Quantifying the Influence of Stomatal Behavior on Photosynthesis

CESM Workshop | June 14, 2023

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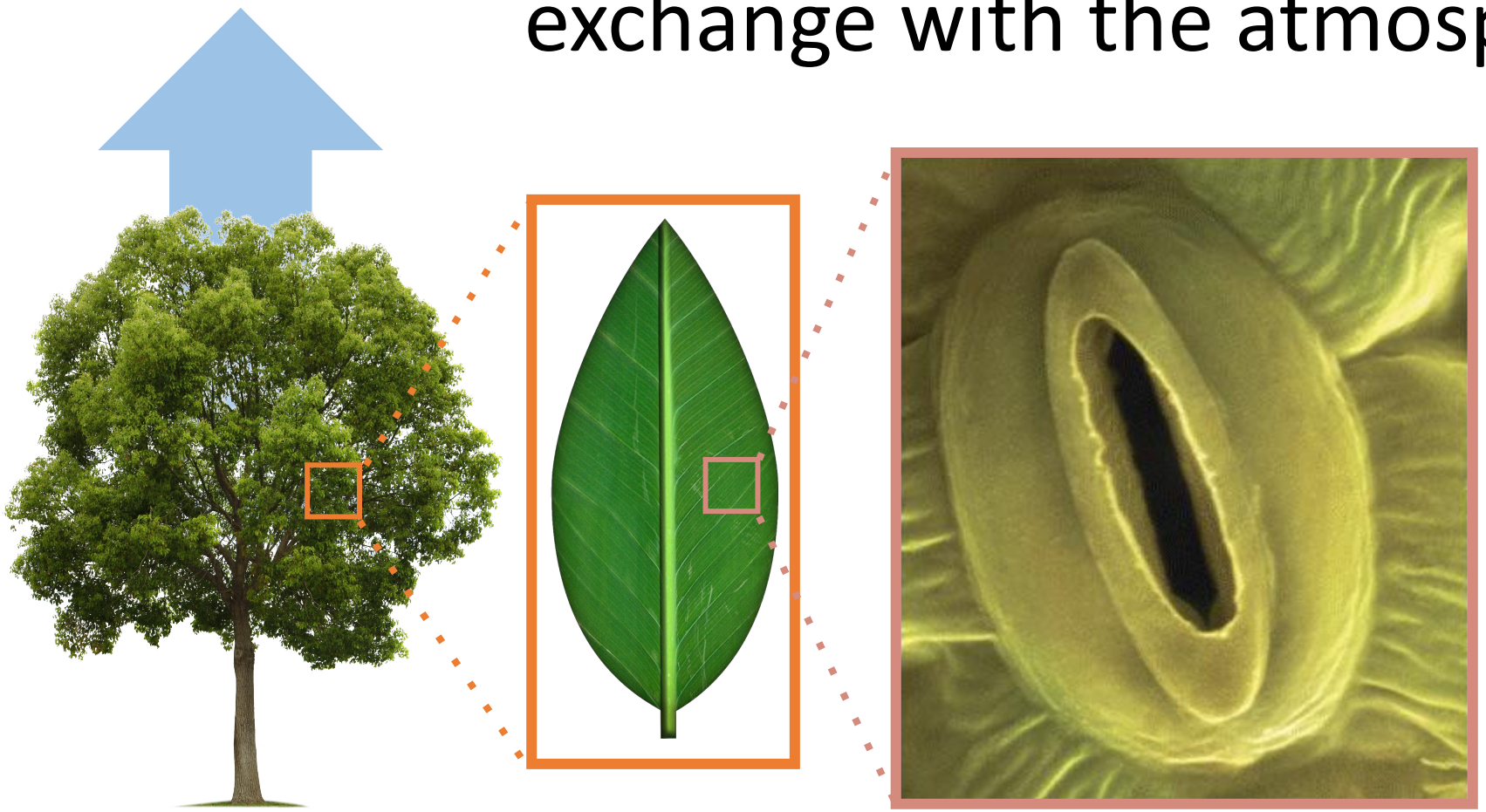
[1]UW; [2]UGA; [3]OSU; [4]CU; [5]NCAR; [6]UCI; [7]LBNL; [8]ORNL

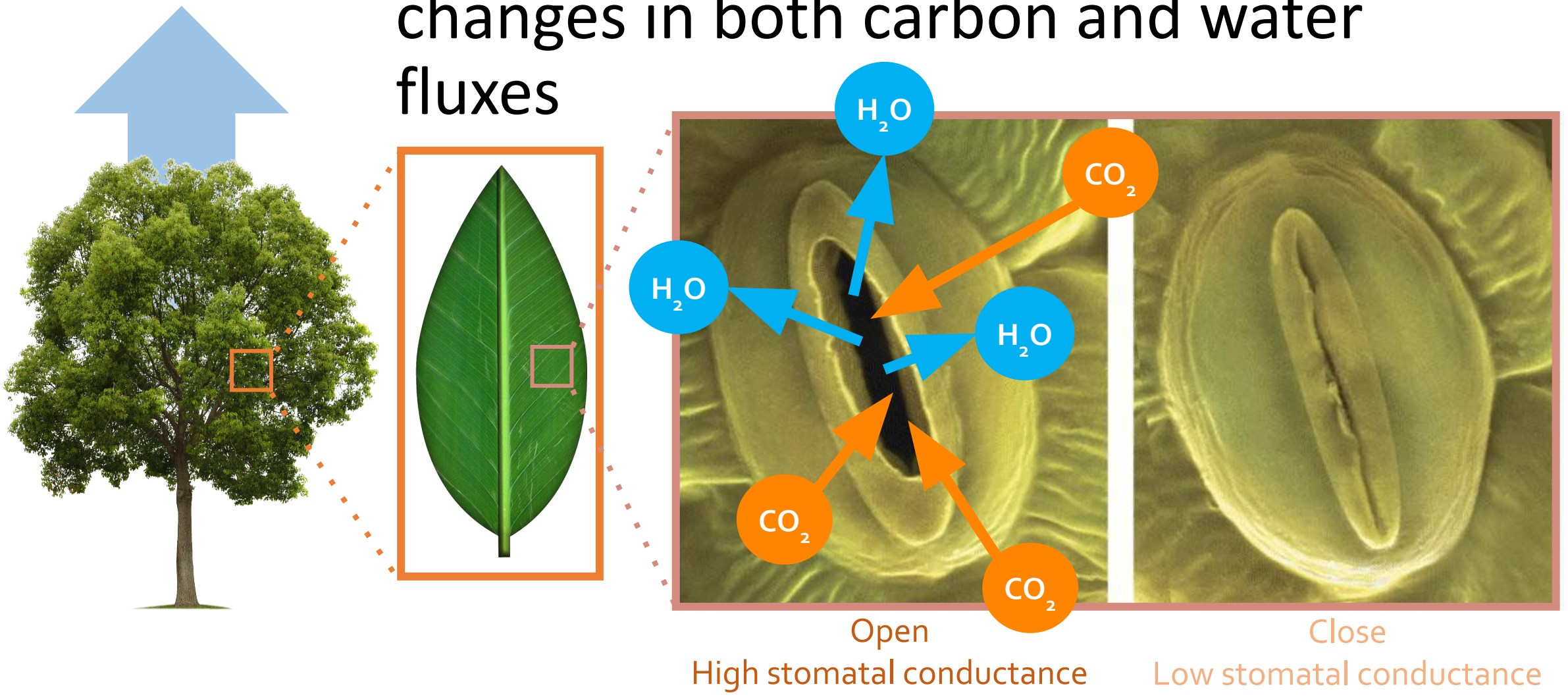
Funding from DOE and NSF

Plants have stomata that regulate gas exchange with the atmosphere



Tree → Leaf → Stomata

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



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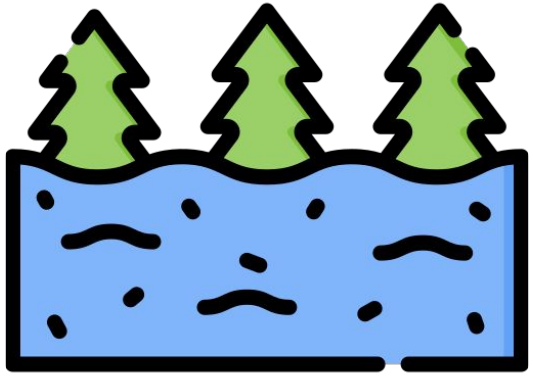
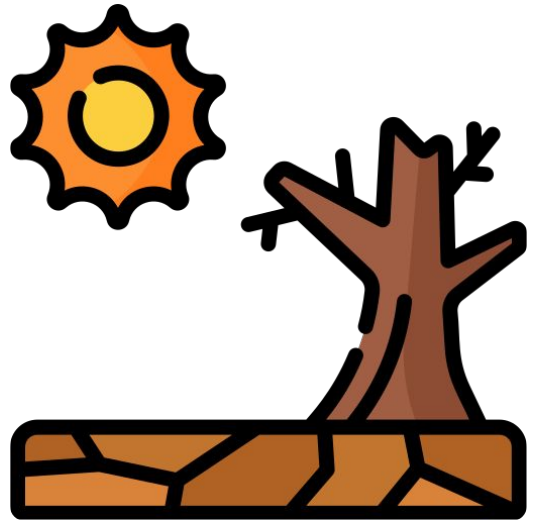
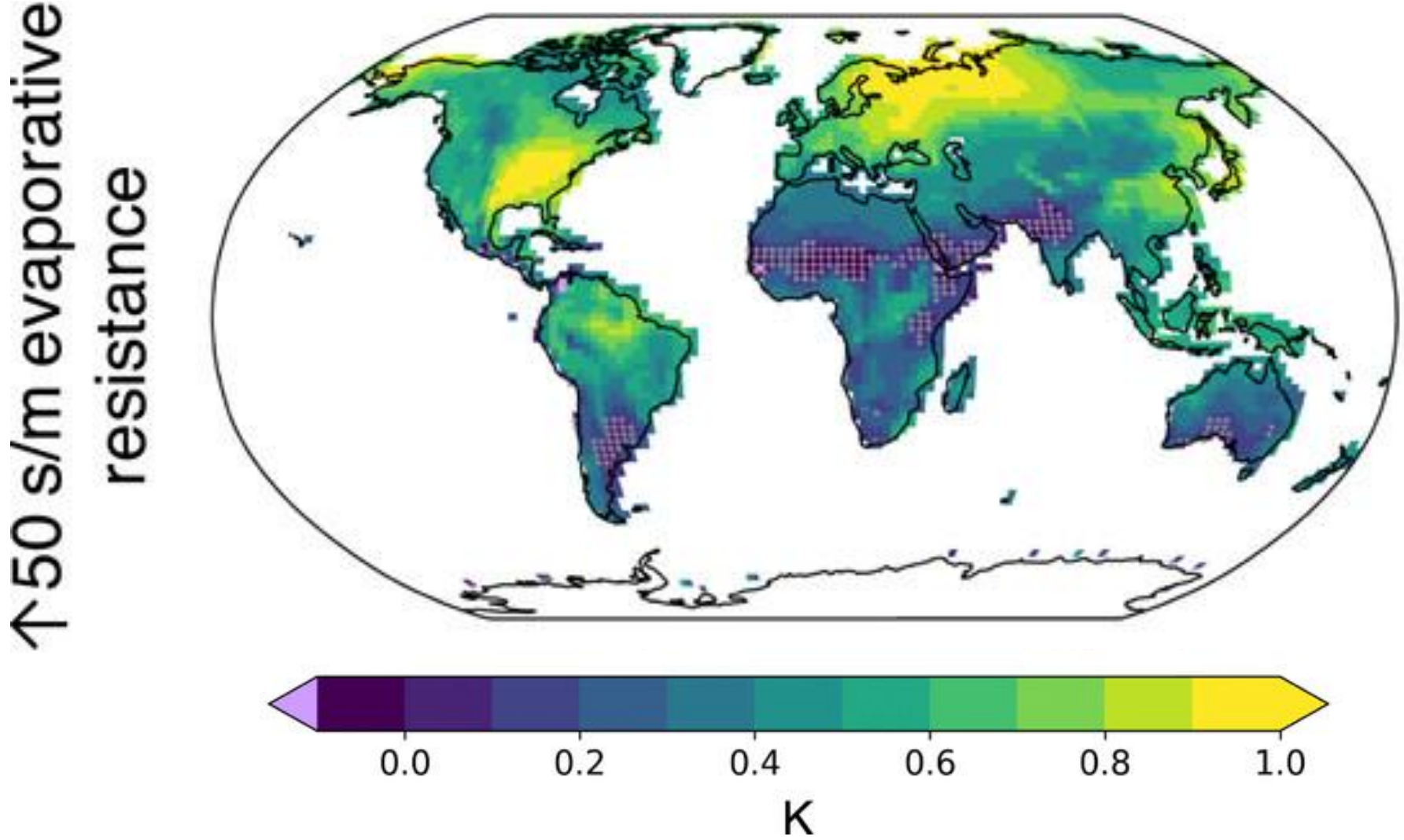




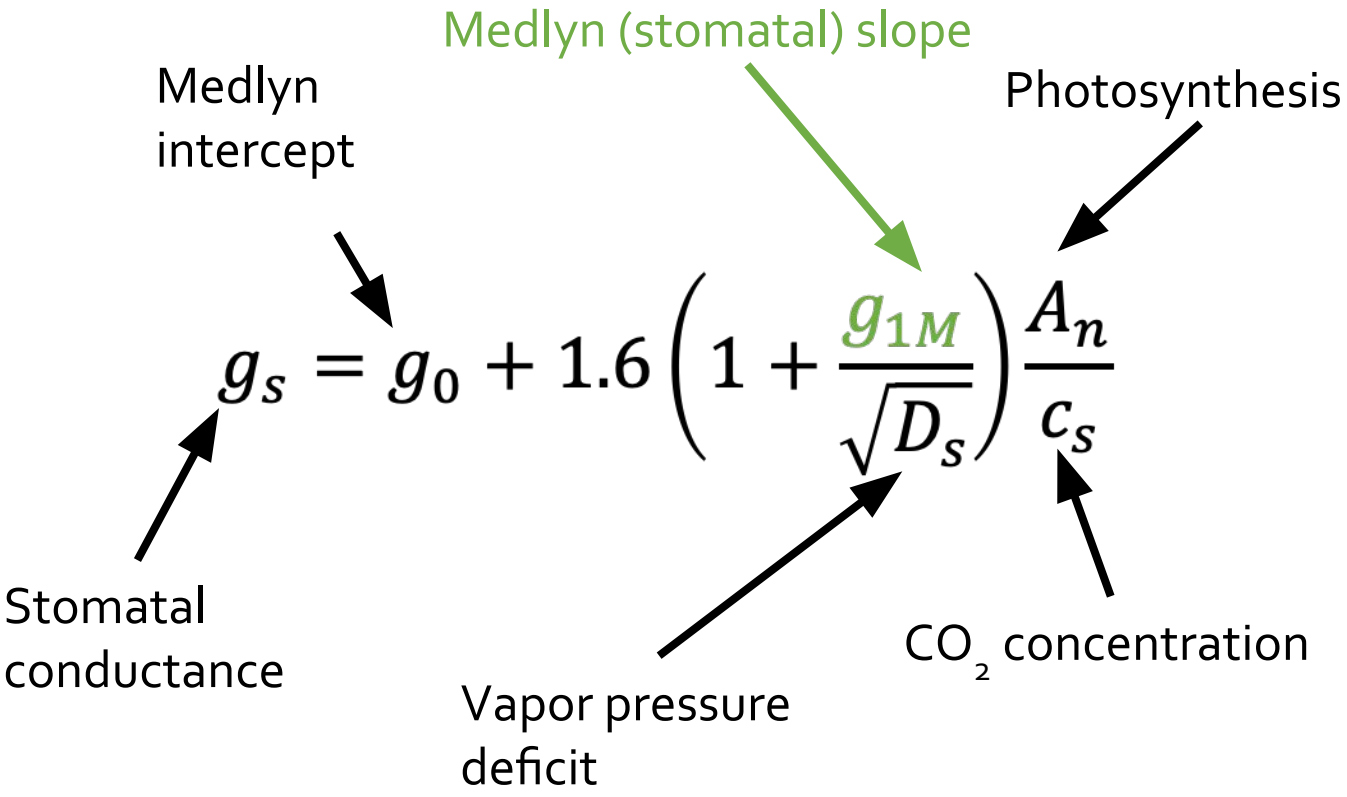
Changes in stomatal conductance drive changes in carbon and water fluxes, which impact the carbon and water cycle, affecting water availability and the risk of extreme climate events like droughts, heatwaves, and floods.

Changes in evaporative resistance affects surface temperature



Laguë et al. 2019

The Medlyn model represents stomatal conductance in CLM



Medlyn et al. 2011

The Medlyn slope is a fitted parameter based on leaf-level observations

Medlyn (stomatal) slope

Medlyn intercept

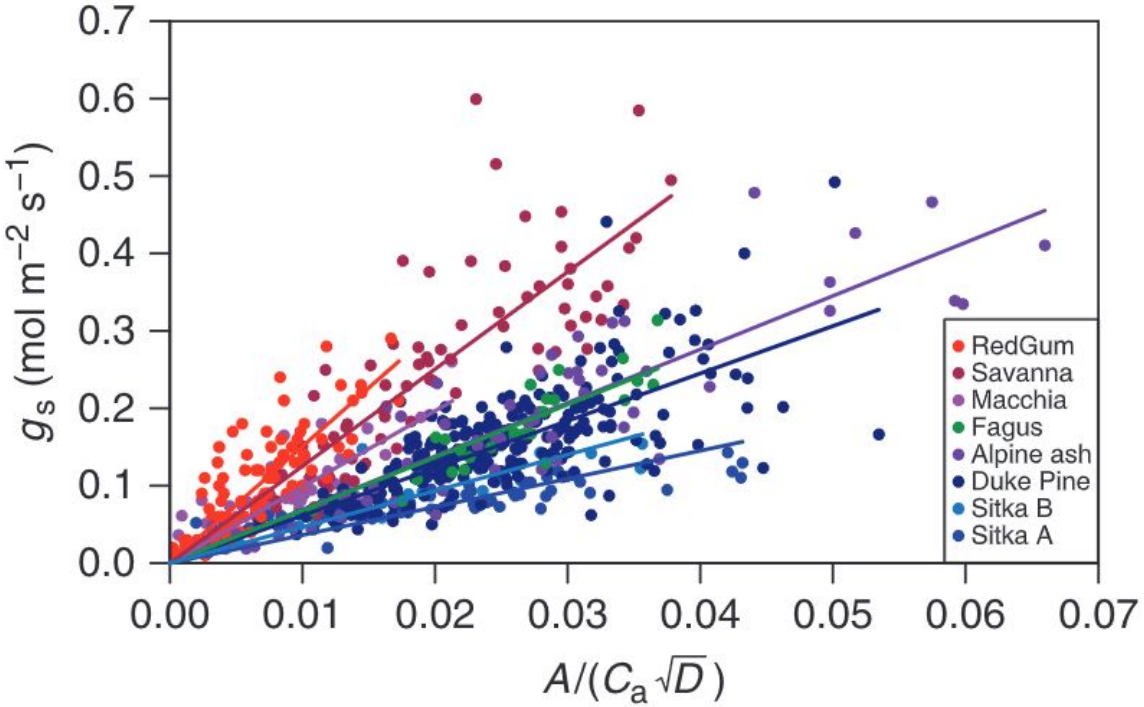
Photosynthesis

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

Stomatal conductance

Vapor pressure deficit

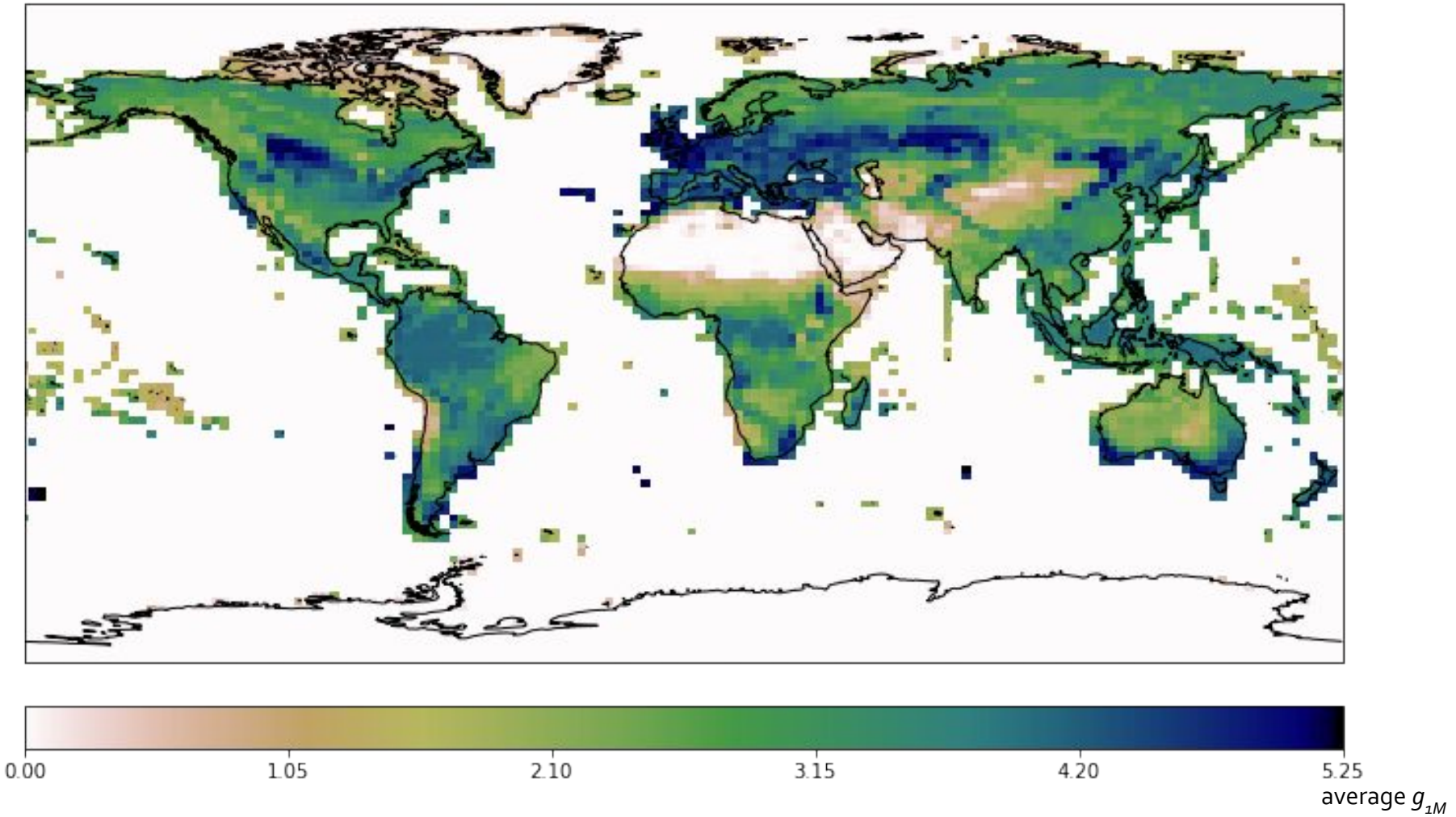
CO_2 concentration



Medlyn et al. 2011

g_{1M} has a varied spatial distribution

Spatial distribution of Default g_{1M} values



There is variability across + within plant types

Medlyn slope

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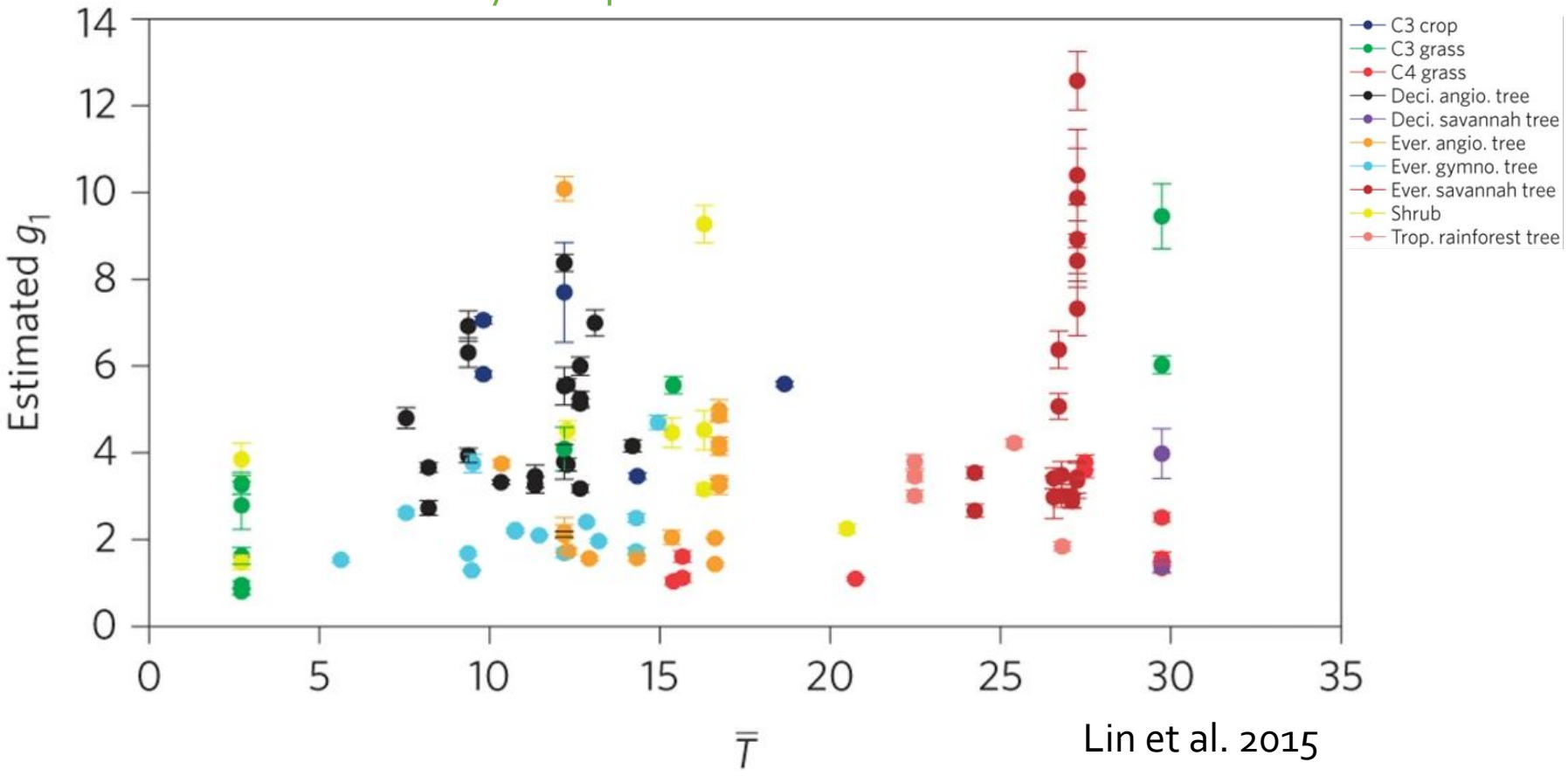
Estimated Medlyn Slope based on Field Observations



Lin et al. 2015

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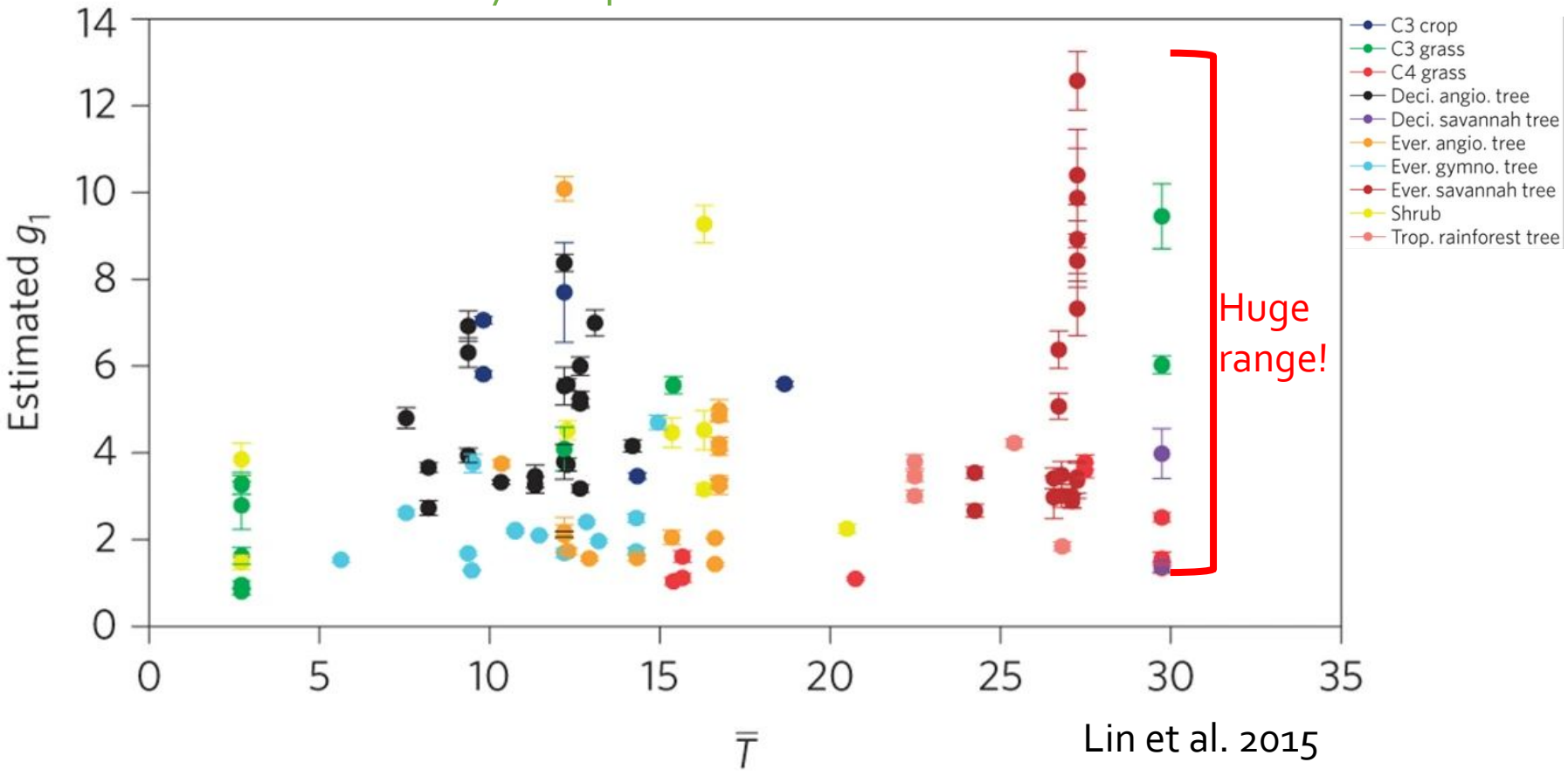

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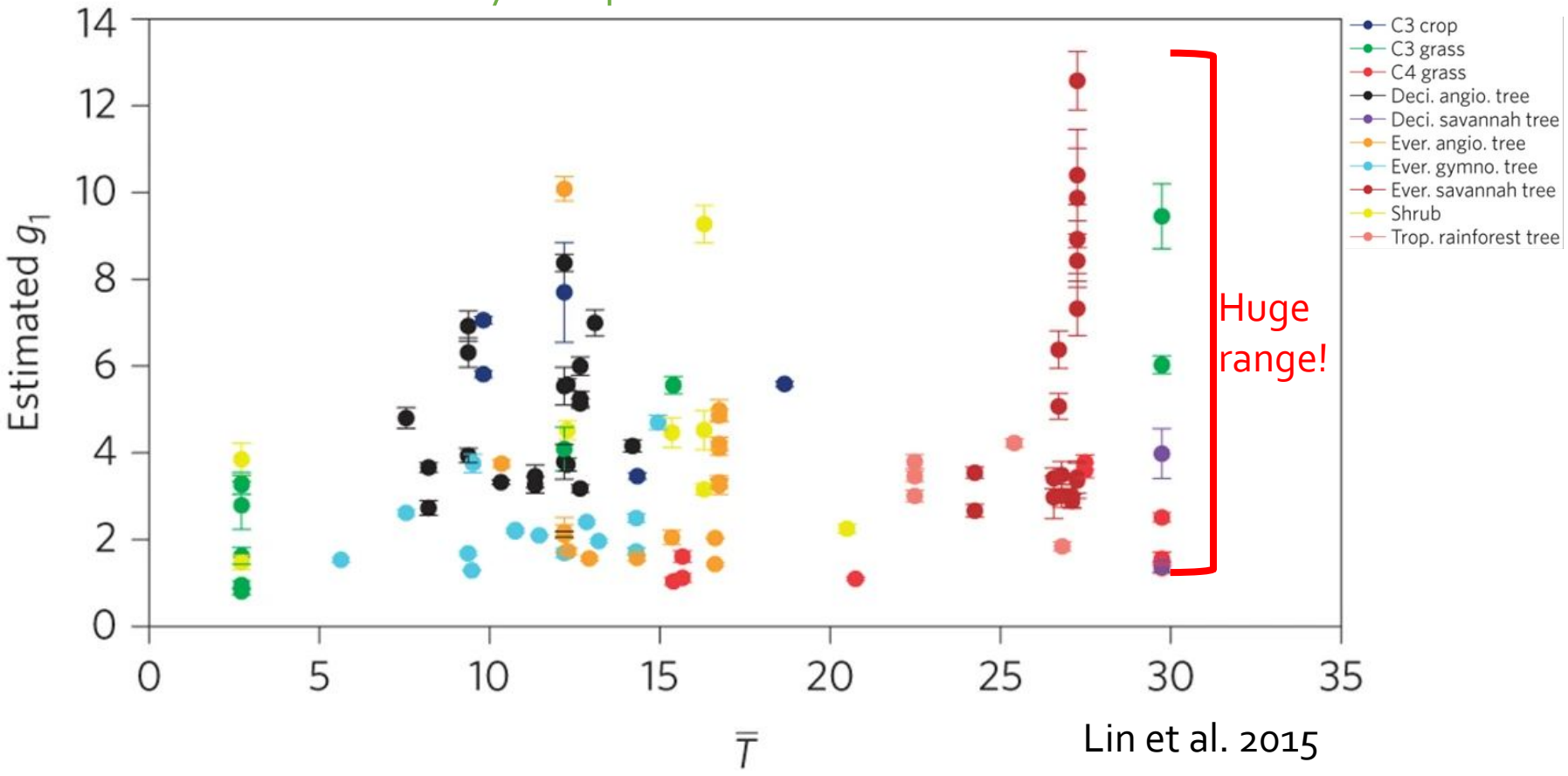

