

Understanding Plant Carbon-Water Tradeoffs in a Coupled Earth System

CLM + BGC Working Group Meeting | February 27, 2024

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¹UW; ²UGA; ³OSU; ⁴CU; ⁵NCAR; ⁶LBL; ⁷UCI; ⁸ORNL

Funding from DOE and NSF

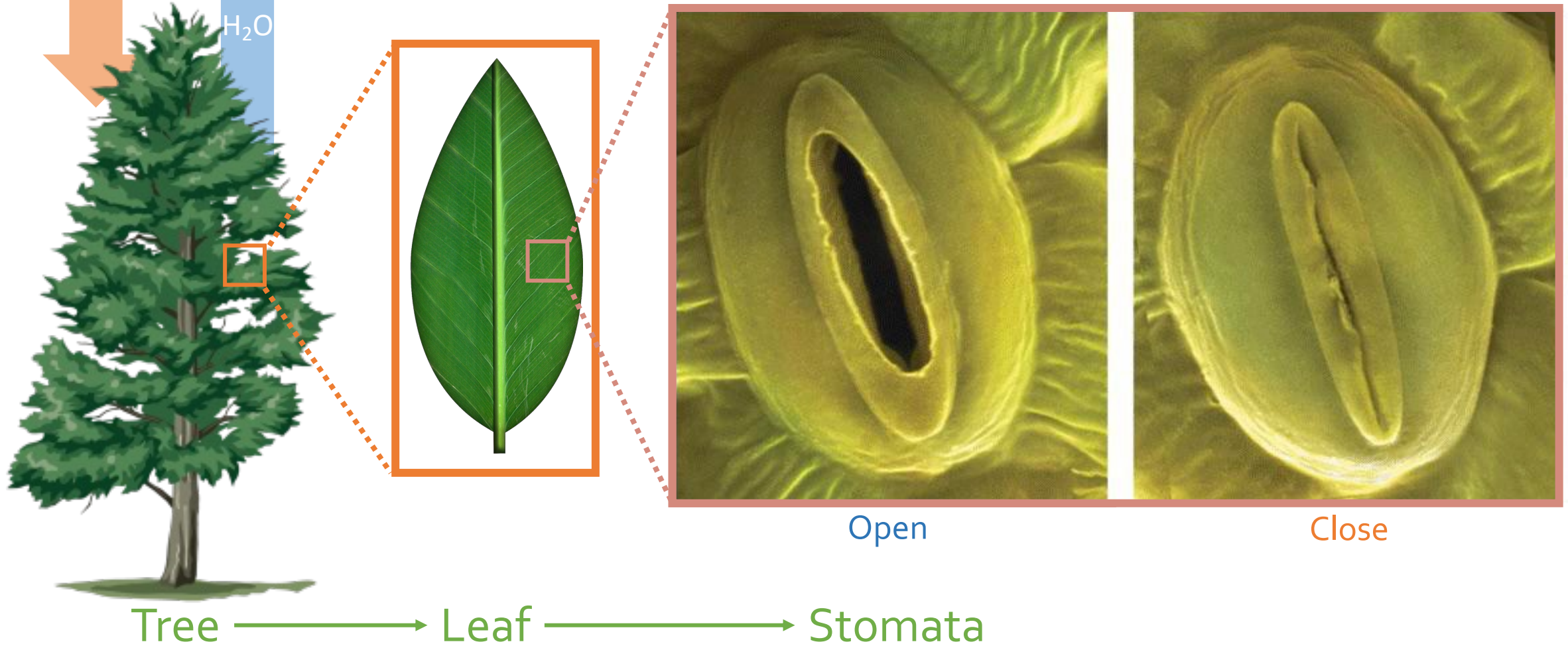
Photosynthesis

CO₂

Transpiration

H₂O

Plants have stomata on their leaves that can open and close



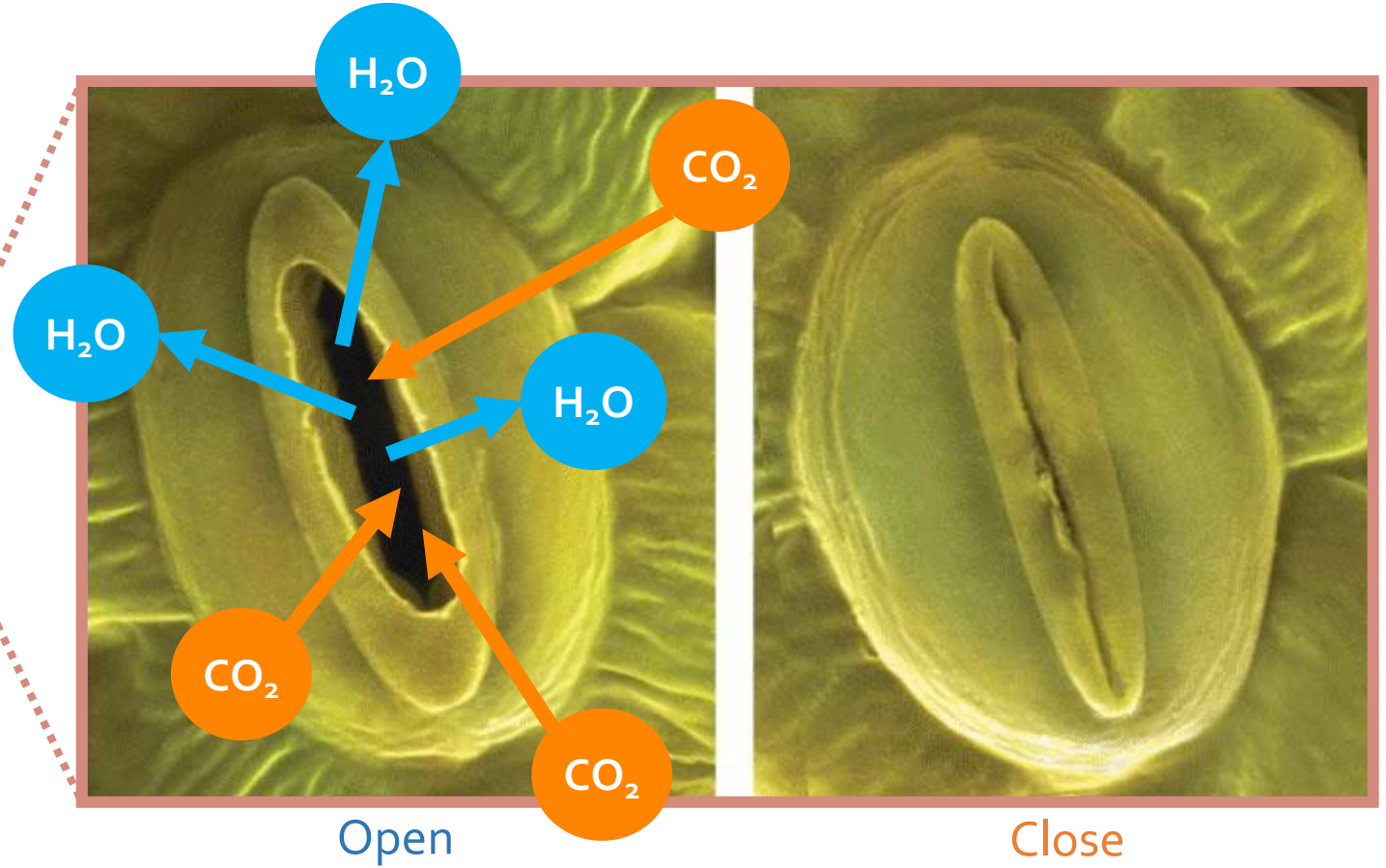
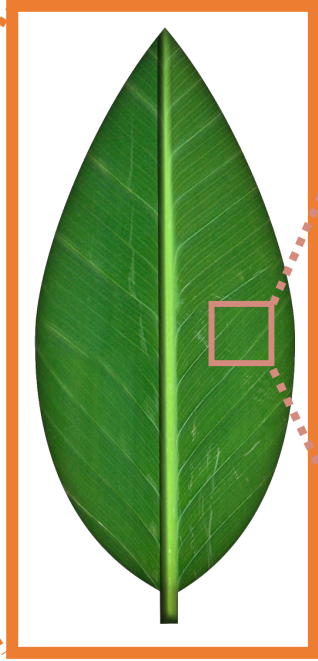
Photosynthesis

CO₂

Transpiration

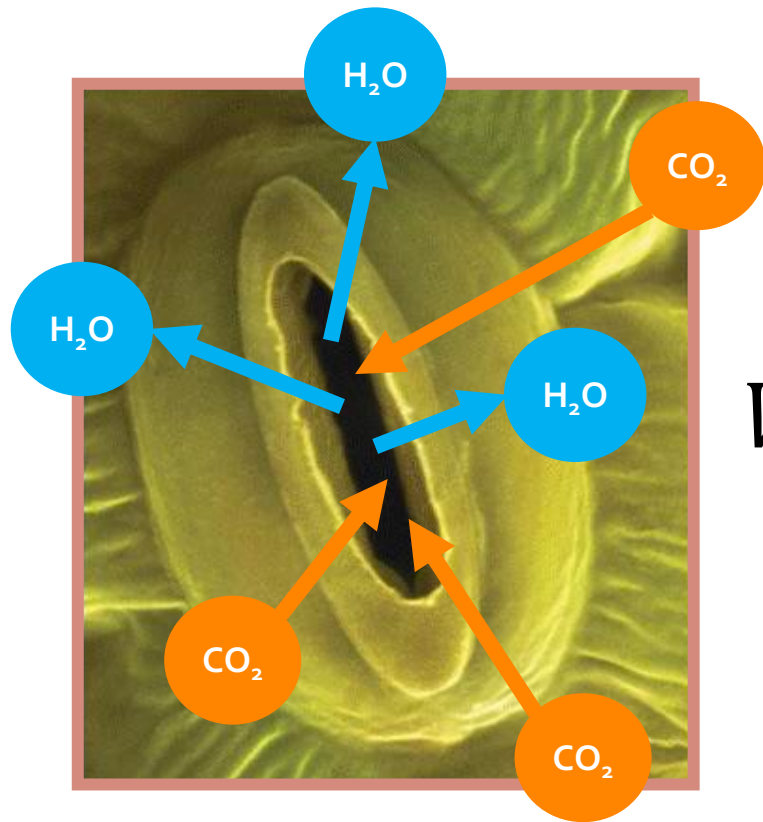
H₂O

Stomata regulate gas exchange with the atmosphere



Tree → Leaf → Stomata

Water use efficiency (WUE) represents the CO₂ and H₂O tradeoff plants make



$$WUE = \frac{\textit{Carbon gain}}{\textit{Water loss}} = \frac{\textit{Photosynthesis}}{\textit{Transpiration}}$$

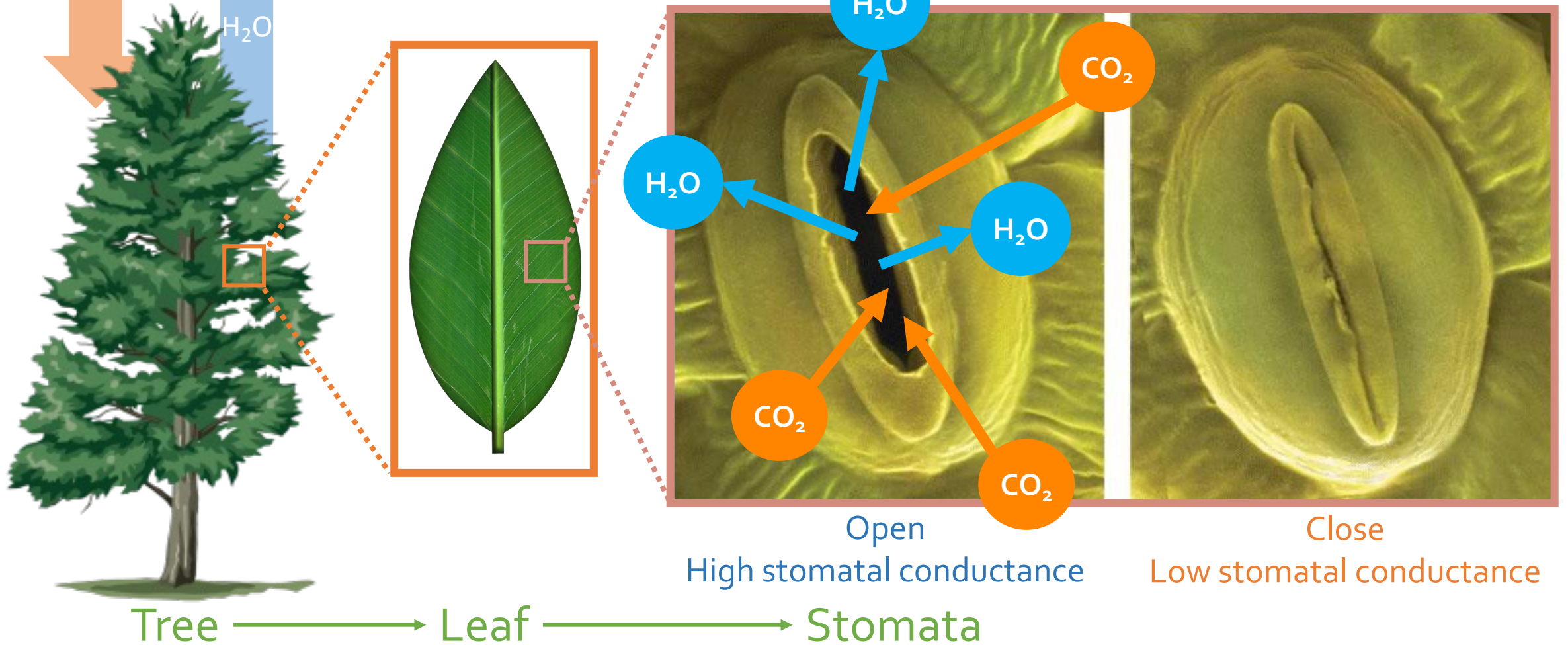
Photosynthesis

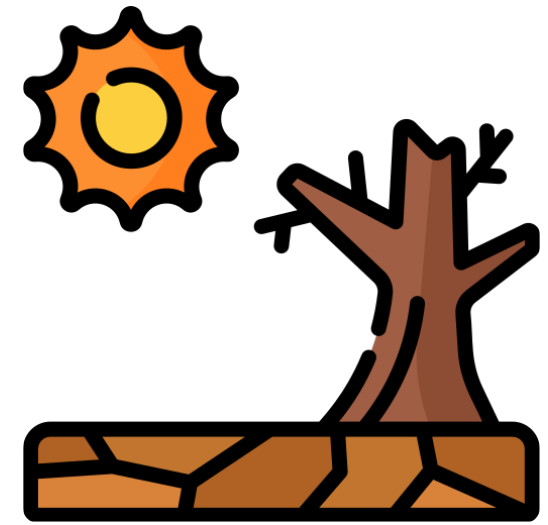
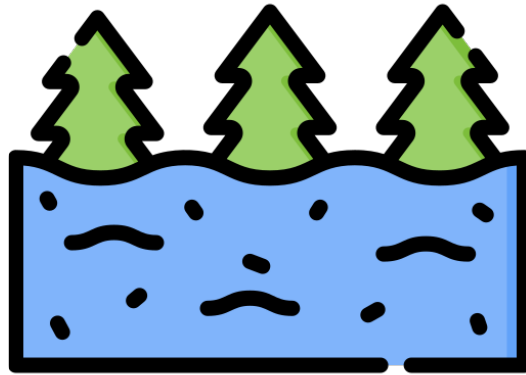
CO₂

Transpiration

H₂O

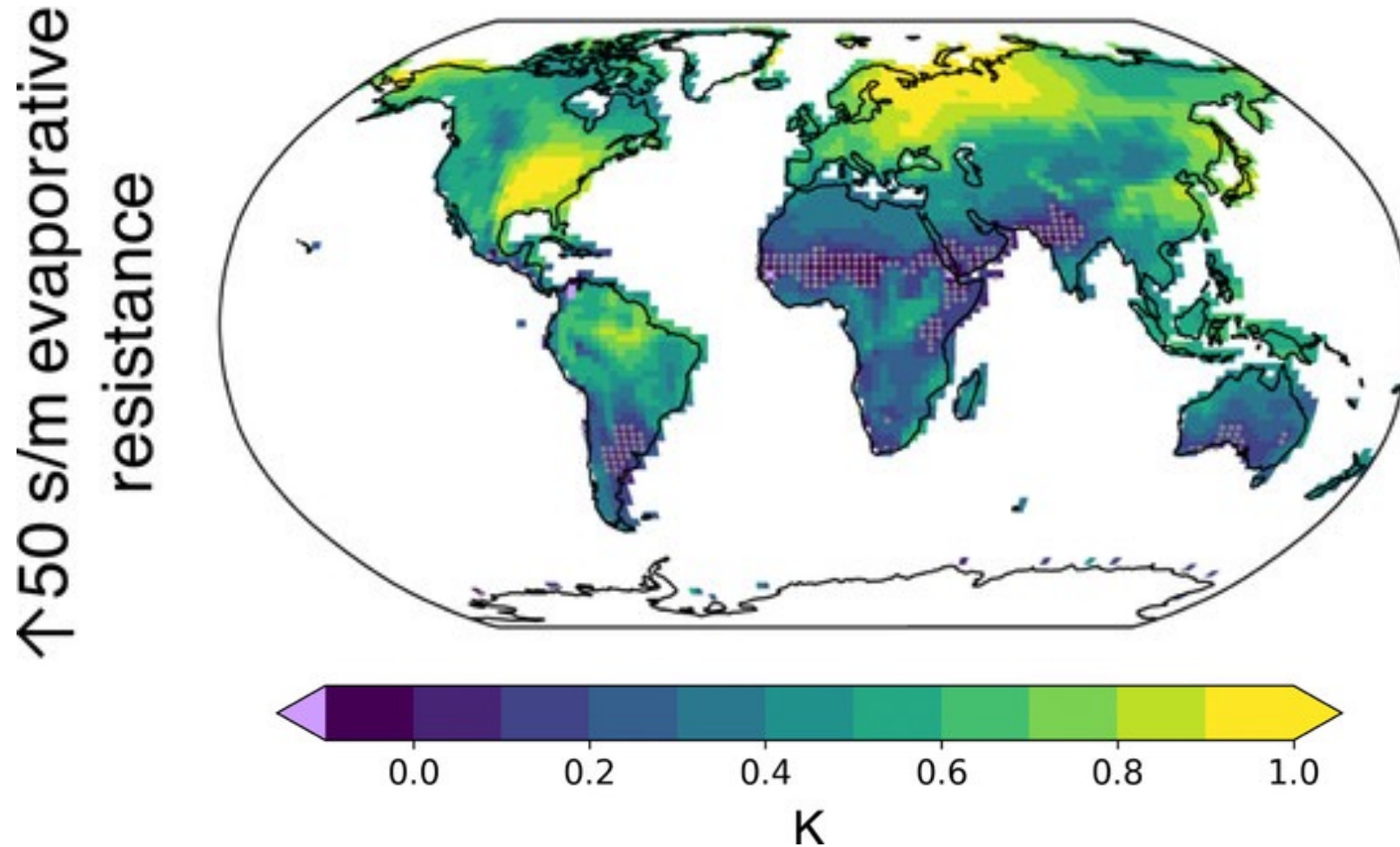
Changes in stomatal conductance drive changes in both carbon and water fluxes





Carbon and water fluxes impact the carbon and water cycle, affecting water availability and the risk of extreme climate events like droughts, heatwaves, and floods.

Changes in evaporative resistance affects surface T



Ran global scale simulations changing *iWUE*

Water Use
Efficiency



$$WUE = \frac{\textit{Carbon gain}}{\textit{Water loss}} = \frac{\textit{Photosynthesis}}{\textit{Transpiration}}$$

Transpiration \propto *stomatal conductance* \times ∇VPD

Intrinsic Water
Use Efficiency



$$iWUE = \frac{\textit{Photosynthesis}}{\textit{Stomatal conductance}}$$

How are we perturbing $iWUE$?

Intrinsic Water Use Efficiency

↓

$$iWUE = \frac{A_n}{g_s}$$

↑

Stomatal conductance

Photosynthesis

↙

Changing $iWUE$ by modifying the Medlyn slope (g_{1M})

Intrinsic Water Use Efficiency

Photosynthesis

$$iWUE = \frac{A_n}{g_s}$$

Stomatal conductance

Medlyn intercept

Medlyn slope

Photosynthesis

$$g_s = g_0 + 1.6 \left(1 + \frac{g_{1M}}{\sqrt{VPD}} \right) \frac{A_n}{c_s}$$

Stomatal conductance

Vapor pressure deficit

CO₂ concentration

Changing $iWUE$ by modifying the Medlyn slope (g_{1M})

Intrinsic Water Use Efficiency

Photosynthesis

$$iWUE = \frac{A_n}{g_s} \propto \frac{1}{g_{1M}}$$

Stomatal conductance

Medlyn intercept

Medlyn slope

Photosynthesis

$$g_s = g_0 + 1.6 \left(1 + \frac{g_{1M}}{\sqrt{VPD}} \right) \frac{A_n}{c_s}$$

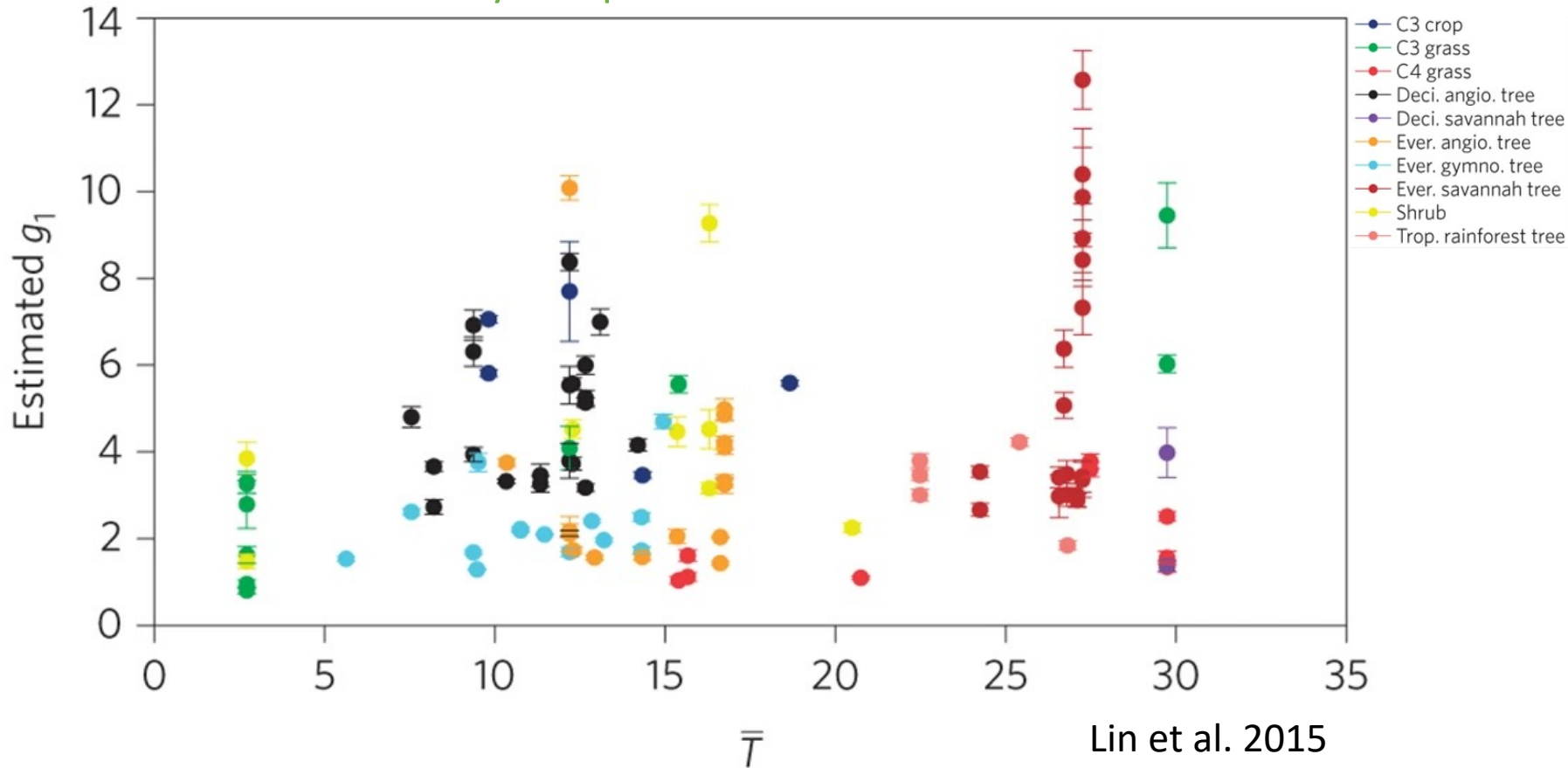
Stomatal conductance

Vapor pressure deficit

CO₂ concentration

There is variability of g_{1M} within + across plant types

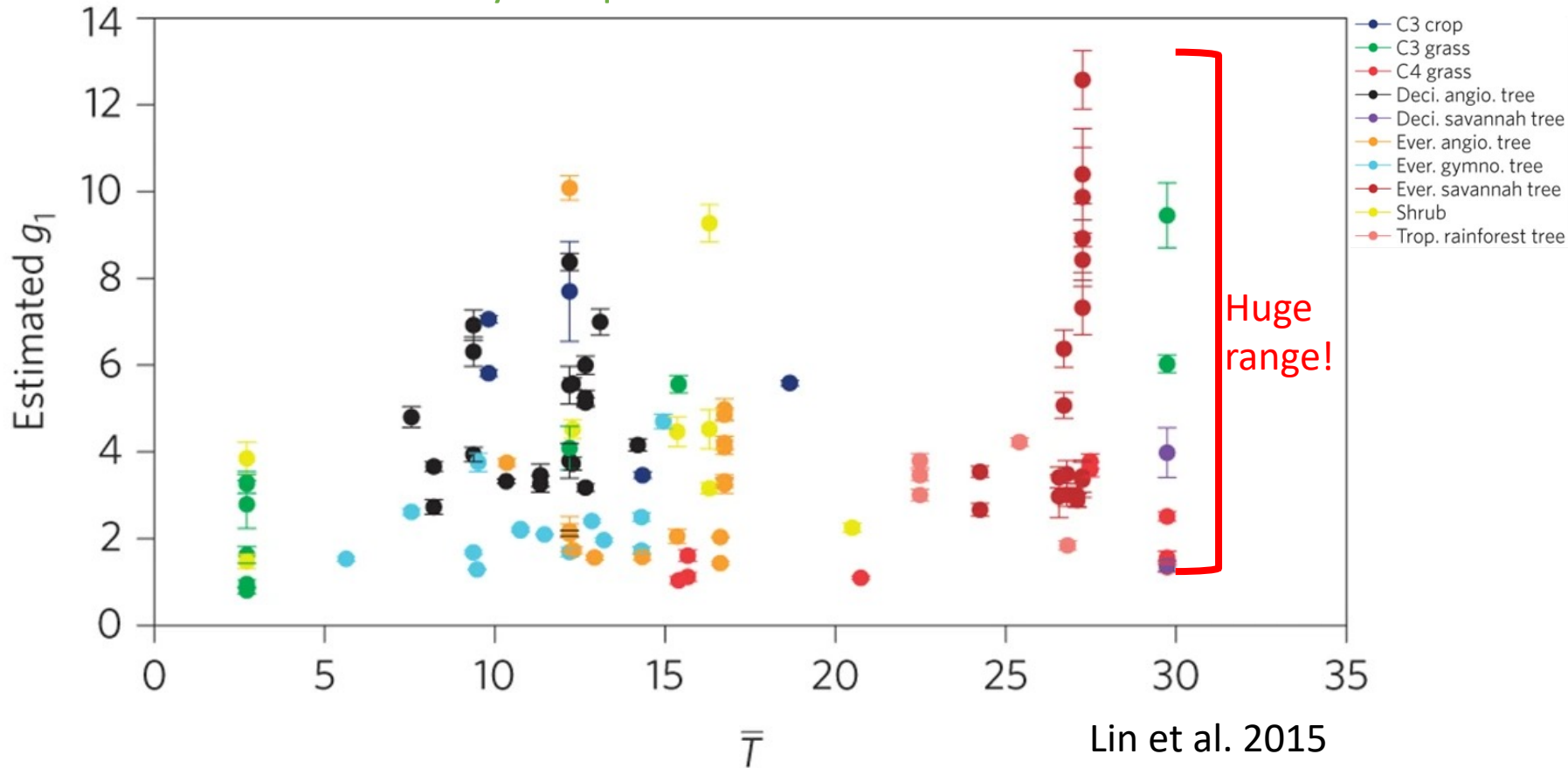
Estimated Medlyn Slope based on Field Observations



