Empirically Derived Sensitivity of Vegetation to Climate as a Possible Functional Constraint

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The International Land Model Benchmarking Project

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University of Washington

May 18th, 2016

ILAMB Constraints

- Annual Mean
- Seasonal Cycle
- Interannual Variability
- Trend

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Empirical Functional Constraint

- Observations at Model Spatial Scale
- Sensitivity of Vegetation to Climate
- Analyzed Across Climate Space

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- Annual Mean
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Earth System Model

Empirical Functional Constraint

- Observations at Model Spatial Scale
- Sensitivity of Vegetation to Climate
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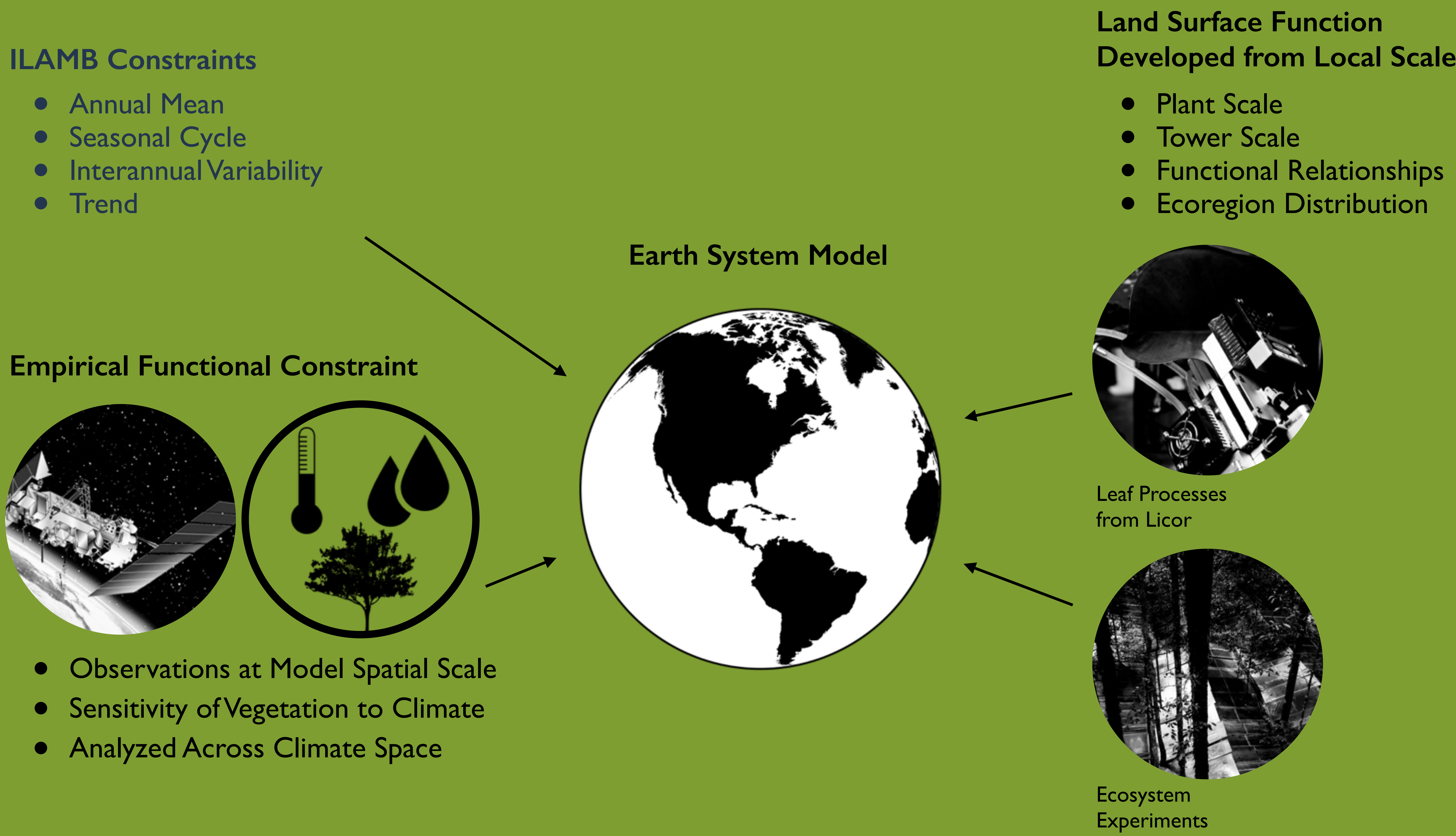
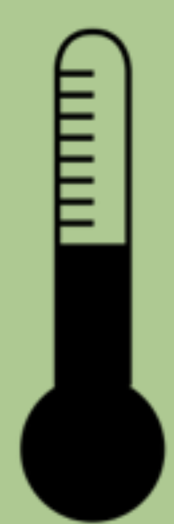

ILAMB Constraints
• Annual Mean
• Seasonal Cycle
• Interannual Variability
• Trend
Land Surface Function
Developed from Local Scale
• Plant Scale
• Tower Scale
• Functional Relationships
• Ecoregion Distribution
Earth System Model
Empirical Functional Constraint
Leaf Processes
from Licor
• Observations at Model Spatial Scale
• Sensitivity of Vegetation to Climate
• Analyzed Across Climate Space
Ecosystem
Experiments

Observations - Climate and Vegetation

Datasets:

Normalized Difference
Vegetation Index 3g

(Pizon and Tucker, 2014)



2 meter Temperature
ERA-Interim Reanalysis

(Dee et al, 2011)

Global Precipitation Climatology
Project (Rain)

(Adler et al, 2003)

Thermometer by Michael Zick Doherty from The Noun Project
Water by Megan Sheehan from The Noun Project
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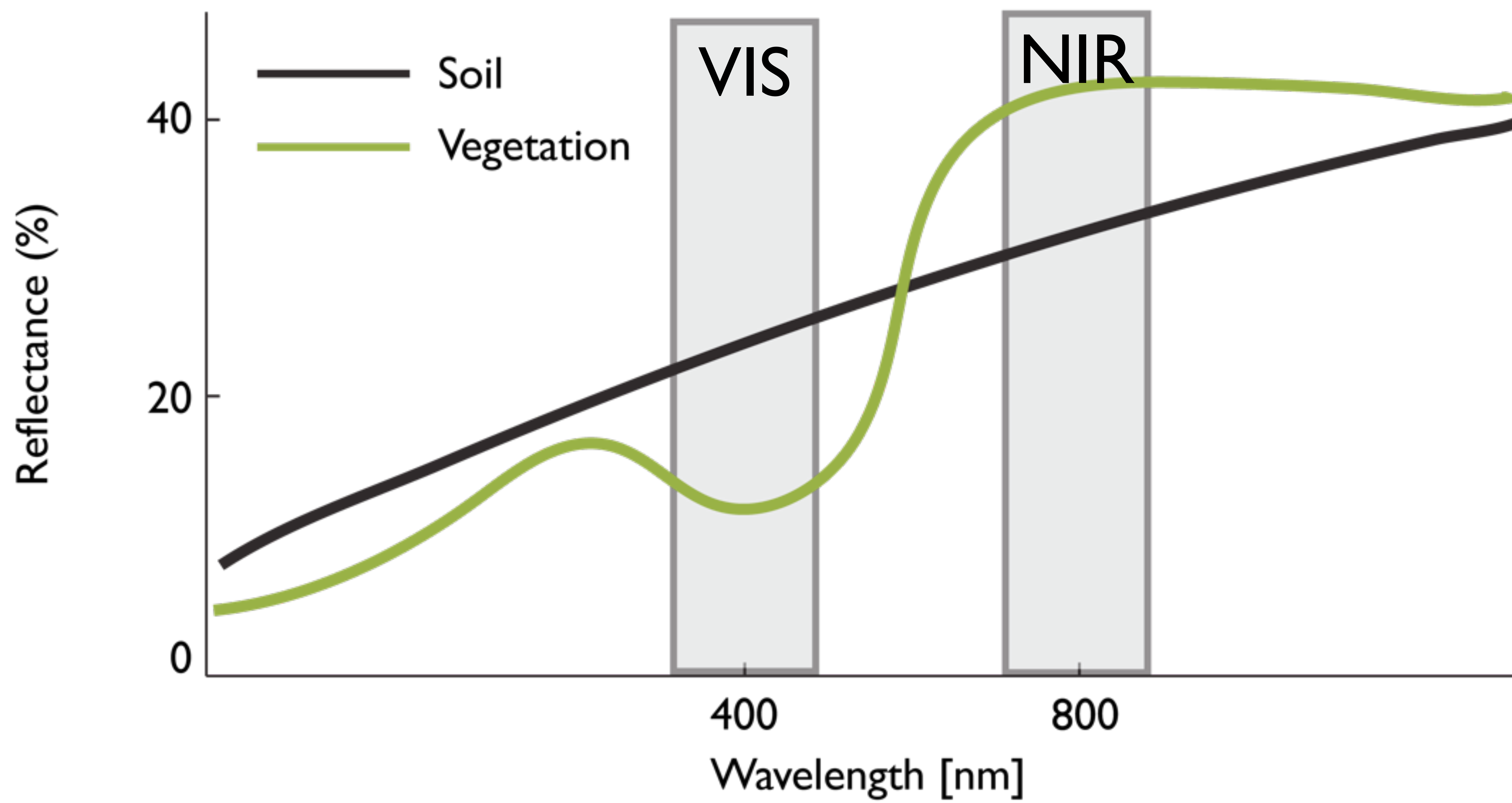
Normalized Difference Vegetation Index

$$NDVI = \frac{NIR - VIS}{NIR + VIS}$$

Pinzon and Tucker 2014

Green leaves absorb strongly in the visible

$$NDVI = \frac{NIR - VIS}{NIR + VIS}$$



http://earthobservatory.nasa.gov
http://www.geoinformatics.com/

Observations - Climate and Vegetation

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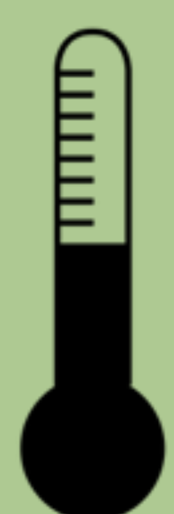

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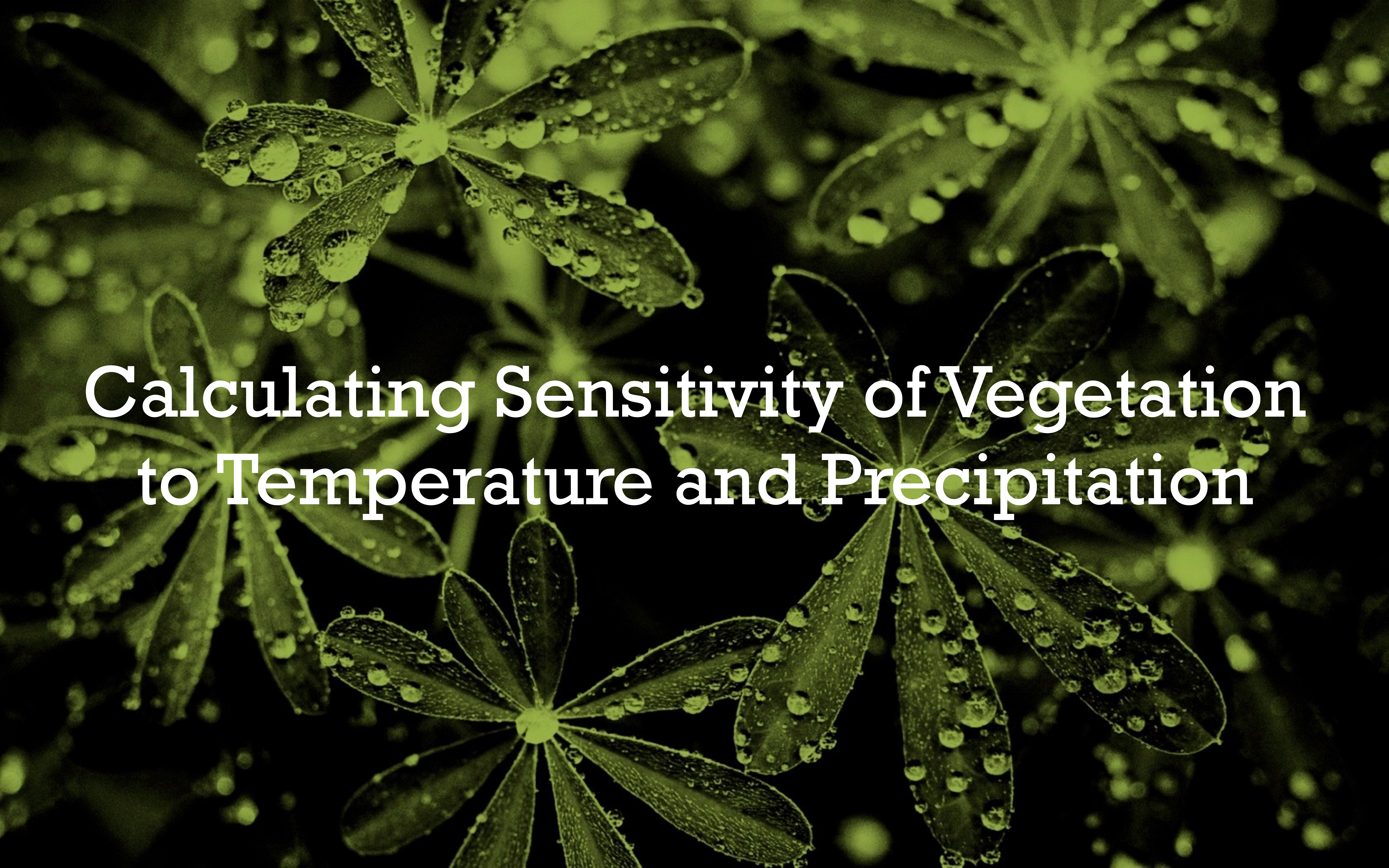
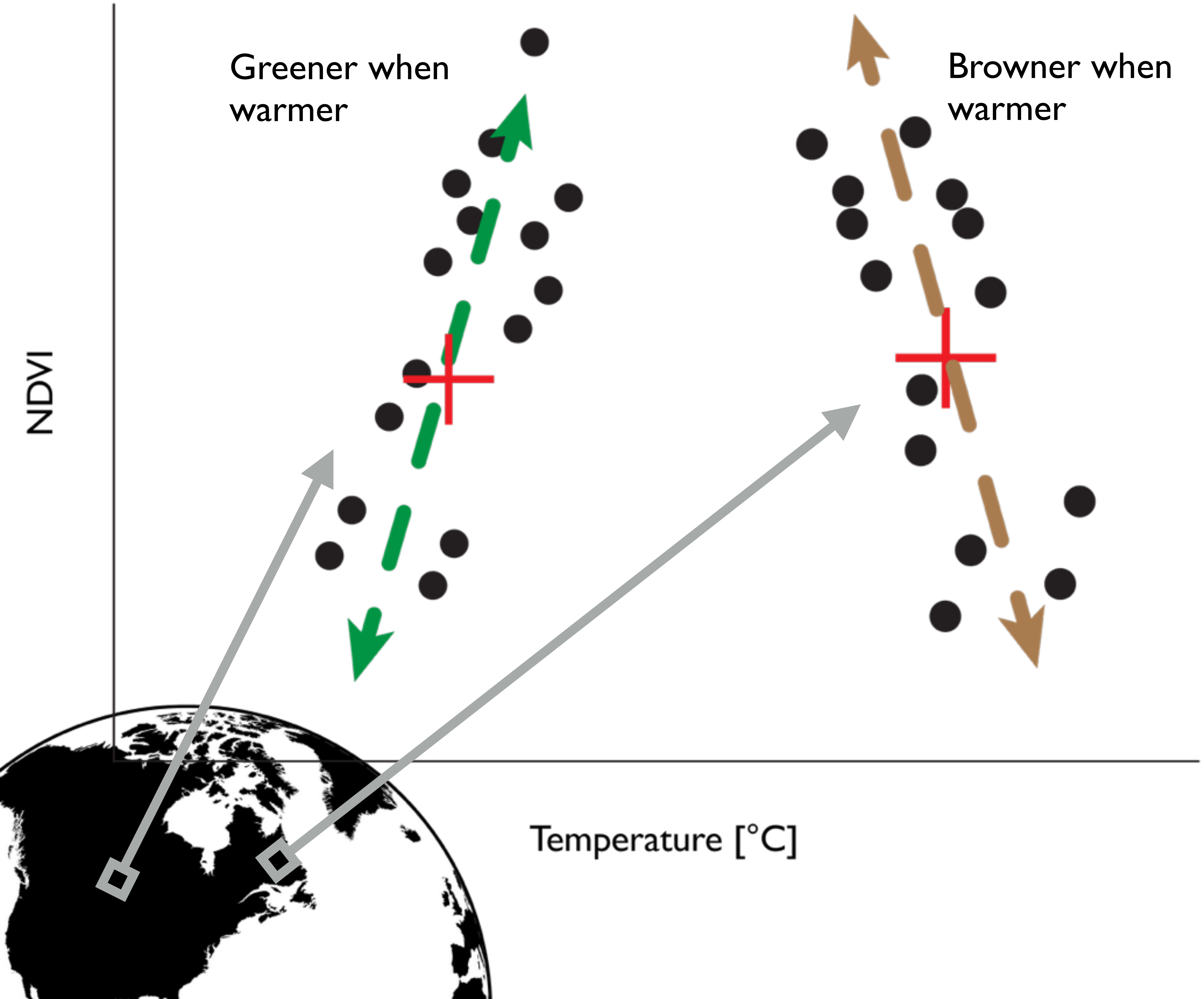

Calculating Sensitivity of Vegetation
to Temperature and Precipitation

Robust Multiple Regression, 1997 - 2012

Sensitivity

$$\%\Delta NDVI = \beta_o + T_{MAT}\,\beta_{Temp} + P_{MAP}\,\beta_{Precip}$$

Example of sensitivity to temperature



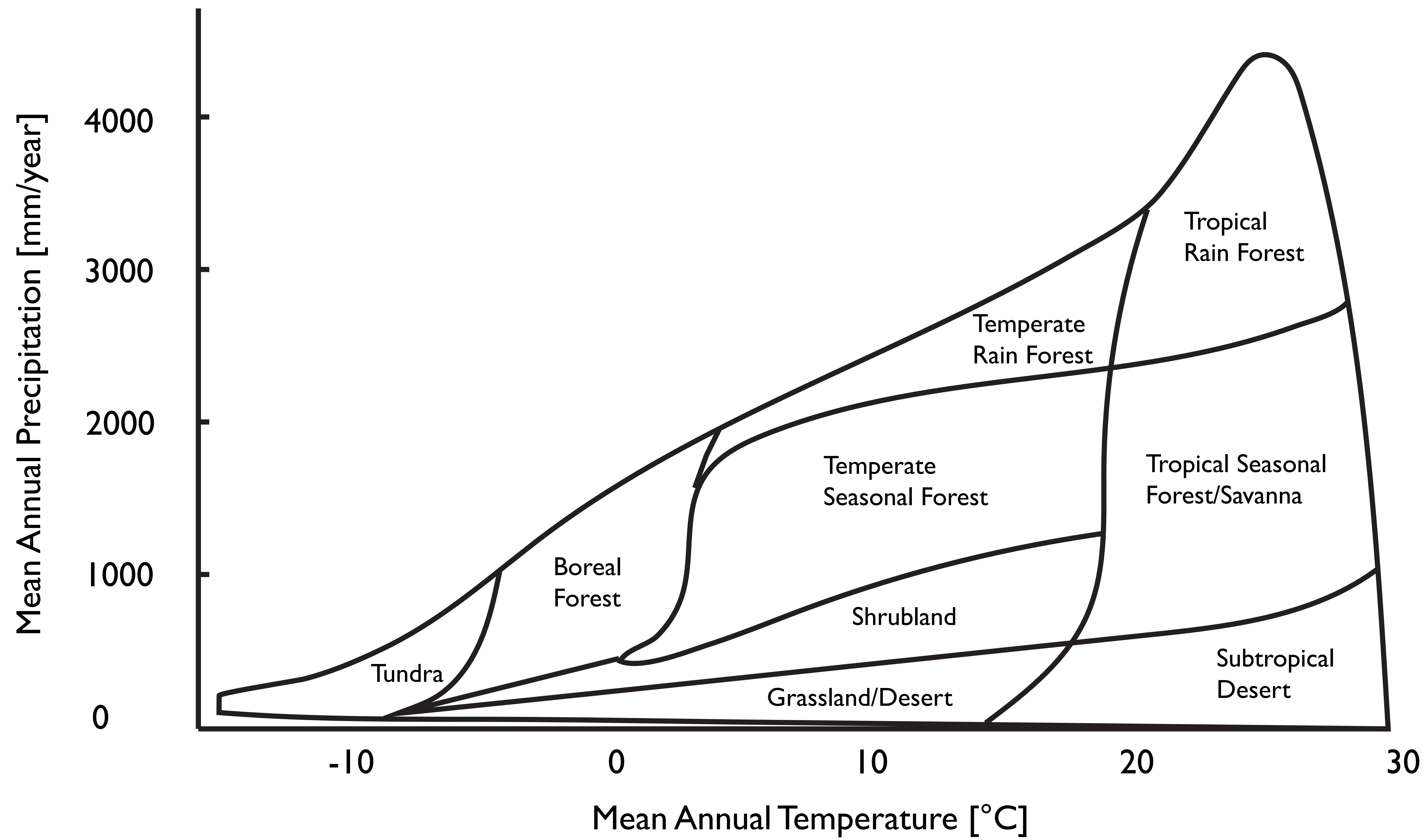
$$\text{Sensitivity} = \frac{\%\Delta NDVI}{\Delta Temp}$$

Whittaker climate space

Classifications built around temperature and precipitation.

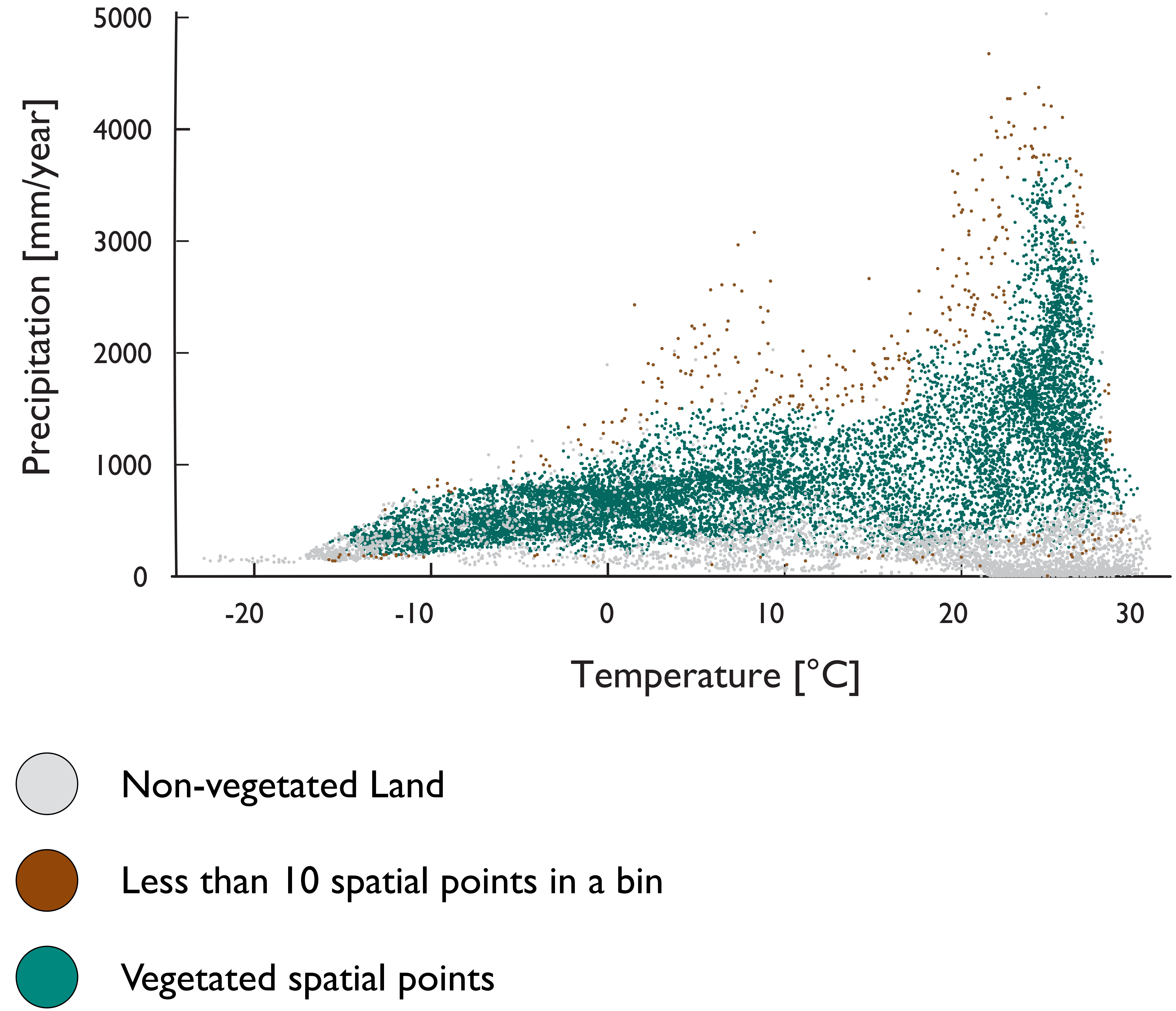
Climate boundaries established along biome boundaries

No observation of vegetation processes.



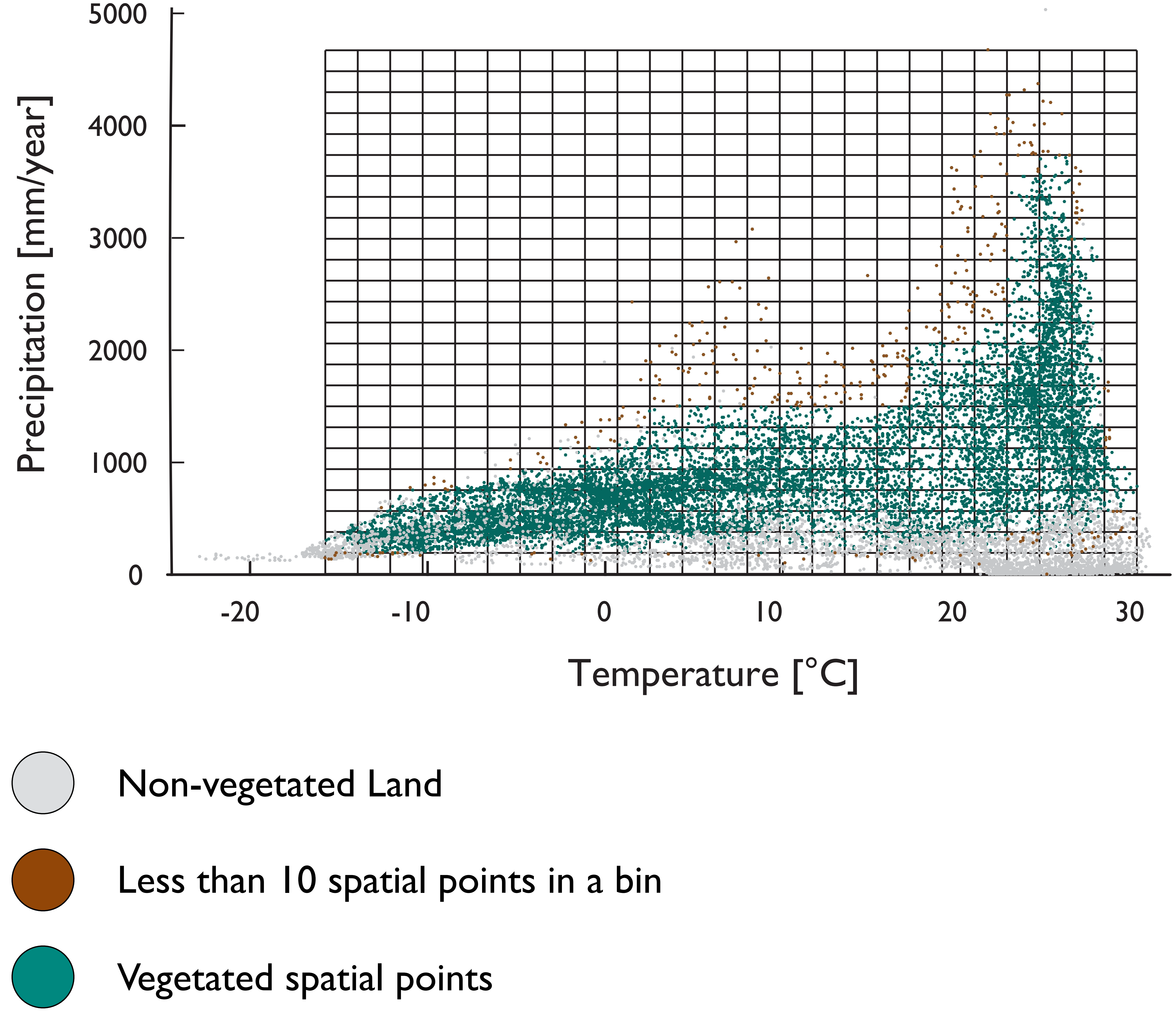
Whittaker 1970

Project from geographic to climate space



Collect spatial grid cells into bins

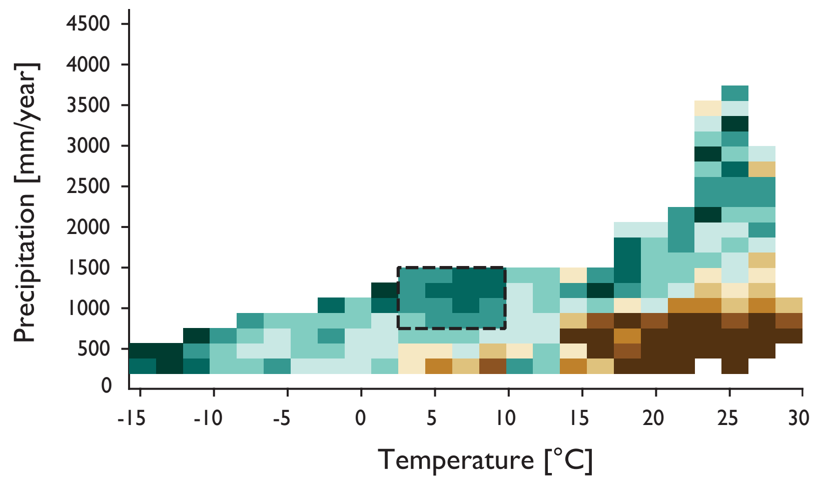
An average of the sensitivity of vegetation to climate is taken in each bin with at least 10 vegetated spatial points in it.