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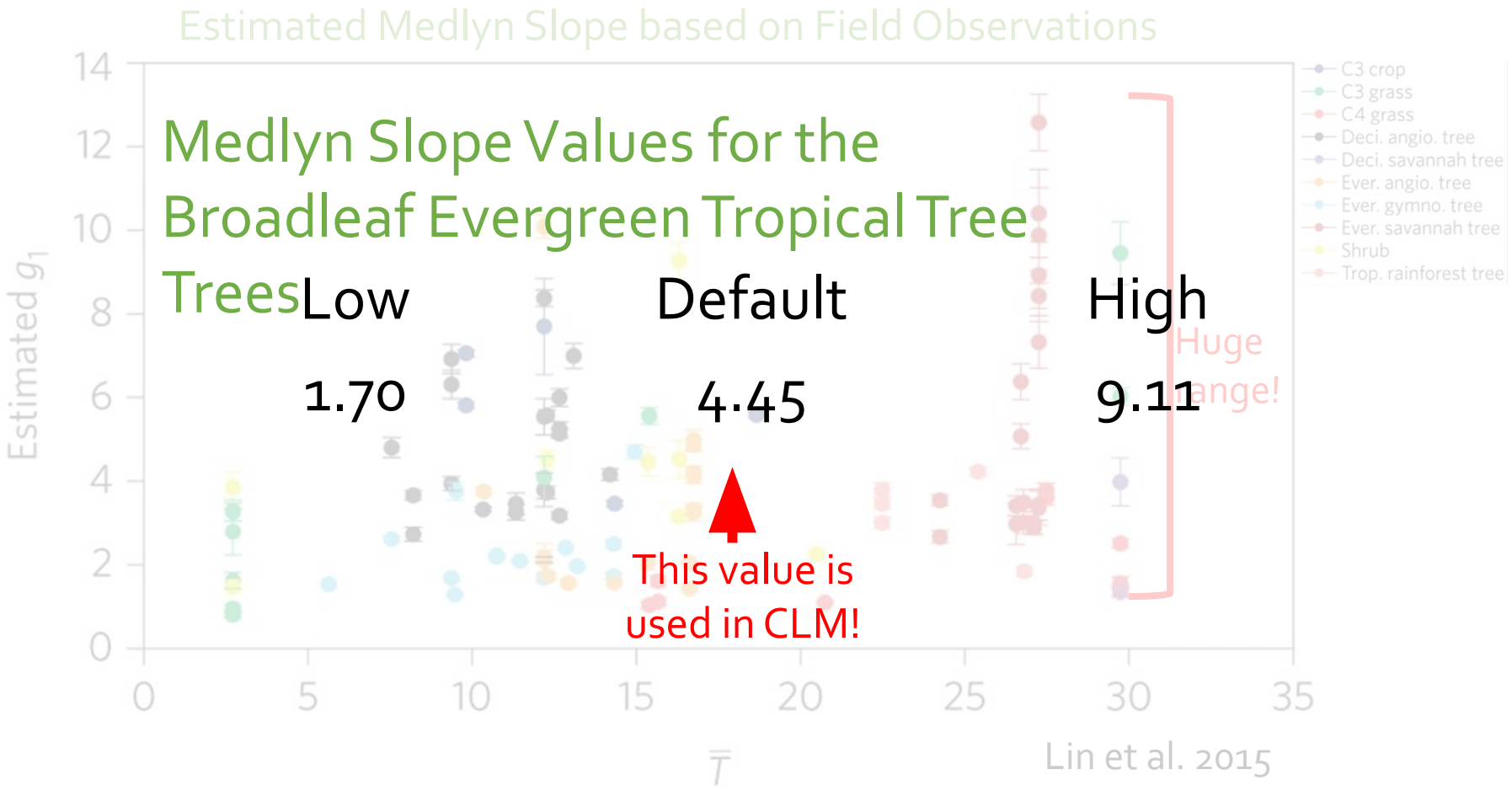
… can lead to large variance for carbon and water fluxes.

One Medlyn slope value is used to represent each plant type in CLM

Medlyn slope

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



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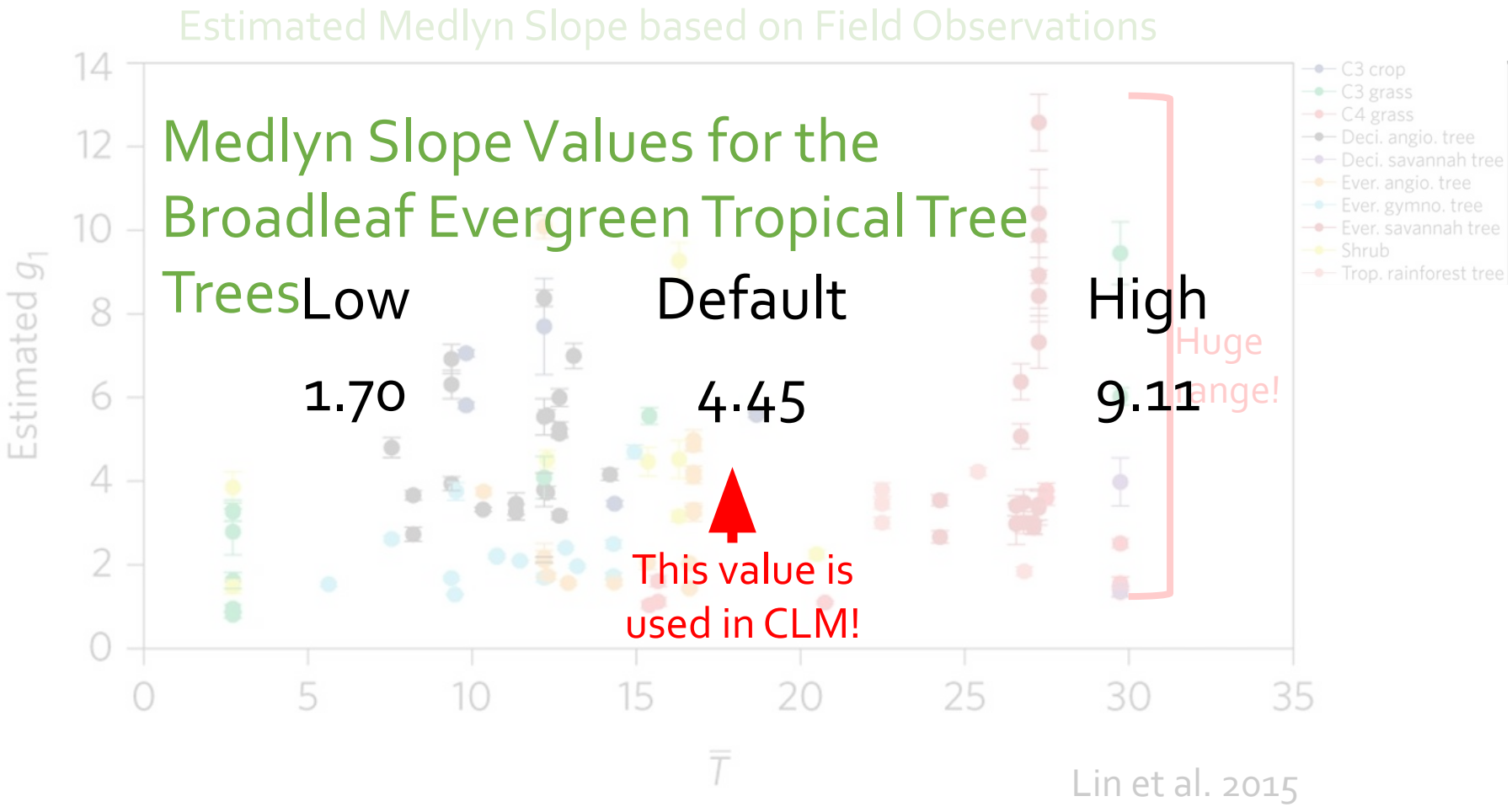
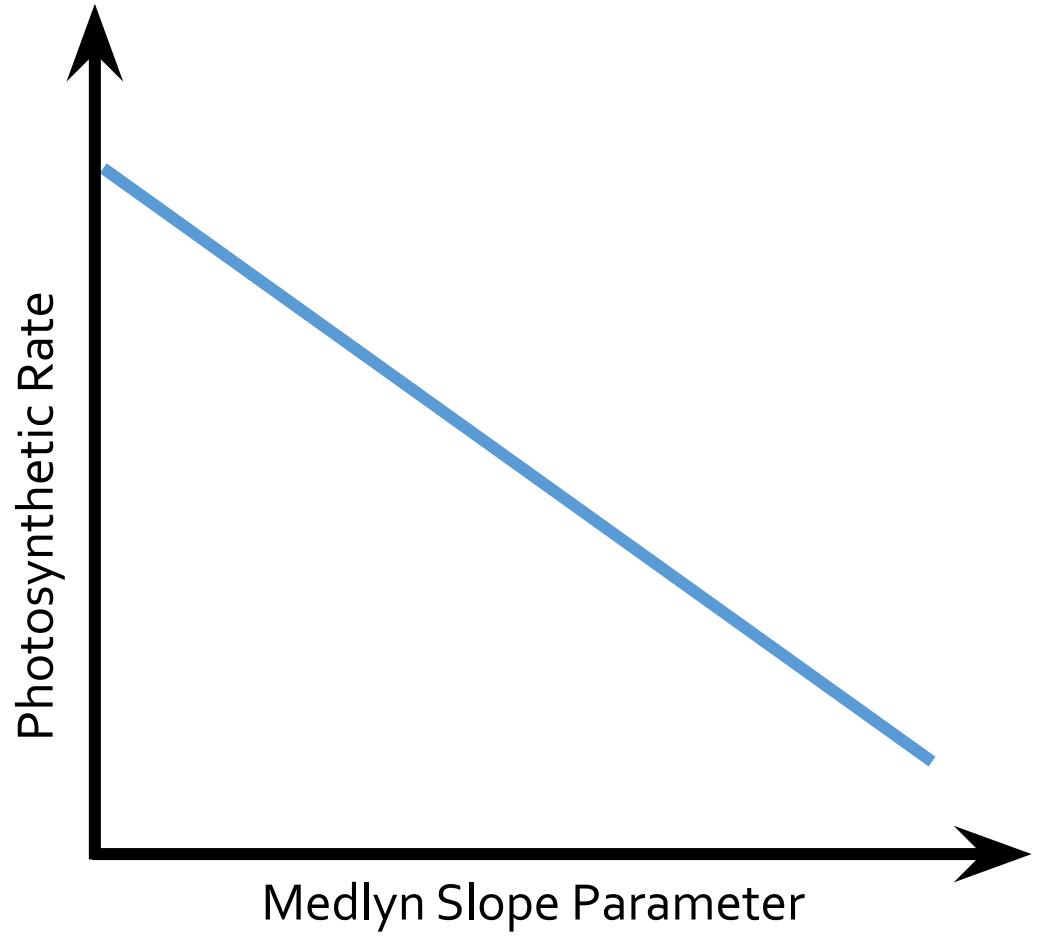


What happens if we use a different Medlyn slope value?

Focusing on the Medlyn slope parameter (g_{1M})



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

$$WUE = \frac{A_n}{Transpiration} \propto \frac{A_n}{\sqrt{D_s}}$$

$$g_{1M} \propto \frac{1}{A_n} \propto \frac{1}{WUE}$$

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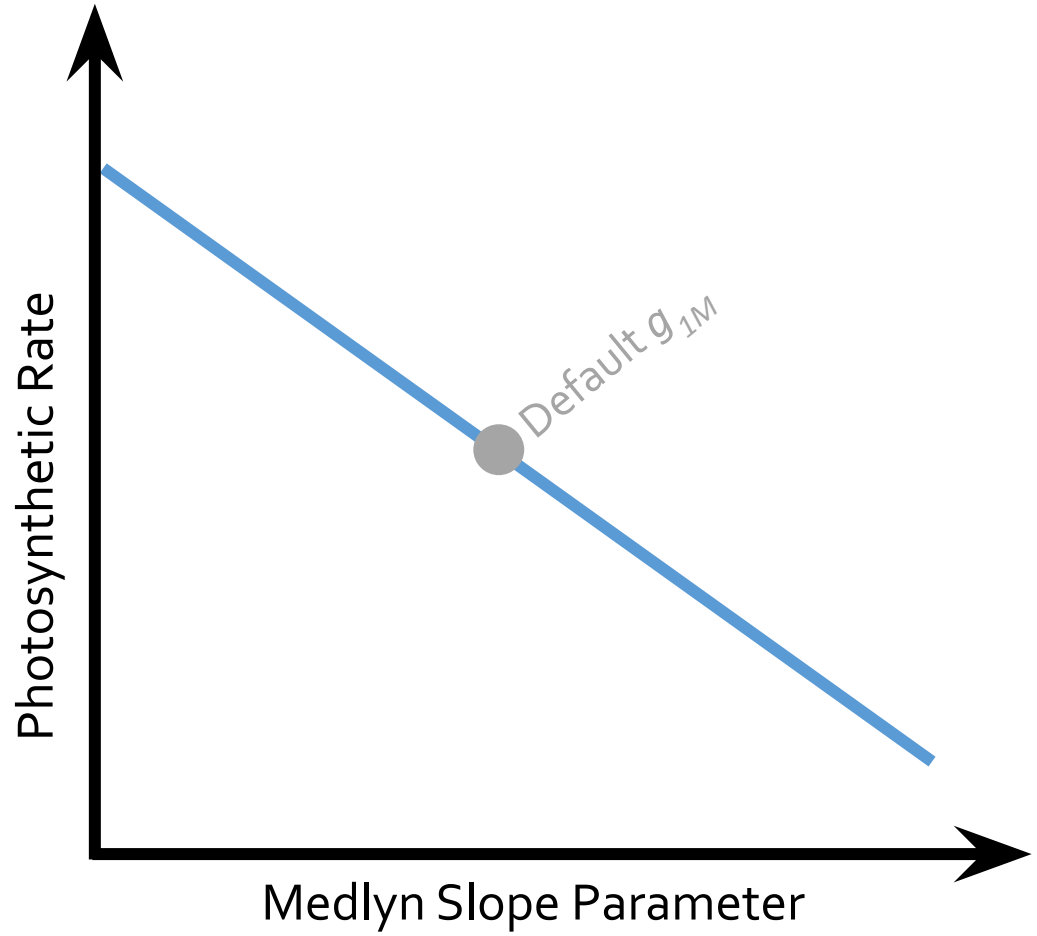

We vary this

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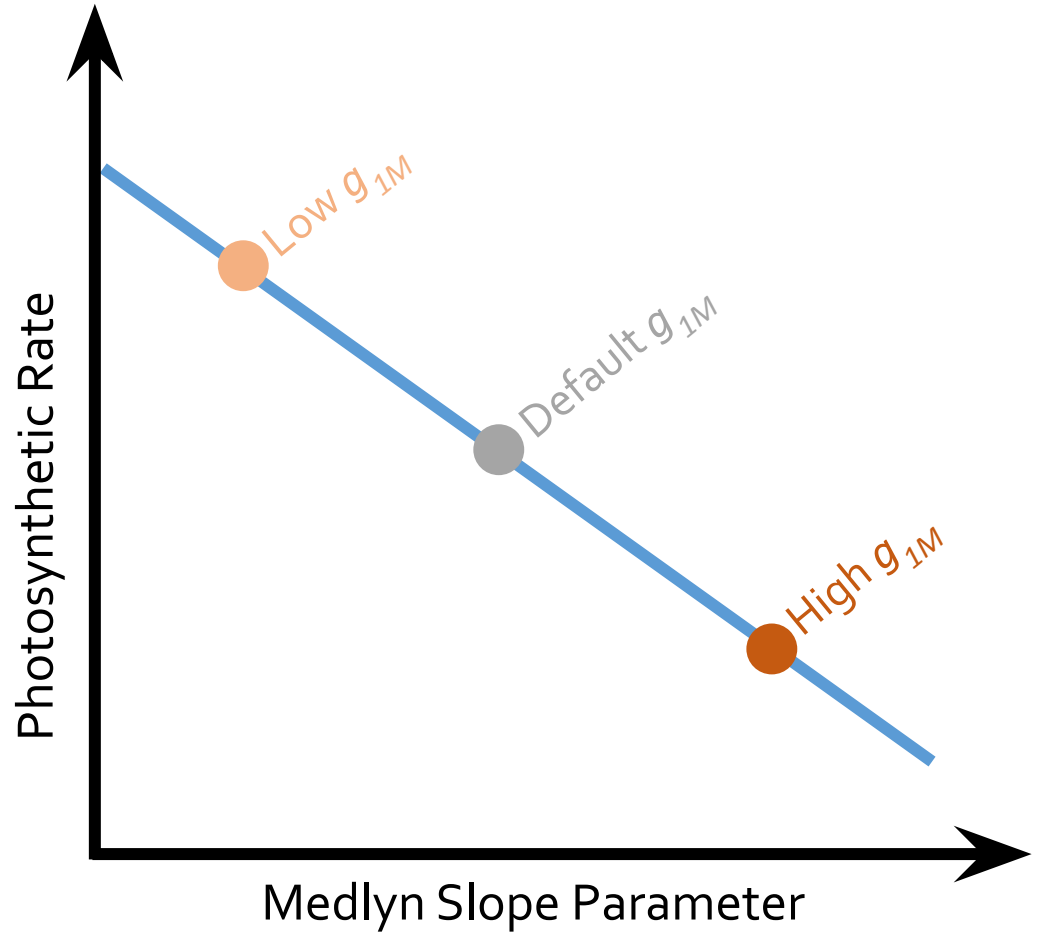

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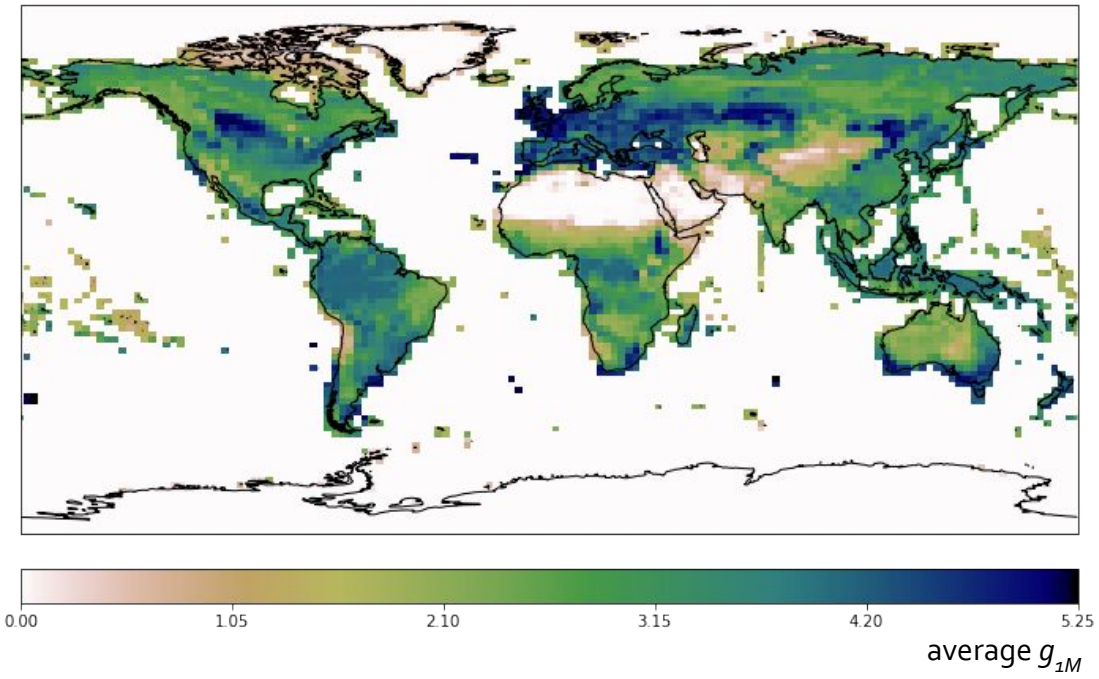
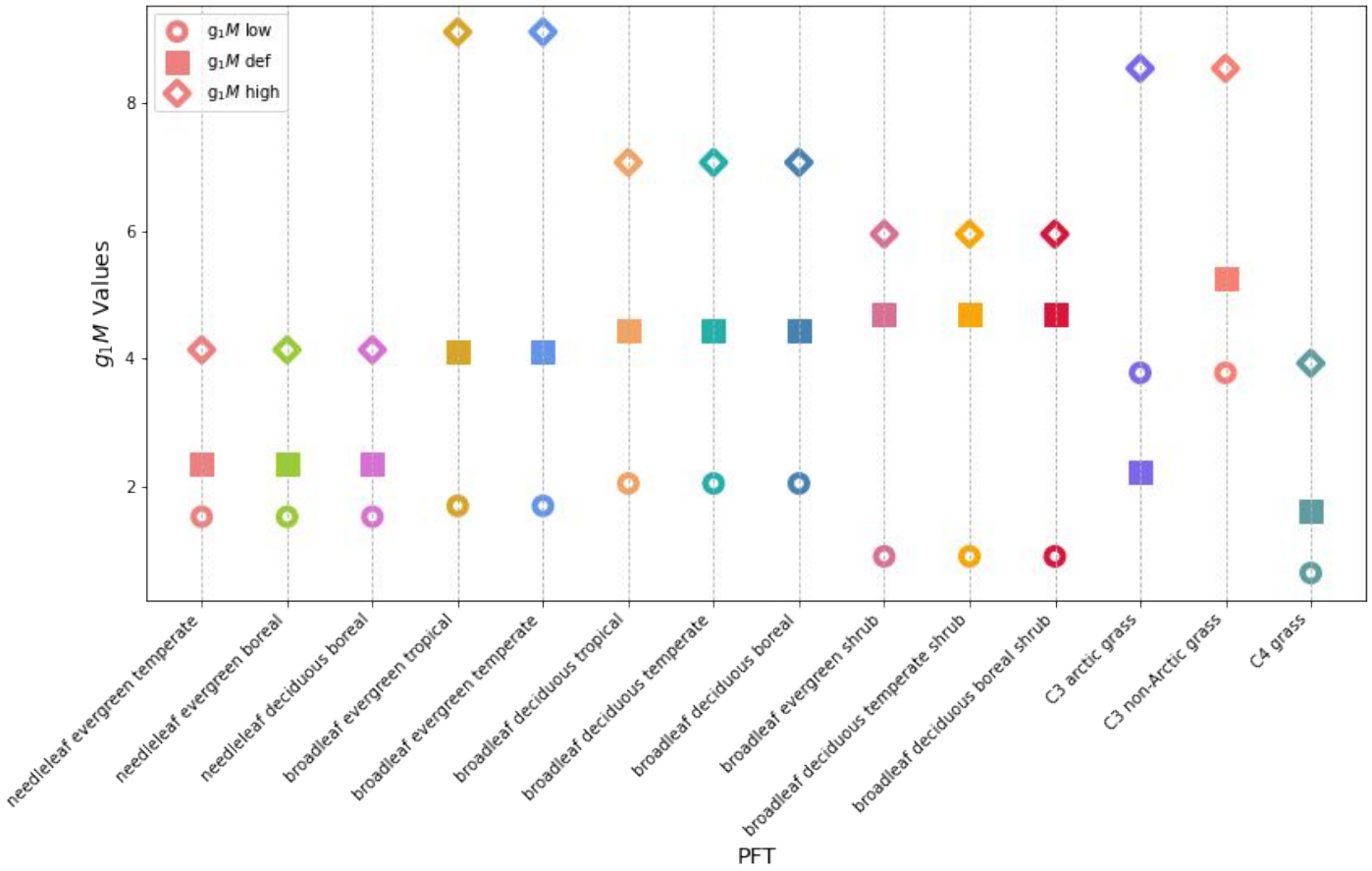
Spatial distribution of Default g_{1M} values



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

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



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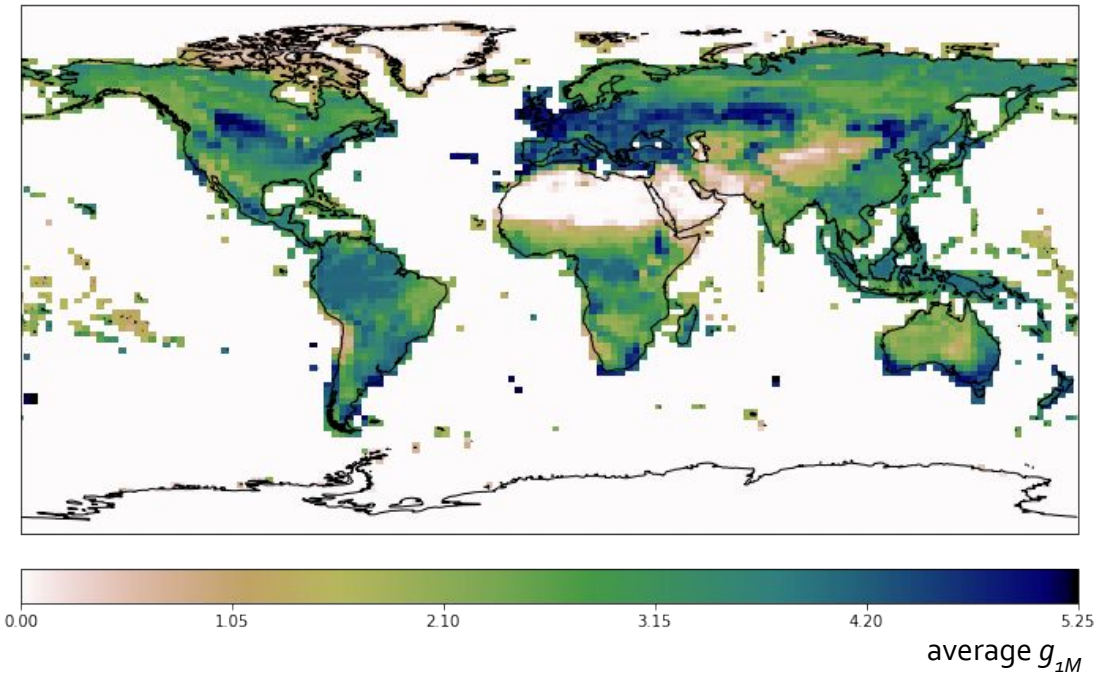
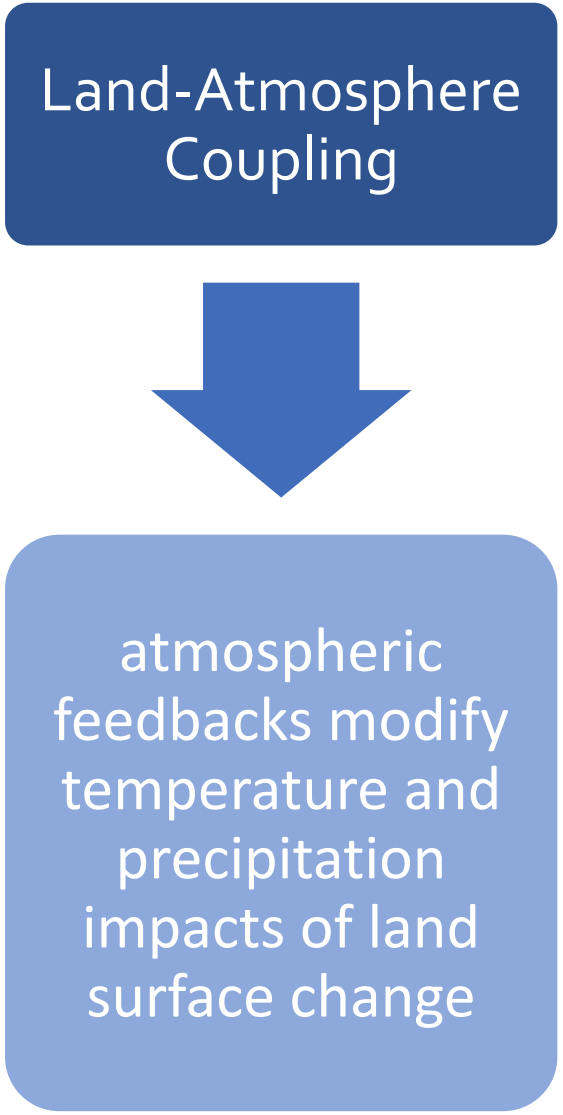


Multiple factors can affect stomatal conductance



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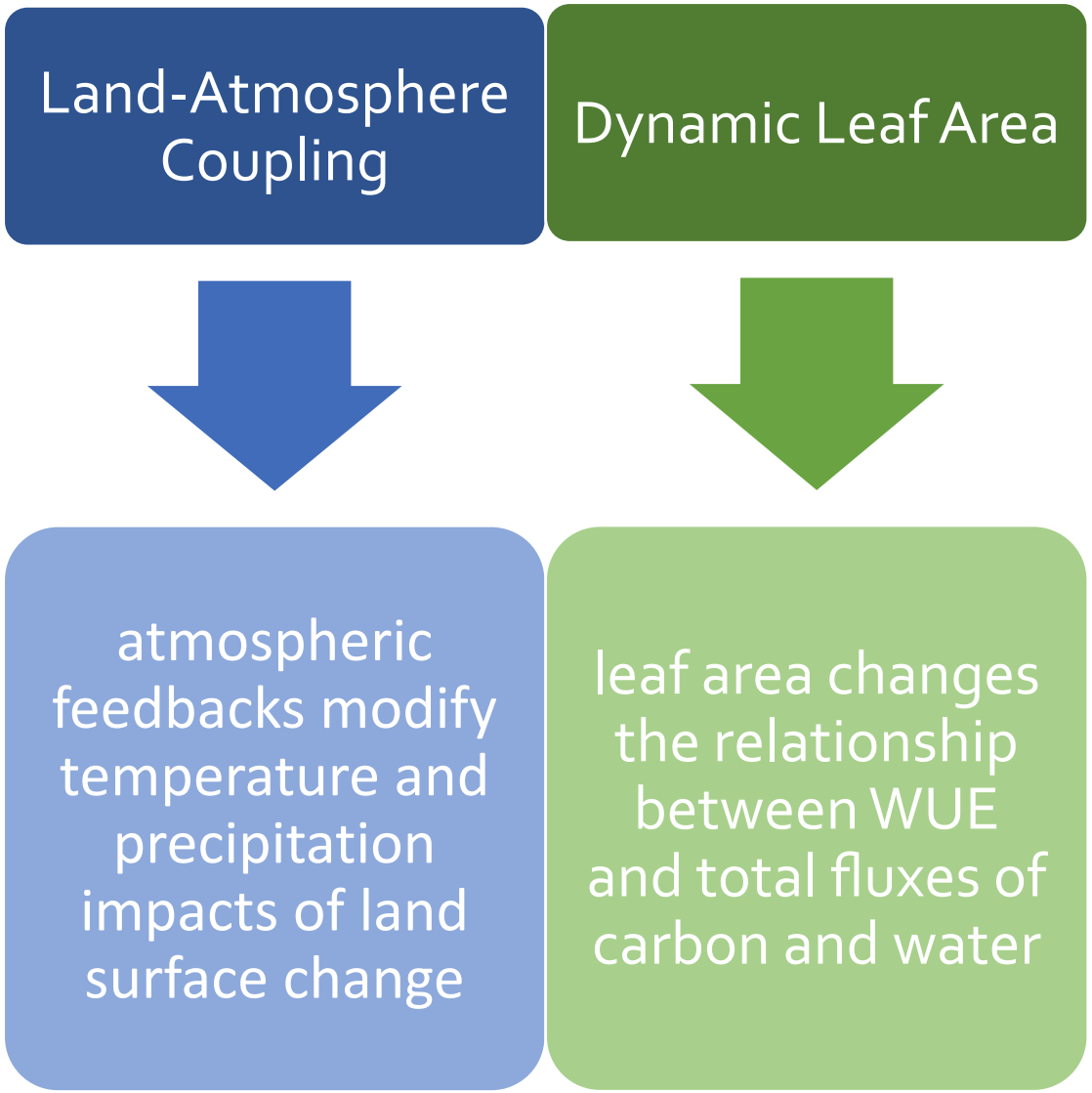