$$iWUE = \frac{A_n}{g_s} \propto \frac{1}{g_{1M}}$$

There is variability of g_{1M} within + across plant types

Estimated Medlyn Slope based on Field Observations

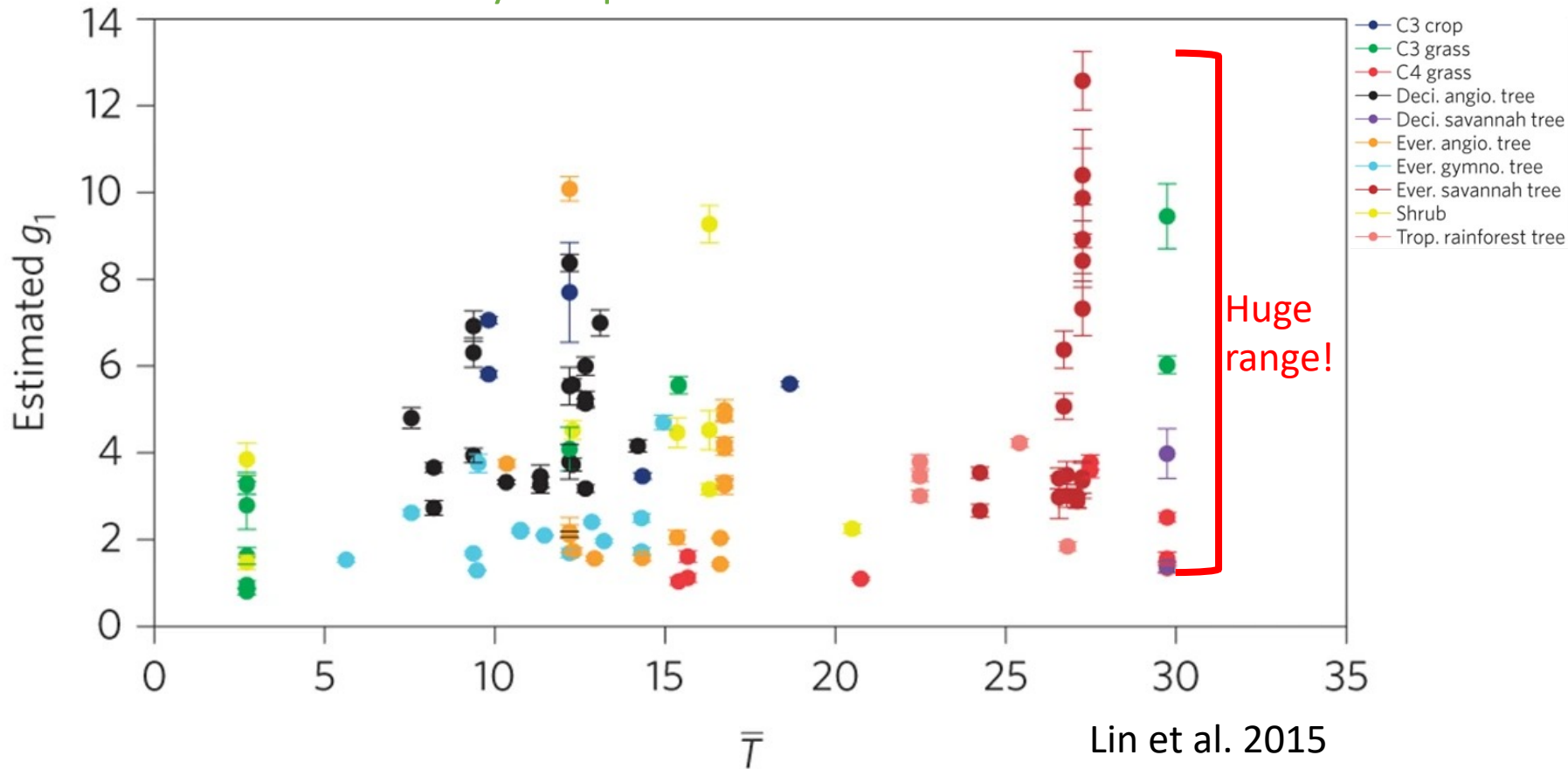


$$iWUE = \frac{A_n}{g_s} \propto \frac{1}{g_{1M}}$$

Lin et al. 2015

There is variability of g_{1M} within + across plant types

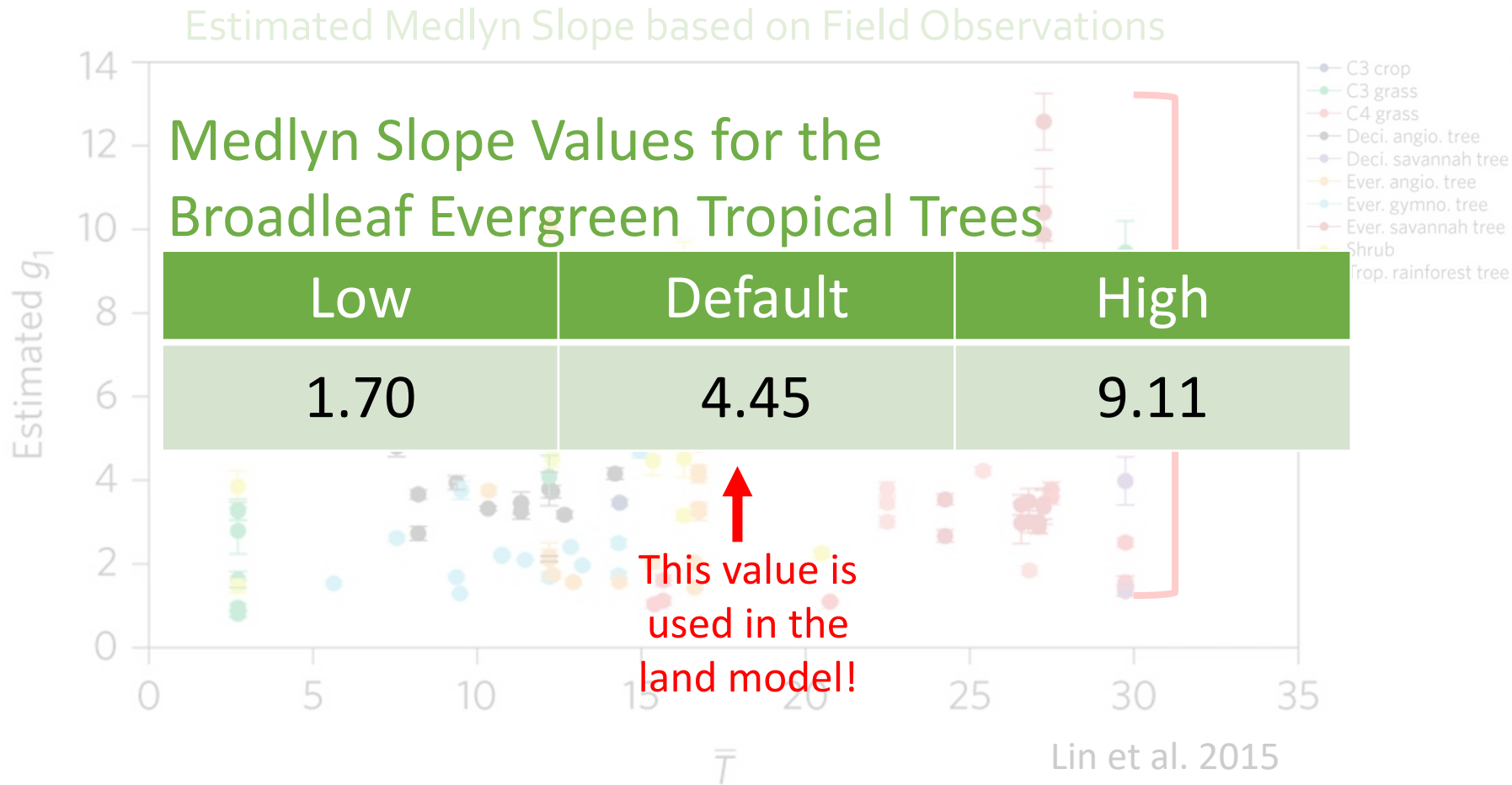
Estimated Medlyn Slope based on Field Observations



$$iWUE = \frac{A_n}{g_s} \propto \frac{1}{g_{1M}}$$

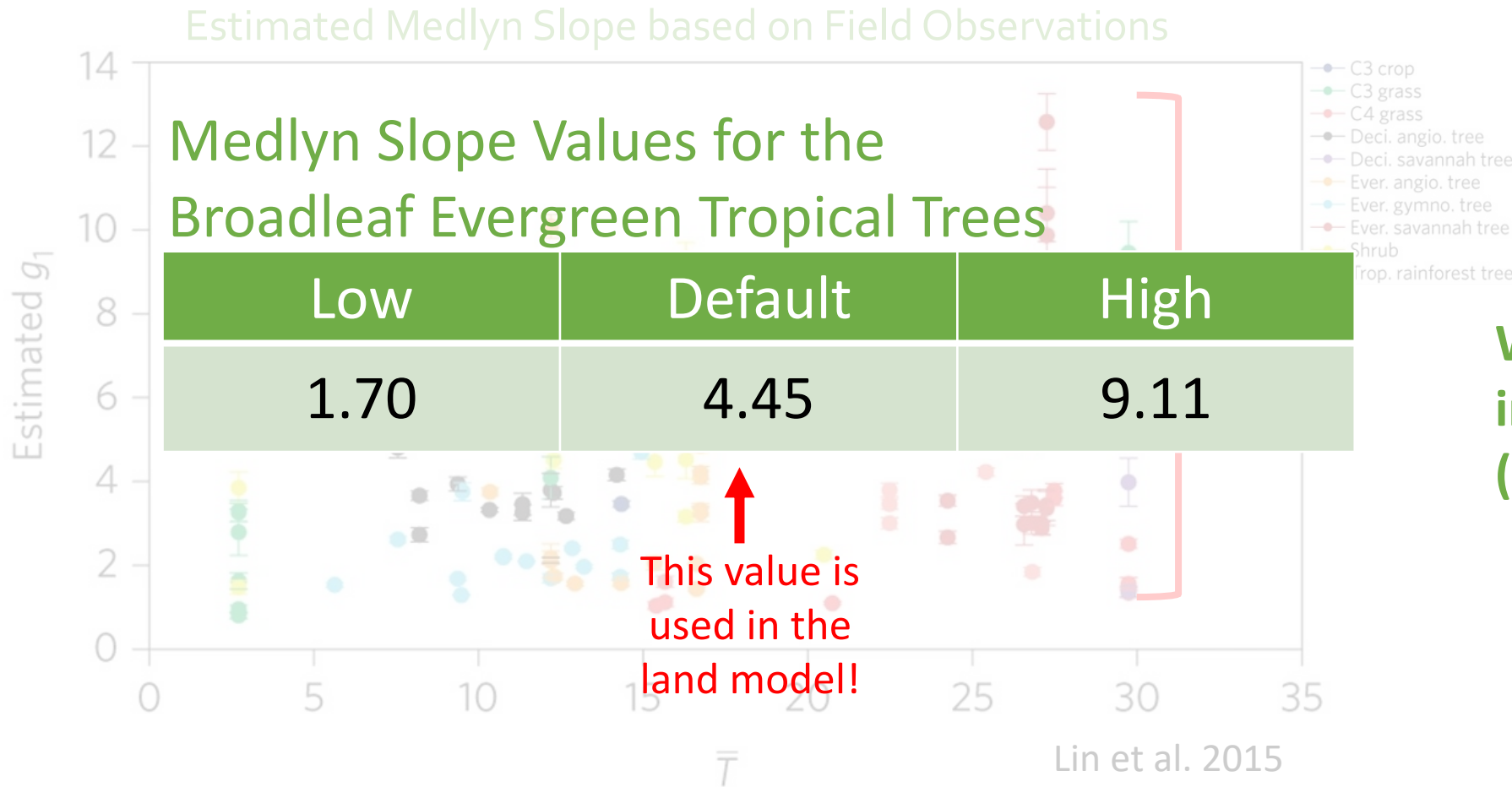
... leading to large range in $iWUE$

One Medlyn slope value is used to represent each plant type in the land model



$$iWUE = \frac{A_n}{g_s} \propto \frac{1}{g_{1M}}$$

One Medlyn slope value is used to represent each plant type in the land model

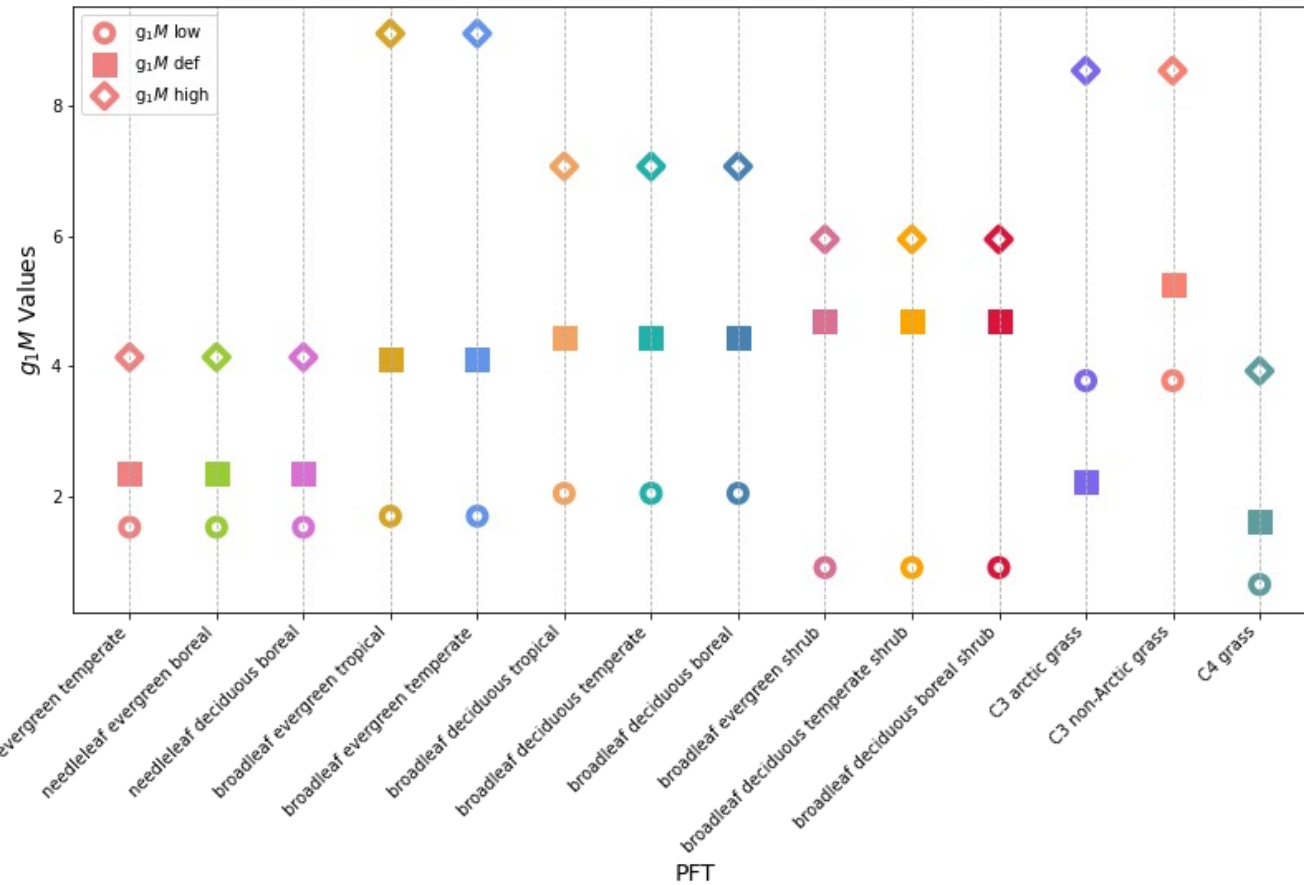


$$iWUE = \frac{A_n}{g_s} \propto \frac{1}{g_{1M}}$$

What are the climate impacts of changing *iWUE* (Medlyn slope)?

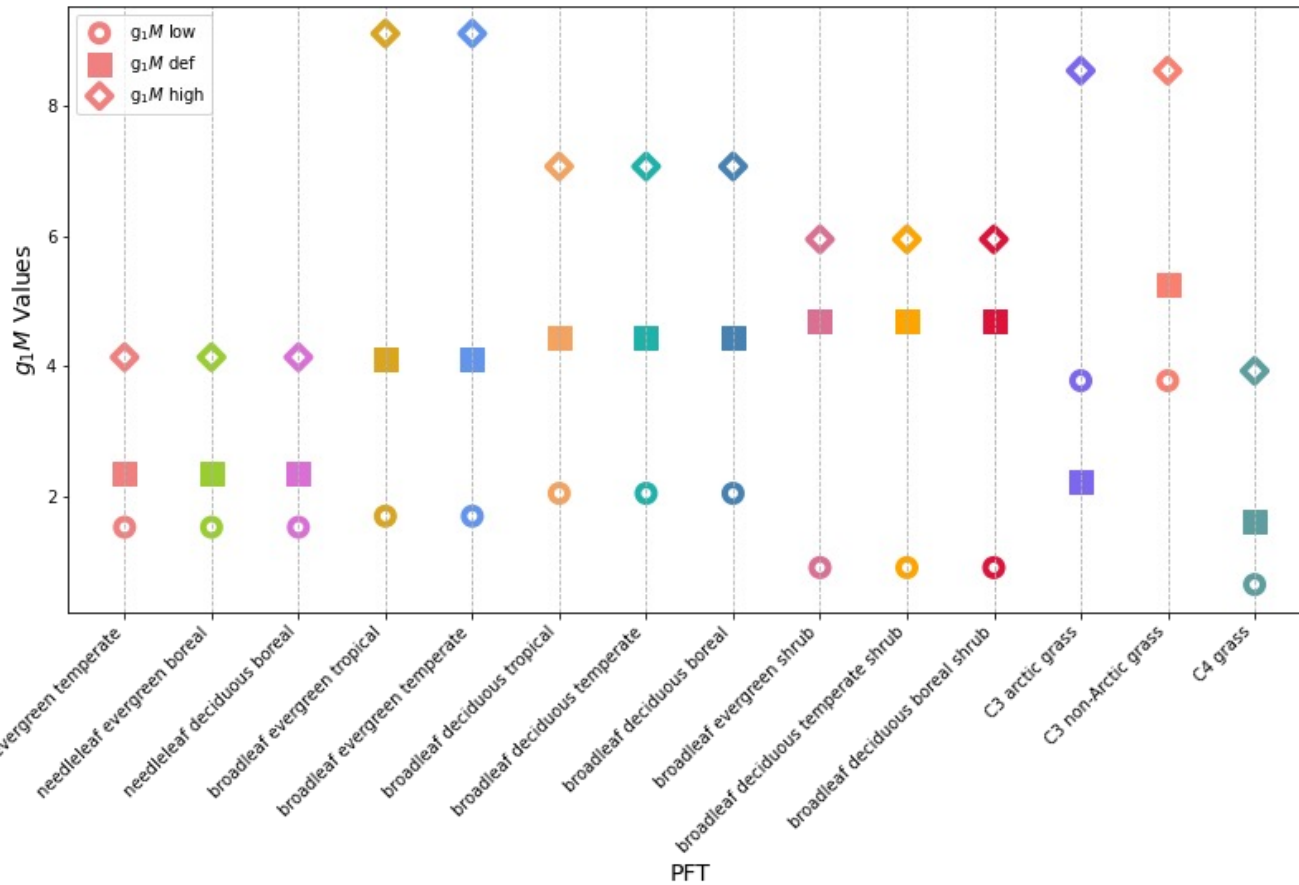
Our perturbed g_{1M} values have large spread within + across PFTs

Low, Default, and High g_{1M} values for each PFT

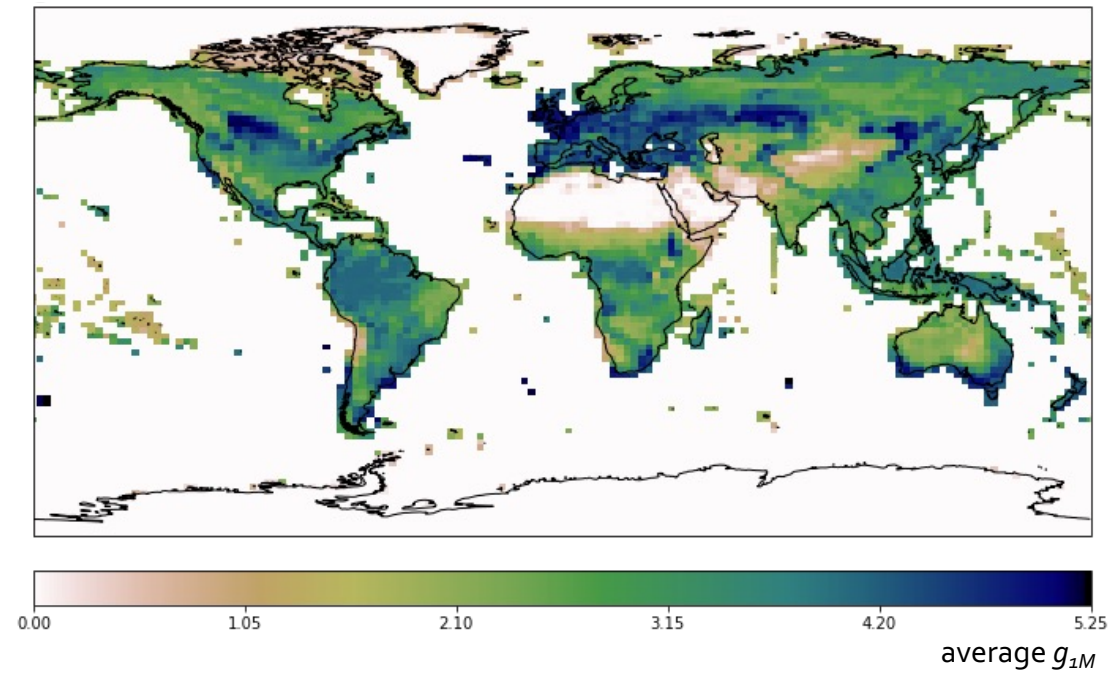


Our perturbed g_{1M} values have large spread within + across PFTs

Low, Default, and High g_{1M} values for each PFT



Spatial distribution of Default g_{1M} values



Questions we aim to answer today:

+/- iWUE *How does our choice of iWUE impact photosynthesis?*

+/- atmosphere
+/- leaf area *How much of the photosynthetic response can be attributed to the inclusion of a coupled atmosphere and dynamic LAI?*

+ CO₂ *Does the photosynthetic response to iWUE perturbation change with increase in atmospheric CO₂?*

Questions we aim to answer today:

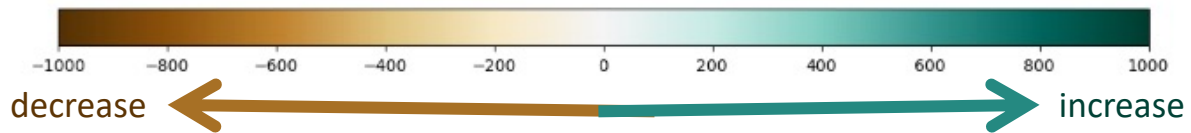
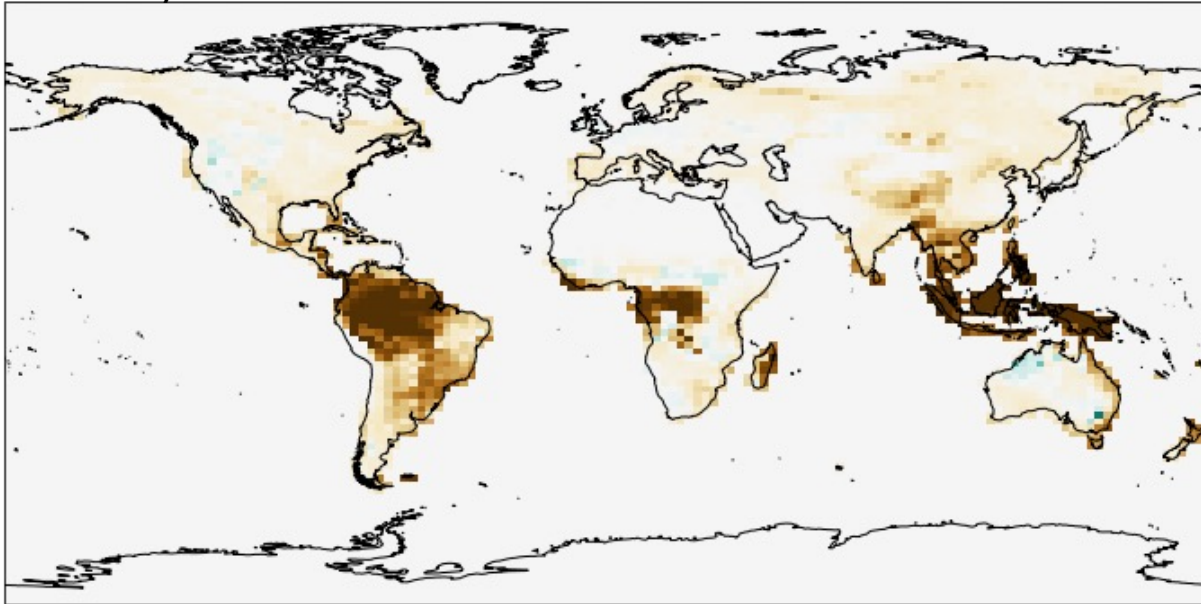
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Photosynthesis decreases with **low** *iWUE*

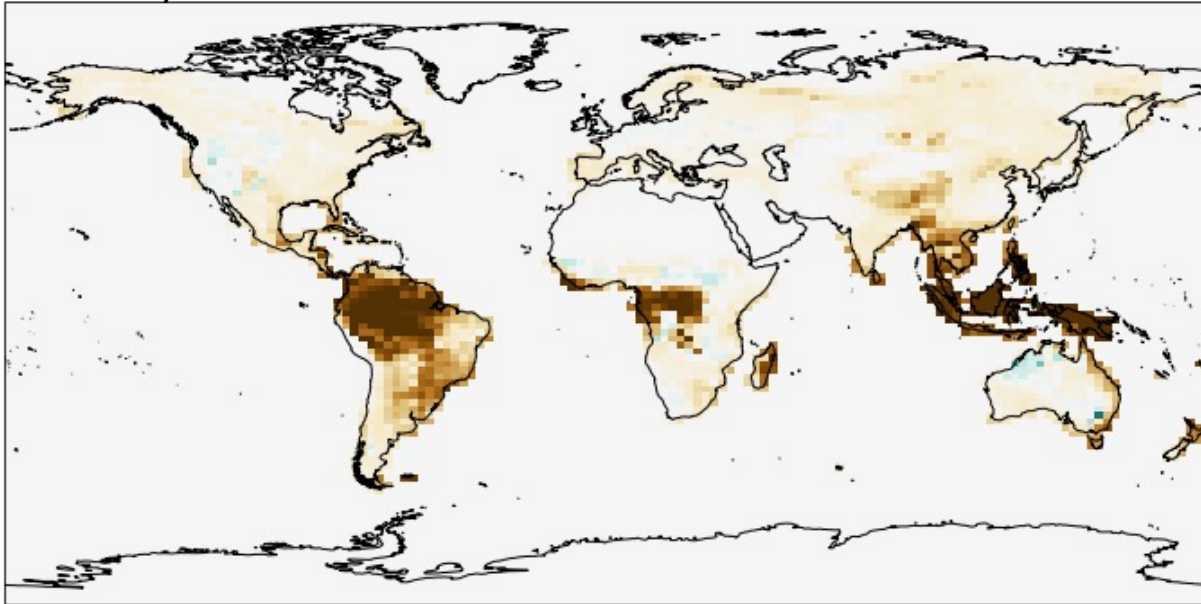
Photosynthesis **Low** – Default *iWUE*



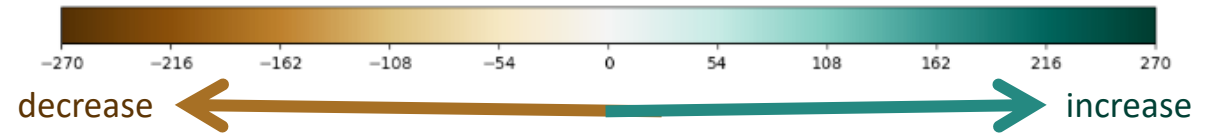
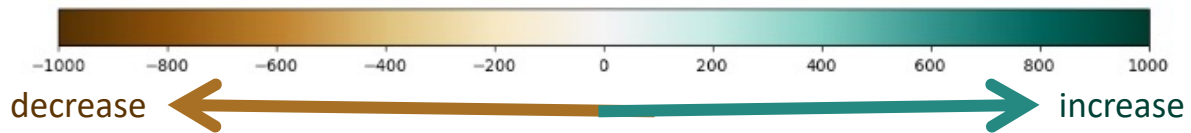
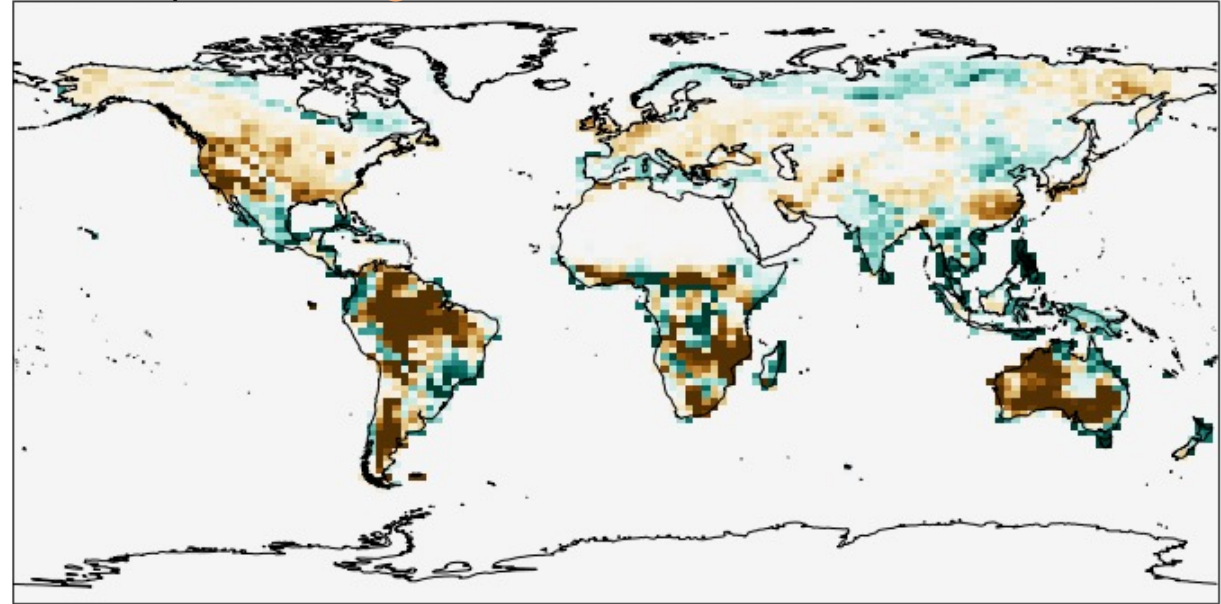
Δ Photosynthesis
($\text{g C m}^{-2} \text{ year}^{-1}$)

Photosynthesis regionally varies with high *iWUE*

Photosynthesis **Low** – Default *iWUE*



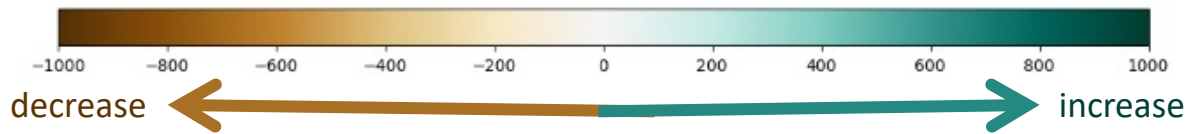
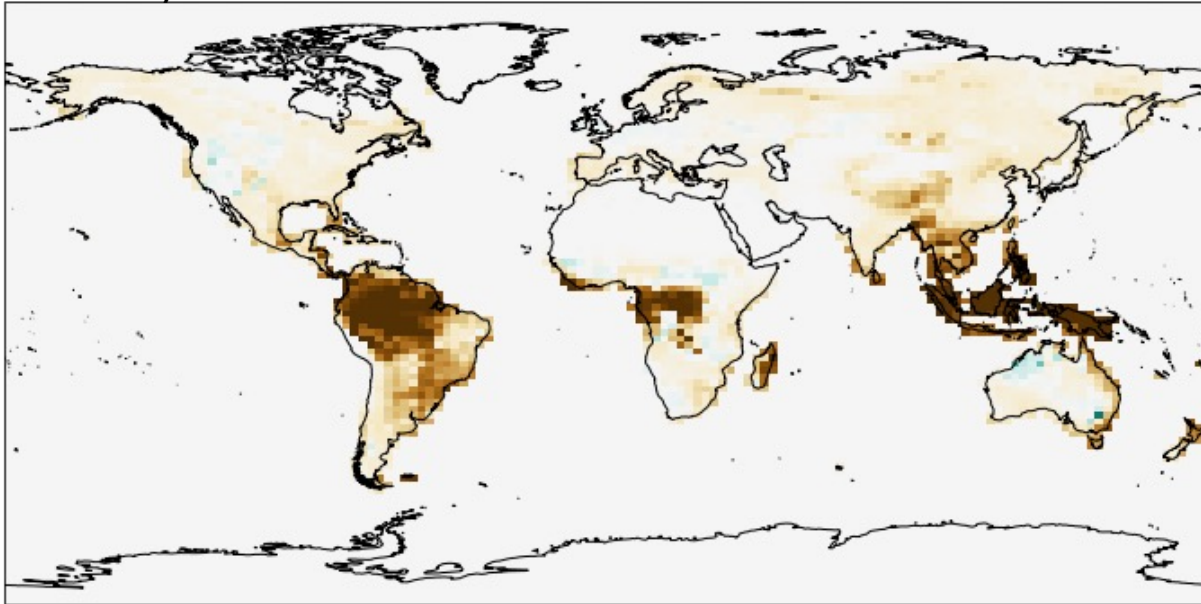
Photosynthesis **High** – Default *iWUE*



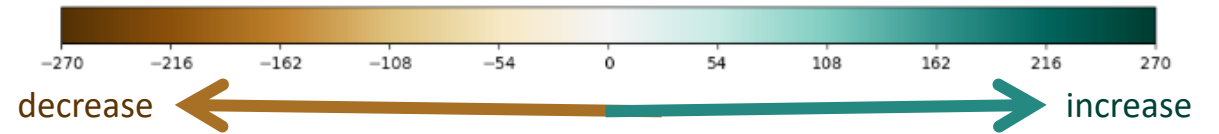
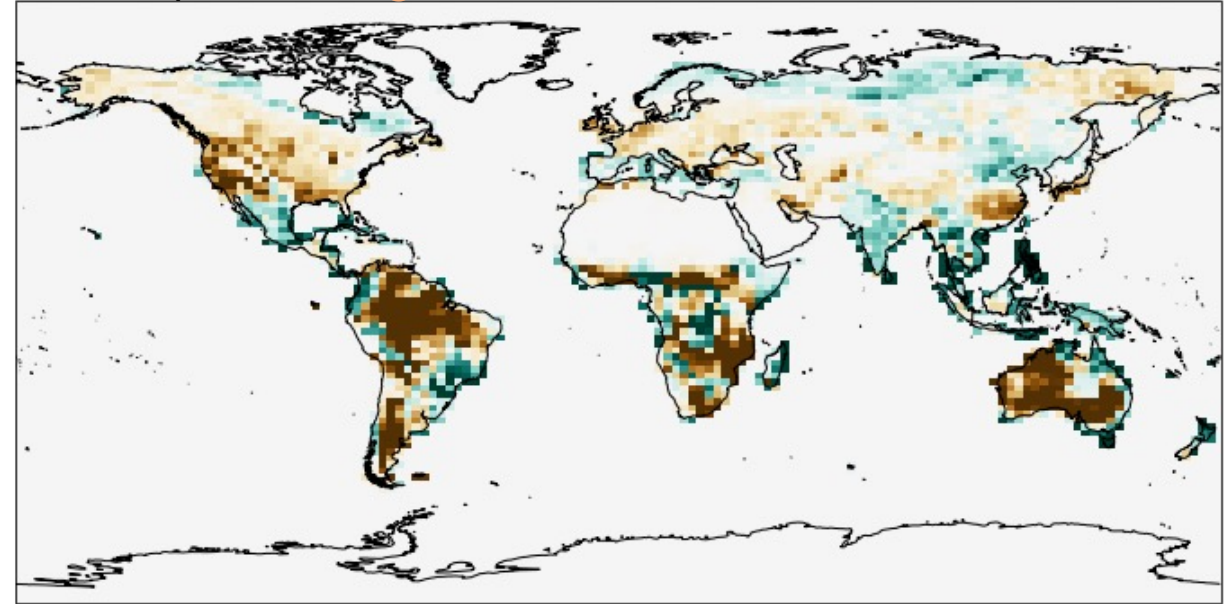
Δ Photosynthesis
(g C m⁻² year⁻¹)

Takehome #1: Our choice of *iWUE* impacts photosynthesis

Photosynthesis **Low** – Default *iWUE*



Photosynthesis **High** – Default *iWUE*



Δ Photosynthesis
(g C m⁻² year⁻¹)

Questions we aim to answer today:

+/- iWUE *How does our choice of iWUE impact photosynthesis?*

+/- atmosphere
+/- leaf area *How much of the photosynthetic response can be attributed to the inclusion of a coupled atmosphere and dynamic LAI?*

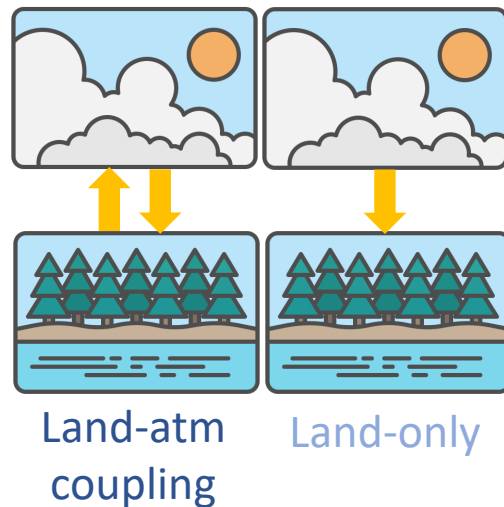
+ CO₂ *Does the photosynthetic response to iWUE perturbation change with increase in atmospheric CO₂?*

How much of the photosynthetic response can be attributed to the inclusion of a **coupled atm** and **dynamic LAI**?

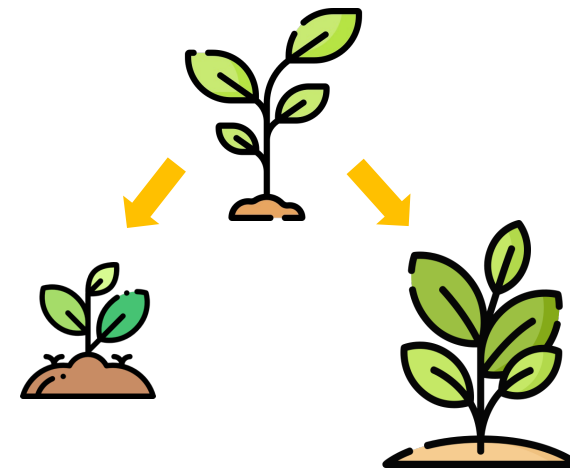
coupled atm

dynamic LAI

Changing atmosphere



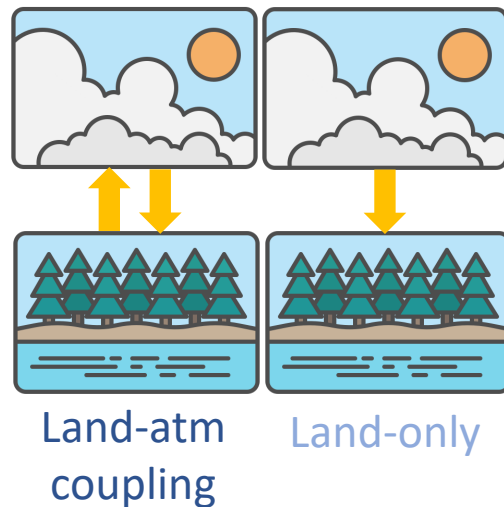
Changing leaf area



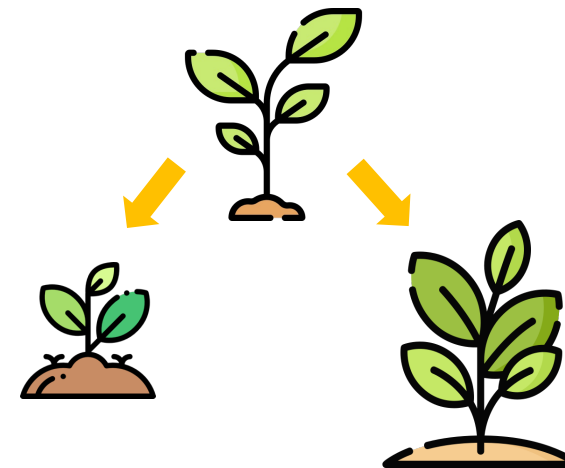
How much of the photosynthetic response can be attributed to the inclusion of a **coupled atm** and **dynamic LAI**?



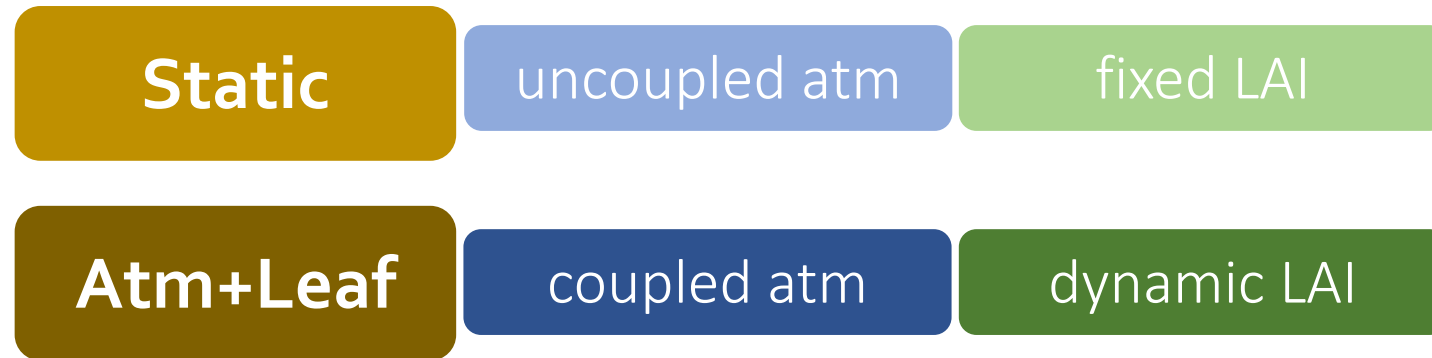
Changing atmosphere



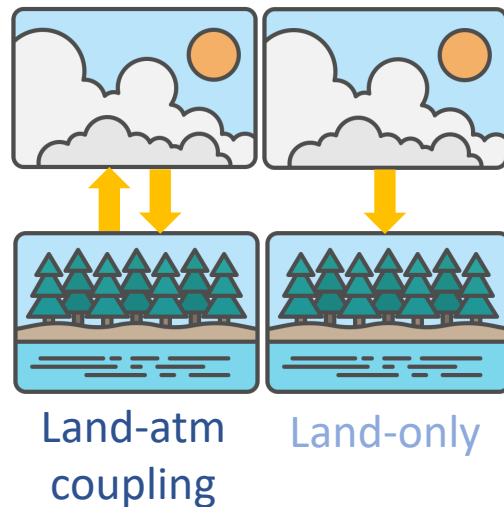
Changing leaf area



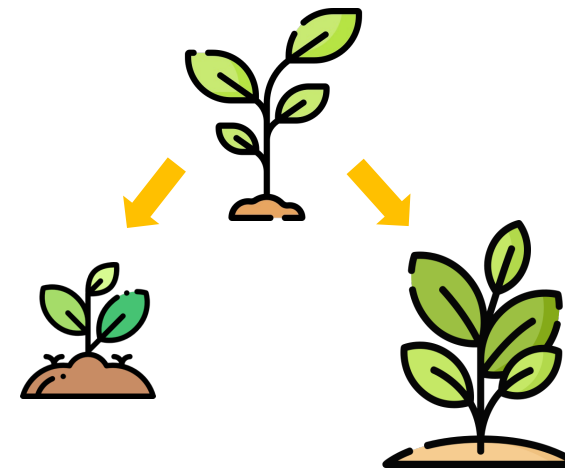
How much of the photosynthetic response can be attributed to the inclusion of a **coupled atm** and **dynamic LAI**?