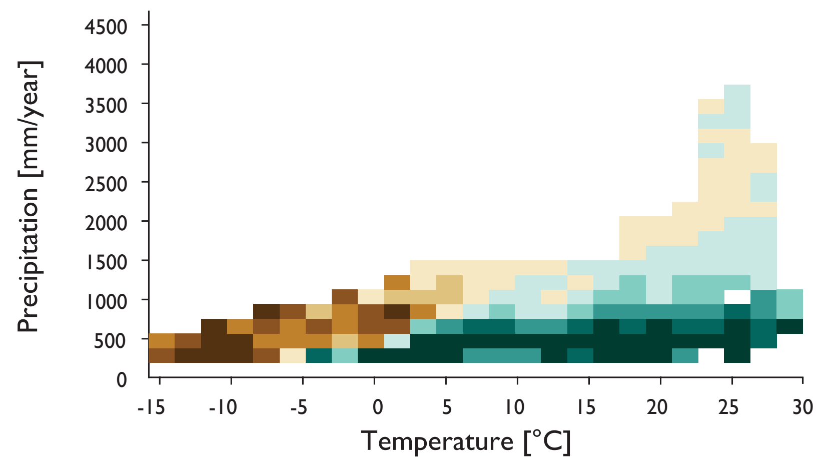


Sensitivity, Temperature and Precipitation

Sensitivity

$$\%\Delta NDVI = \beta_o + T_{MAT}\,\beta_{Temp} + P_{MAP}\,\beta_{Precip}$$

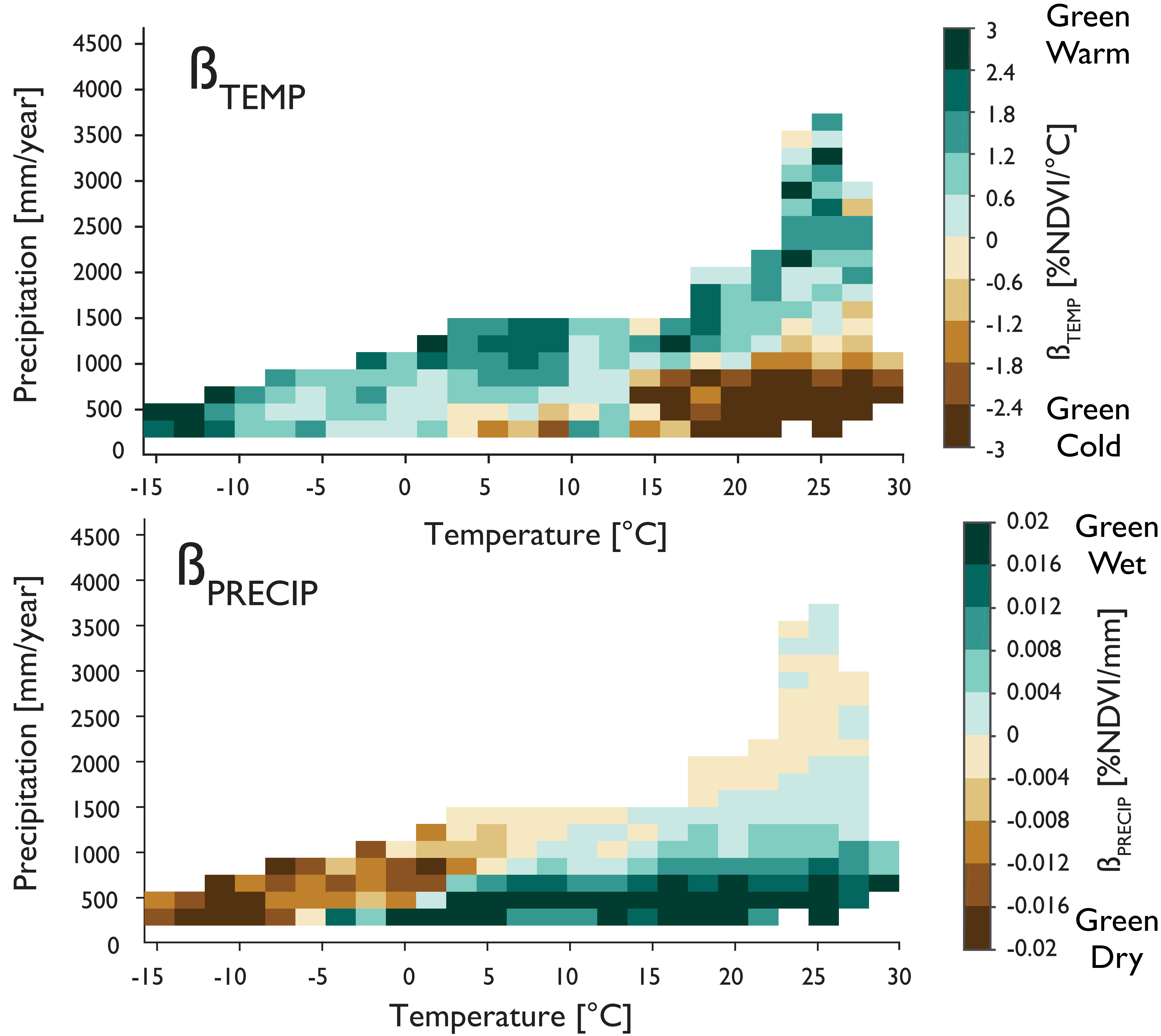




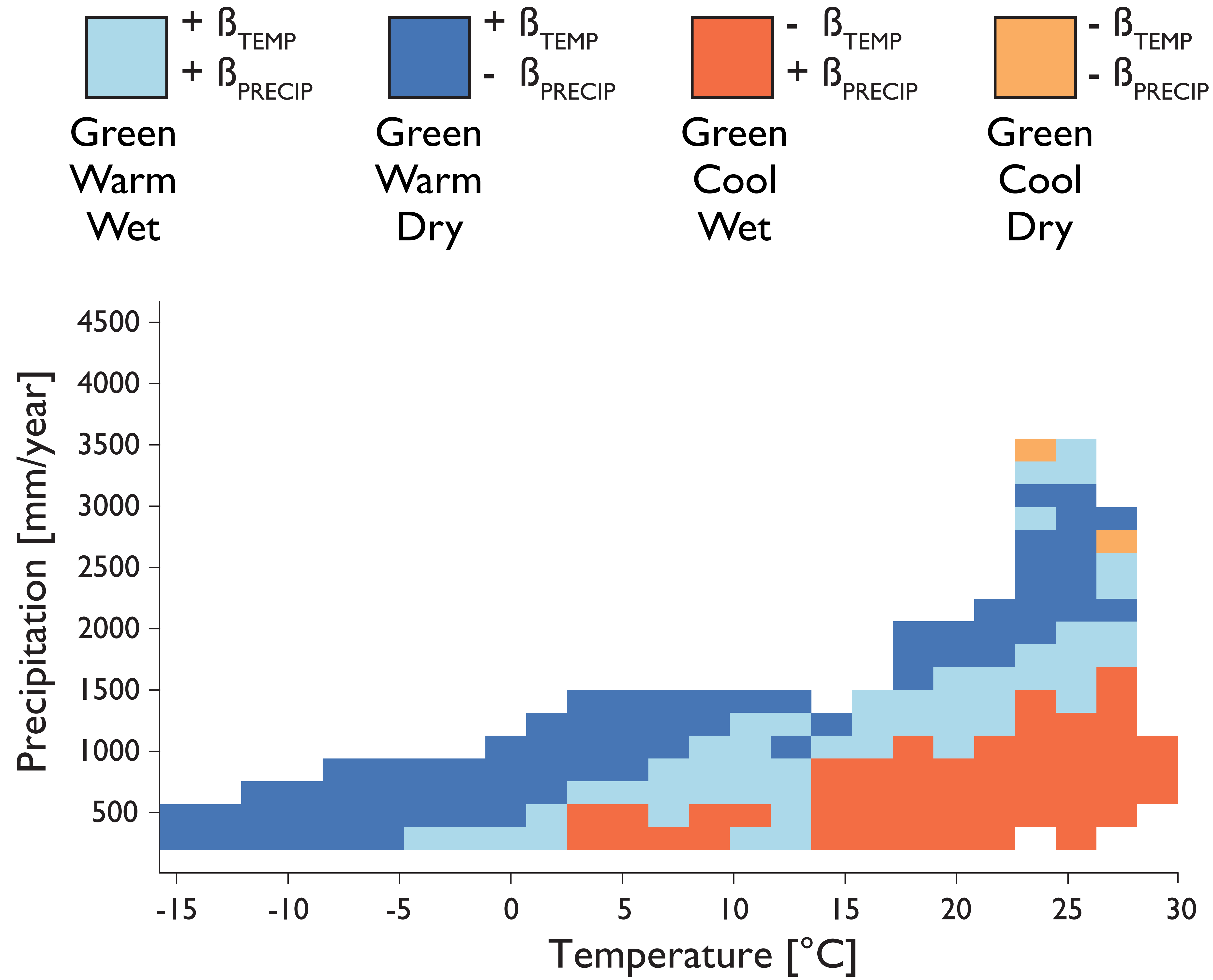
Aggregated Global Patterns

Sensitivity of Vegetation to Interannual Climate

Combine patterns using the sign of the sensitivity of vegetation to create four categories.



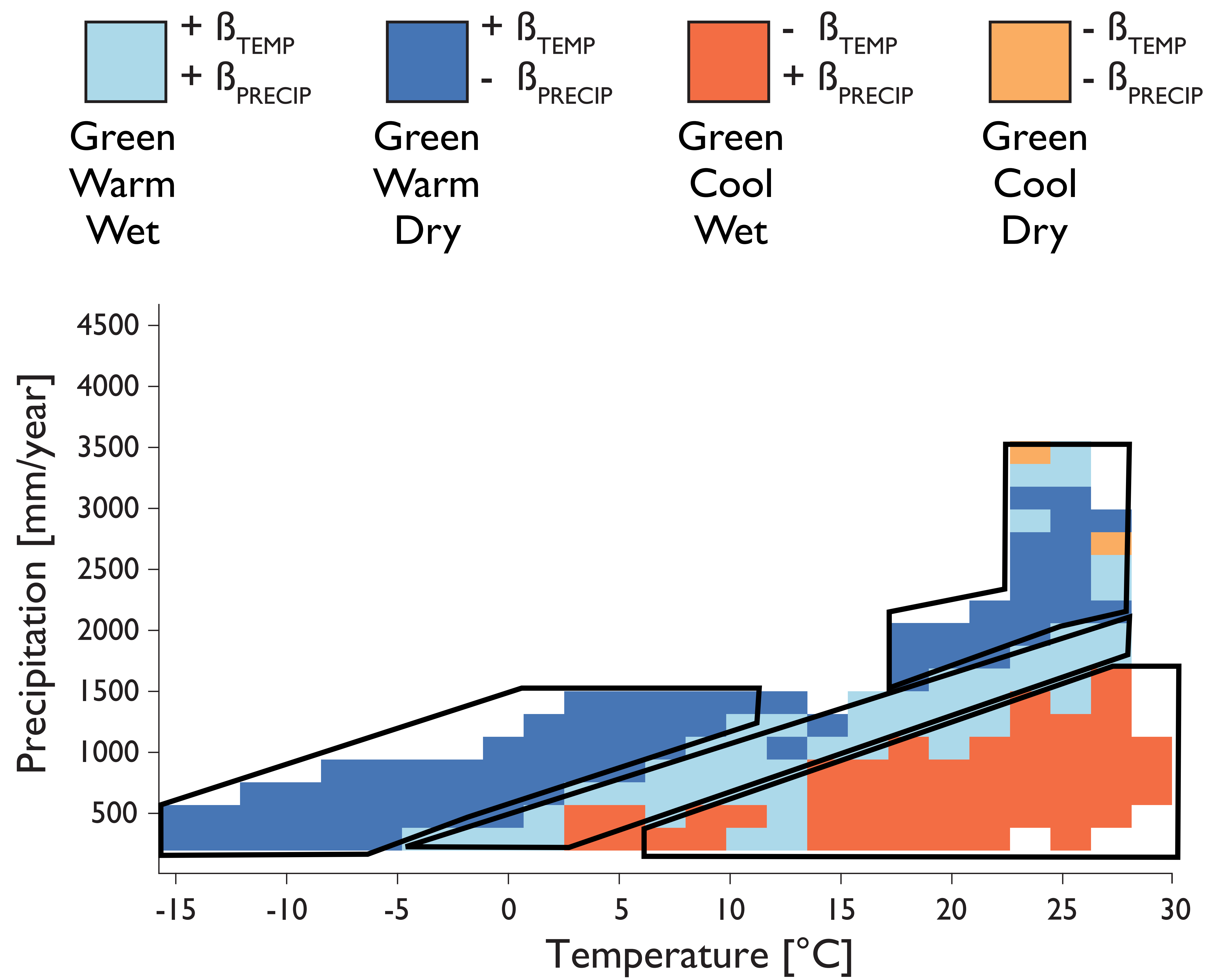
Aggregated Patterns



Combine patterns using the sign of the sensitivity of vegetation to create four categories.

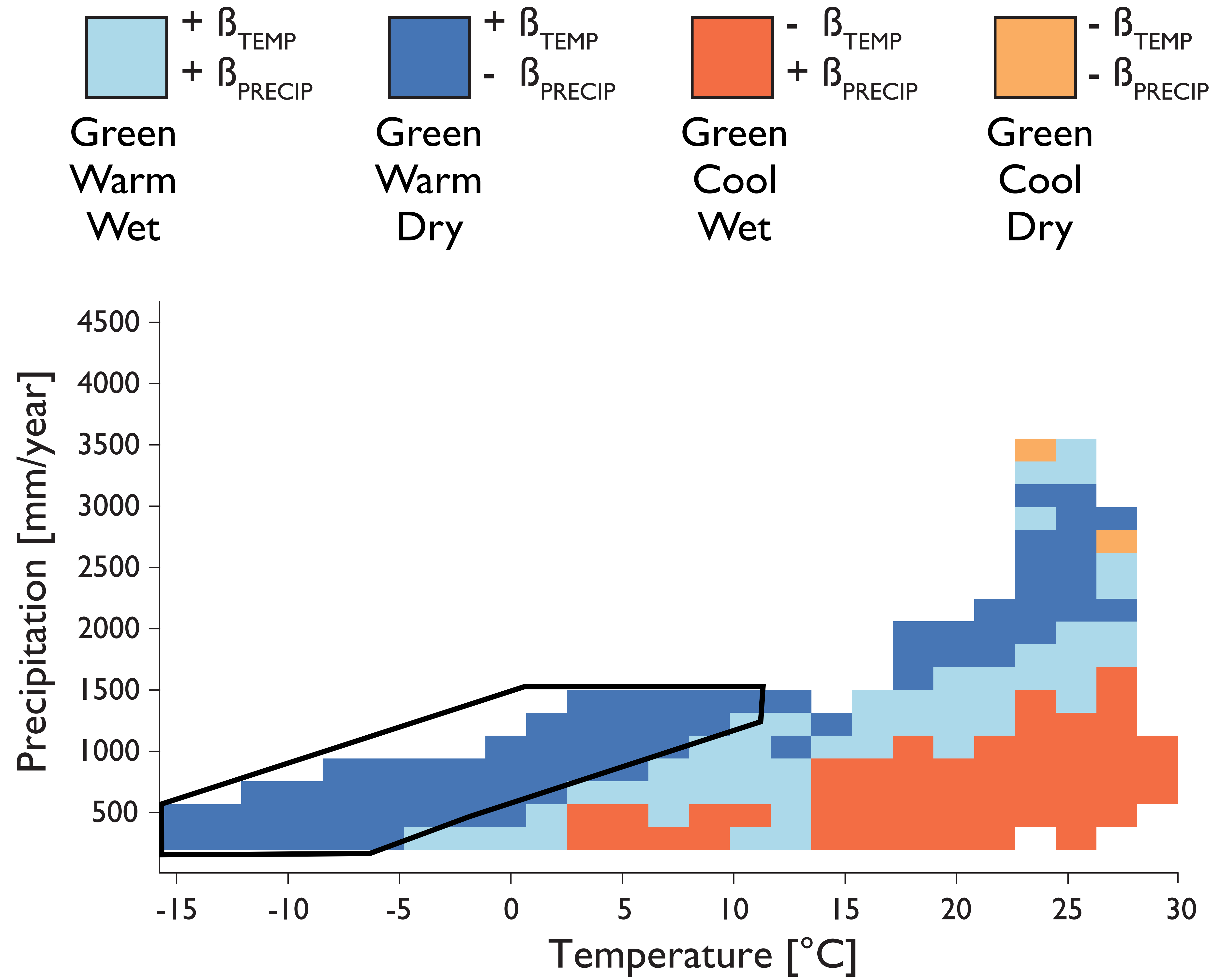
Empirical Global Regions

4 Distinct regions emerge when the sensitivity of vegetation to both temperature and precipitation are combined.



Empirical Global Regions

- Cold Region

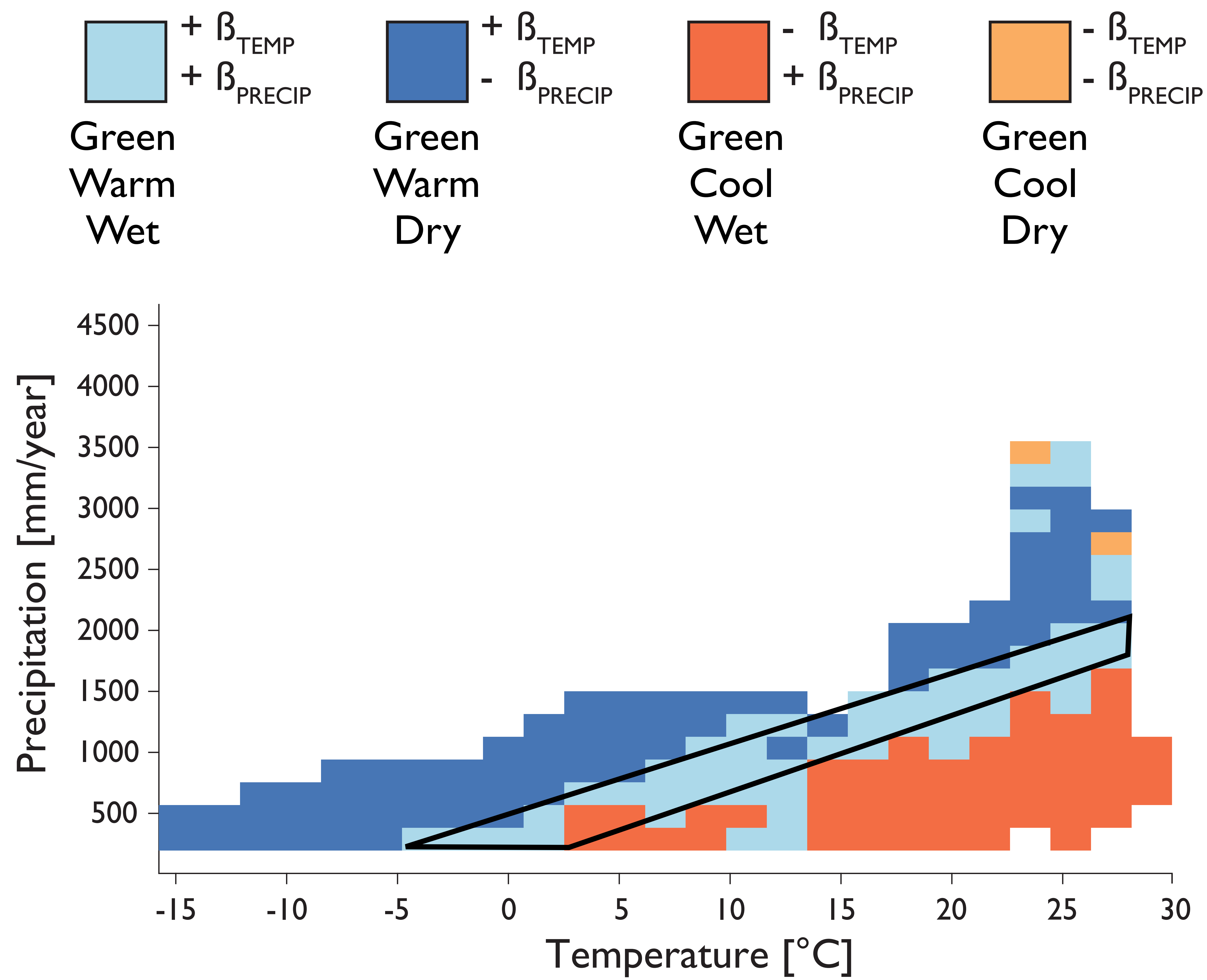


The cold region is greener during warmer and drier years. These annual changes primarily effect the length of the growing season through growing degree days and snow cover.

Empirical Global Regions

- Cold Region
- Transition Region

The transition region separates cold regions from warm regions and is bounded by two linear contours that show a proportionality between temperature and precipitation in the sensitivity of vegetation.



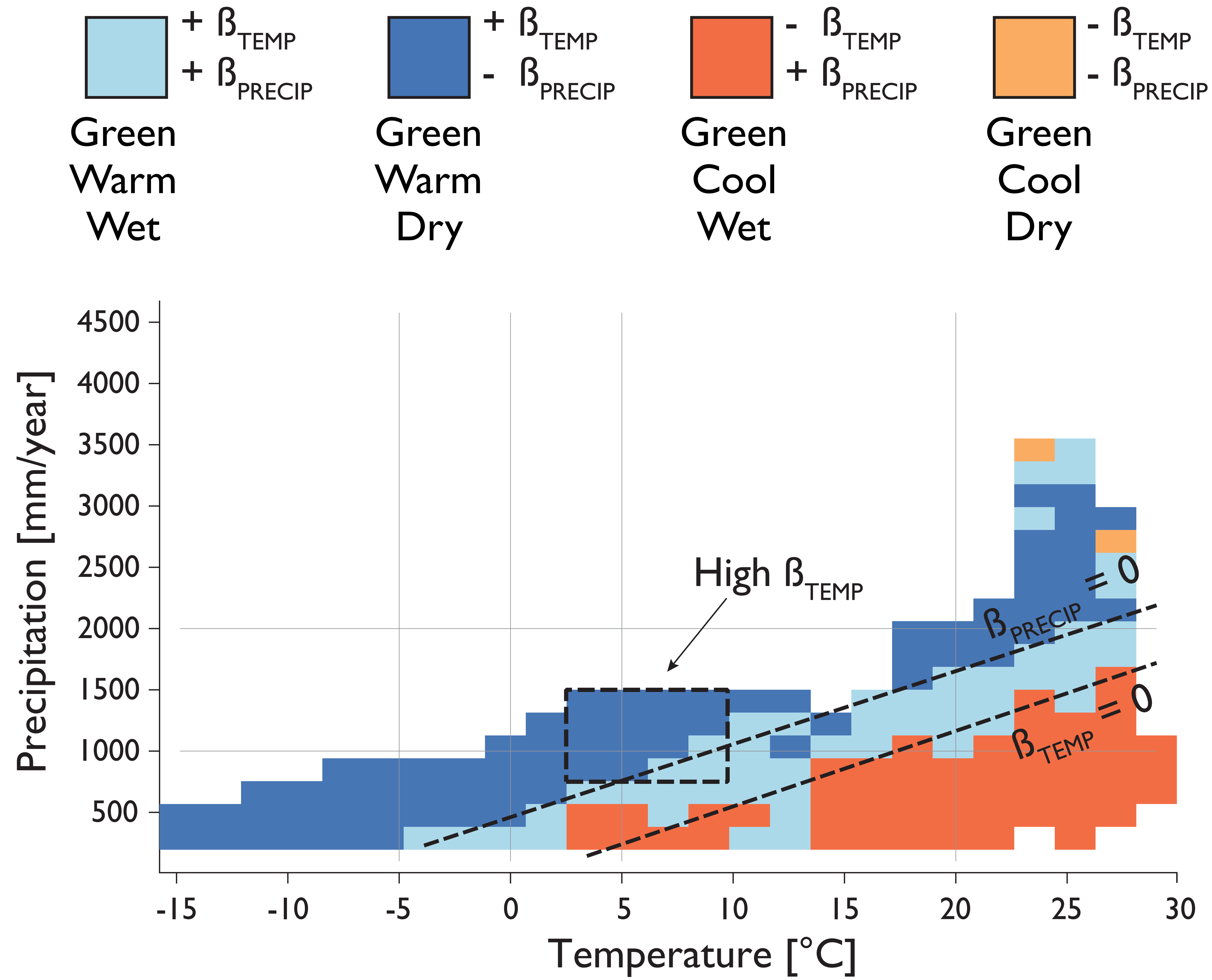
Empirical Global Regions

- Cold Region
- Transition Region

Proportional contour across a broad range of Temperature and Precipitation.

1.6 C per 100 mm/year rainfall.

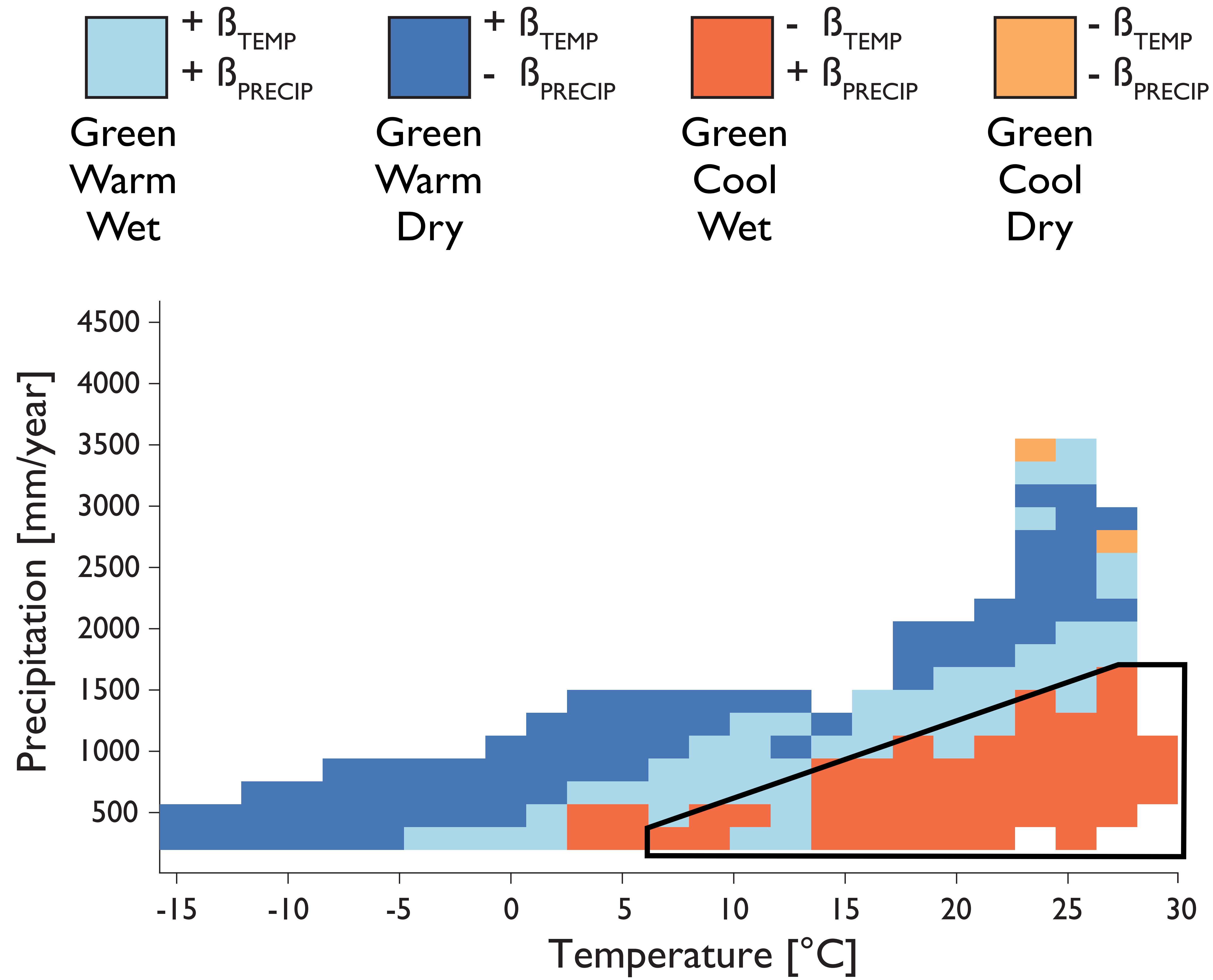
7.9 C offset



Empirical Global Regions

- Cold Region
- Transition Region
- Hot-Dry Region

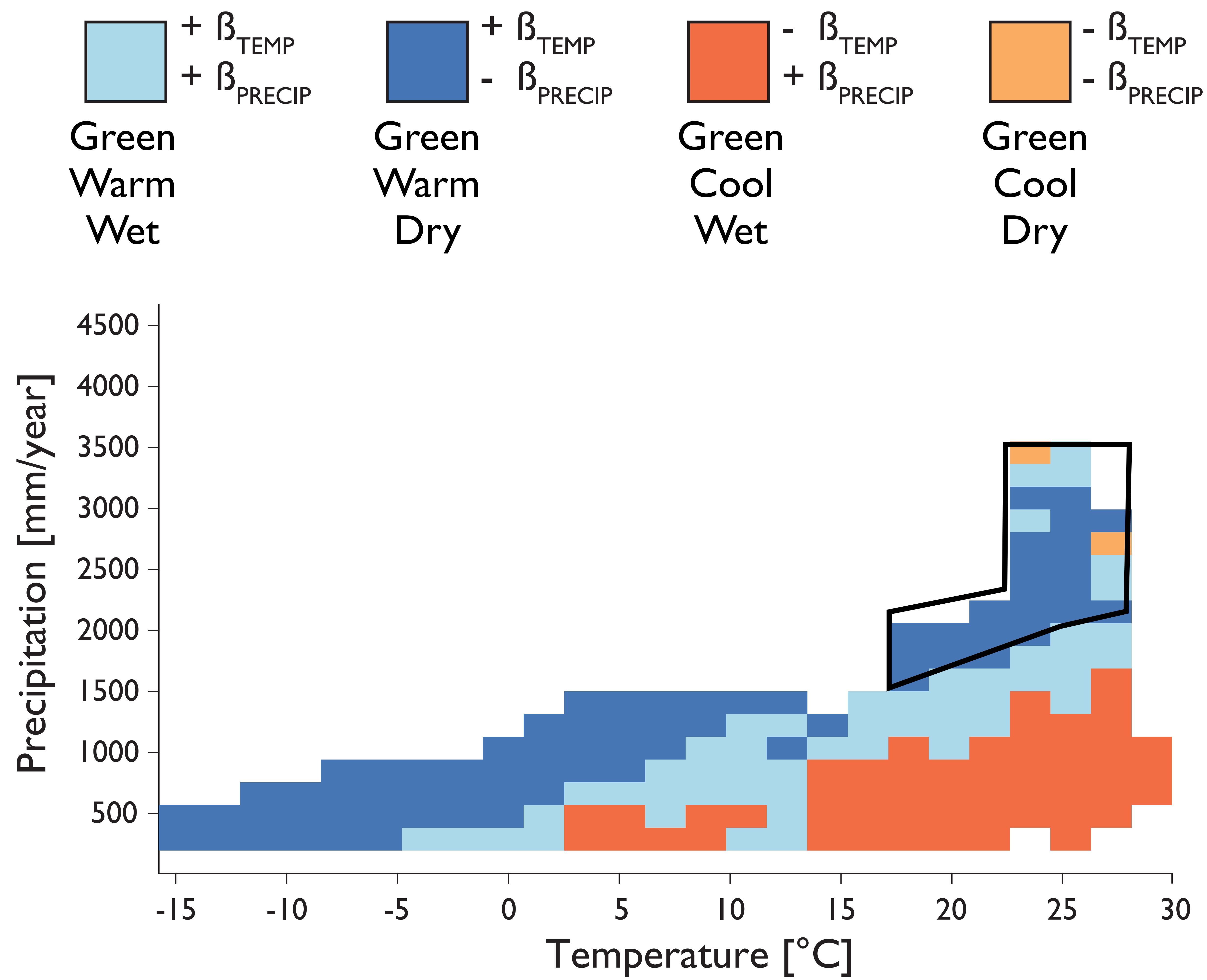
The hot-dry region is primarily found on the edge of deserts where there is no vegetation. Over a broad range of temperatures, these places are greener when it is wetter or cooler.