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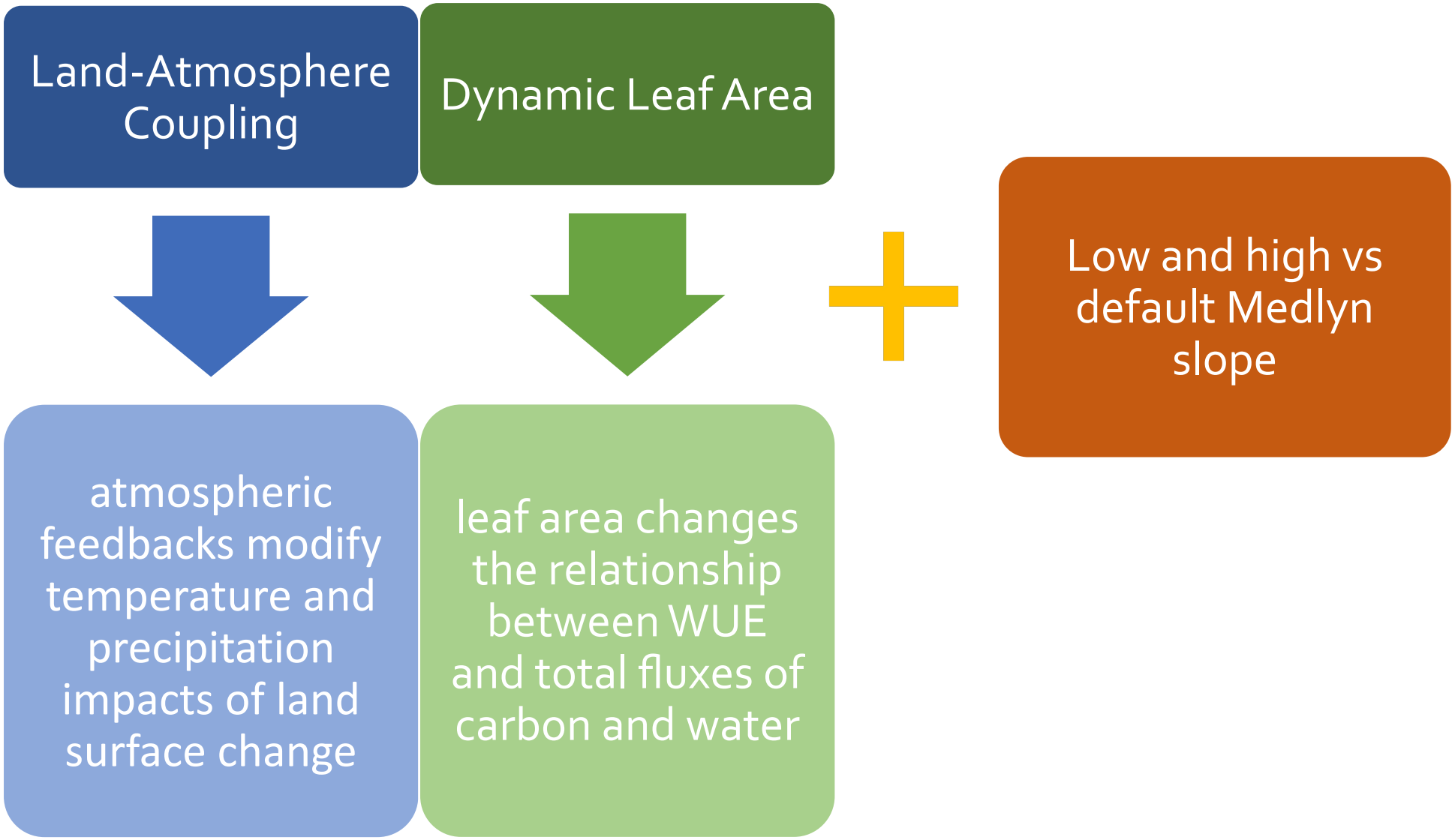
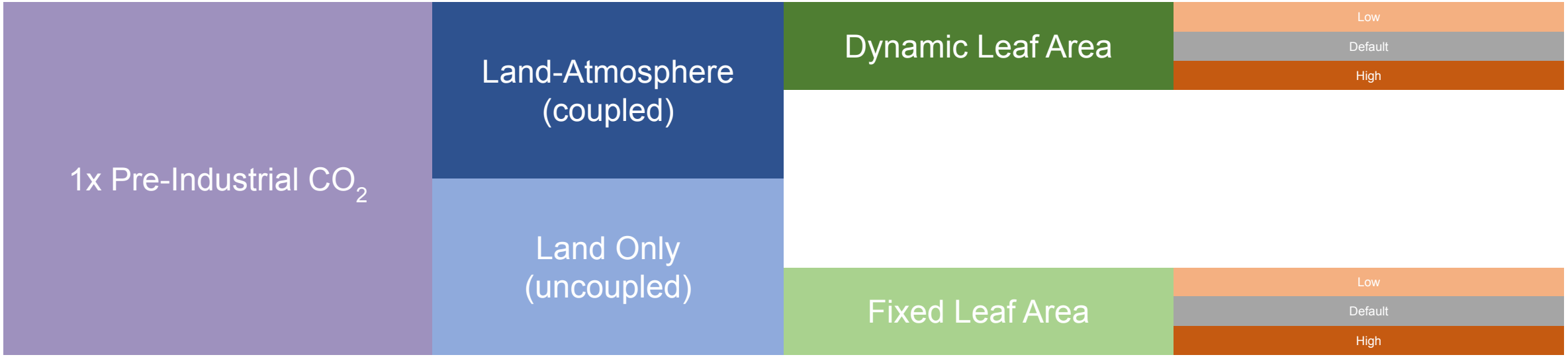


Comparing two configurations



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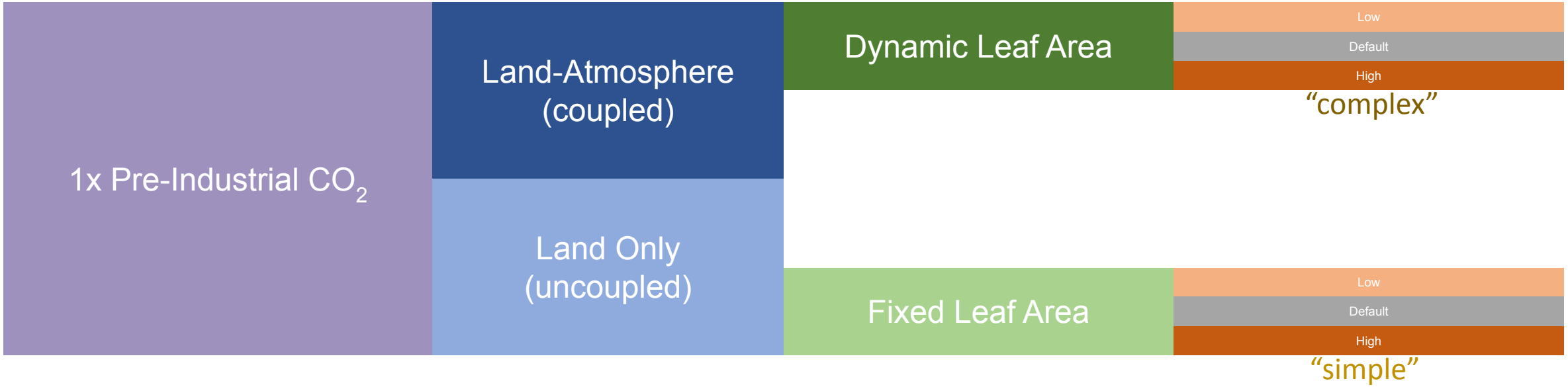
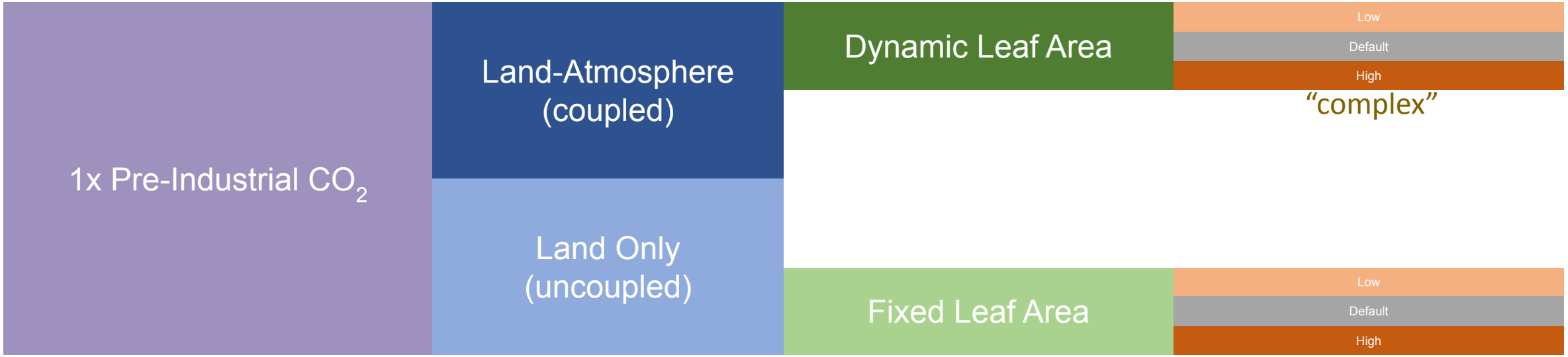


Summary of runs (mostly not discussed today)

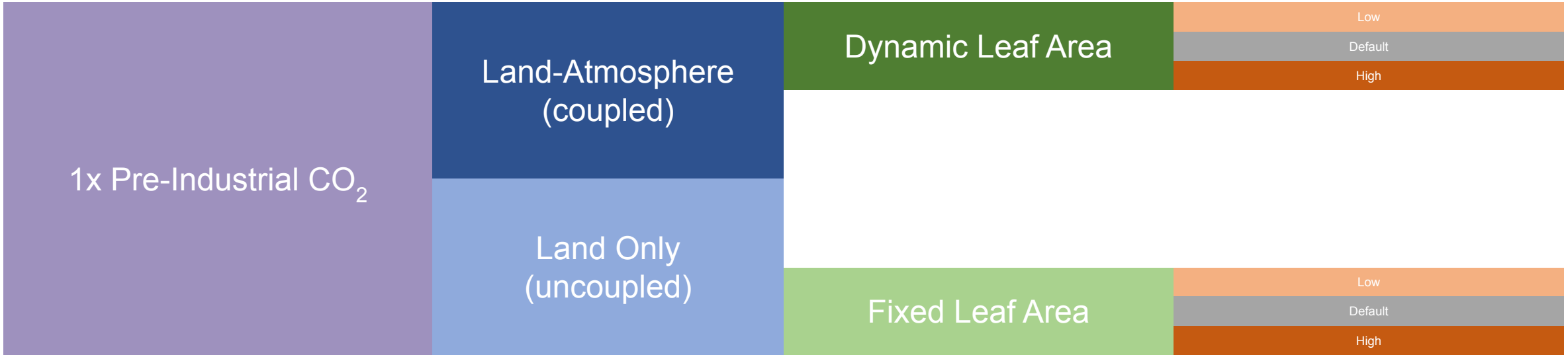
1x Pre-Industrial CO_2	Land-Atmosphere (coupled)	Dynamic Leaf Area	Low
			Default
			High
		Fixed Leaf Area	Low
			Default
			High
	Land Only (uncoupled)	Dynamic Leaf Area	Low
			Default
			High
		Fixed Leaf Area	Low
			Default
			High
2x Pre-Industrial CO_2	Land-Atmosphere (coupled)	Dynamic Leaf Area	Low
			Default
			High
		Fixed Leaf Area	Low
			Default
			High
	Land Only (uncoupled)	Dynamic Leaf Area	Low
			Default
			High
		Fixed Leaf Area	Low
			Default
			High

Comparing two configurations



simple high g_{1m} — simple default g_{1m}

Comparing two configurations



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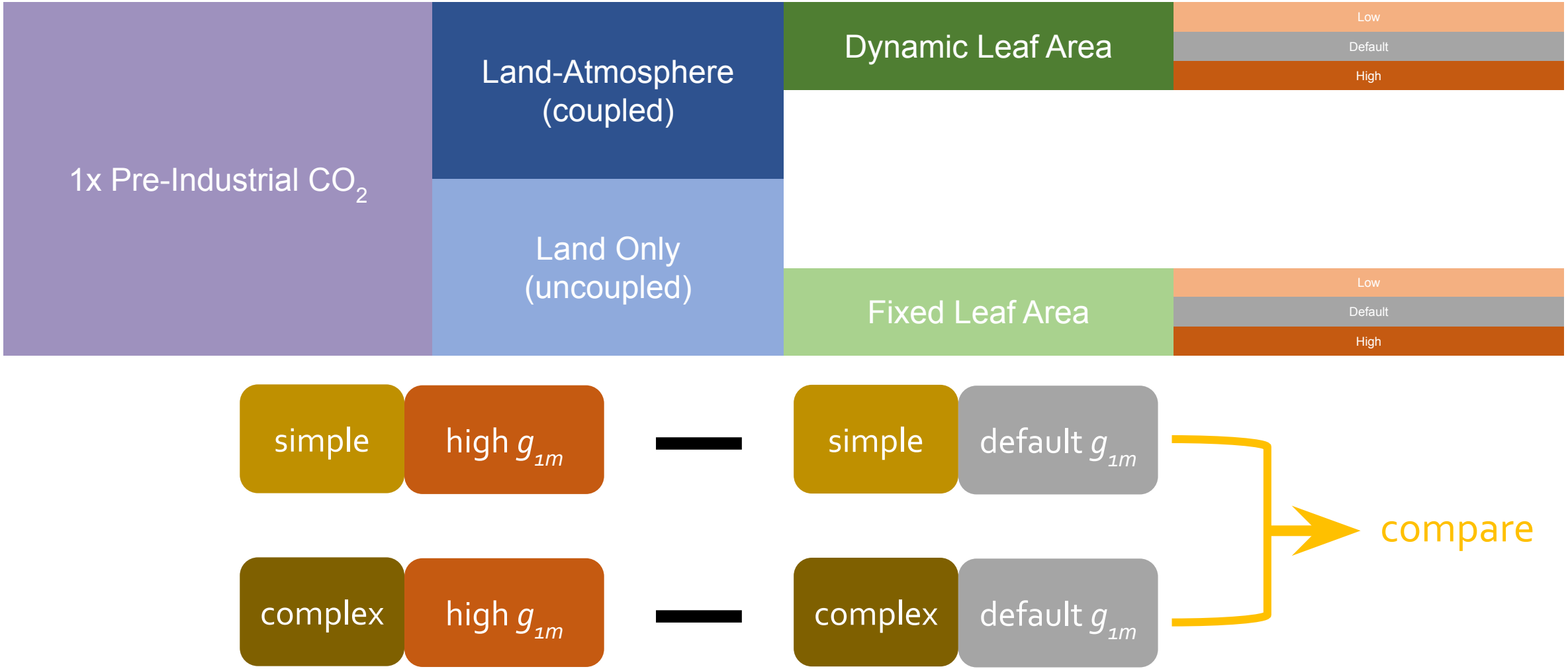
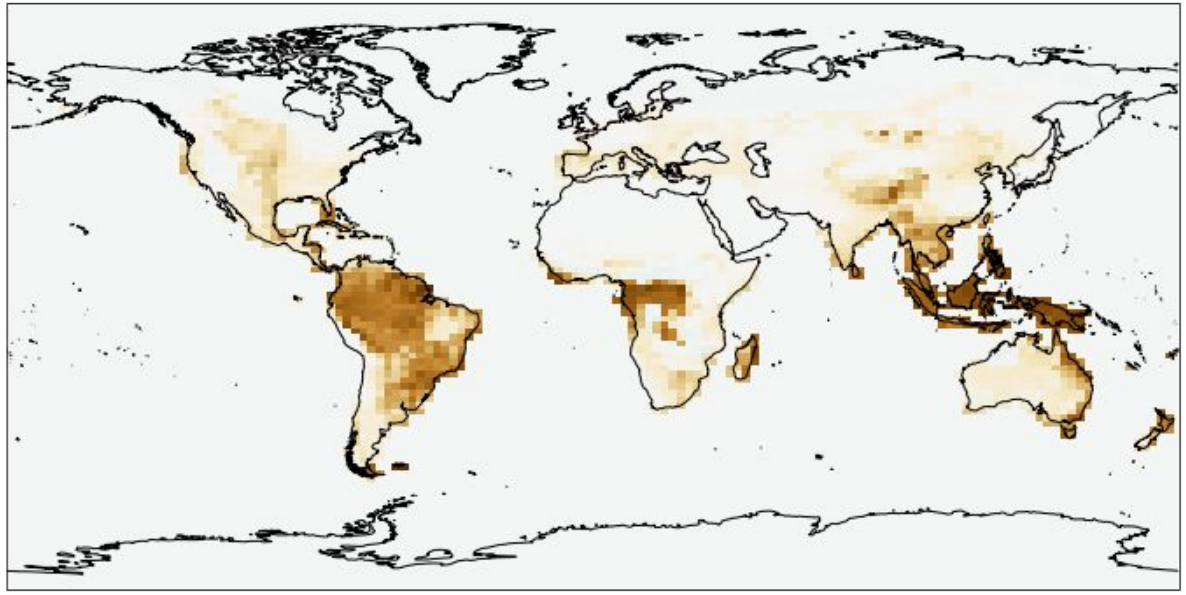
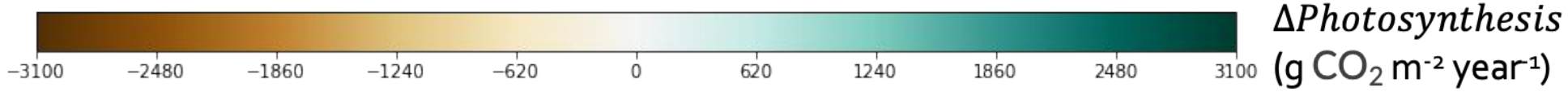


Photosynthesis decreases for simple high g_{1M} case

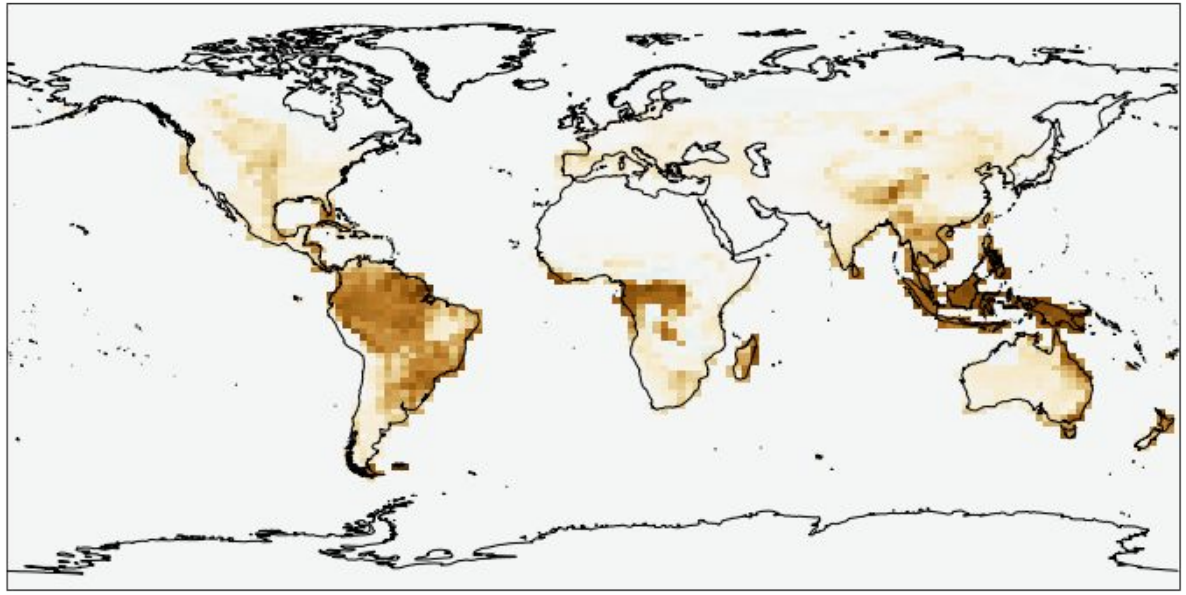
Simple: Photosynthesis High – Default g_{1M}



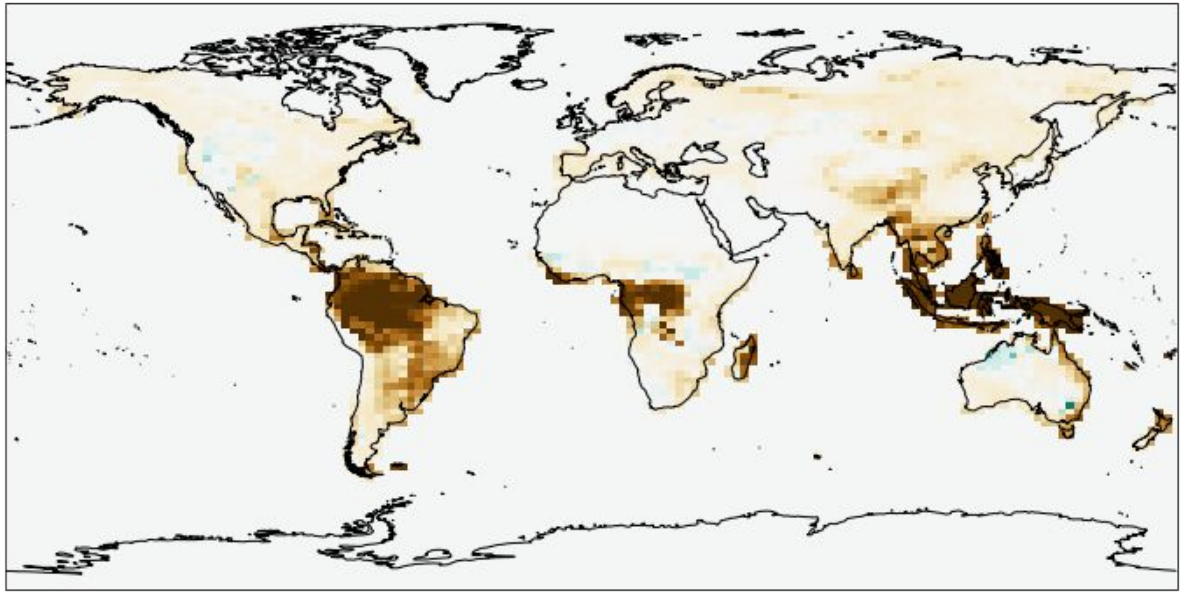


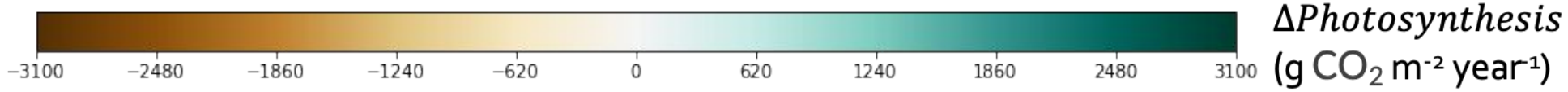
Photosynthesis decreases for both high g_{1M} cases

Simple: Photosynthesis High – Default g_{1M}



Complex: Photosynthesis High – Default g_{1M}

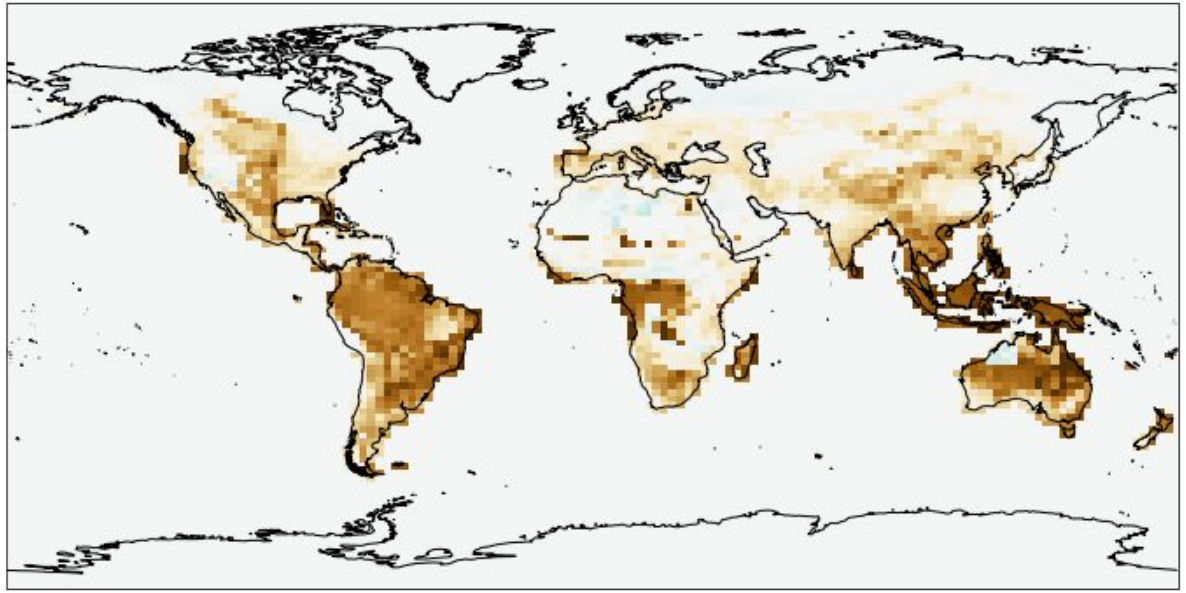




$\Delta Photosynthesis$
(g CO_2 m^{-2} $year^{-1}$)

Photosynthesis decreases for both high g_{1M} cases

Simple: Photosynthesis High – Default g_{1M}



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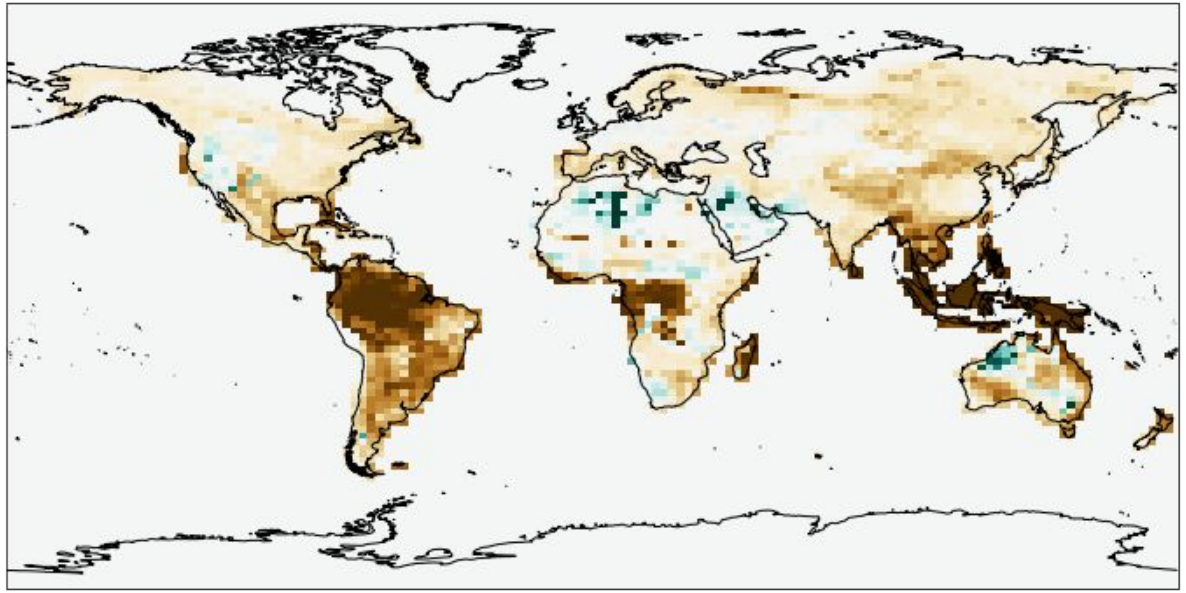
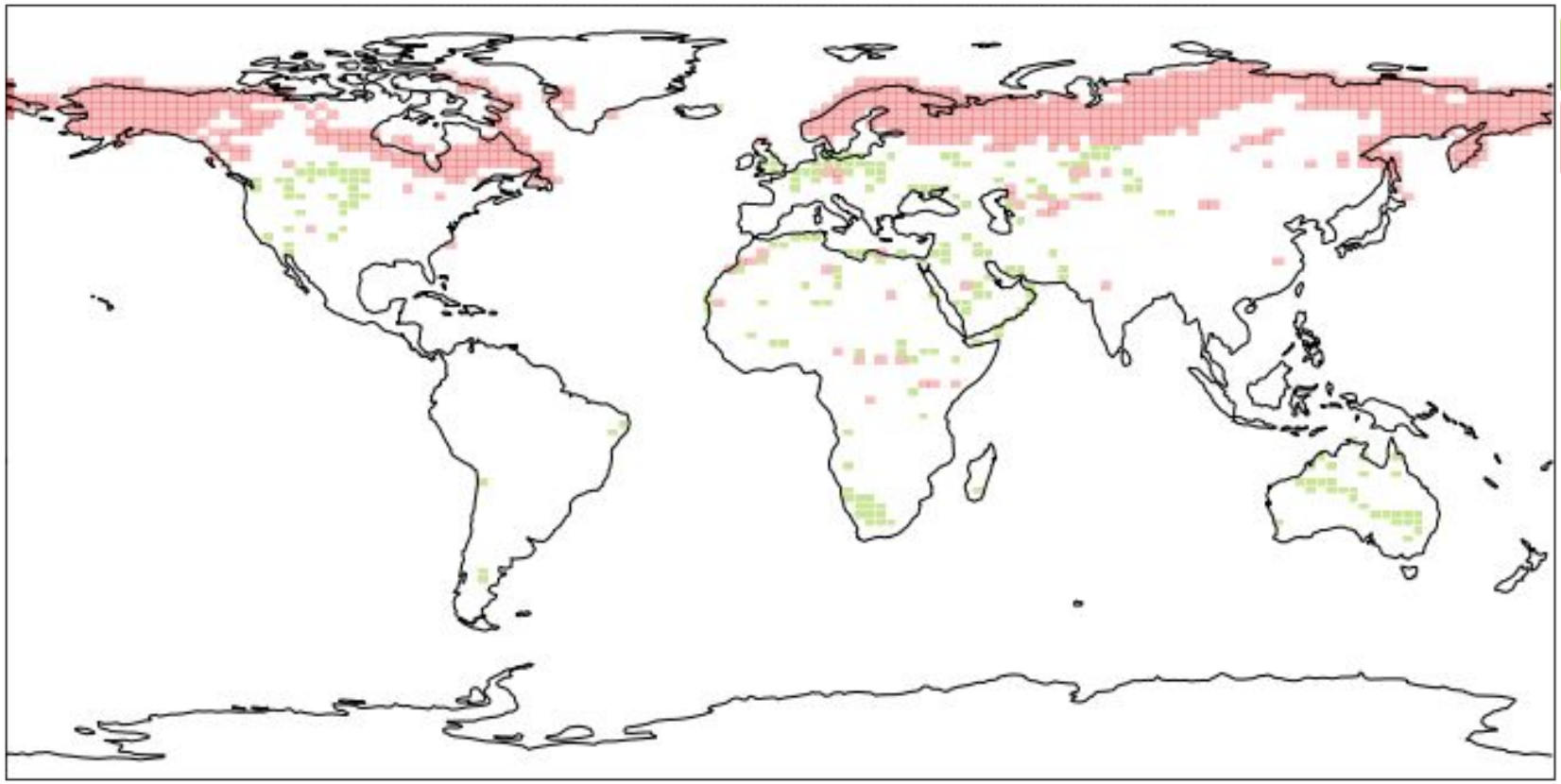


$$\frac{\Delta Photosynthesis}{\Delta g_{1M}}$$

Differences in photosynthetic response for high g_{1M} cases are largely in boreal regions

Photosynthesis Sign Change Map between Simple and Complex for High – Default g_{1M}

