The role of terrestrial phosphorus limitation in carbon cycle-climate feedbacks

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Outline

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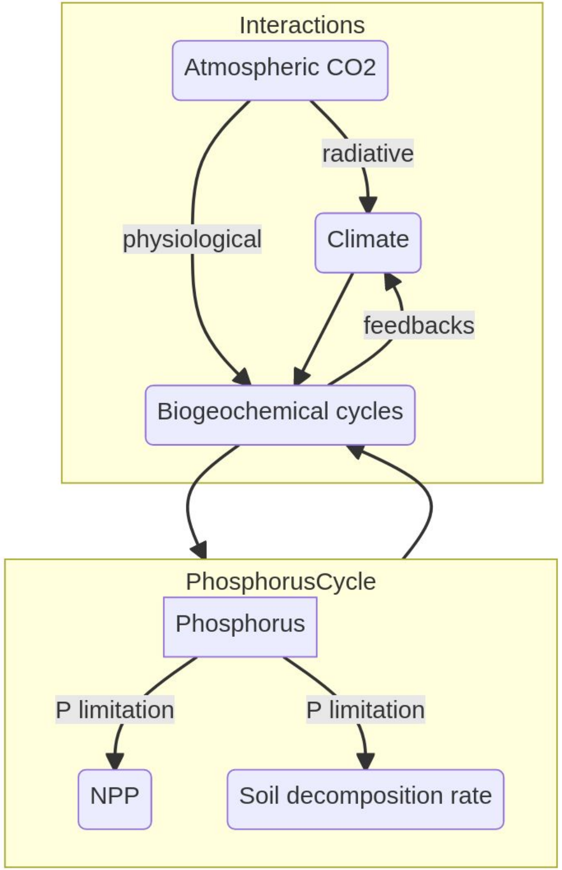
Motiviations

- Phosphorus (P) is an essential nutrient for plant growth, a low concentration of soil P available to plants will limit the potential of plants to uptake CO_2 from the atmosphere. This effect is called P limitation.
- More than 43% of global land is limited by P, only 18% is limited by nitrogen (N), and 39% is N-P co-limited (Du et al. 2020)
- P limitation may reduce soil water consumption by 8-30% during wet periods, thus increase the tolerance of the tropical ecosystem to drought (Goll et al. 2018)

As the atmospheric CO2 concentration rises, the projected climate will become warmer and more extreme. Therefore, it is important to study the role of phosphorus limitation in carbon cycle-climate feedbacks.

Introduction



<u>Science questions:</u>

- How will phosphorus and nitrogen limitation change with increases in atmospheric CO_2 concentration and surface temperature?
- Will nitrogen have more constraints on the global carbon cycle in a future climate?
- What is the role of the phosphorus limitation on the global carbon cycle and carbon-climate feedbacks?

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Global nitrogen and phosphorus limitation

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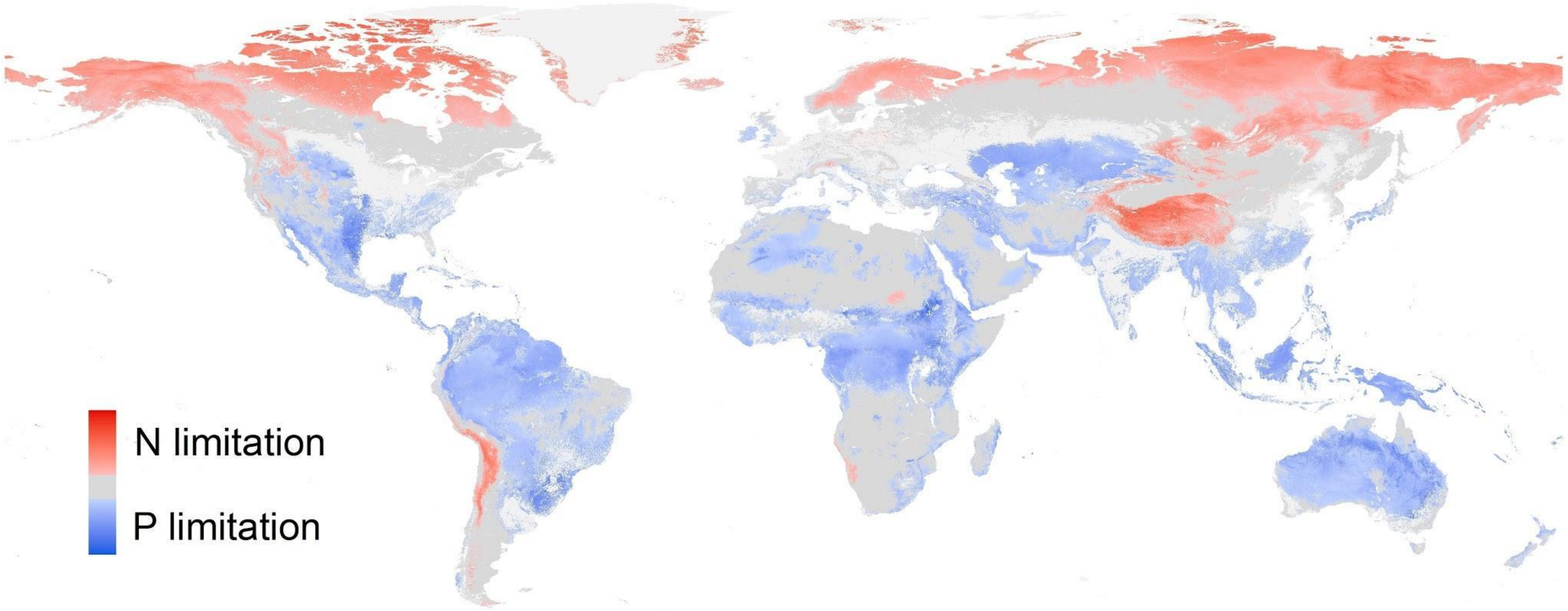

Figure: Map of terrestrial nitrogen and phosphorus limitation (Du et al., 2020, Nature Geoscience)

Model and Experiments

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The Energy Exascale Earth System Model (**E3SM**) version 1.1 (Burrows et al. 2020) is used in this study. We conducted four experiments following the protocols of C4MIP (Jones et al. 2016) with an active BGC model while holding all other forcings at pre-industrial levels.

- **PiControl (CTL)**: A pre-industrial control simulation with non-evolving pre-industrial conditions.
- **1pctCO2BGC (BGC)**: the CO_2 concentration increases at 1%/yr for the BGC model with the CO_2 concentration keeping pre-industrial level for the RAD model
- **1pctCO2RAD (RAD)**: similar to 1pctCO2BGC, but vice versa
- **1pctCO2FULL (FULL)**: the CO_2 concentration increase at 1% /yr for the BGC and RAD models

To study the effects of P on the global carbon cycle and feedbacks, we simulated the E3SM with carbon-nitrogen (**CN**) and carbon-nitrogen-phosphorus coupling (**CNP**) for each experiment.