Changing atmosphere

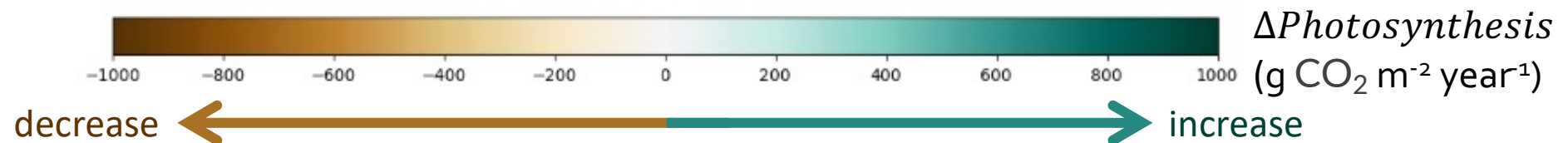
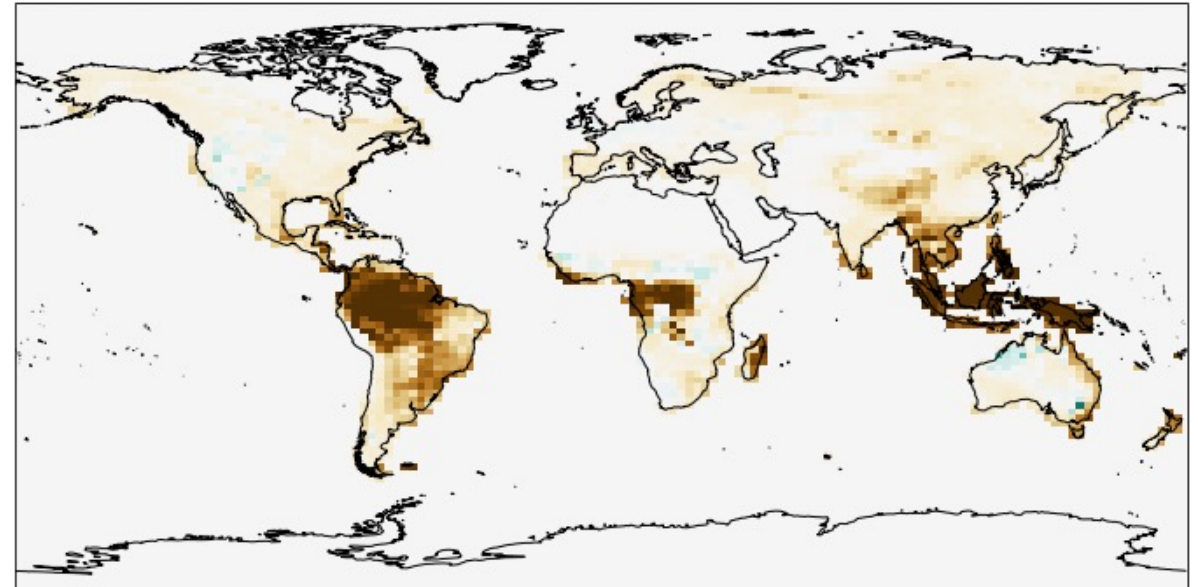


Changing leaf area



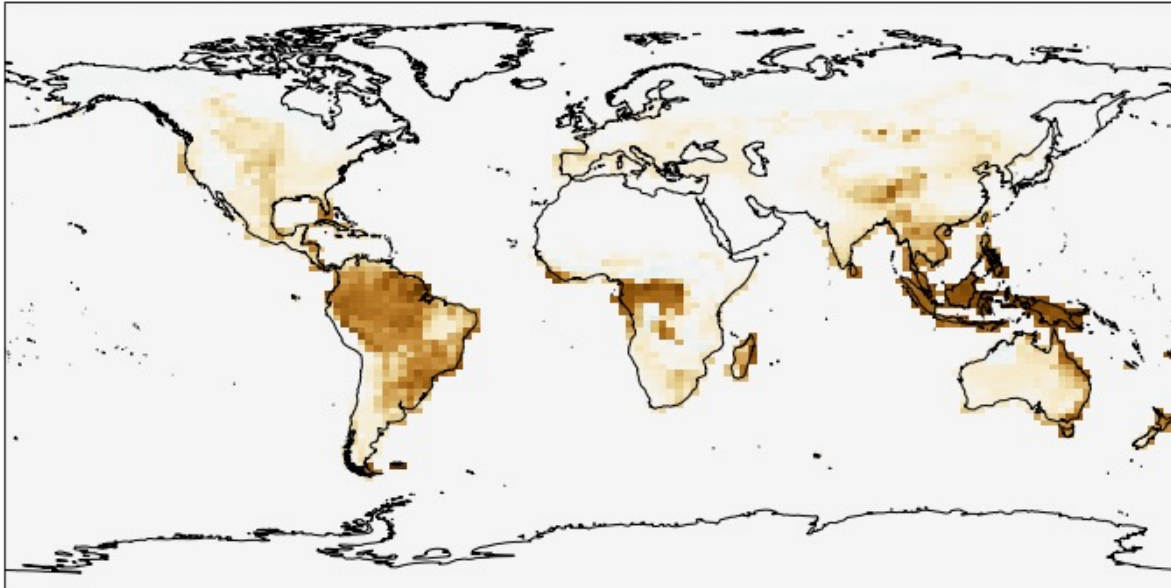
Previously: Photosynthesis decreases for the
Atm+Leaf **low** *iWUE* case

Atm+Leaf: Photosynthesis **Low** – Default *iWUE*

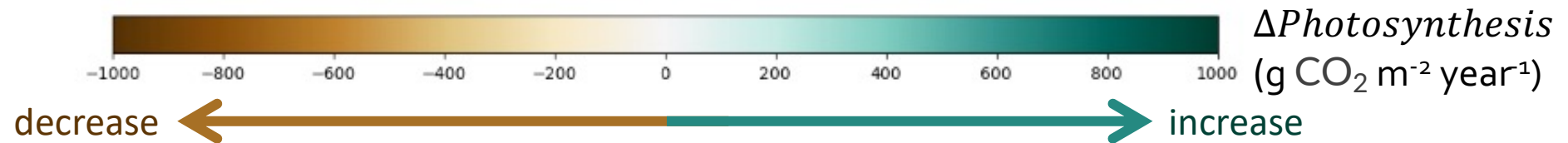
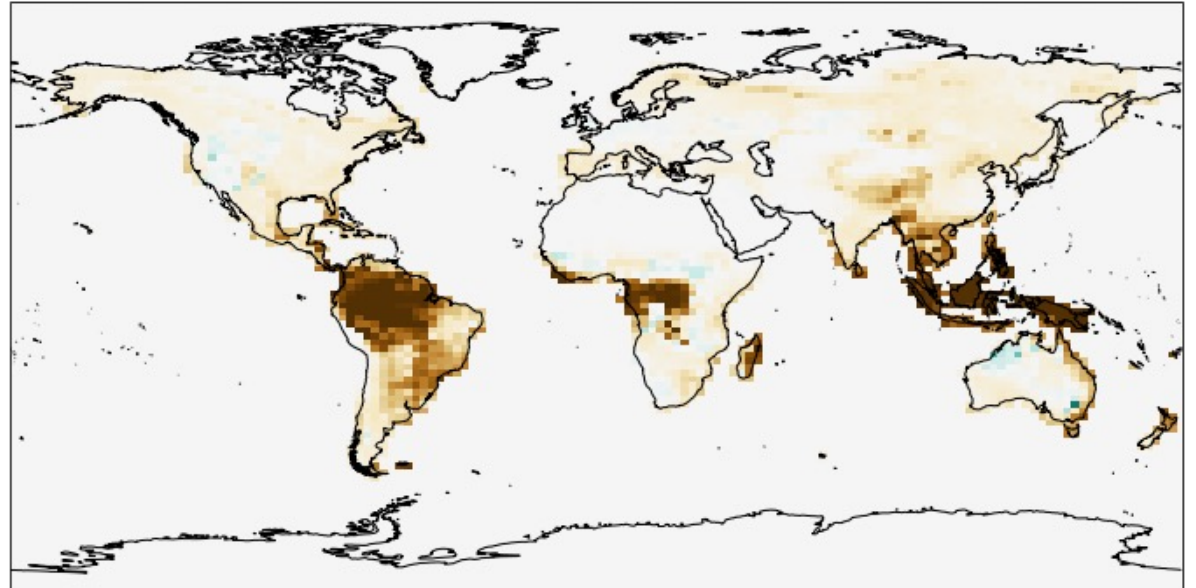


Photosynthesis decreases for both **low** *iWUE* cases

Static: Photosynthesis **Low** – Default *iWUE*

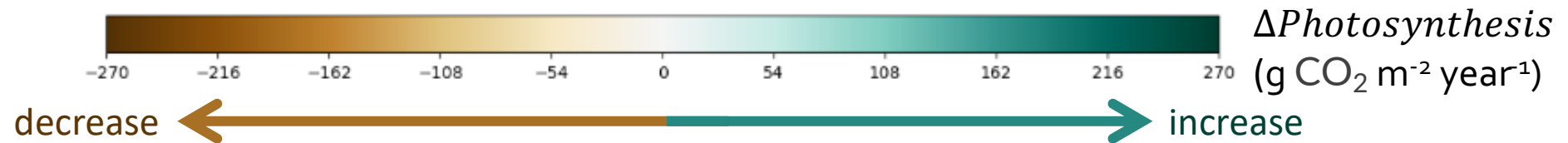
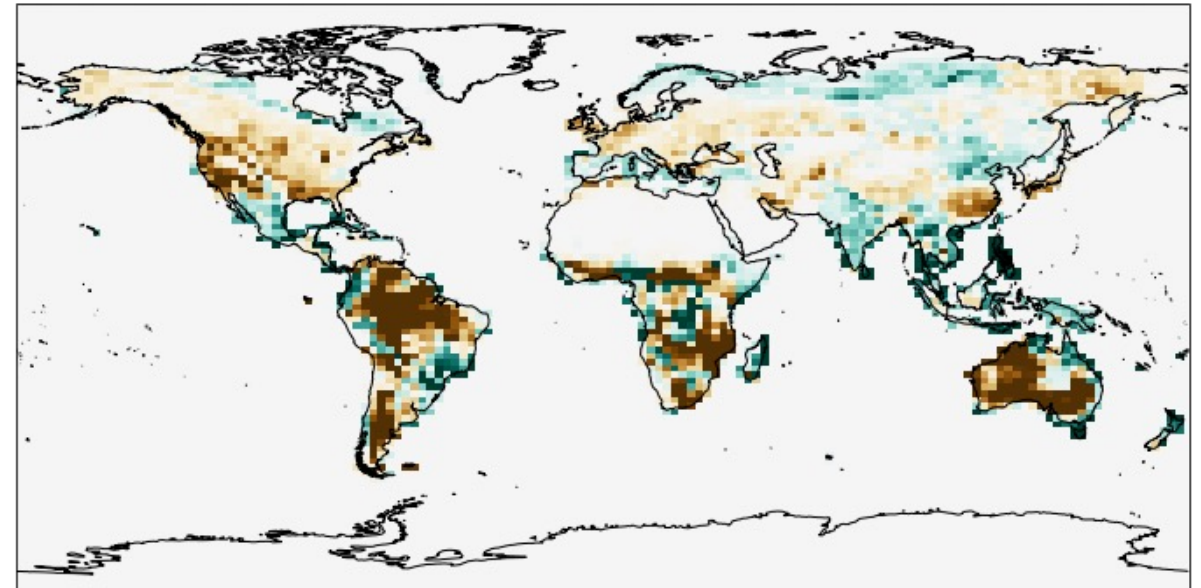


Atm+Leaf: Photosynthesis **Low** – Default *iWUE*



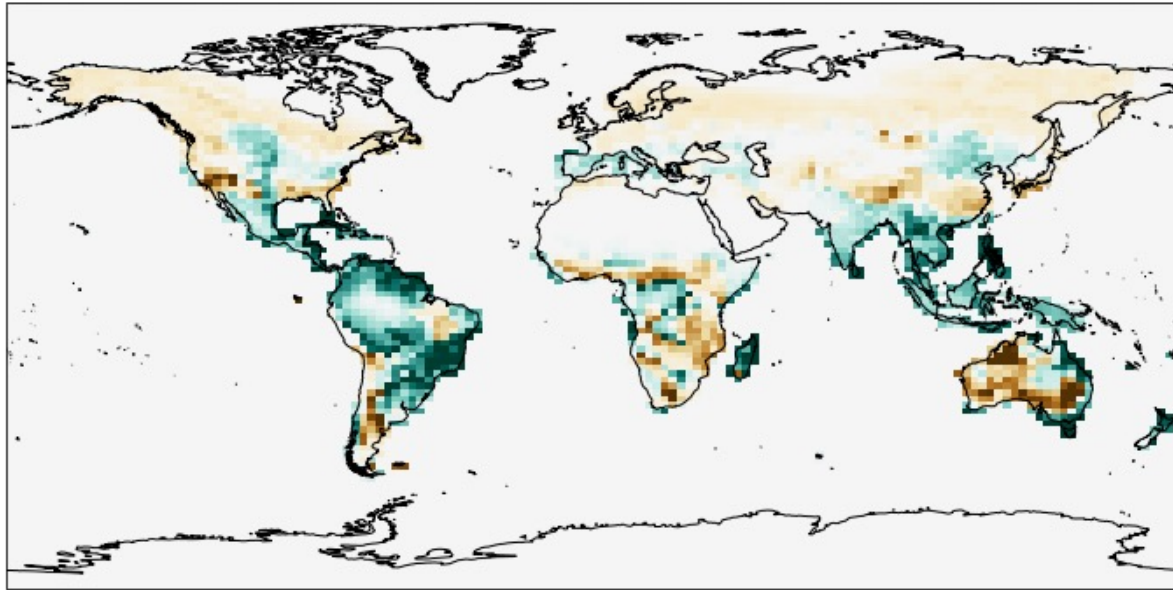
Previously: Photosynthetic response is regionally sensitive for **Atm+Leaf high** *iWUE* case

Atm+Leaf: Photosynthesis High – Default *iWUE*

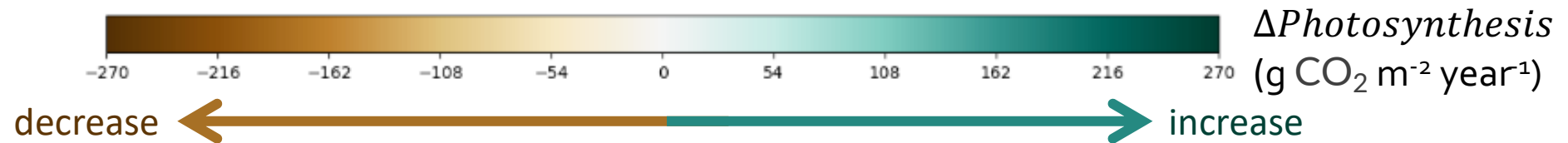
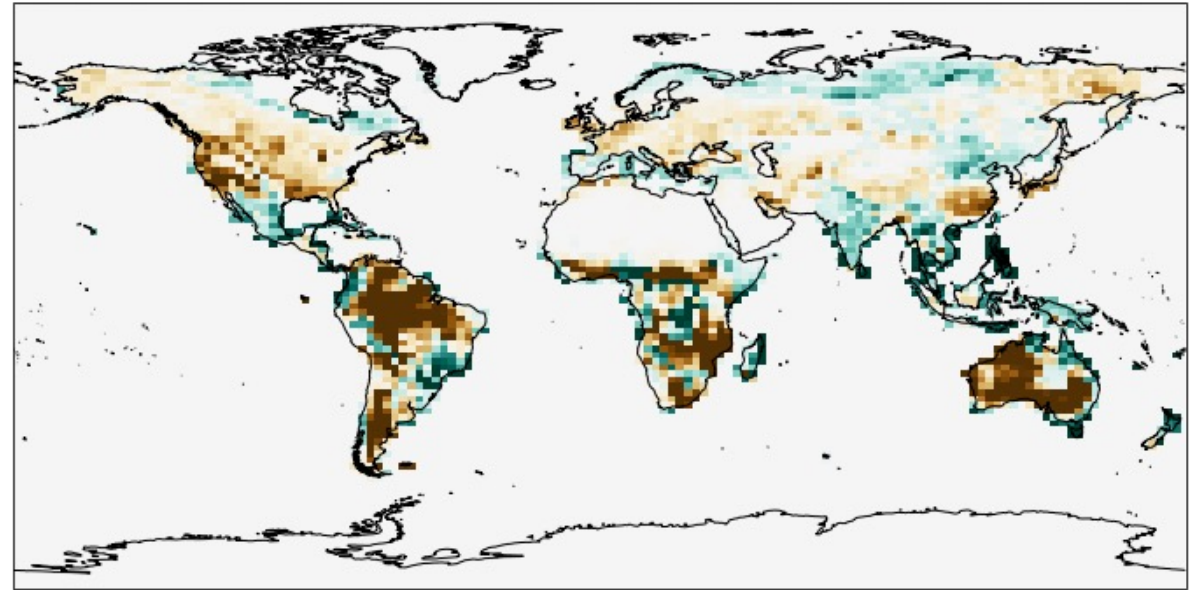


Photosynthesis also has different responses for static high *iWUE* cases

Static: Photosynthesis High – Default *iWUE*

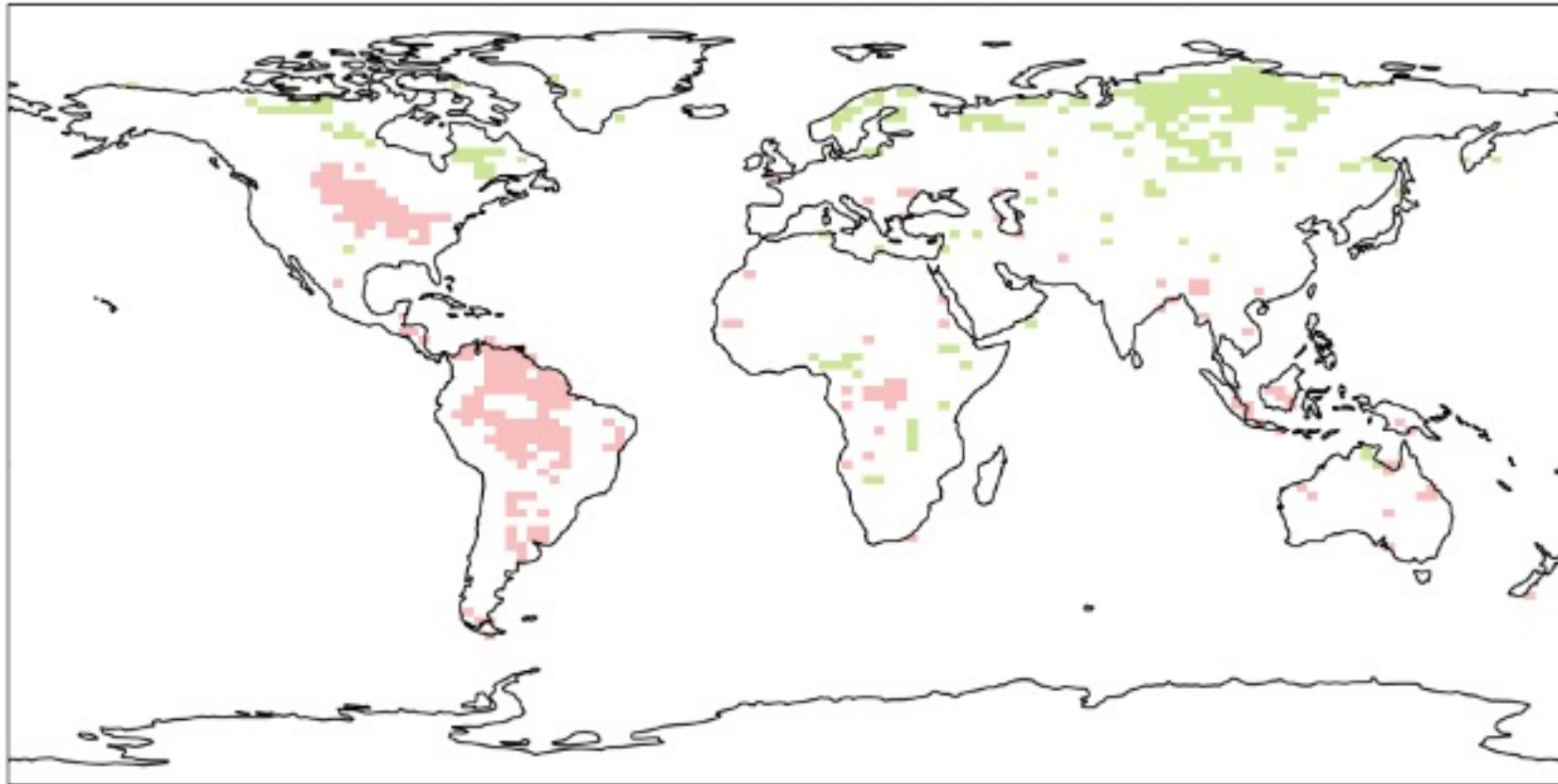


Atm+Leaf: Photosynthesis High – Default *iWUE*



Atm+Leaf changes the sign of photosynthetic response to high *iWUE*

Photosynthesis Sign Change Map between Static and Atm+Leaf for High – Default *iWUE*

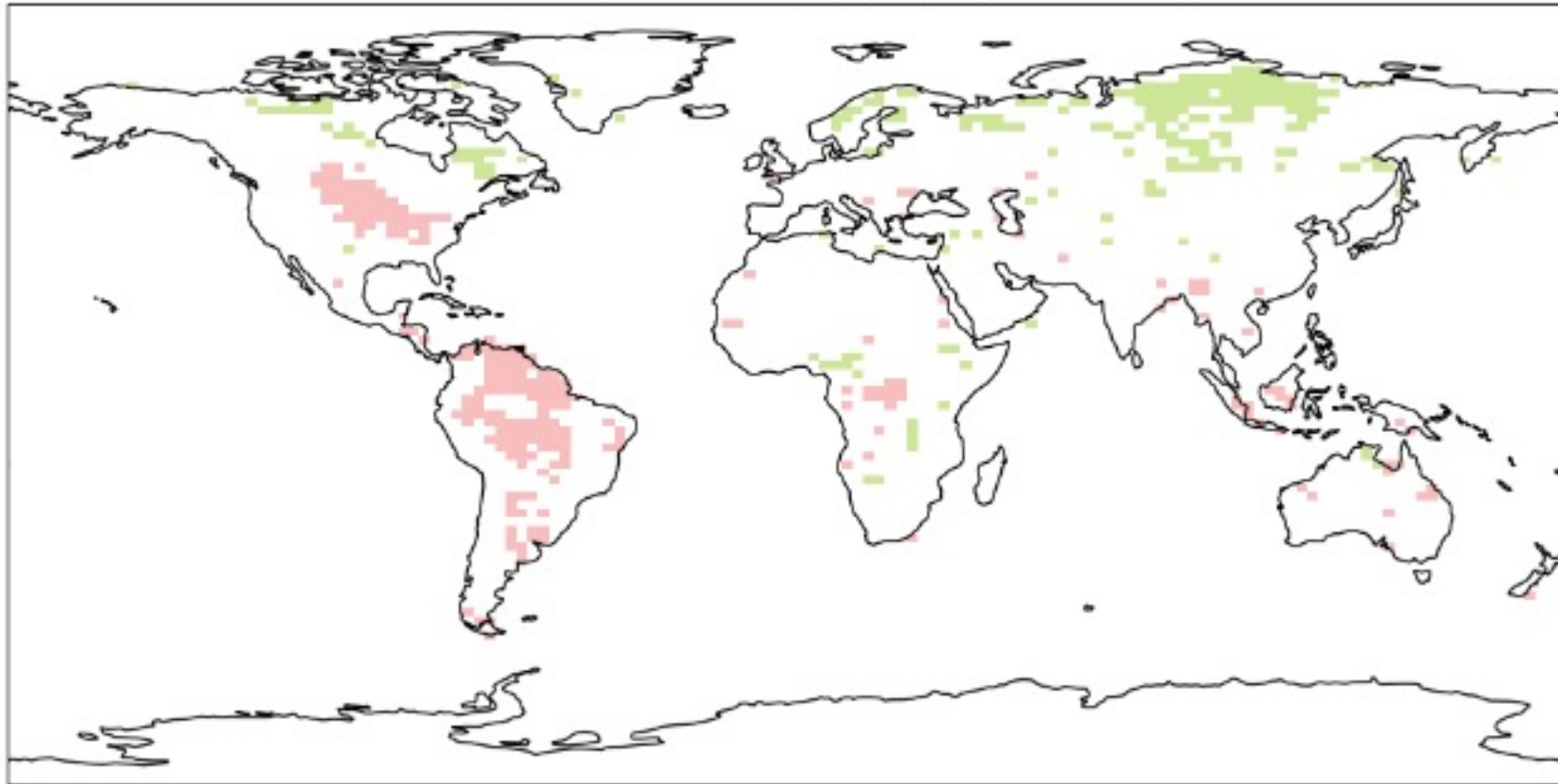


Static negative; Atm+Leaf positive

Static positive; Atm+Leaf negative

Takehome #2: A coupled atmosphere enables the climate to respond differently

Photosynthesis Sign Change Map between **Static** and **Atm+Leaf** for **High** – Default *iWUE*



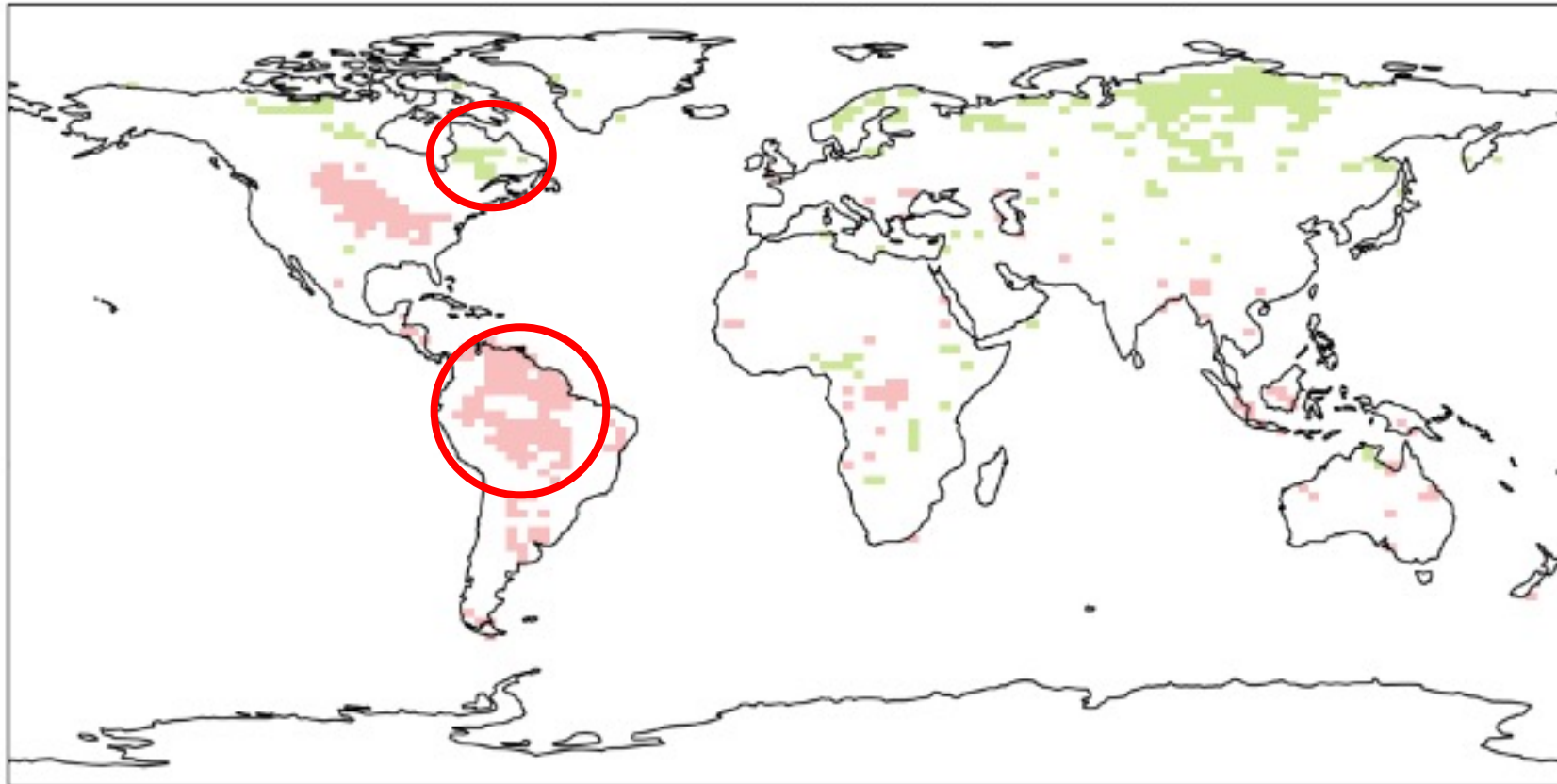
Static negative; Atm+Leaf positive

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Takehome #2: A coupled atmosphere enables the climate to respond differently

Spoiler: Temperature increases!