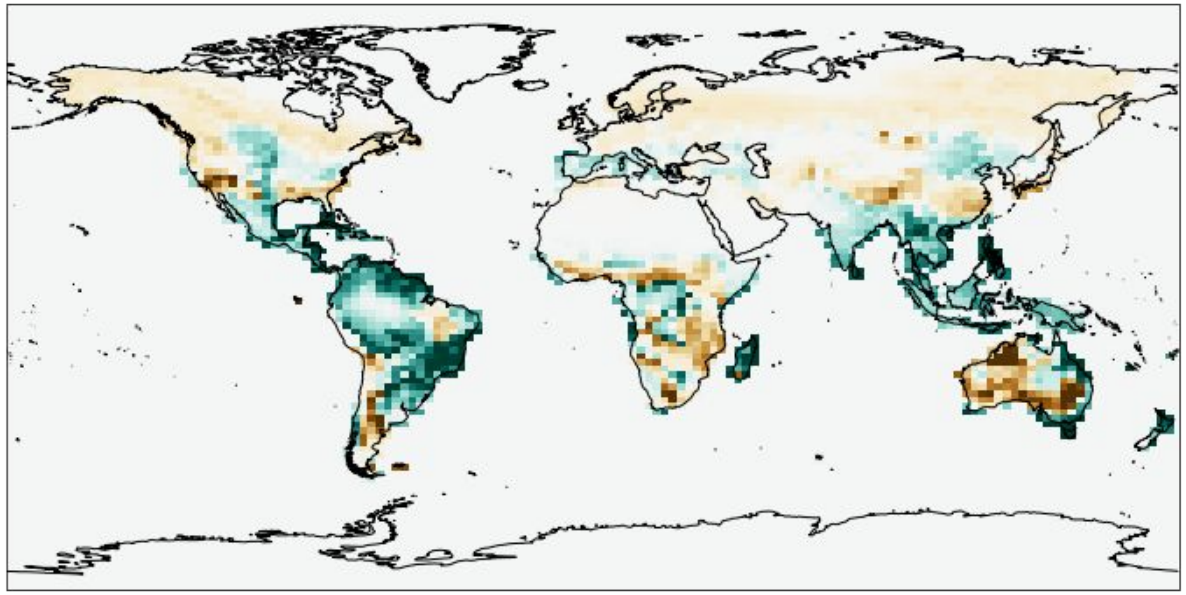


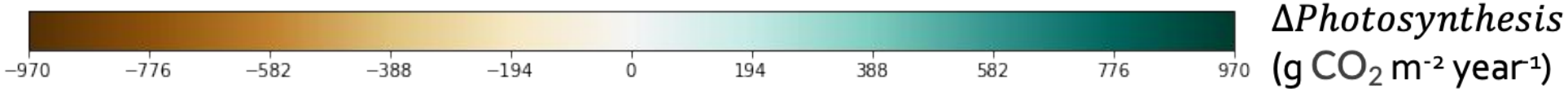
Simple negative; Complex positive

Simple positive; Complex negative

Photosynthesis regionally varies for the simple low g_{1M} case

Simple: Photosynthesis Low – Default g_{1M}

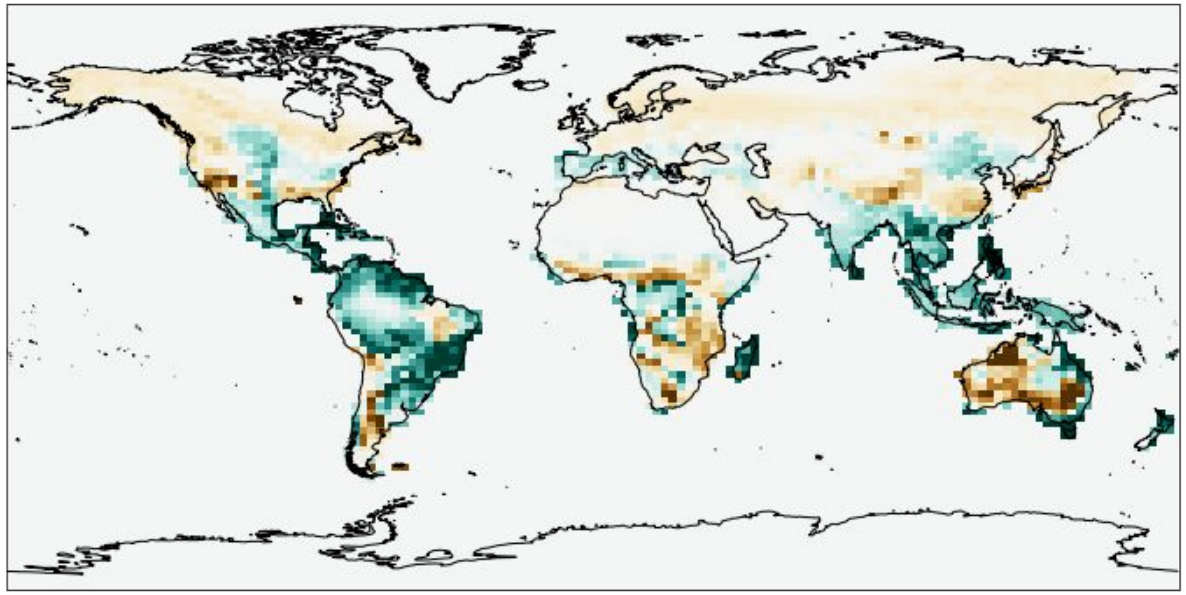




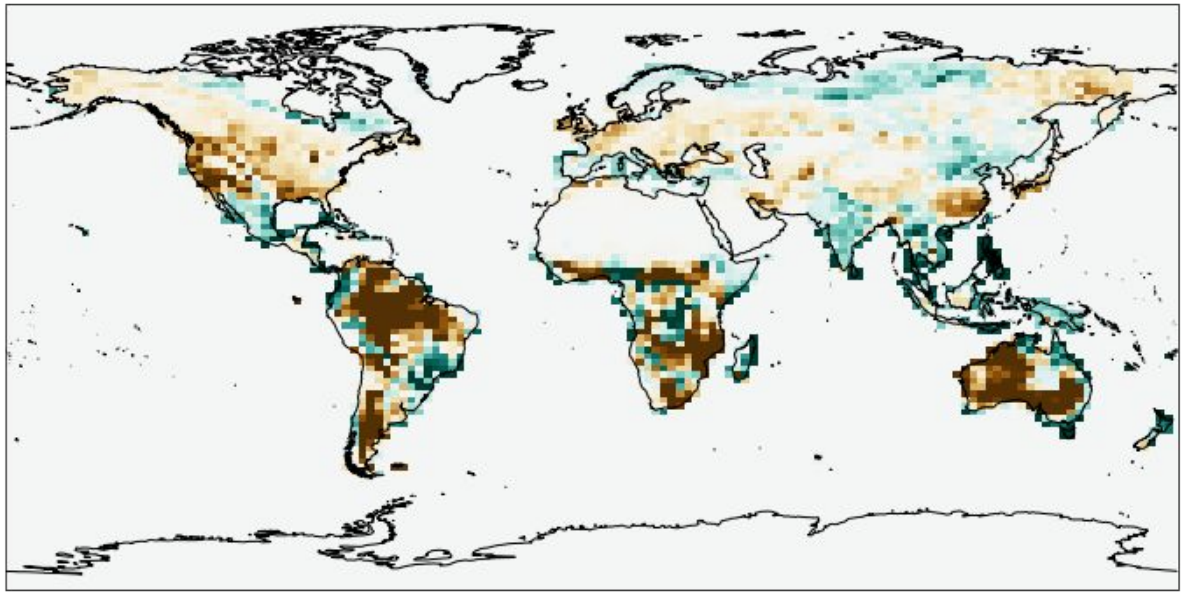
$\Delta Photosynthesis$
(g CO_2 m^{-2} $year^{-1}$)

Photosynthesis also has different responses for low g_{1M} cases

Simple: Photosynthesis Low – Default g_{1M}



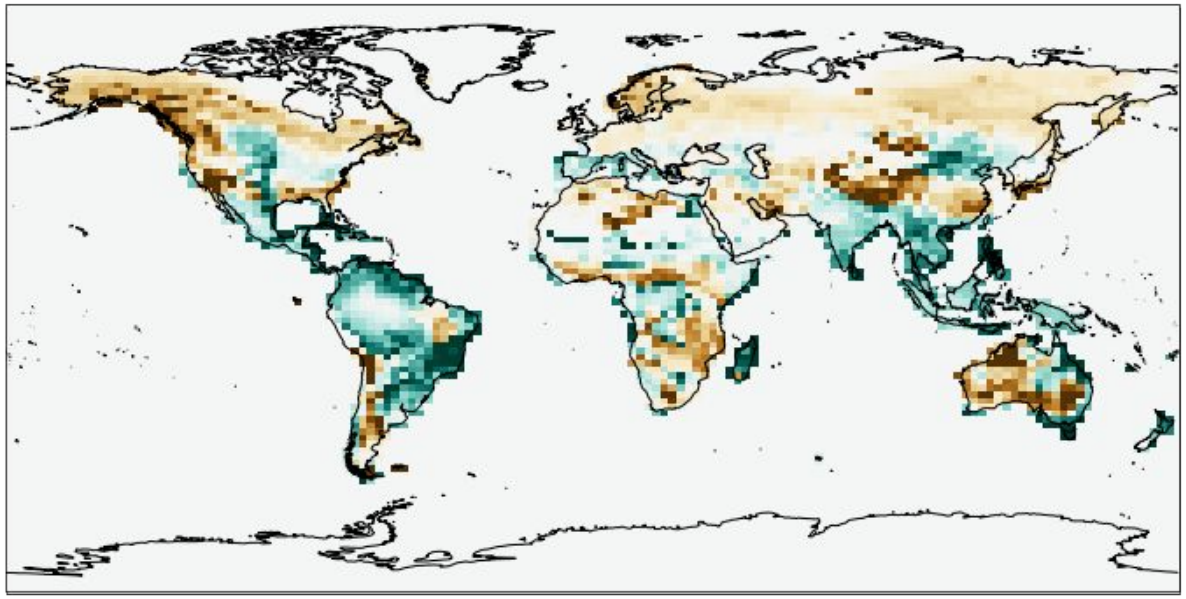
Complex: Photosynthesis Low – Default g_{1M}



$\Delta Photosynthesis$
(g CO_2 m^{-2} $year^{-1}$)

Photosynthesis changes outside of the tropics are more comparable when normalized by g_{1M} difference from default

Simple: Photosynthesis Low – Default g_{1M}



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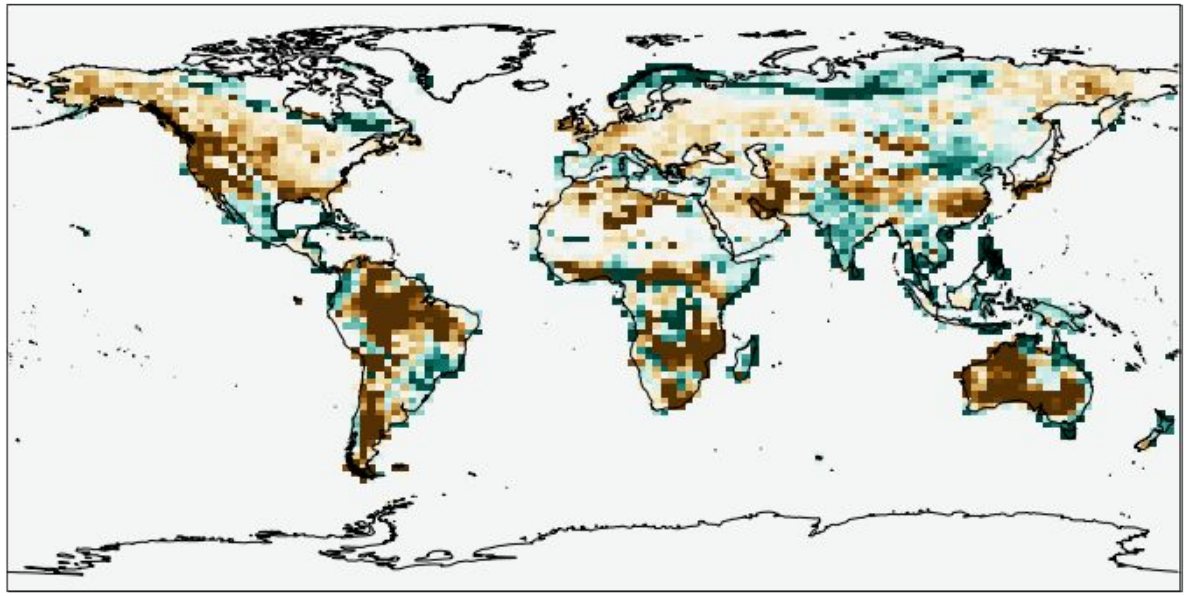
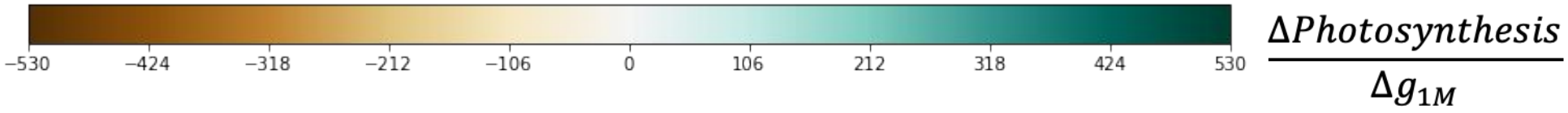
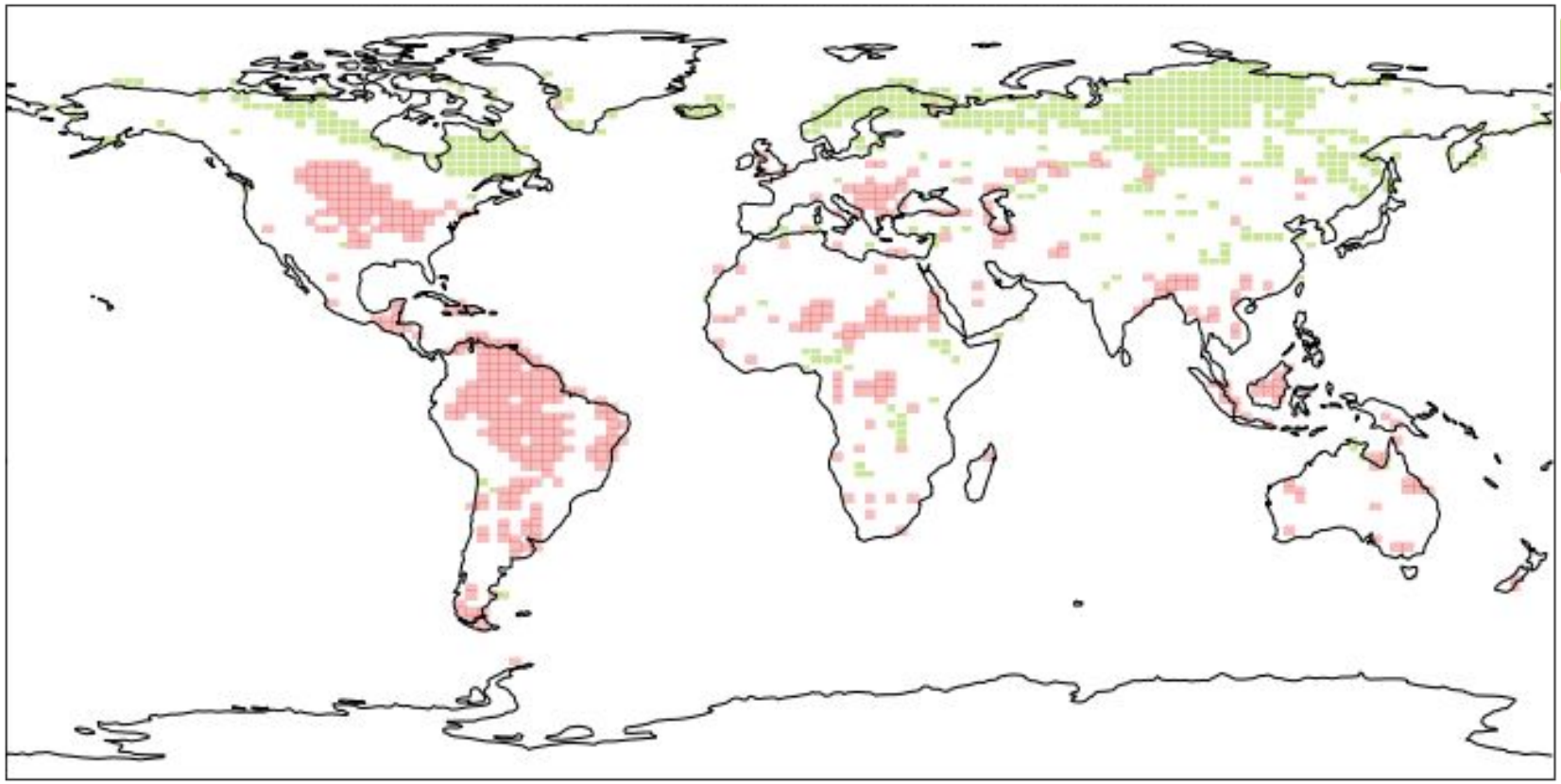




$$\frac{\Delta Photosynthesis}{\Delta g_{1M}}$$

Differences in the sign of photosynthetic response for low g_{1M} cases are largely clustered in the Amazon, central NA, and boreal regions

Photosynthesis Sign Change Map between Simple and Complex for Low – Default g_{1M}

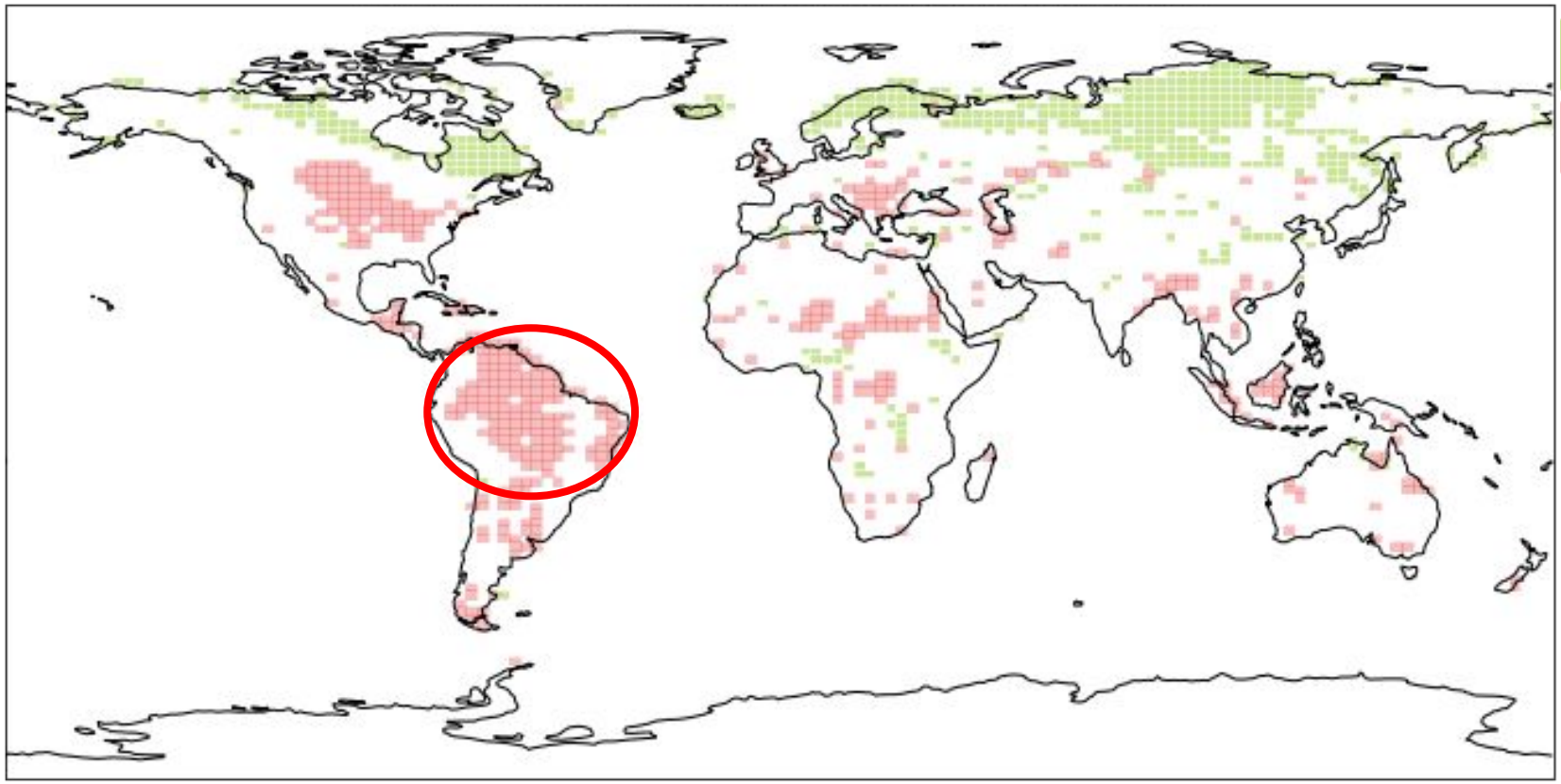


Simple negative; Complex positive

Simple positive; Complex negative

Zoom in on the Amazon

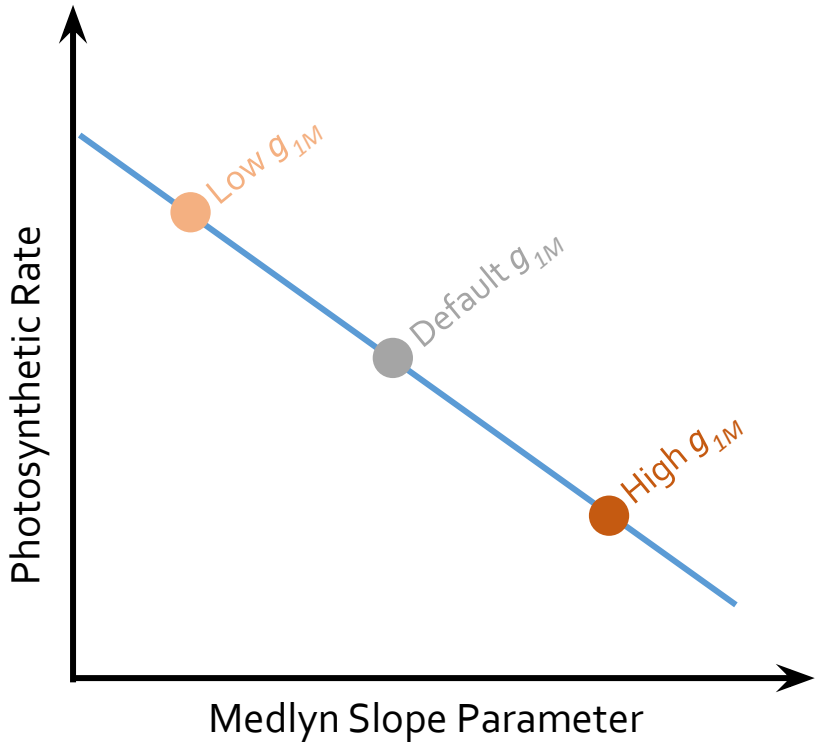
Photosynthesis Sign Change Map between Simple and Complex for Low – Default g_{1M}



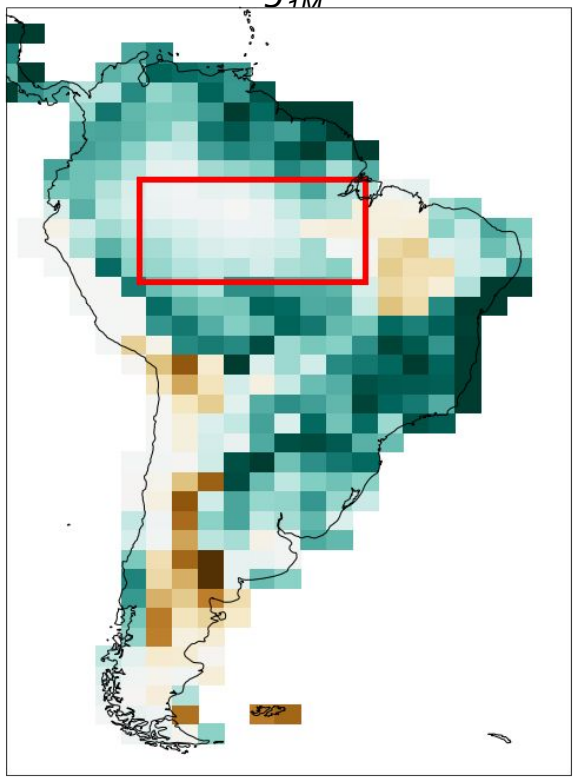
Simple negative; Complex positive

Simple positive; Complex negative

In the simple low g_{1M} case, photosynthesis increases as expected in the Amazon

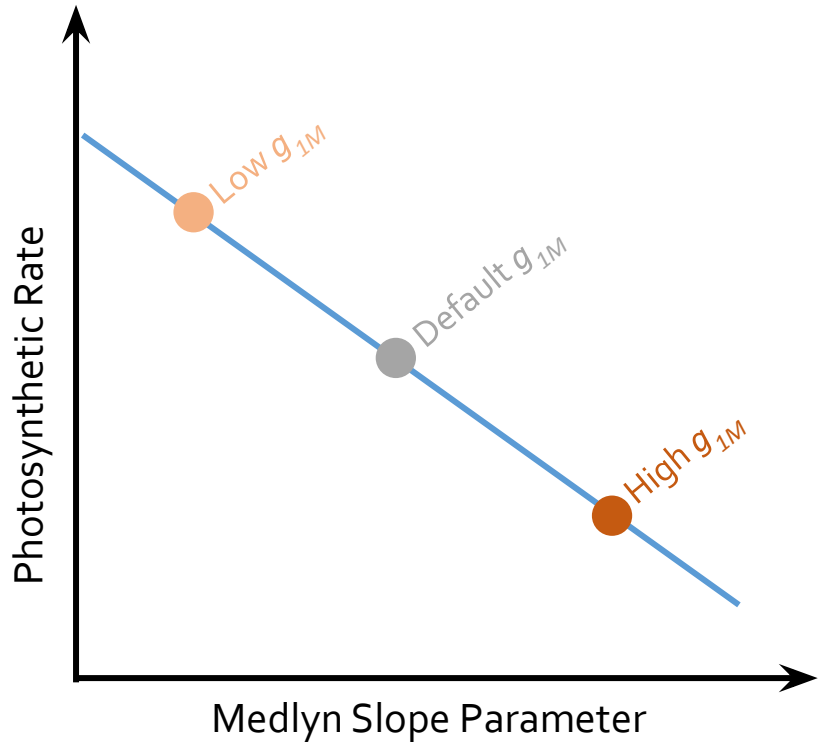


Simple:
Photosynthesis
Low – Default g_{1M}



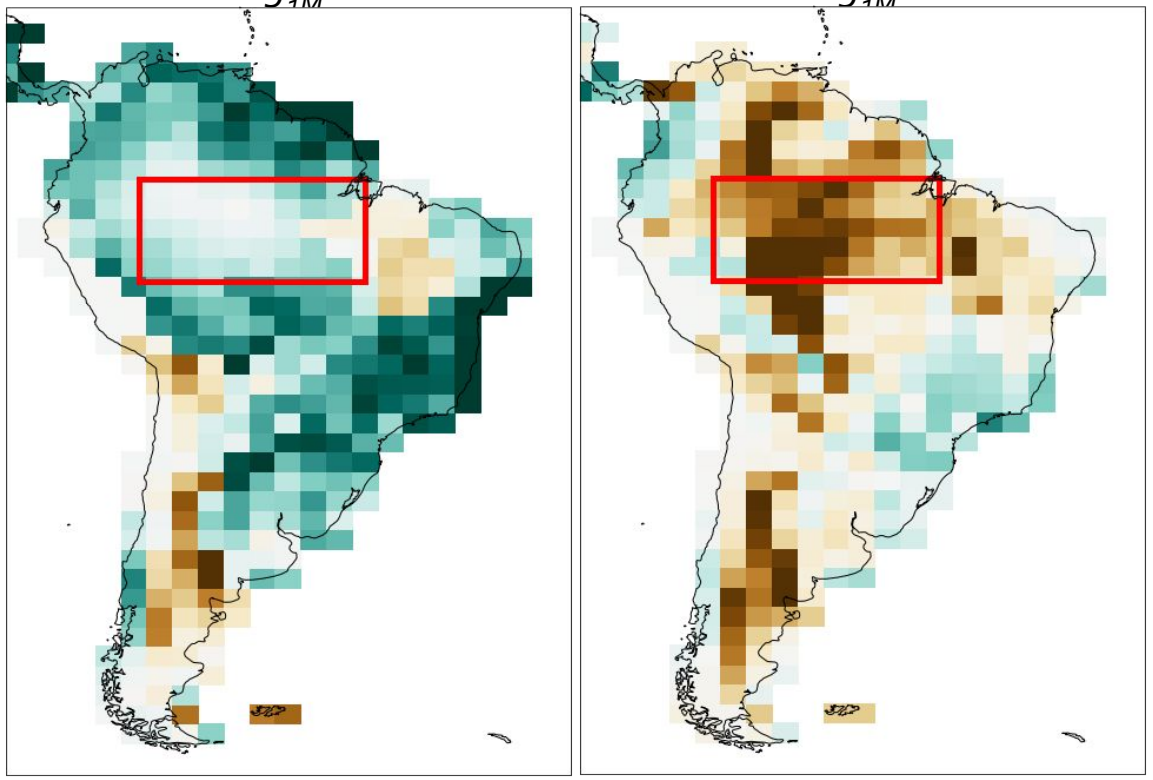
1x CO_2
uncoupled
fixed LAI

With a coupled atmosphere and dynamic LAI, photosynthesis unexpectedly decreases in the Amazon



Simple:
Photosynthesis
Low – Default g_{1M}

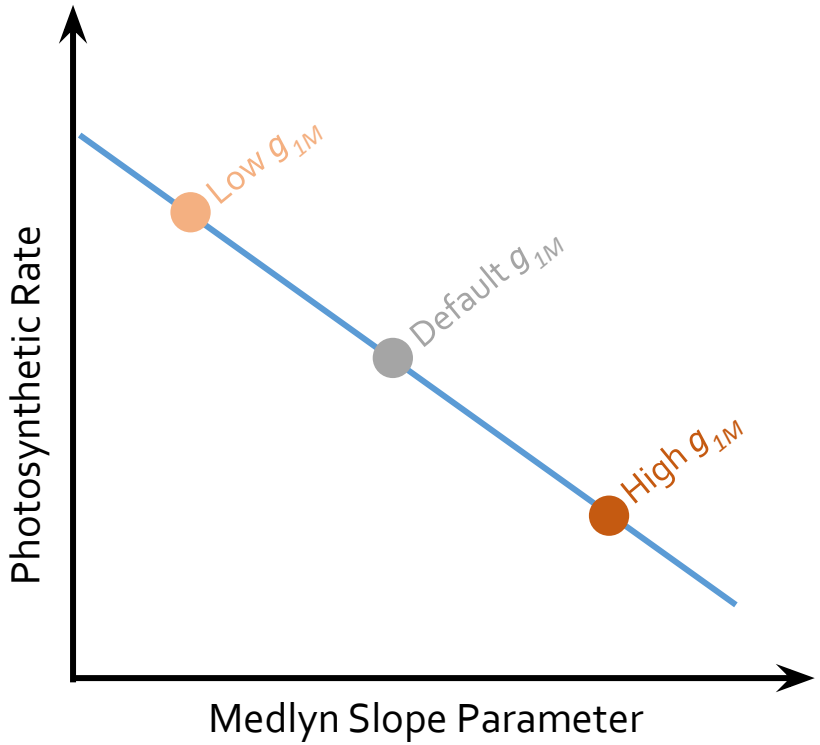
Complex:
Photosynthesis
Low – Default g_{1M}

