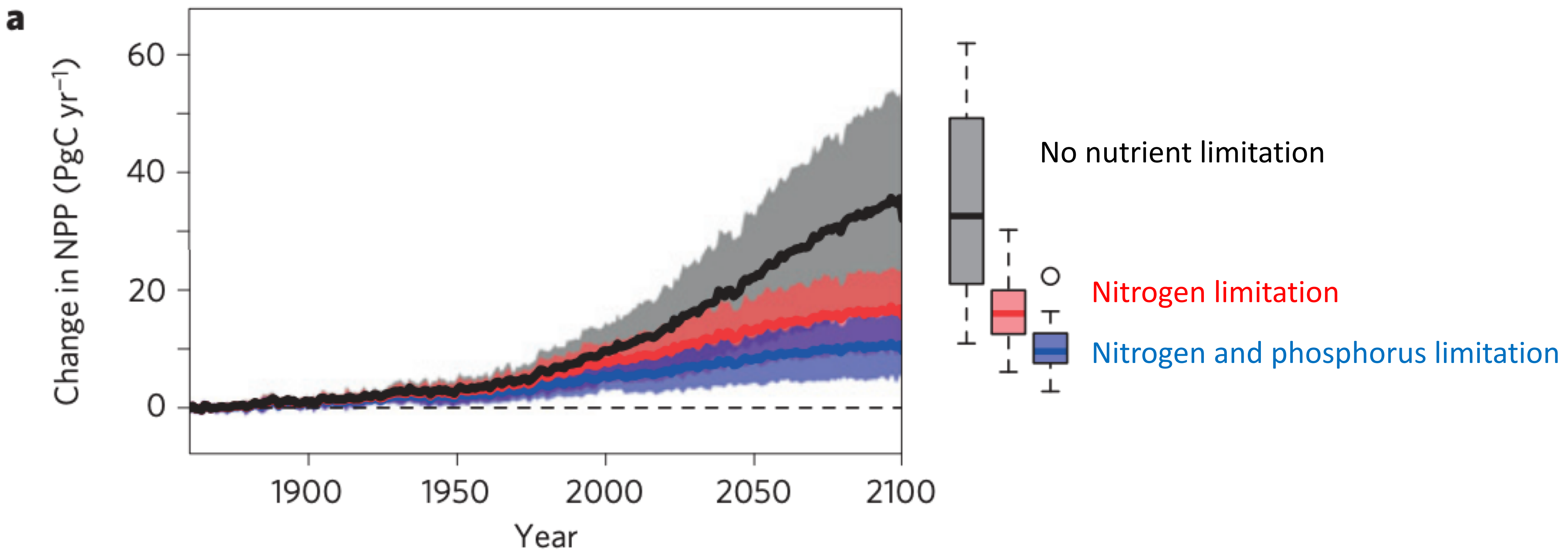
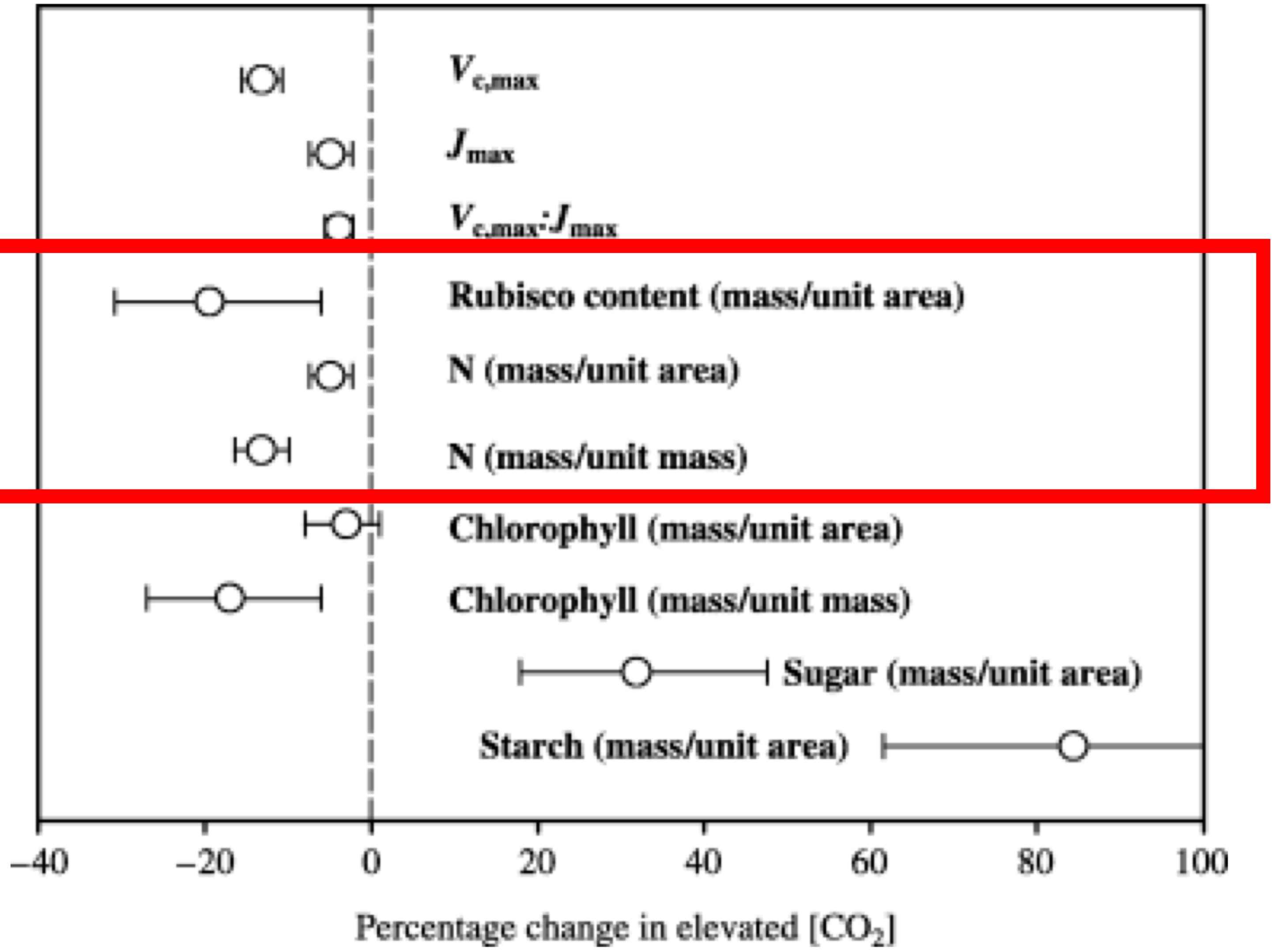