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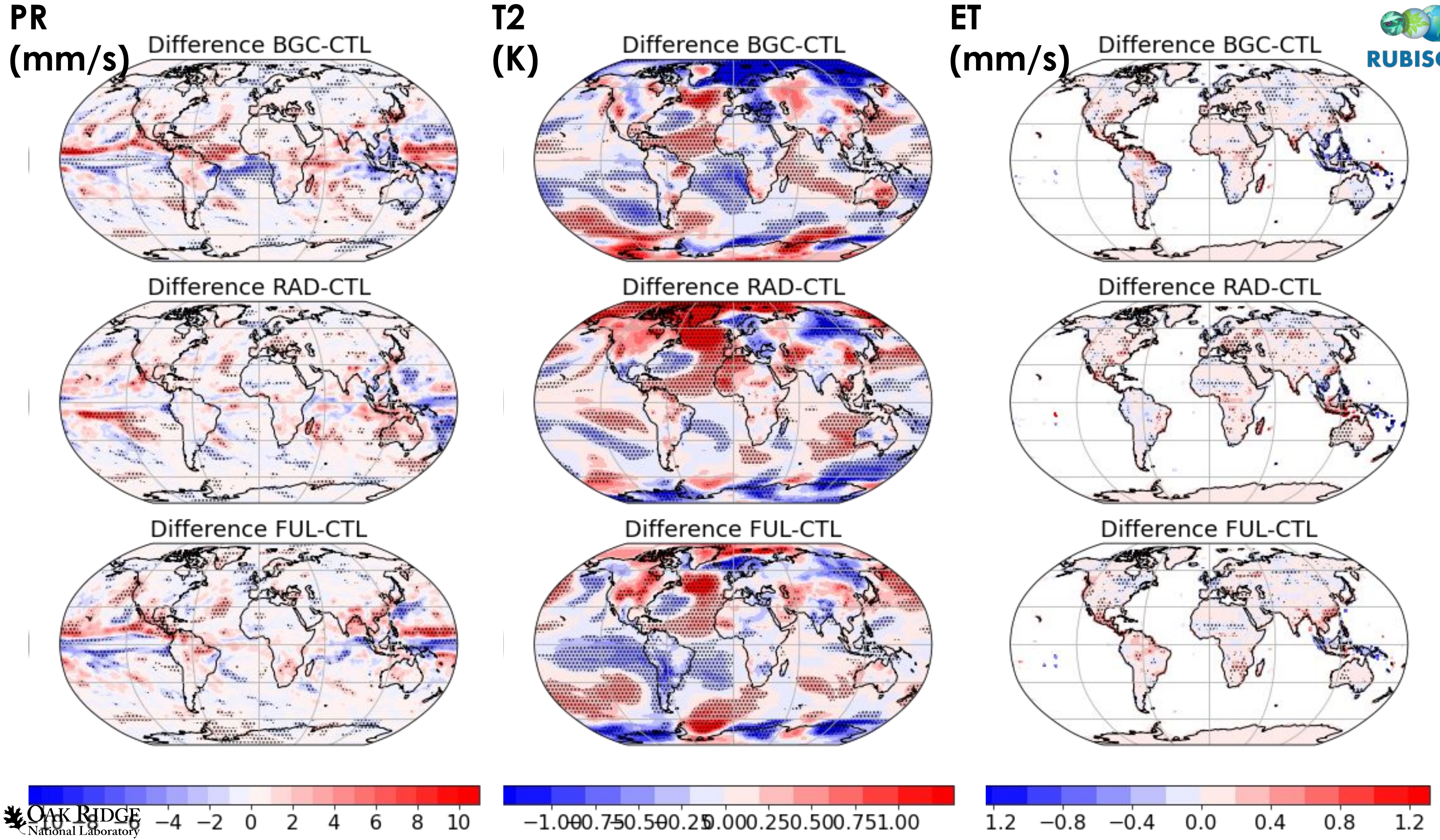
PR
(mm/s)
T2
(K)
ET
(mm/s)
Difference BGC-CTL
Difference BGC-CTL
Difference BGC-CTL
Difference RAD-CTL
Difference RAD-CTL
Difference RAD-CTL
Difference FUL-CTL
Difference FUL-CTL
Difference FUL-CTL
−4 −2 0 2 4 6 8 10
−1.00 −0.75 −0.50 −0.25 0.00 0.25 0.50 0.75 1.00
1.2 −0.8 −0.4 0.0 0.4 0.8 1.2

Strong interactions between P limitation and climate

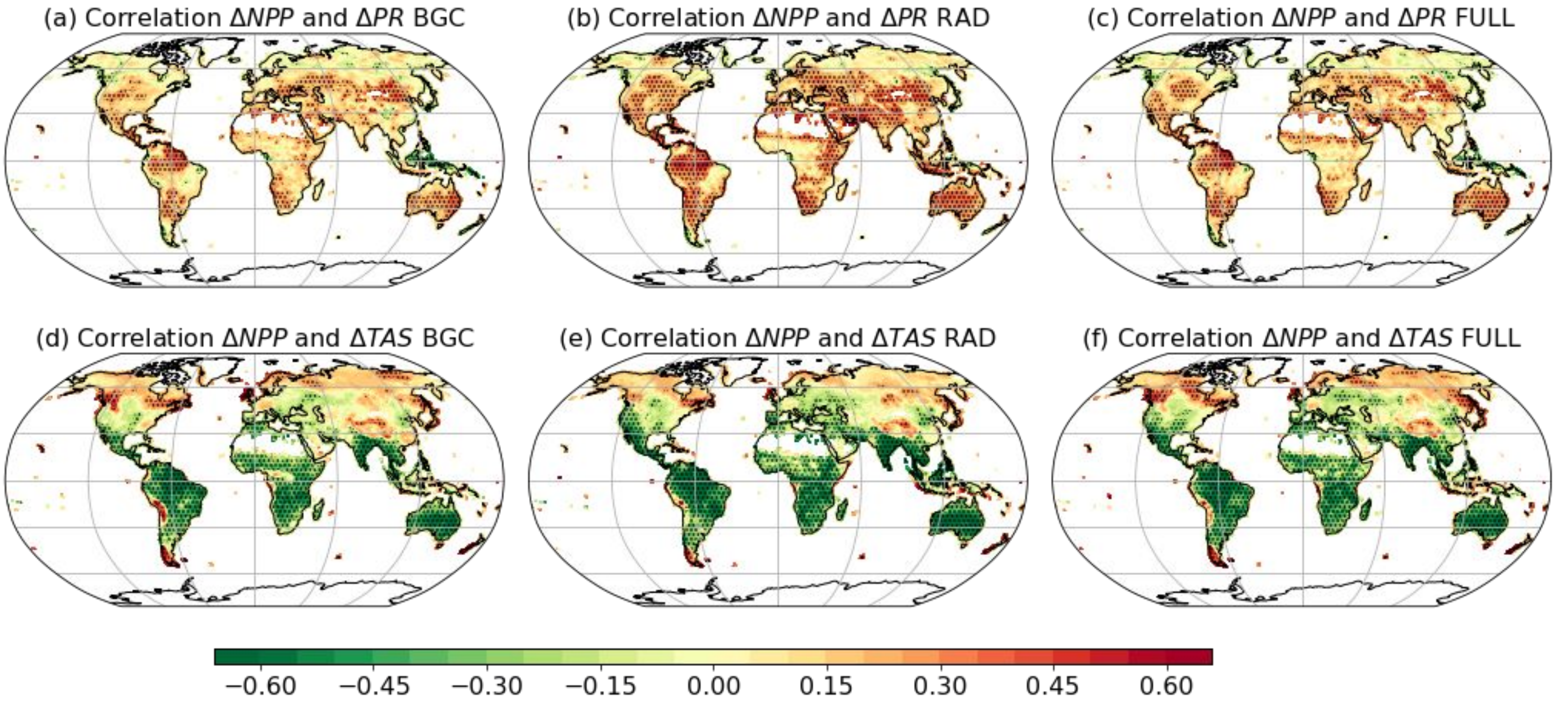

Figure: Correlations between the NPP and precipitation (a-c) and temperature (d-f)differences (CNP minus CN) in biogeochemically (a,d), radiatively(b,e), and fully coupled (c,f) 1pctCO2 experiments, respectively. (Stippled area indicates significance in a 90% confidence level.)

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Cumulative net primary production

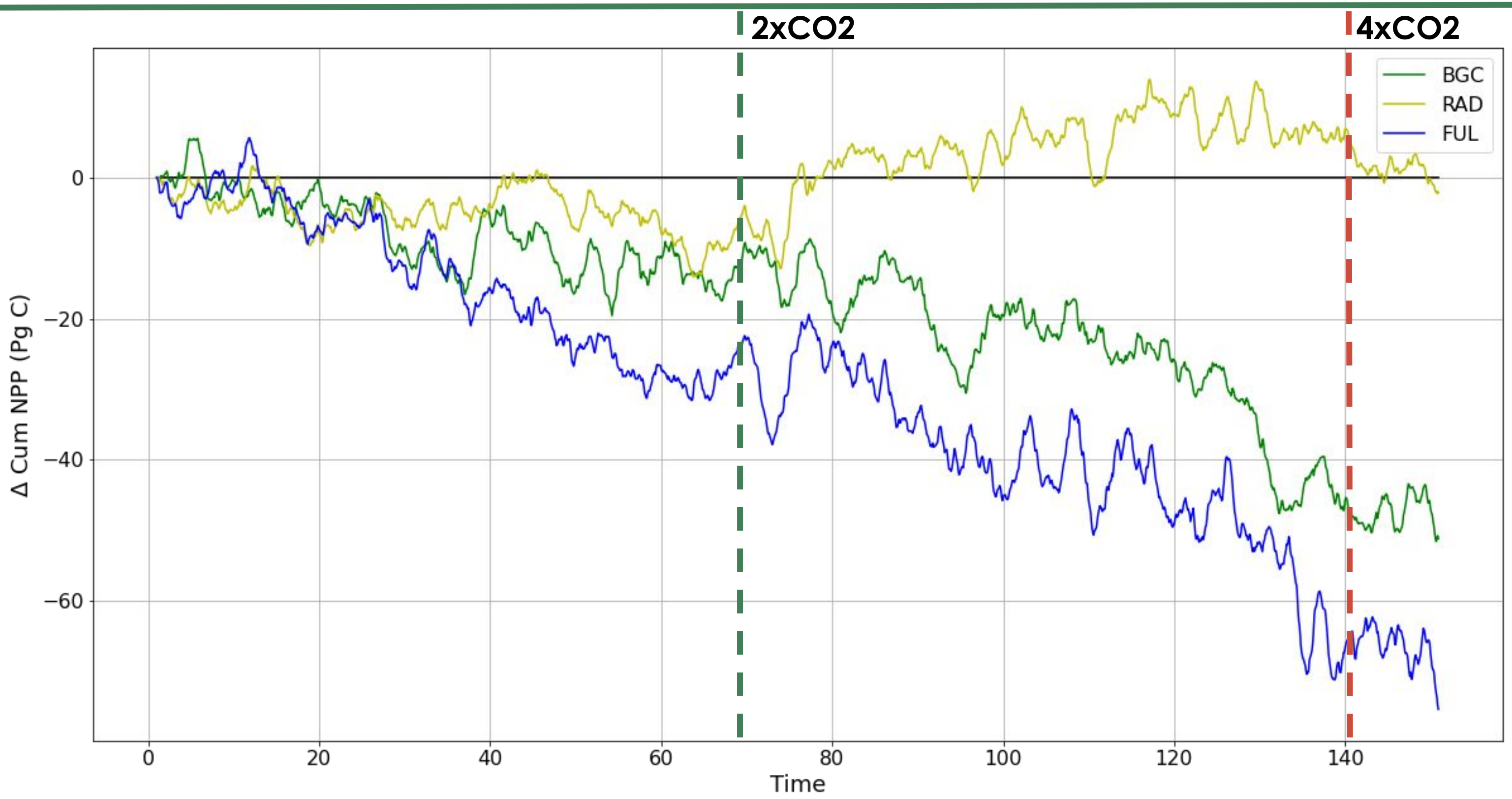

Figure: the NPP differences between CNP and CN (CNP minus CN) for three experiments. The cumulative NPPs are relative to their PiControl values.