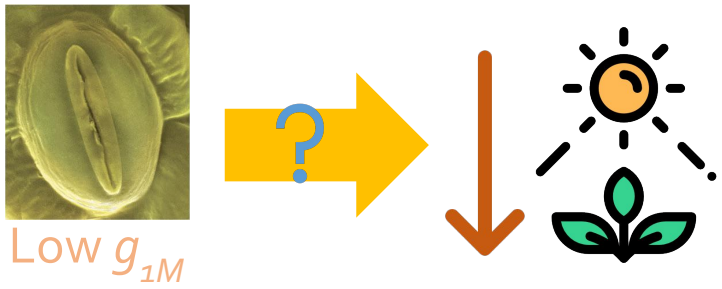


1x CO_2

uncoupled	coupled atm
fixed LAI	dynamic LAI

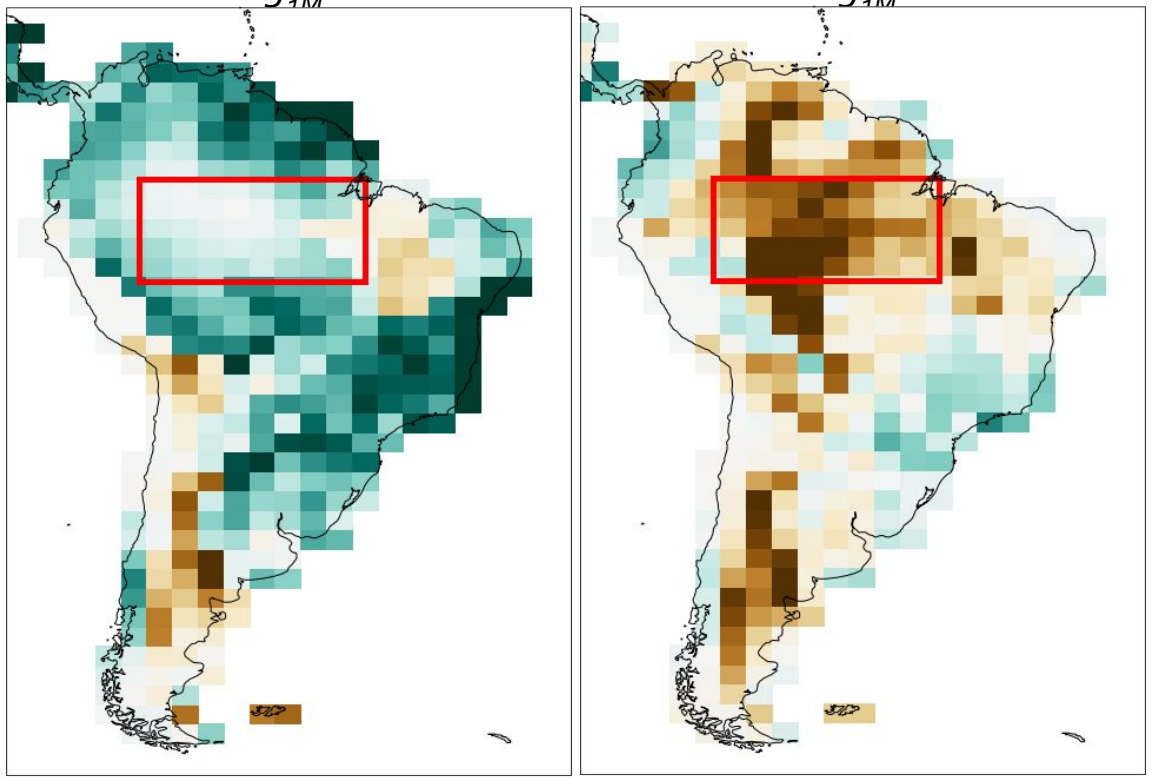
With a coupled atmosphere and dynamic LAI, photosynthesis unexpectedly decreases in the Amazon





Simple:
Photosynthesis
Low – Default g_{1M}

Complex:
Photosynthesis
Low – Default g_{1M}

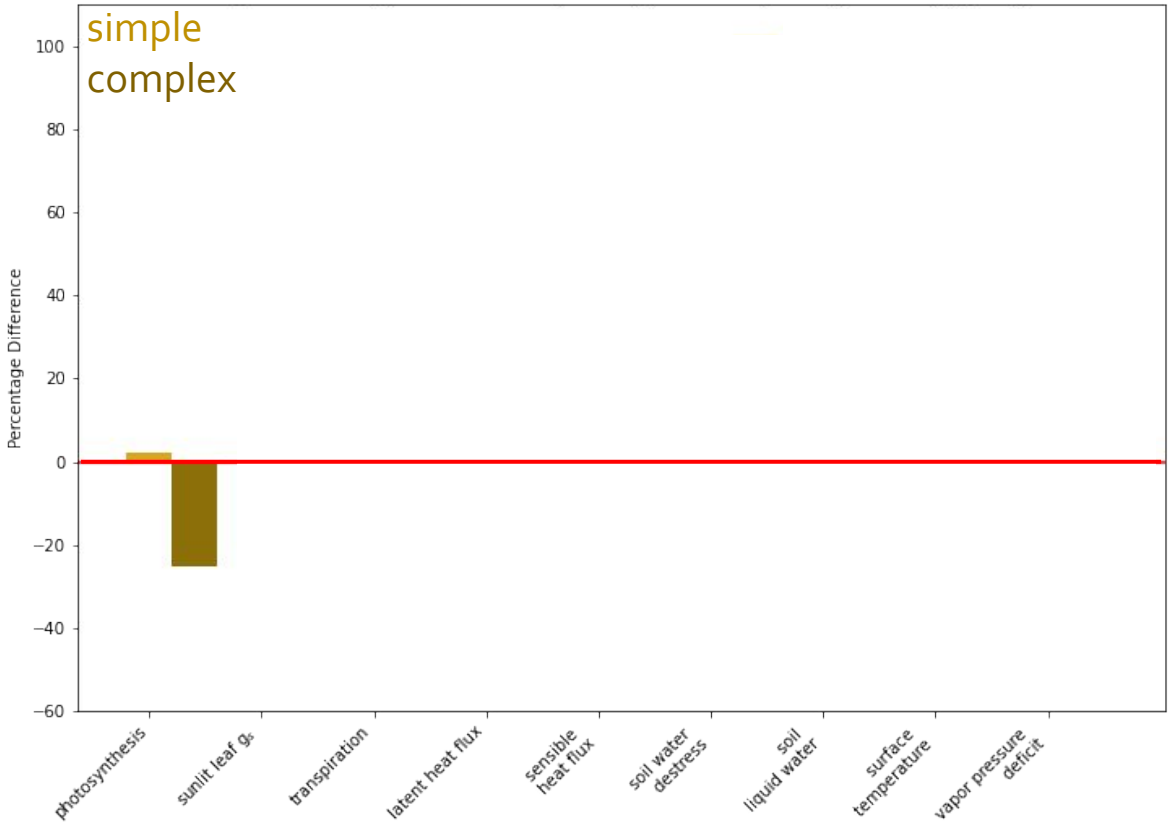


1x CO_2

uncoupled	coupled atm
fixed LAI	dynamic LAI

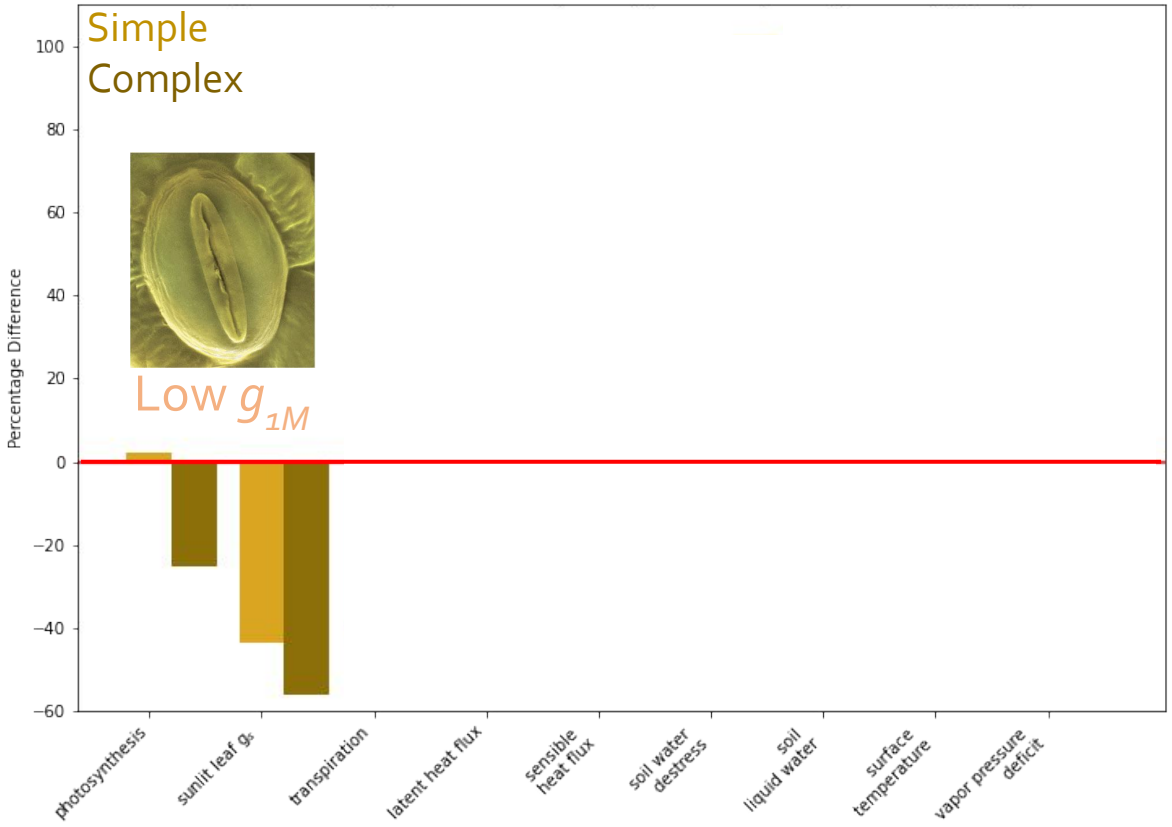
Photosynthesis increases for simple and decreases for complex low g_{1M}

Variable % Differences for Low – Default g_{1M} in the Amazon



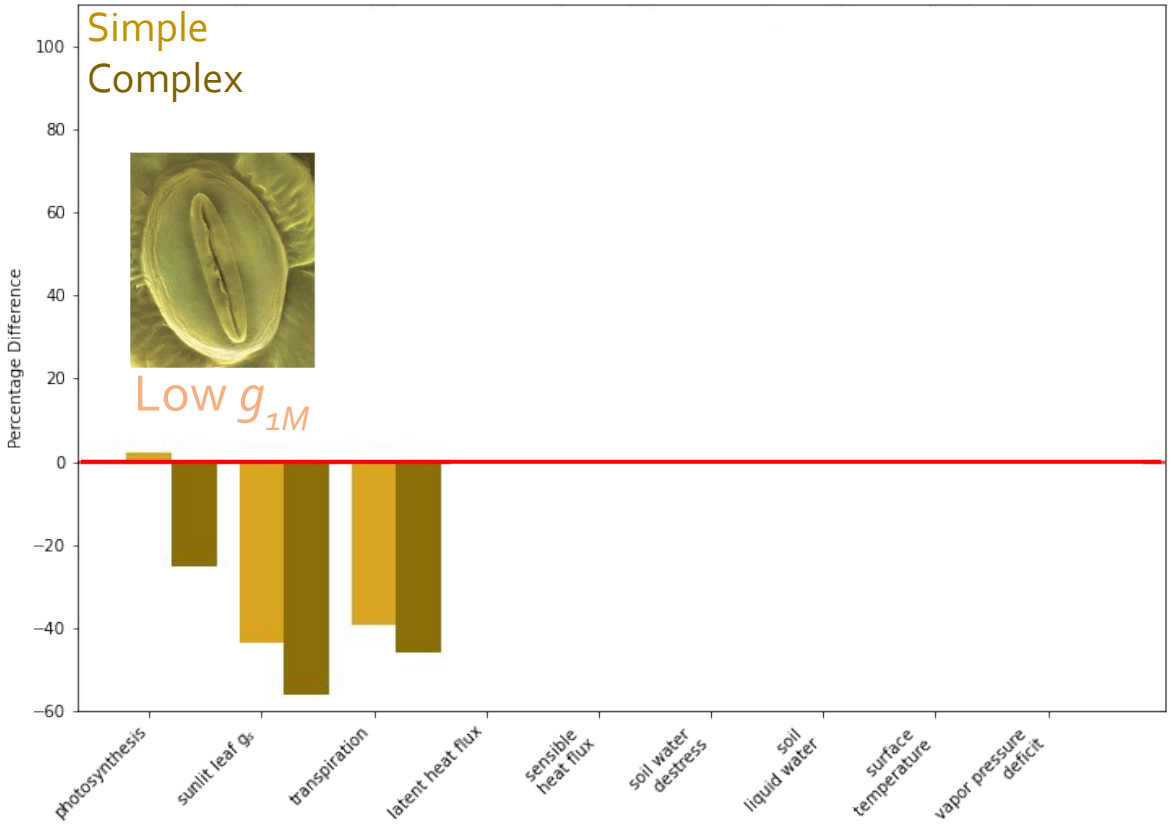
Low g_{1M} consistently decreases stomatal conductance (stomatal closure)

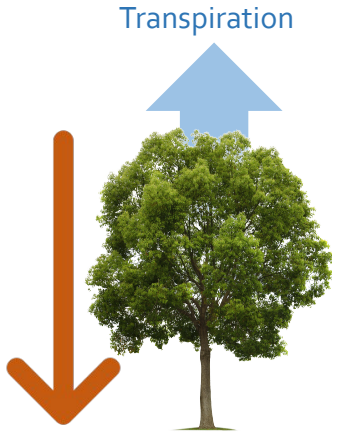
Variable % Differences for Low – Default g_{1M} in the Amazon



Transpiration decreases as expected with stomatal closure

Variable % Differences for Low – Default g_{1M} in the Amazon



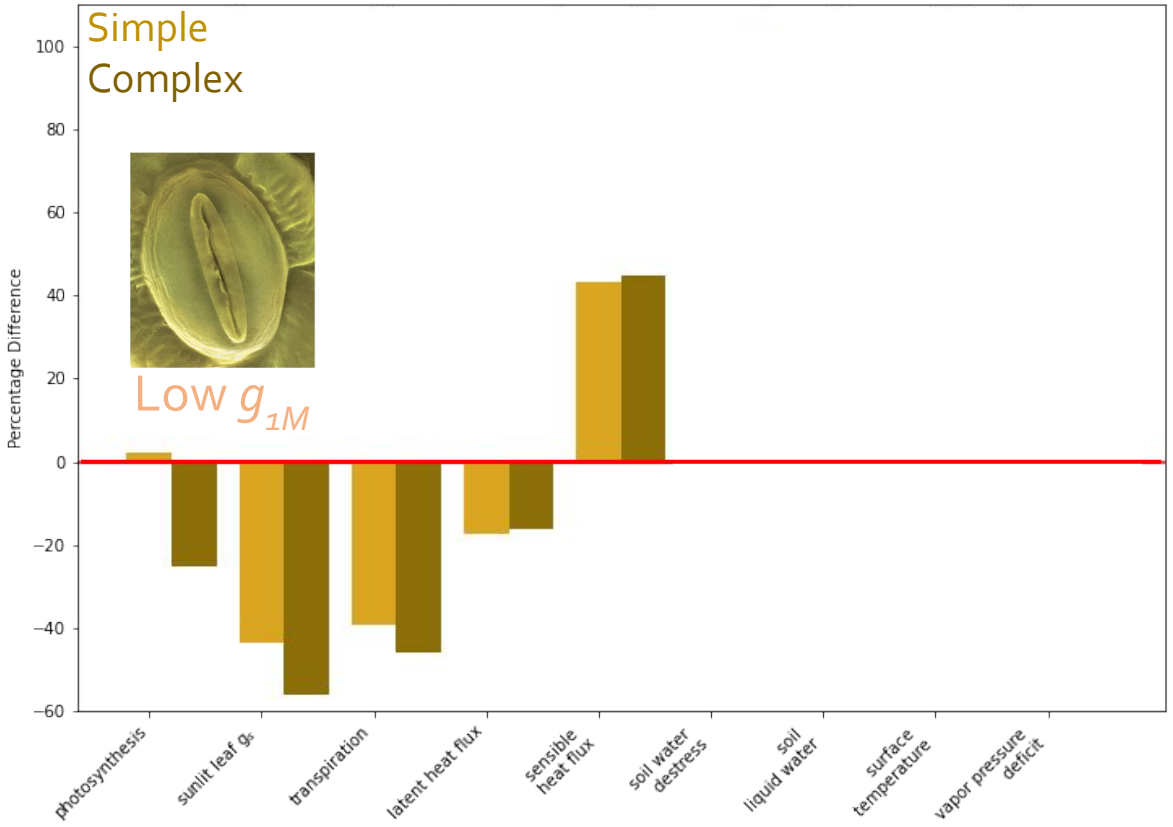


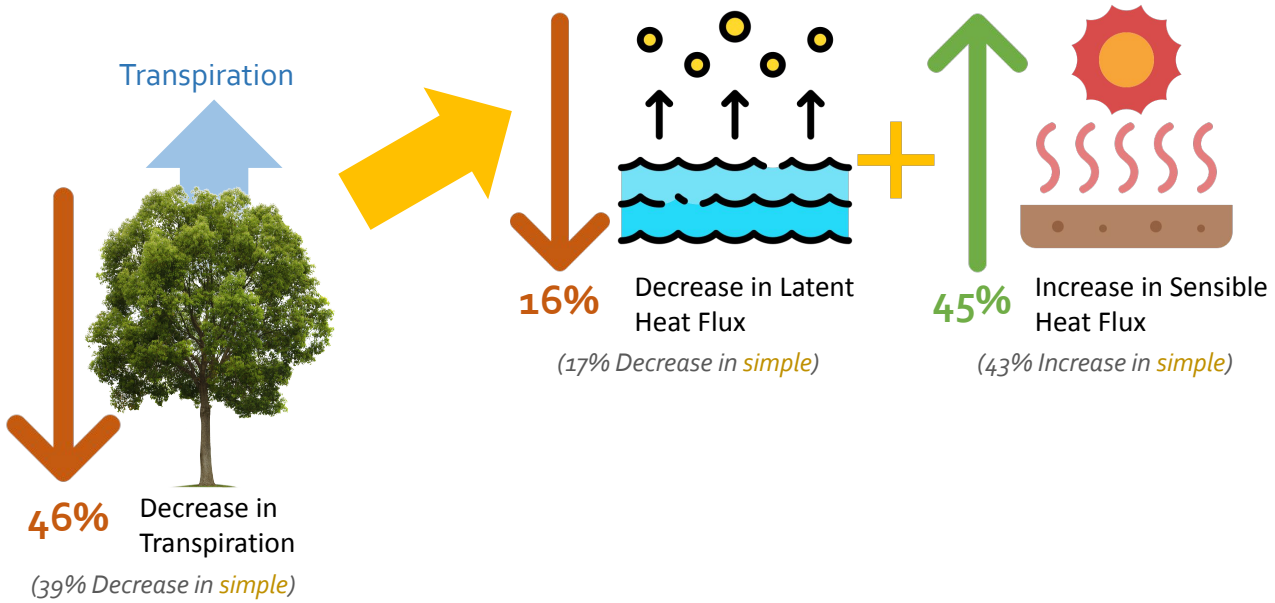
46% Decrease in Transpiration

(39% Decrease in simple)

The heat fluxes also change as expected

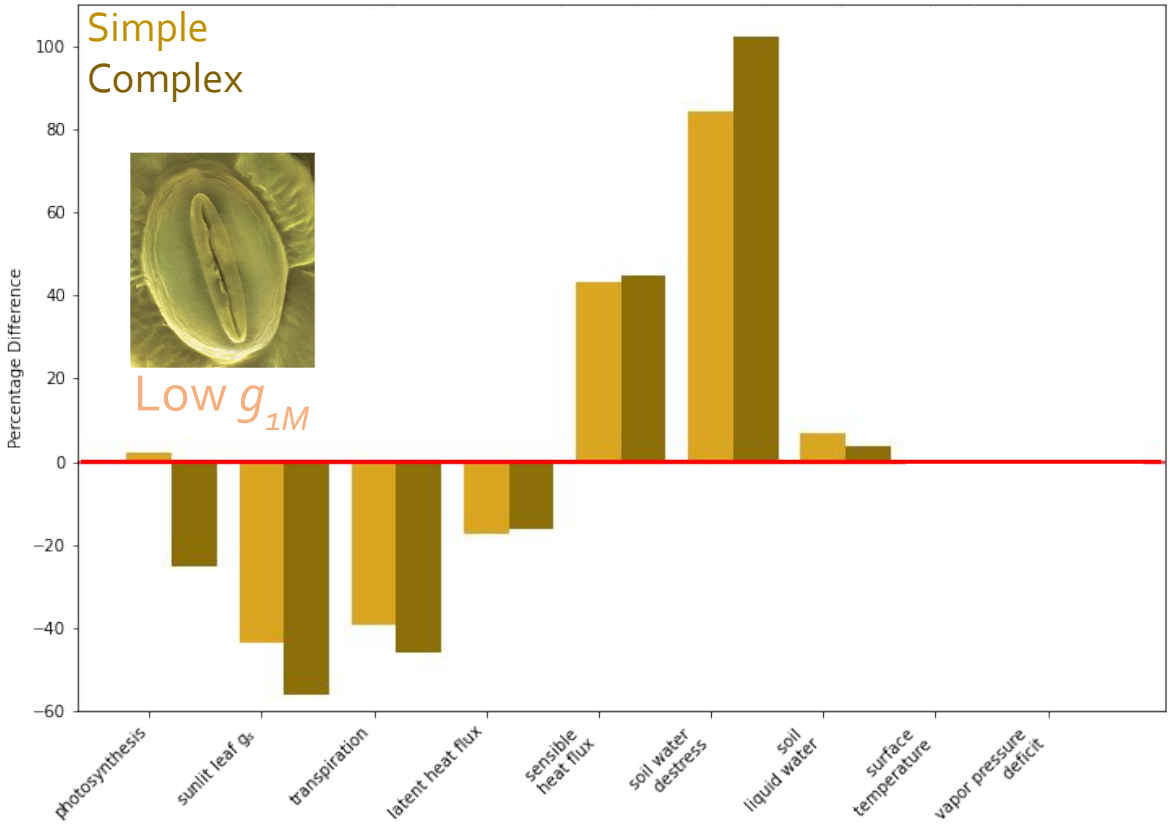
Variable % Differences for Low – Default g_{1M} in the Amazon

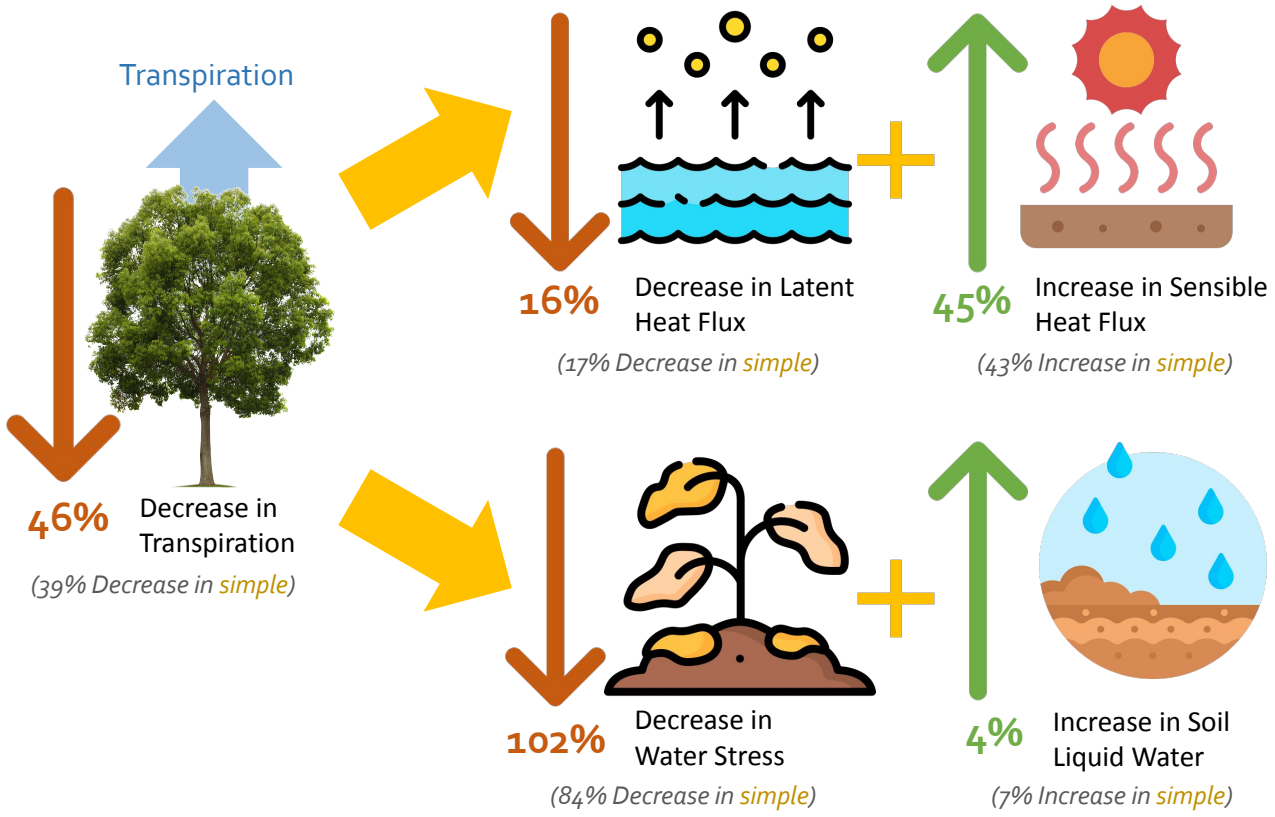




Increase in WUE decreases soil water stress and increases water availability

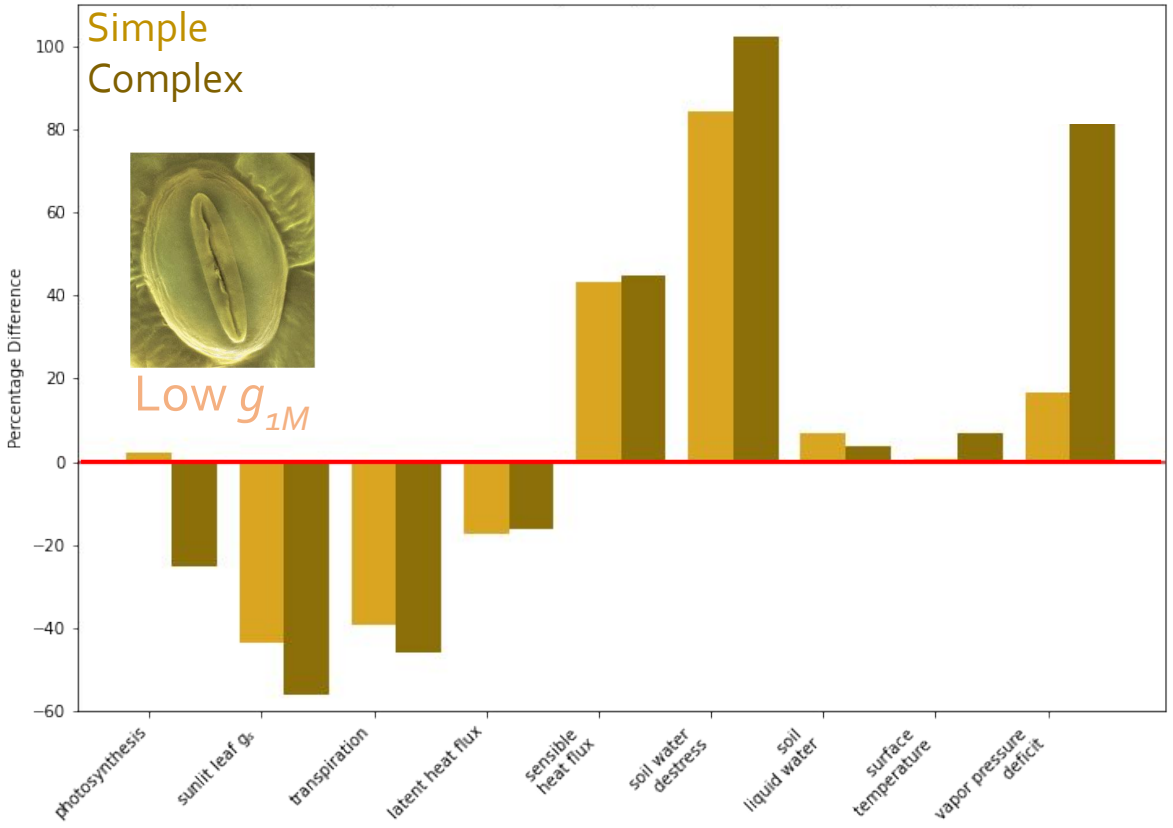
Variable % Differences for Low – Default g_{1M} in the Amazon





In the complex case, large increase in temperature and VPD decreases photosynthesis

Variable % Differences for Low – Default g_{1M} in the Amazon



7% Increase Surface Temperature

(0.4% Increase in simple)

82% Increase in Vapor Pressure Deficit

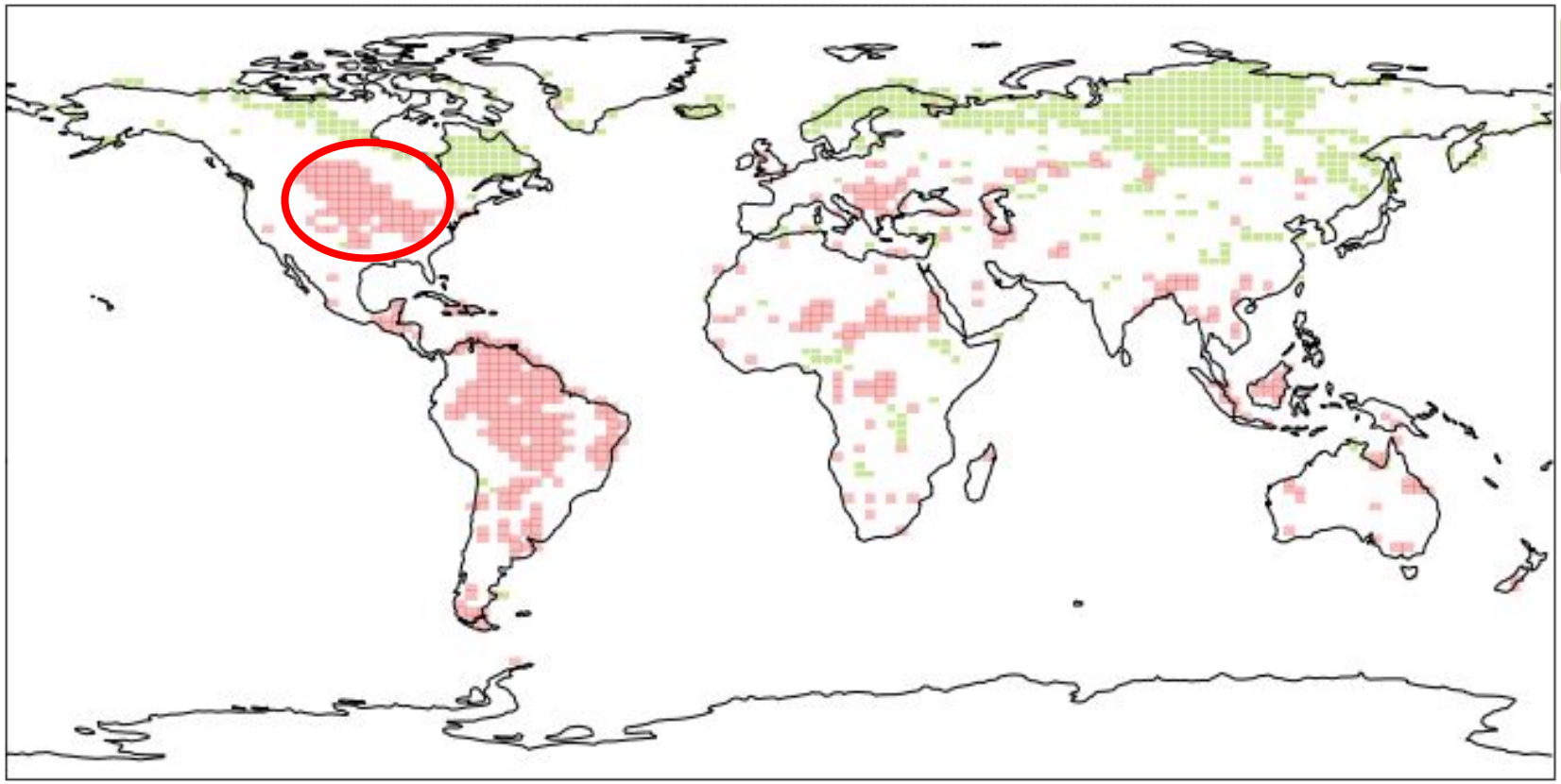
(17% Increase in simple)

25% Decrease in Photosynthesis

(2% Increase in simple)

Zoom in on central North America

Photosynthesis Sign Change Map between Simple and Complex for Low – Default g_{1M}