Figure 2. Schematic diagram of the progressive nitrogen limitation (PNL)-centered framework for identifying patterns of interactions between carbon (C) and nitrogen (N) under elevated carbon dioxide (CO_2). If elevated CO_2 does not stimulate enough biomass growth and C accumulation (net primary production, or NPP) in soil during the initial phase of CO_2 experiments, as in Nevada's Mojave Desert and Alaska's tussock tundra, N sequestration in the long-lived plant biomass and soil organic matter will not be substantial enough to affect soil N availability. In this case, PNL may not develop. If the initial stimulation of C sequestration under elevated CO_2 is high, N demand will build up to balance the C influx. If this extra N demand can be met through short-, medium-, or long-term supply mechanisms, as in Kansas tallgrass prairie, PNL may not occur. However, if N supplies cannot satisfy the N demand, as in Texas grassland and Florida scrub oak woodland, PNL may occur.

Luo et al. (2004)

Progressive N limitation is suggested to reduce the CO_2 fertilization effect





Is this a sign of progressive nutrient limitation or plant acclimation?

Ainsworth and Long (2005)

Global Change Biology

Volume 26, Issue 9
September 2020
Pages 5202-5216

PRIMARY RESEARCH ARTICLE | Full Access

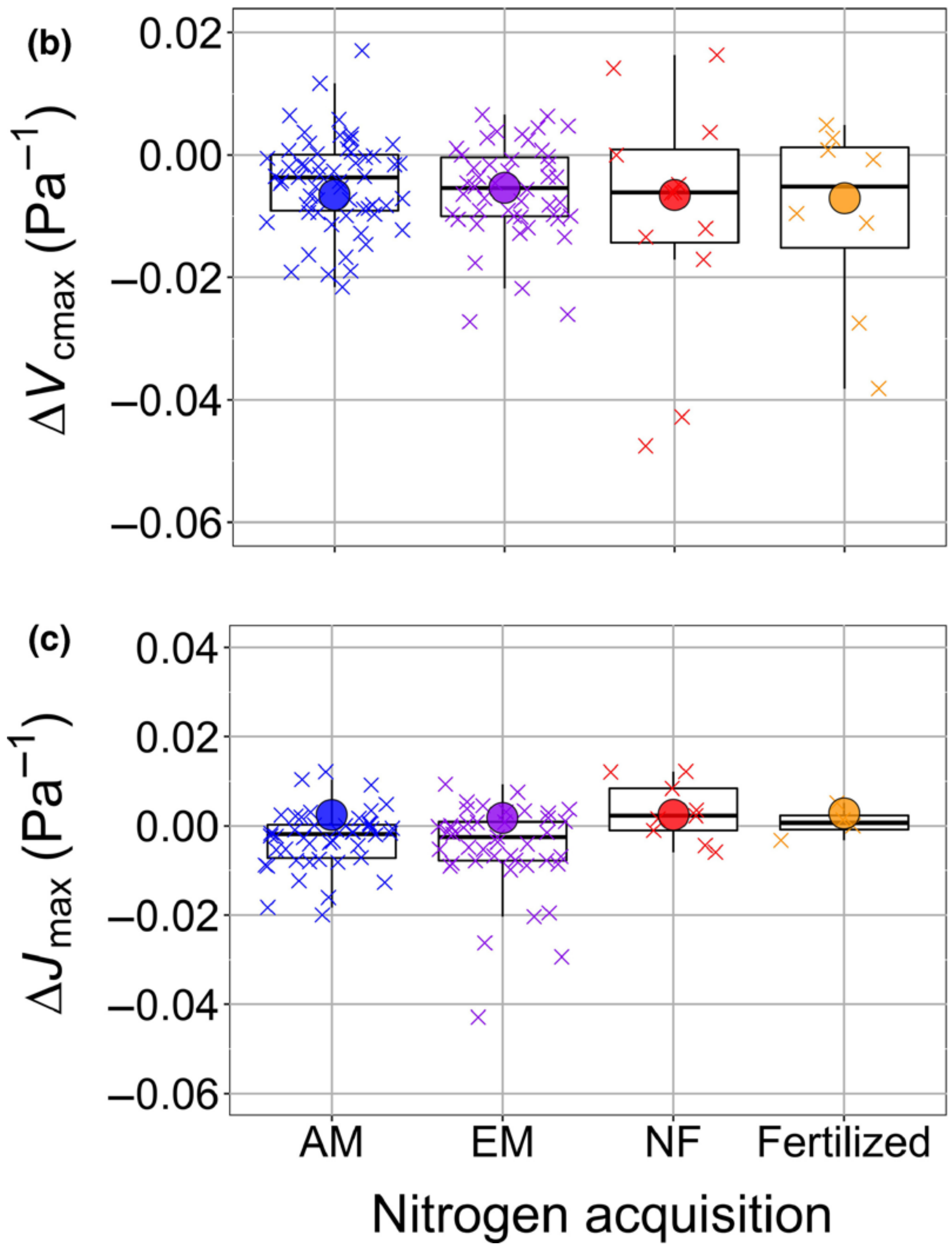
Mechanisms underlying leaf photosynthetic acclimation to warming and elevated CO_2 as inferred from least-cost optimality theory