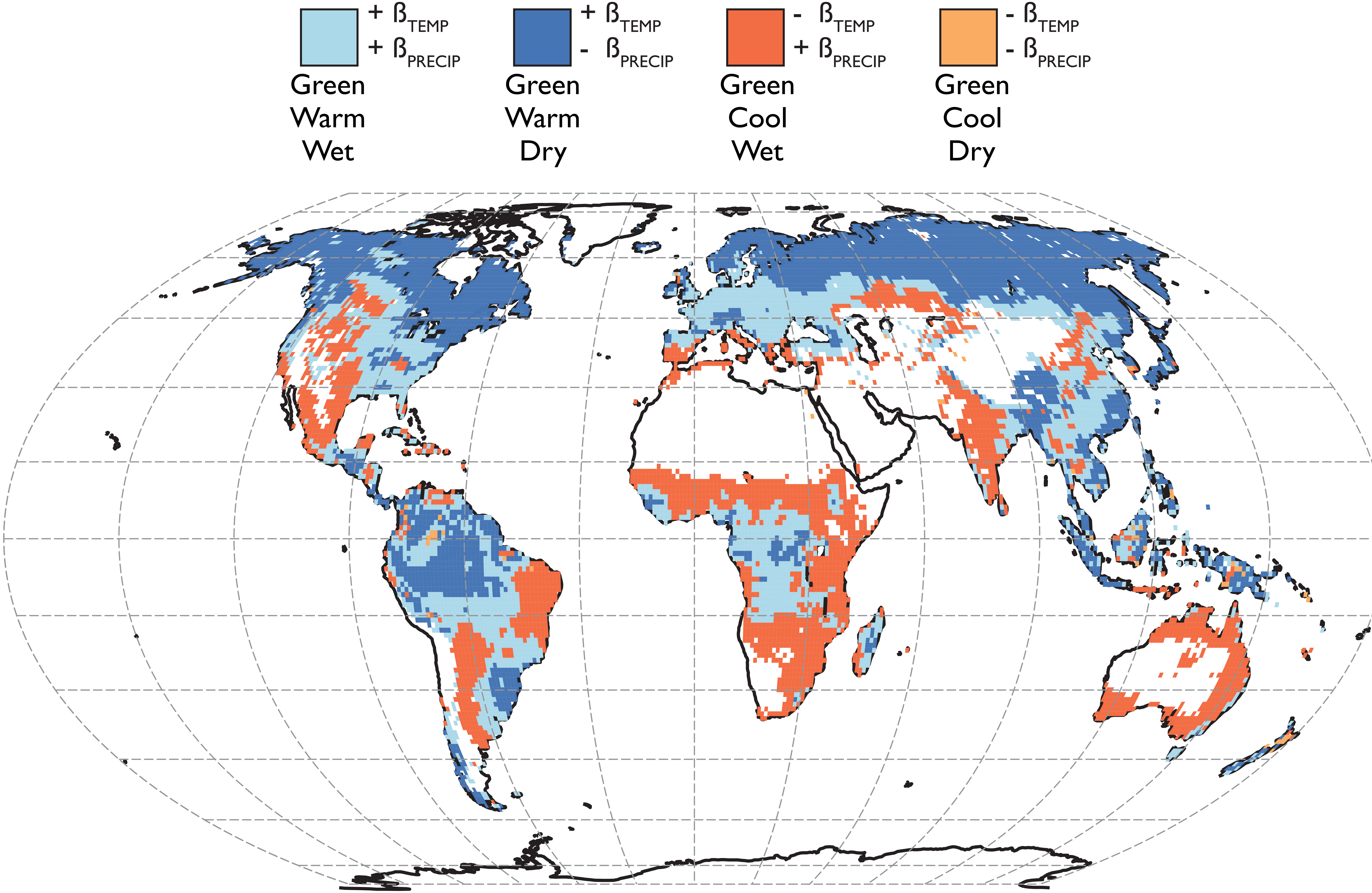


Empirical Global Regions

- Cold Region
- Transition Region
- Hot-Dry Region
- Hot-Wet Region

The hot-wet region suggests that water stress, rather than the absolute temperature in the main constraint on vegetation. It seems probable that clouds play a major role in offsetting the costs of warmer years so that vegetation is greener when warmer and dryer.





+ β_{TEMP}
+ β_{PRECIP}
Green Warm Wet
+ β_{TEMP}
- β_{PRECIP}
Green Warm Dry
- β_{TEMP}
+ β_{PRECIP}
Green Cool Wet
- β_{TEMP}
- β_{PRECIP}
Green Cool Dry


Conclusions

Conclusions

Empirical Functional constraint built from vegetation and climate observations.

- The observed sensitivity of vegetation to climate is another way to constrain models using the growing time series of satellite observations.
- Analyzing these observed relationships in climate space allows mechanisms to be hypothesized.

There are a number of emergent patterns observed in the sensitivity of vegetation to temperature and precipitation.

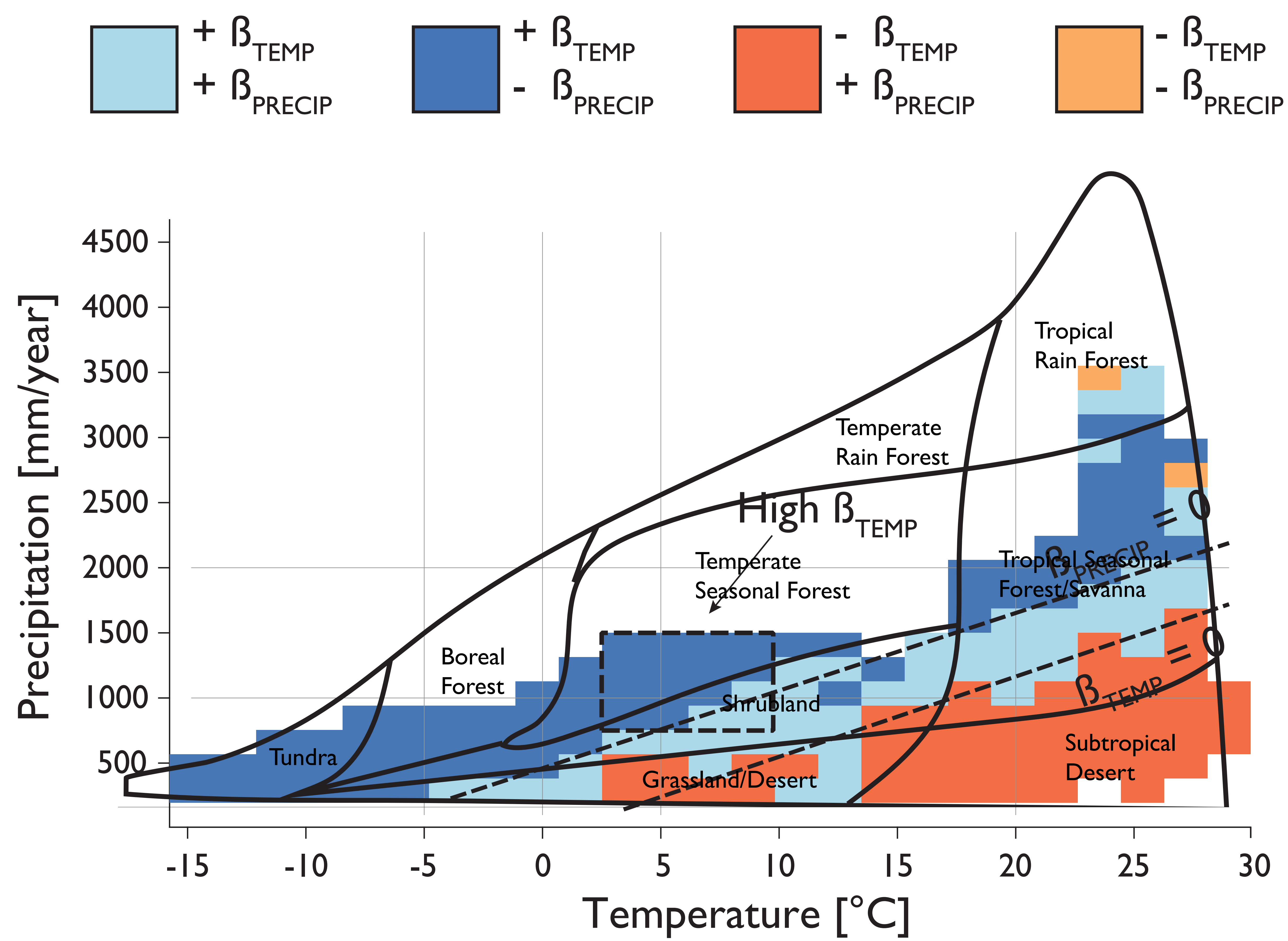
- Parallel proportional relationships in both the sensitivity of vegetation to temperature and precipitation.
- A region of strong sensitivity of vegetation to temperature suggesting unique ecoclimate dynamics.
- Four distinct regions resulting from analyzing the signs of both the sensitivity of vegetation to temperature and precipitation across climate

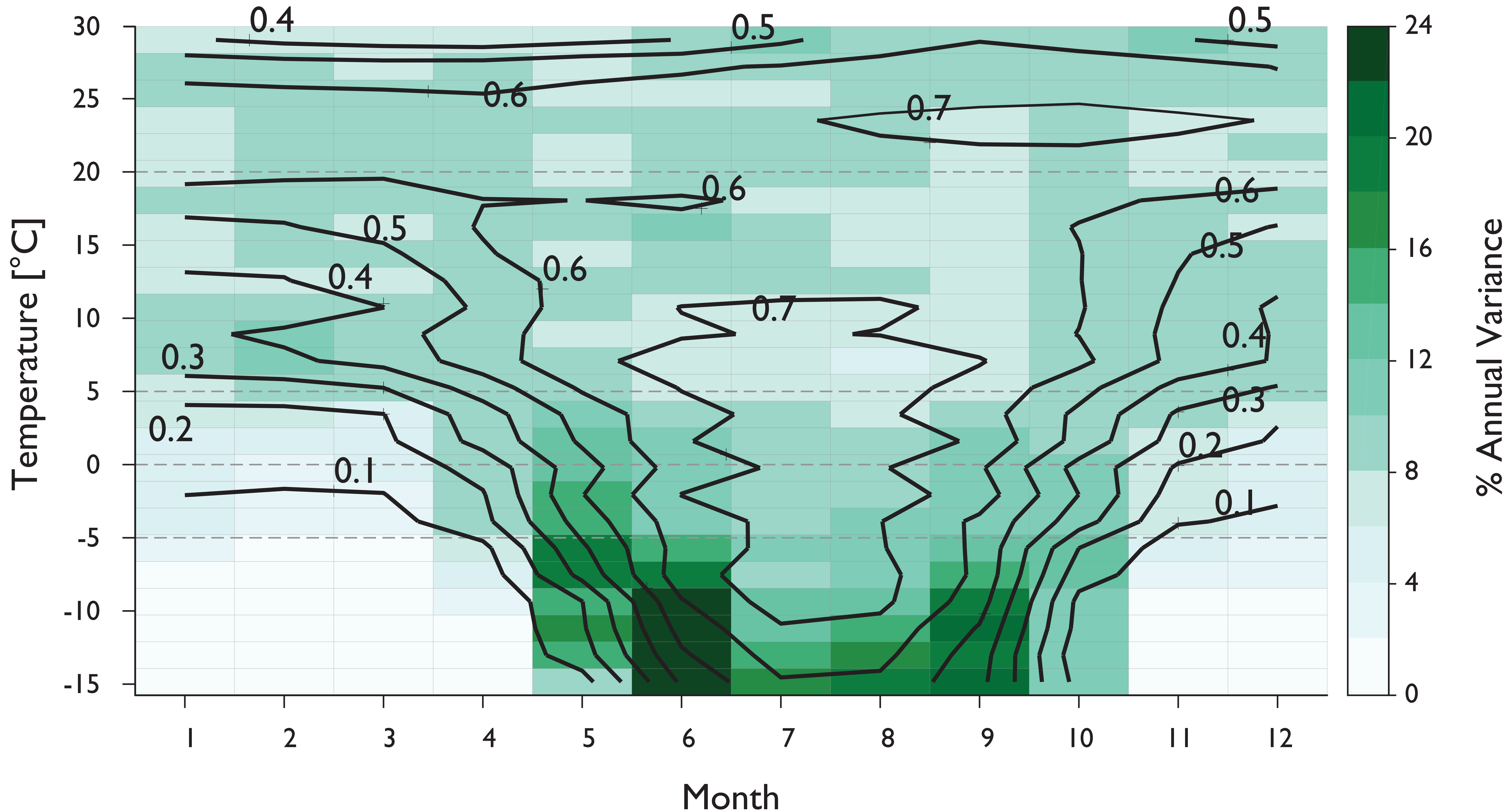
Acknowledgements


Questions?

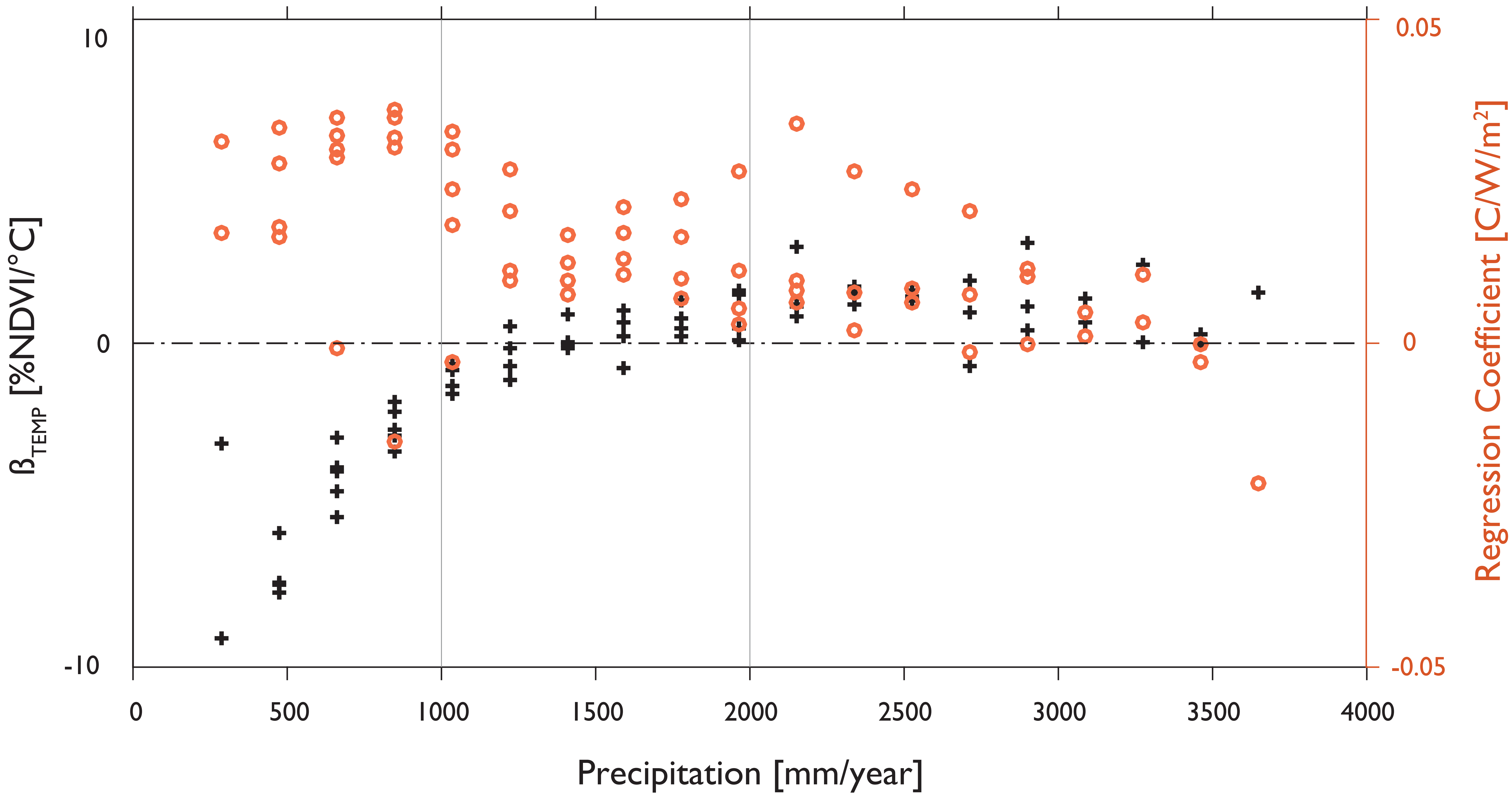
Back Up

Comparison of Whittaker Ecoregions with observed Vegetation Function.

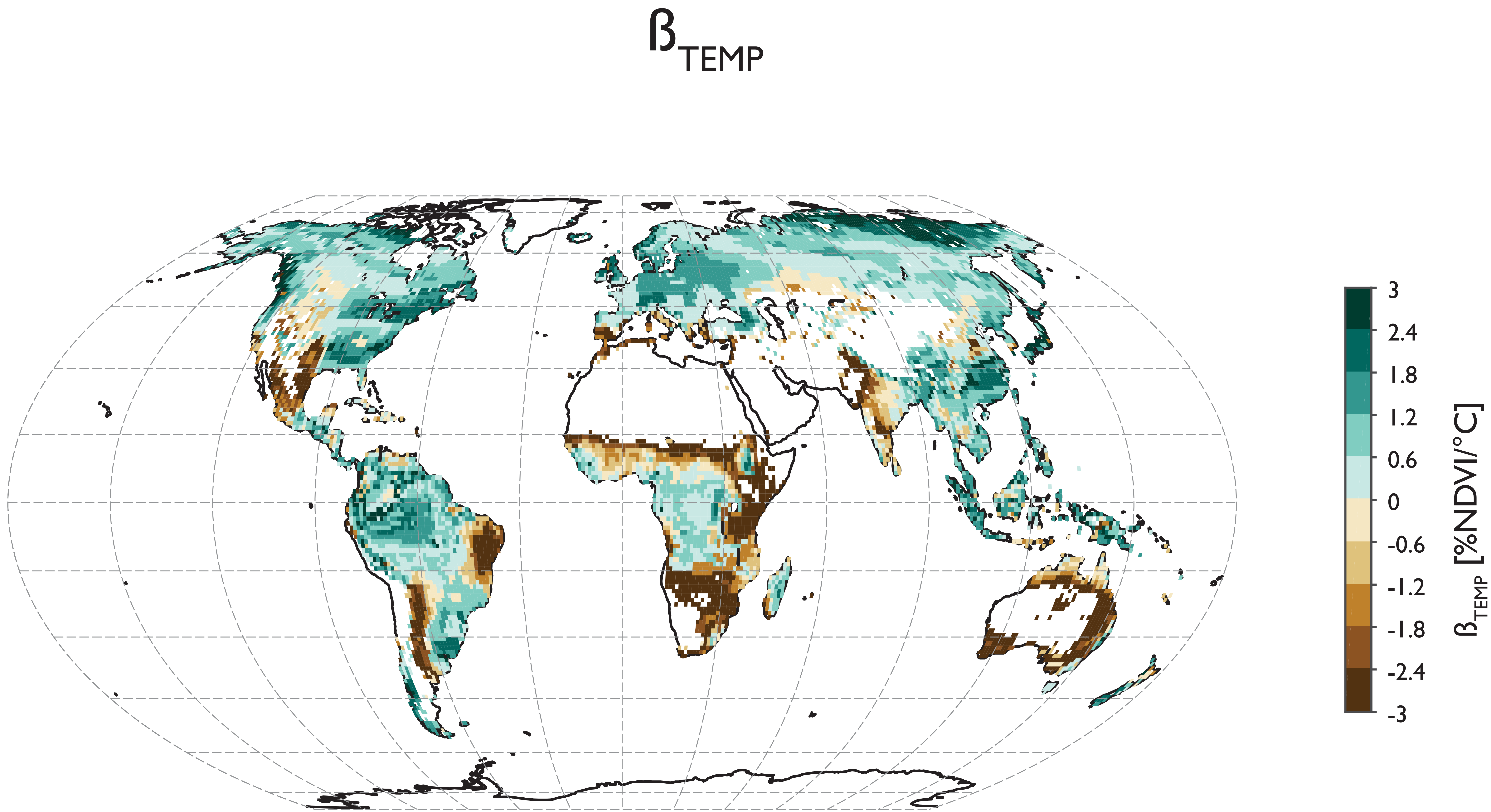




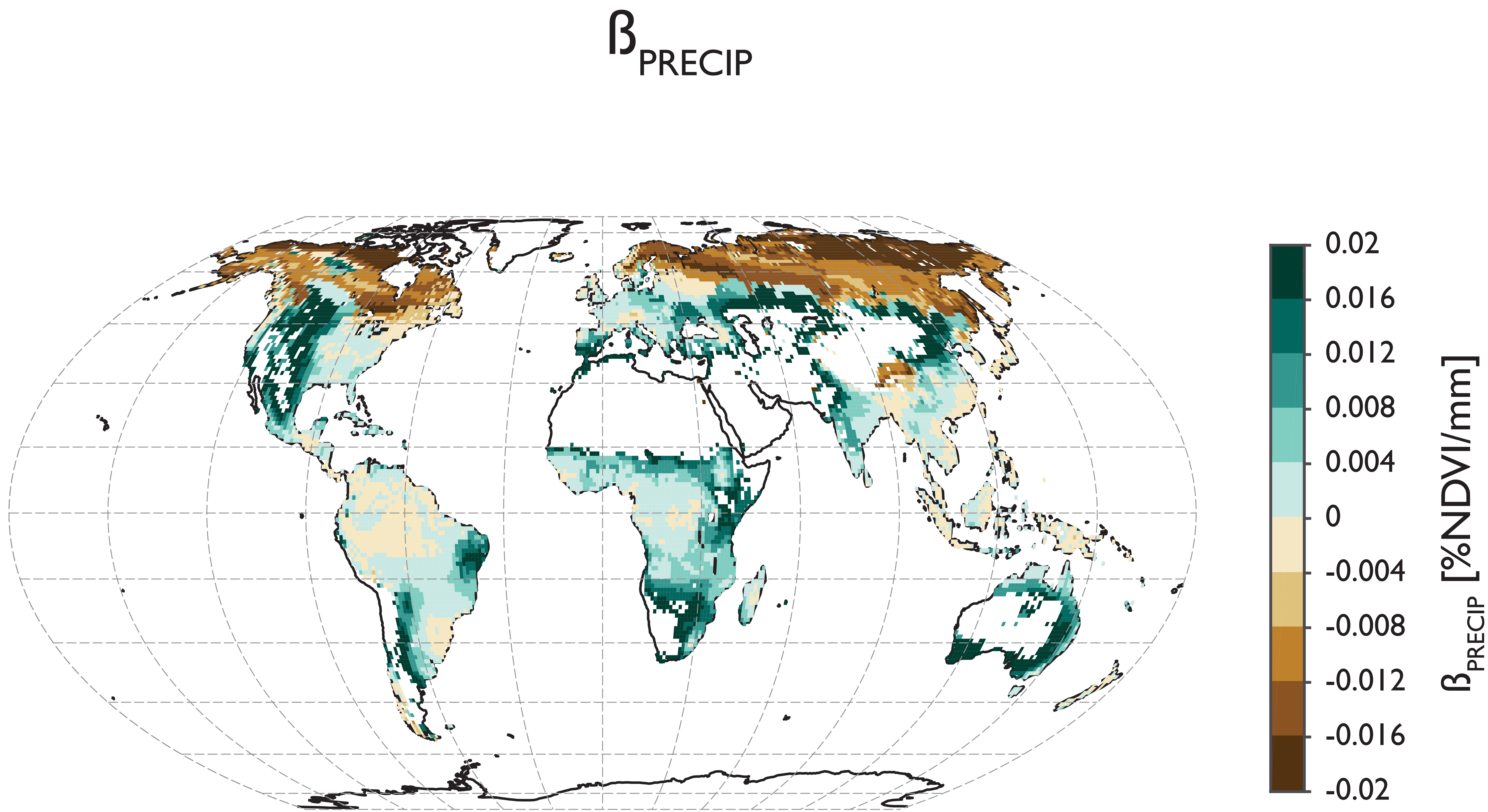
Temperature [°C]
Month
% Annual Variance
0.1
0.2
0.3
0.4
0.5
0.6
0.7



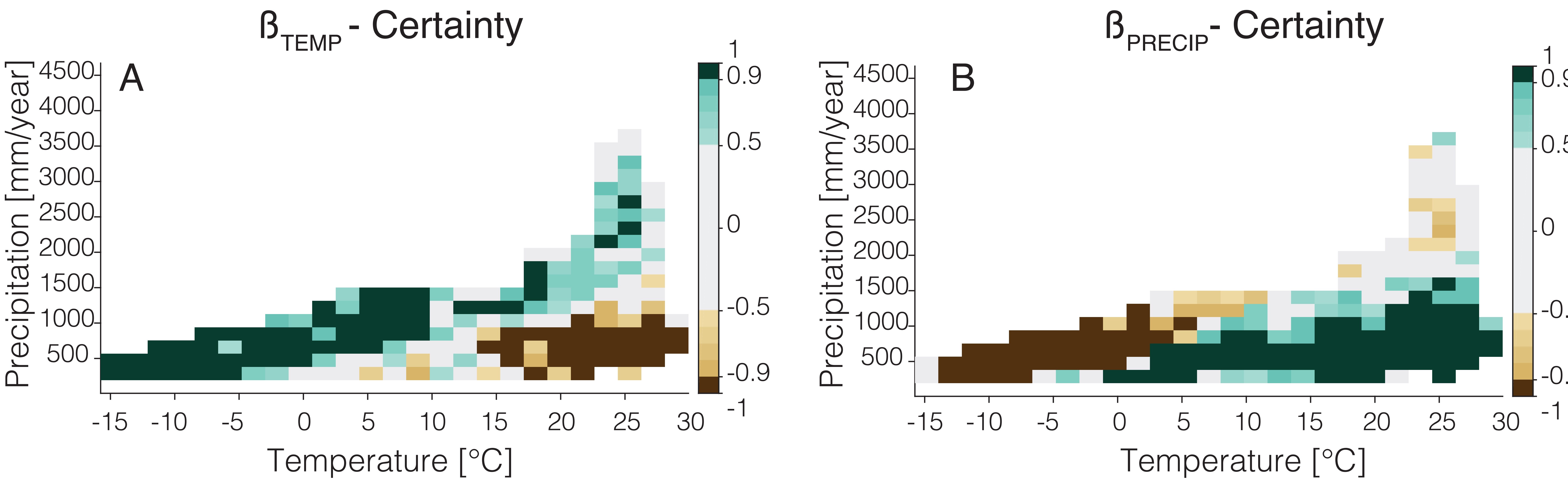
10
0
-10
β_TEMP [%NDVI/°C]
0.05
0
-0.05
Regression Coefficient [C/W/m²]
0
500
1000
1500
2000
2500
3000
3500
4000
Precipitation [mm/year]



β_{TEMP}
3
2.4
1.8
1.2
0.6
0
-0.6
-1.2
-1.8
-2.4
-3
β_{TEMP} [%NDVI/°C]

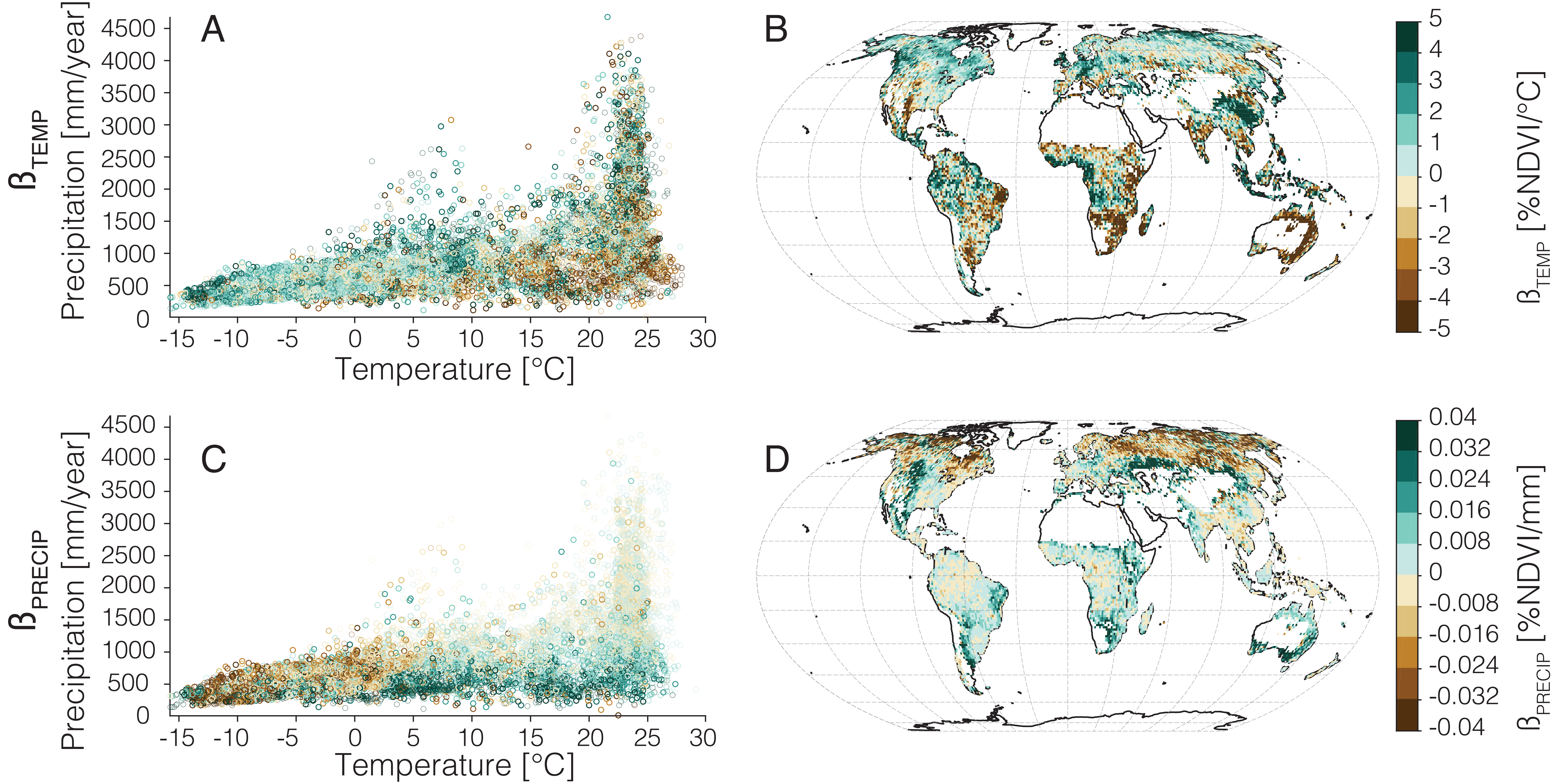


β_{PRECIP}
0.02
0.016
0.012
0.008
0.004
0
-0.004
-0.008
-0.012
-0.016
-0.02
β_{PRECIP} [%NDVI/mm]