Cumulative gross primary production

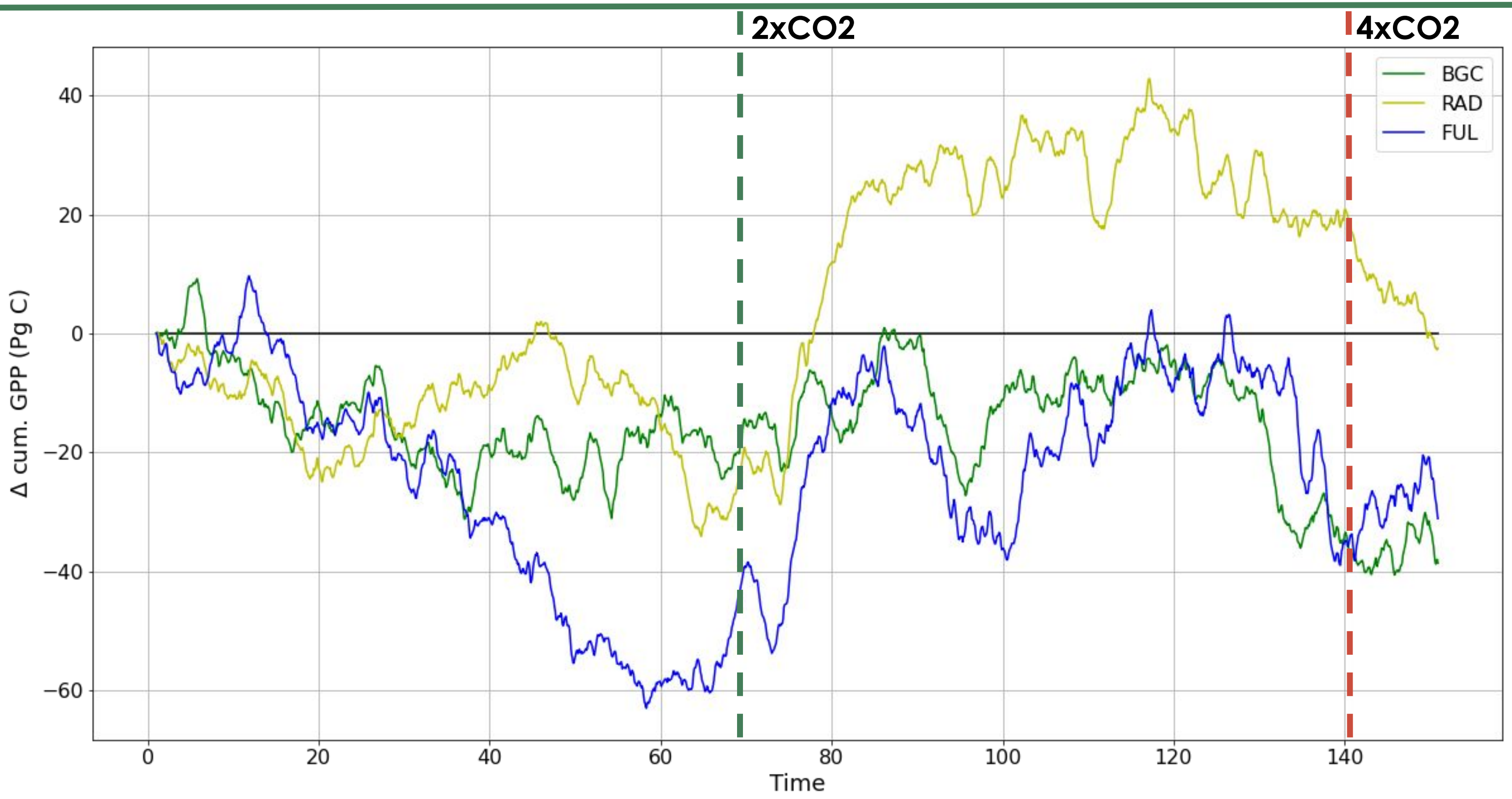

Figure: the GPP differences between CNP and CN (CNP minus CN) for three experiments. The cumulative GPPs are relative to their PiControl values.

Heterotrophic respiration

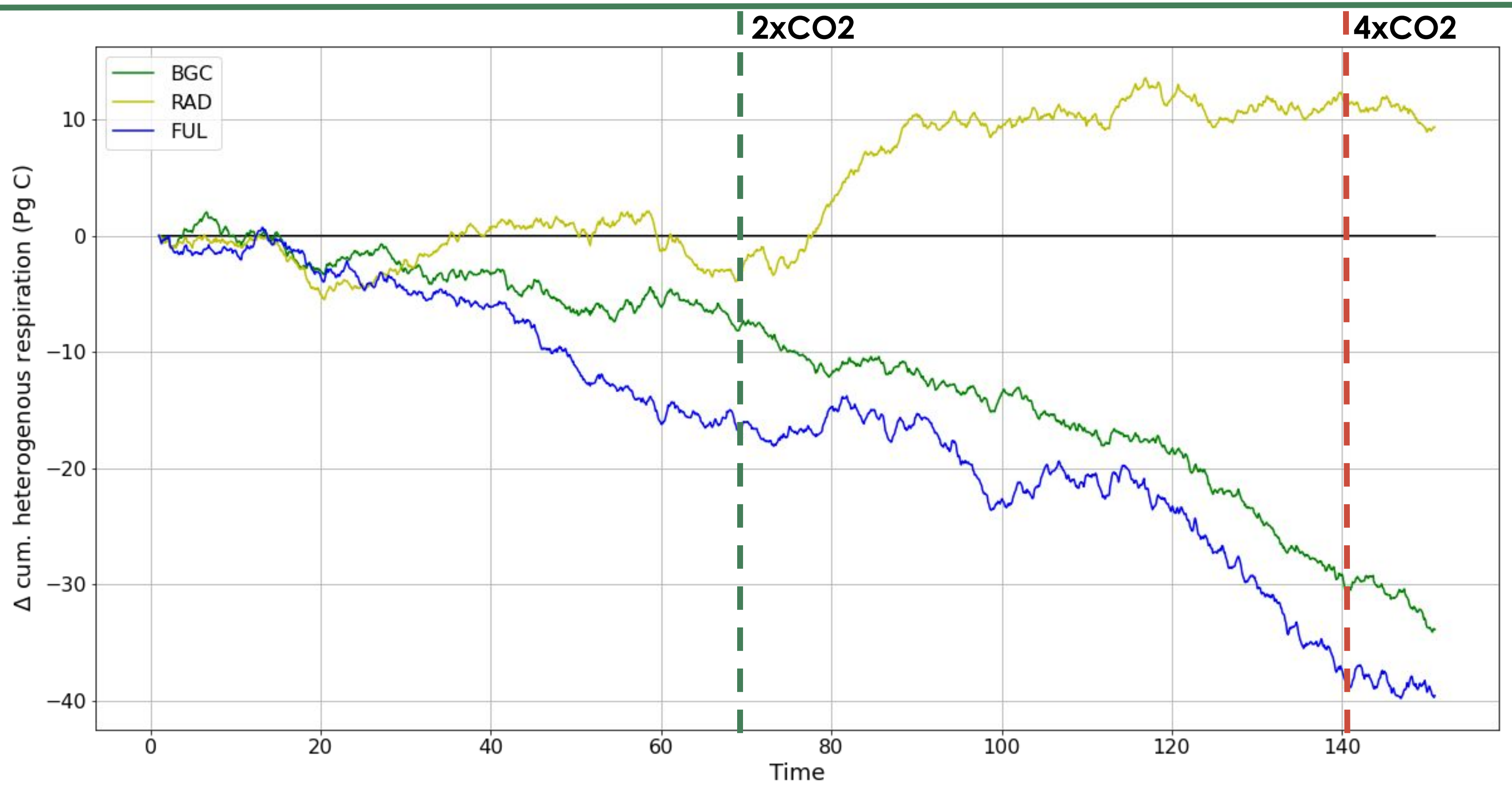

Figure: the HR differences between CNP and CN (CNP minus CN) for three experiments. The cumulative HRs are relative to their PiControl values.