Nicholas G. Smith, Trevor F. Keenan

First published: 11 June 2020 | https://doi.org/10.1111/gcb.15212 |

Abstract

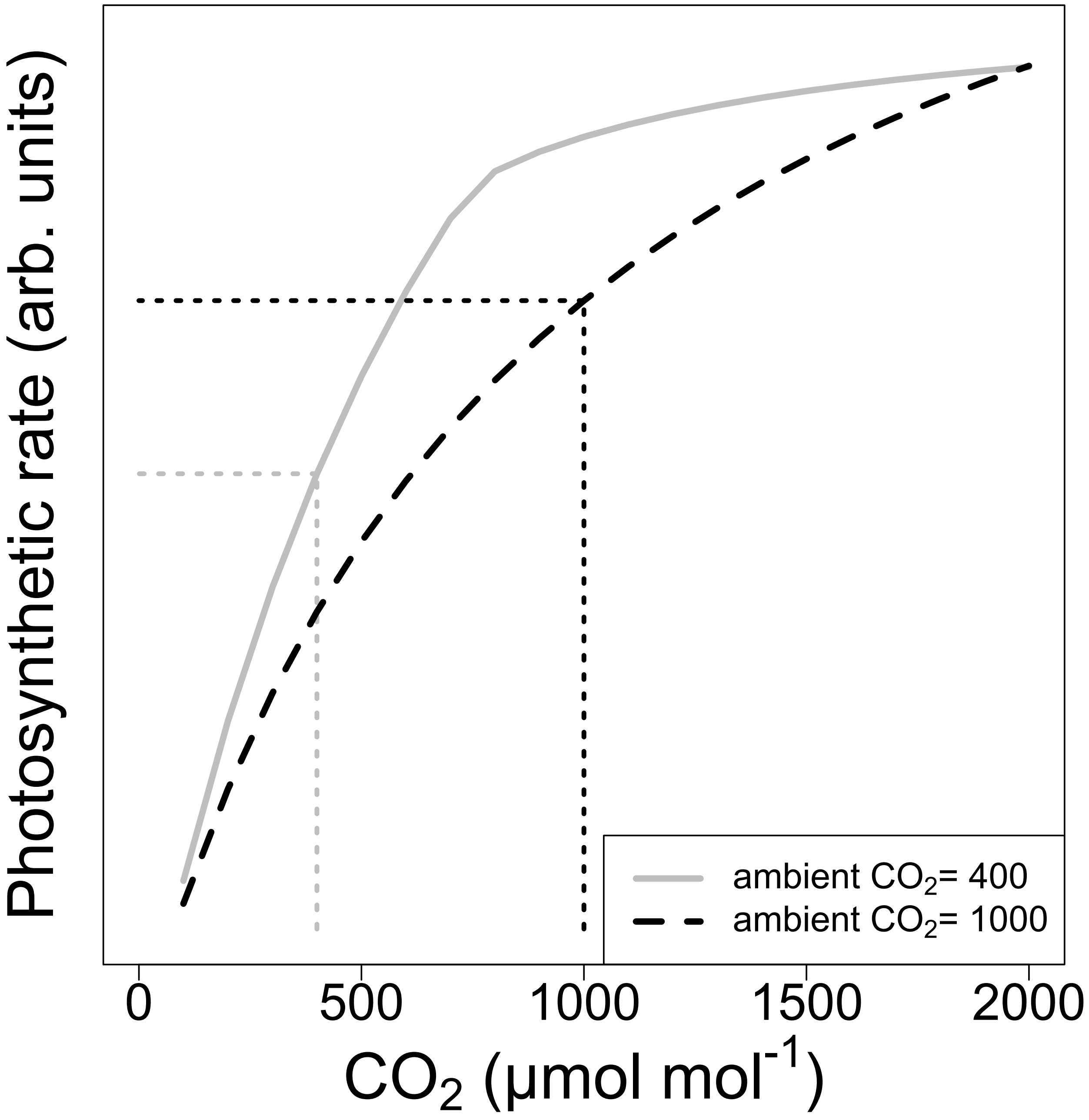
The mechanisms responsible for photosynthetic acclimation are not well understood, effectively limiting predictability under future conditions. Least-cost optimality theory can



Boxes and "x"s are data from elevated CO2 experiments, showing change (Δ) under elevated CO2 relative to ambient CO2. Circles are estimates based on just acclimation responses.

Takehome: acclimation-only responses match data. Therefore, PNL does not happen at the leaf level.

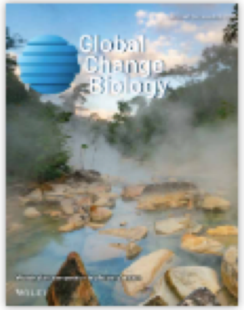
Smith and Keenan (2020)



Photosynthetic rate (arb. units)
0
500
1000
1500
2000
CO2 (µmol mol-1)
ambient CO2= 400
ambient CO2= 1000

What does this mean for models?

Global Change Biology



Volume 30, Issue 11
November 2024
e17558

RESEARCH ARTICLE | Full Access

Acclimation of Photosynthesis to CO_2 Increases Ecosystem Carbon Storage due to Leaf Nitrogen Savings