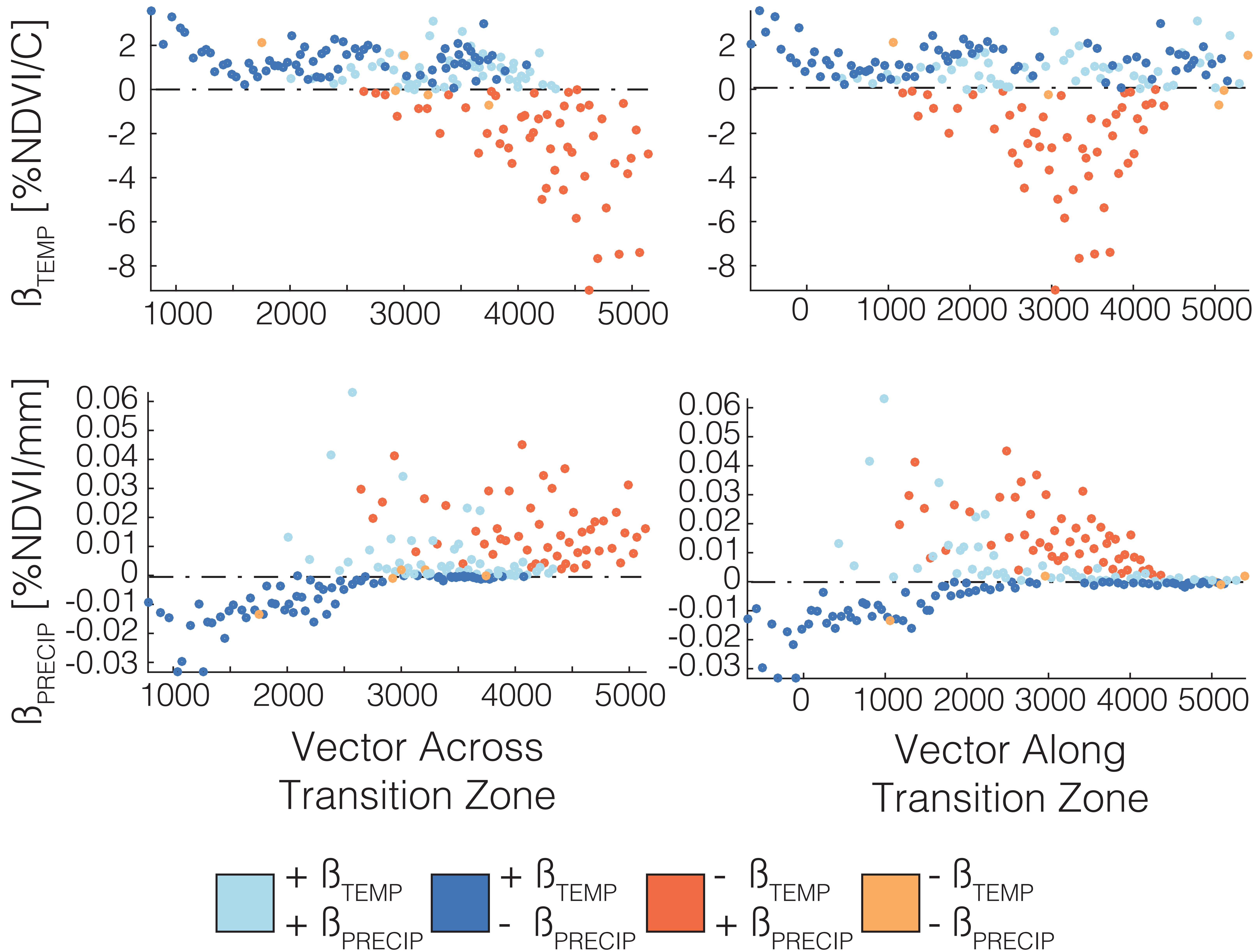


Estimating Certainty

- 10,000 regressions at each spatial point
- 10,000 draws of combined regressions in each bin
- Results in estimation of uncertainty due to binning and time

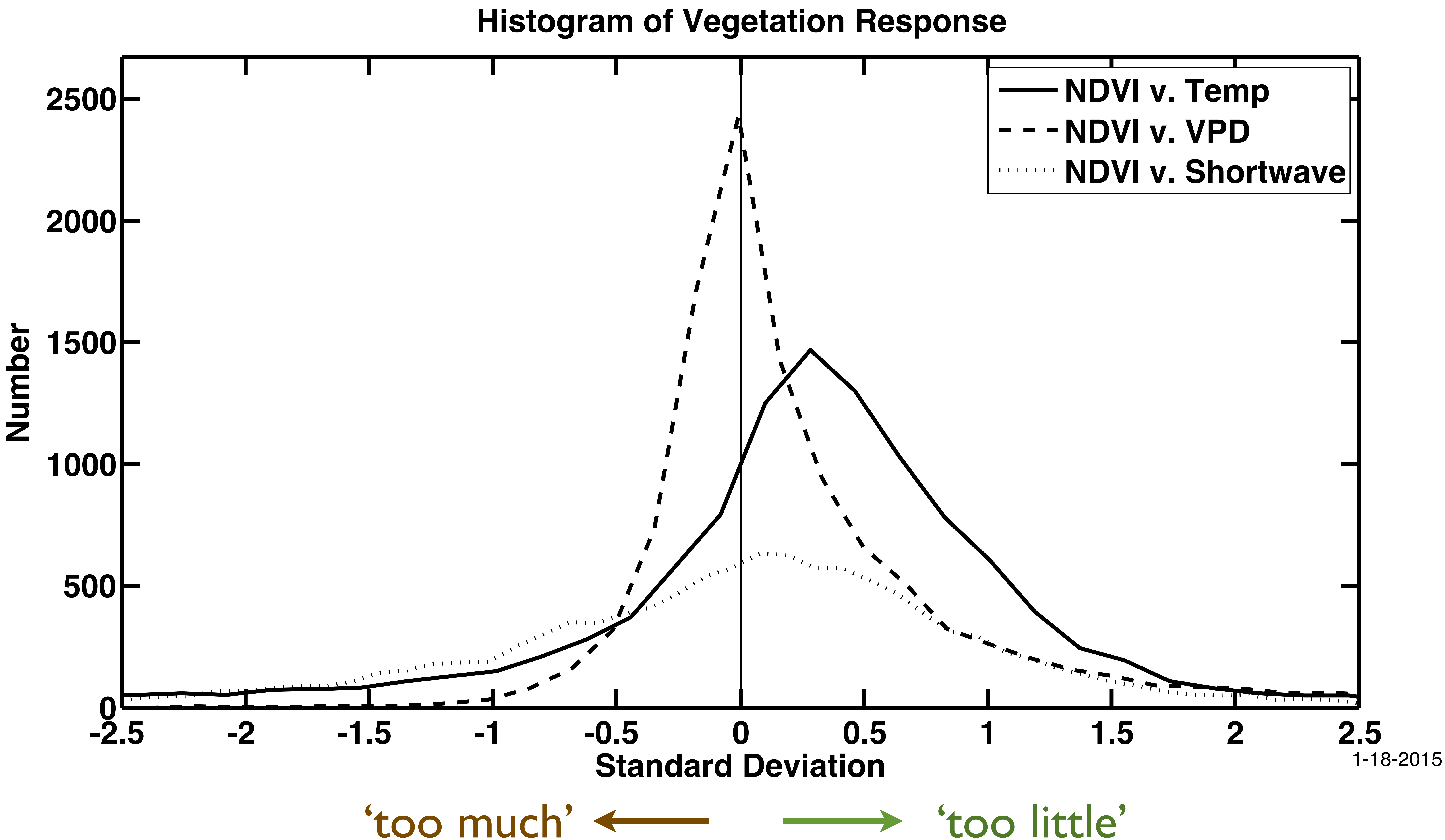


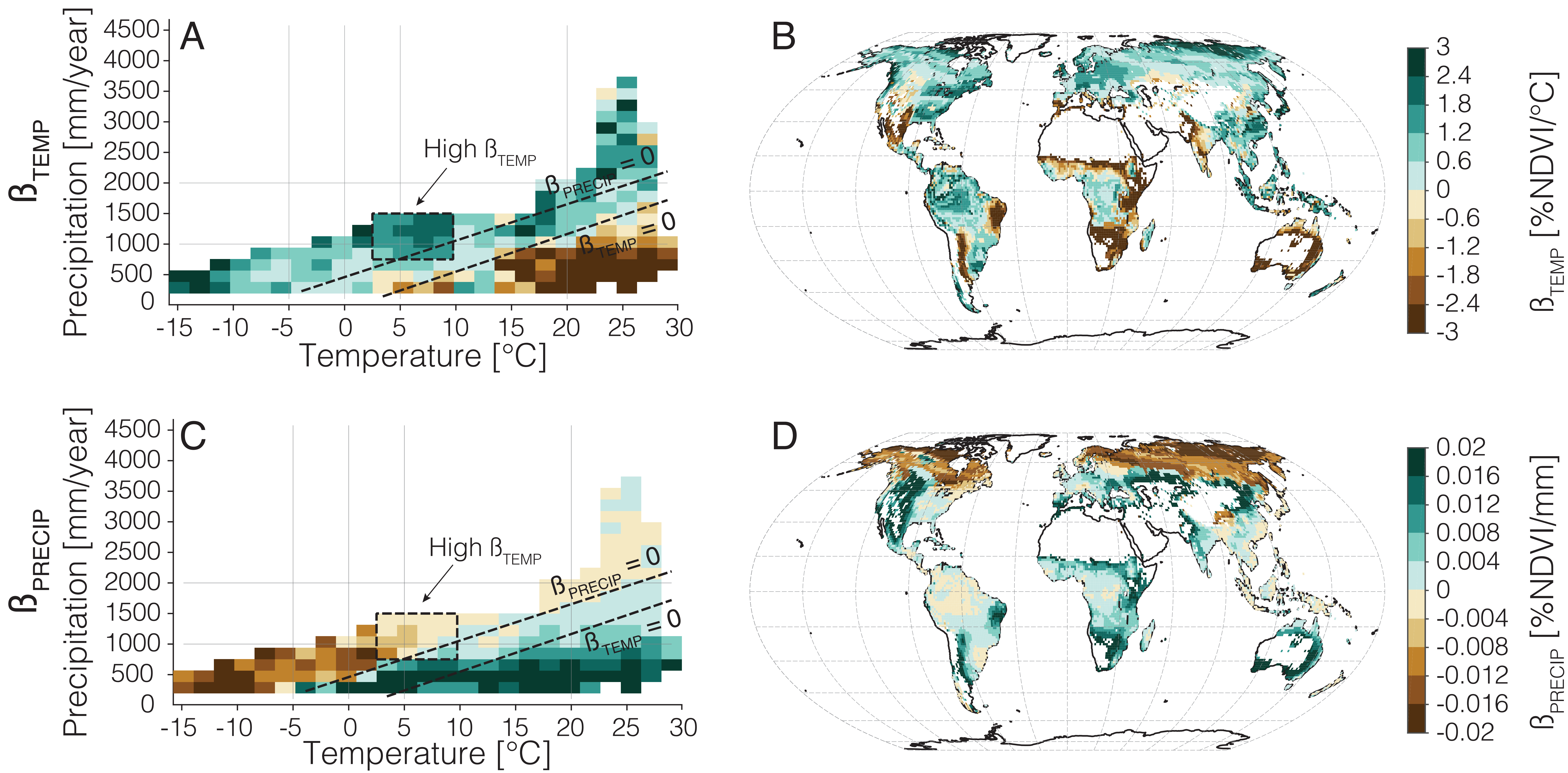
A
B
C
D
β_TEMP
β_PRECIP
Precipitation [mm/year]
Temperature [°C]
β_TEMP [%NDVI/°C]
β_PRECIP [%NDVI/mm]



β_TEMP [%NDVI/C]
β_PRECIP [%NDVI/mm]
Vector Across Transition Zone
Vector Along Transition Zone
+ β_TEMP + β_PRECIP
+ β_TEMP - β_PRECIP
- β_TEMP + β_PRECIP
- β_TEMP - β_PRECIP

Vegetation sensitivity global distribution




A
B
C
D
β_TEMP
β_PRECIP
Precipitation [mm/year]
Temperature [°C]
High β_TEMP
β_PRECIP = 0
β_TEMP = 0
β_TEMP [%NDVI/°C]
β_PRECIP [%NDVI/mm]
3
2.4
1.8
1.2
0.6
0
-0.6
-1.2
-1.8
-2.4
-3
0.02
0.016
0.012
0.008
0.004
0
-0.004
-0.008
-0.012
-0.016
-0.02

Climate Classification

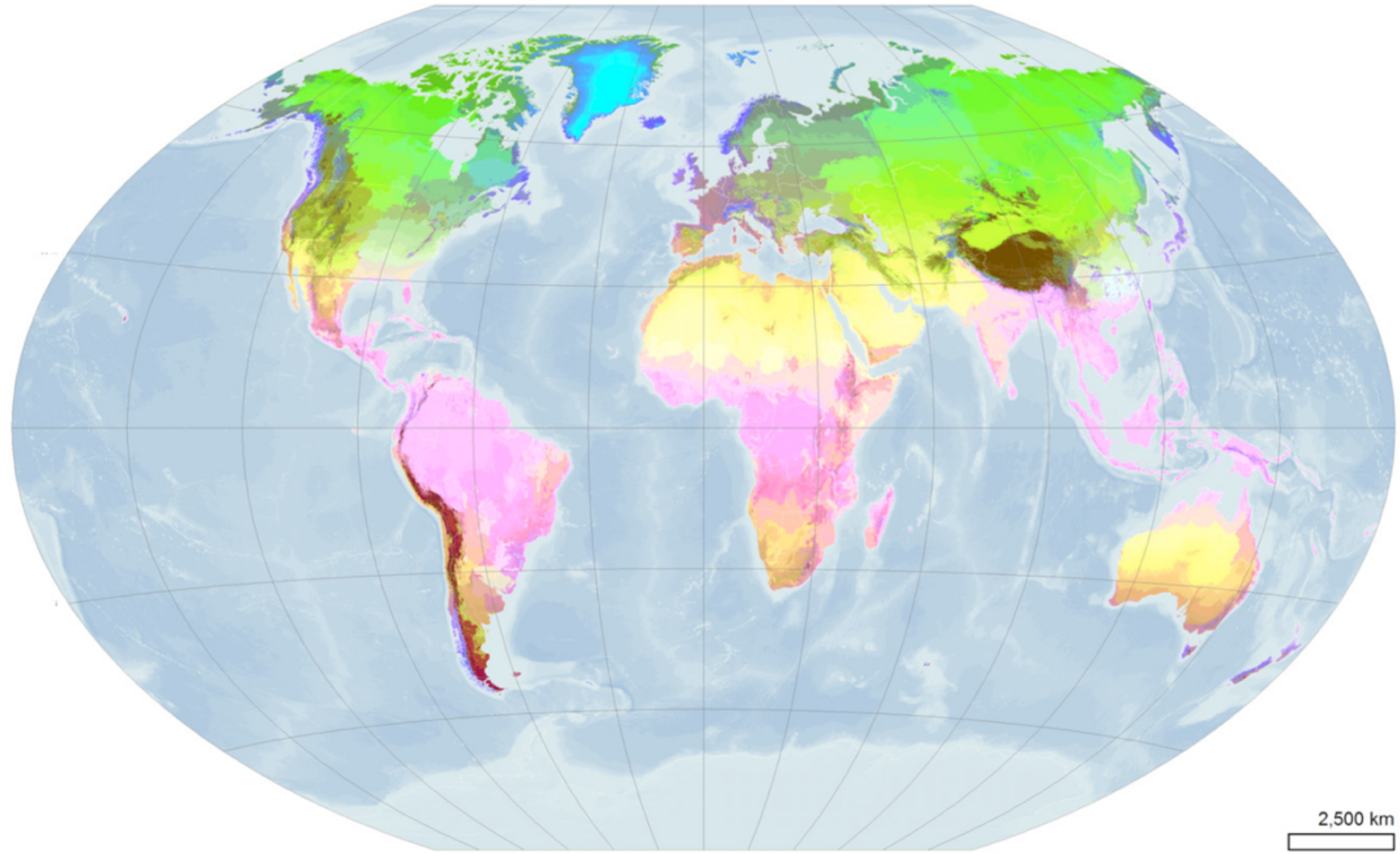
Bioclimatic Map

Growing Degree Days

Aridity Index

T seasonality

PET Seasonality



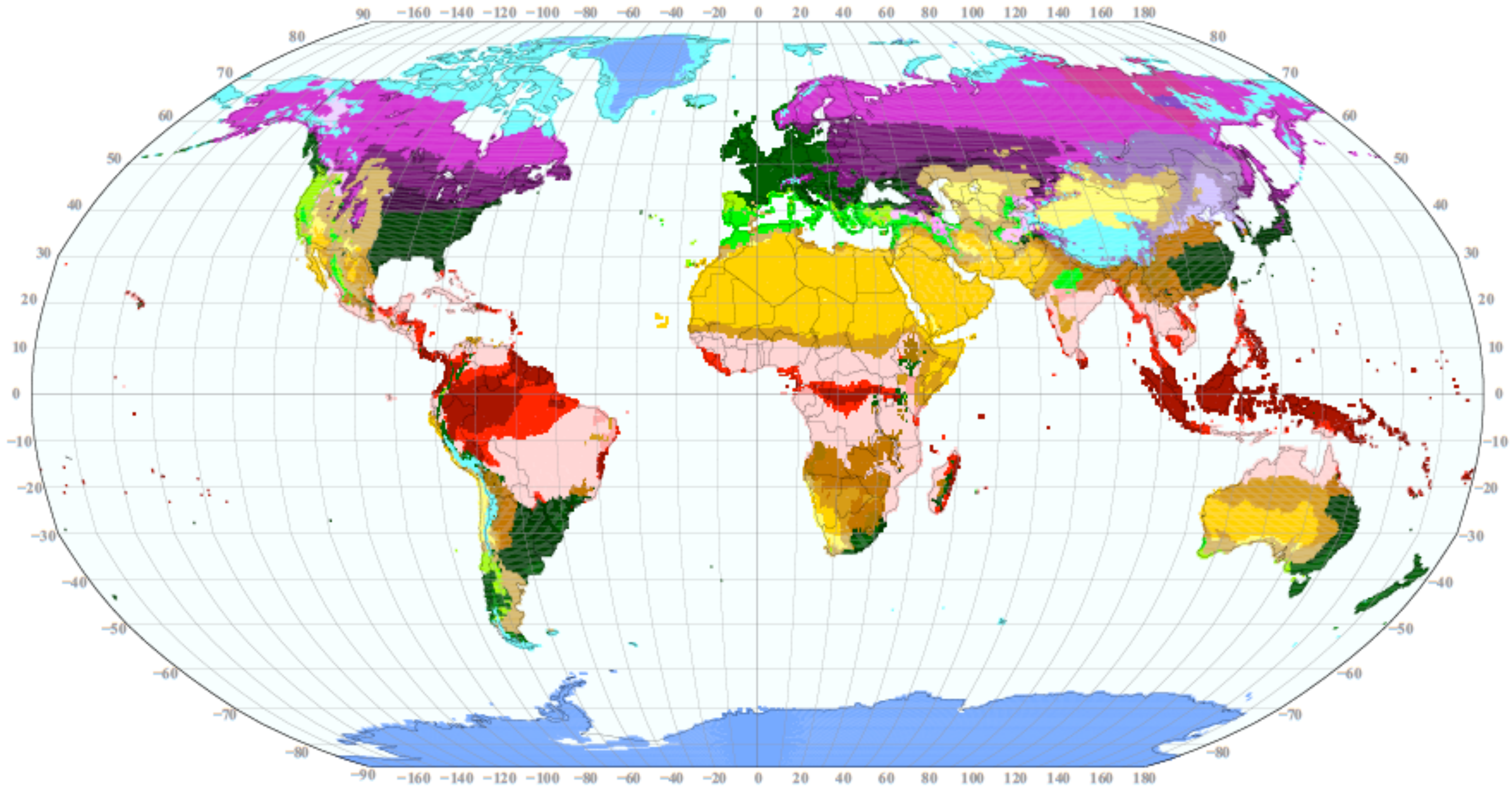
Metzger et al. 2013

Koppen-Geiger Climate Classification

Climate boundaries established along biome boundaries

Classifications built around temperature and precipitation.

No observation of vegetation processes.



Kottek et al. 2006

Threshold in Temp & Precip

Climate boundaries established along biome boundaries

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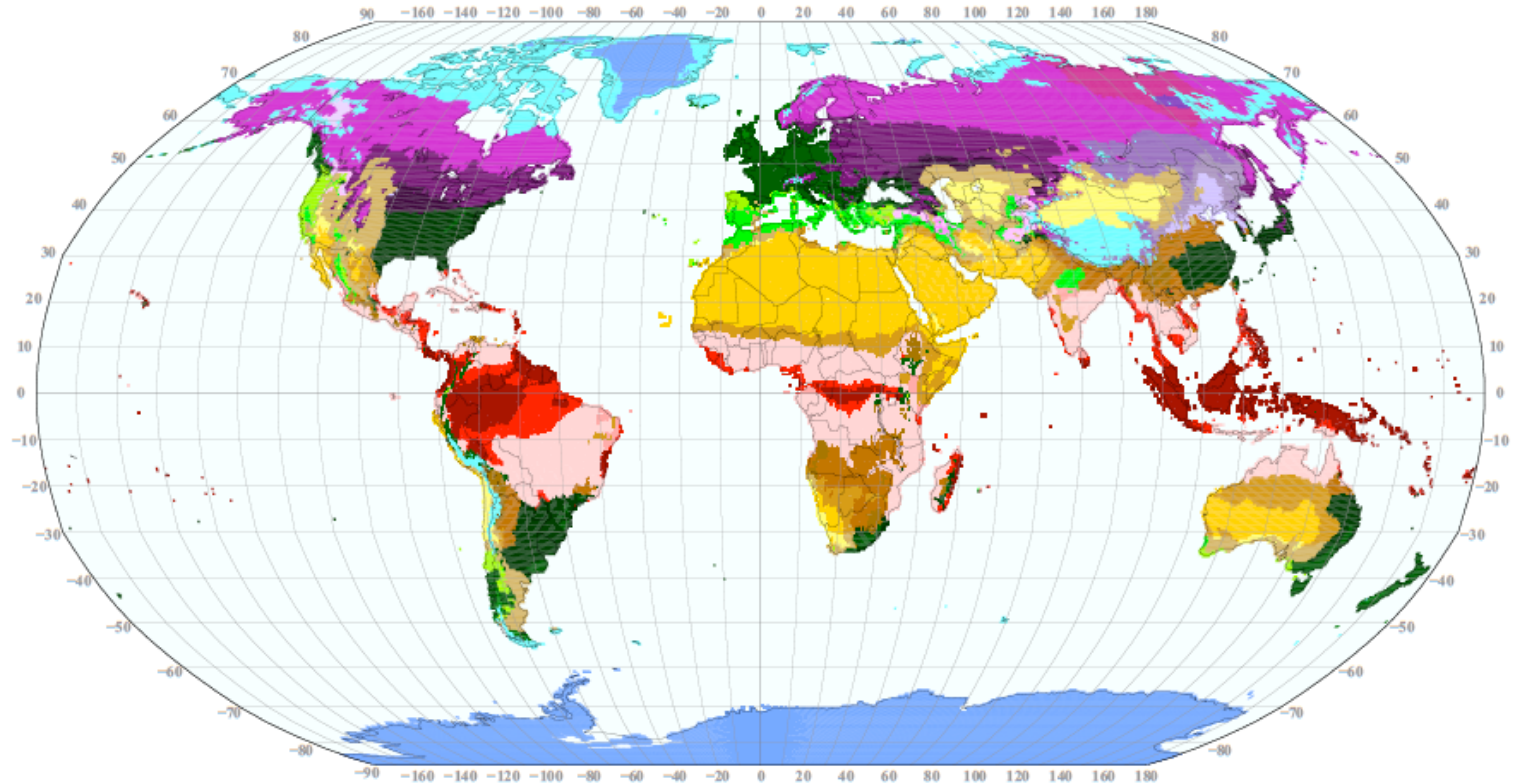
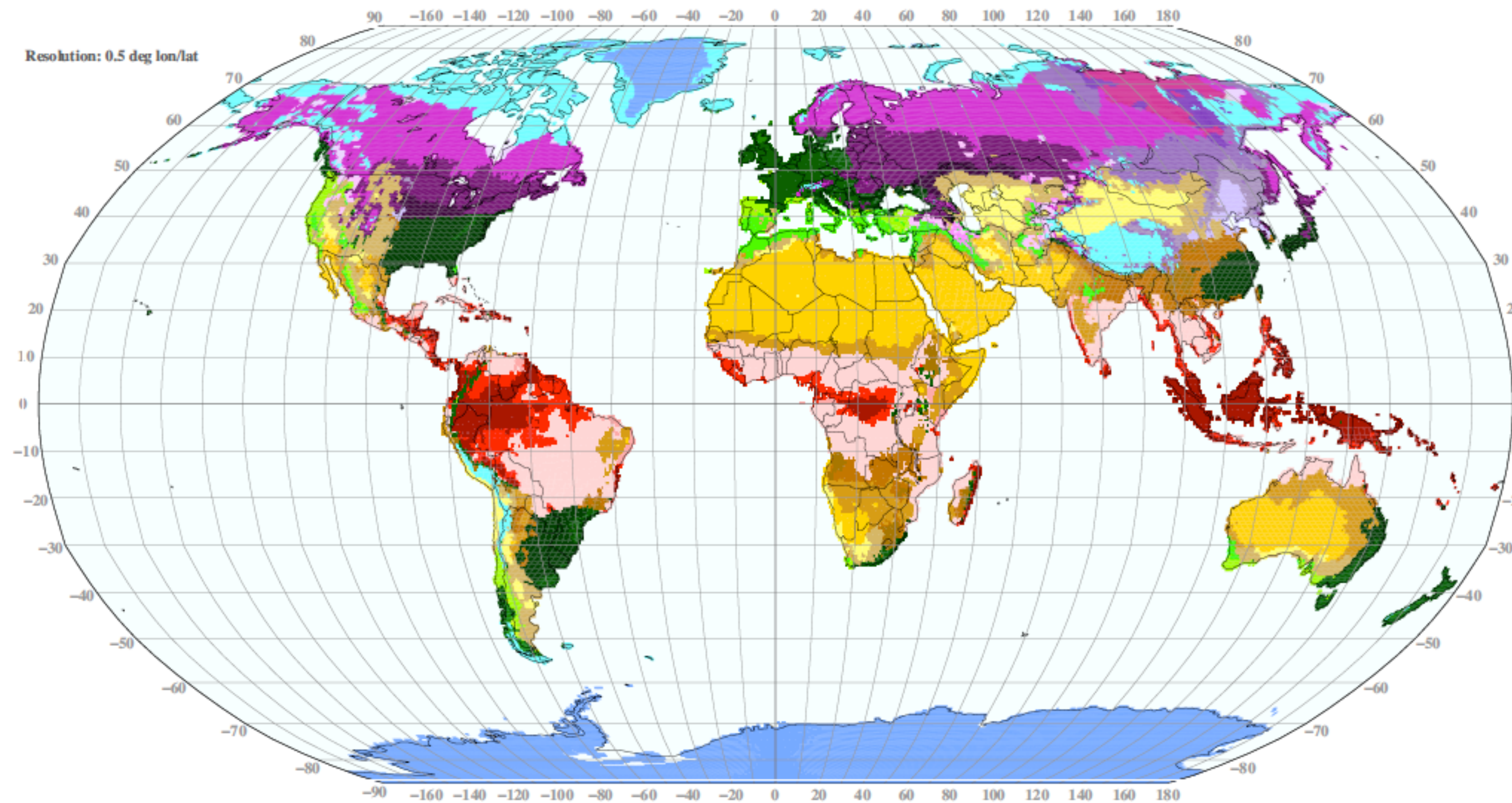