Photosynthesis Sign Change Map between **Static** and **Atm+Leaf** for **High** – Default *iWUE*

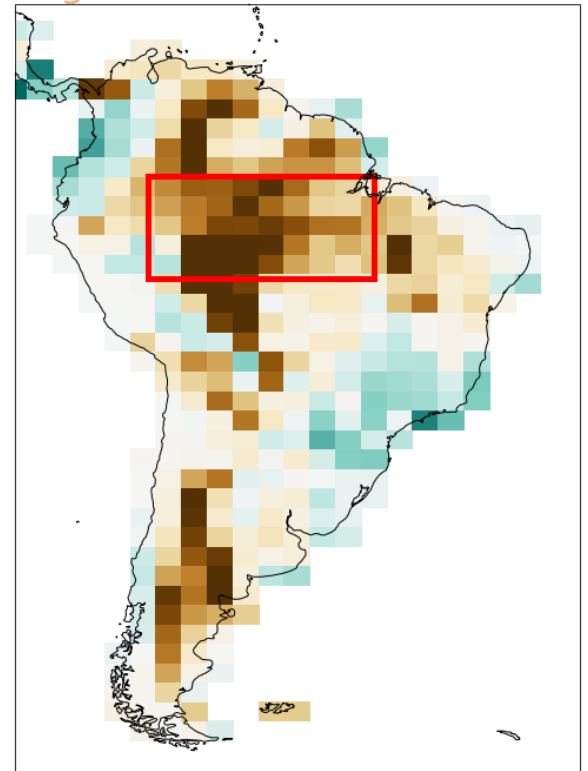


Static negative; Atm+Leaf positive

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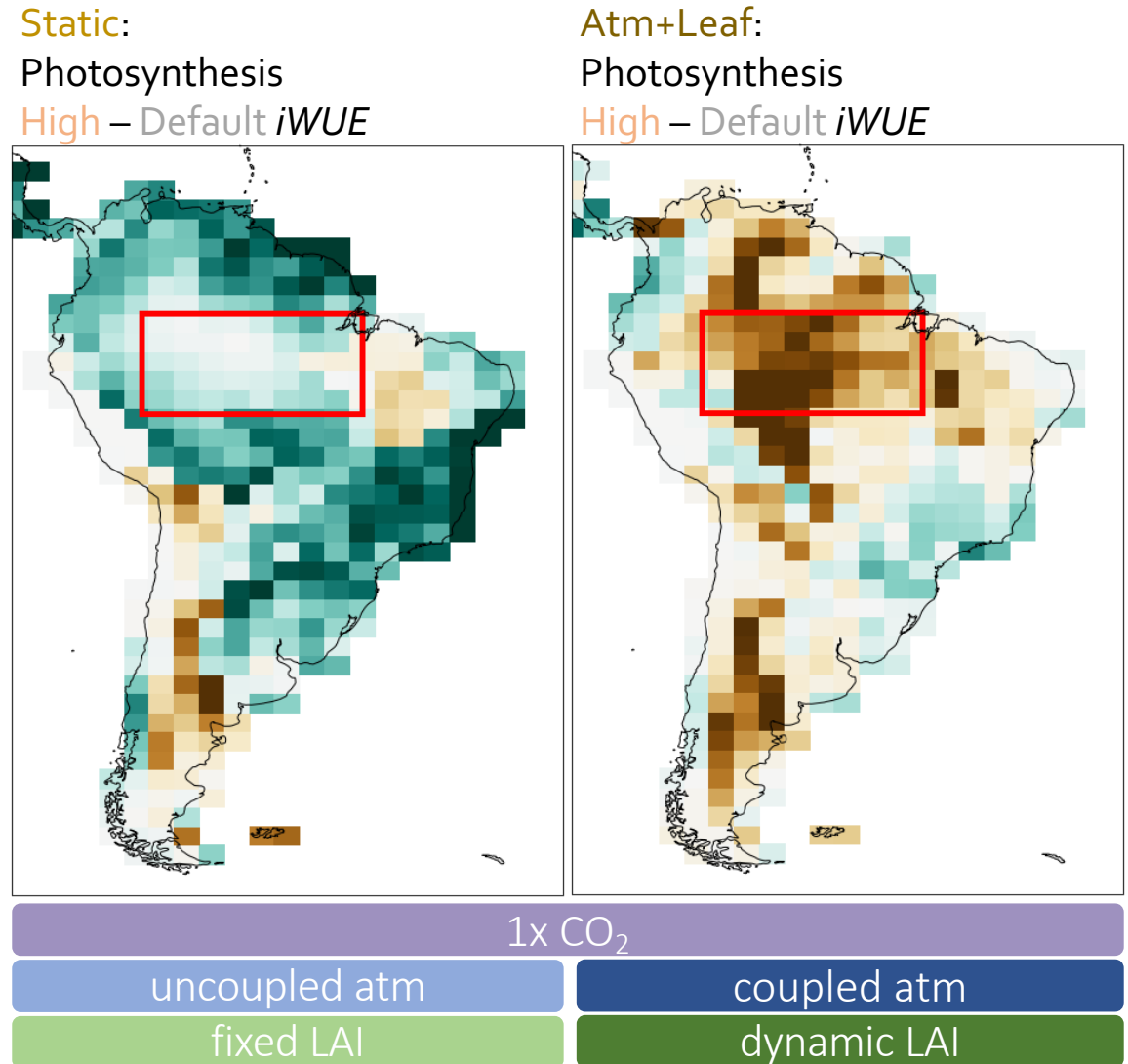
With a **coupled** atmosphere and **dynamic** leaf area, photosynthesis **decreases** in the Amazon

Atm+Leaf:
Photosynthesis
High – Default *iWUE*



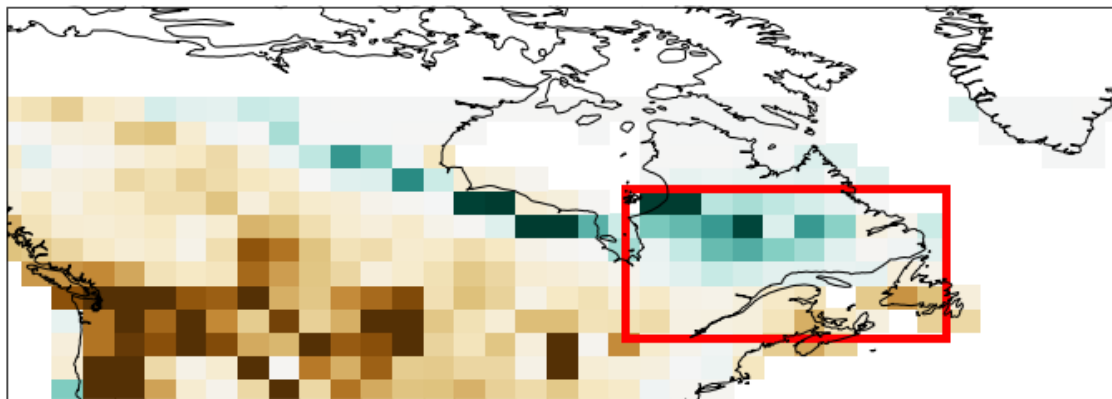
1x CO₂
coupled atm
dynamic LAI

In the **static high *iWUE*** case, photosynthesis increases



In the boreal Canada **Atm+Leaf high *iWUE*** case, photosynthesis increases

Atm+Leaf: Photosynthesis High – Default *iWUE*

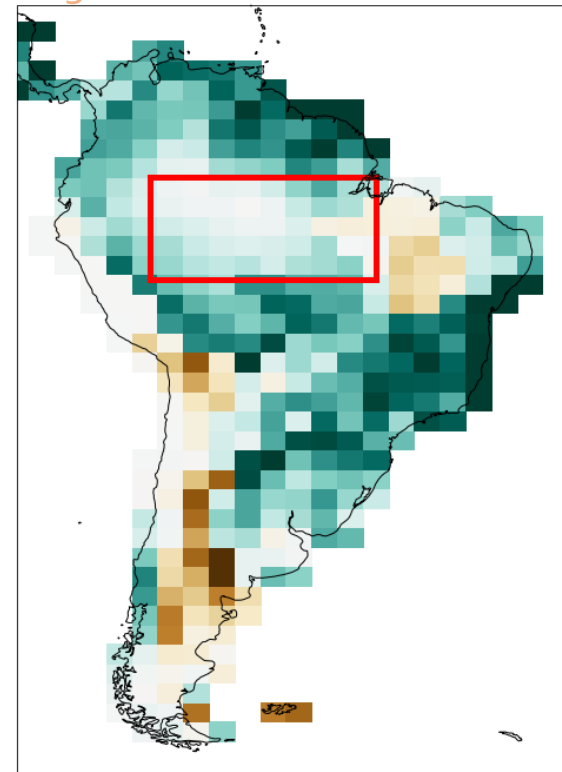


1x CO₂

coupled atm

dynamic LAI

Static: Photosynthesis High – Default *iWUE*

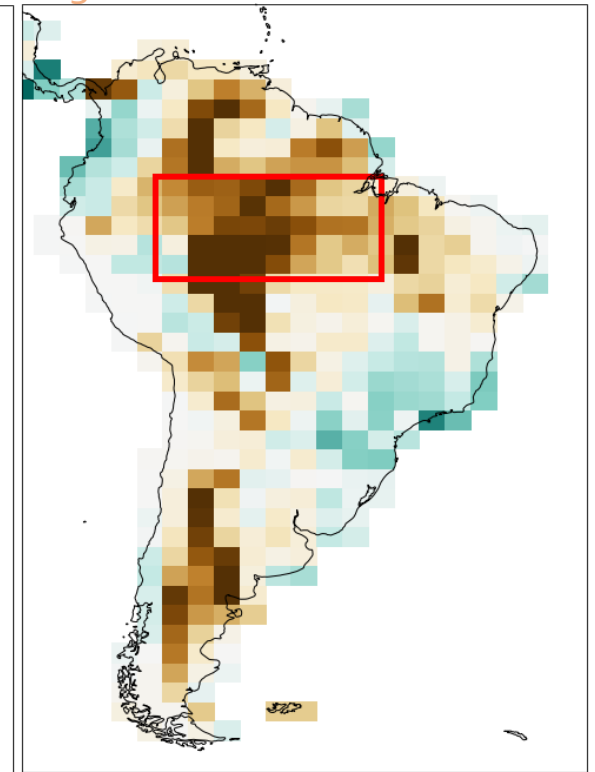


1x CO₂

uncoupled atm

fixed LAI

Atm+Leaf: Photosynthesis High – Default *iWUE*

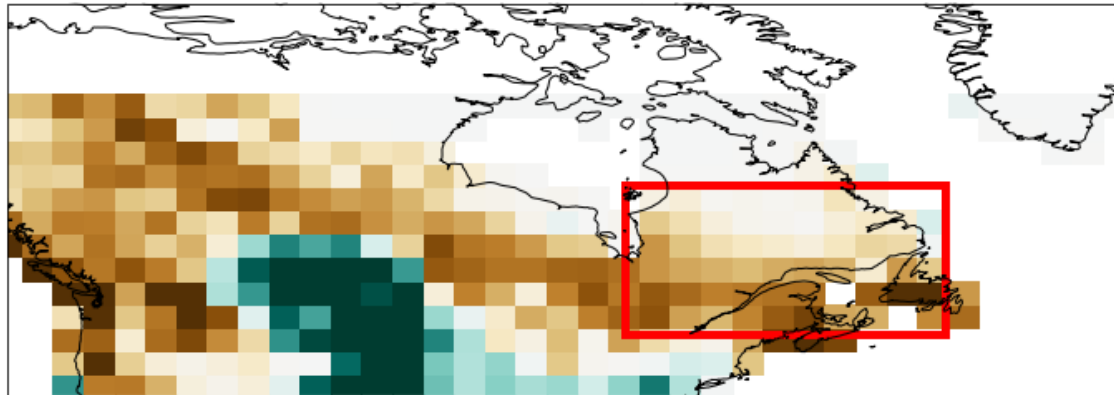


coupled atm

dynamic LAI

In the boreal Canada **static high *iWUE*** case, photosynthesis decreases

Static: Photosynthesis **High** – Default *iWUE*

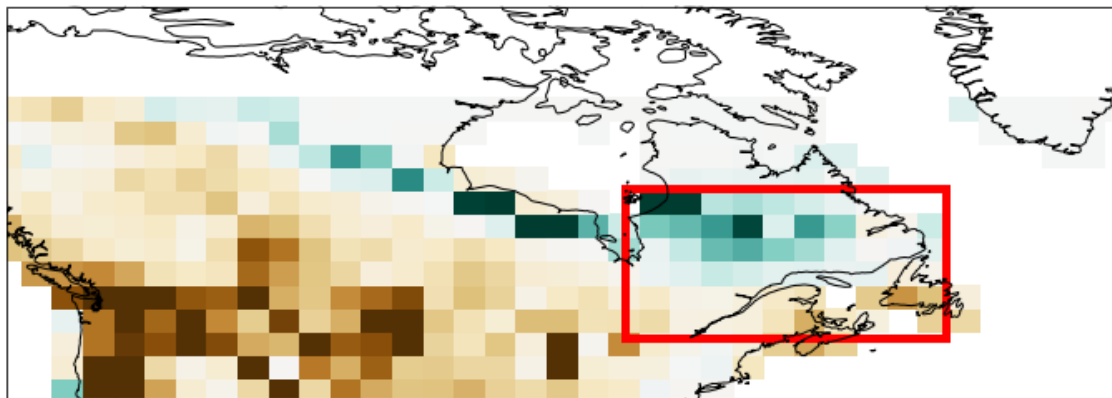


1x CO₂

uncoupled atm

fixed LAI

Atm+Leaf: Photosynthesis **High** – Default *iWUE*

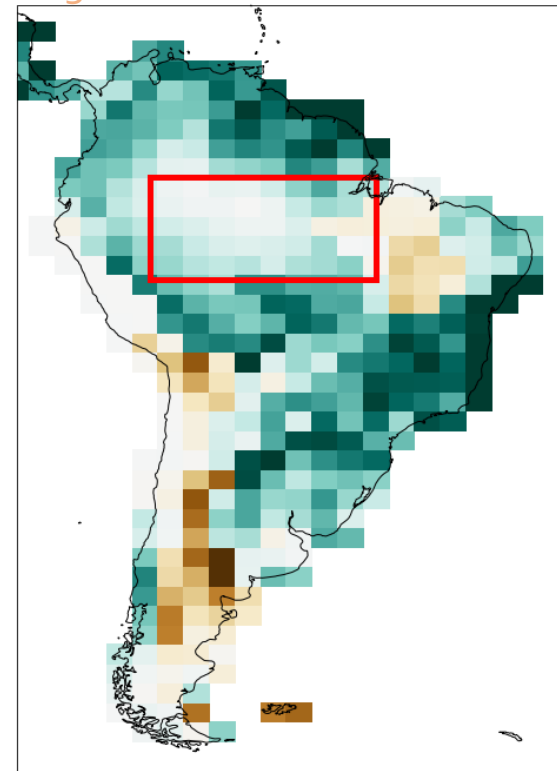


1x CO₂

coupled atm

dynamic LAI

Static: Photosynthesis **High** – Default *iWUE*

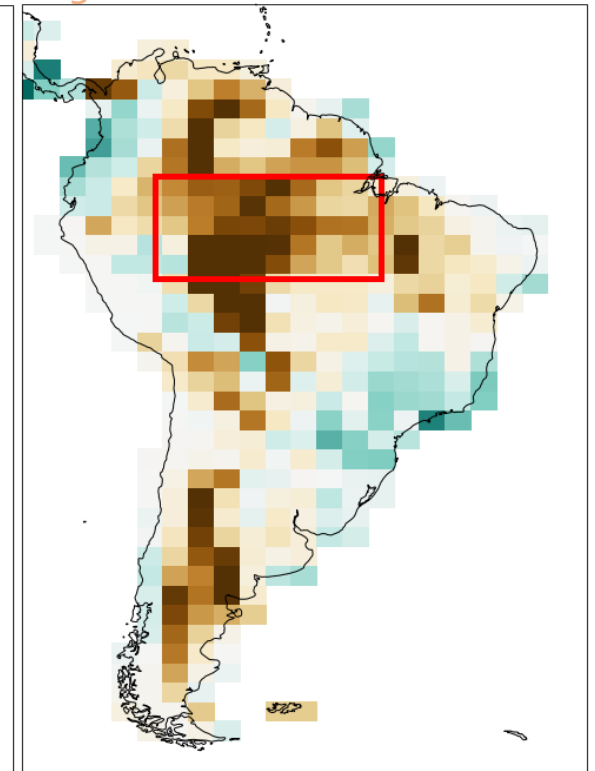


1x CO₂

uncoupled atm

fixed LAI

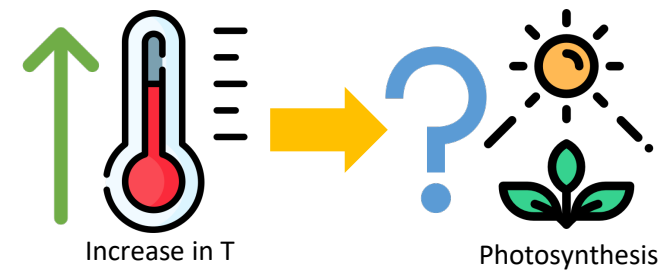
Atm+Leaf: Photosynthesis **High** – Default *iWUE*