Nicholas G. Smith, Qing Zhu, Trevor F. Keenan, William J. Riley

First published: 02 November 2024 | https://doi.org/10.1111/gcb.17558

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ABSTRACT

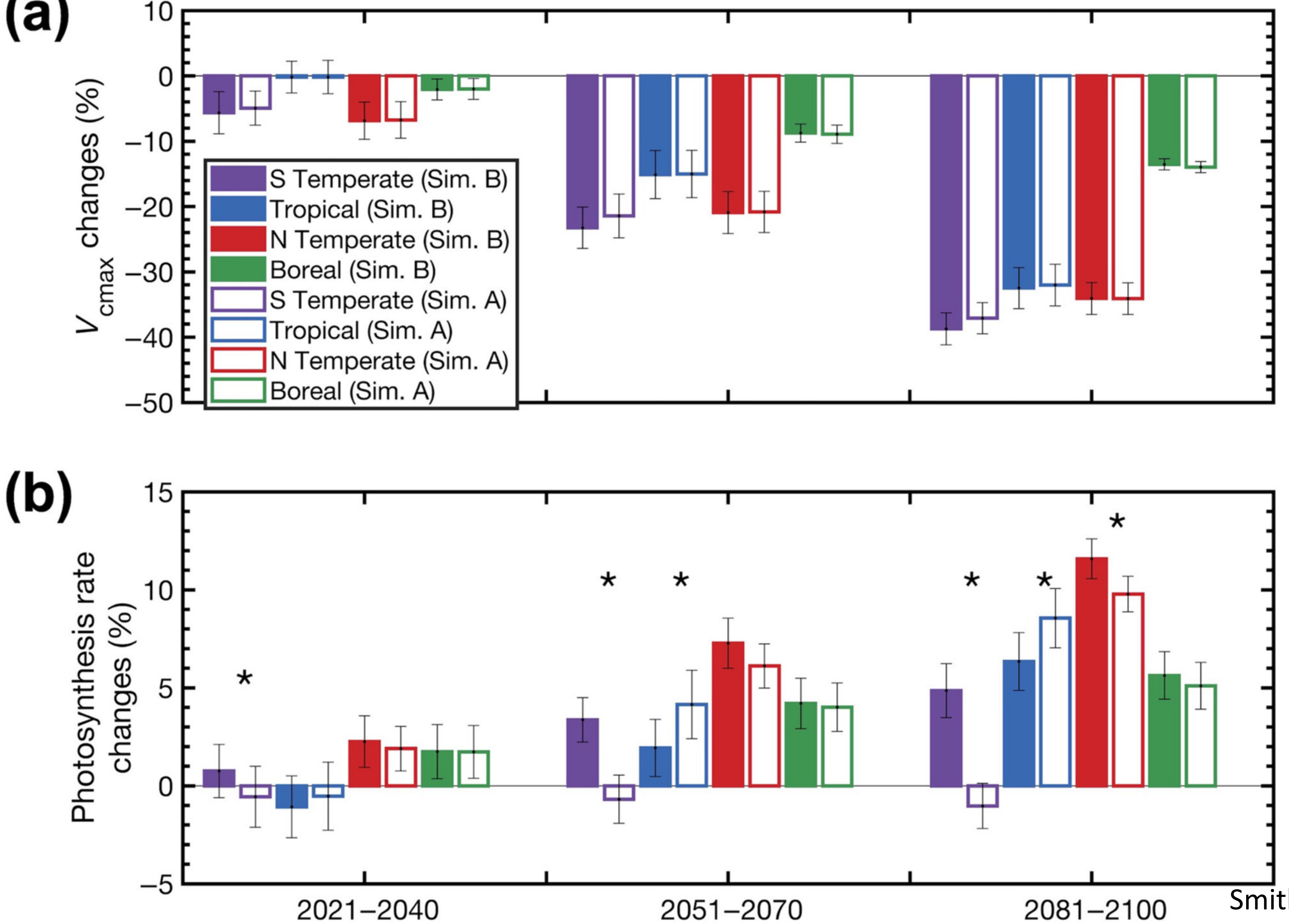
Photosynthesis is the largest flux of carbon between the atmosphere and Earth's surface and is driven by enzymes that require nitrogen, namely, ribulose-1,5-bisphosphate (RuBisCO). Thus, photosynthesis is a key link between the terrestrial carbon and nitrogen

TABLE 1 | Summarized configuration of ELM simulations.[a]