Dfb minimum Temperature ≤ -3 °C

Continental/microthermal climates

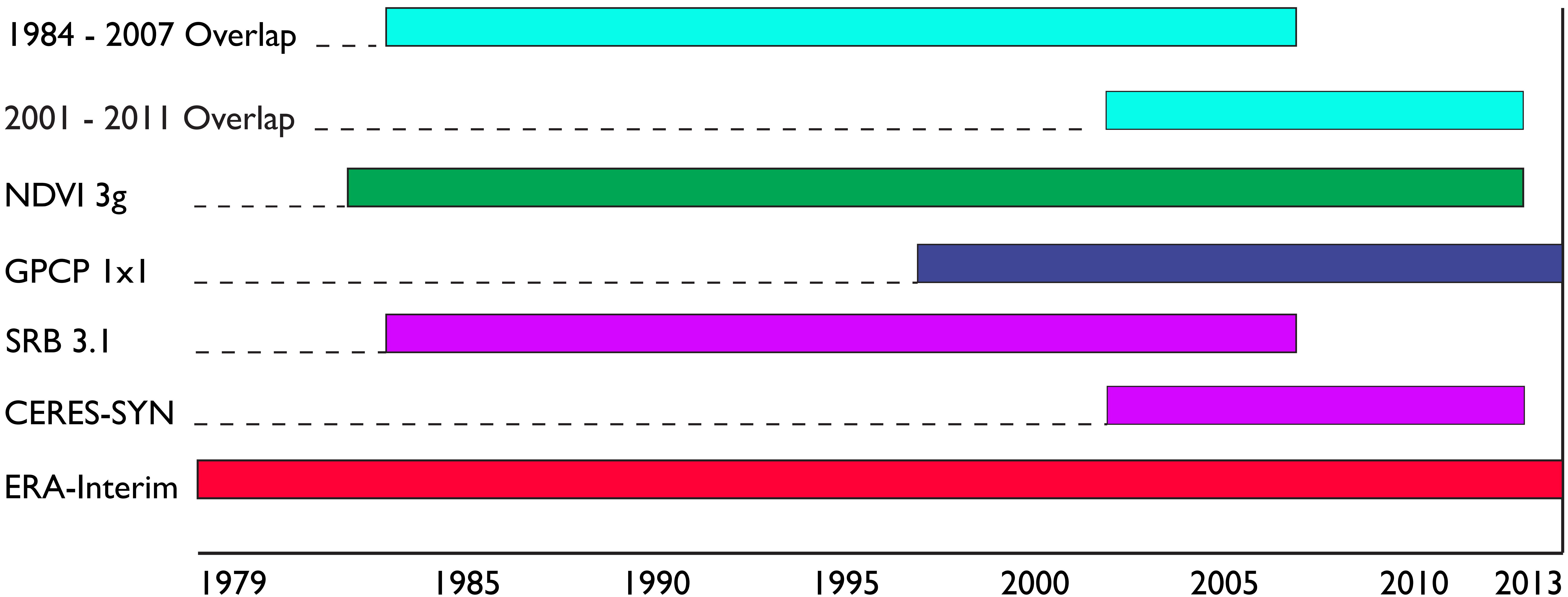
Kottek et al. 2006

Climate Controls Vegetation

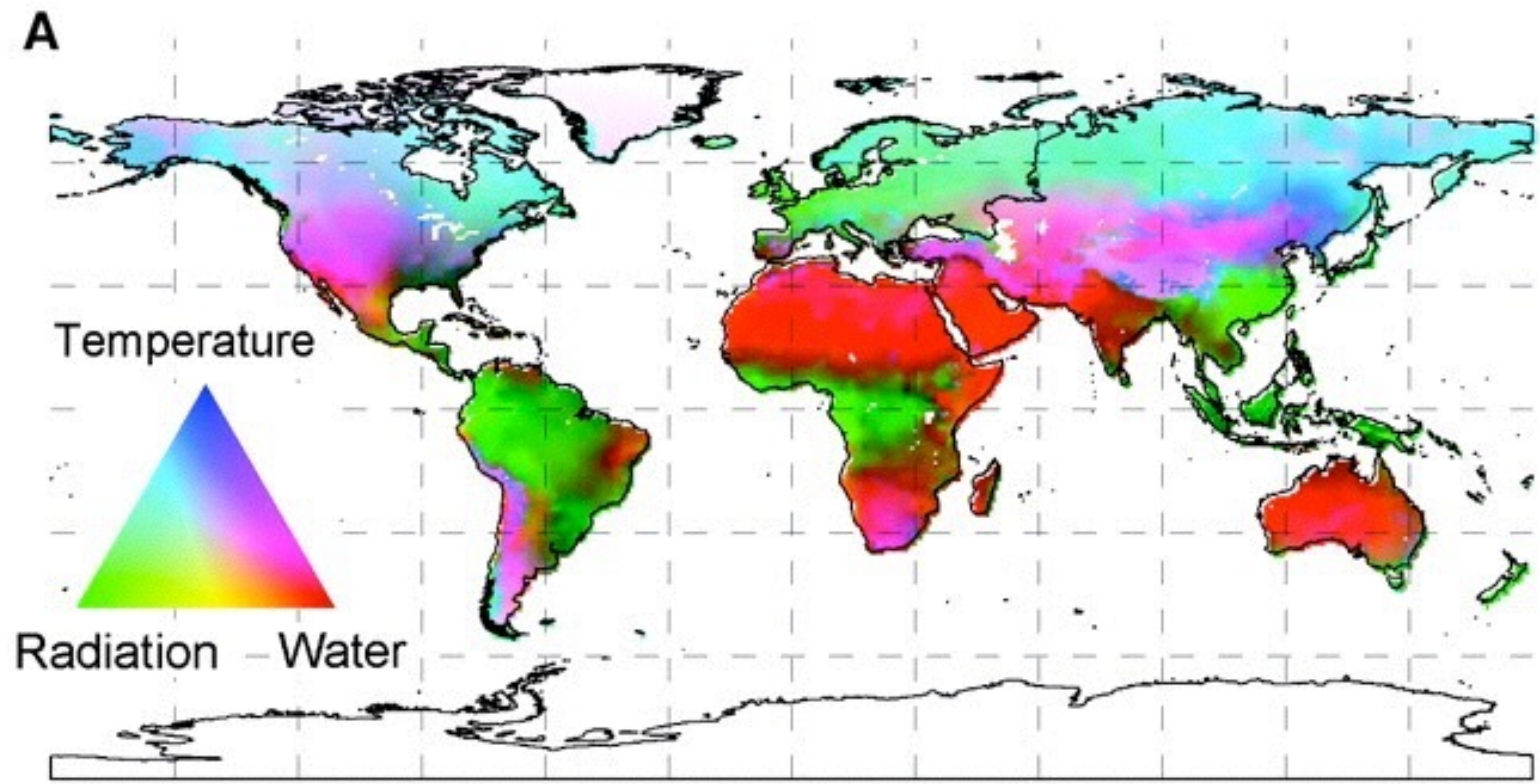


Rubel et al. 2010

Data used and available

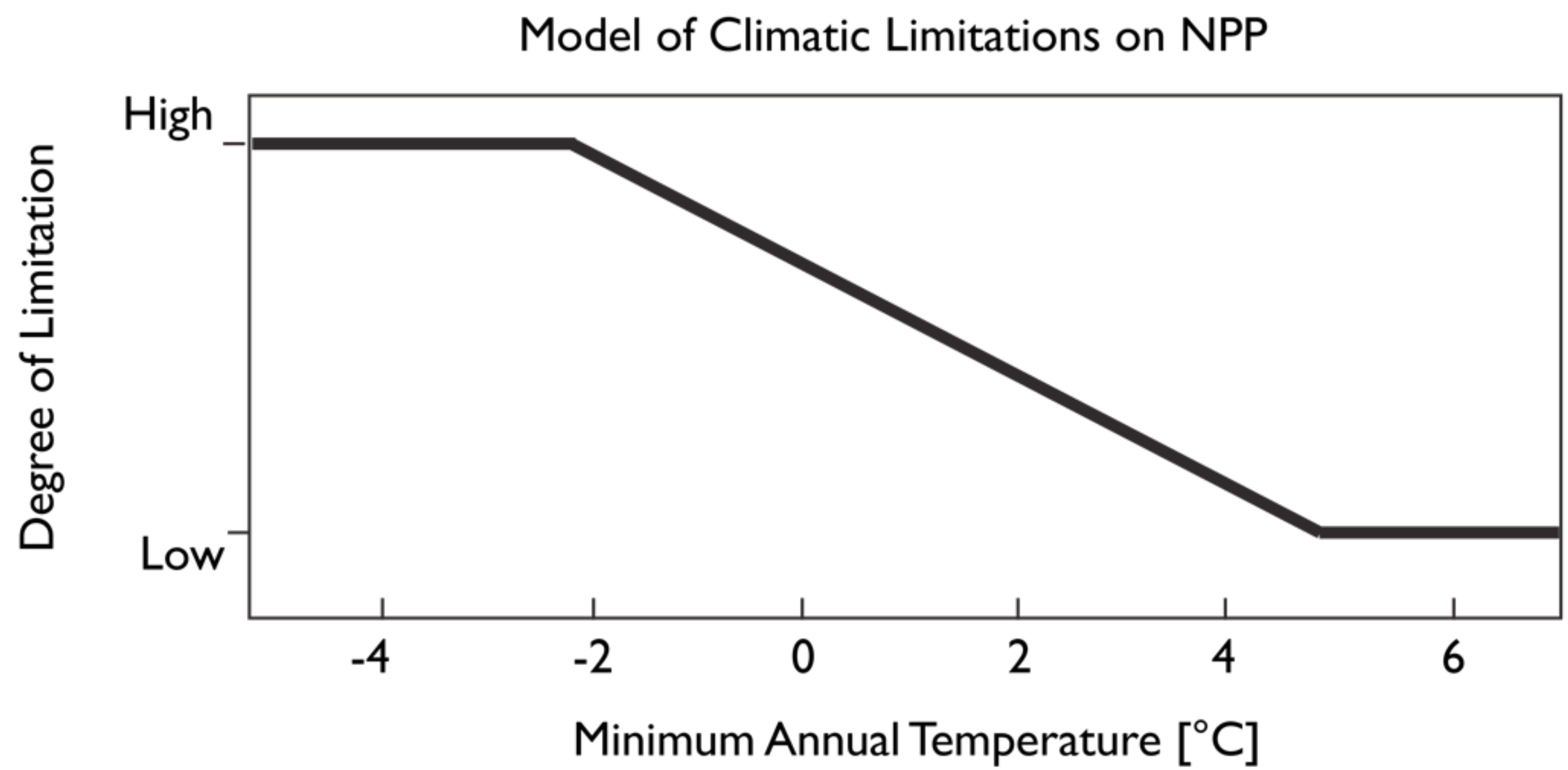


Mix of Climate and Plant Physiology



Nemani et al. 2003

Constraint on vegetation, models behind the map



Jolly et al. 2005

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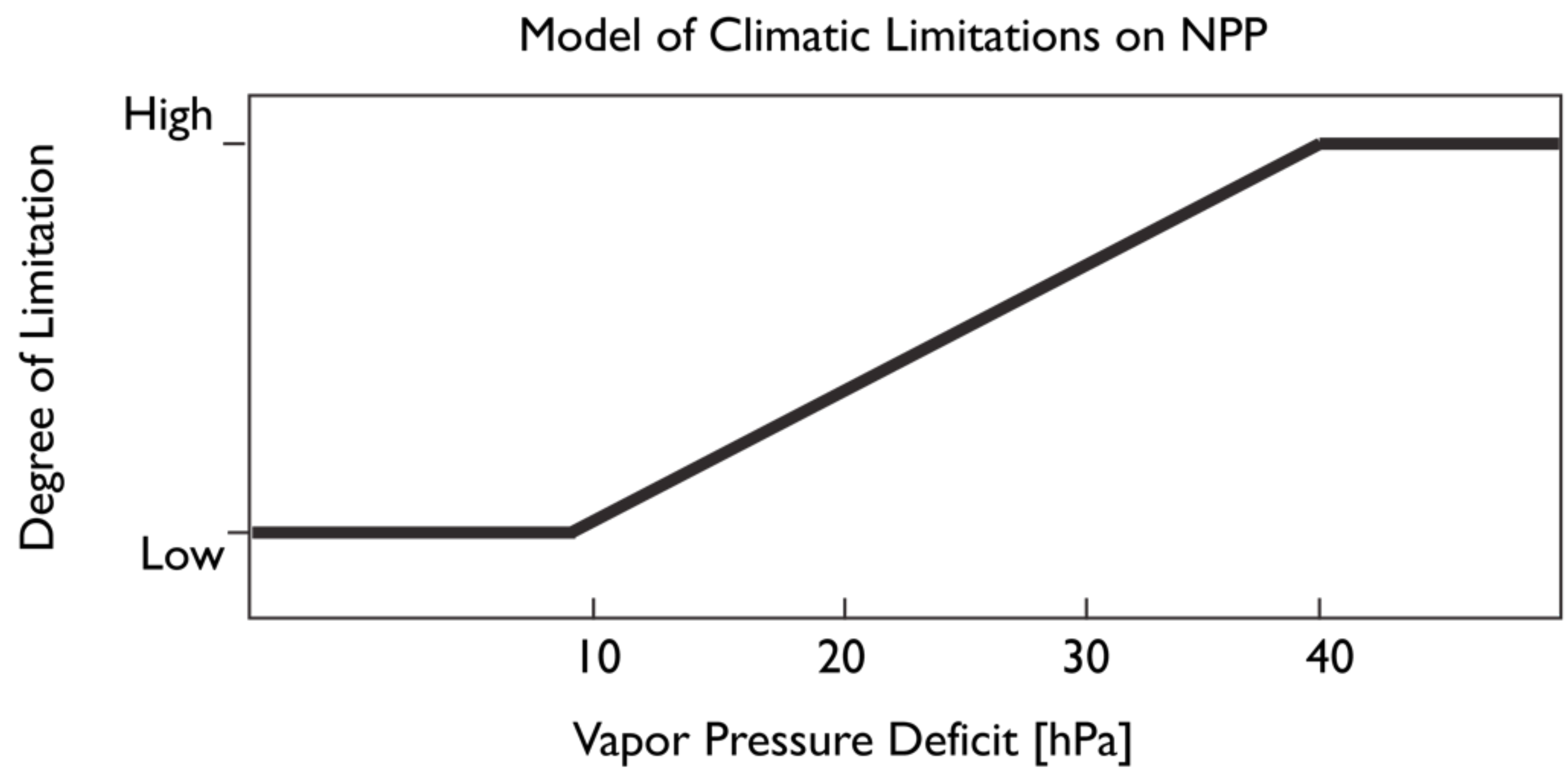

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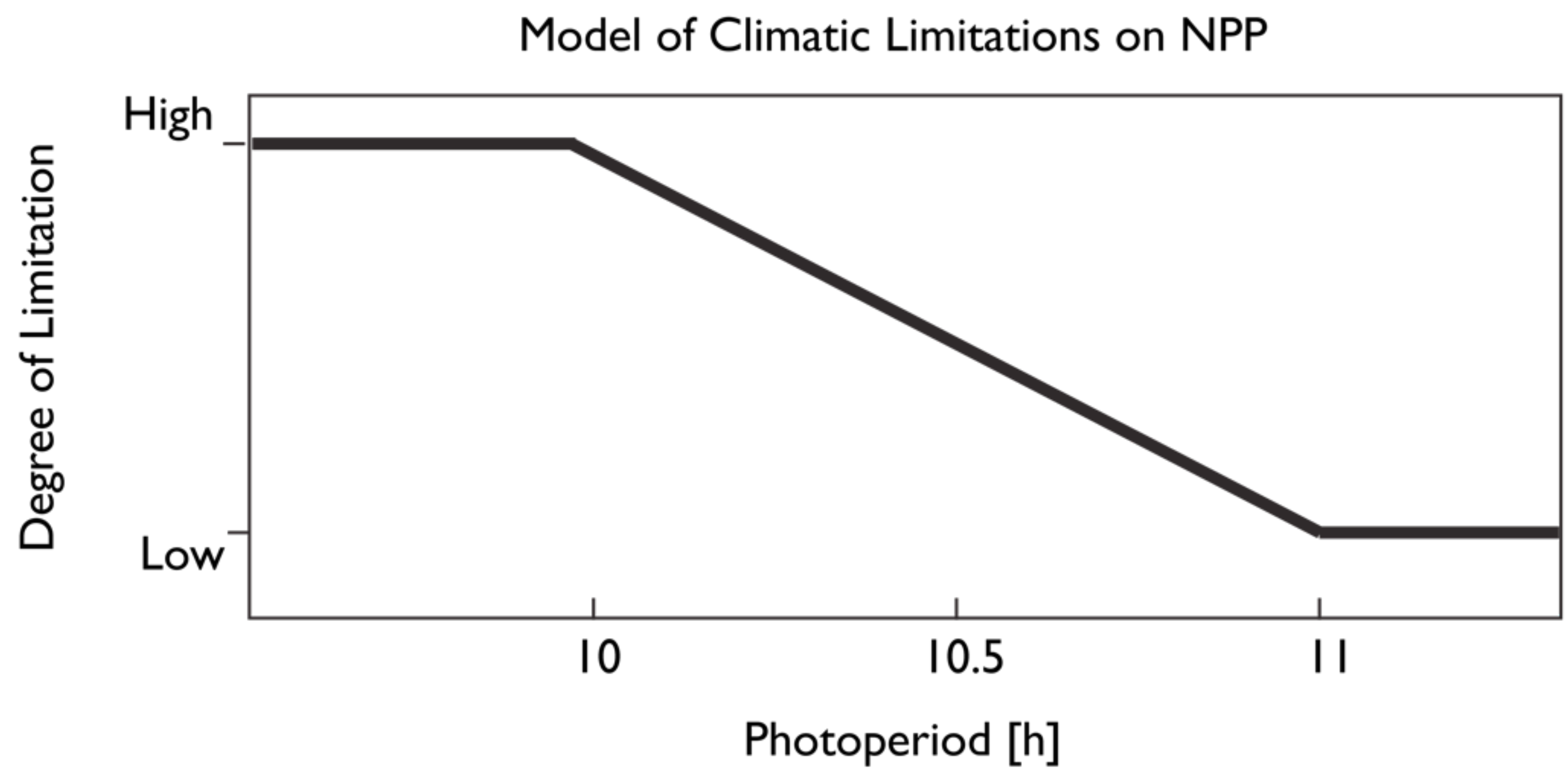
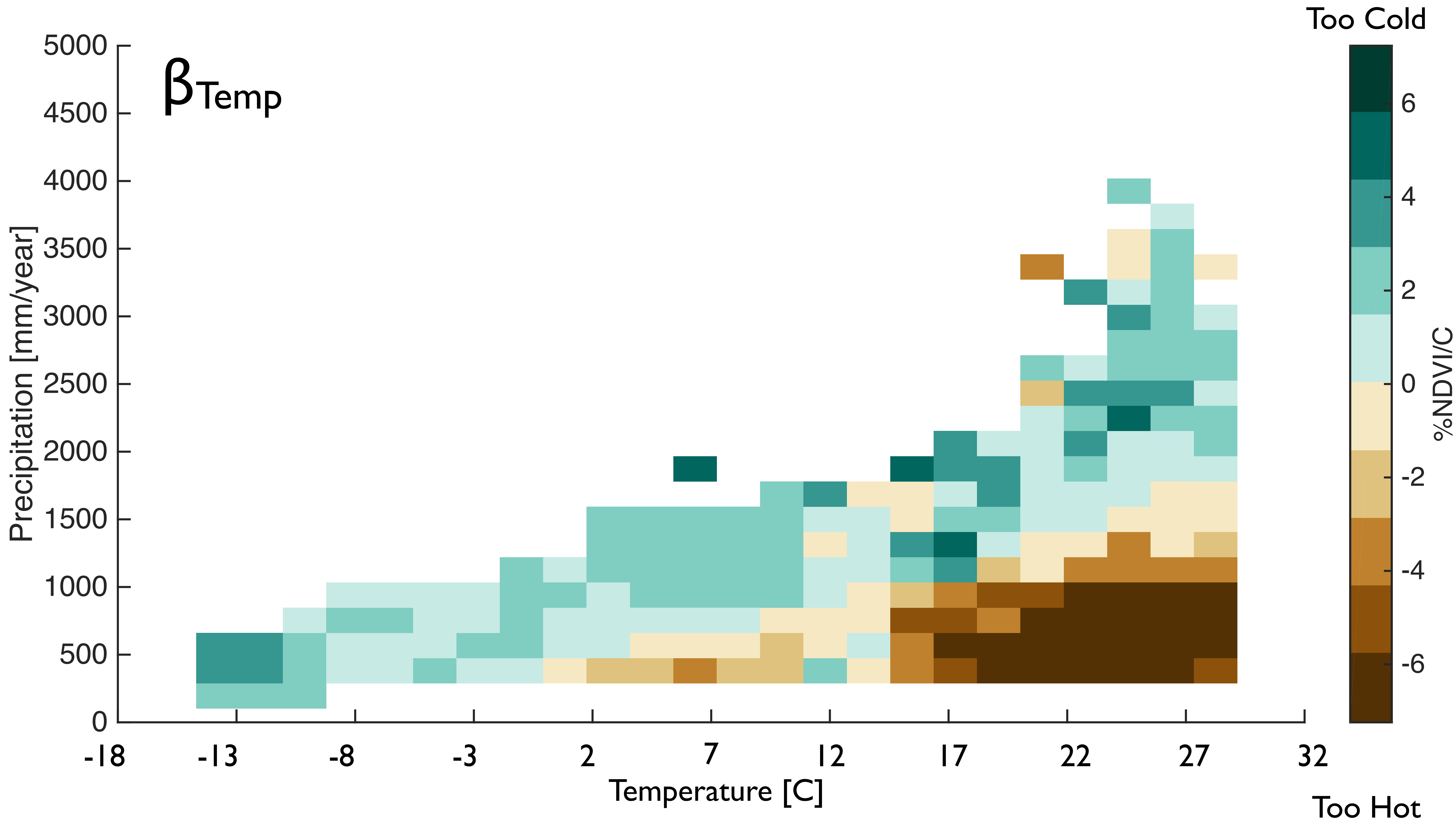