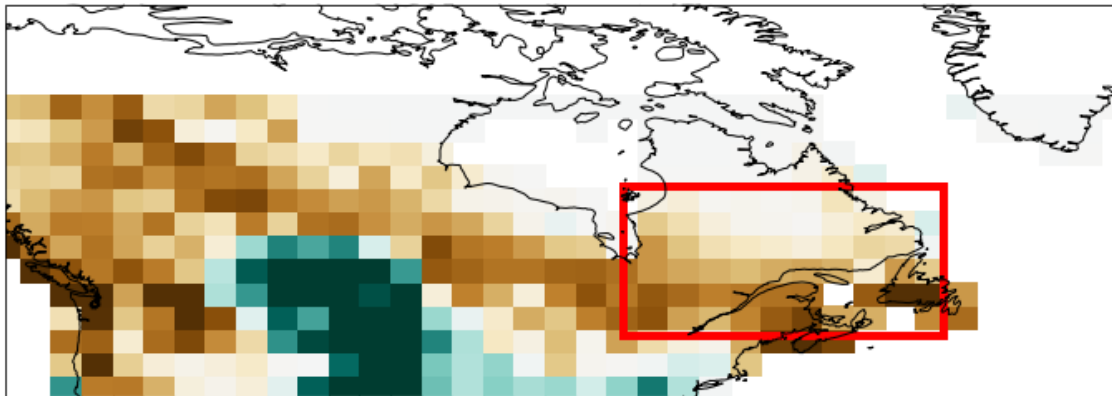
coupled atm

dynamic LAI

Same temperature response, but different photosynthetic response

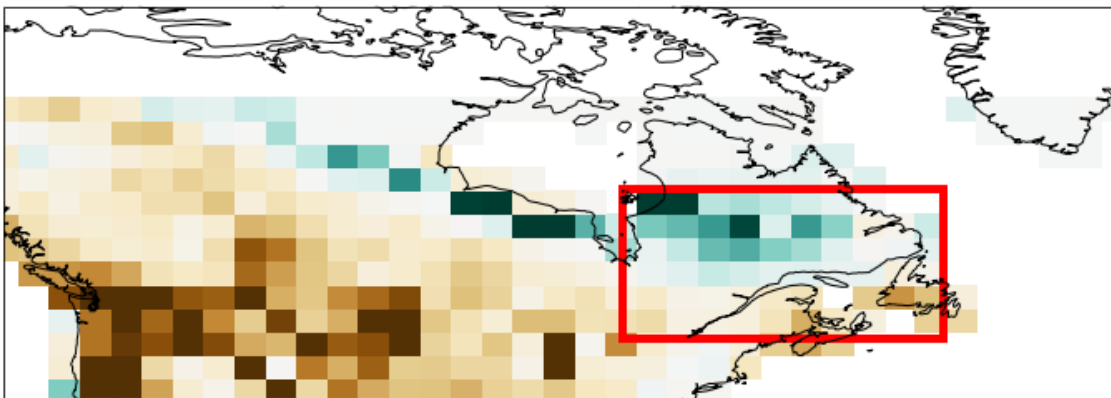


Static: Photosynthesis High – Default *iWUE*



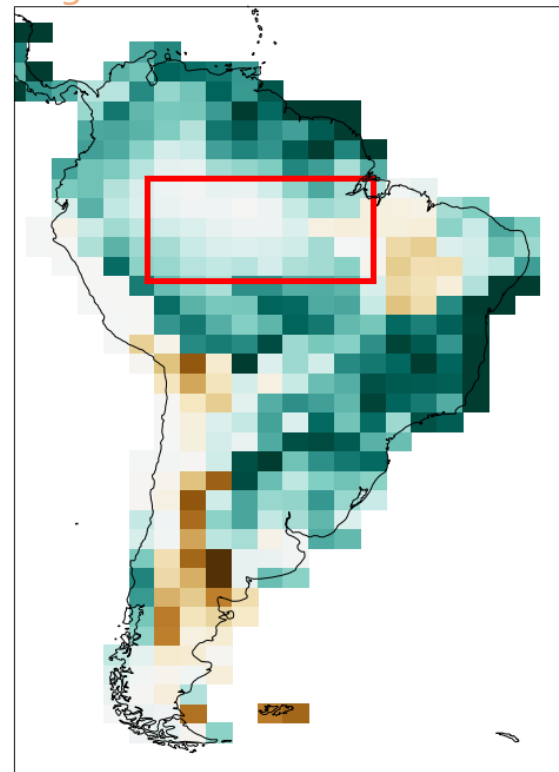
1x CO₂ uncoupled atm fixed LAI

Atm+Leaf: Photosynthesis High – Default *iWUE*



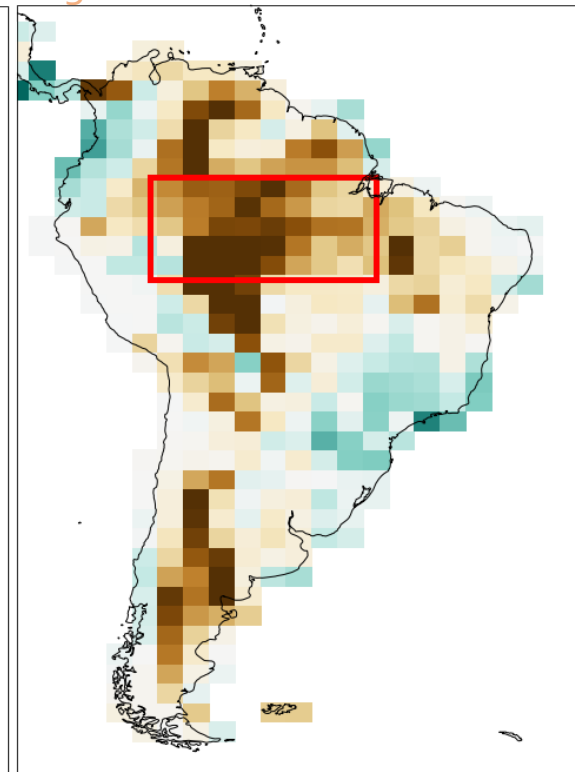
1x CO₂ coupled atm dynamic LAI

Static: Photosynthesis High – Default *iWUE*



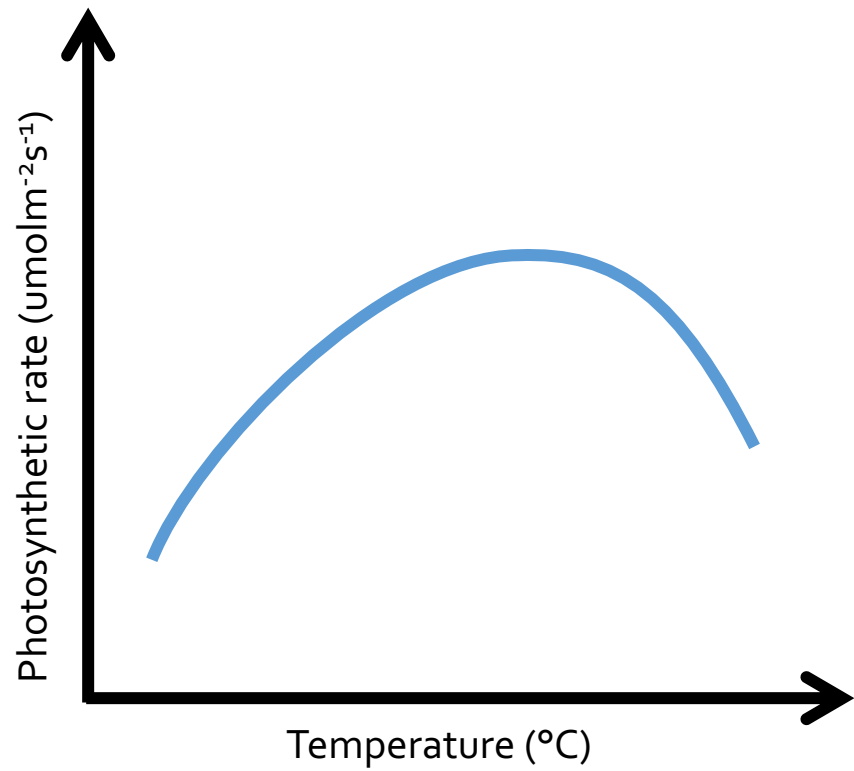
1x CO₂
uncoupled atm fixed LAI

Atm+Leaf: Photosynthesis High – Default *iWUE*

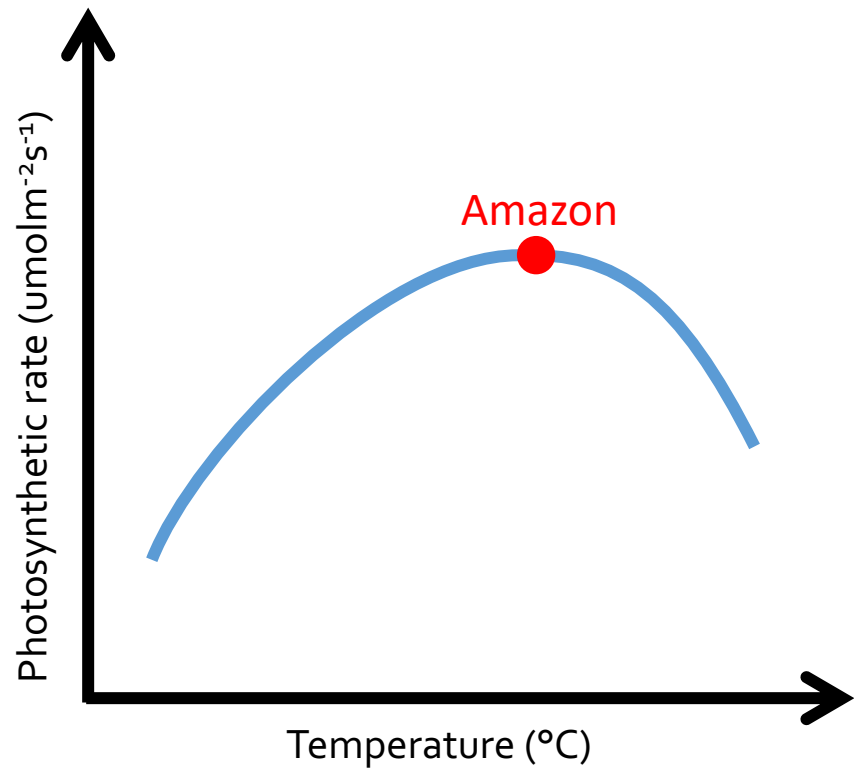


coupled atm dynamic LAI

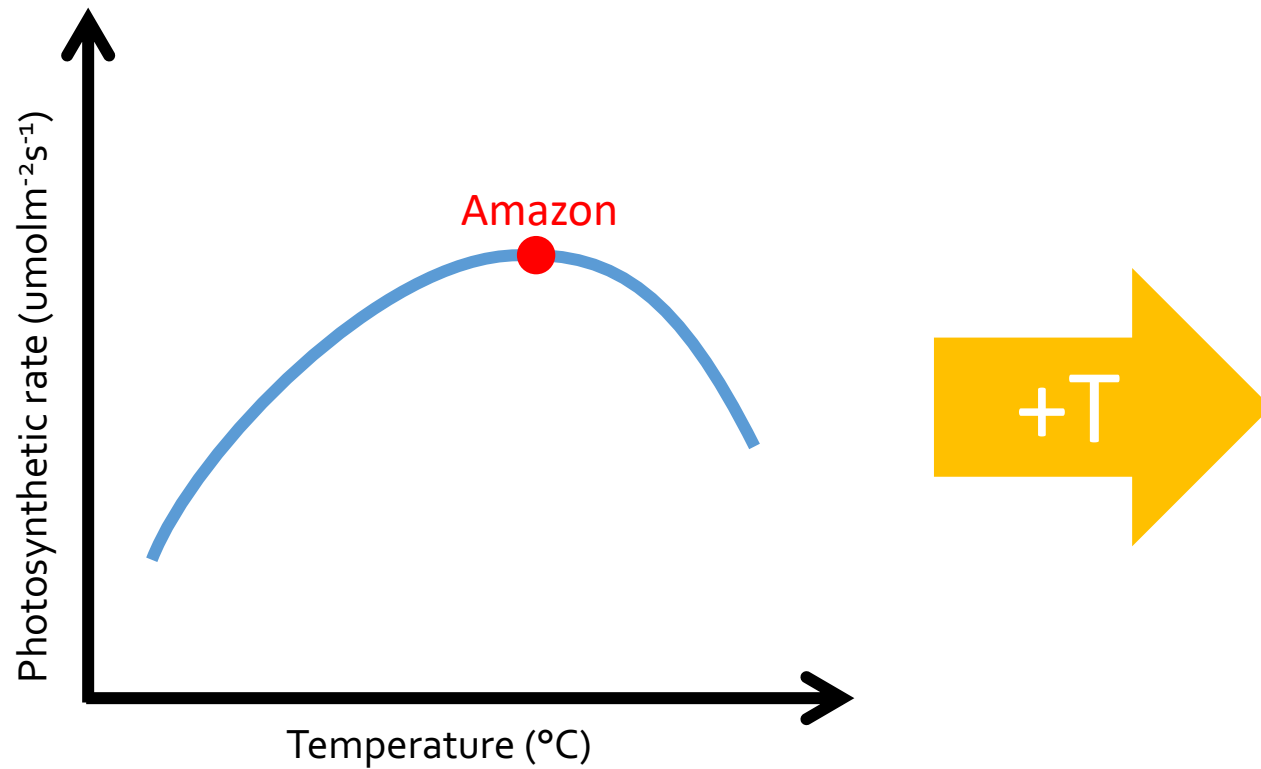
Photosynthesis has an optimal temperature



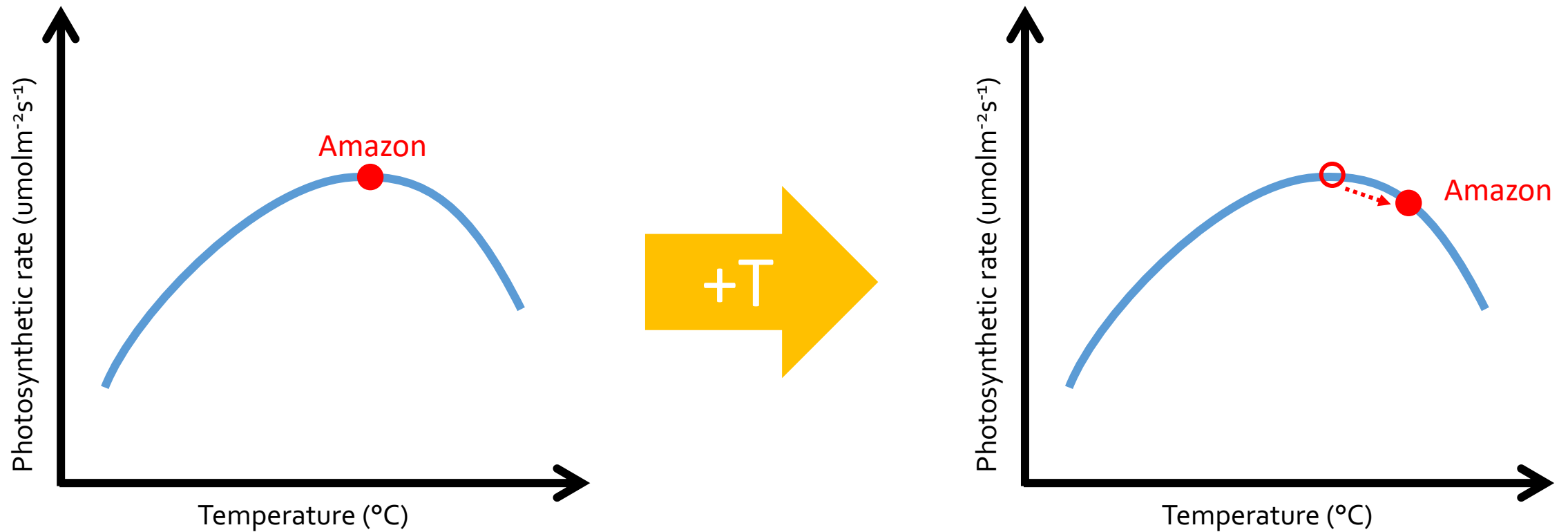
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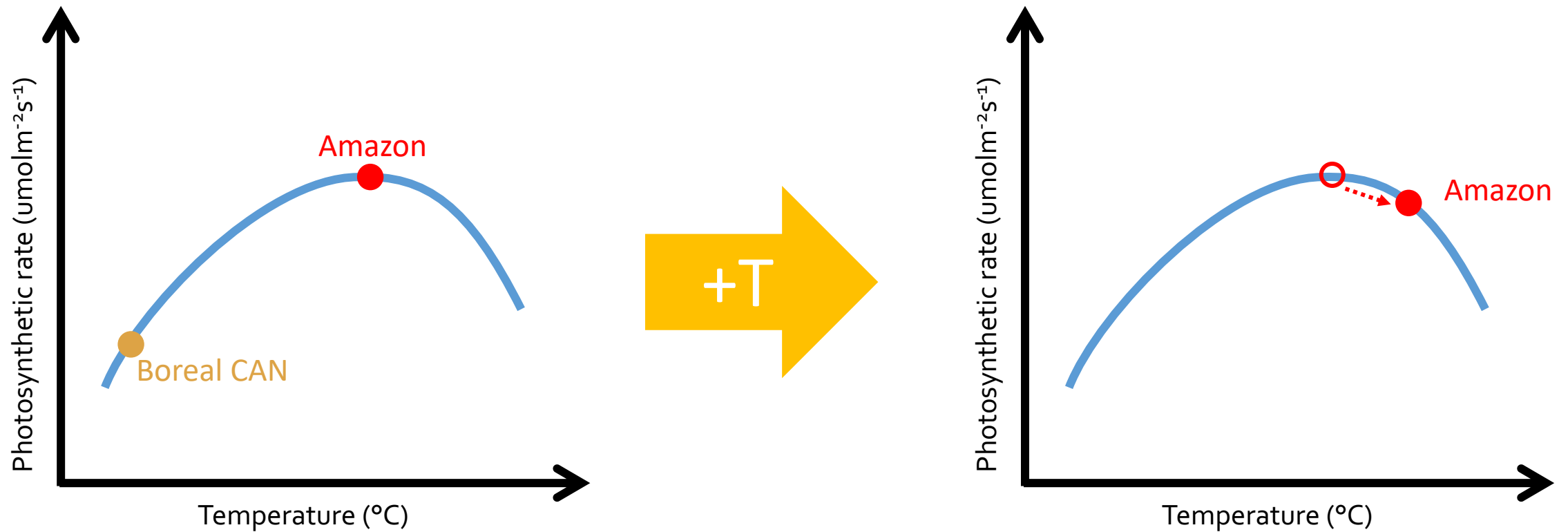
Photosynthesis has an optimal temperature



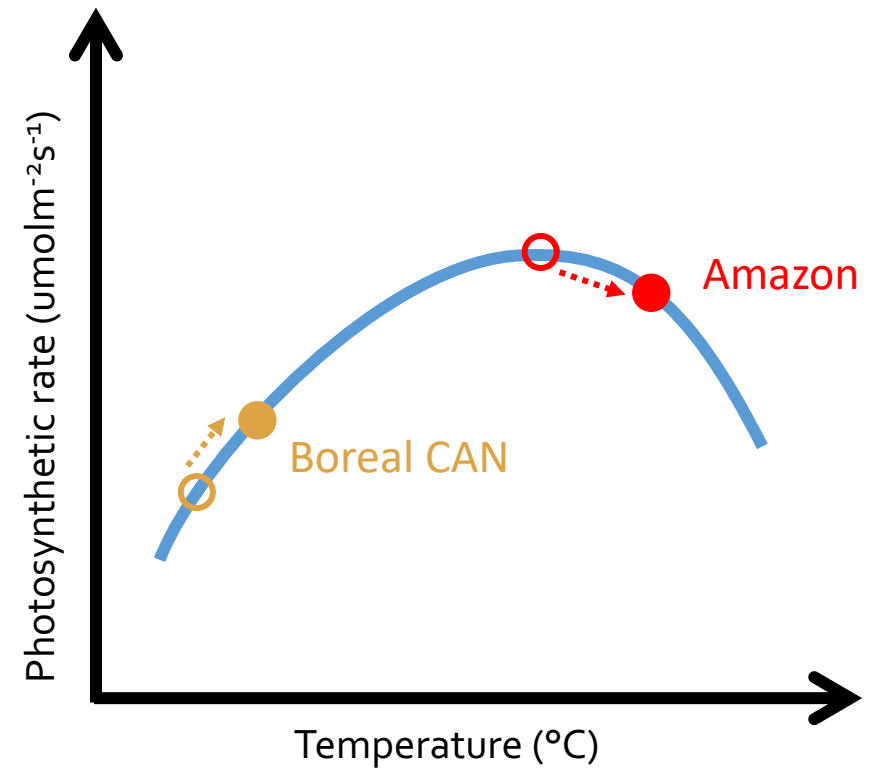
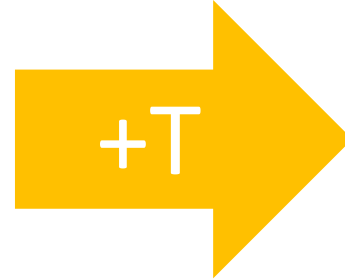
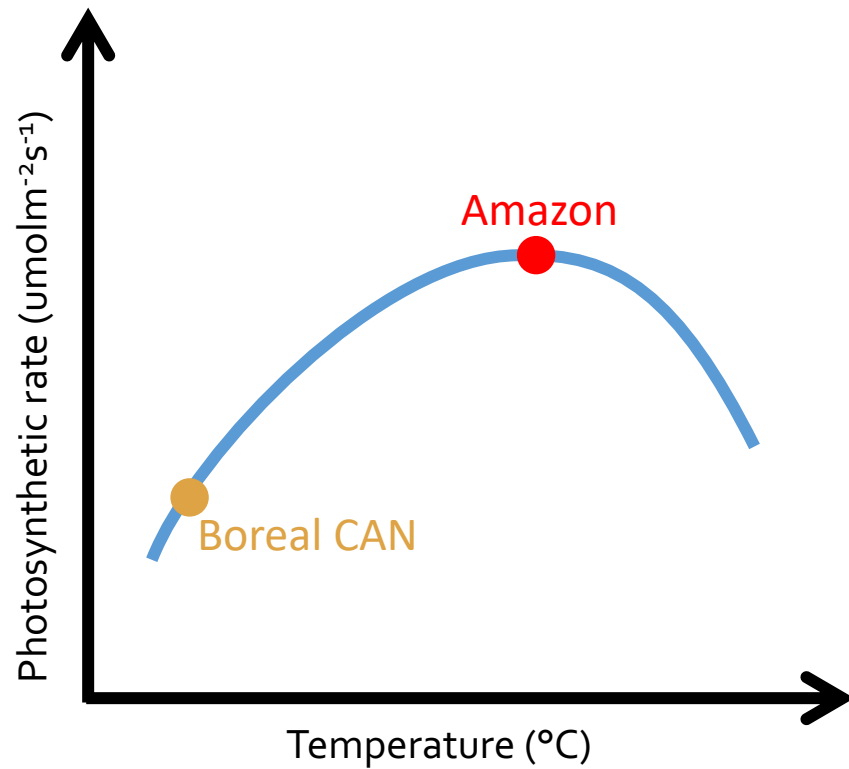
An increase in temperature pushes the Amazon *past* the thermal optimum for photosynthesis



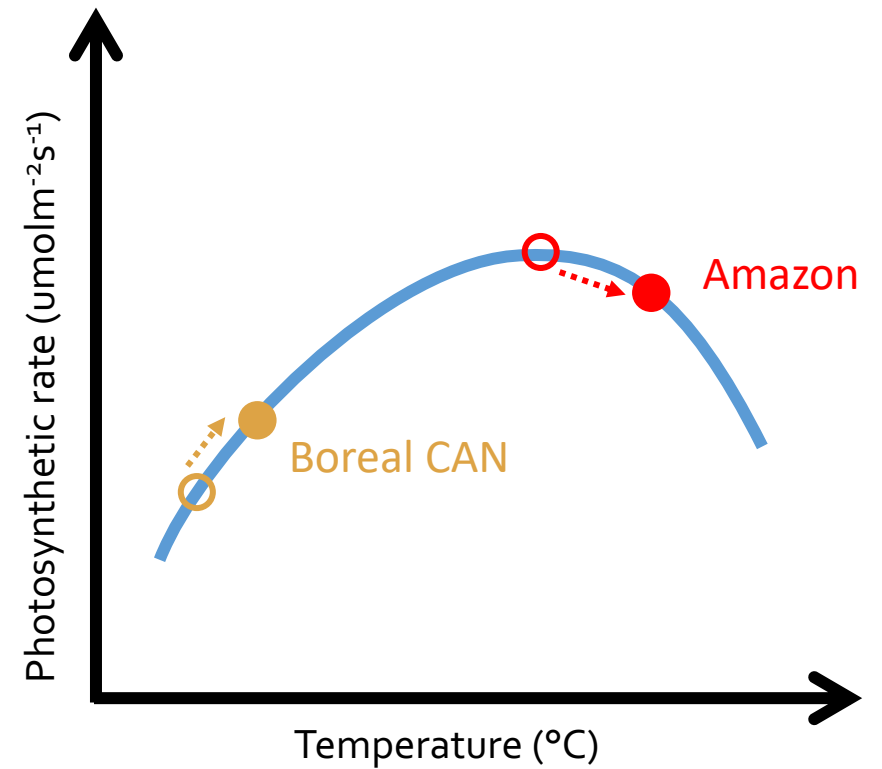
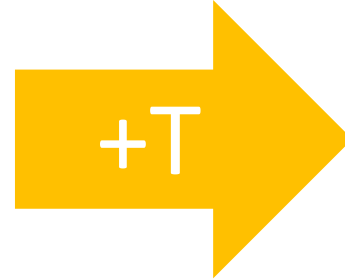
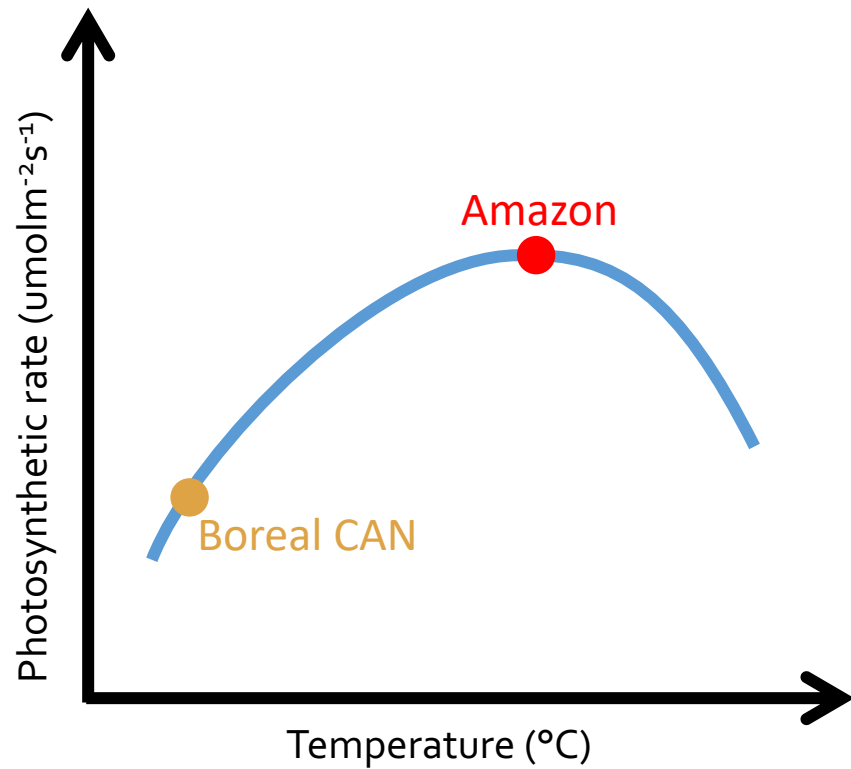
An increase in temperature pushes the Amazon *past* the thermal optimum for photosynthesis



An increase in temperature pushes boreal Canada *towards* the thermal optimum for photosynthesis



Takehome #3: Photosynthetic response to $+T$ is different in hot vs cold places



Questions we aim to answer today:

+/- iWUE

How does our choice of iWUE impact photosynthesis?

+/- atmosphere

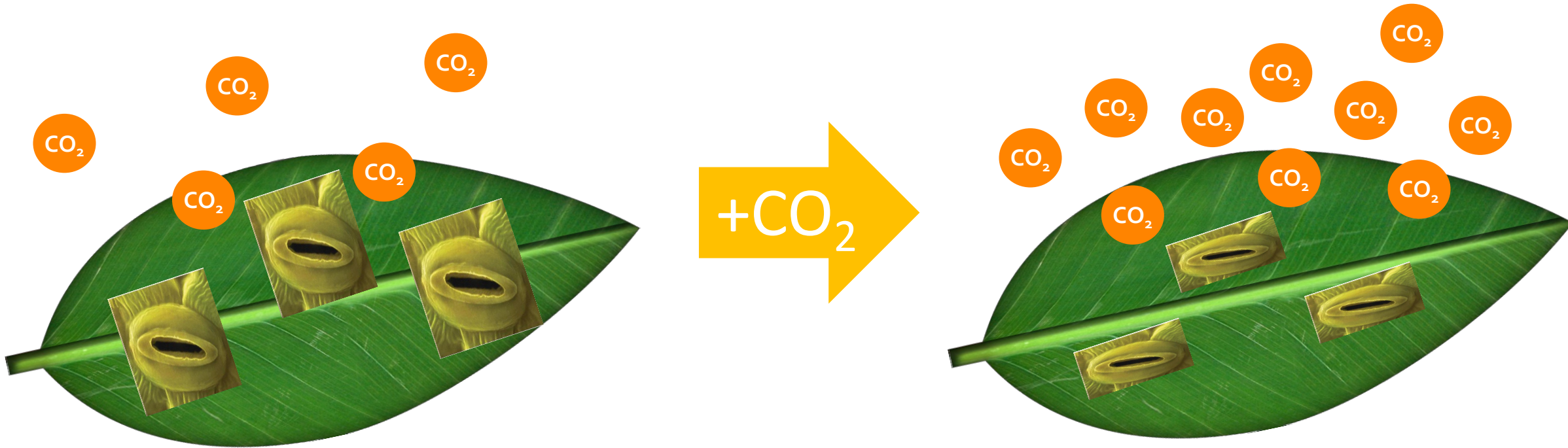
+/- leaf area

How much of the photosynthetic response can be attributed to the inclusion of a coupled atmosphere and dynamic LAI?