Autotrophic respiration

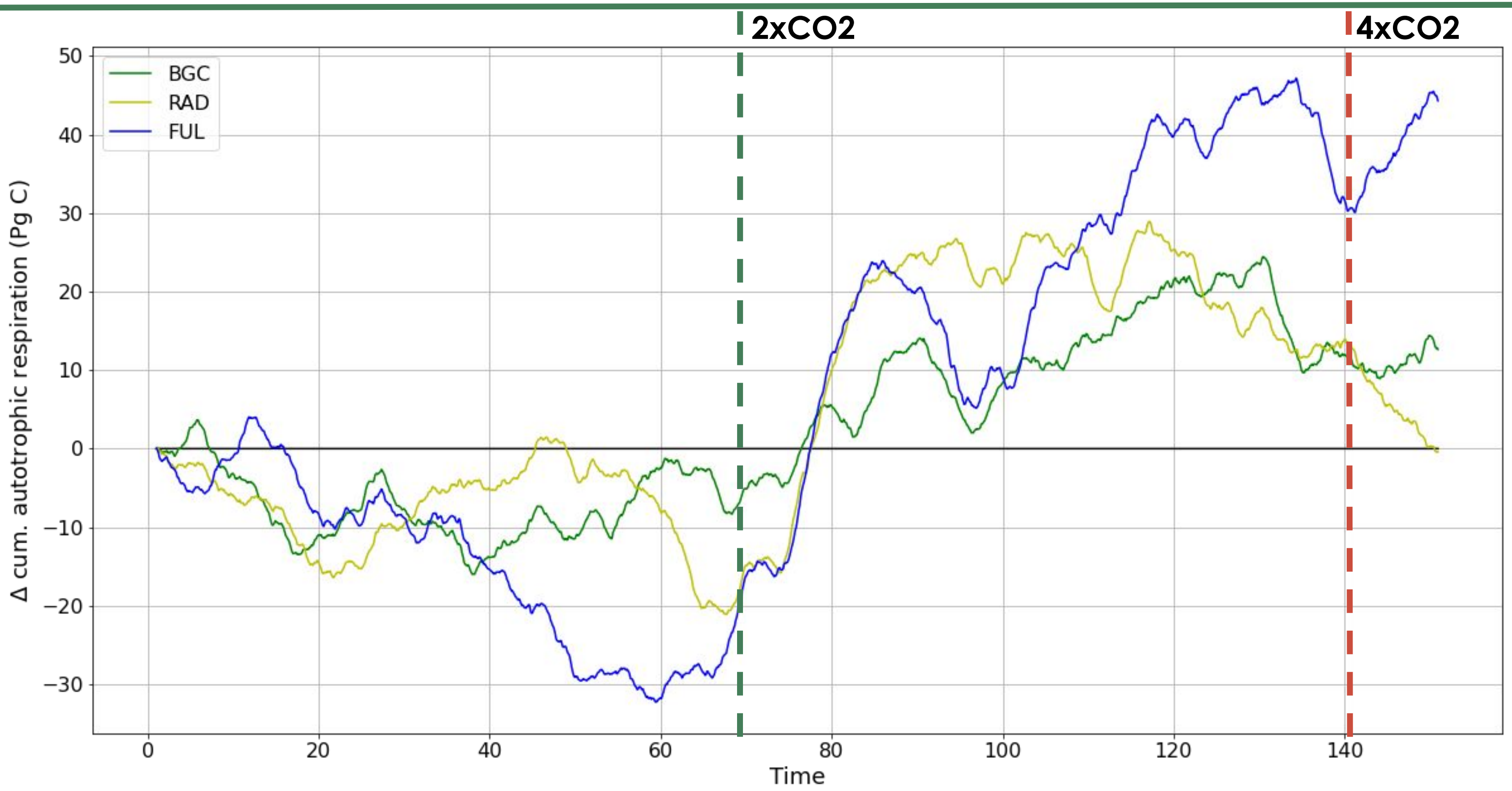

Figure: the AR differences between CNP and CN (CNP minus CN) for three experiments. The cumulative ARs are relative to their PiControl values.

Net ecosystem exchange

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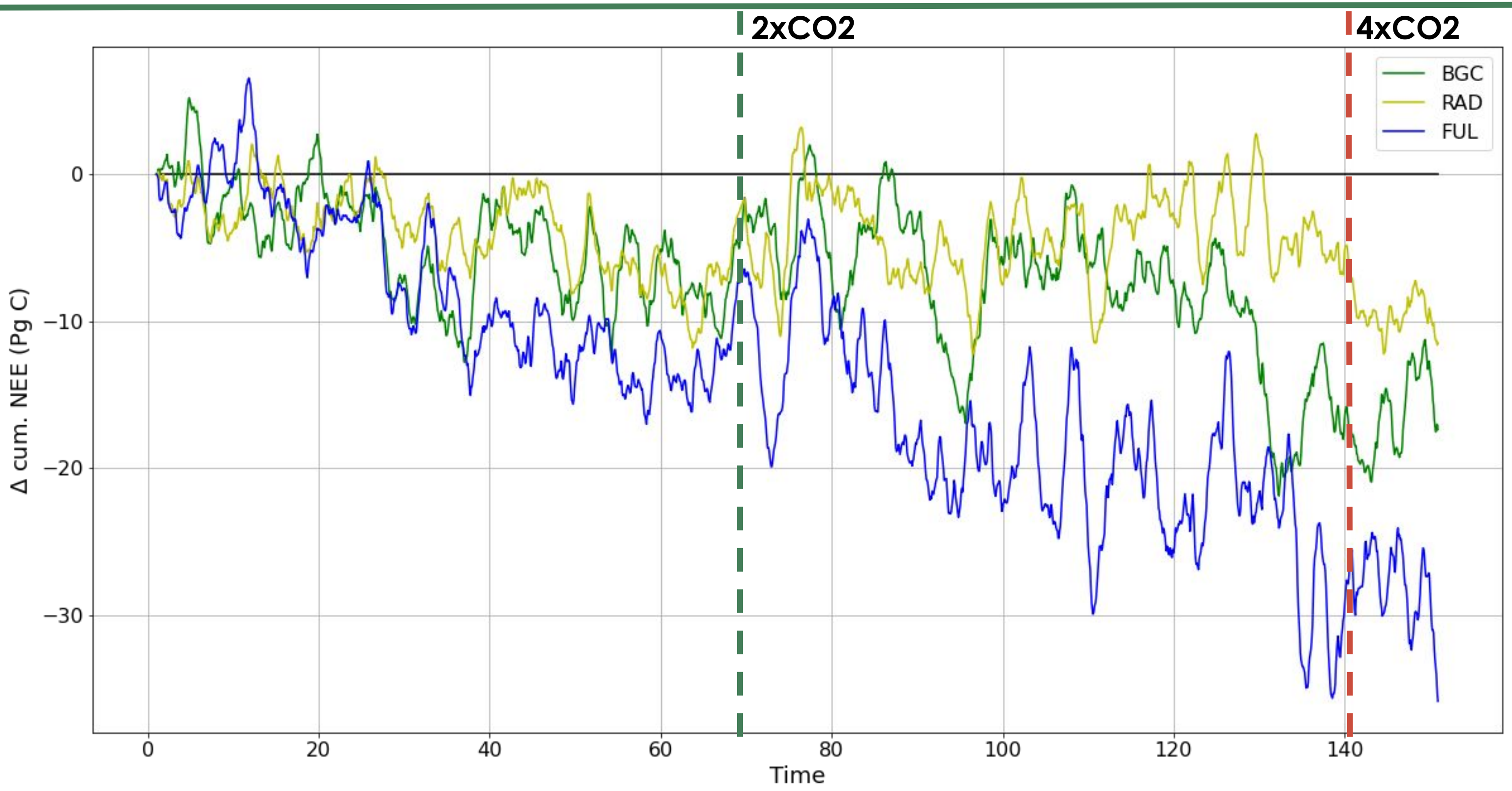

Figure: the NEE differences between CNP and CN (CNP minus CN) for three experiments. The cumulative NEEs are relative to their PiControl values.