Jolly et al. 2005

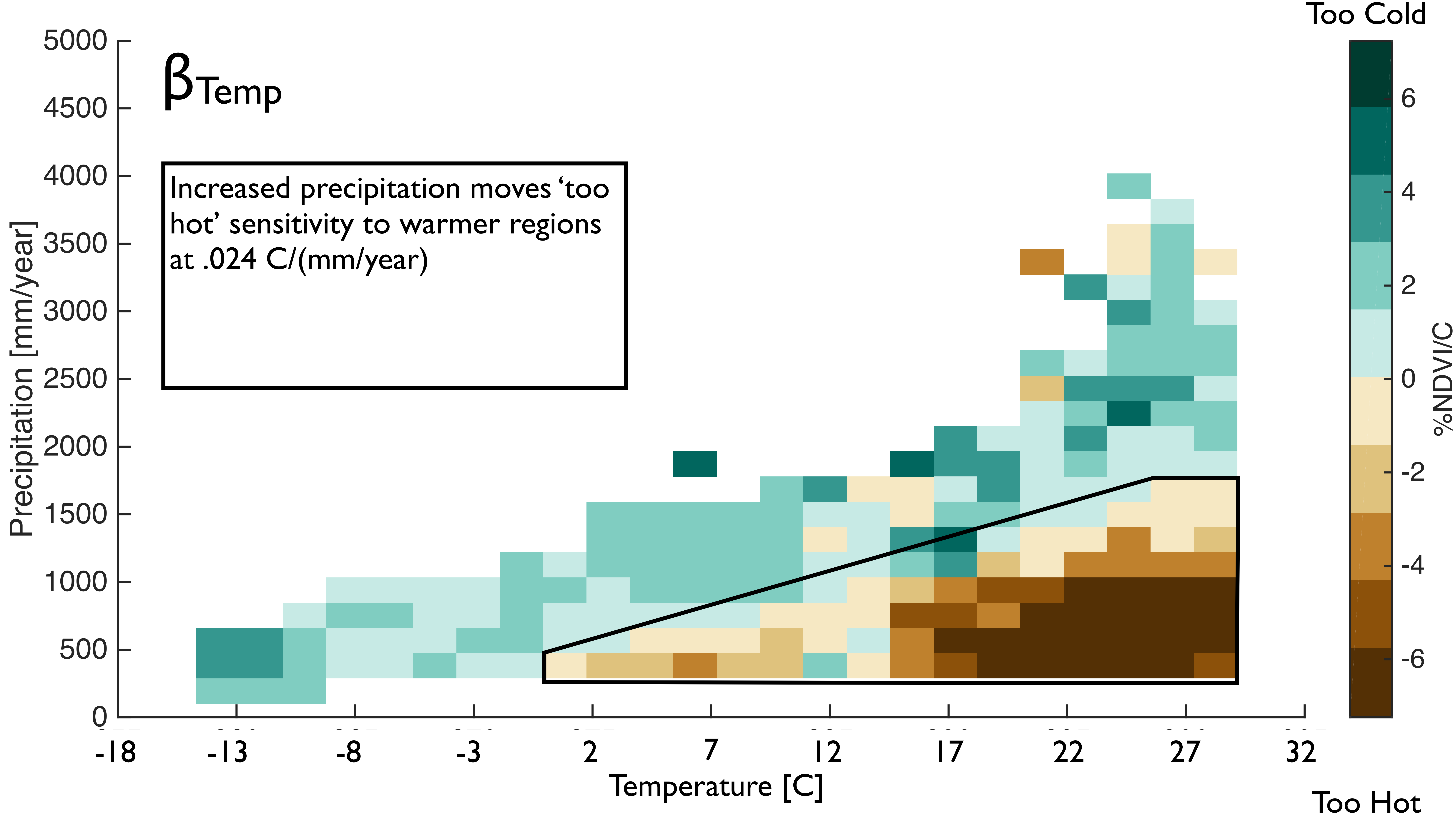
BackBack Up


Old Plots

Vegetation Sensitivity to Temperature



Hot dry regions

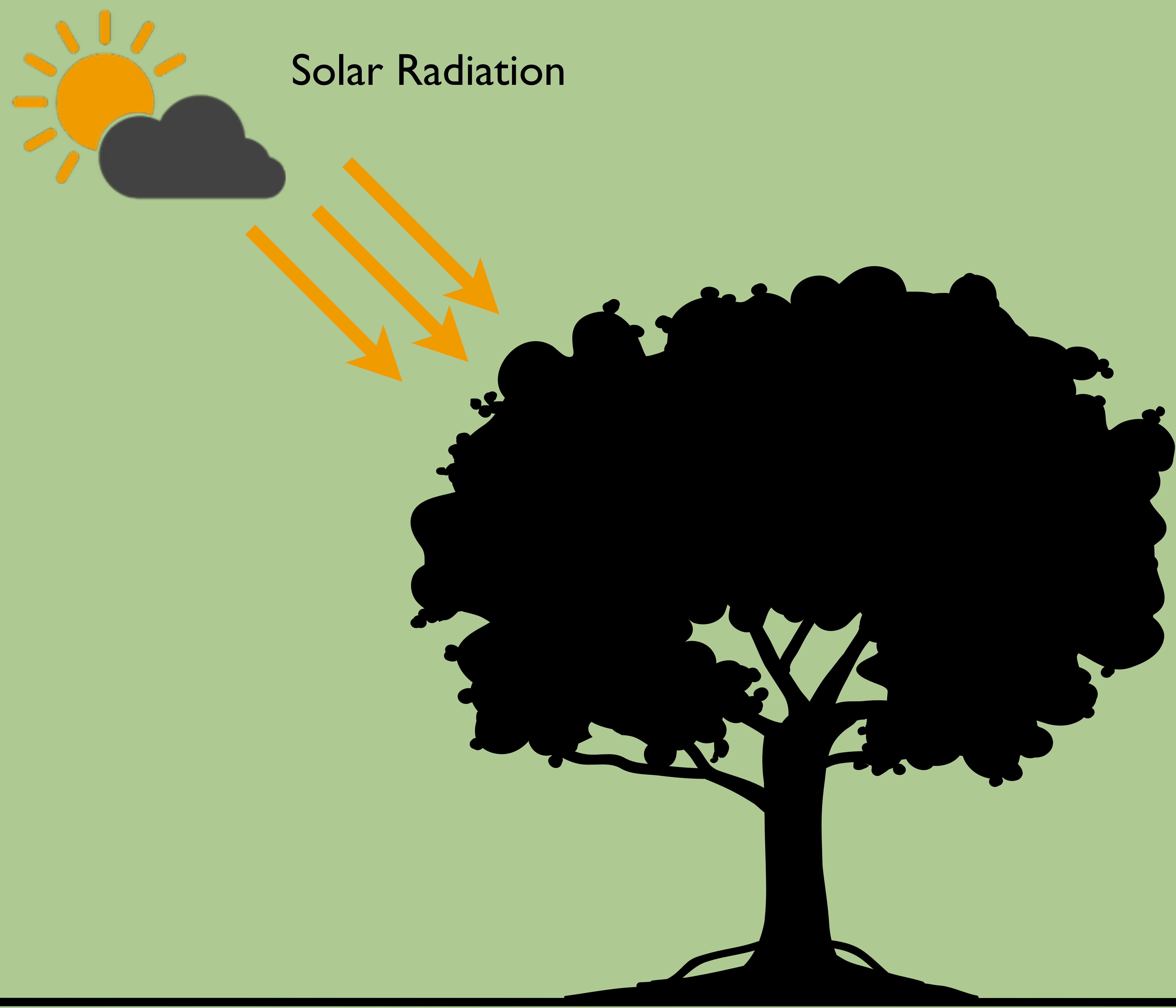


Trading Water for Carbon

Ball et al 1987

Photos: Wikimedia Commons

Trading Water for Carbon

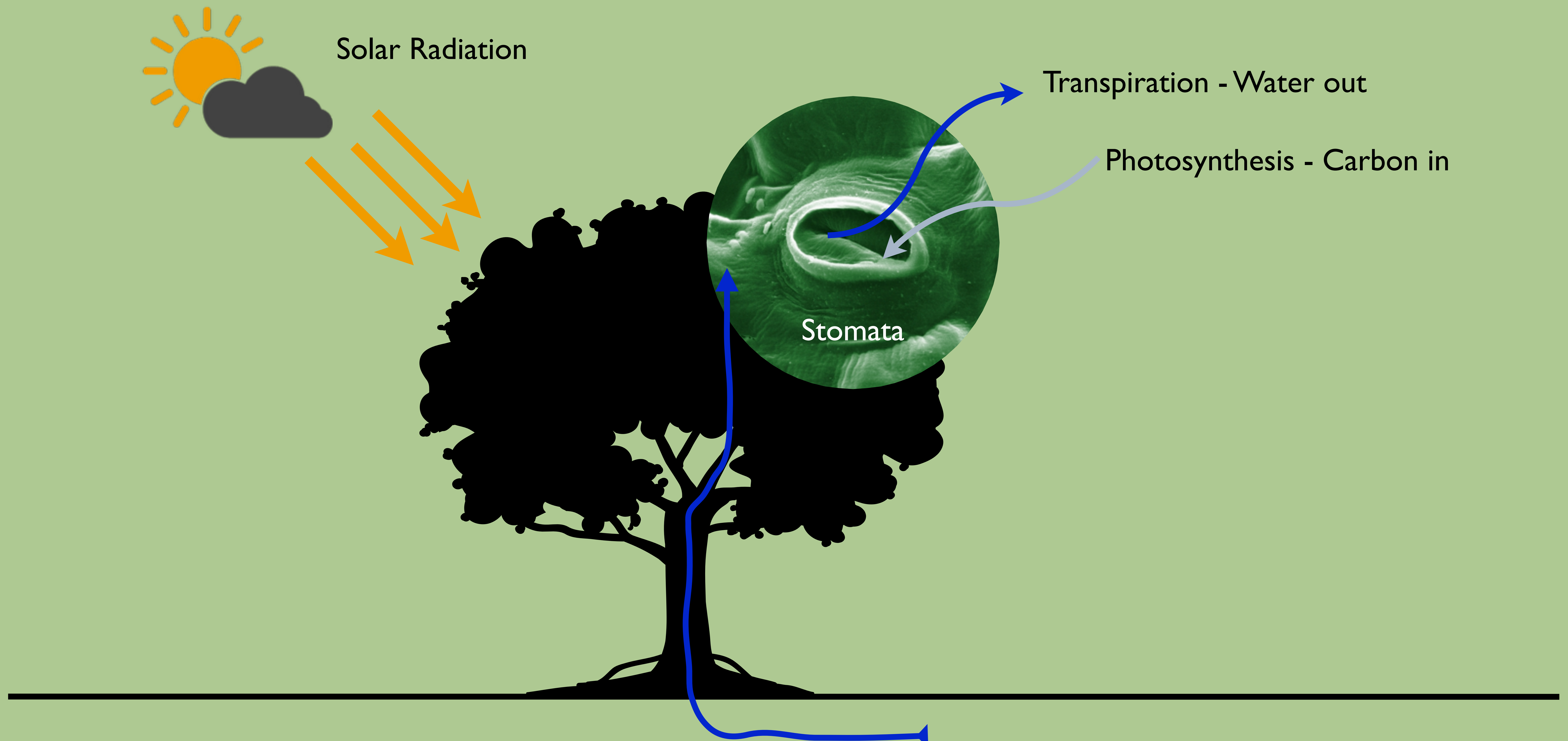


Shortwave radiation heats canopy and drives photosynthesis

Ball et al 1987

Photos: Wikimedia Commons

Trading Water for Carbon

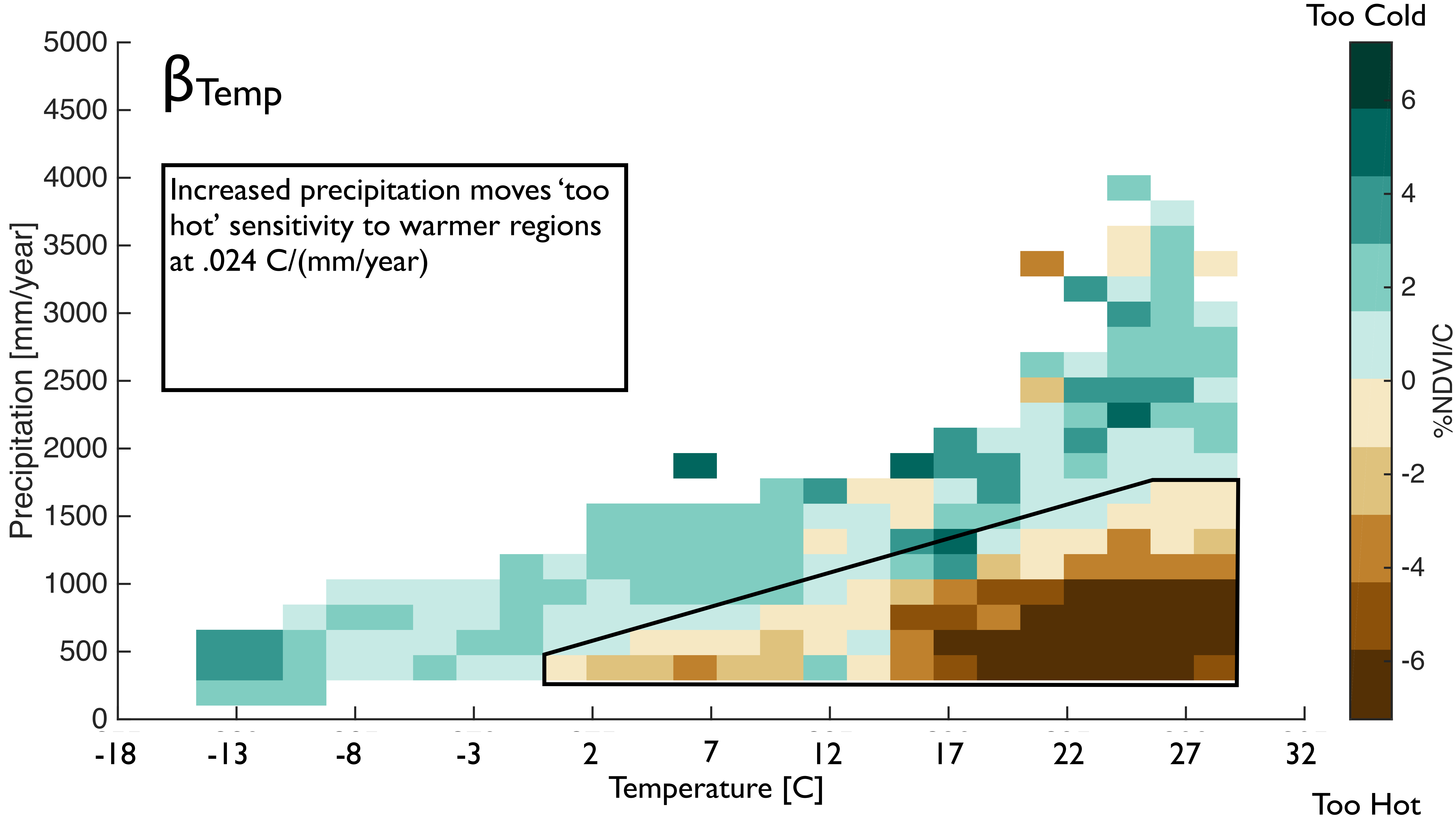


CO2 comes in through stomata, water goes out

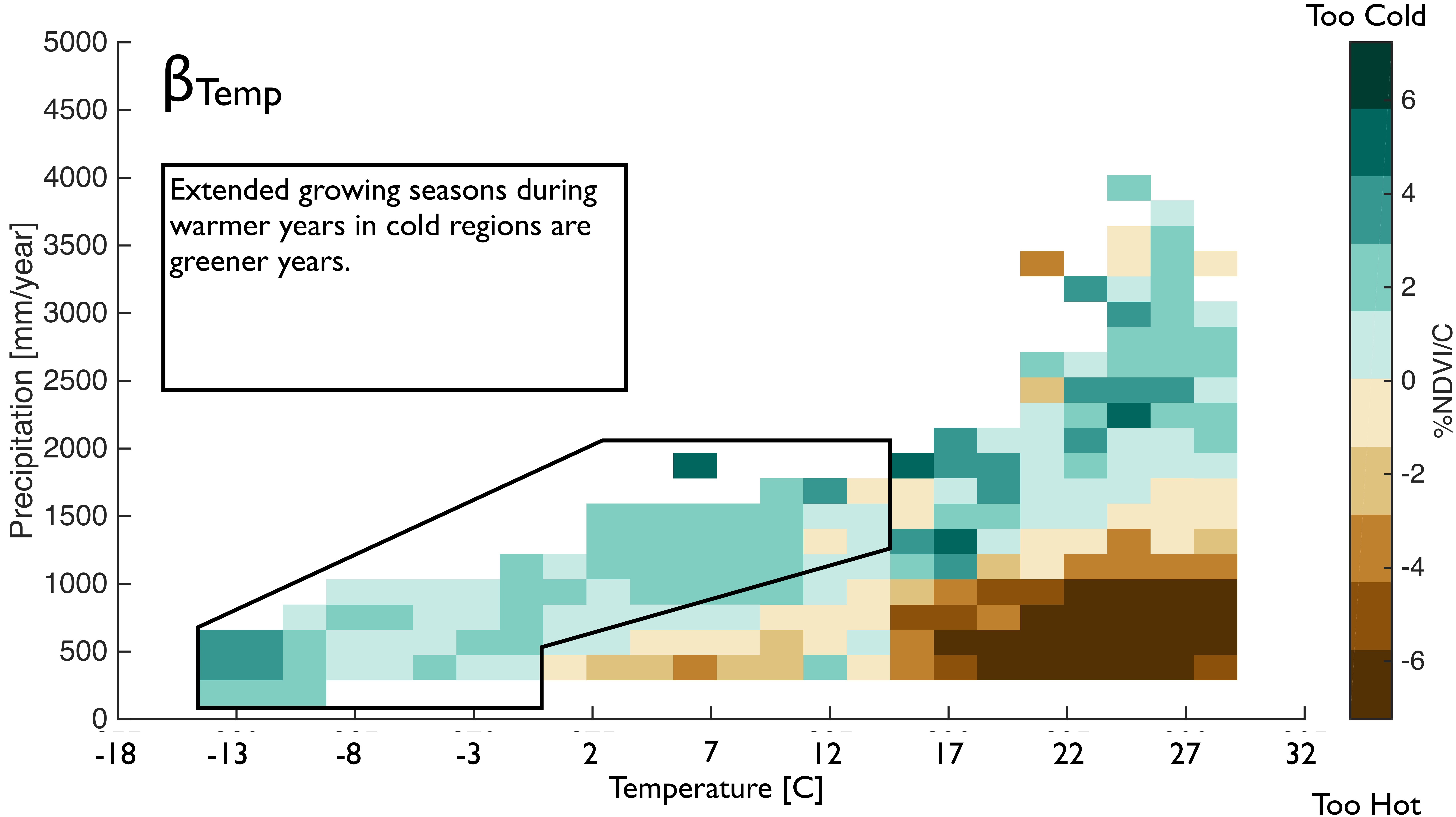
Ball et al 1987

Photos: Wikimedia Commons

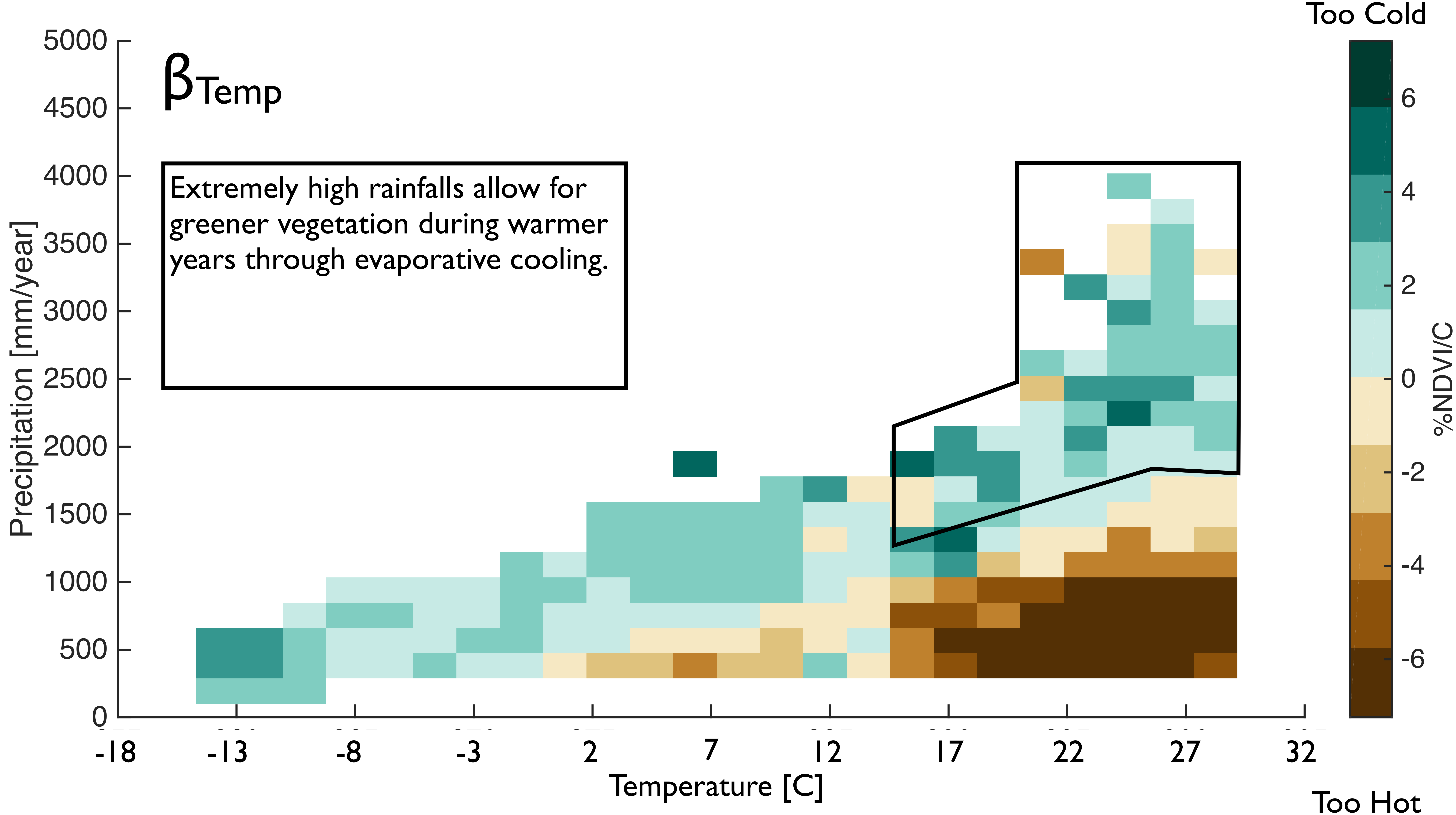
Hot dry regions



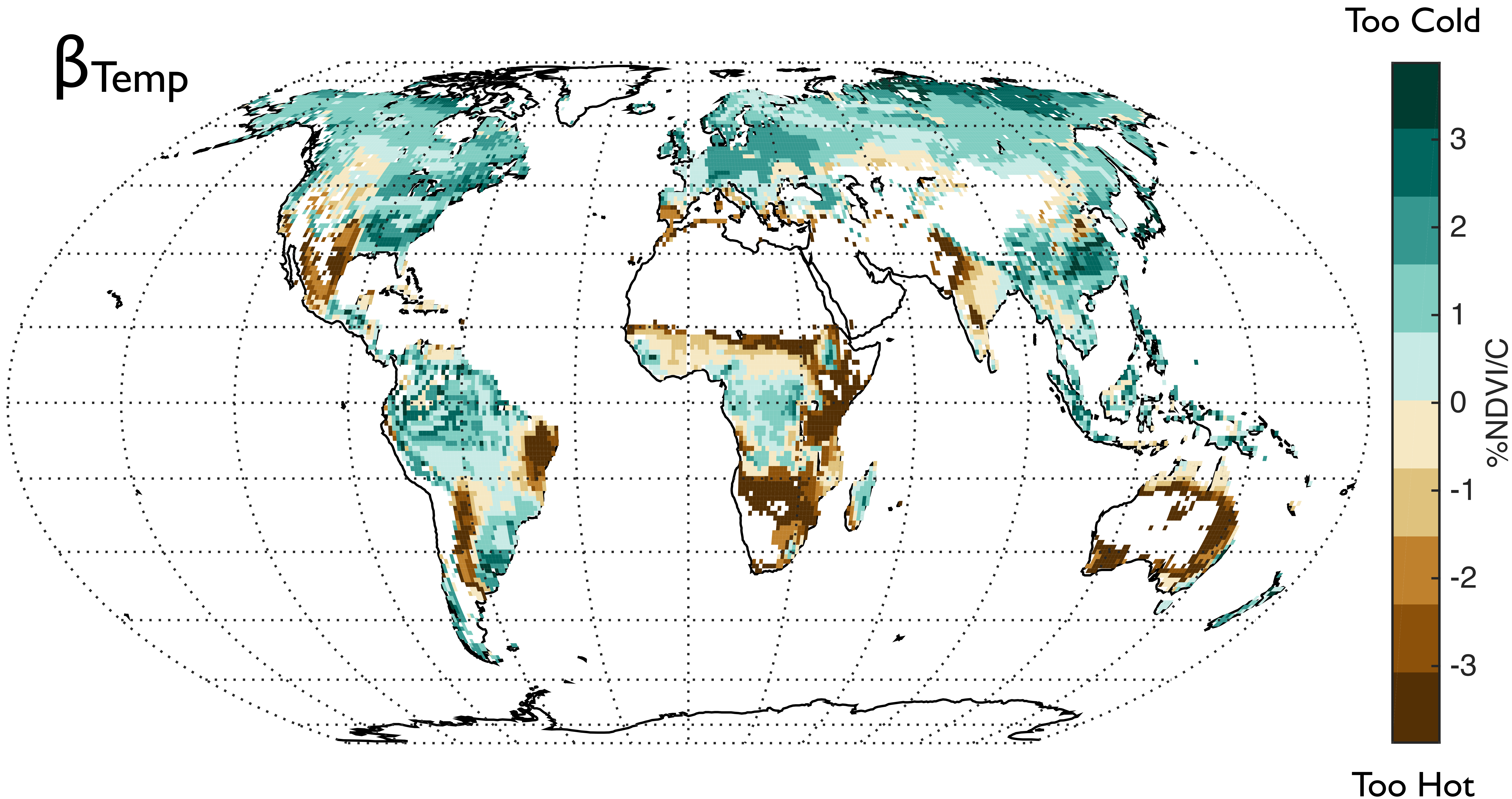
Cold regions



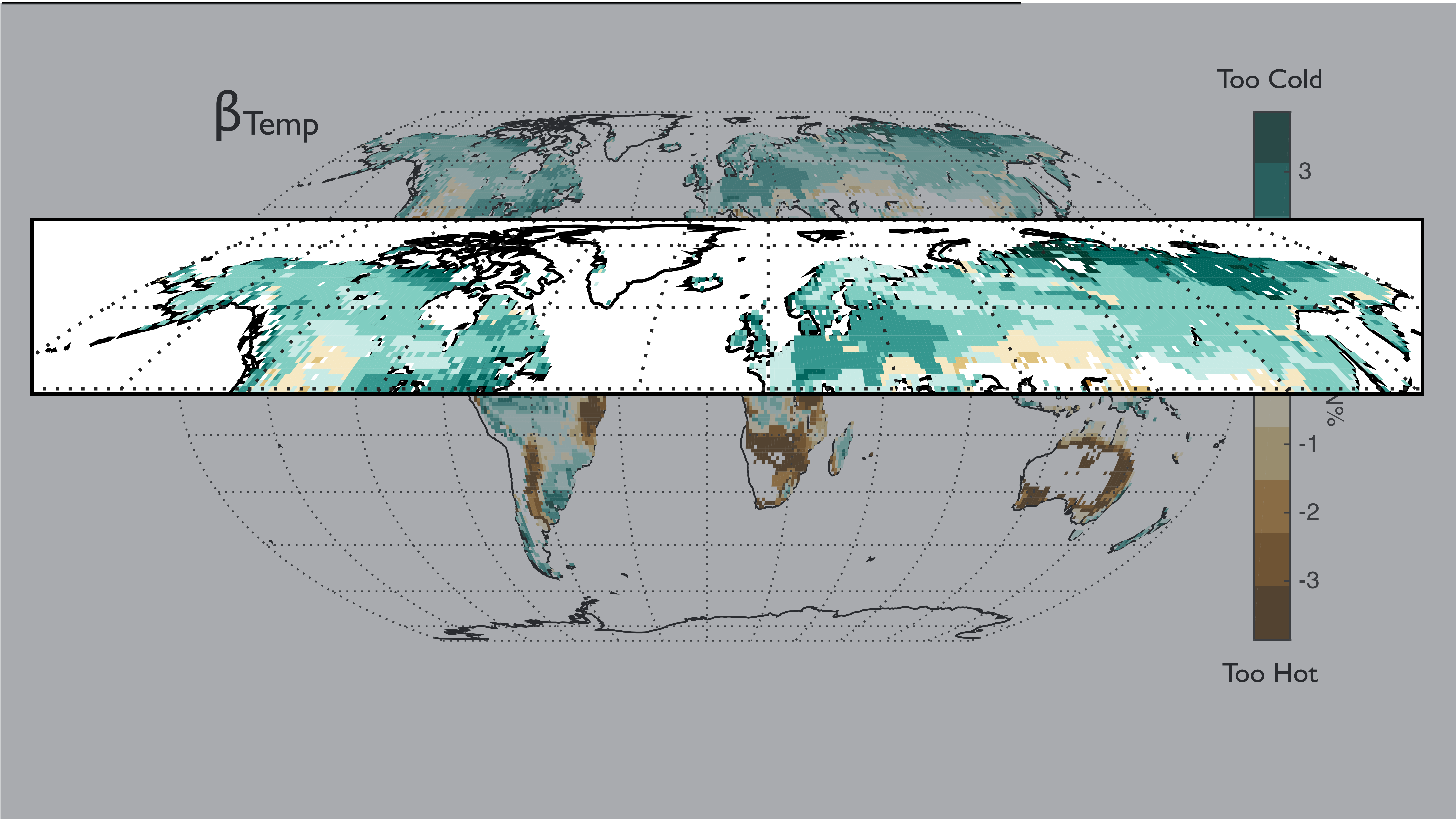
Hot wet tropics: greener in warmer years



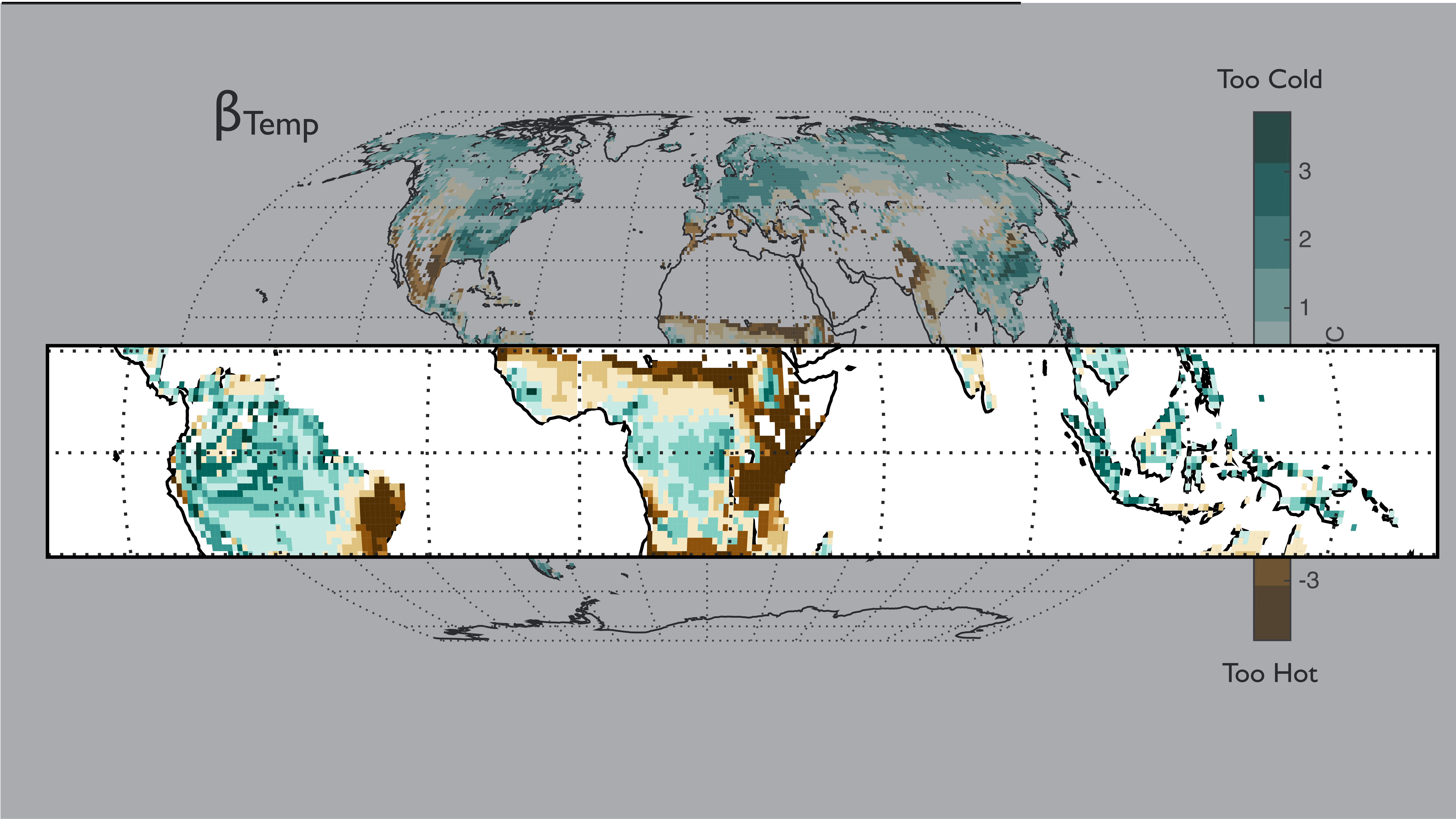
Vegetation sensitivity projected spatially