+ CO₂

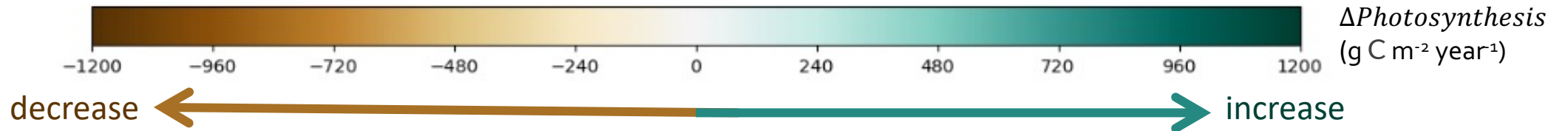
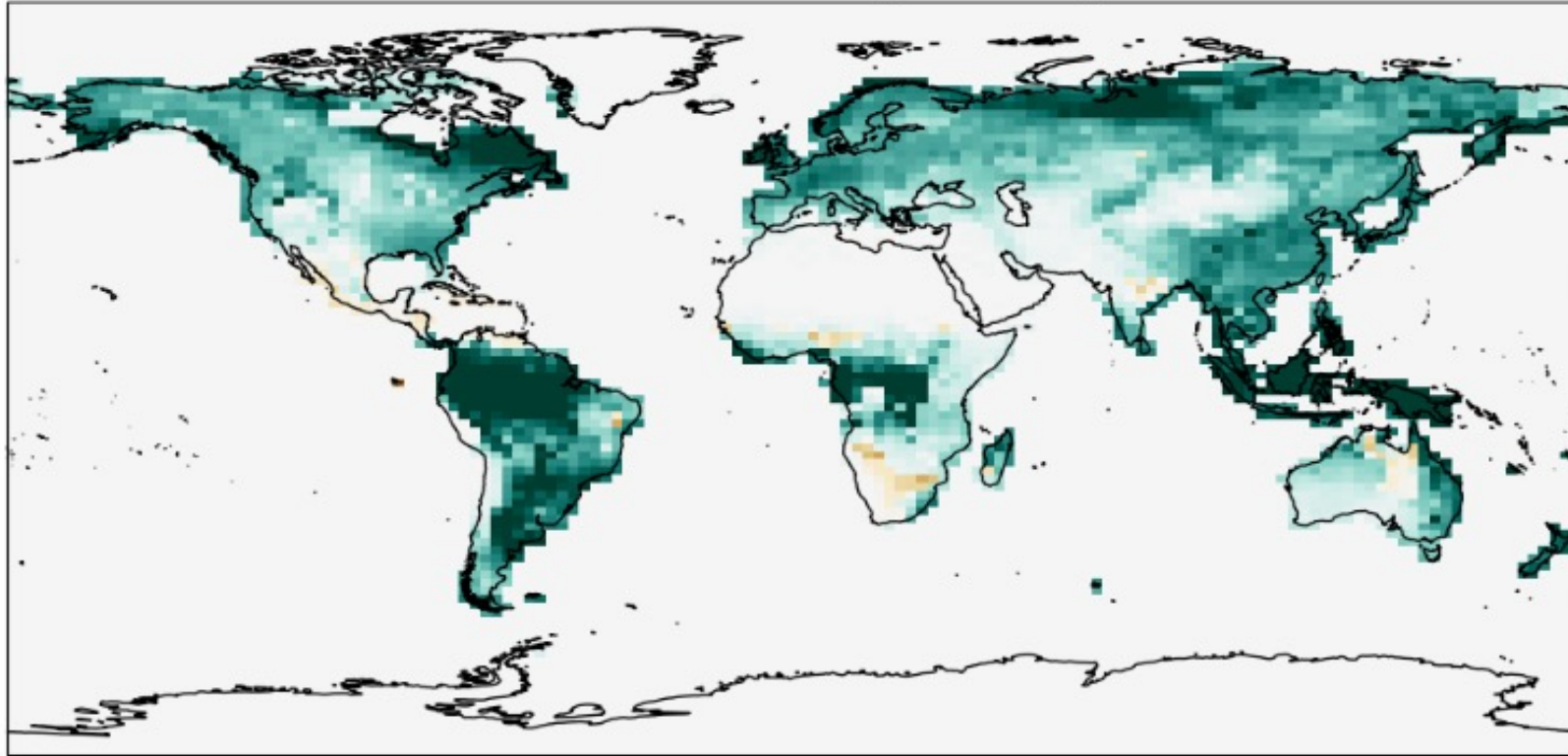
Does the photosynthetic response to iWUE perturbation change with increase in atmospheric CO₂?

Does the photosynthetic response to iWUE perturbation change with **increase** in atmospheric CO₂?



Increase in atmospheric CO₂ increases photosynthesis

Photosynthesis Default *iWUE* 2xCO₂ - 1xCO₂

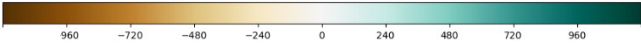
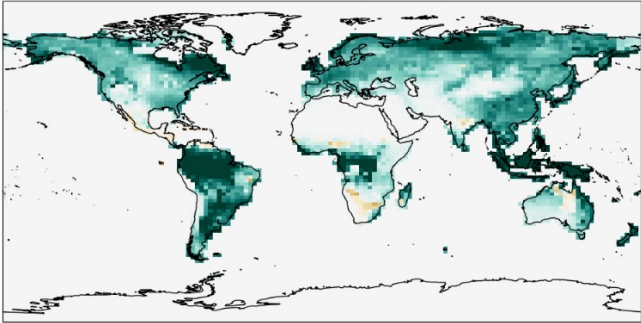


def *iWUE*

2x CO₂

—

1x CO₂



-1200

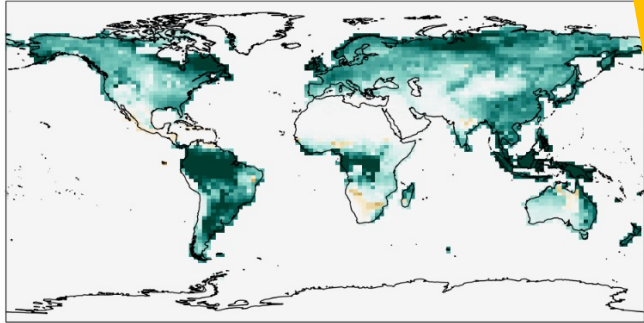
1200

def *iWUE*

2x CO₂

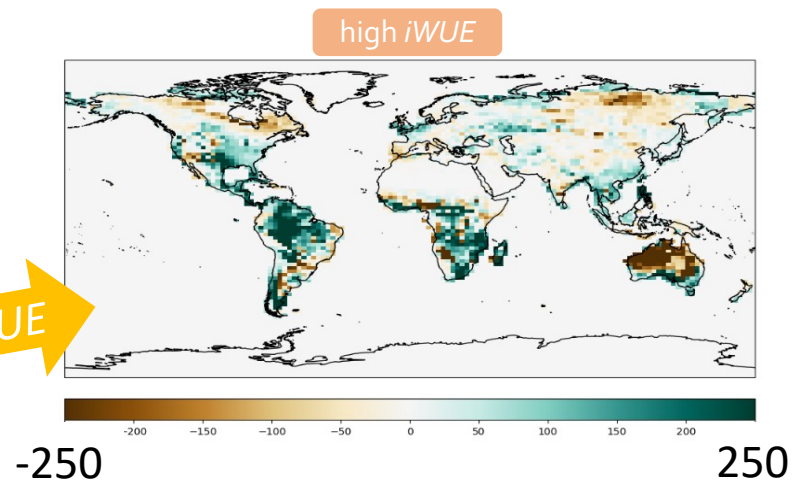
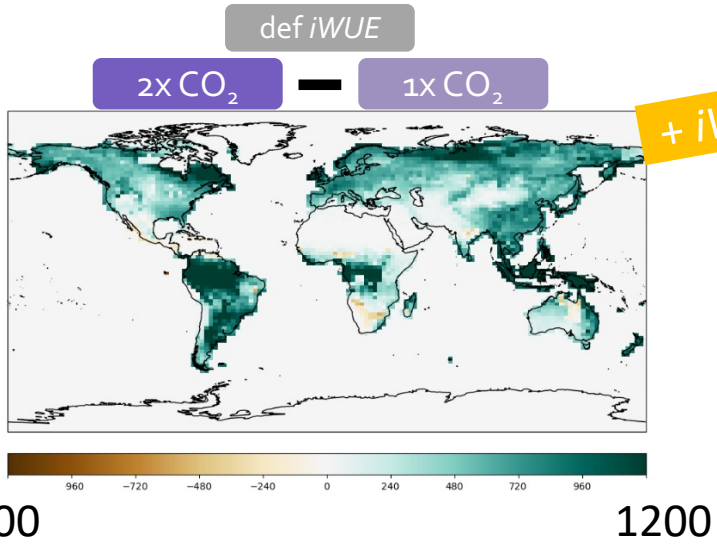
1x CO₂

+ *iWUE*

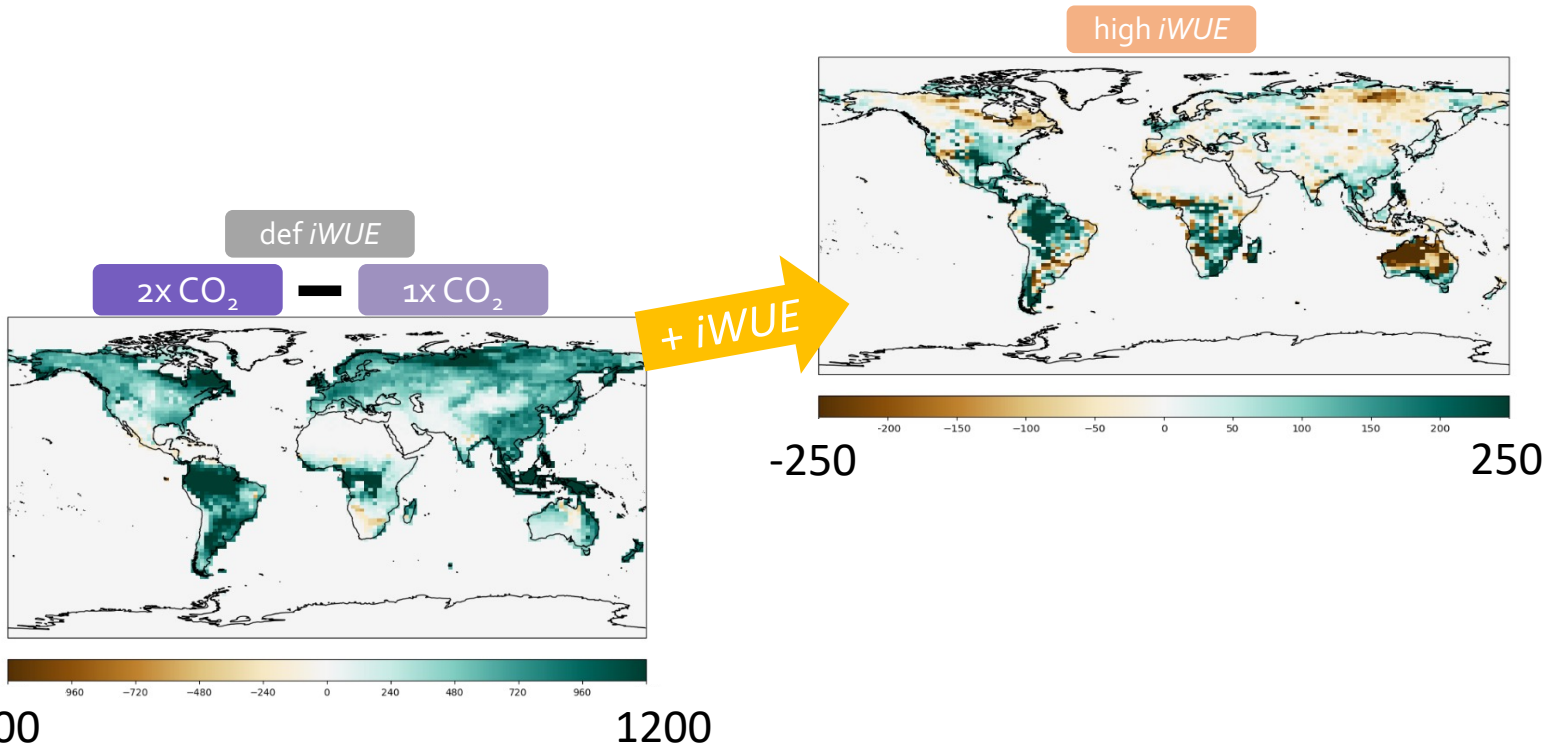


-1200

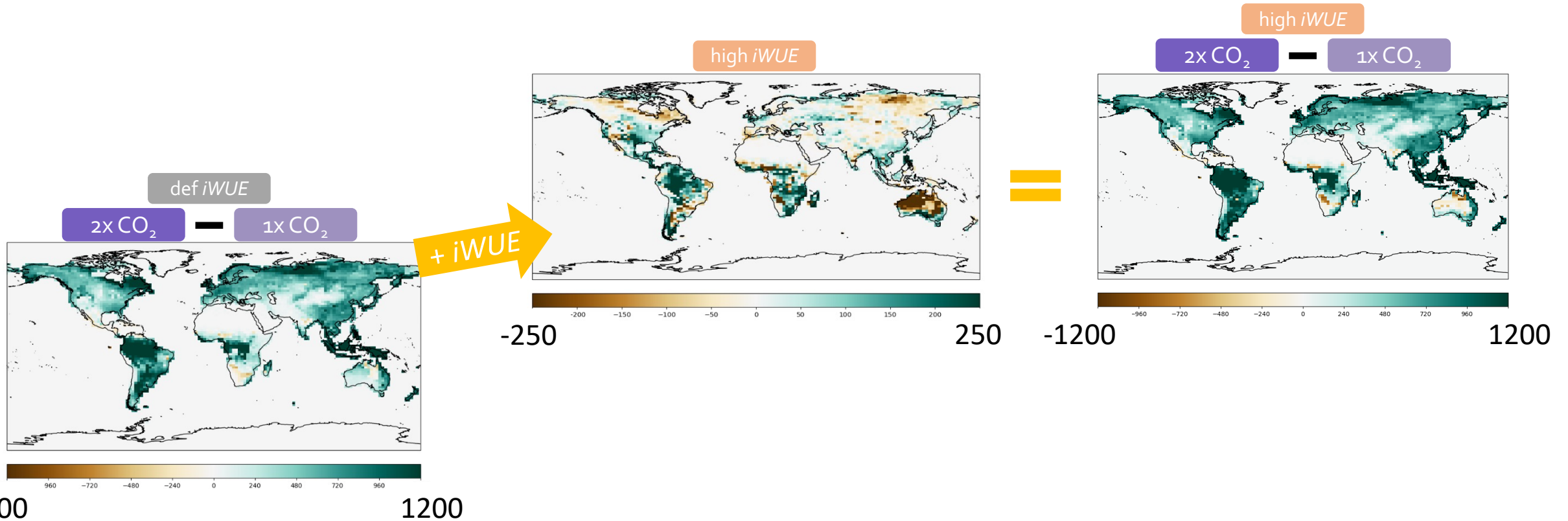
1200



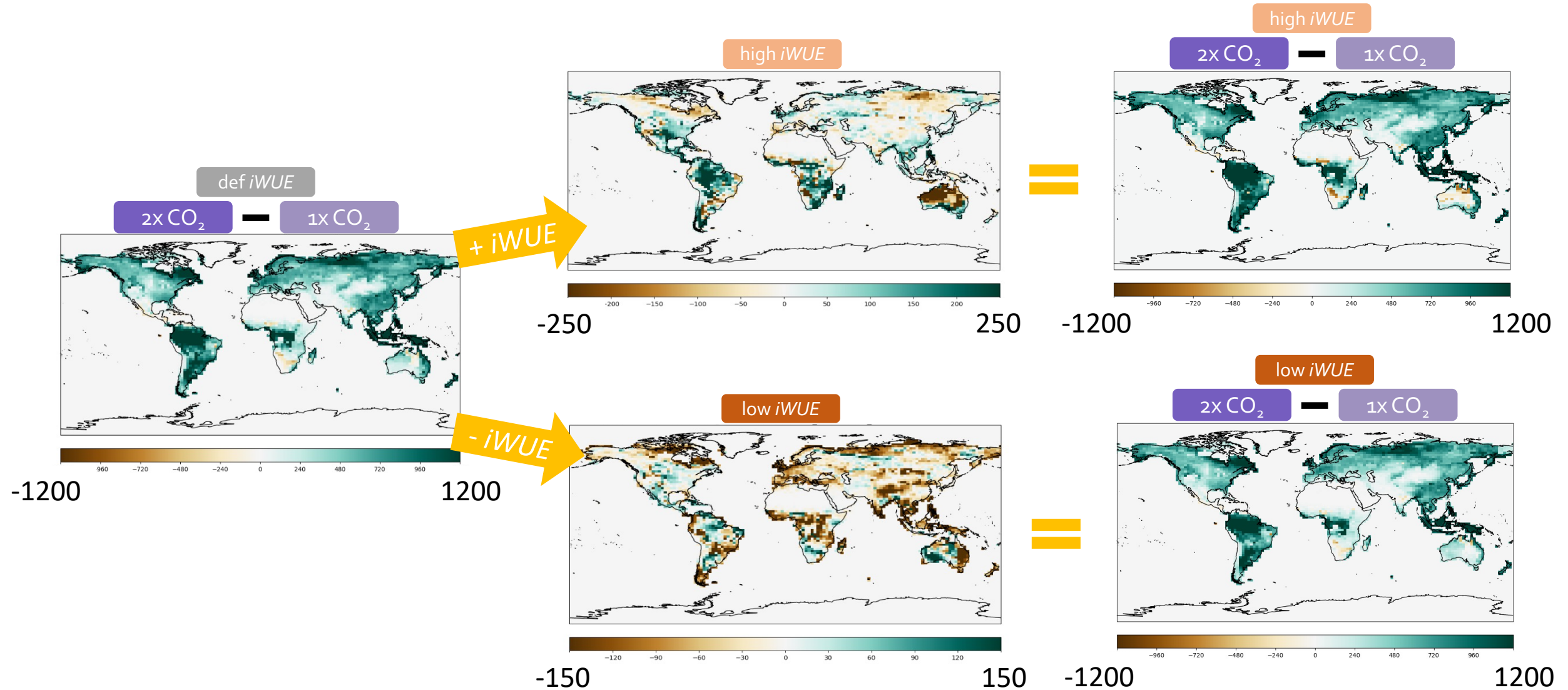
This is the change in photosynthetic response caused by *iWUE* perturbation at +CO₂



Gives us the overall response to *iWUE* perturbation at $+CO_2$

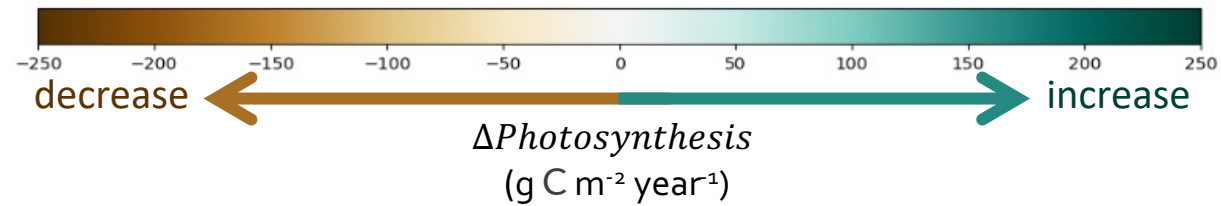
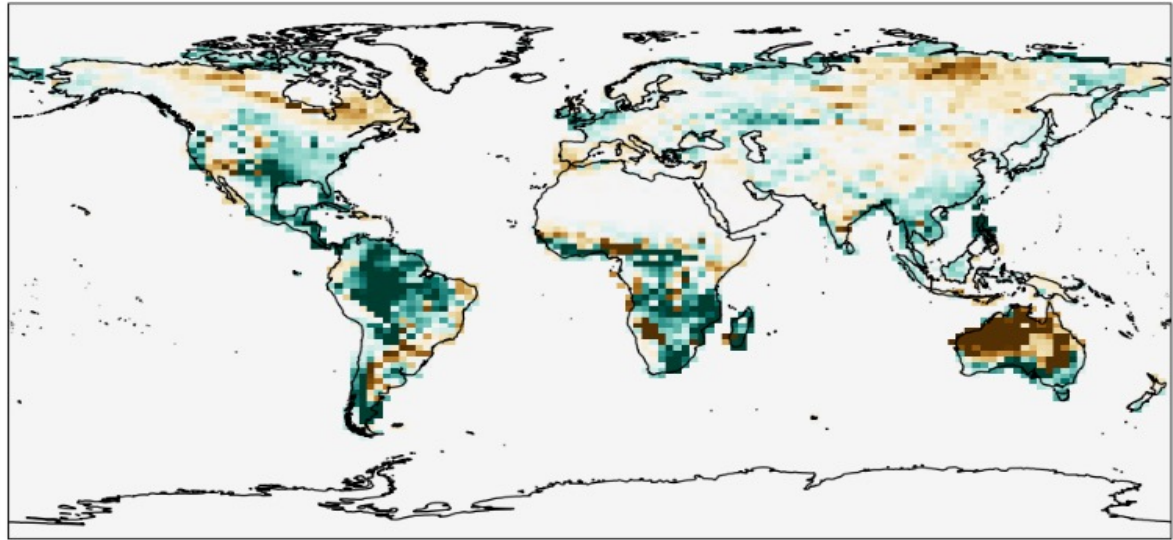


Gives us the overall response to *iWUE* perturbation at +CO₂

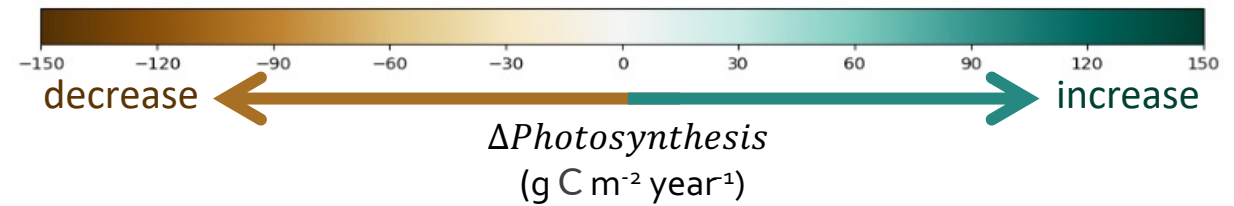
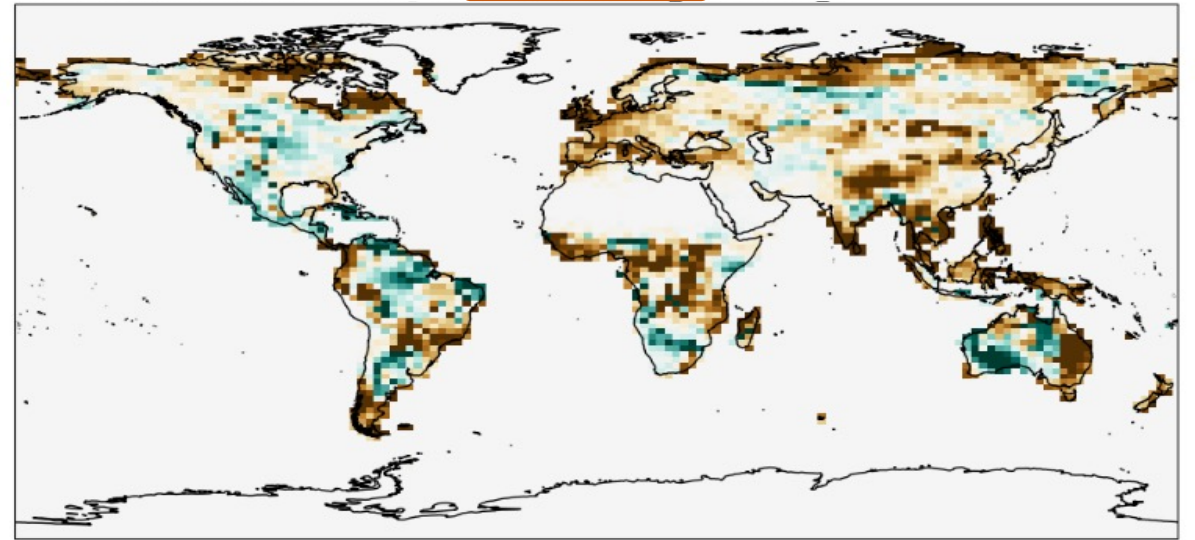


There are general responses to *iWUE* perturbations

High *iWUE*

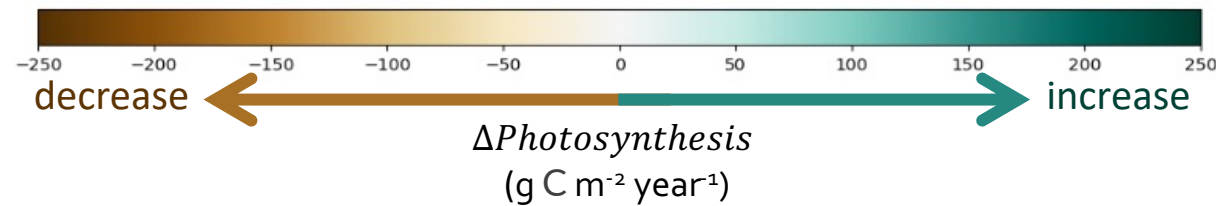
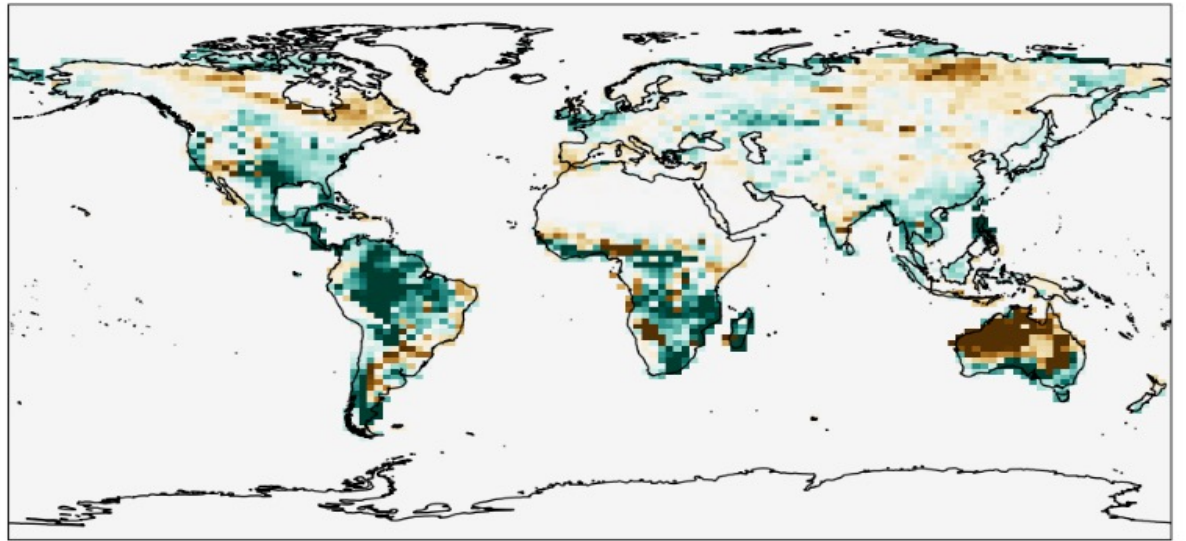


Low *iWUE*



Why do **high** *iWUE* perturbations generally have increasing photosynthesis?