Soil carbon

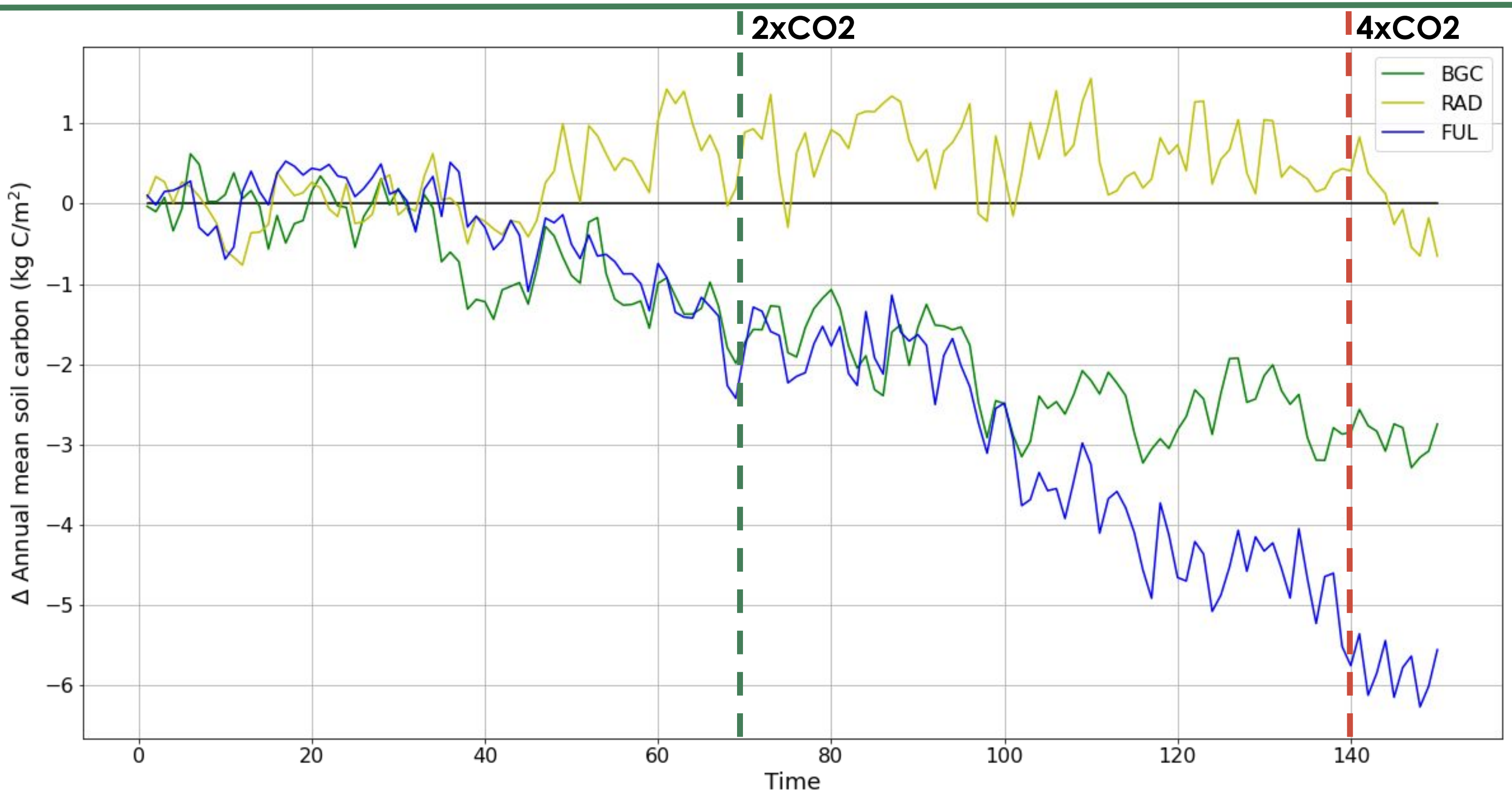

Figure: the cSoil differences between CNP and CN (CNP minus CN) for three experiments. The cumulative cSoils are relative to their PiControl values.

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P limitation-soil moisture feedbacks

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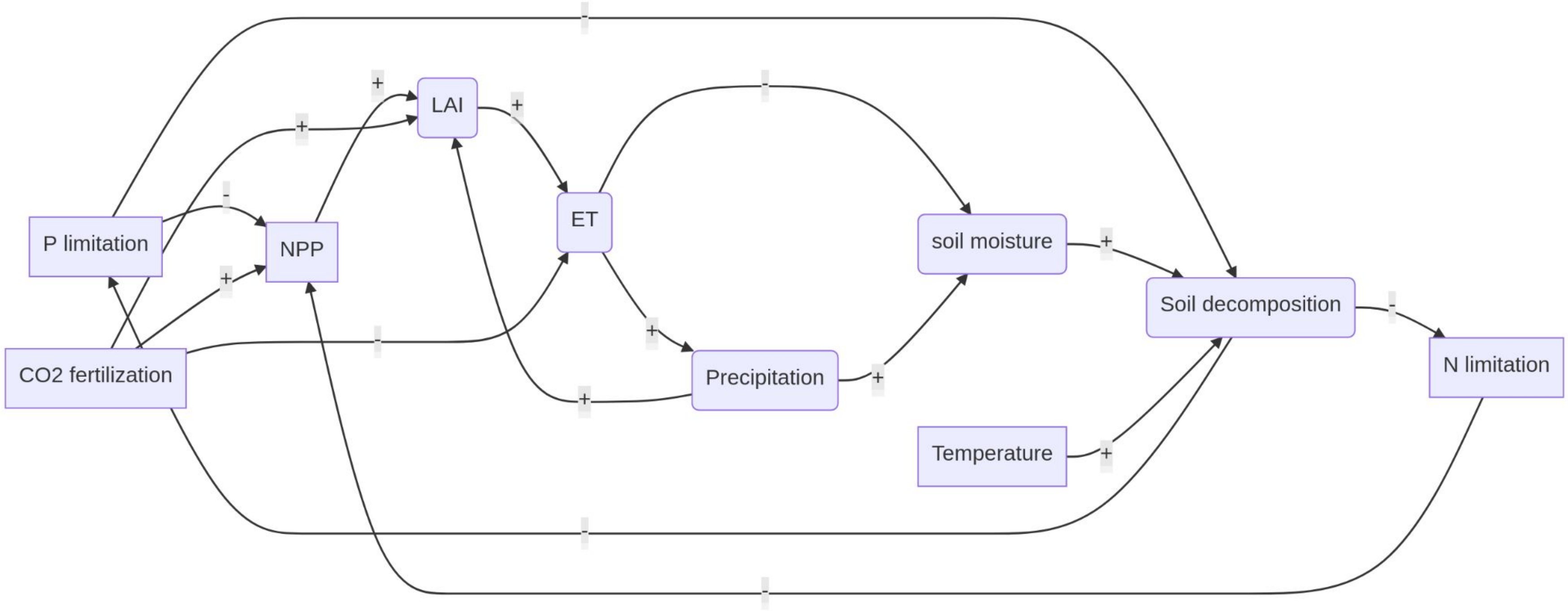
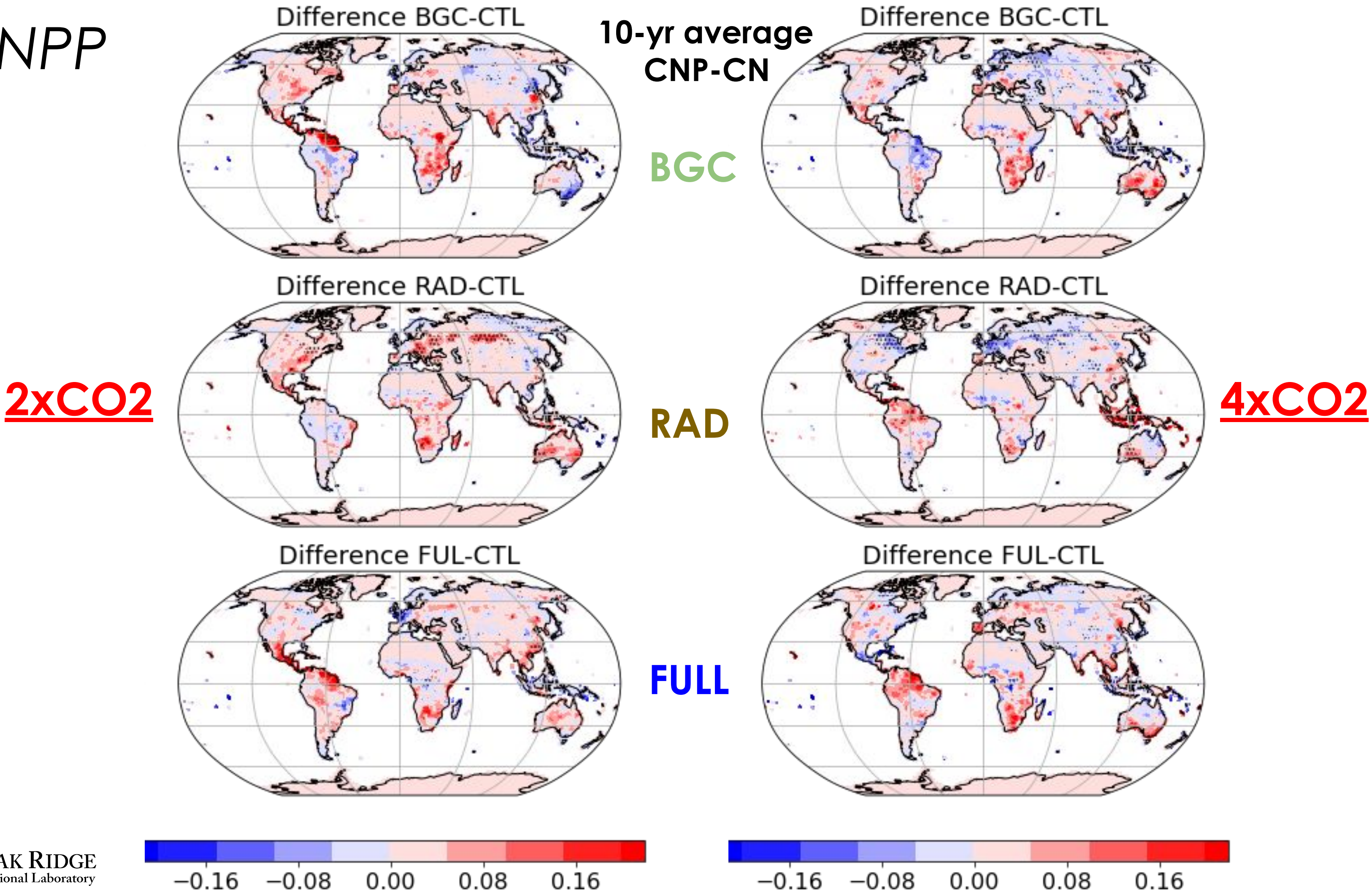