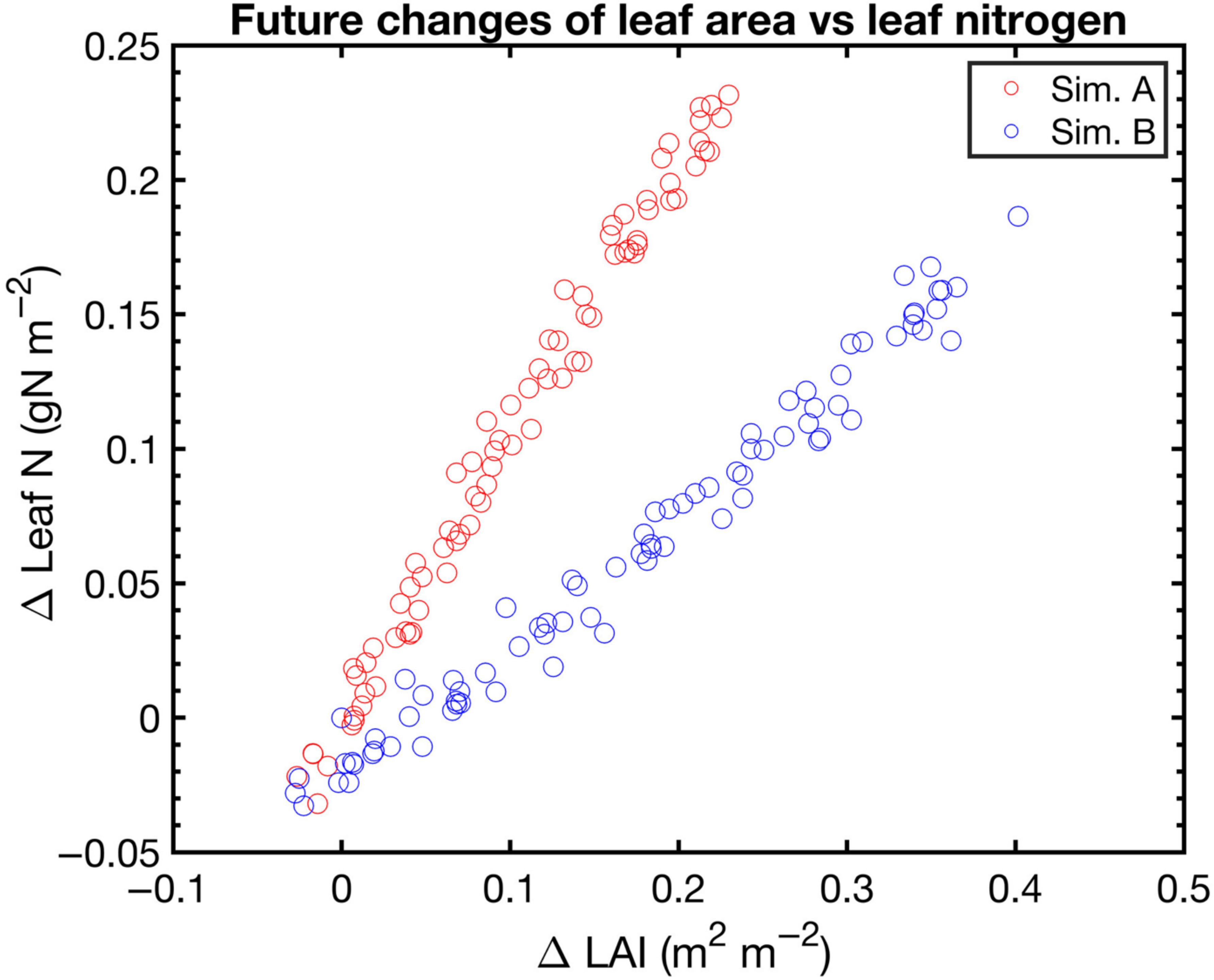
	Simulation A	Simulation B	Difference
Time period	1900–2100	1900–2100	No
Climate forcing	1901 to 2010: GSWP3 reanalysis forcing 2011–2100: 2001–2010 repeated climate forcings	1901 to 2010: GSWP3 reanalysis forcing 2011–2100: 2001–2010 repeated climate forcings	No
CO_2 forcing	1901–2010: transient CO_2 concentrations; 2011–2100: CO_2 concentrations from RCP8.5	1901–2010: transient CO_2 concentrations; 2011–2100: CO_2 concentrations from RCP8.5	No
Photosynthesis	Farquhar, von Caemmerer, and Berry (1980) scheme with acclimation of V_{cmax} following Smith and Keenan (2020)	Farquhar, von Caemmerer, and Berry (1980) scheme with acclimation of V_{cmax} following Smith and Keenan (2020)	No
Leaf nitrogen	Leaf nitrogen savings from acclimated V_{cmax} remain in the leaf	**Leaf nitrogen savings from acclimated V_{cmax} can be allocated throughout the plant**	**Yes**
Whole-plant allocation	Dynamic allocation of carbon and nitrogen to leaf, stem, and root tissue in response to light, water, and nitrogen limitations (Friedlingstein et al. 1999)	Dynamic allocation of carbon and nitrogen to leaf, stem, and root tissue in response to light, water, and nitrogen limitations (Friedlingstein et al. 1999)	No
Nitrogen acquisition	Competition for soil nitrogen among plant, microbial immobilizers, nitrifiers, and denitrifiers resolved with equilibrium chemistry approximation (Zhu et al. 2016)	Competition for soil nitrogen among plant, microbial immobilizers, nitrifiers, and denitrifiers resolved with equilibrium chemistry approximation (Zhu et al. 2016)	No

[a]Table contains relevant similarities and differences between the two simulations performed in this study. The full description of each simulation can be found in the Section 2. The key difference (indicated in bolded text) is whether leaf nitrogen savings under elevated CO_2 can be allocated throughout the plant (as in Simulation B).

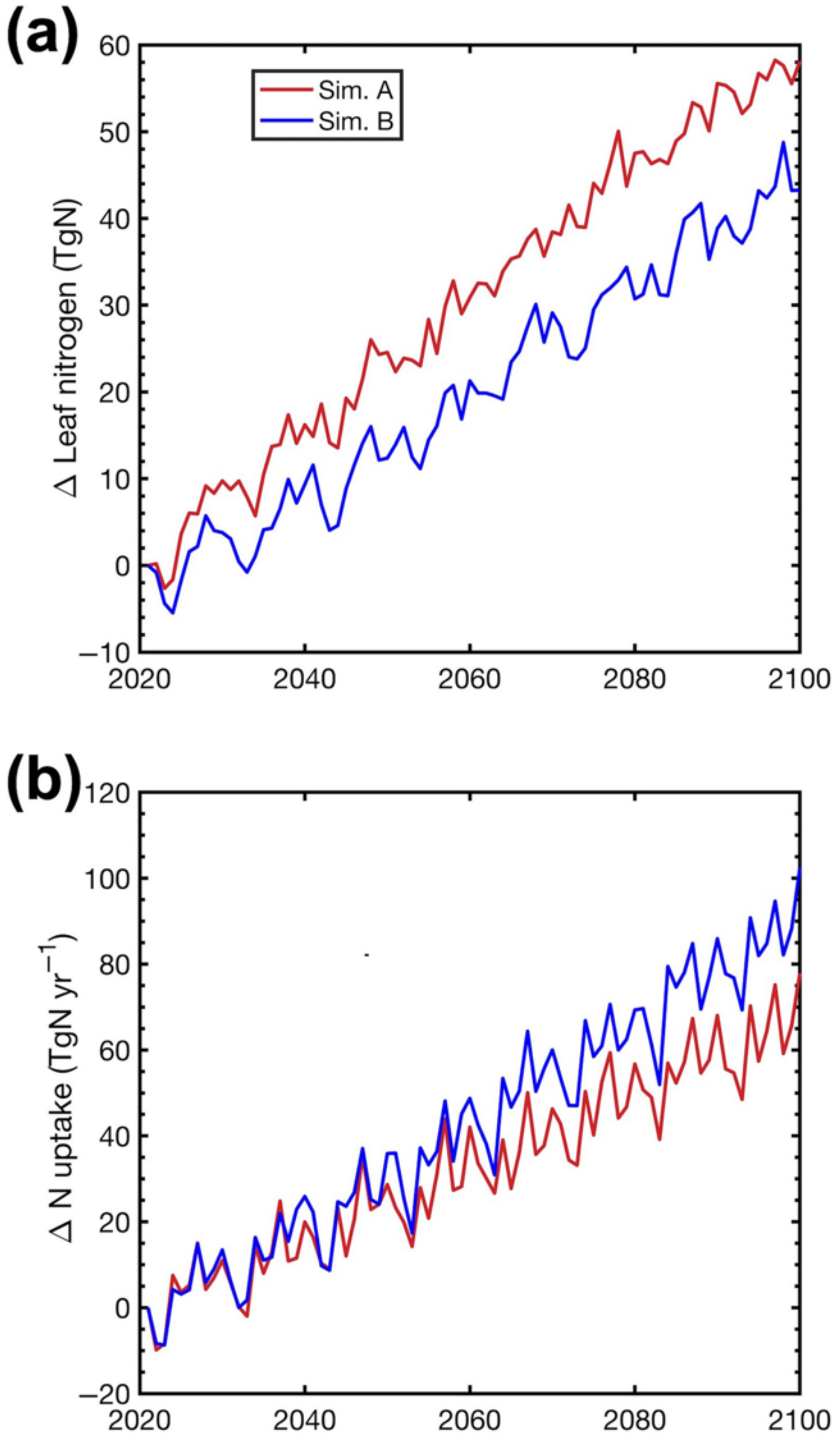
Smith et al. (2024)