High *iWUE*



$$\uparrow iWUE = \frac{\uparrow \text{Photosynthesis}}{g_s}$$

iWUE increases + g_s constant

➔ *Photosynthesis* increases

Largely green!

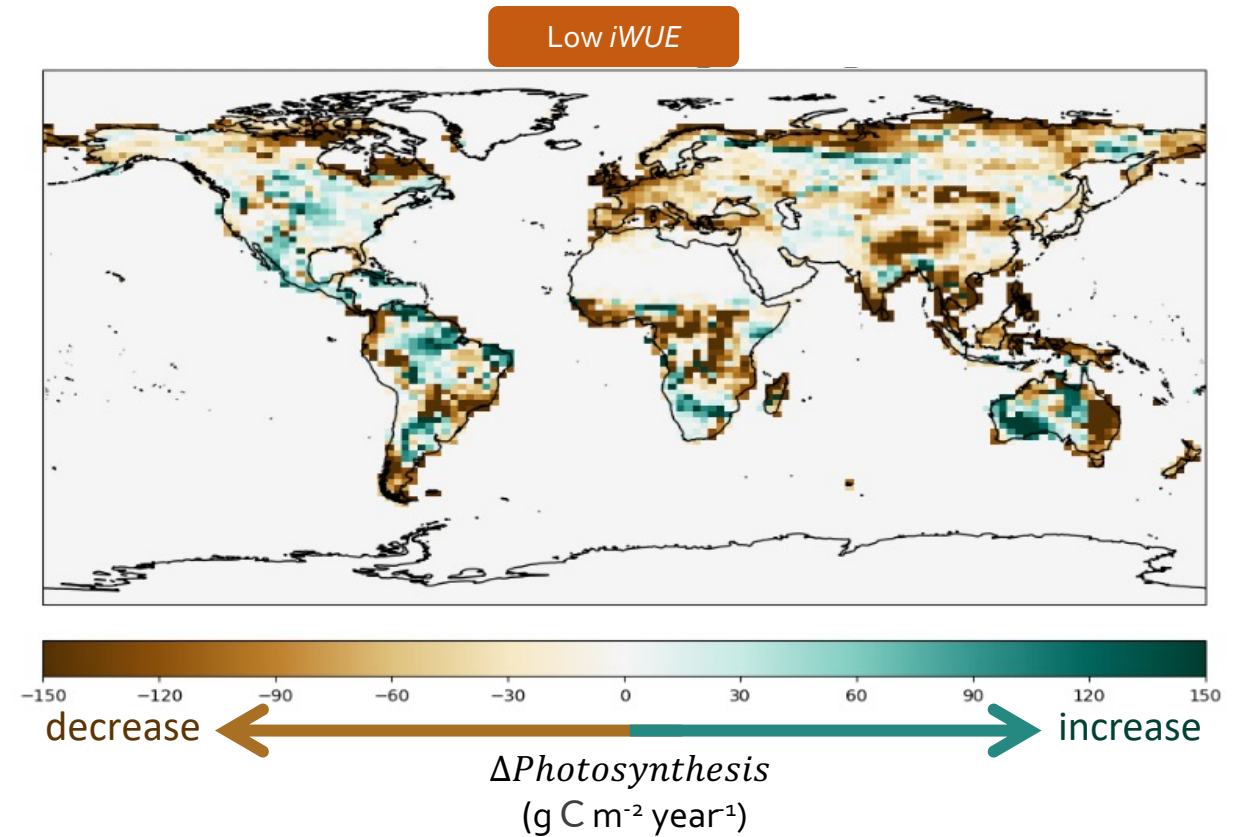
Why do **low** *iWUE* perturbations generally have decreasing photosynthesis?

$$\downarrow iWUE = \frac{\downarrow \text{Photosynthesis}}{g_s}$$

iWUE decreases + g_s constant

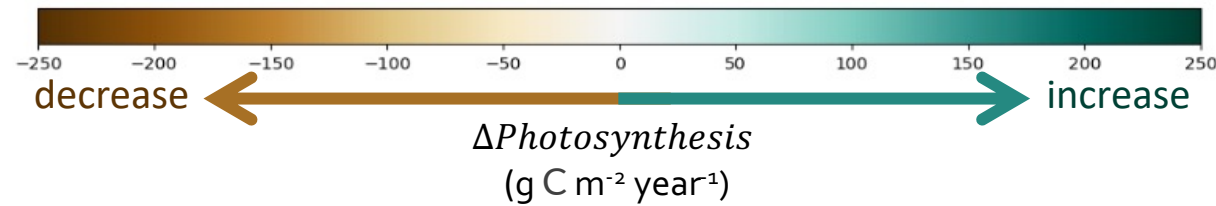
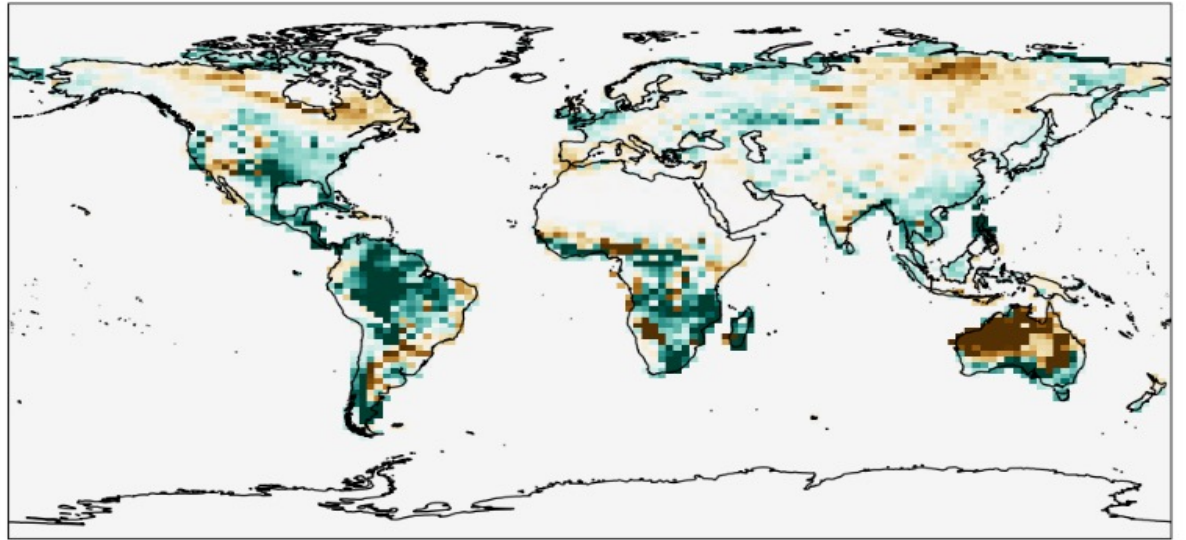
➡ *Photosynthesis* decreases

Largely brown!

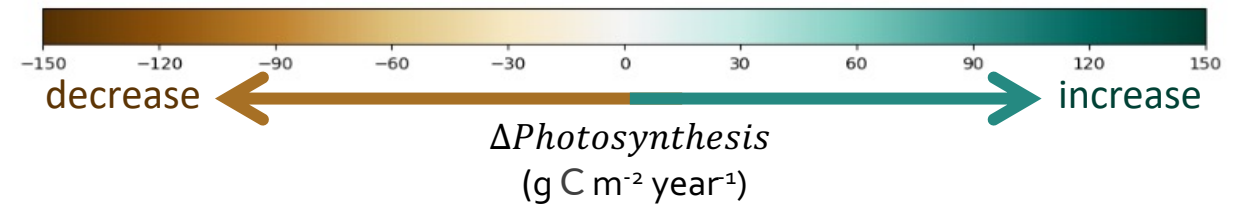
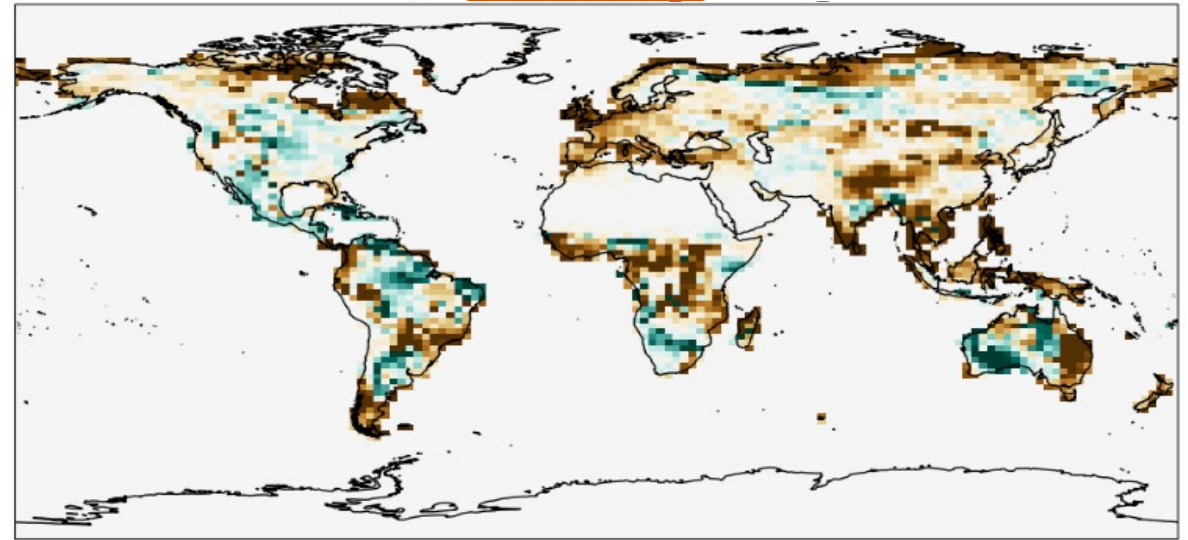


Photosynthetic response to $iWUE$ perturbations at $+CO_2$ are generally as expected

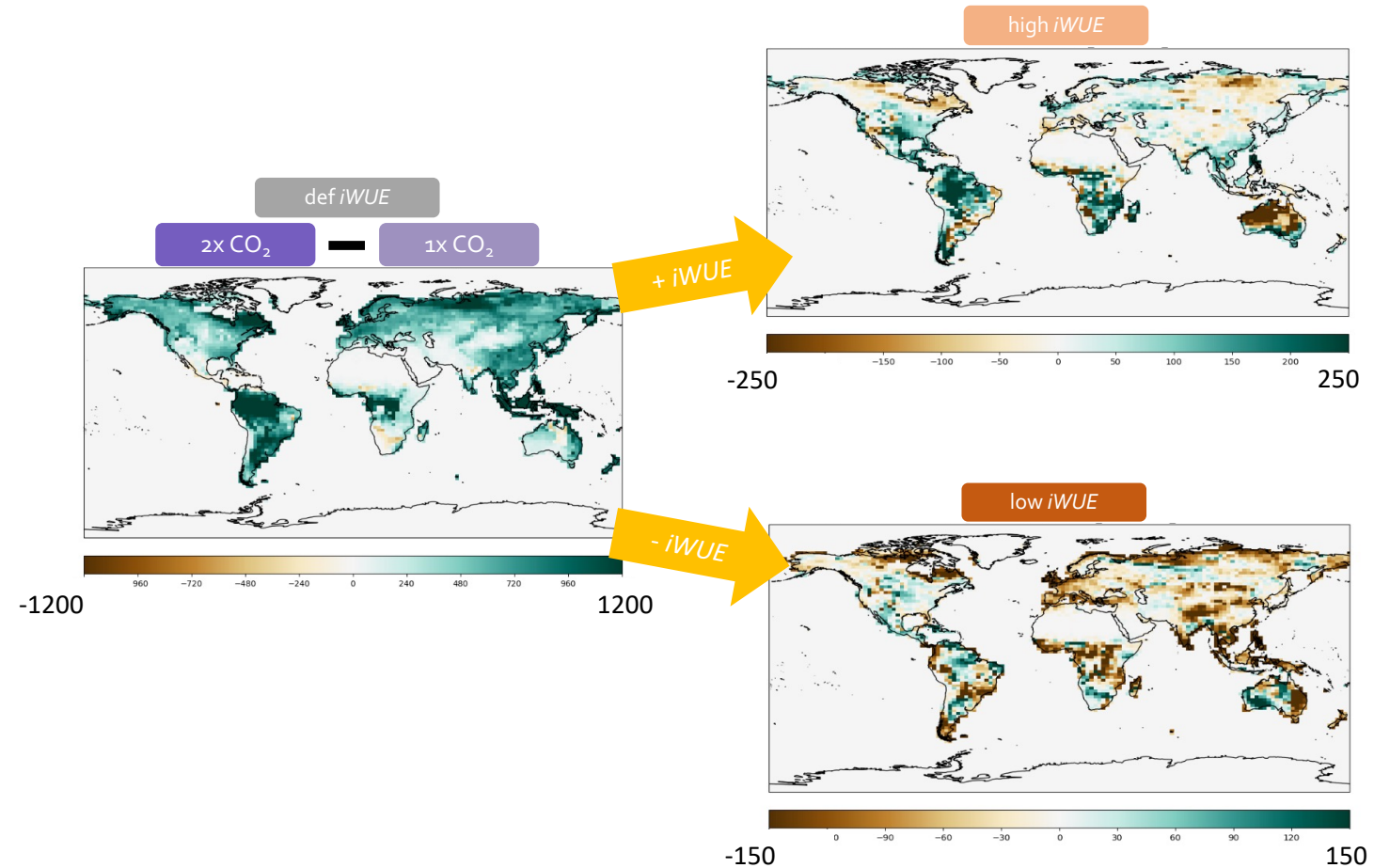
High $iWUE$



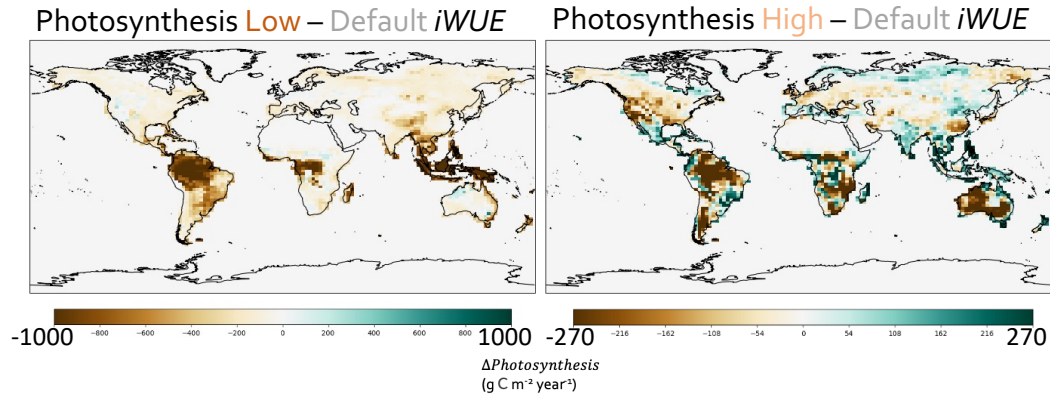
Low $iWUE$



Takehome #4:
iWUE perturbation
changes the
photosynthetic
response to $+CO_2$

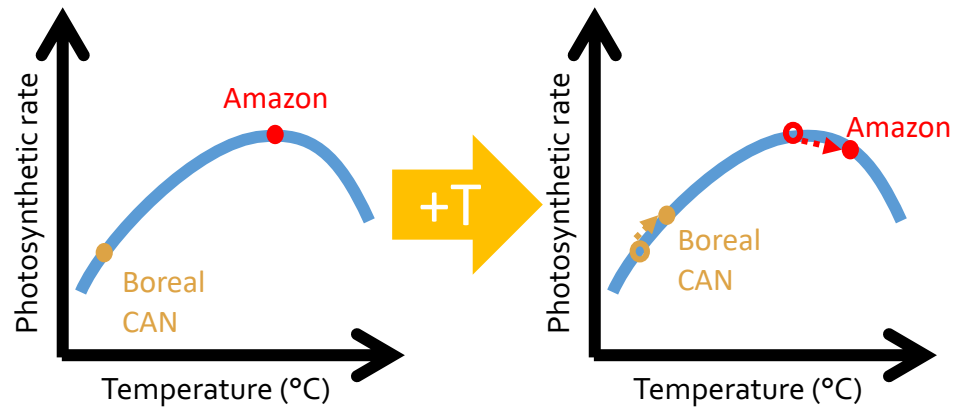


Takehome #1:



↓ *iWUE* → ↓ *photosynthesis*
 ↑ *iWUE* → *regional response*

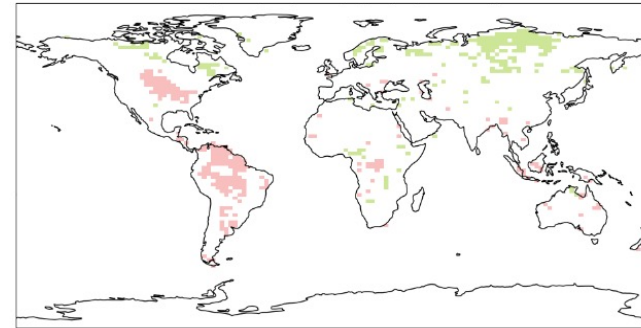
Takehome #3:



Photosynthetic response to +T depends on background climate

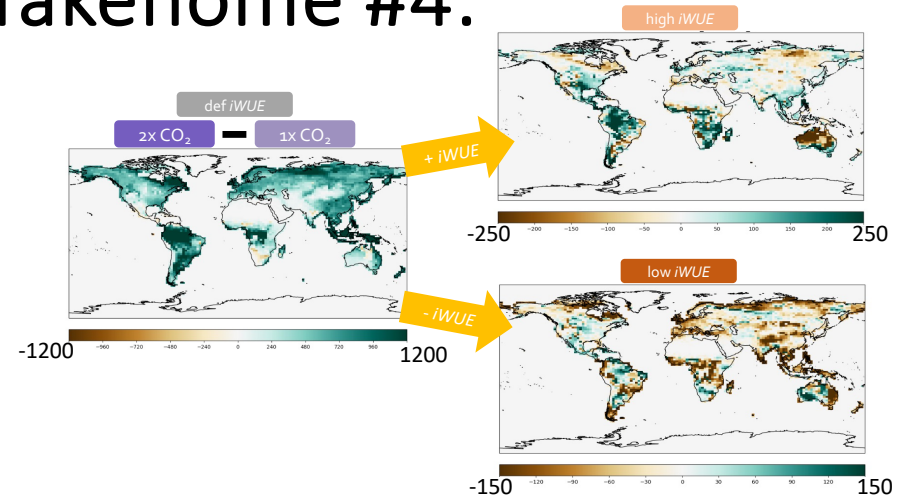
Takehome #2:

Photosynthesis Sign Change Map between Static and Atm+Leaf for High - Default *iWUE*



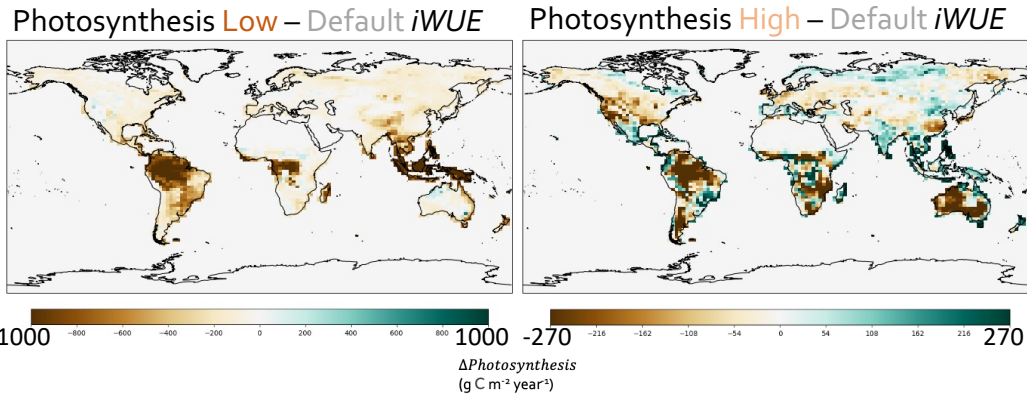
Coupled atmosphere enables ↑ *T*

Takehome #4:



+/- iWUE changes the photosynthetic response to +CO₂

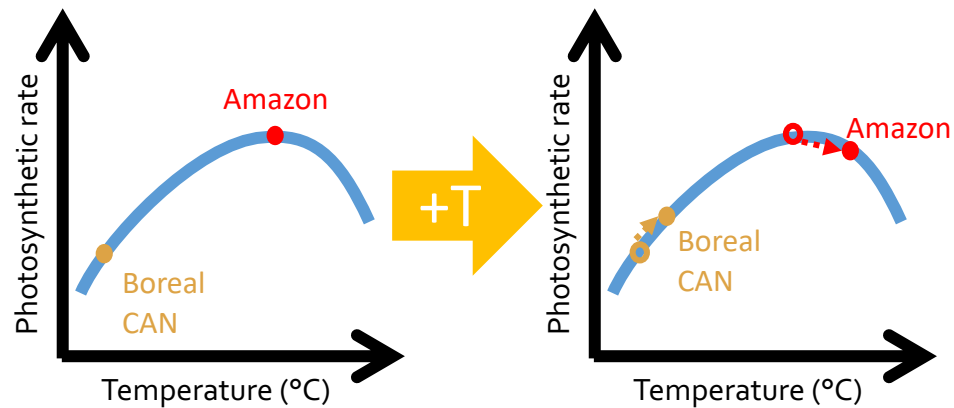
Takehome #1:



↓ *iWUE* → ↓ *photosynthesis*
 ↑ *iWUE* → regional response

What does this mean for hydrological cycling and how does it impact events like floods and droughts?

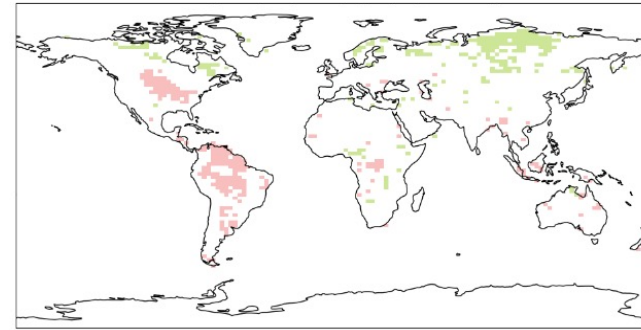
Takehome #3:



Photosynthetic response to +T depends on background climate

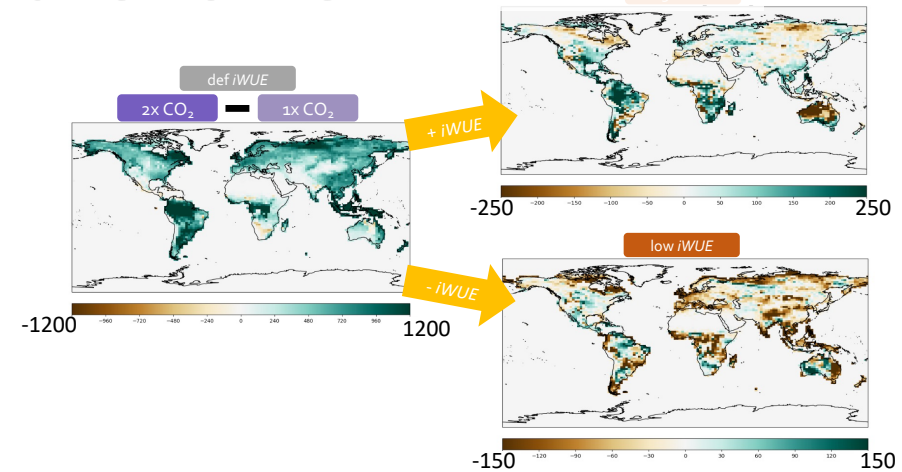
Takehome #2:

Photosynthesis Sign Change Map between Static and Atm+Leaf for High - Default *iWUE*



Coupled atmosphere enables ↑ *T*

Takehome #4:



+/- iWUE changes the photosynthetic response to +CO₂

Thank you