NPP



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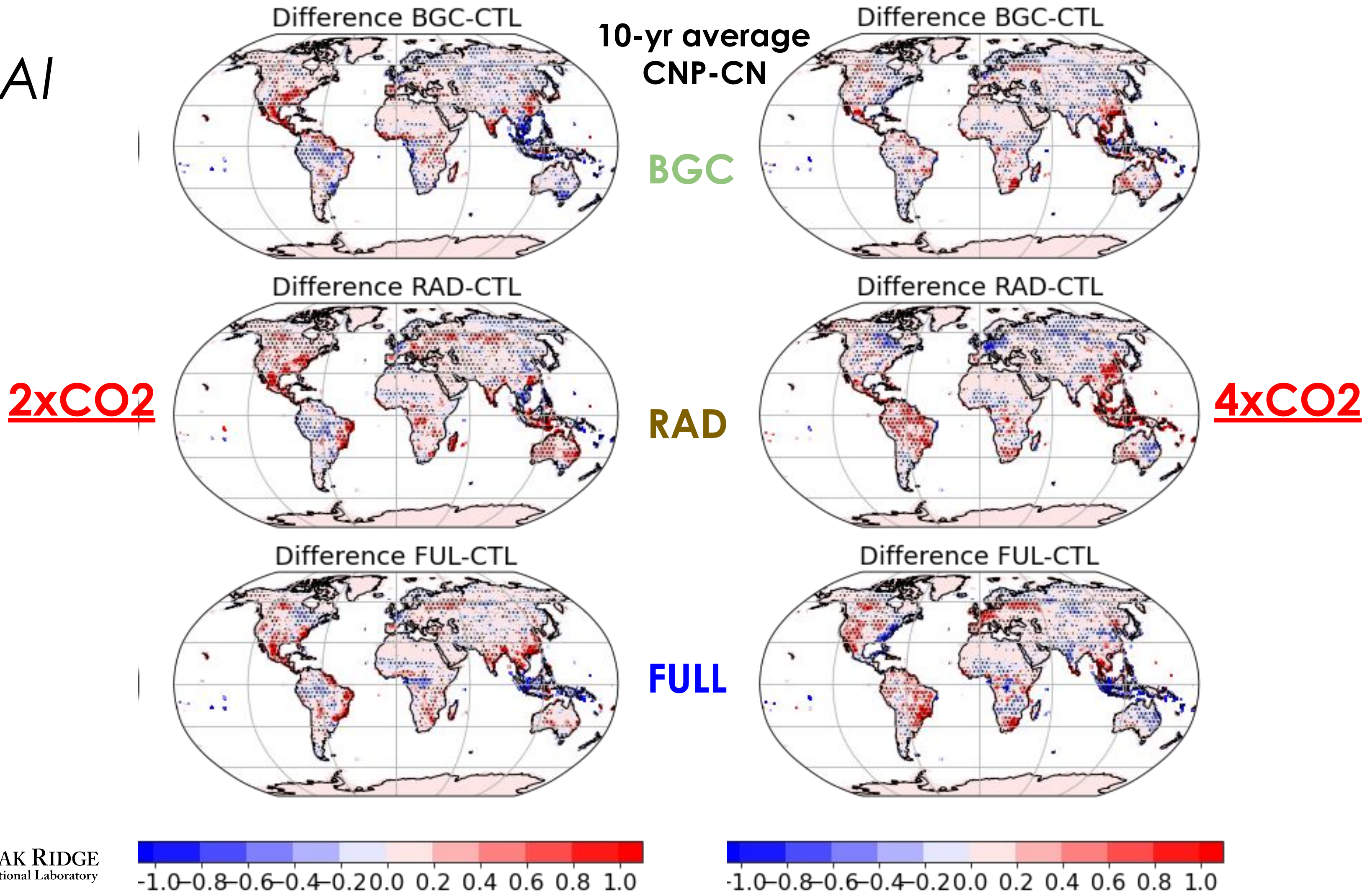
LAI

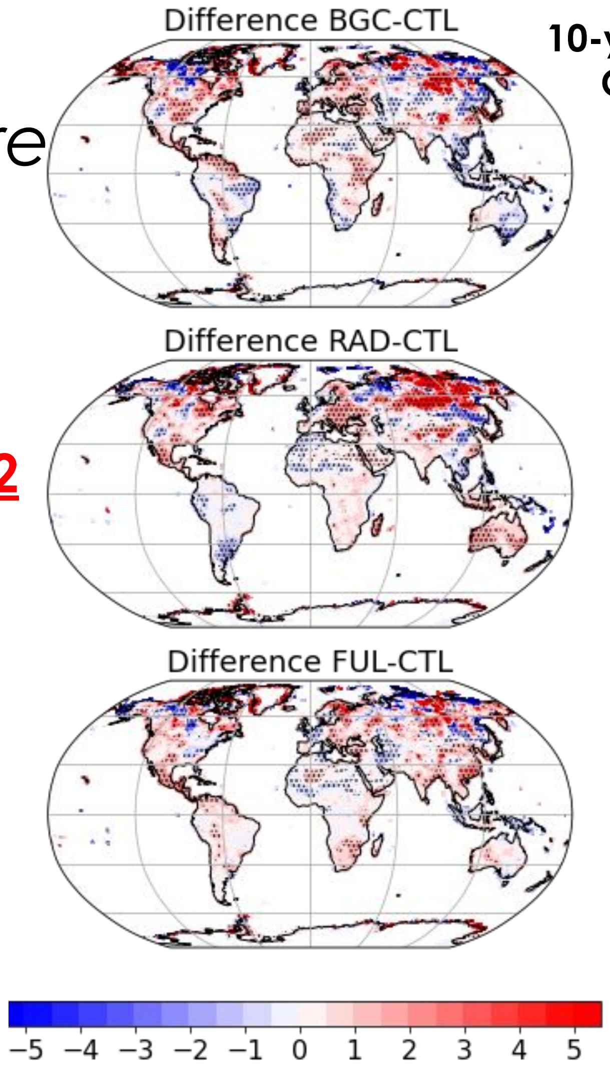


10-yr average
CNP-CN
2xCO2
4xCO2
BGC
RAD
FULL
Difference BGC-CTL
Difference BGC-CTL
Difference RAD-CTL
Difference RAD-CTL
Difference FUL-CTL
Difference FUL-CTL
-1.0 -0.8 -0.6 -0.4 -0.2 0.0 0.2 0.4 0.6 0.8 1.0
-1.0 -0.8 -0.6 -0.4 -0.2 0.0 0.2 0.4 0.6 0.8 1.0