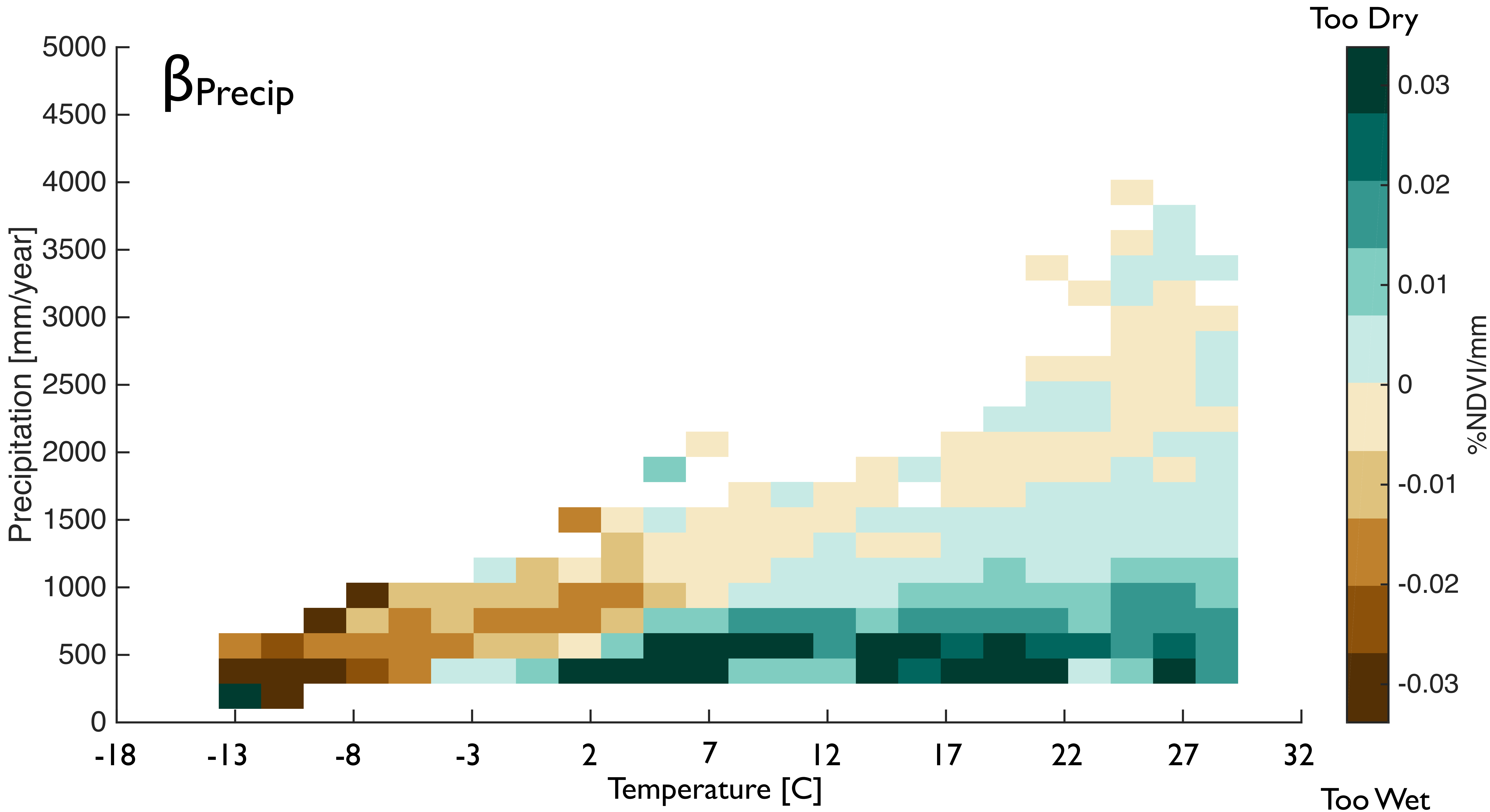
Water driven high latitudes



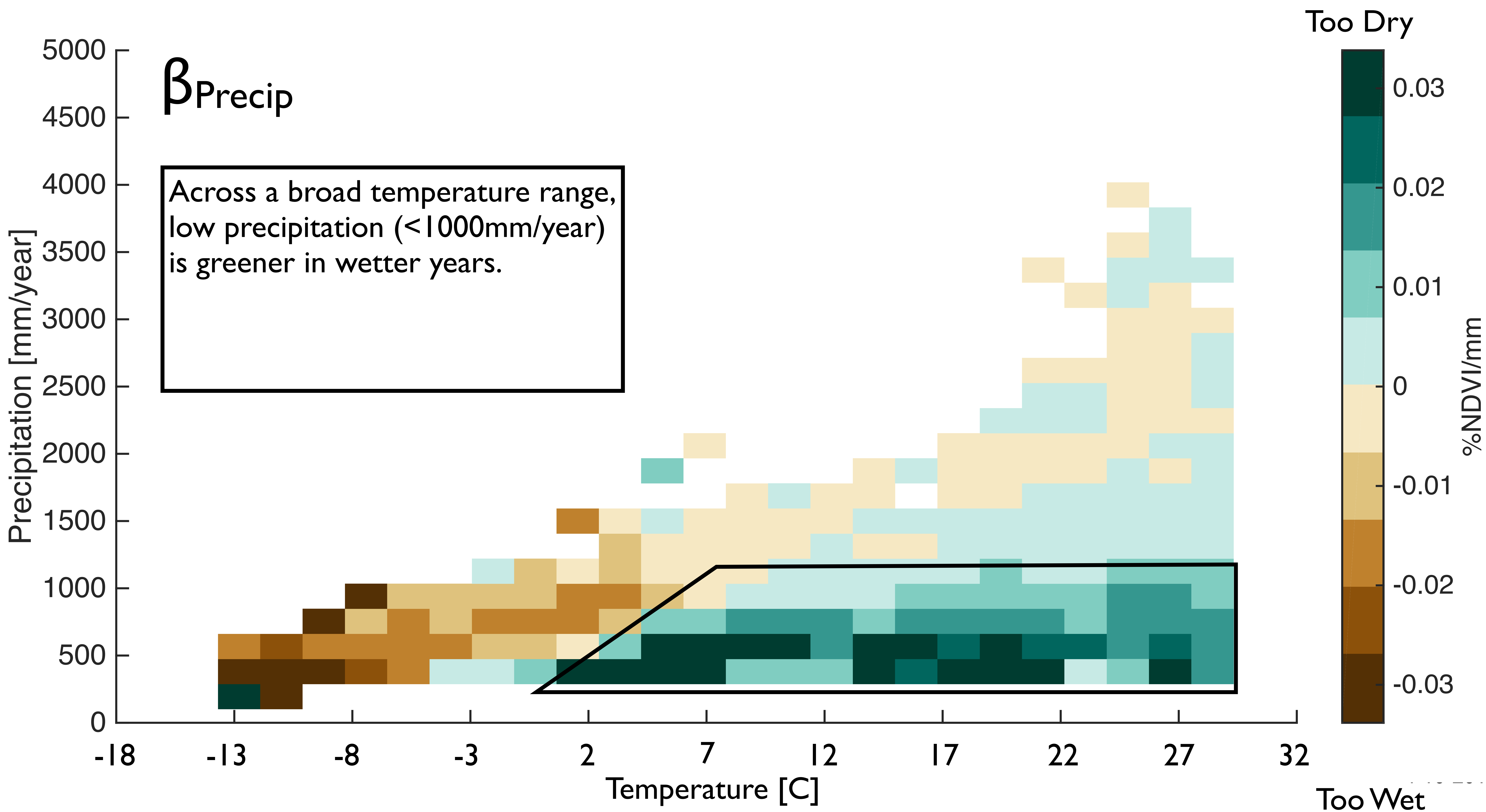
Amazon Basin - Greener when warmer



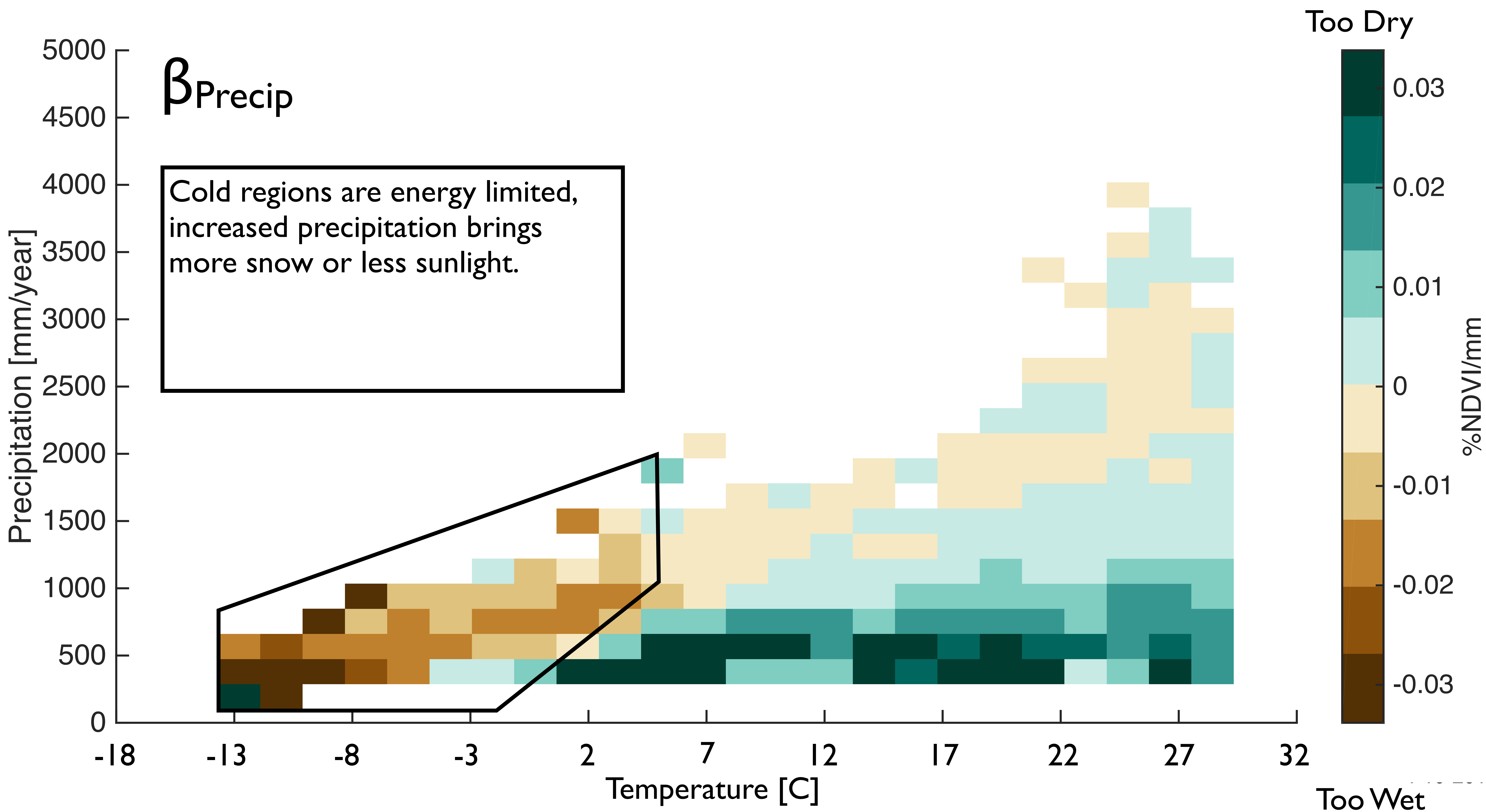
Vegetation Sensitivity to Precipitation



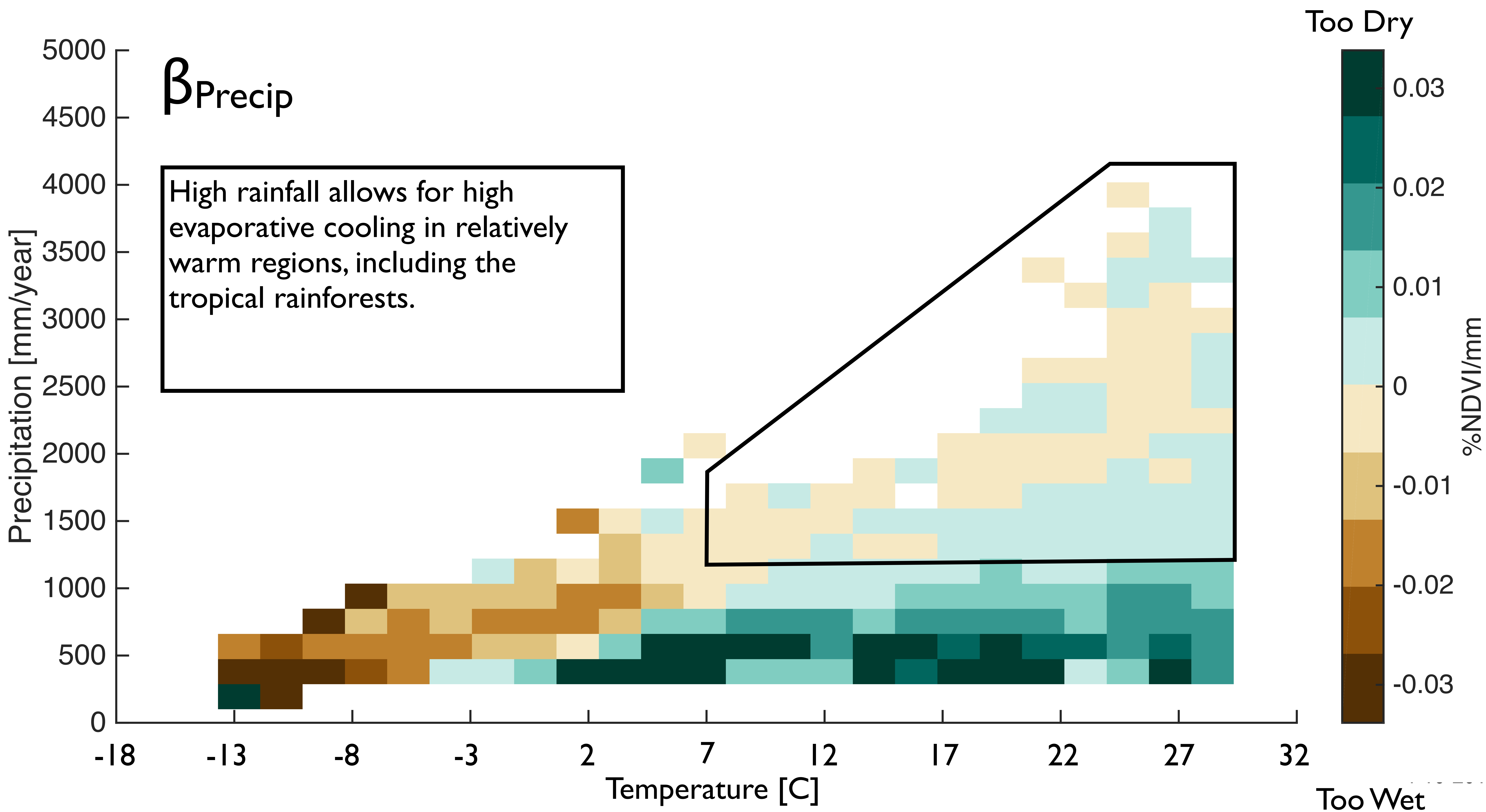
Water Limited Vegetation



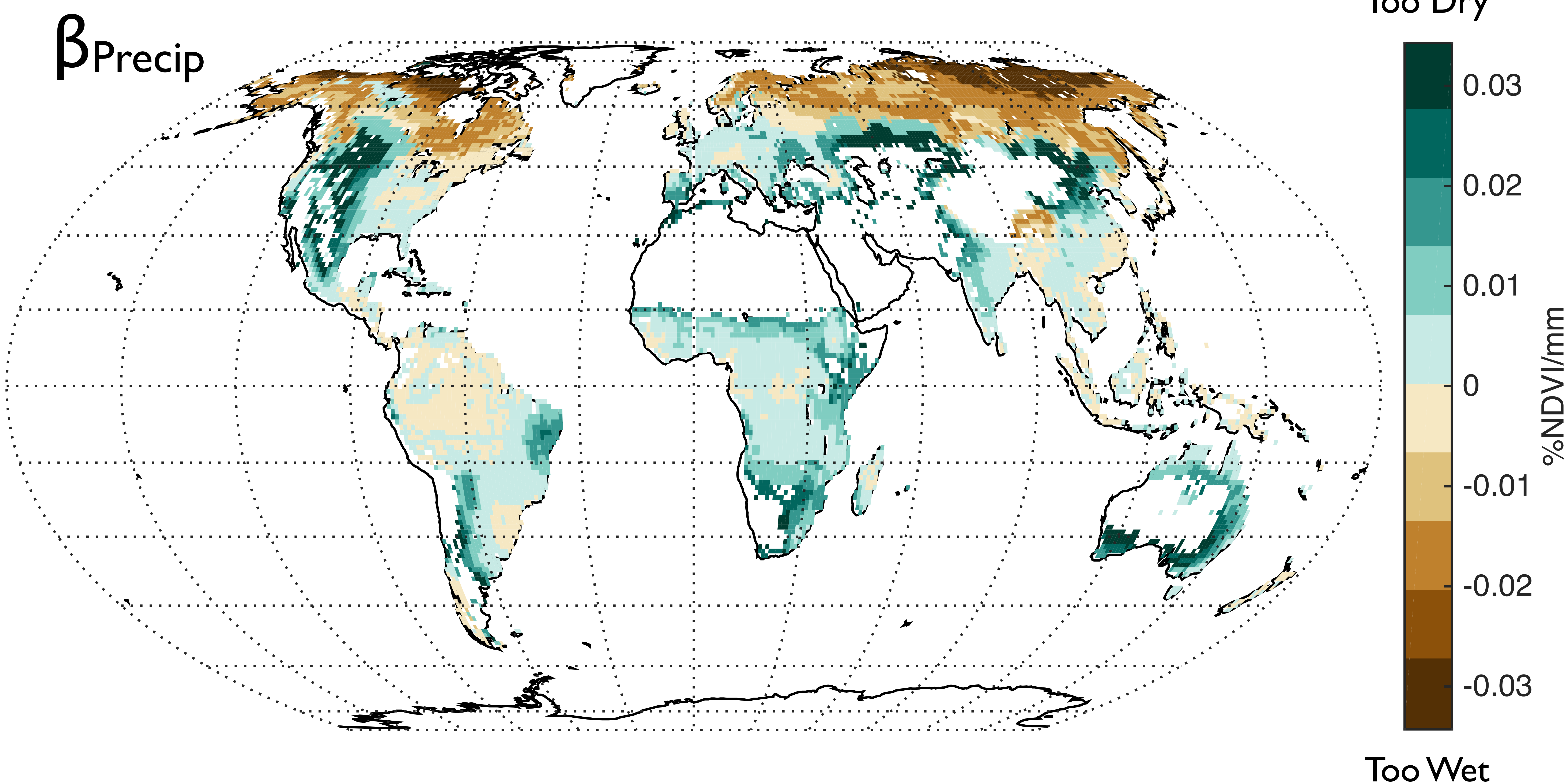
Energy Limited Region



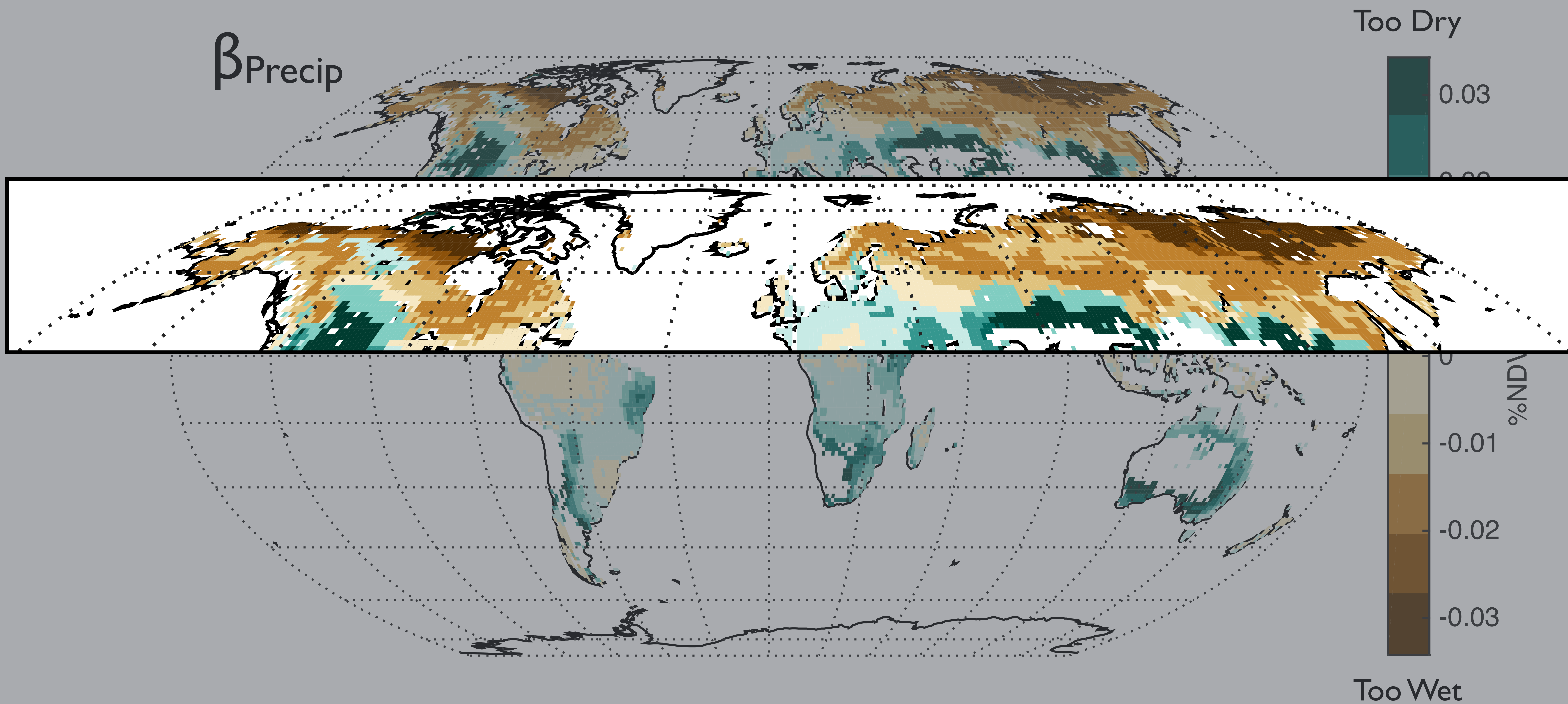
Low Vegetation Sensitivity to Precipitation



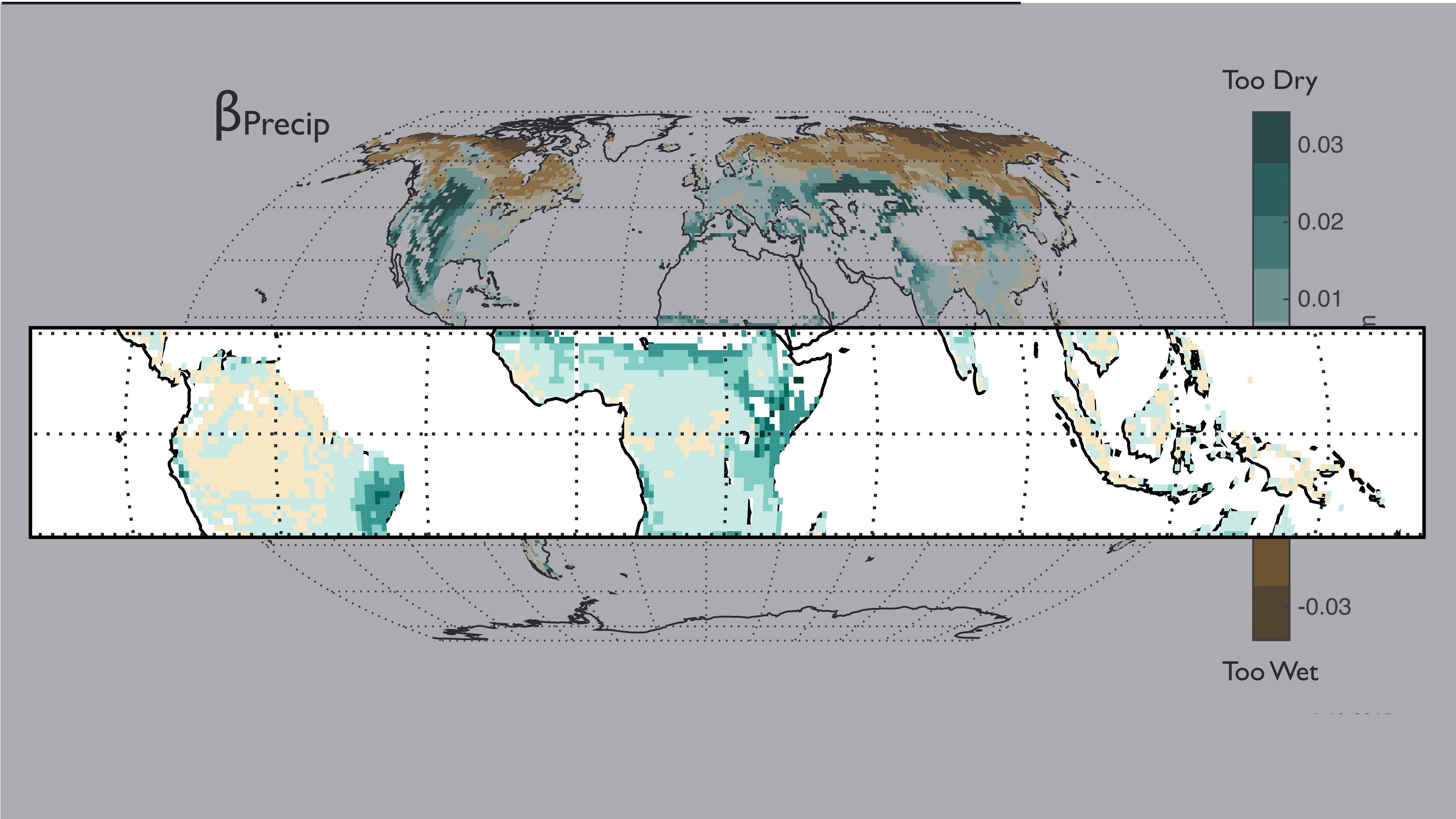
Vegetation sensitivity projected spatially



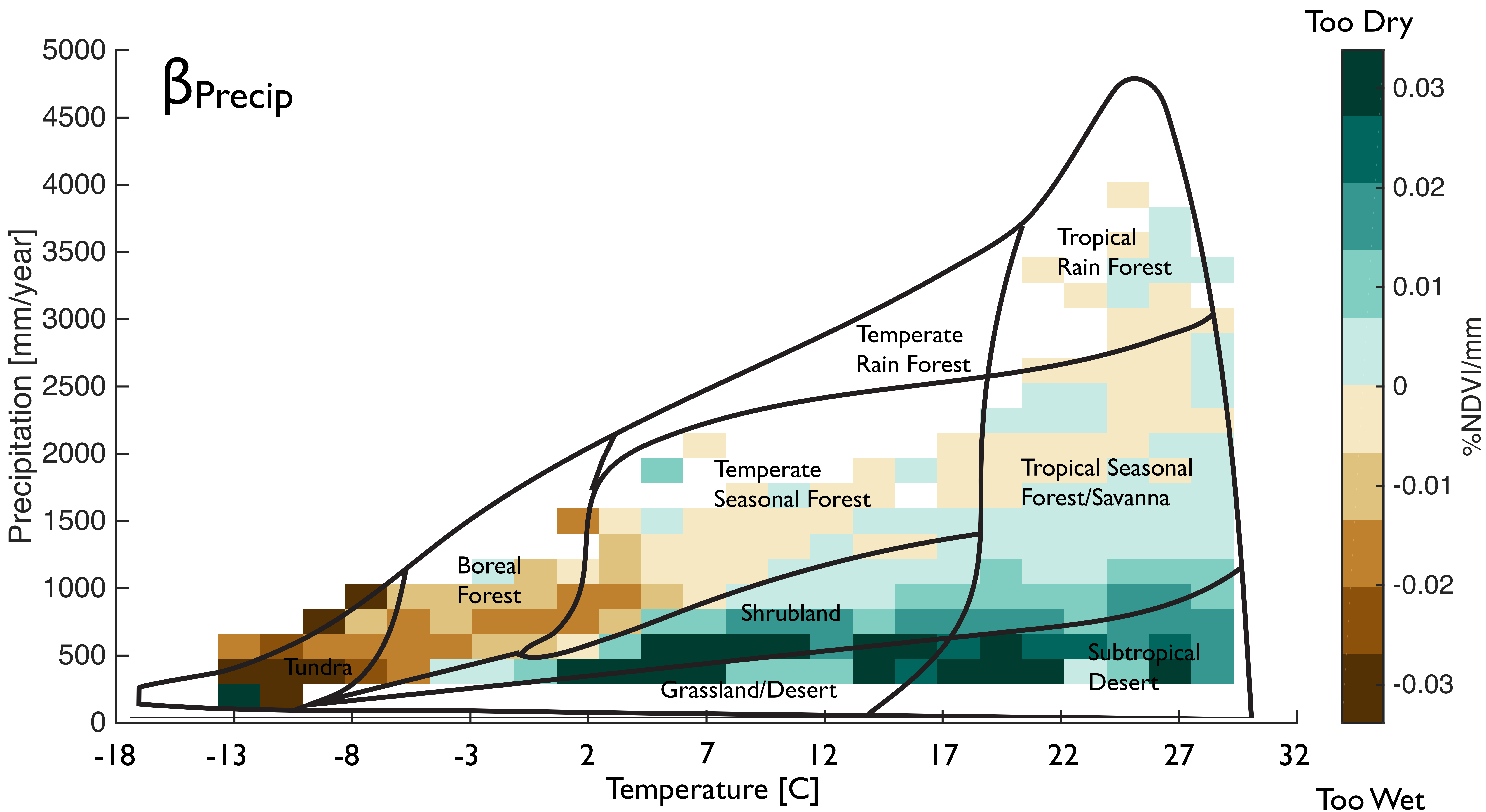
Energy limited high latitudes



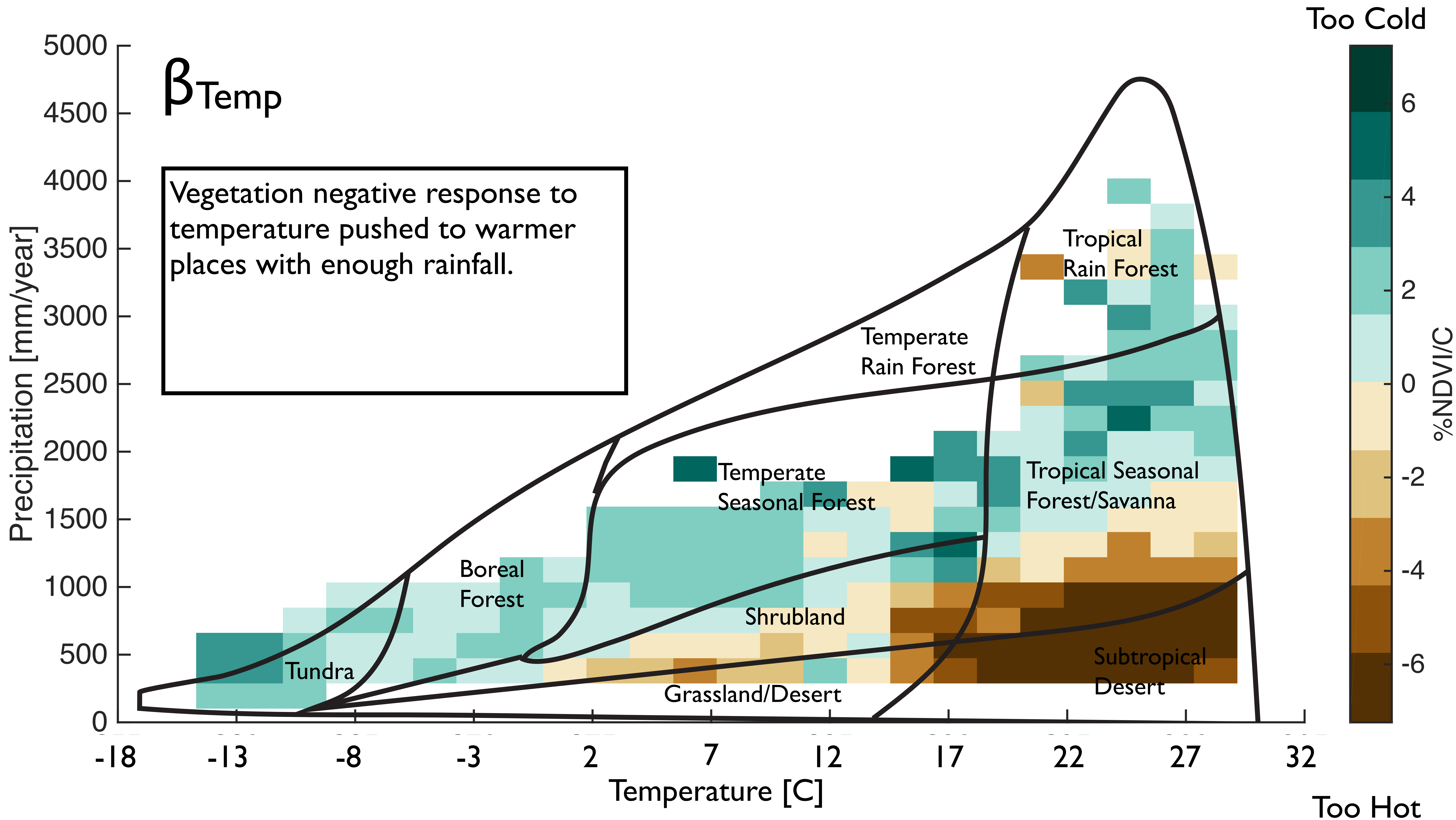
Low vegetation sensitivity to precipitation



Comparison with traditional biome map

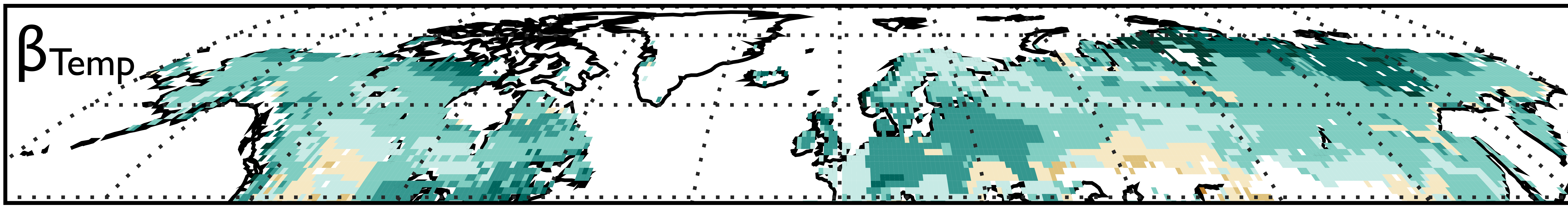


Data driven view of vegetation function

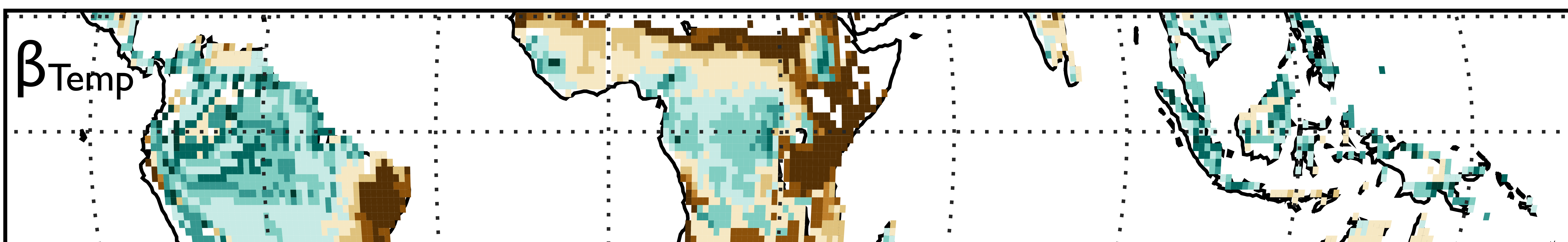


Functional relationships to constrain models

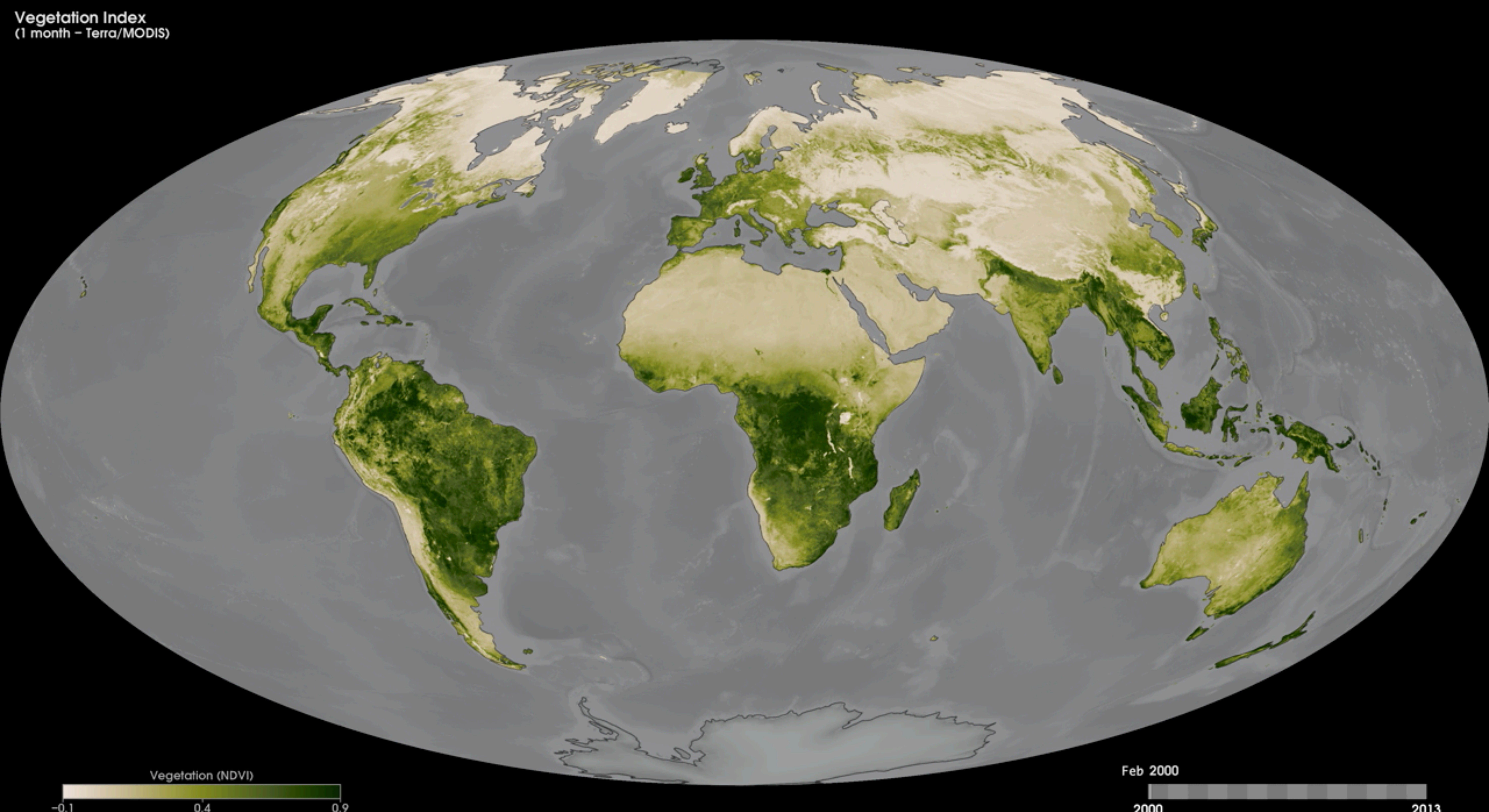
High latitudes vegetation sensitivity depends on water as well as temperature, less positive sensitivity where dry

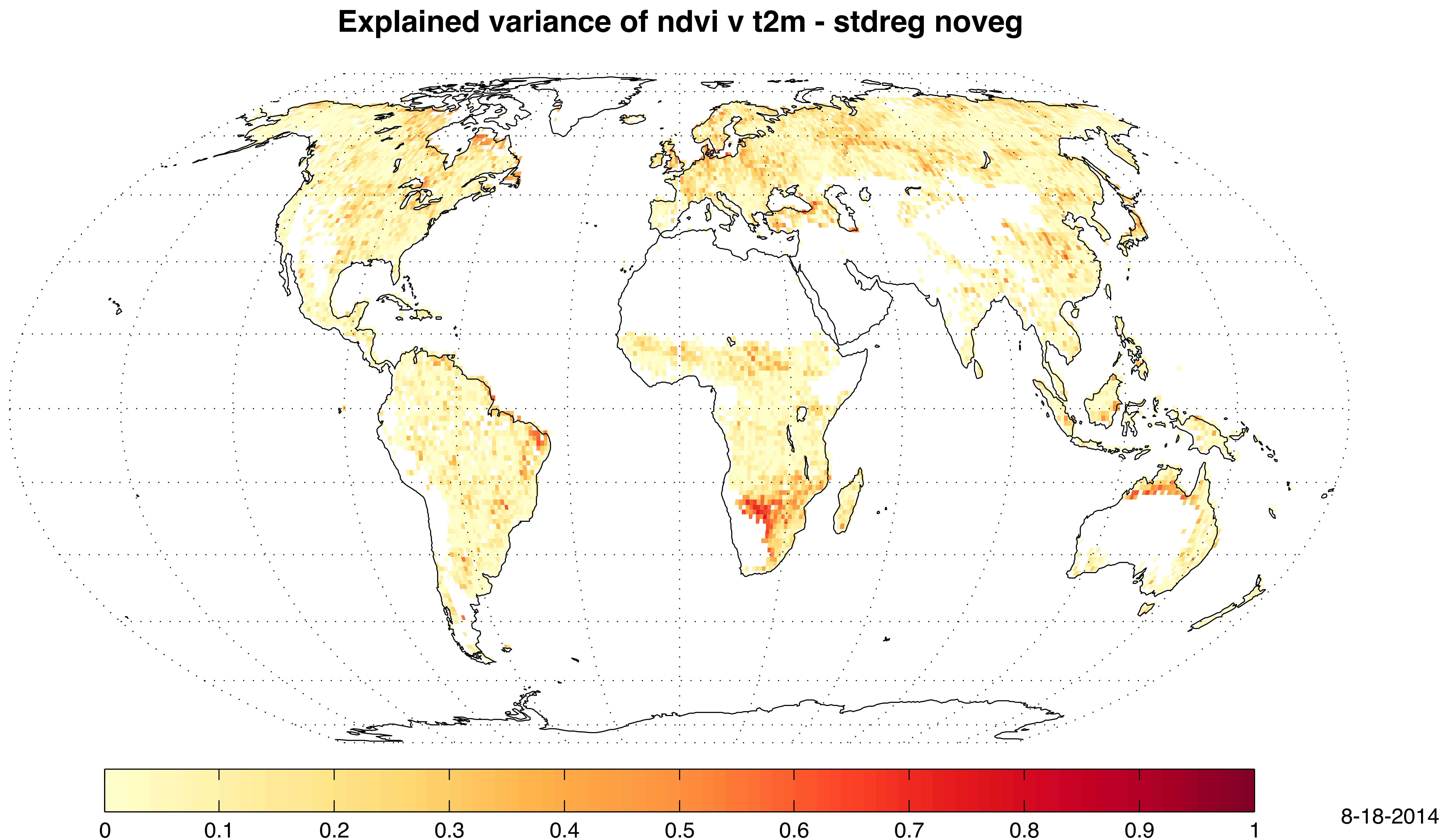


Tropical Rainforests do not show negative vegetation sensitivity to interannual variations of warming