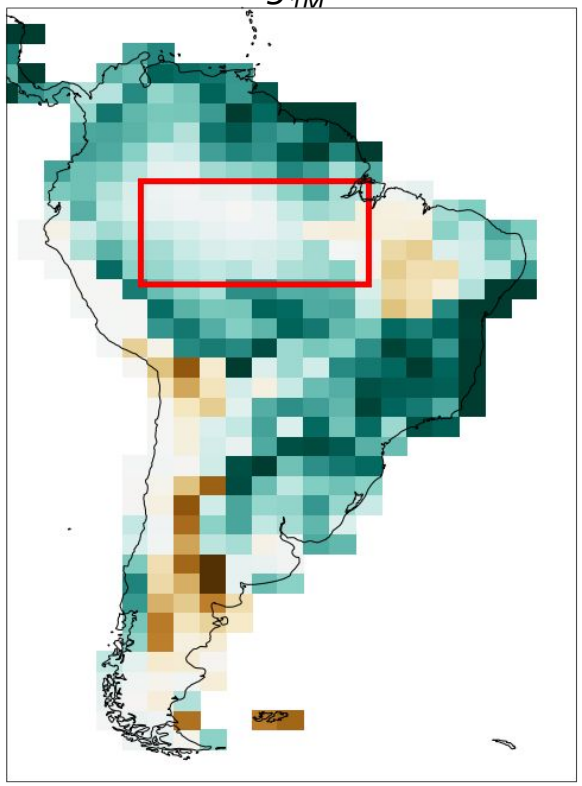


Simple negative; Complex positive

Simple positive; Complex negative

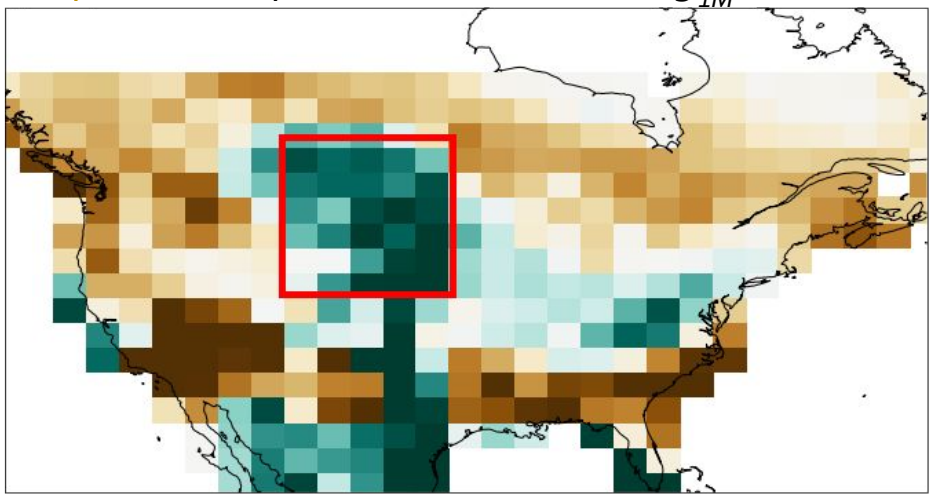
Like in the Amazon, photosynthesis increases in central NA for the simple low g_{1M} case

Simple:
Photosynthesis
Low – Default g_{1M}



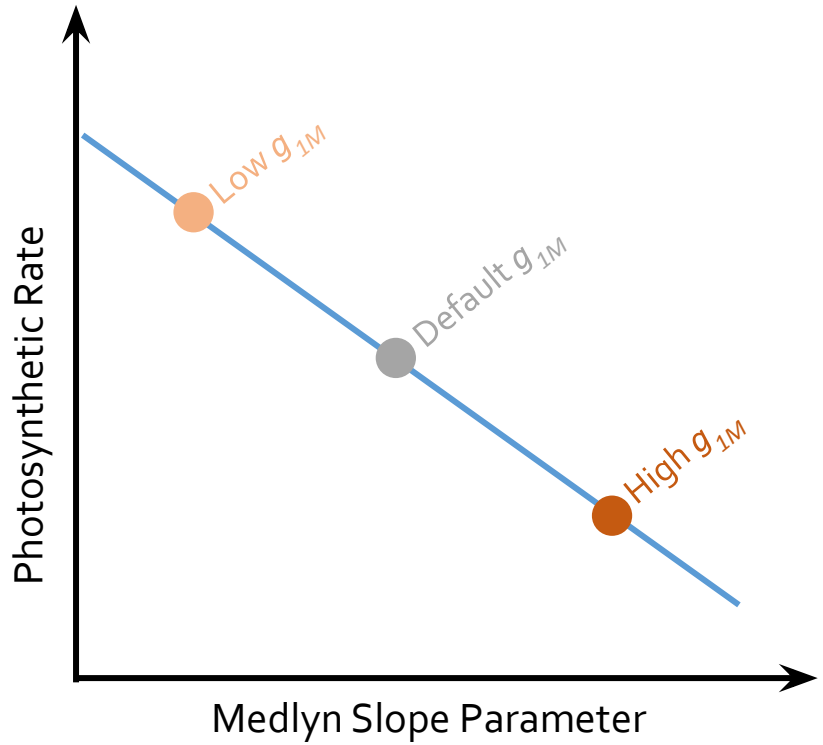
1x CO_2
uncoupled
fixed LAI

Simple: Photosynthesis Low – Default g_{1M}

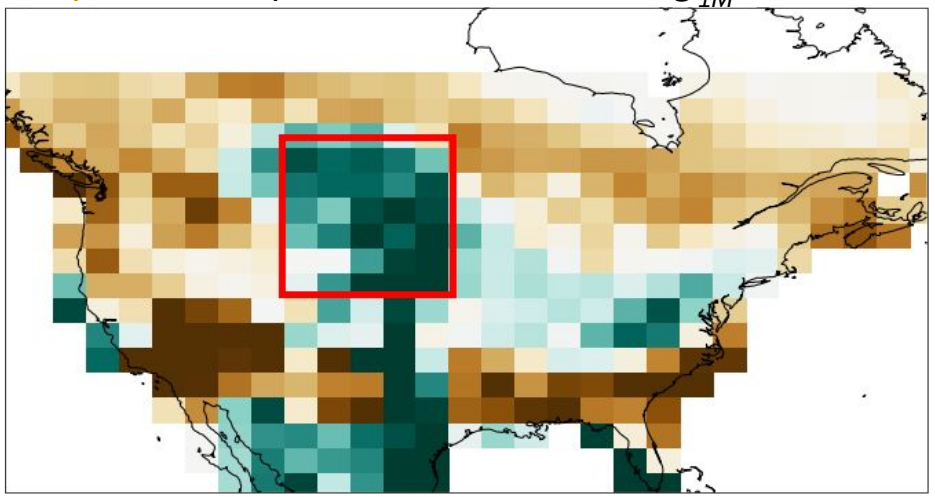


1x CO_2 | uncoupled | fixed LAI

Like in the Amazon, photosynthesis increases in central NA for the simple low g_{1M} case

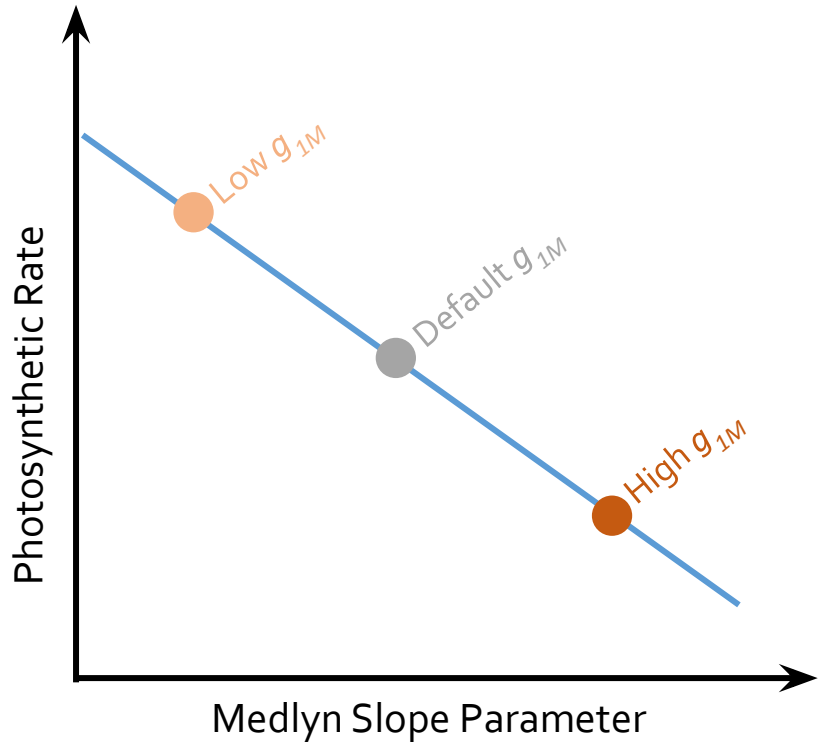


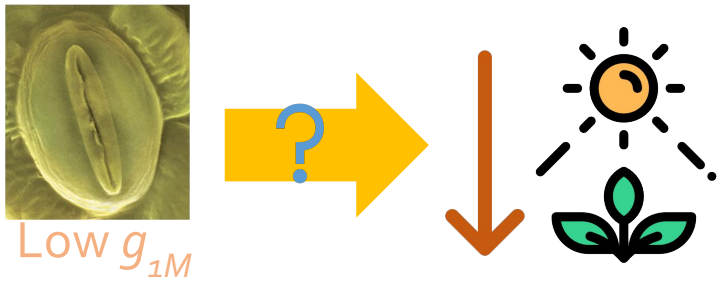
Simple: Photosynthesis Low – Default g_{1M}



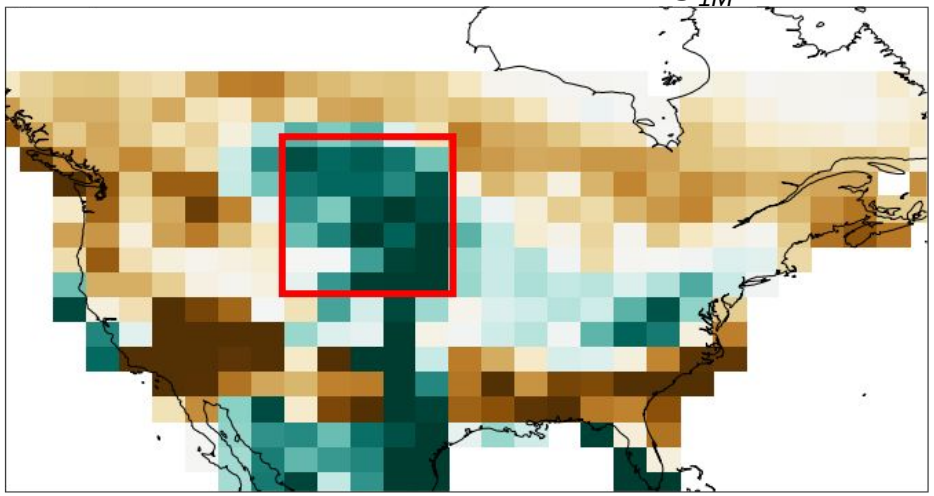
1x CO_2 | uncoupled | fixed LAI

In the complex low g_{1M} case, photosynthesis increases as expected



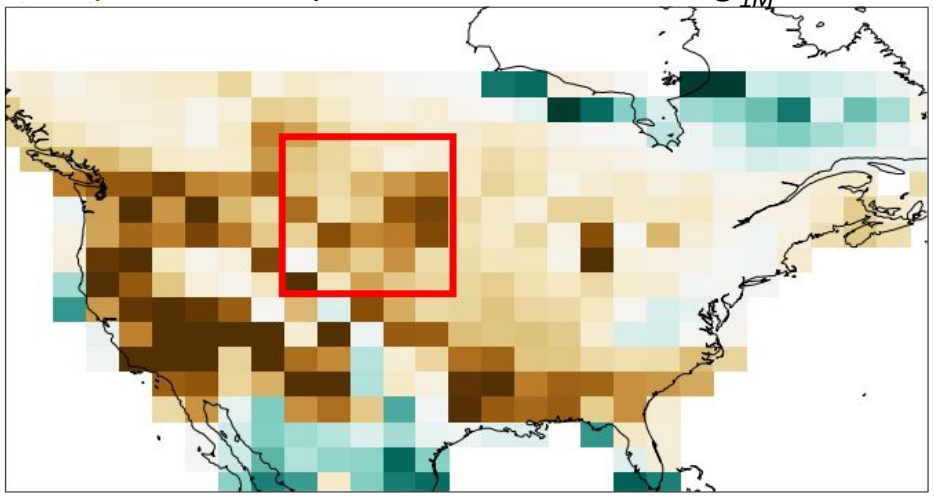


Simple: Photosynthesis Low – Default g_{1M}



1x CO_2 | uncoupled | fixed LAI

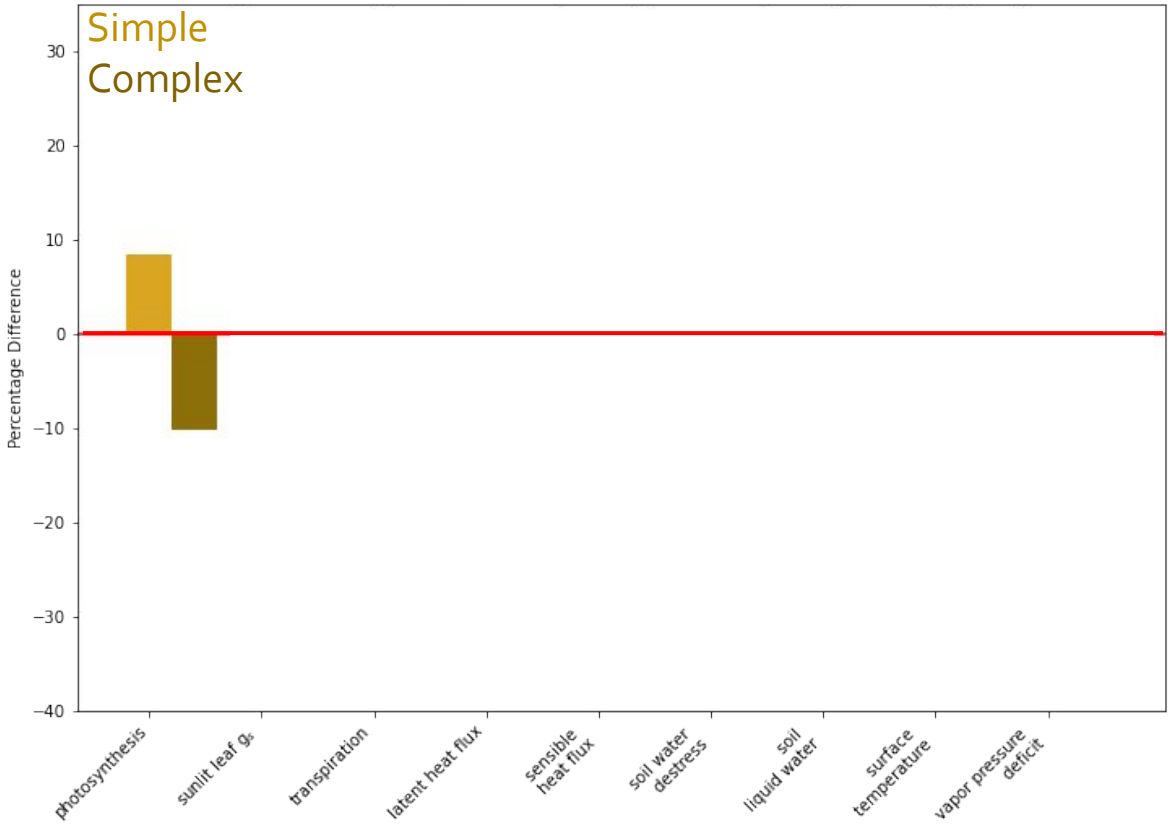
Complex: Photosynthesis Low – Default g_{1M}



1x CO_2 | coupled | dynamic LAI

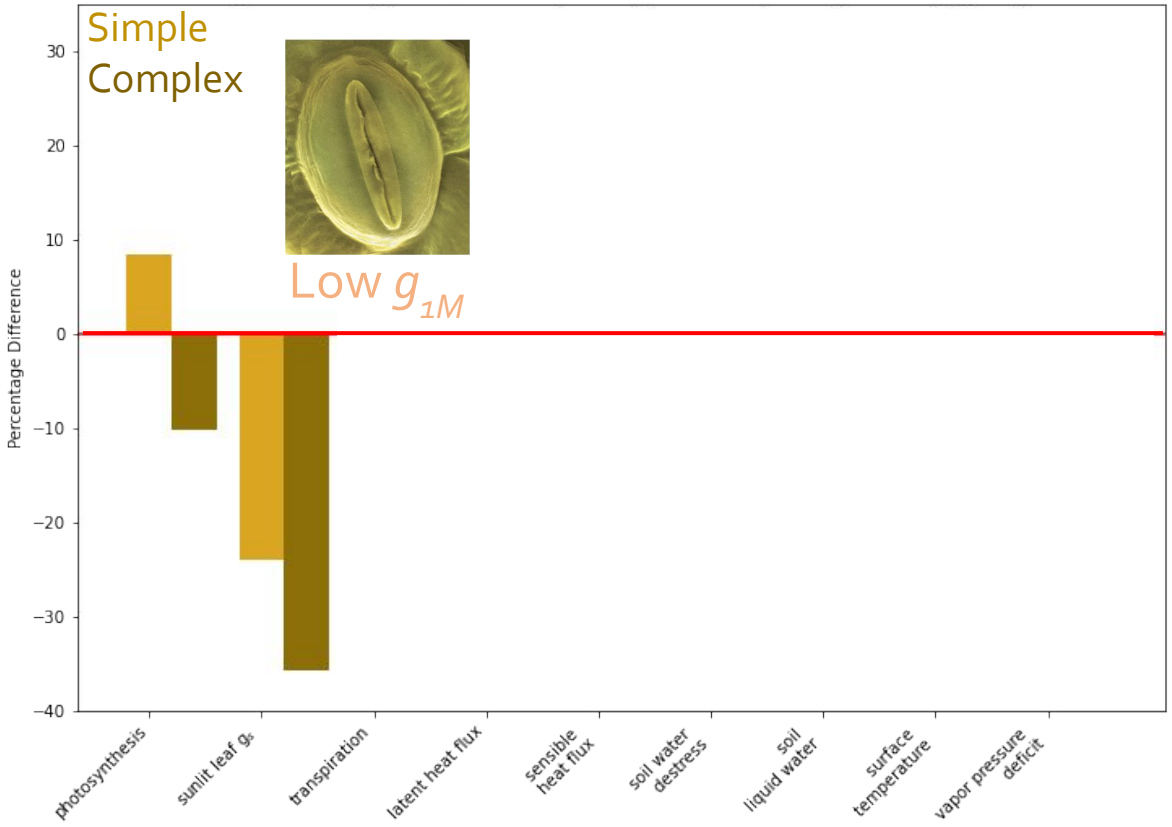
Photosynthesis decreases for simple and increases for complex low g_{1M}

Variable % Differences for Low – Default g_{1M} in central NA



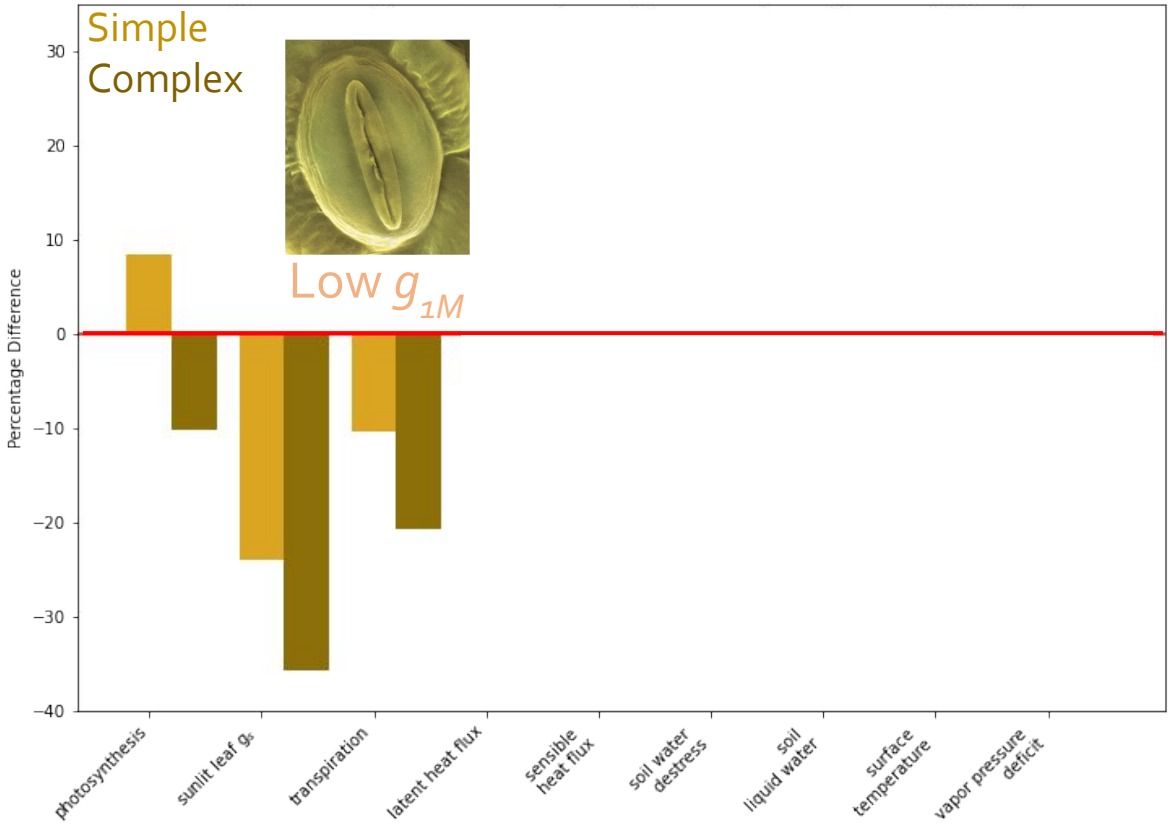
Photosynthesis increases for simple and decreases for complex low g_{1M}

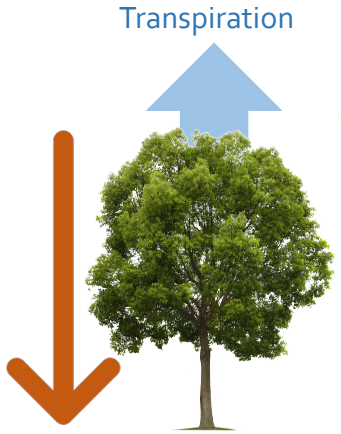
Variable % Differences for Low – Default g_{1M} in central NA



Transpiration decreases more for the complex case

Variable % Differences for Low – Default g_{1M} in central NA

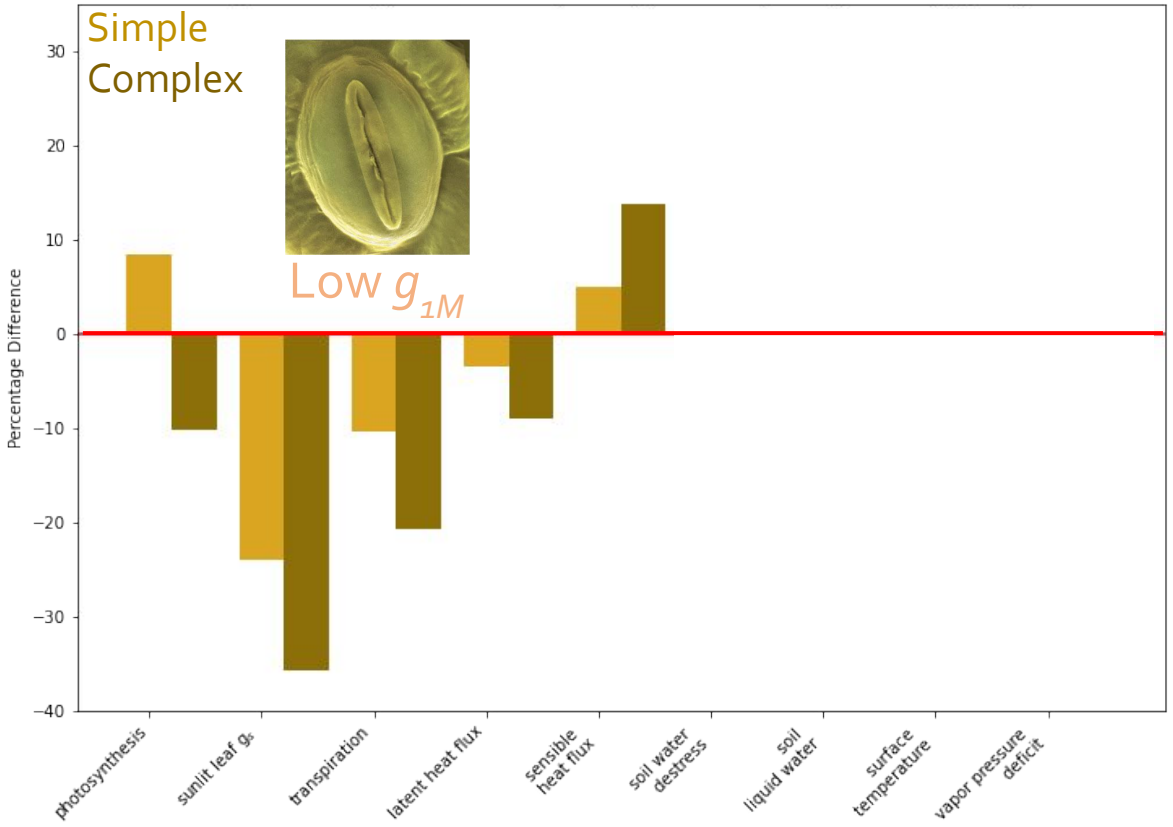


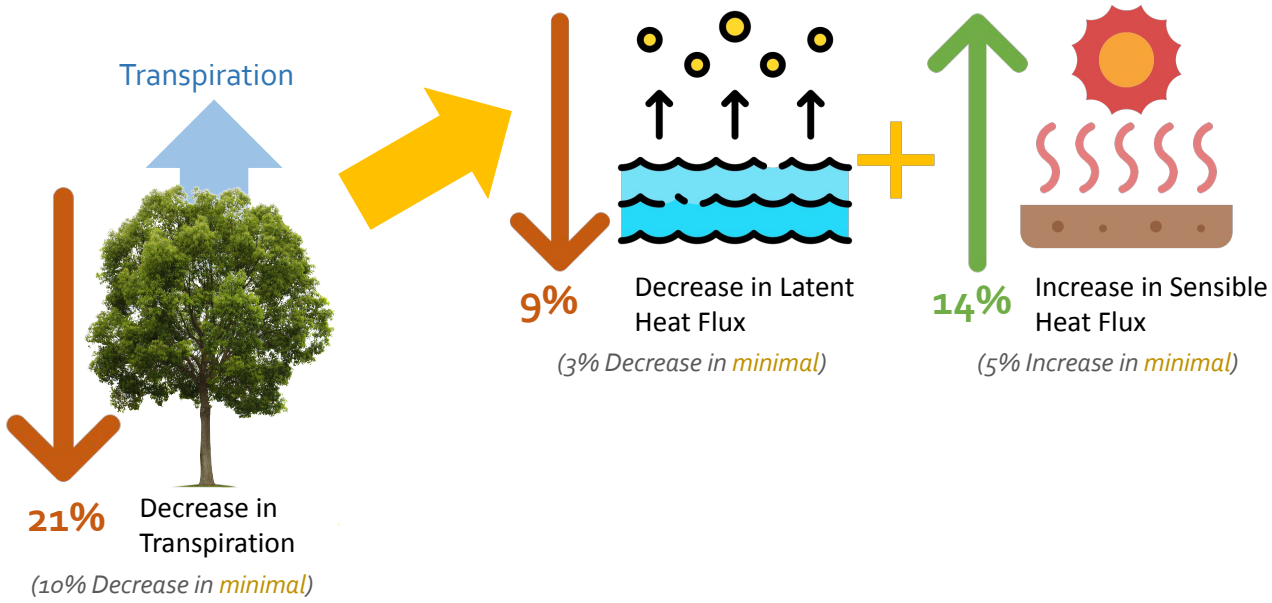


(10% Decrease in minimal)

The heat fluxes change as expected

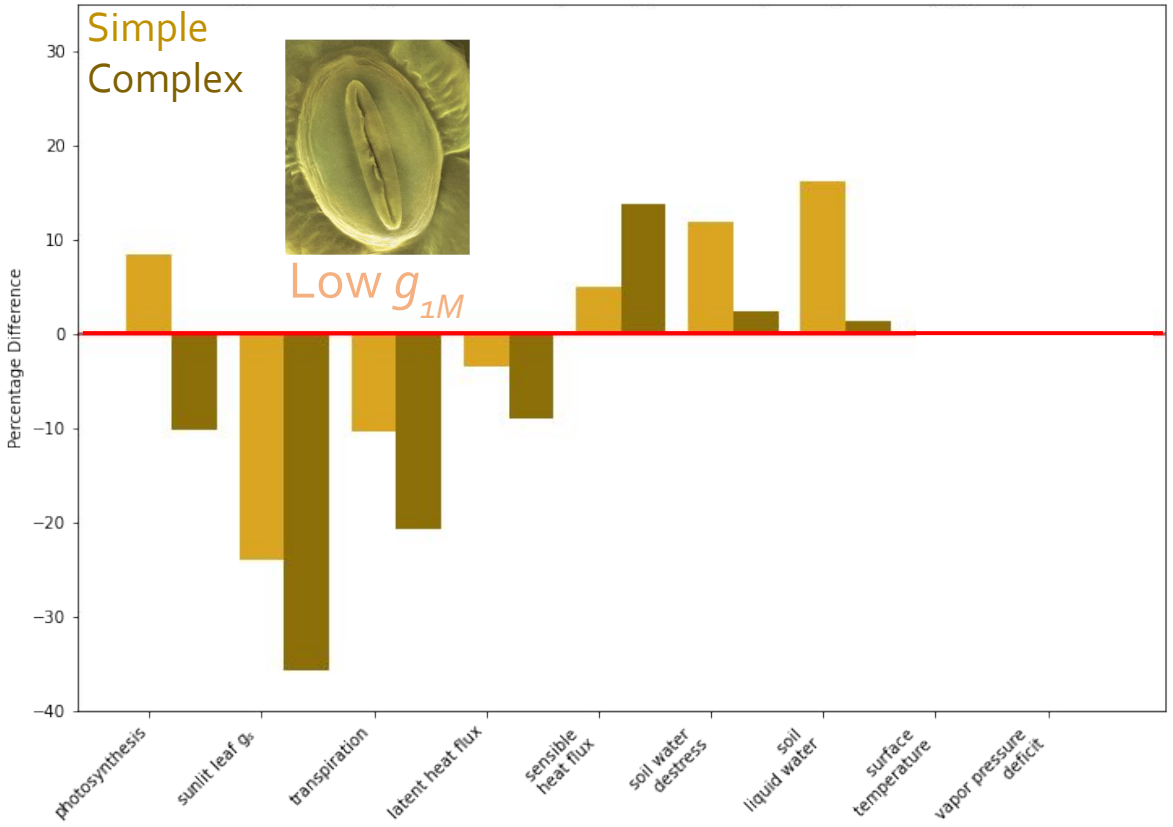
Variable % Differences for Low – Default g_{1M} in central NA