Soil moisture

10-yr average CNP-CN

2xCO2

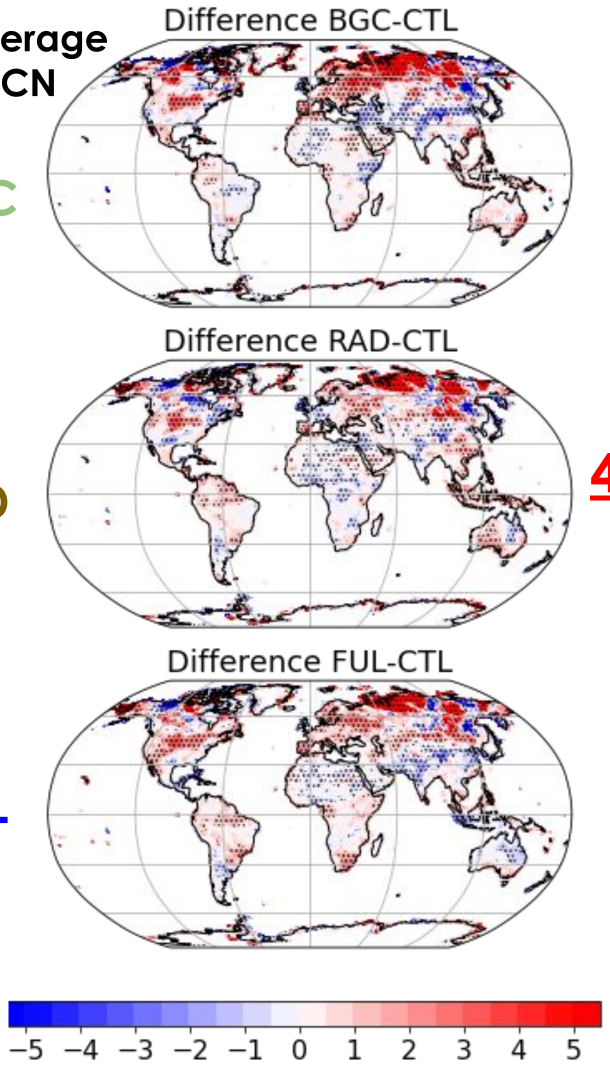


BGC

RAD

FULL

4xCO2



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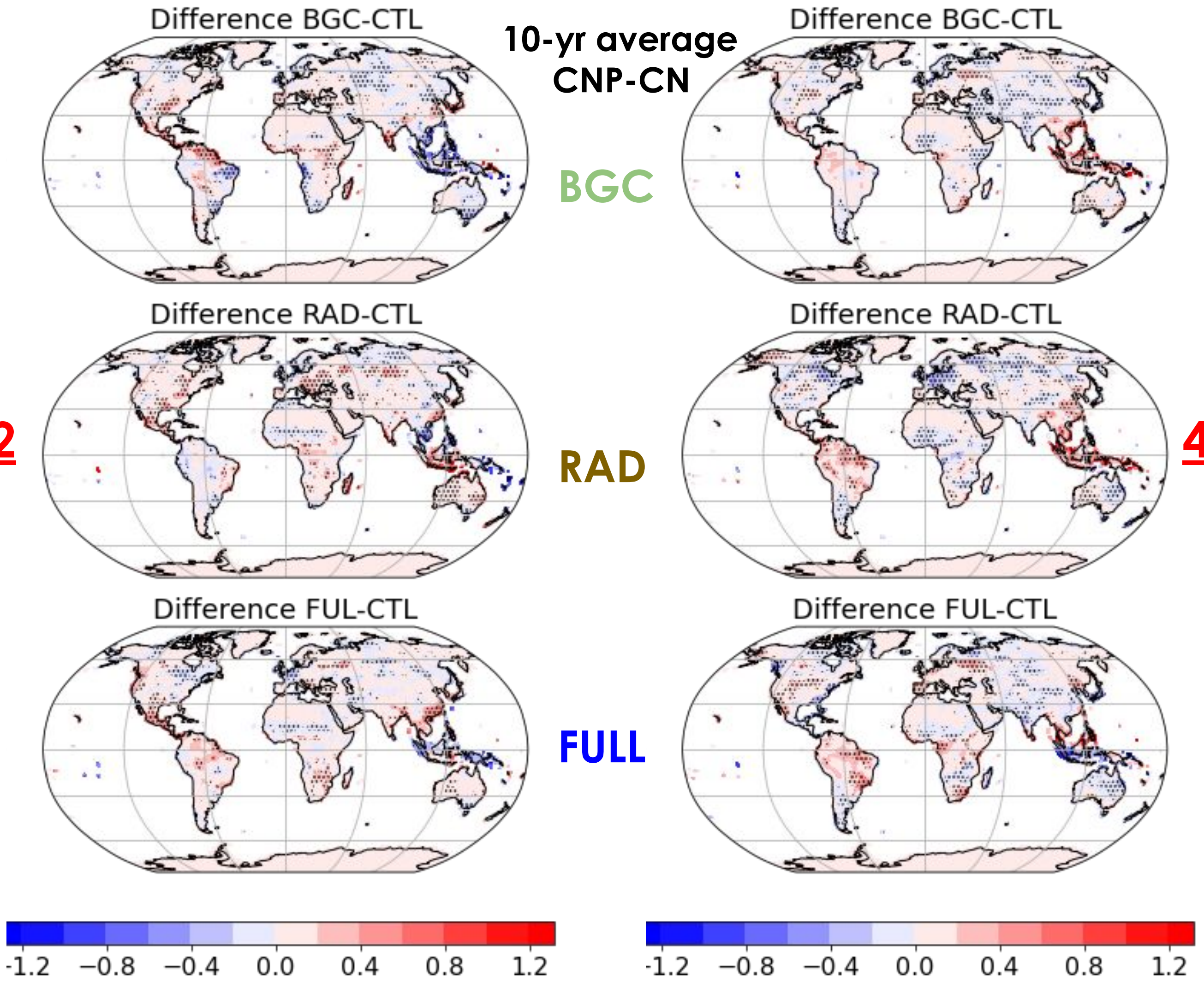
ET

2xCO2



4xCO2

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Plant N limitation (FPG_N) **The larger the value, the less the limit !**

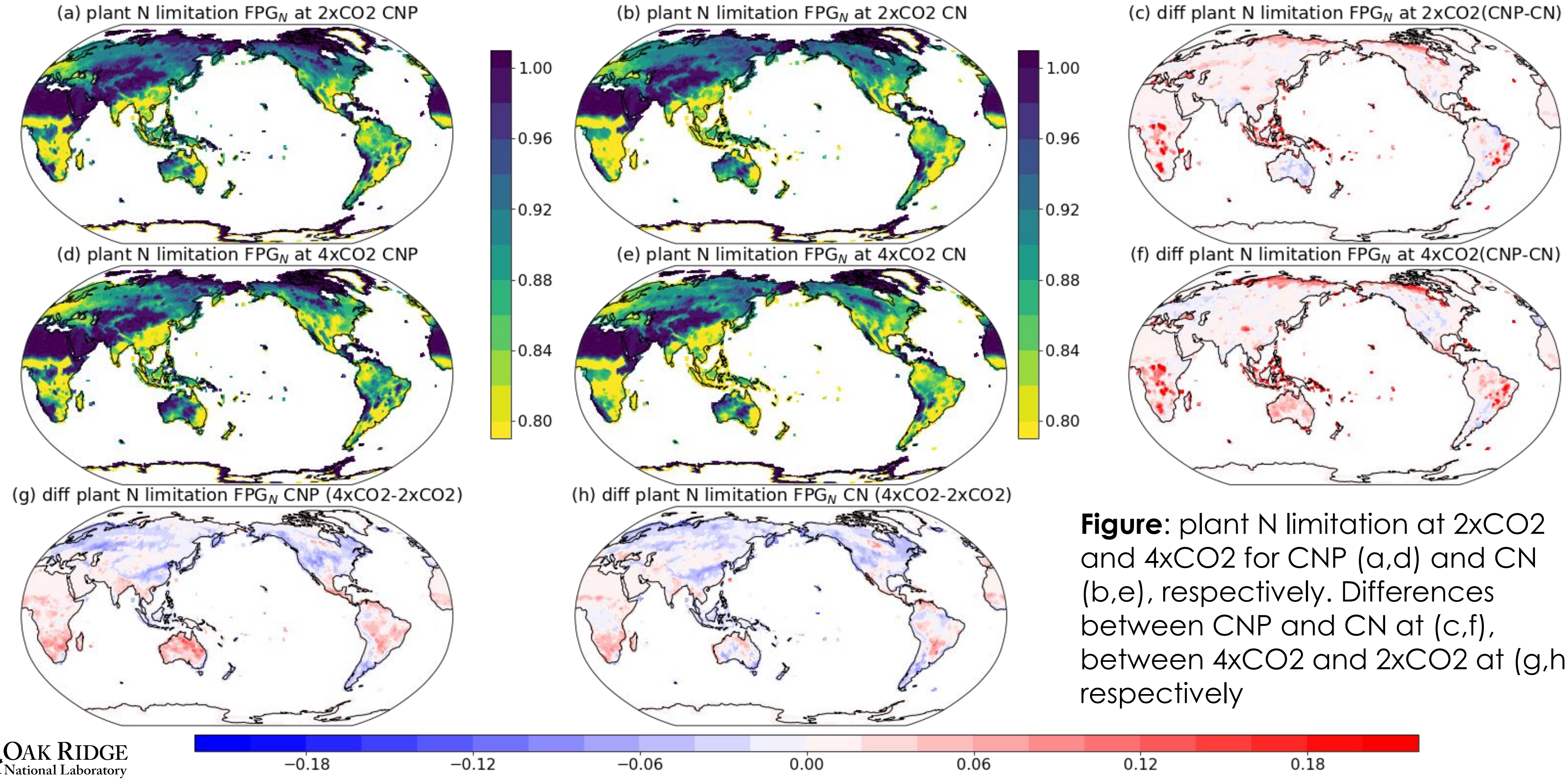

Figure: plant N limitation at 2xCO2 and 4xCO2 for CNP (a,d) and CN (b,e), respectively. Differences between CNP and CN at (c,f), between 4xCO2 and 2xCO2 at (g,h), respectively