Smith et al. (2024)

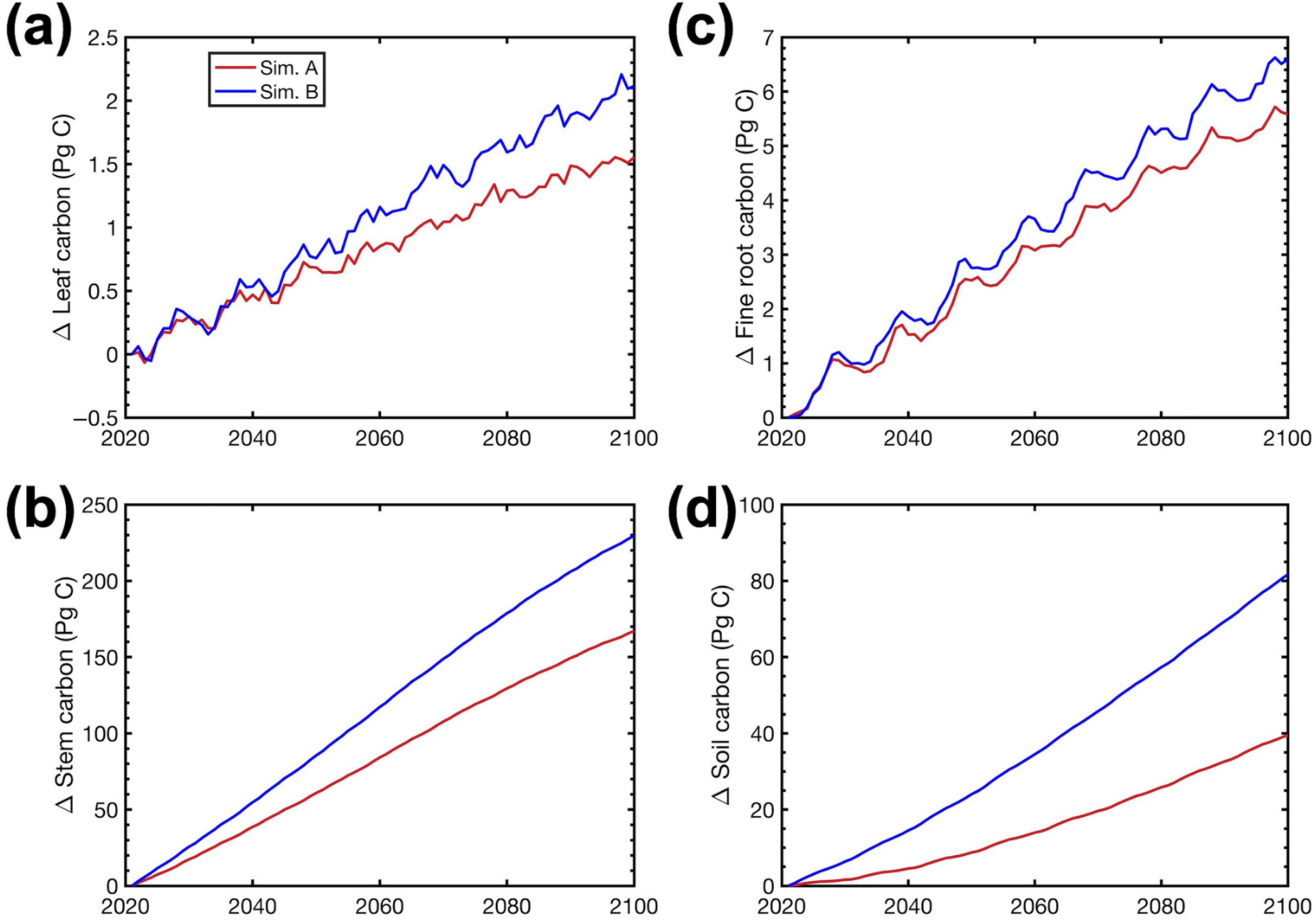


Smith et al. (2024)