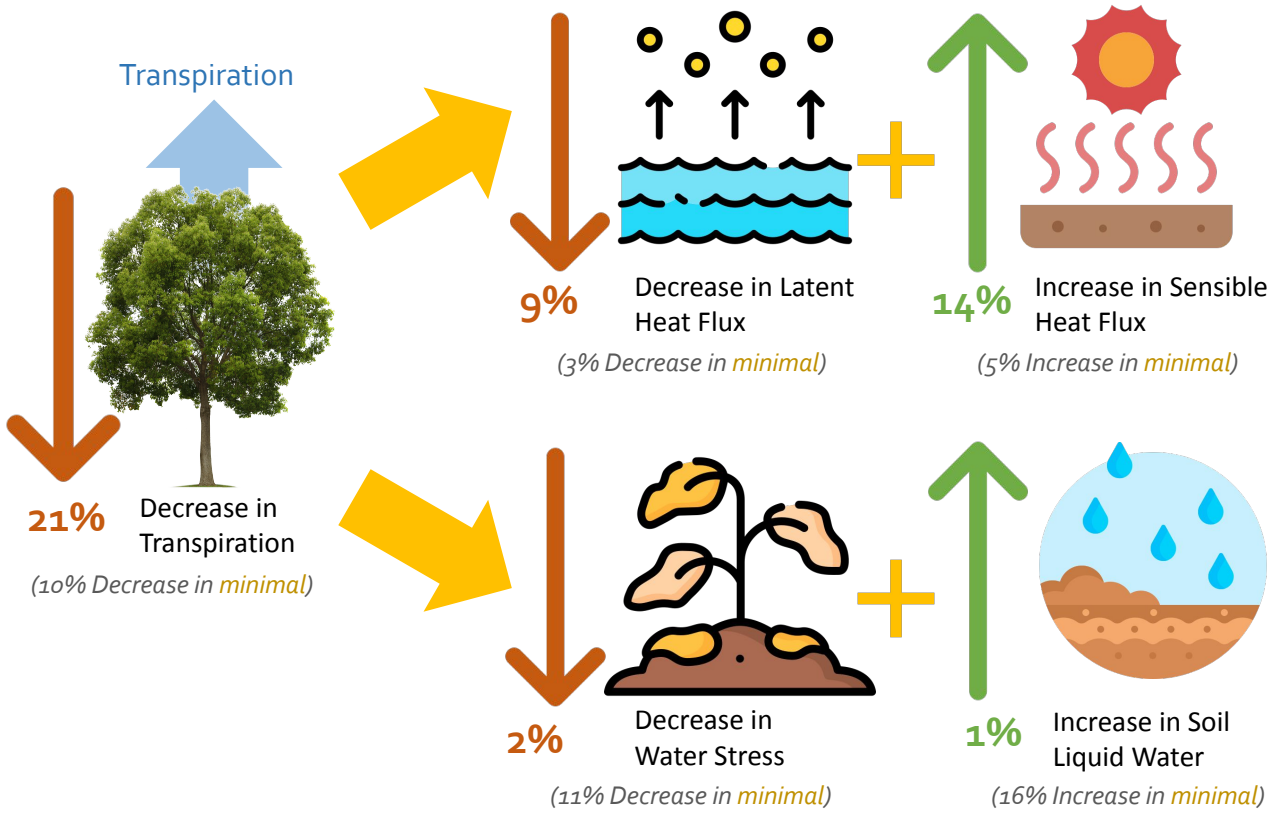




The simple case has much higher increase in water availability

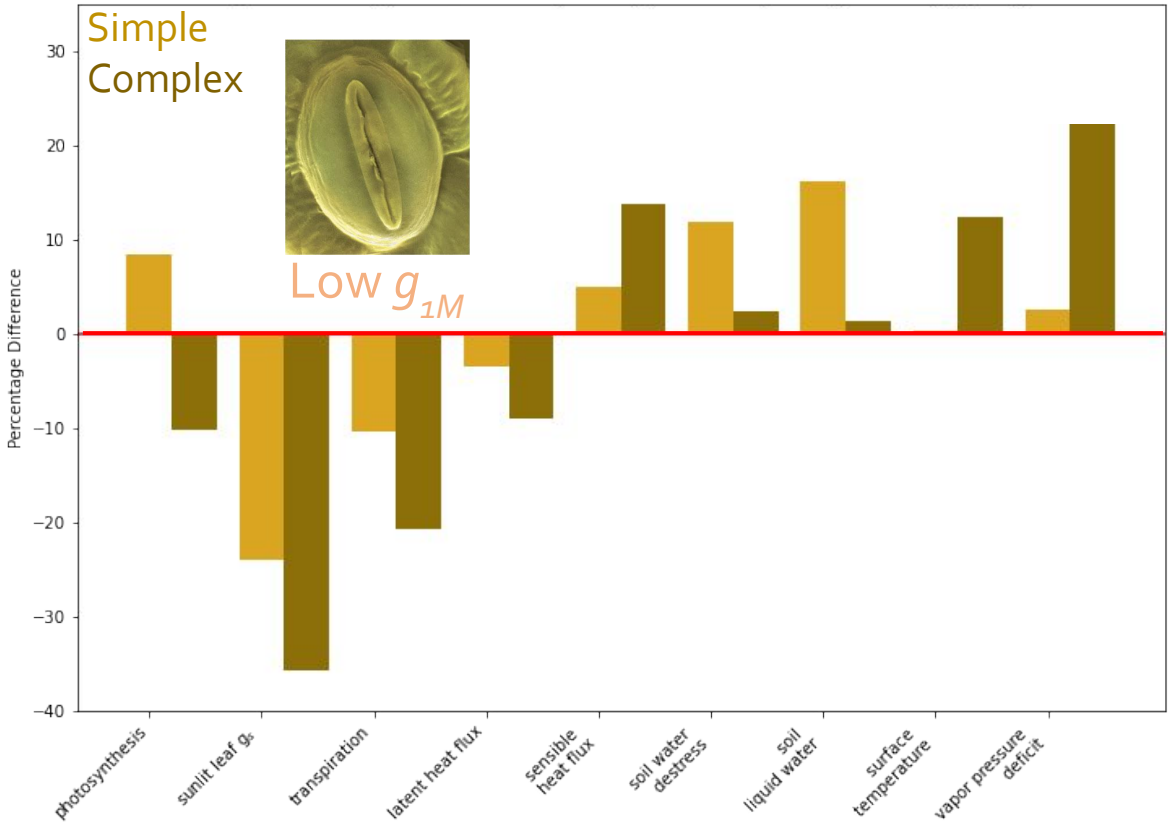
Variable % Differences for Low – Default g_{1M} in central NA

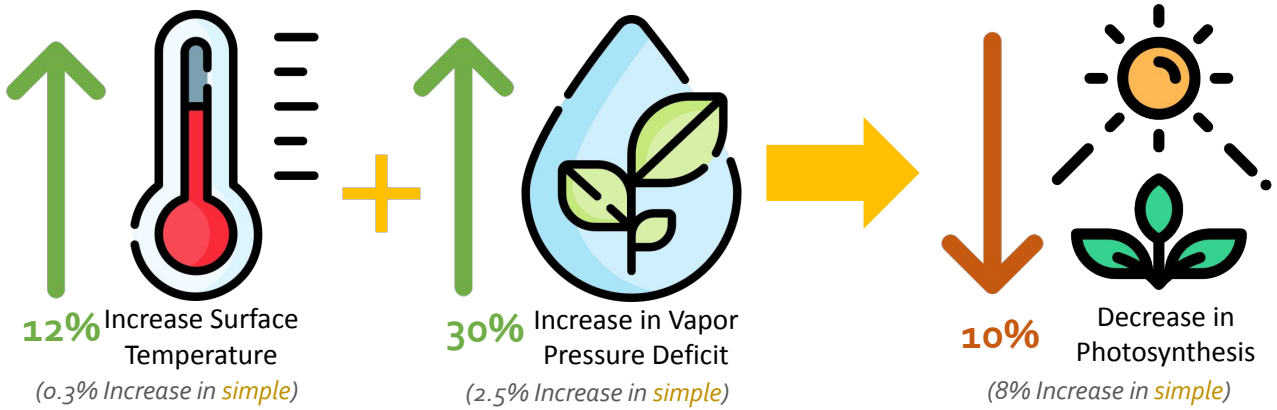




In the complex case, larger increase in temperature and VPD also increases photosynthesis

Variable % Differences for Low – Default g_{1M} in central NA

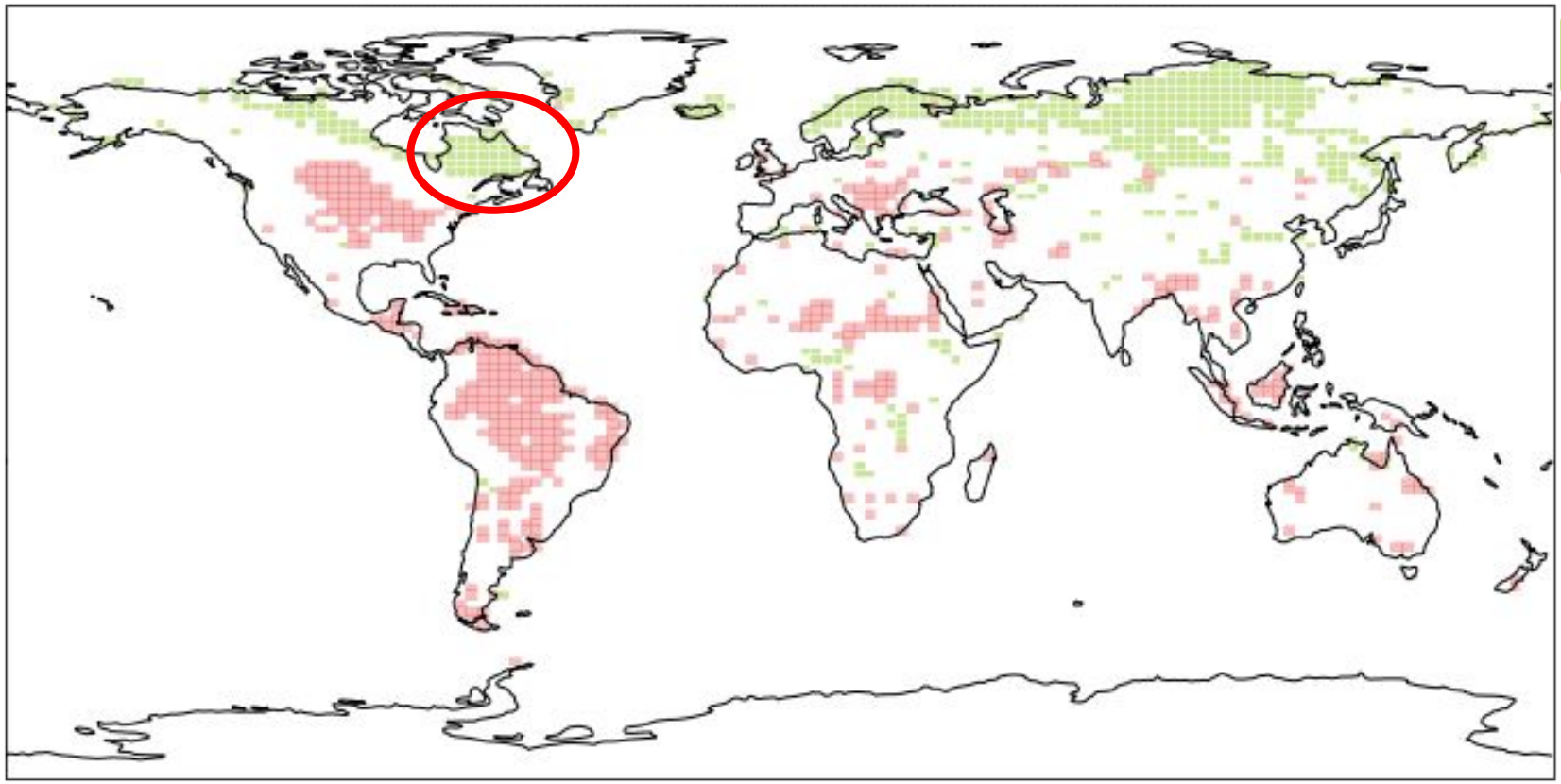




Compared to the Amazon, there is greater % Surface temperature increase, less increase in VPD, and less water availability increase (wrt to the simple case) □ plants in Central NA are more sensitive?

Zoom in on boreal Canada

Photosynthesis Sign Change Map between Simple and Complex for Low – Default g_{1M}

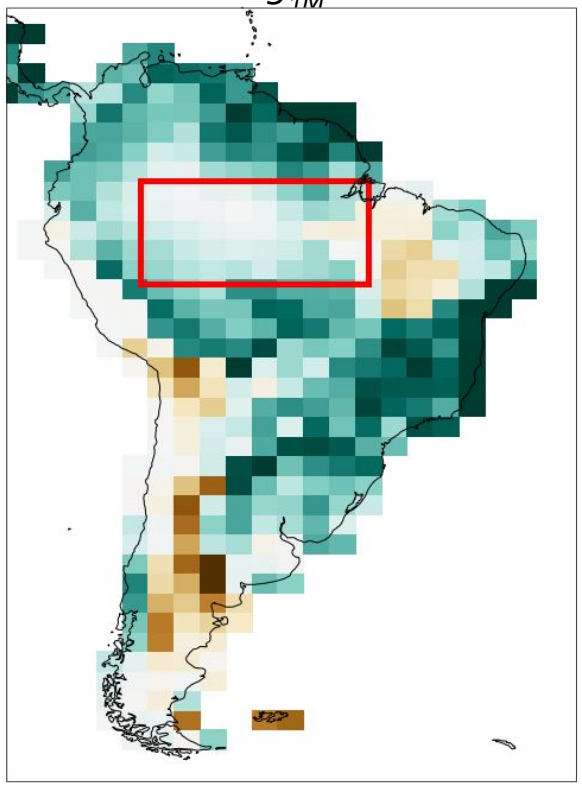


Simple negative; Complex positive

Simple positive; Complex negative

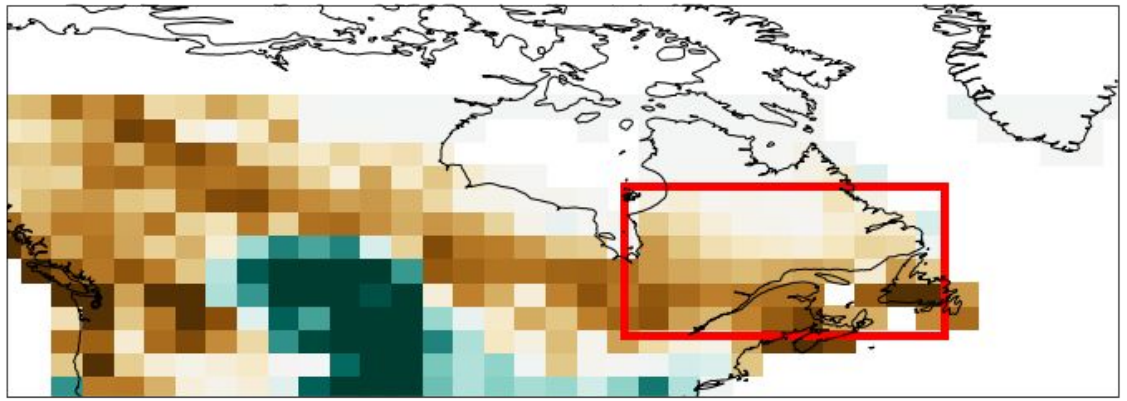
In the simple low g_{1M} case, photosynthesis unexpectedly decreases for boreal Canada

Simple:
Photosynthesis
Low – Default g_{1M}



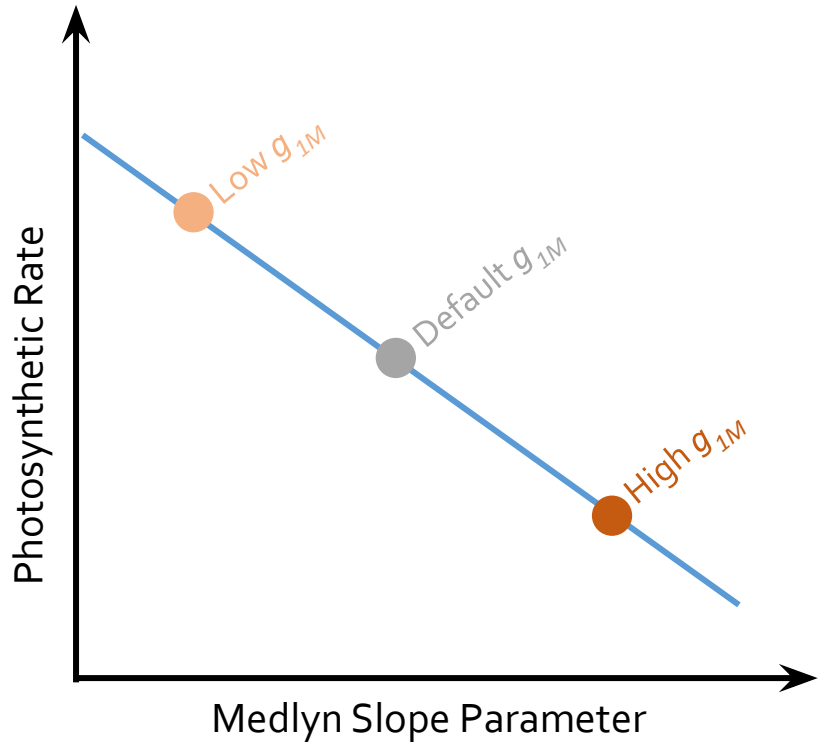
1x CO_2
uncoupled
fixed LAI

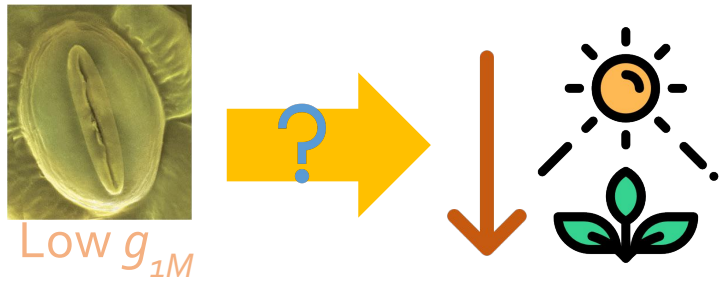
Simple: Photosynthesis Low – Default g_{1M}



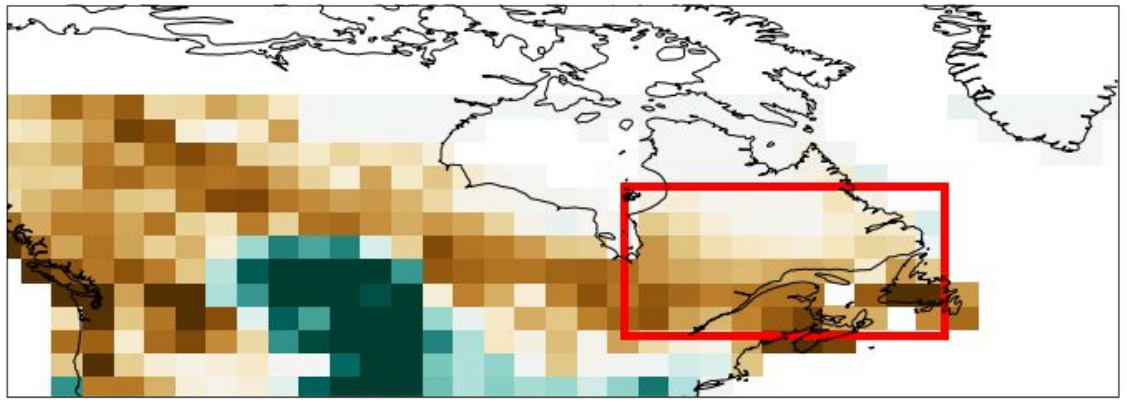
1x CO_2 | uncoupled | fixed LAI

In the simple low g_{1M} case, photosynthesis unexpectedly decreases for boreal Canada



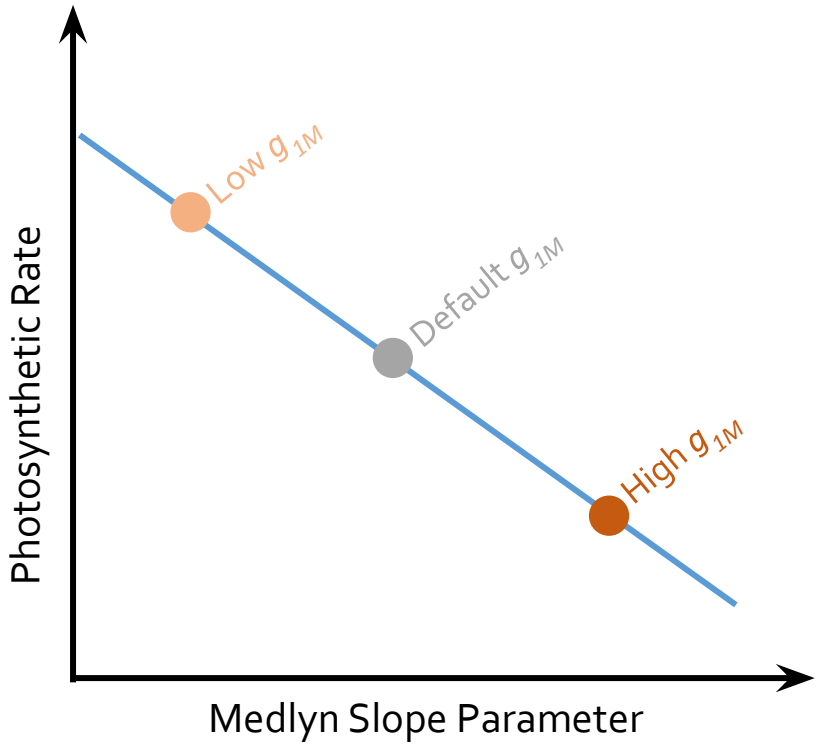


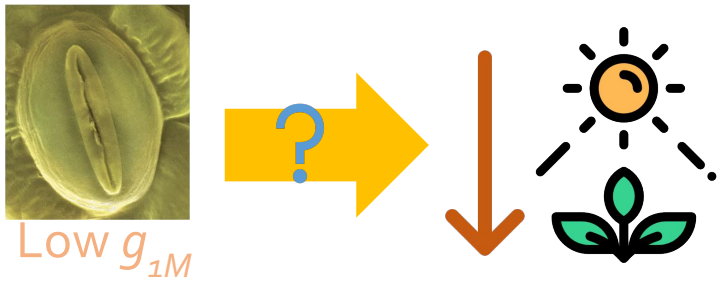
Simple: Photosynthesis Low – Default g_{1M}



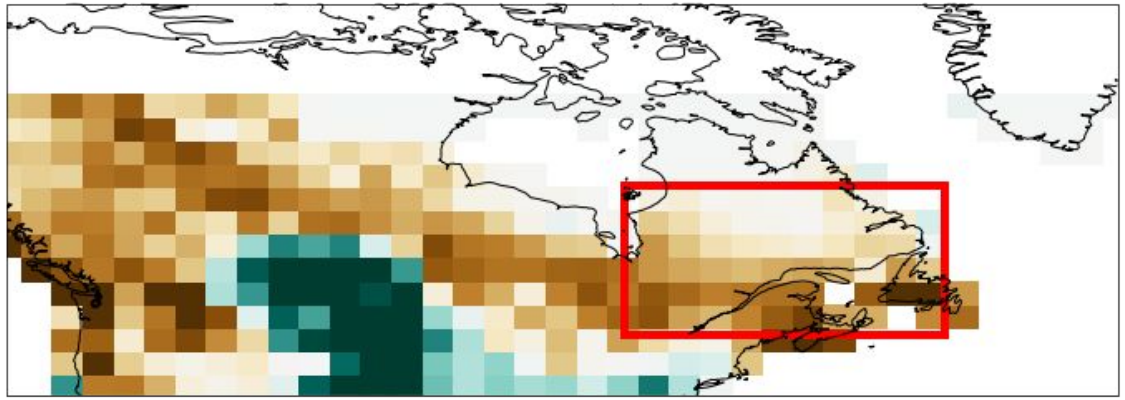
1x CO_2 | uncoupled | fixed LAI

In the complex low g_{1M} case, photosynthesis increases as expected



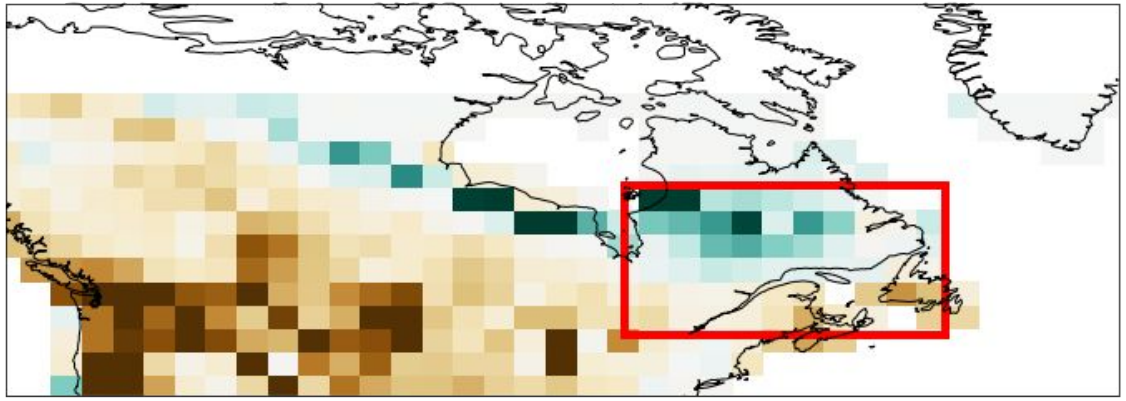


Simple: Photosynthesis Low – Default g_{1M}



1x CO_2 | uncoupled | fixed LAI

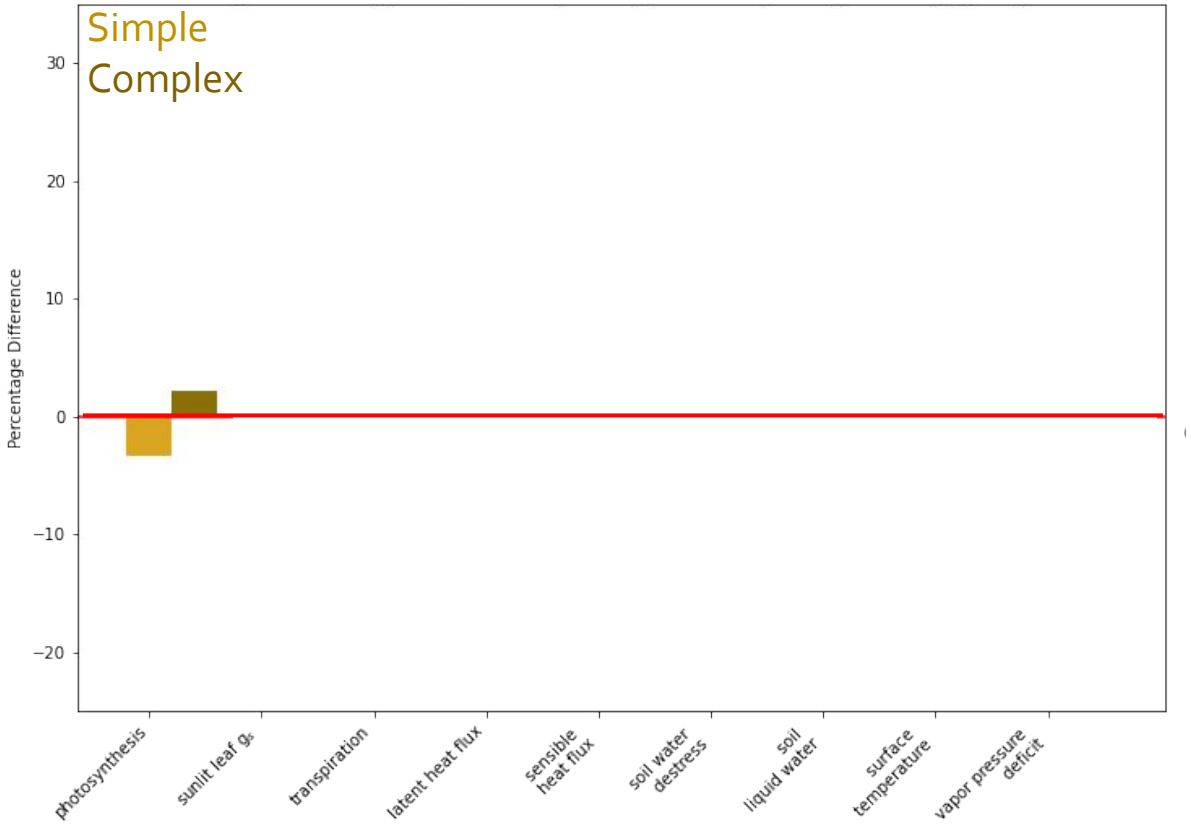
Complex: Photosynthesis Low – Default g_{1M}



1x CO_2 | coupled | dynamic LAI

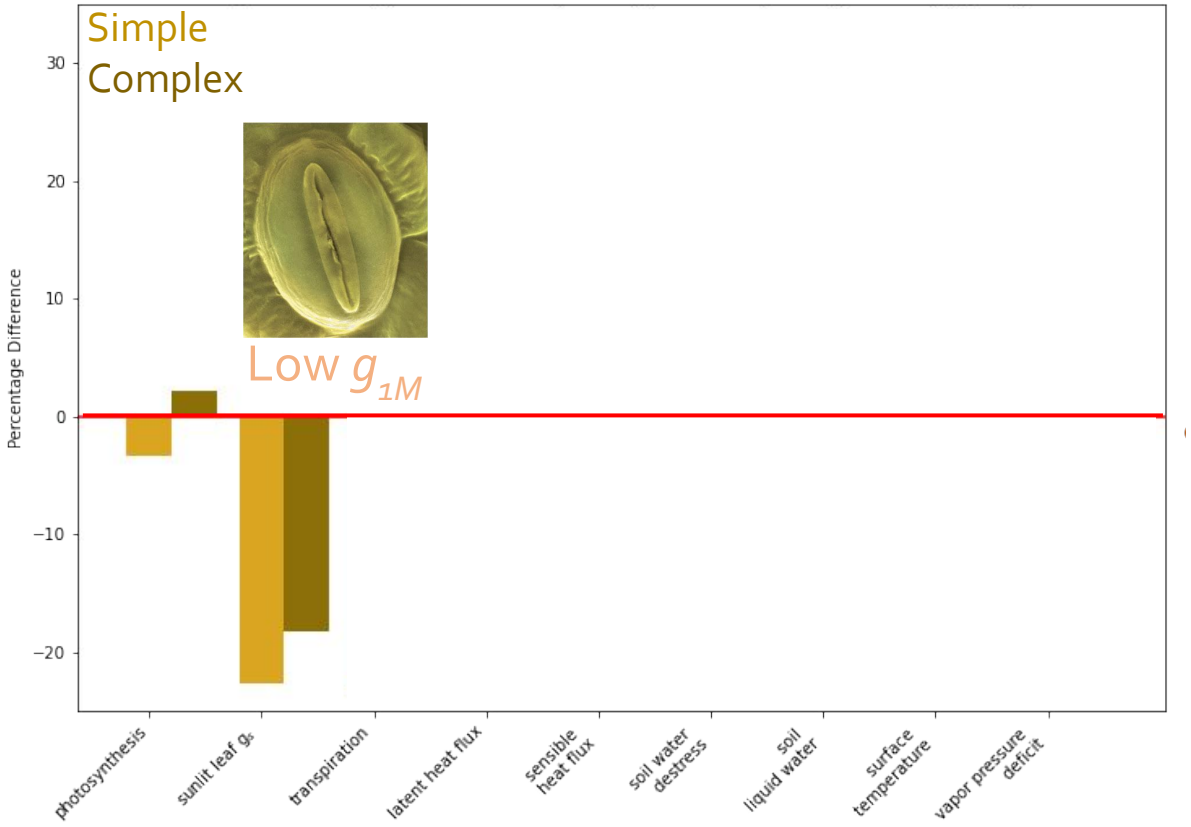
Photosynthesis decreases for simple and increases for complex low g_{1M}

Variable % Differences for Low – Default g_{1M} in boreal Canada



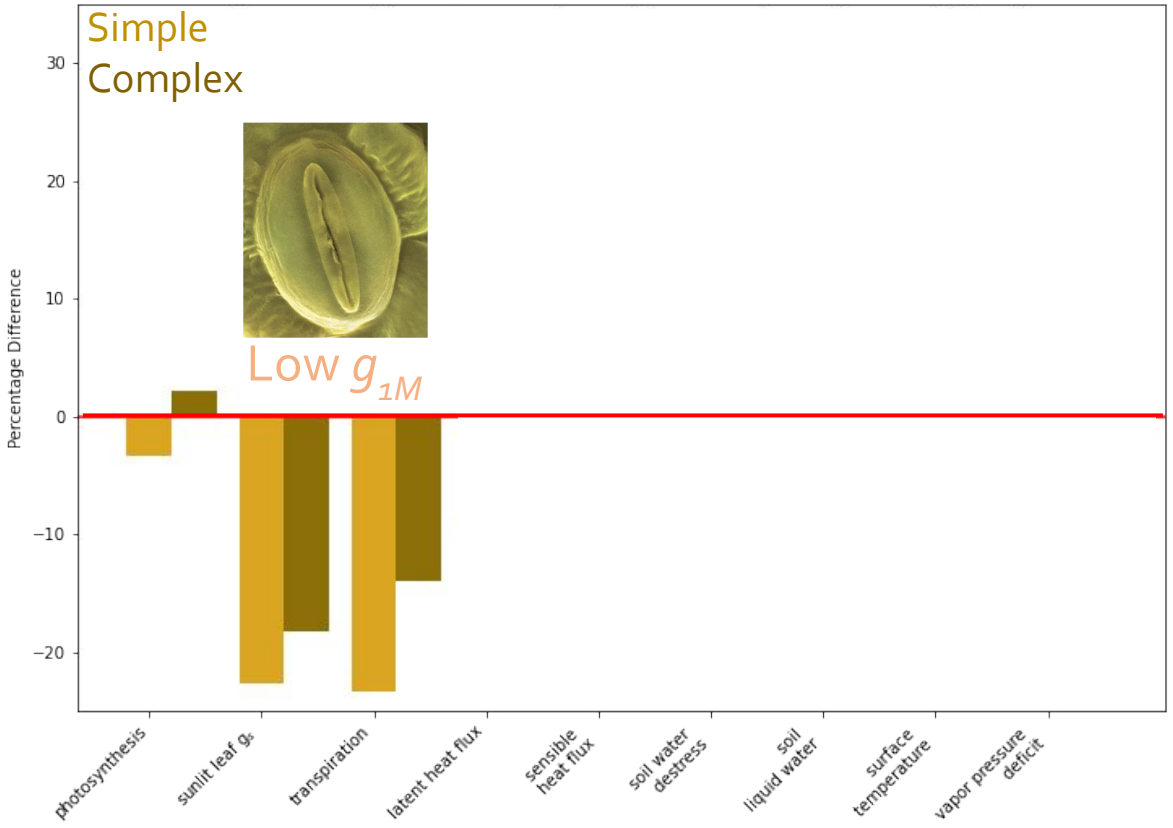
Low g_{1M} consistently decreases stomatal conductance (stomatal closure)

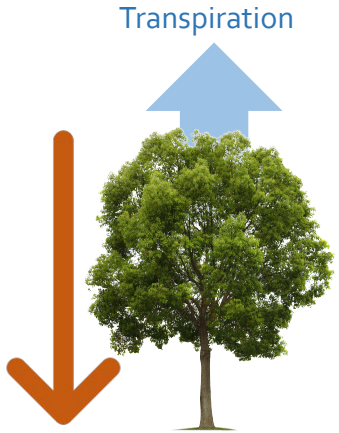
Variable % Differences for Low – Default g_{1M} in boreal Canada