Soil N limitation (FPI_N) **The larger the value, the less the limit !**

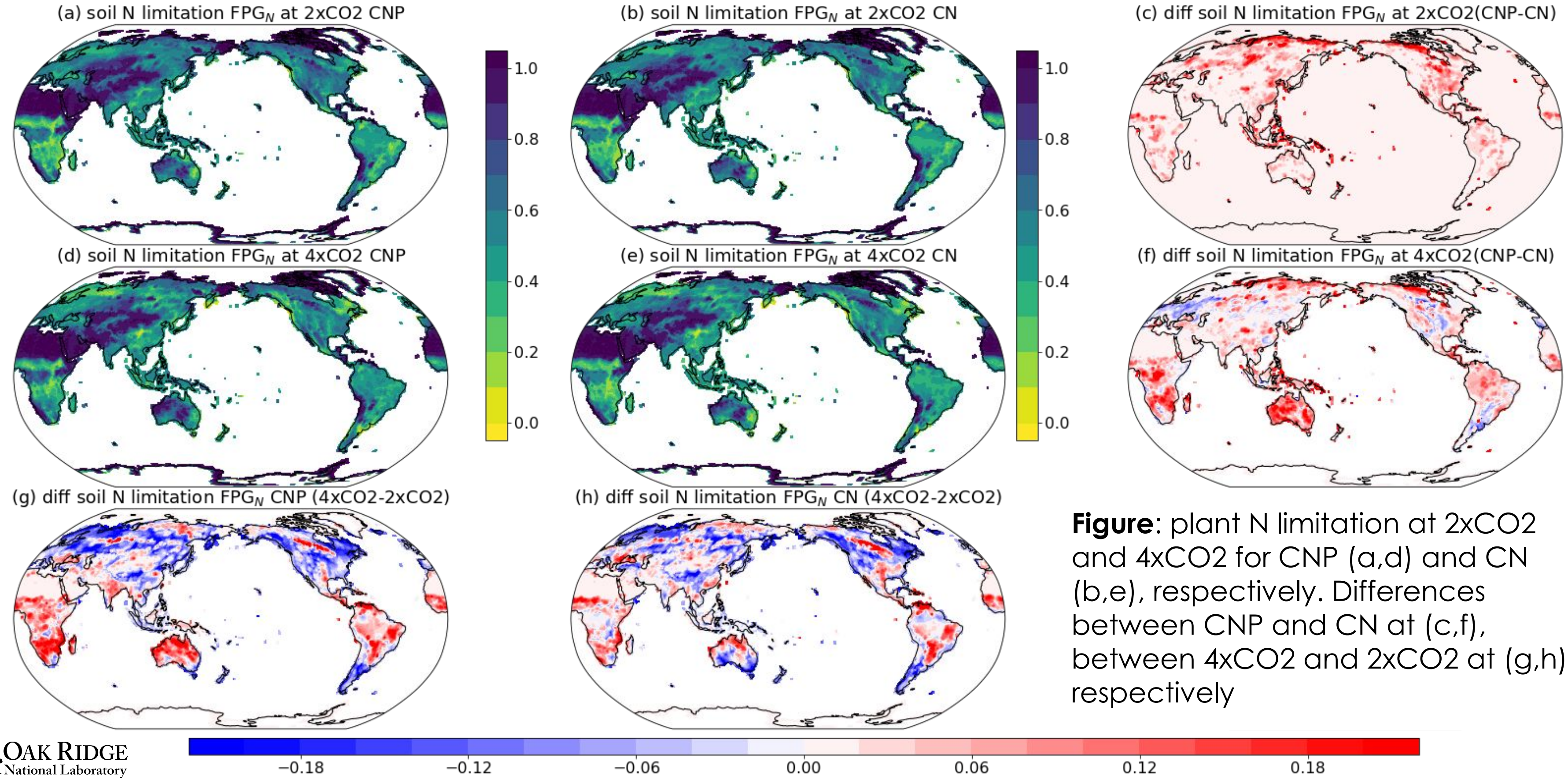

Figure: plant N limitation at 2xCO2 and 4xCO2 for CNP (a,d) and CN (b,e), respectively. Differences between CNP and CN at (c,f), between 4xCO2 and 2xCO2 at (g,h), respectively

P limitation at 2x and 4xCO2 **The larger the value, the less the limit !**

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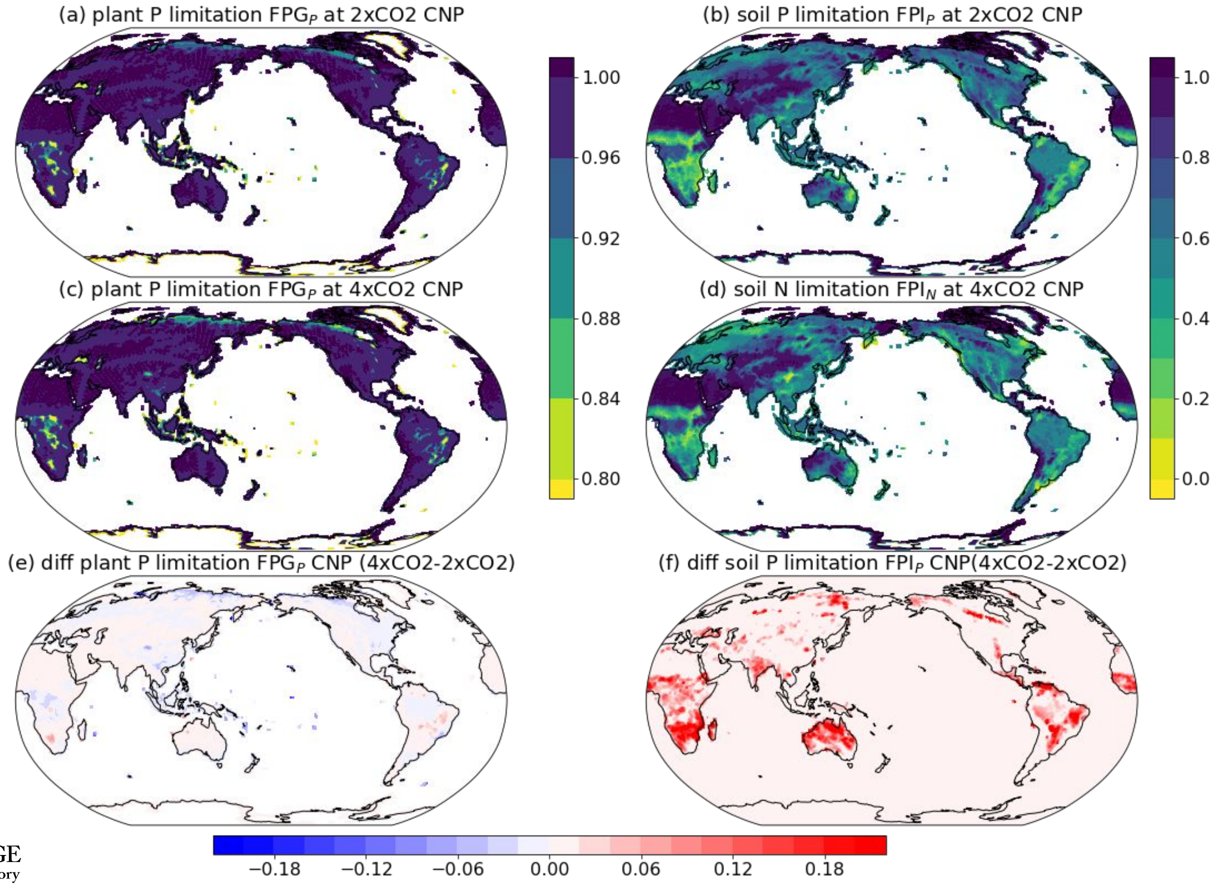

Figure: plant (a,c) and soil (b,d) P limitation at 2xCO2 and 4xCO2 for CNP, respectively. Differences in plant (e)and soil (f) between 4xCO2 and 2xCO2, respectively

Conclusions

1. The feedbacks of the P limitation to climate are significant.
2. The 40%-80% variance of NPP differences between CNP and CN simulations can be explained by precipitation and surface temperature differences between CNP and CN at a 90% confidence level. It indicates that there is a strong coupling between the P limitation and climate.
3. P limitation is strongest in the FULL experiment and weakest in the BGC experiment.
4. N limitation will be the more dominant factor in the future in most areas of the boreal region, East Asia, most areas of the US, the southern coastal areas of Australia, and southern Argentina.
5. P limitation becomes weaker globally in the future due to the P limitation-soil moisture feedback.
6. Though the global carbon uptake still decreases due to the direct effect of P limitation, the P limitation-soil moisture feedback plays an important role when the soil dries out with the increases in the atmospheric CO2. It will lead to more carbon uptake in some dry regions. This feedback is particularly important in the tropics, as the soil is expected to be drier with the CO_2 rising.

Acknowledgment

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Special thanks to the E3SM Biogeochemical Cycles Group for their significant contributions and tremendous efforts to make the E3SM v1.1 available. Thank Mingquan and Jim Randerson for their helpful discussions.

E3SM
Energy Exascale
Earth System Model

NERSC

Thank you!

Questions?