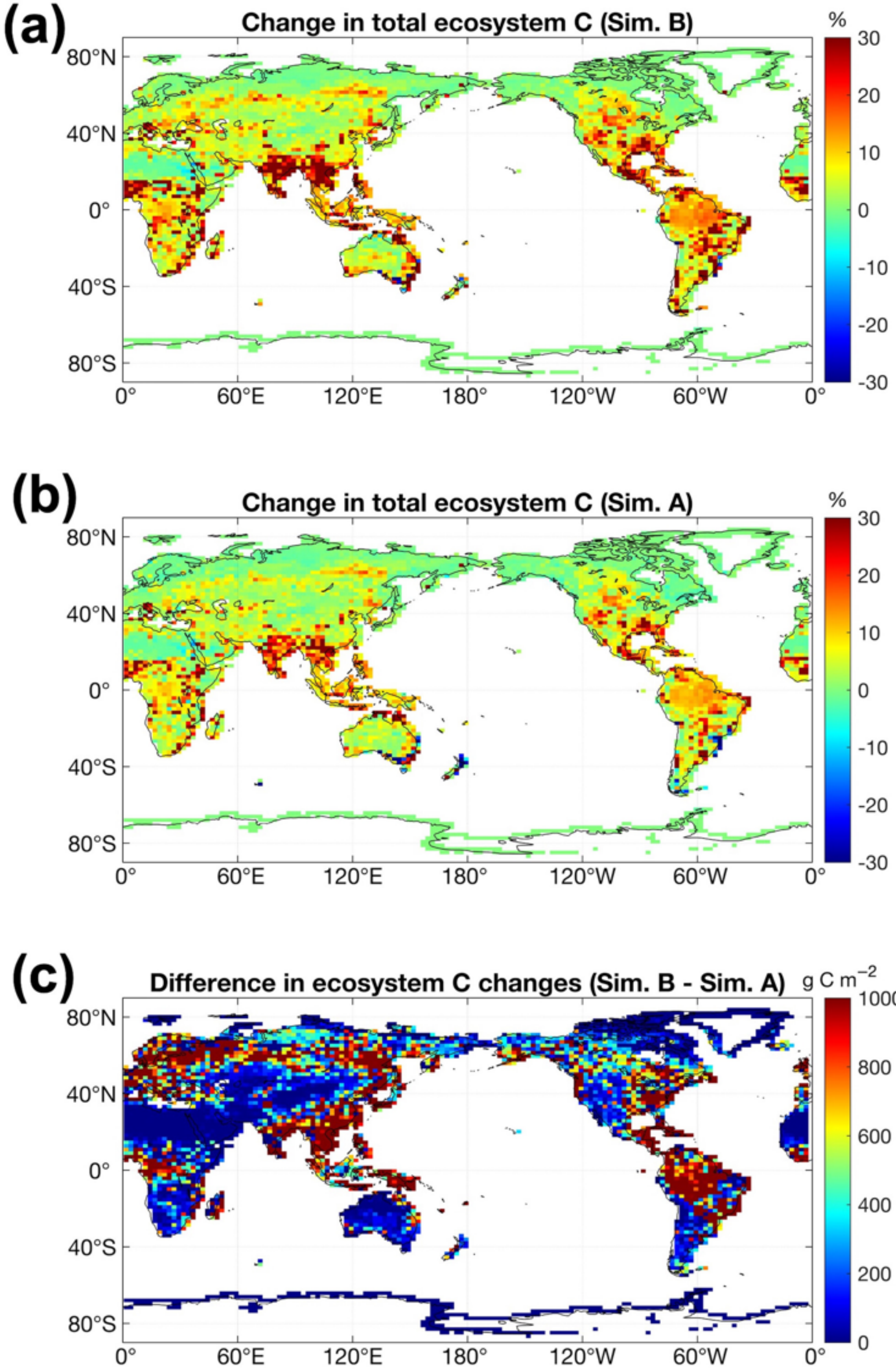


Saving leaf N, but why taking up more?

Smith et al. (2024)



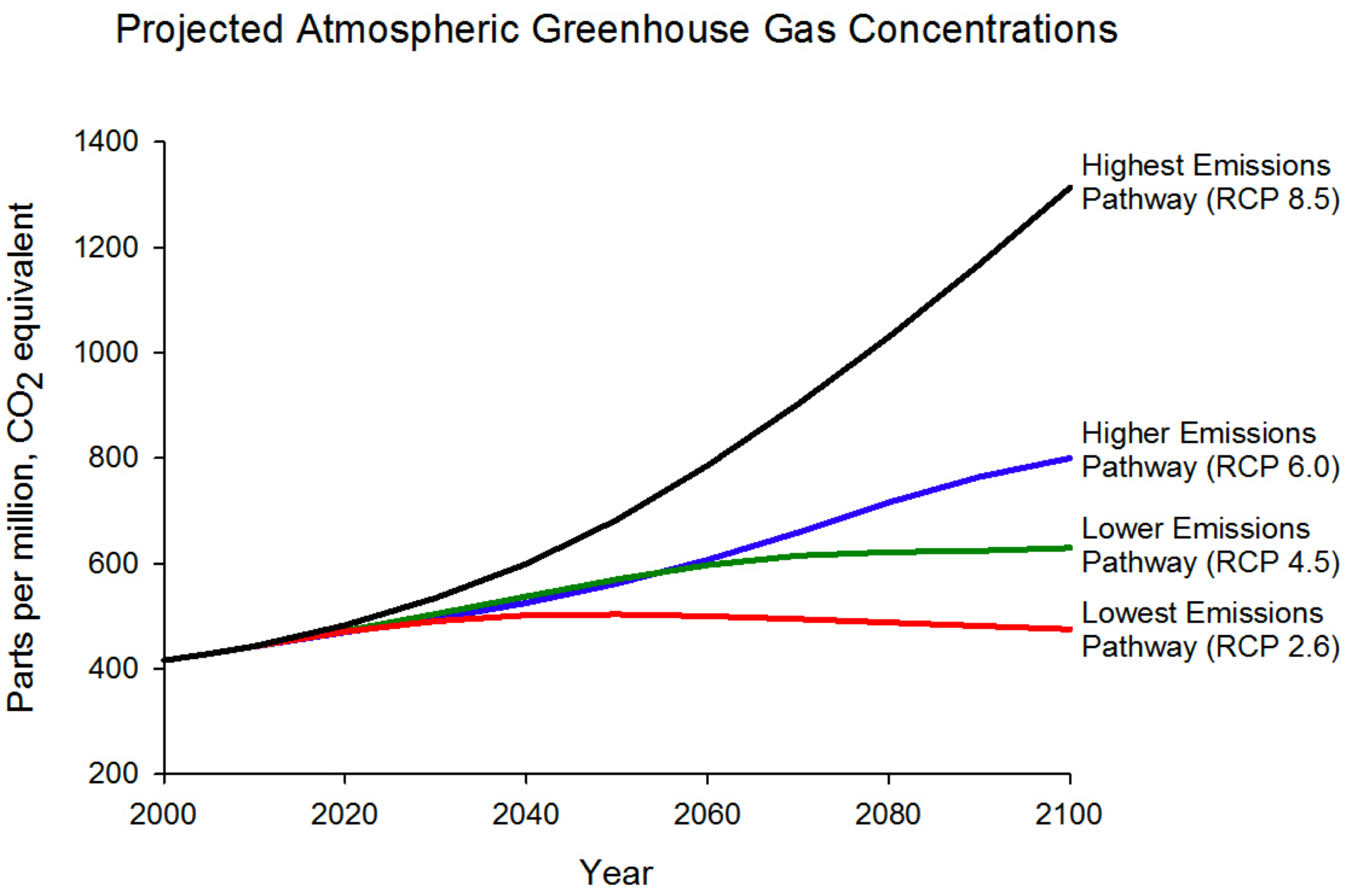
Smith et al. (2024)