Transpiration decreases as expected with stomatal closure, though not as much as the Amazon

Variable % Differences for Low – Default g_{1M} in boreal Canada



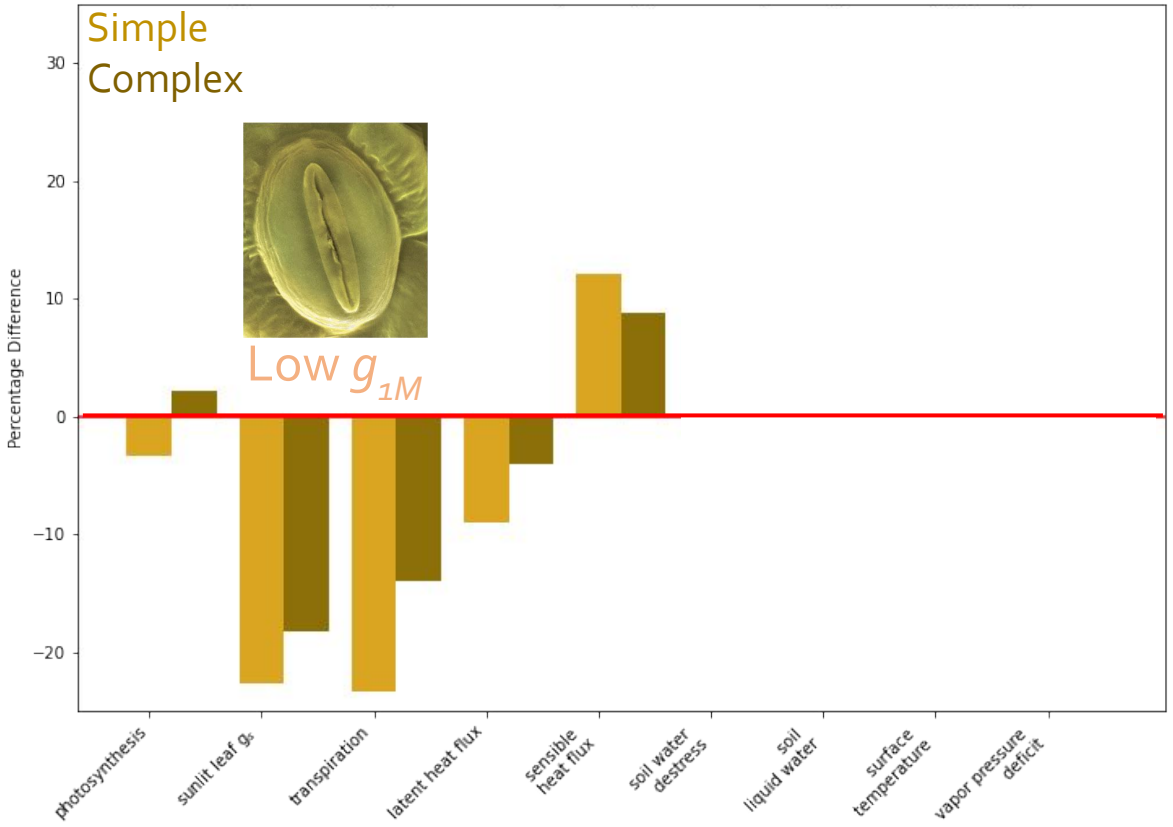


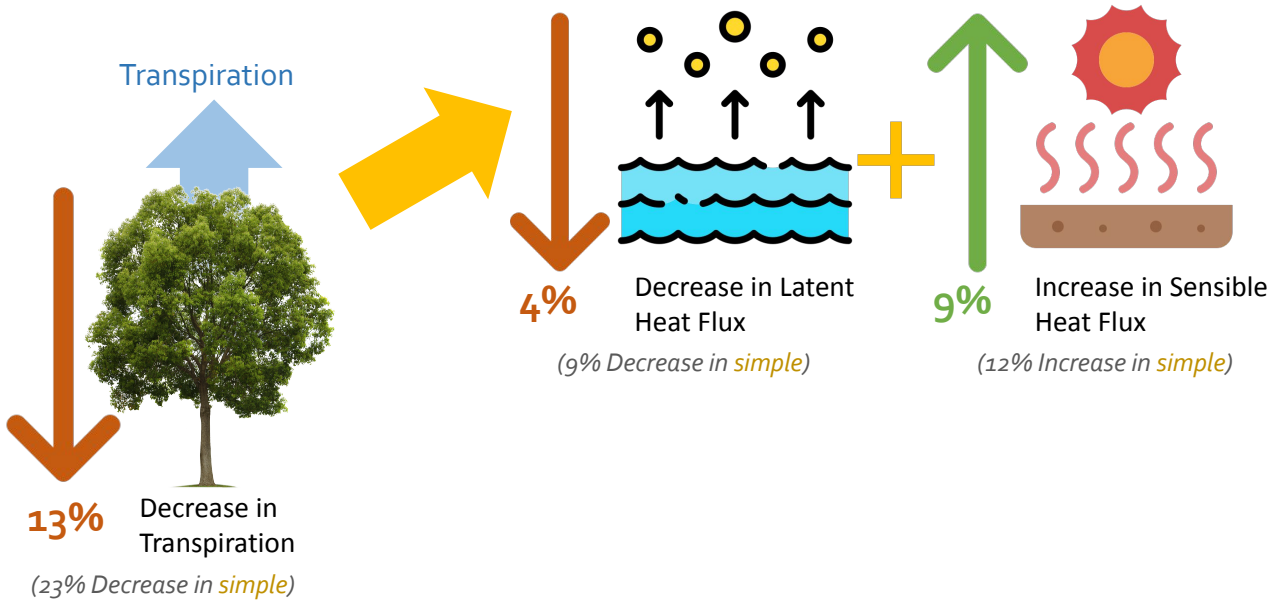
13% Decrease in Transpiration

(23% Decrease in simple)

The heat fluxes also change as expected

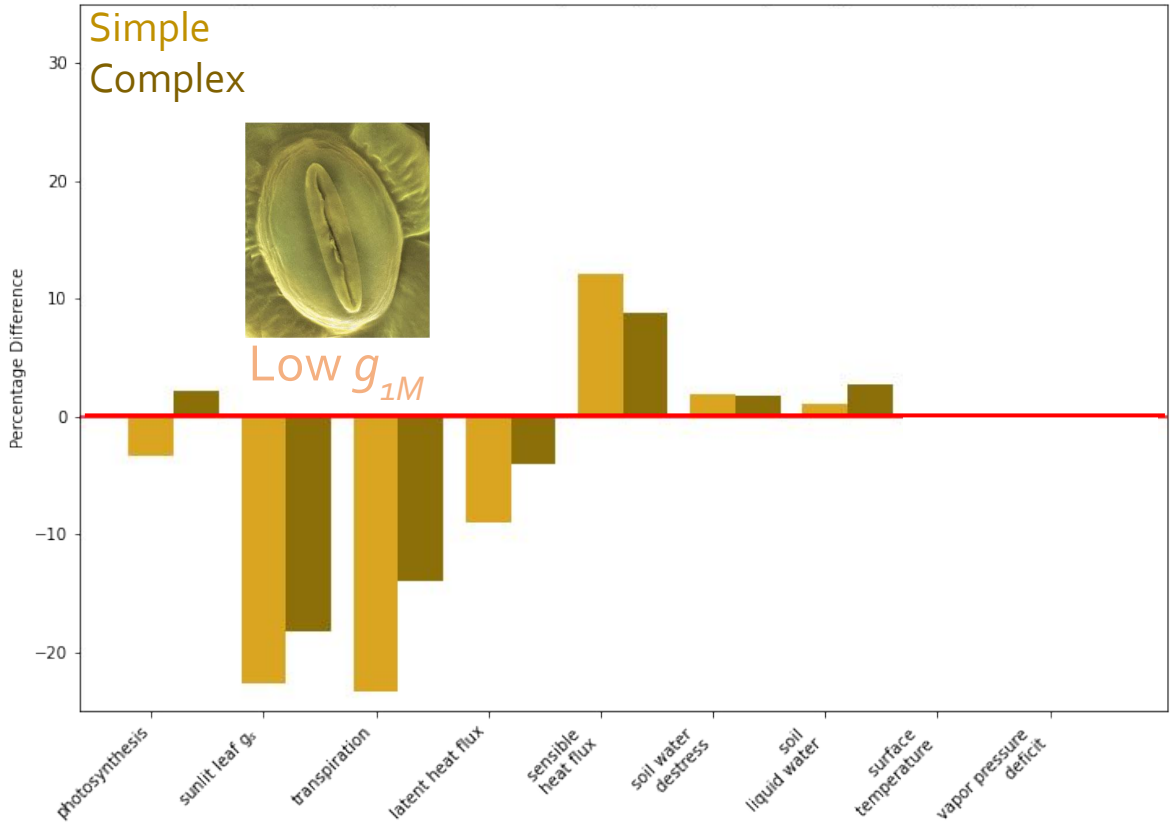
Variable % Differences for Low – Default g_{1M} in boreal Canada

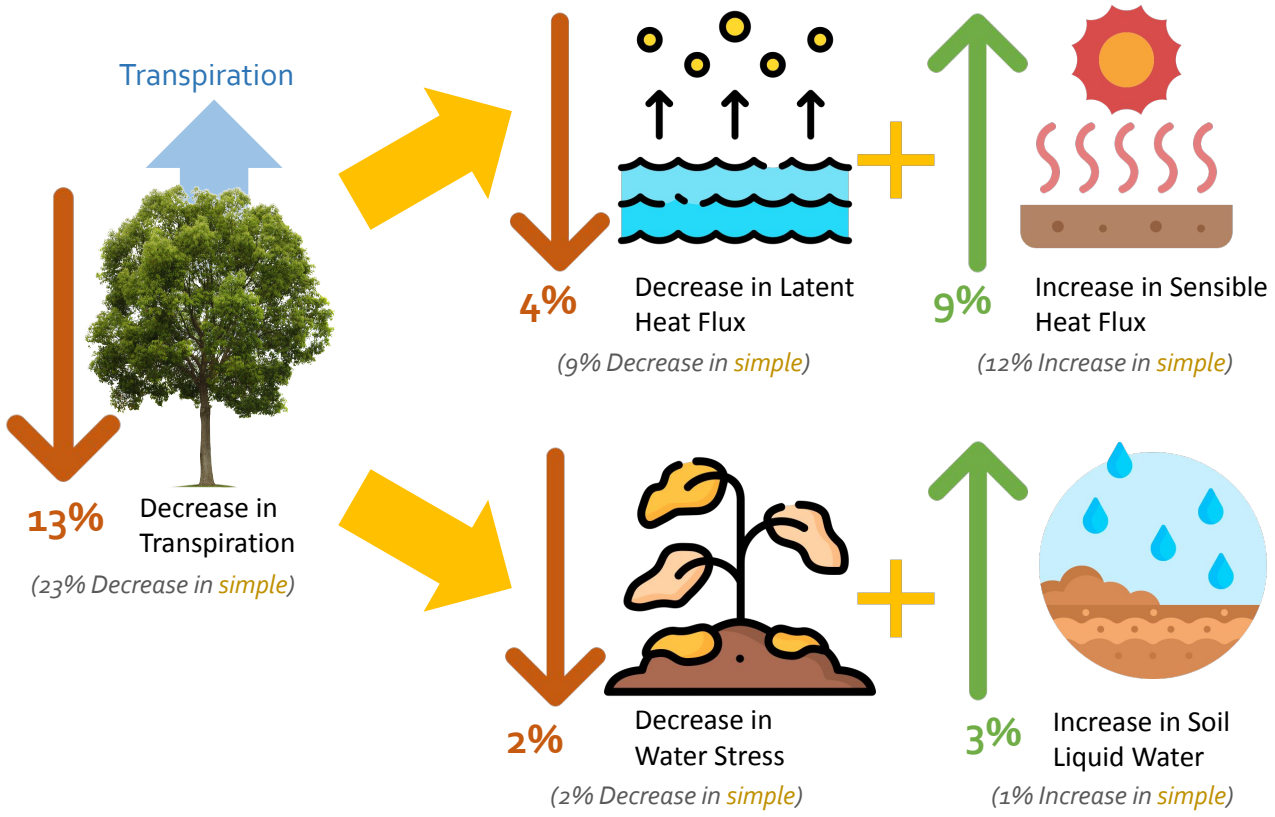




Not much changes in water availability

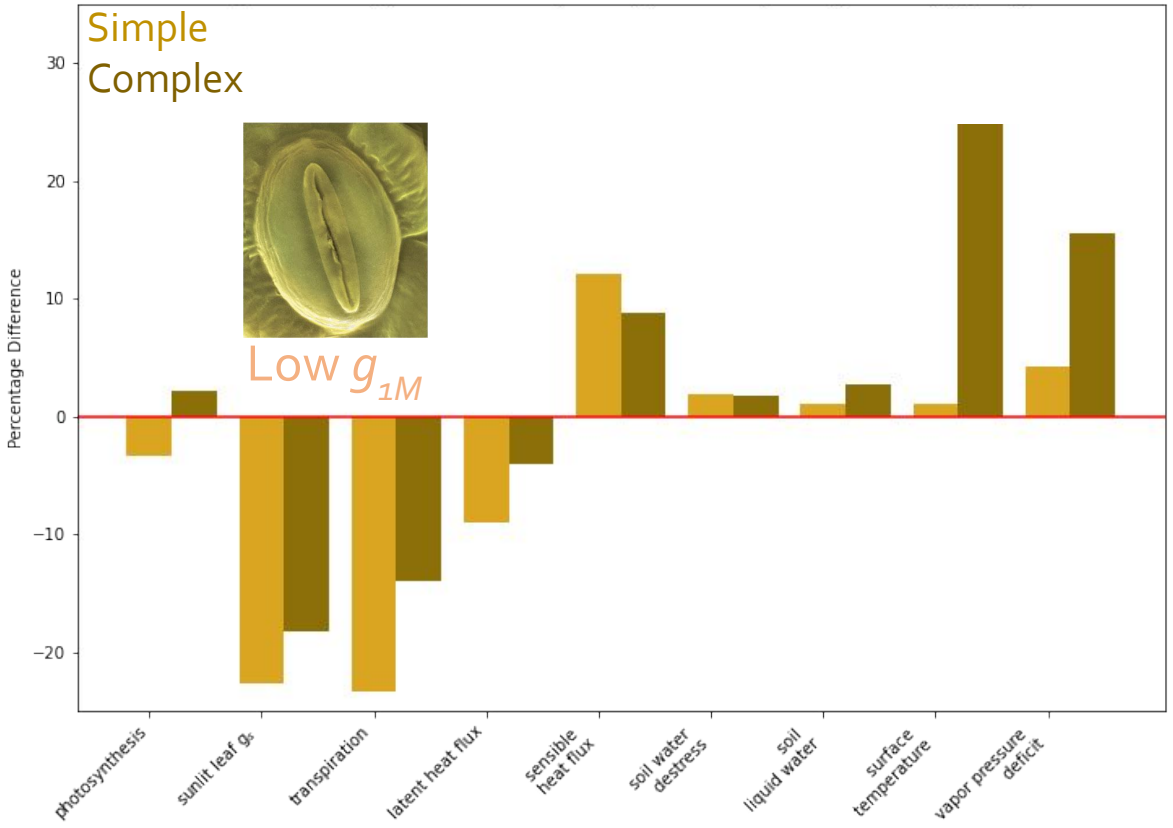
Variable % Differences for Low – Default g_{1M} in boreal Canada

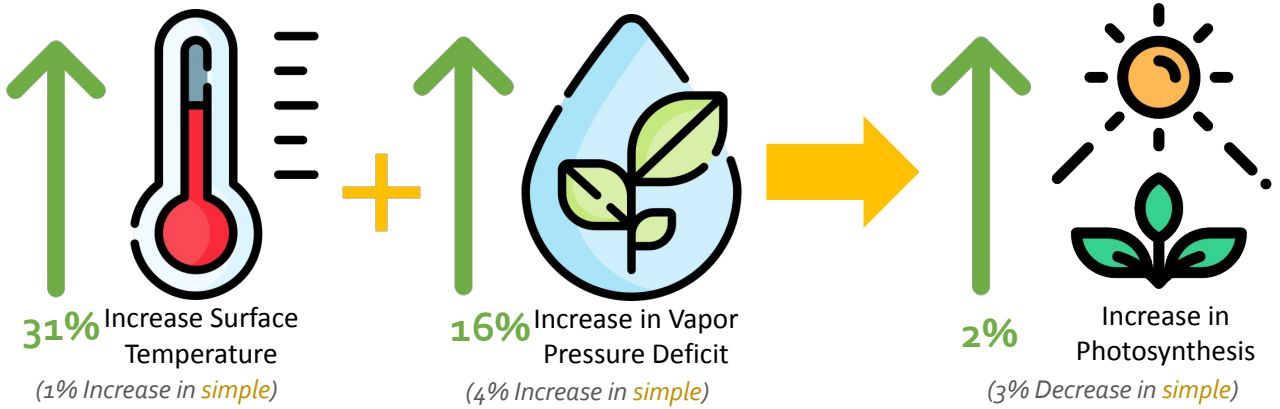




In the complex case, large increase in temperature and VPD increases photosynthesis

Variable % Differences for Low – Default g_{1M} in boreal Canada





To summarize

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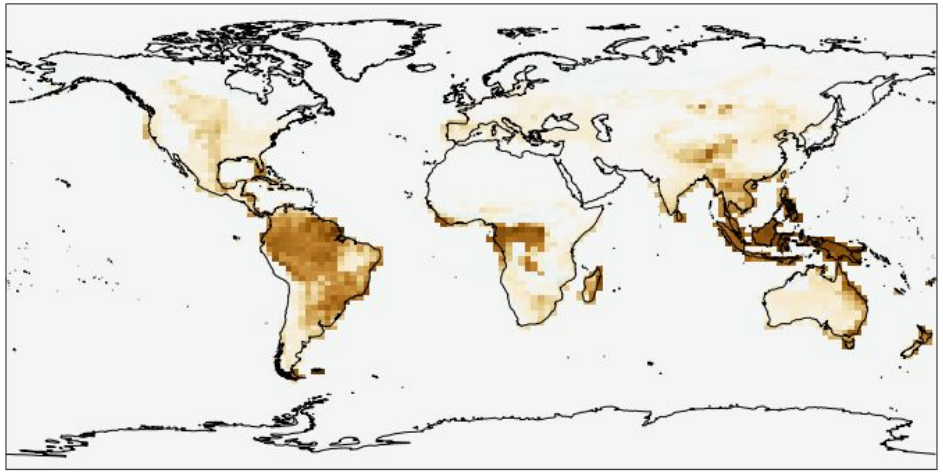
- High Medlyn slope decreasing photosynthesis is consistent

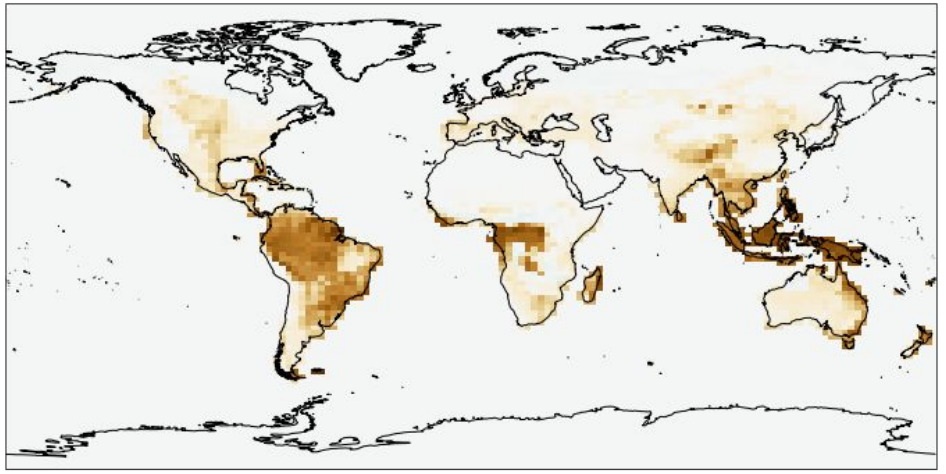
Simple: Photosynthesis High – Default g_{1M}



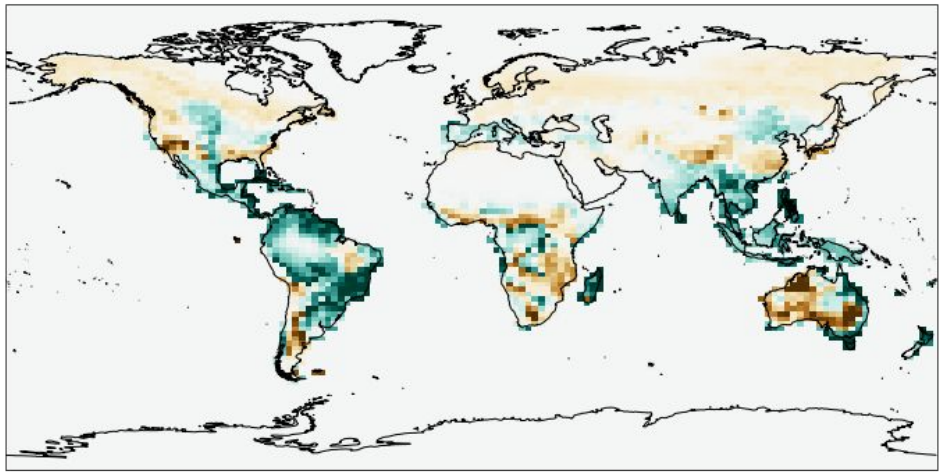
To summarize

- High Medlyn slope decreasing photosynthesis is consistent
- Low Medlyn slope effects on photosynthesis are regionally dependent

Simple: Photosynthesis High – Default g_{1M}

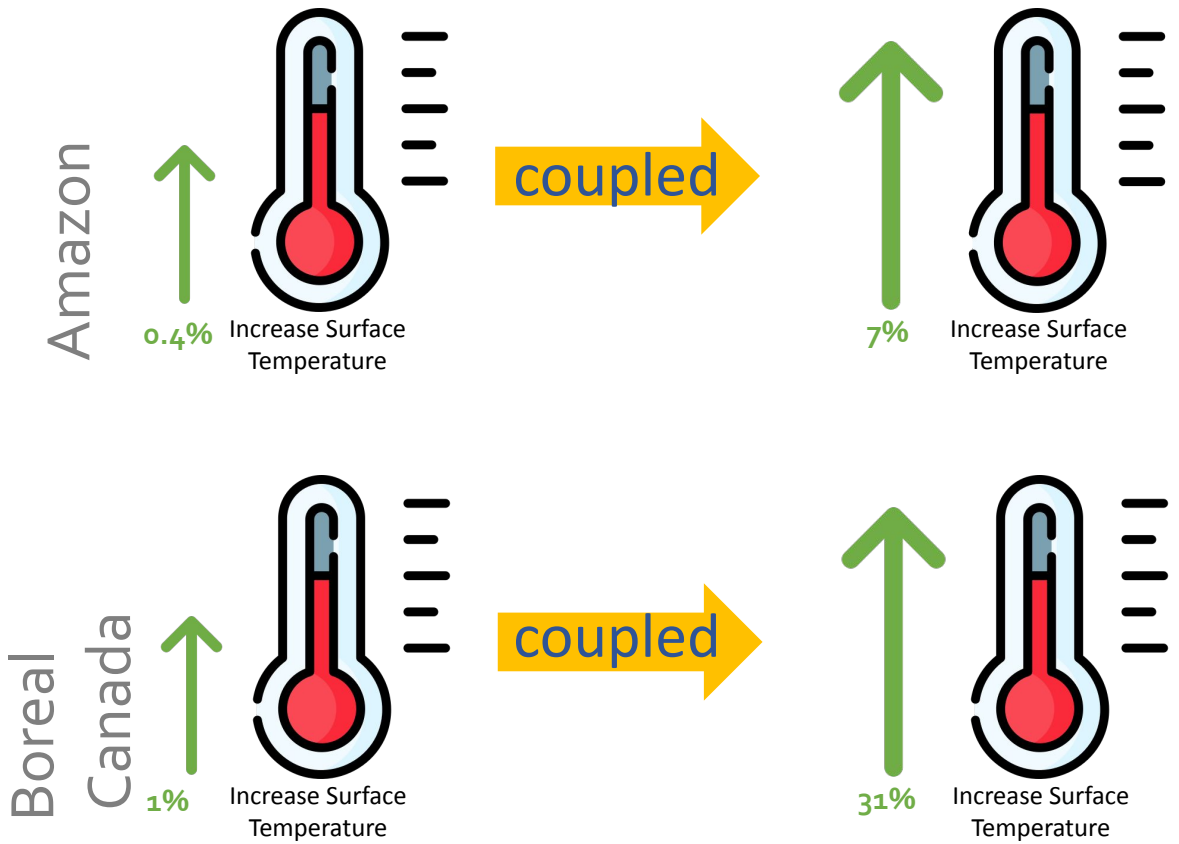


Simple: Photosynthesis Low – Default g_{1M}



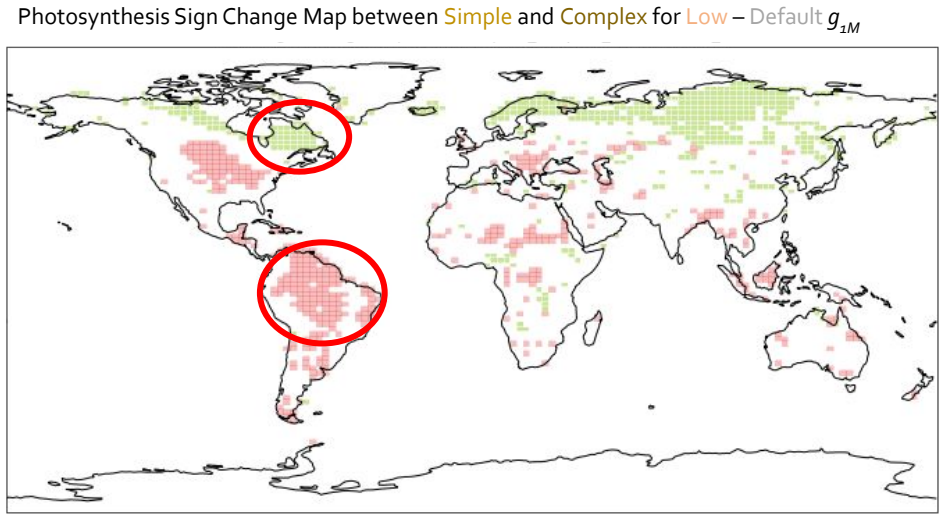
To summarize

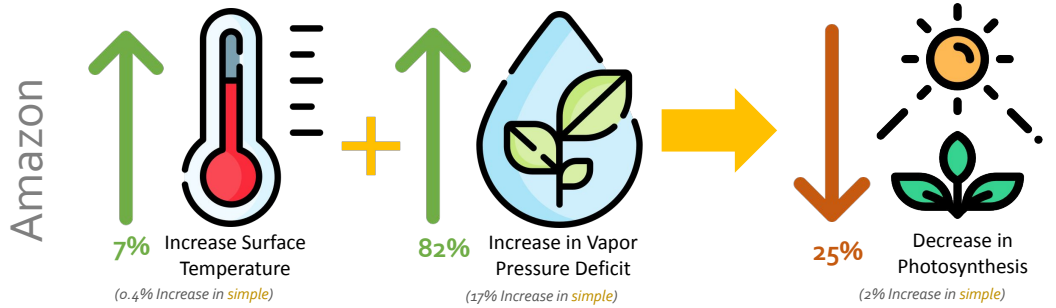
- High Medlyn slope decreasing photosynthesis is consistent
- Low Medlyn slope effects on photosynthesis are regionally dependent
- A coupled atmosphere enables the climate to respond differently

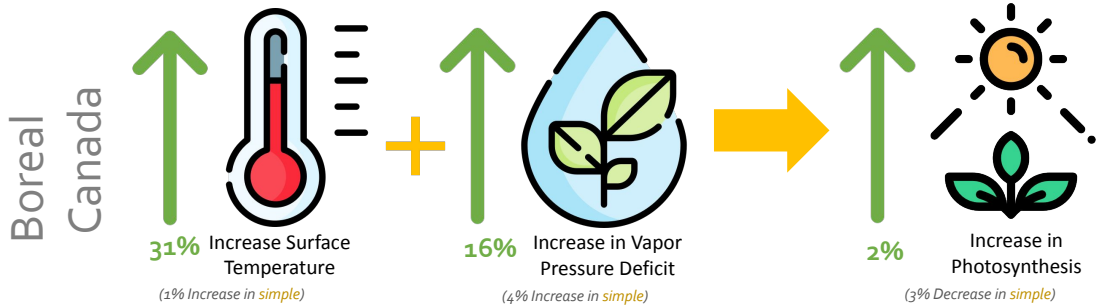


To summarize

- High Medlyn slope decreasing photosynthesis is consistent
- Low Medlyn slope effects on photosynthesis are regionally dependent
- A coupled atmosphere enables the climate to respond differently
- Photosynthesis is sensitive to the temperature changes depending on region







Thank you

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

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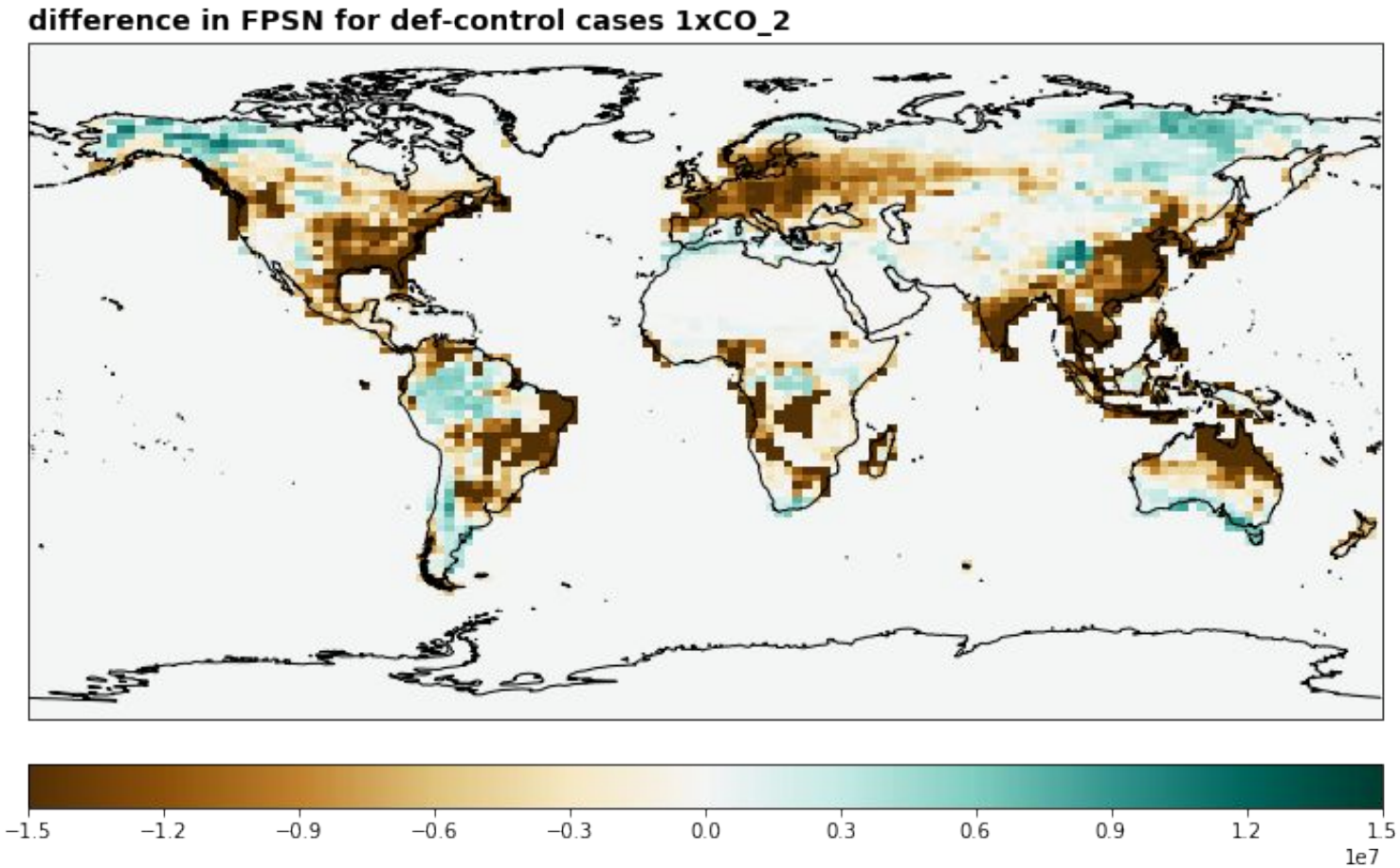
Difference between simple and complex configuration