Smith et al. (2024)

Smith et al. (2024) takehomes

- Plants acclimate to elevated CO_2 by reducing leaf nitrogen demand for Rubisco
- This results in lower leaf nitrogen, but still higher photosynthesis
- Plants respond by increase nitrogen allocation to roots to take up more nitrogen!
- This reduces progressive nitrogen limitation



What do you expect the plant response to be?

Draw a systems diagram

Bazzaz figure for discussion

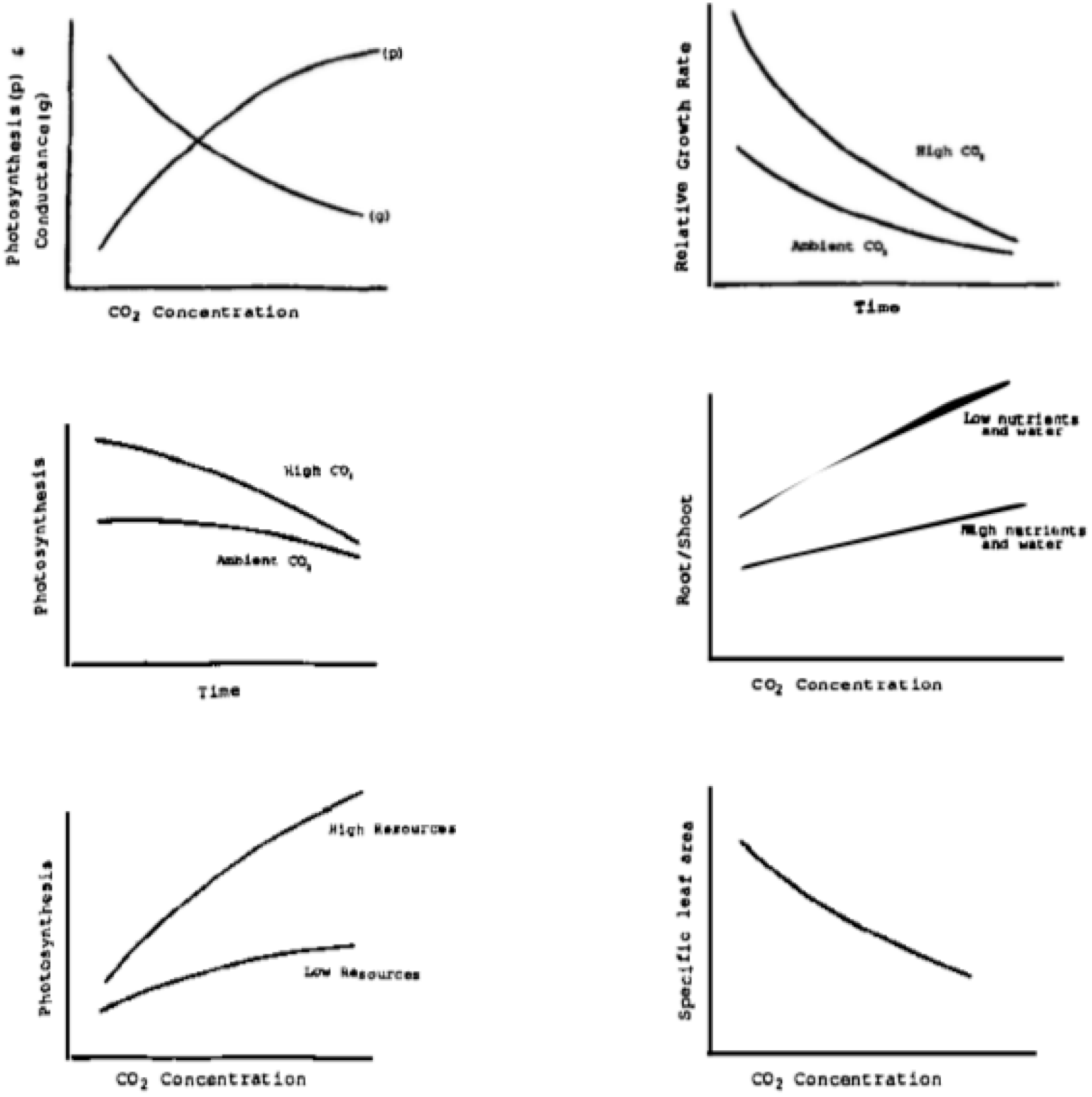


Figure 1 General trends of response of plants to CO_2 concentrations.

Bazzaz (1990)