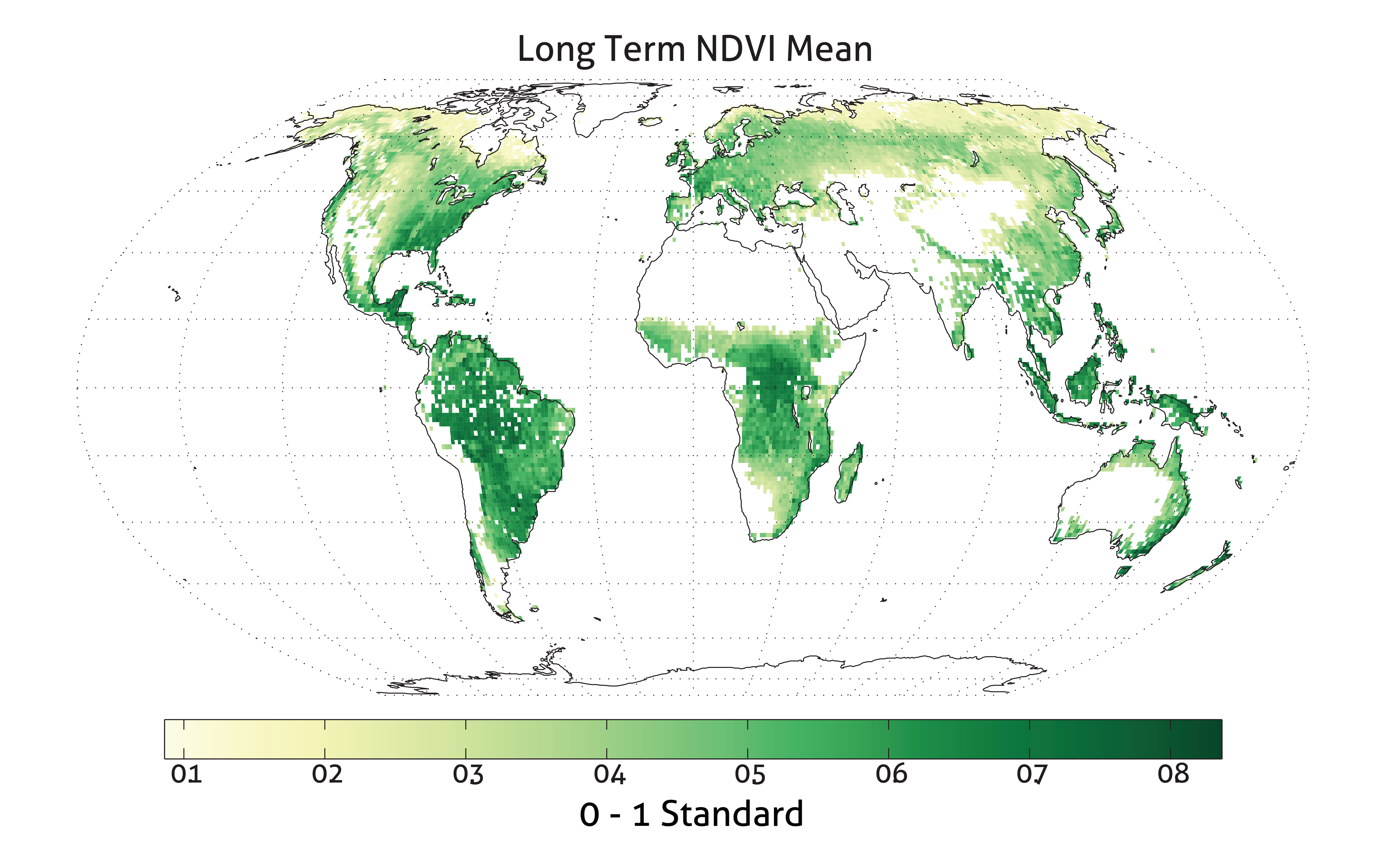


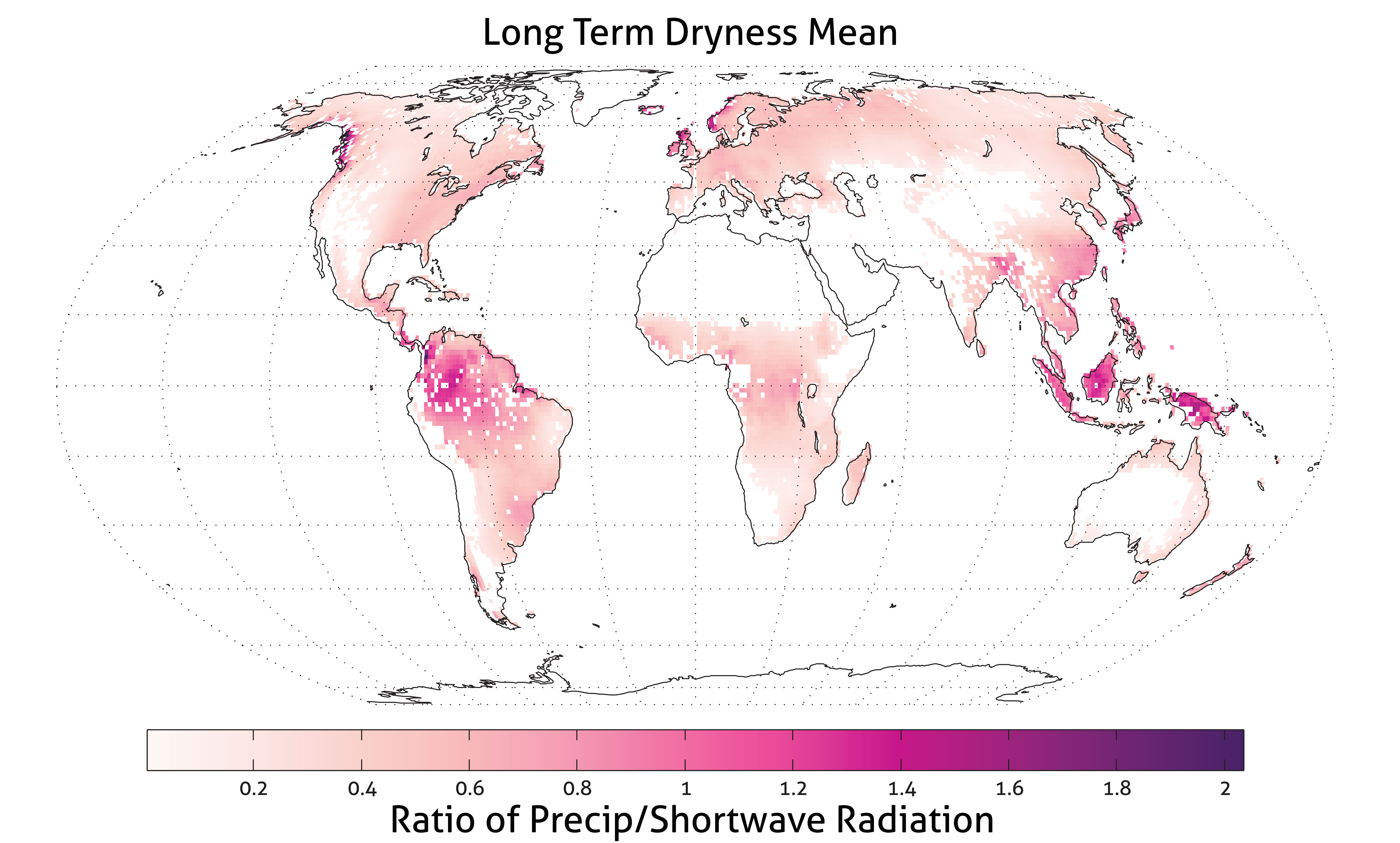

Climate Fields

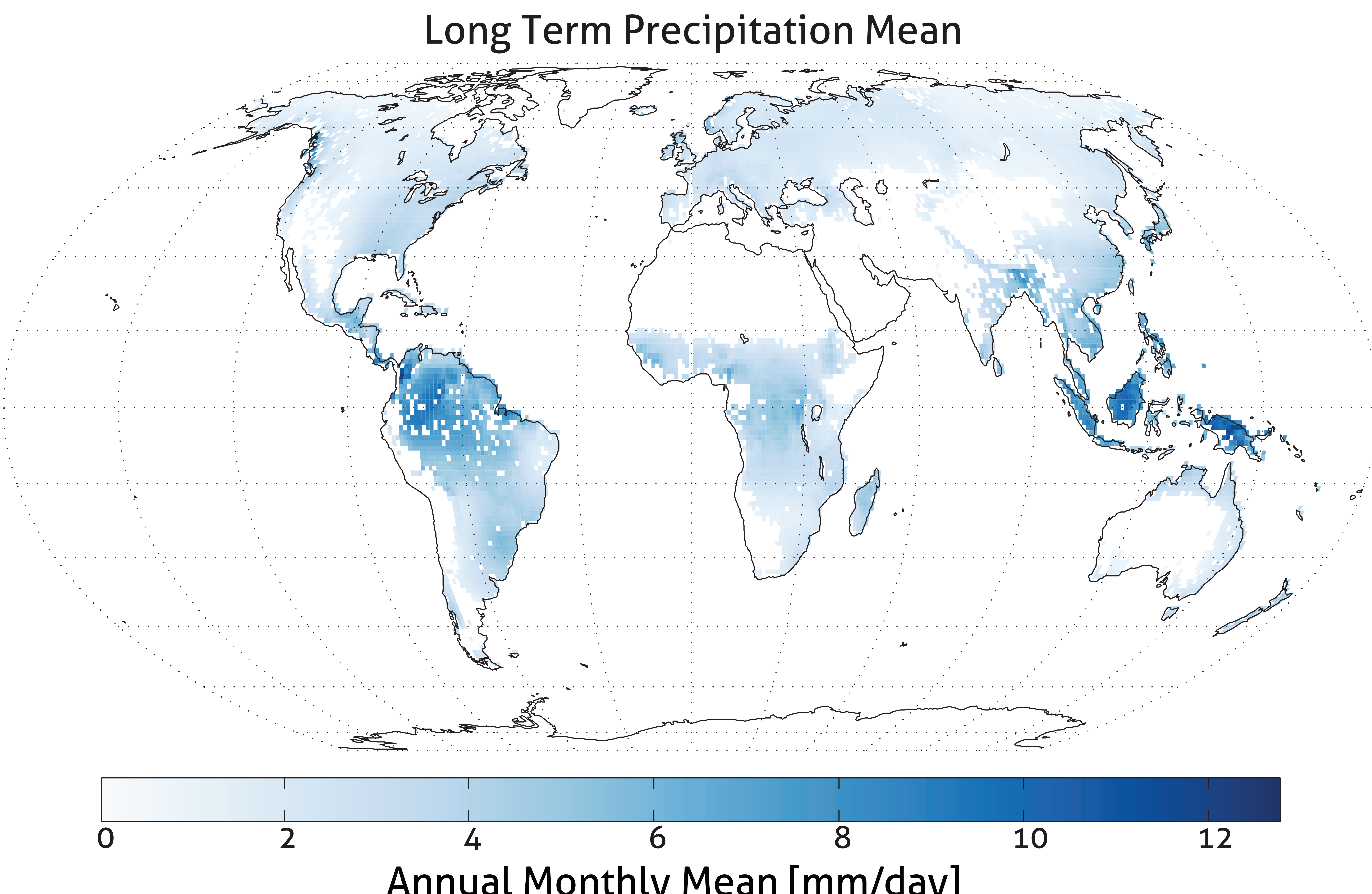

Vegetation Index
(1 month – Terra/MODIS)
Vegetation (NDVI)
−0.1
0.4
0.9
Feb 2000
2000
2013



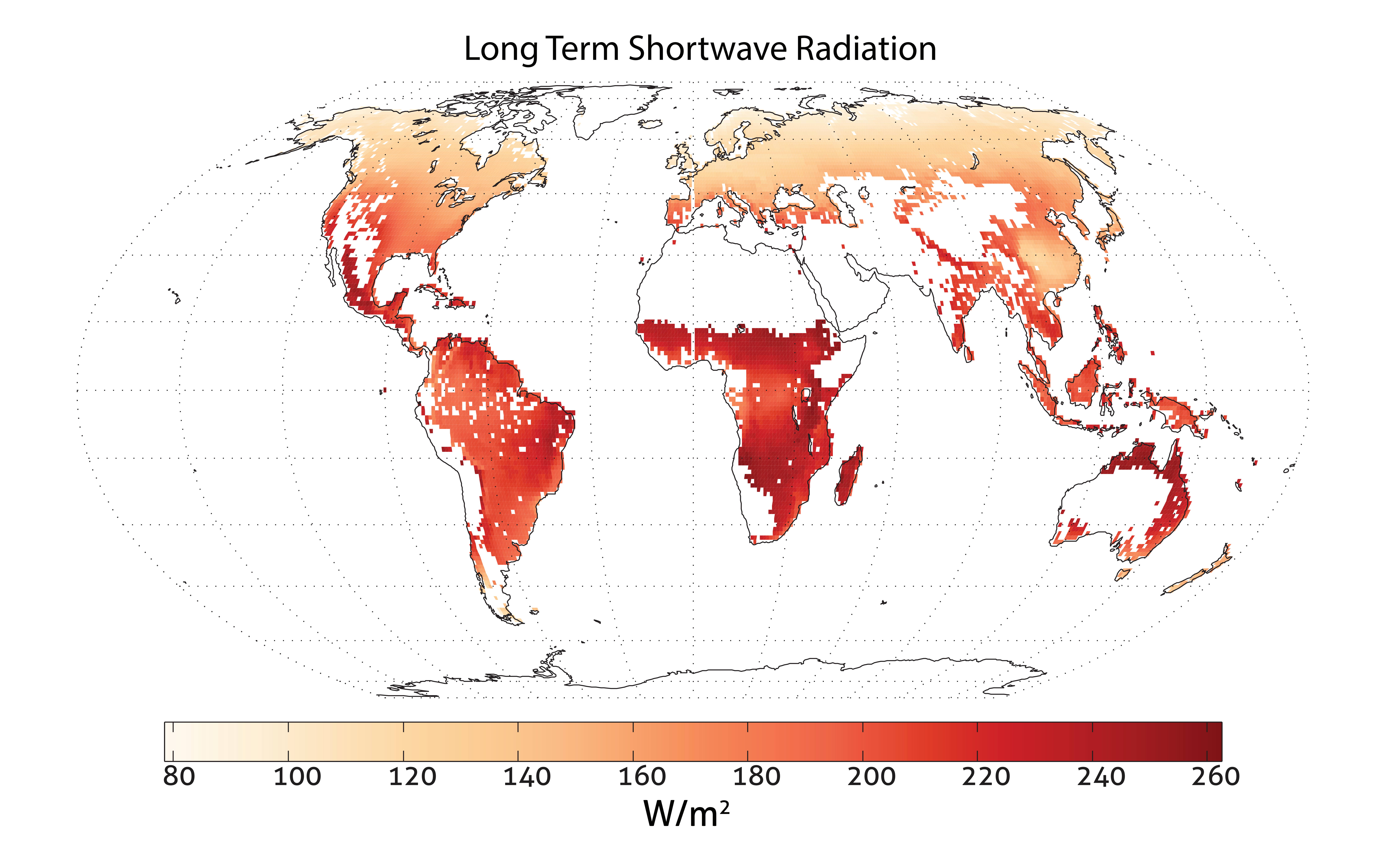
Explained variance of ndvi v t2m - stdreg noveg
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
8-18-2014


Long Term NDVI Mean
01
02
03
04
05
06
07
08
0 - 1 Standard

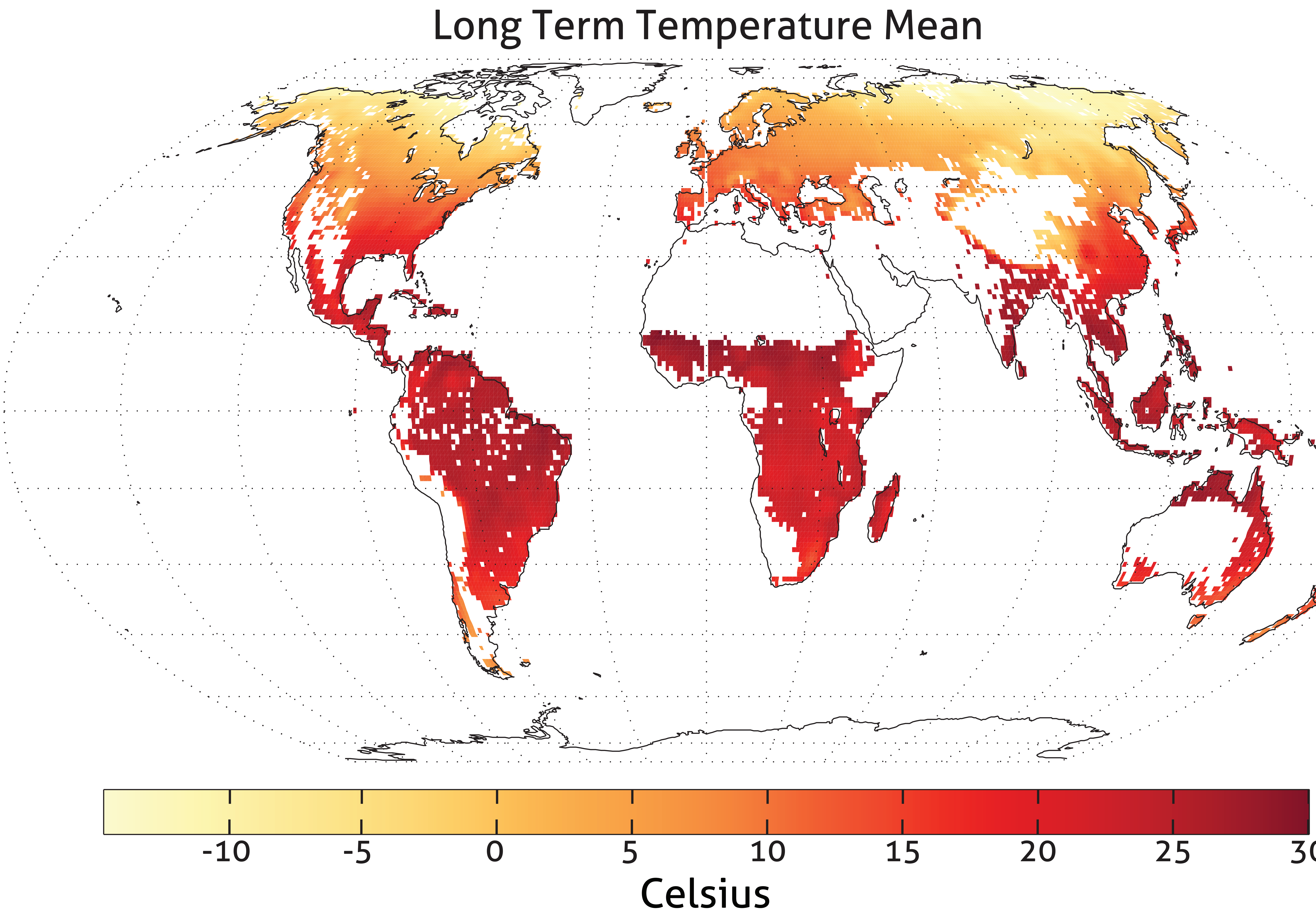

Long Term Dryness Mean
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
Ratio of Precip/Shortwave Radiation

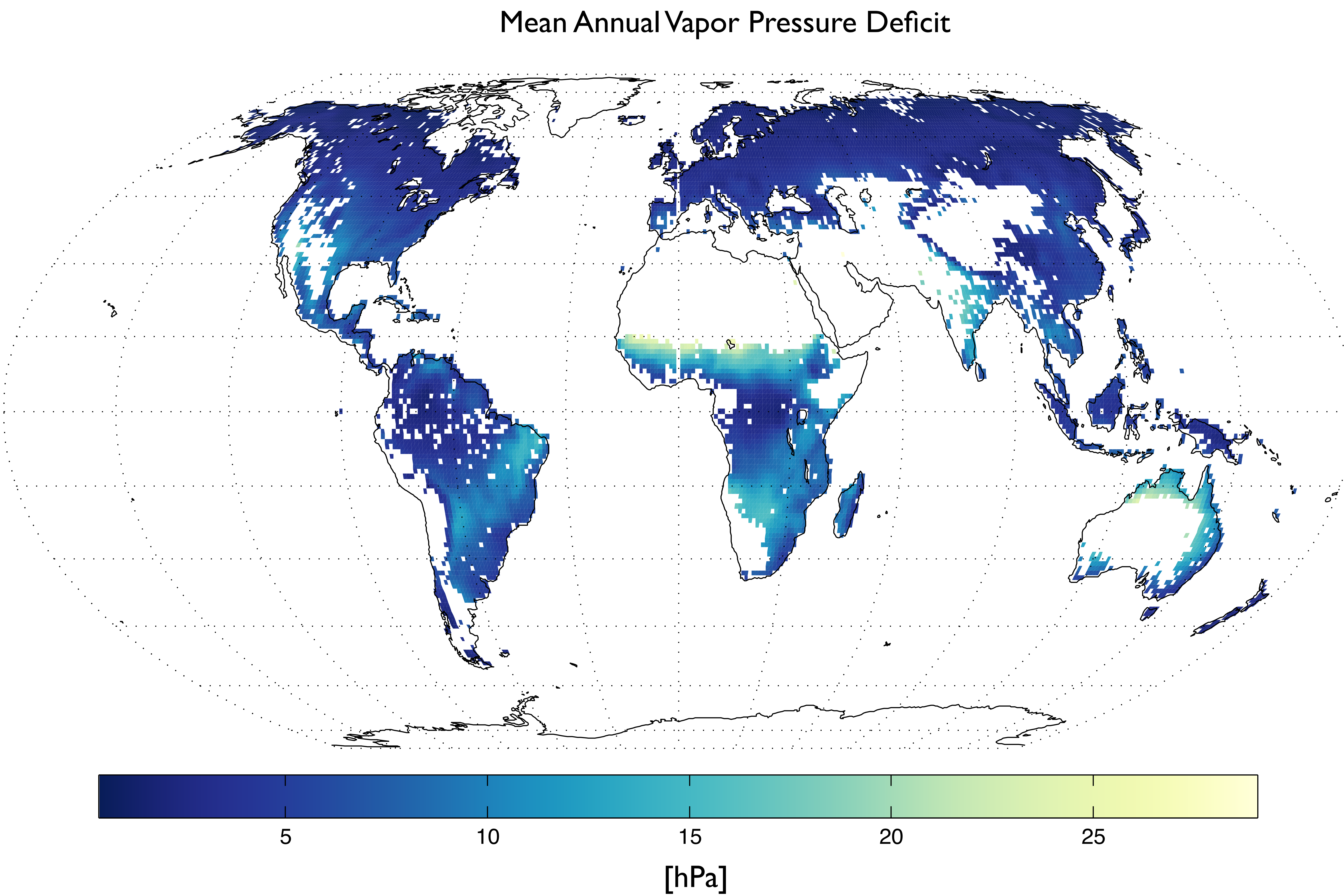


Long Term Precipitation Mean
0
2
4
6
8
10
12
Annual Monthly Mean [mm/day]



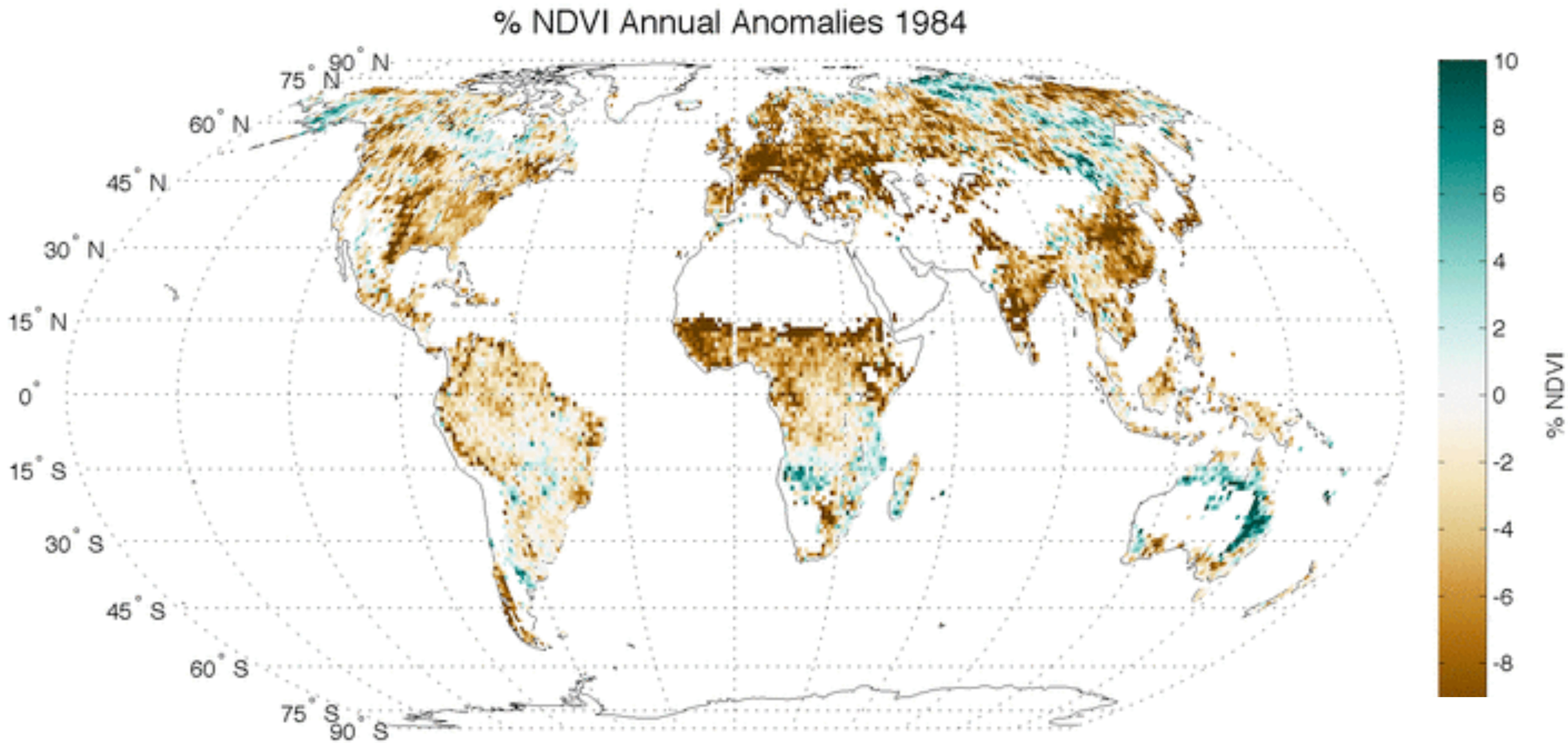
Long Term Shortwave Radiation
80
100
120
140
160
180
200
220
240
260
W/m²


Long Term Temperature Mean
-10
-5
0
5
10
15
20
25
30
Celsius

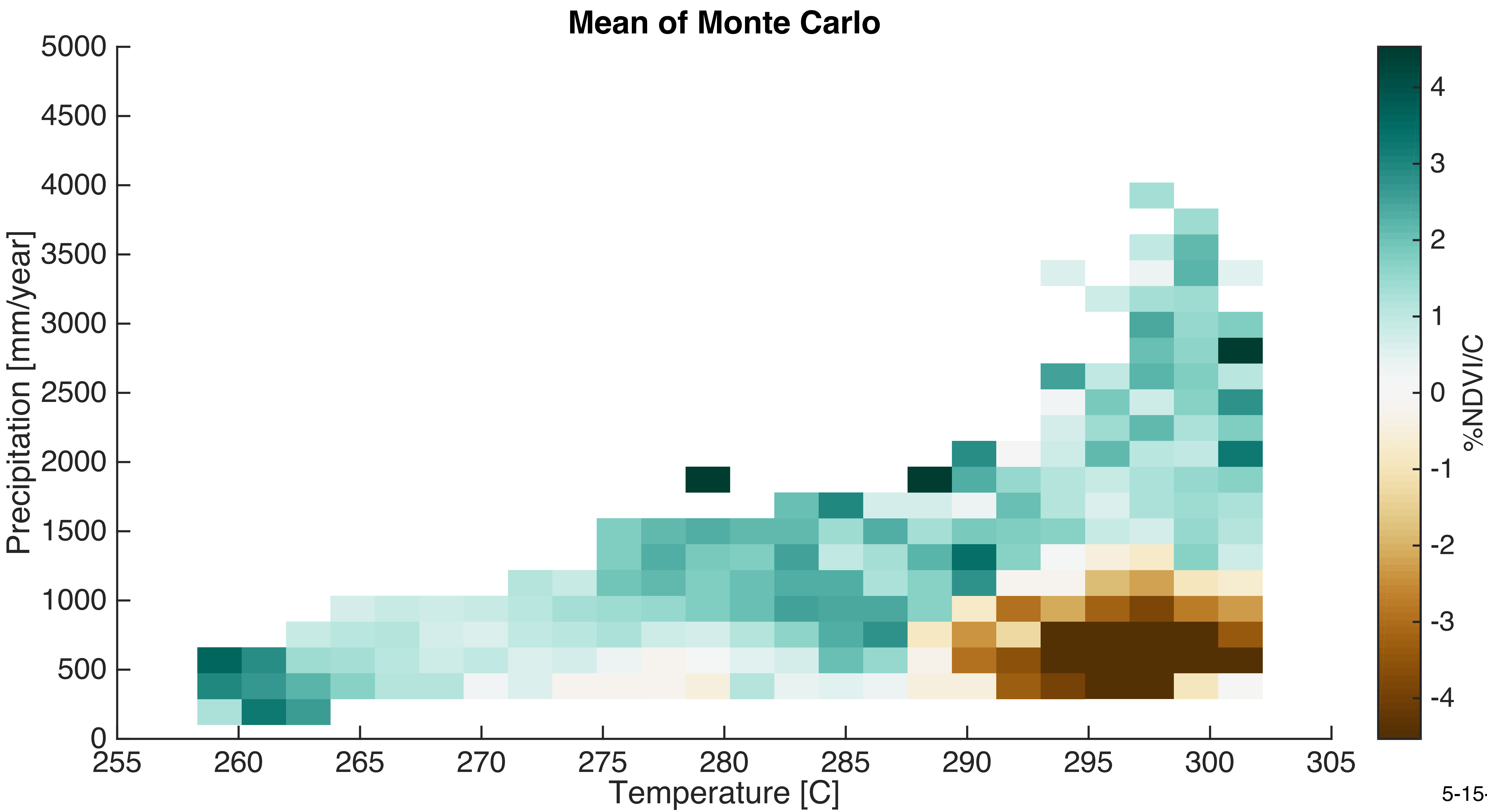


Mean Annual Vapor Pressure Deficit
5
10
15
20
25
[hPa]

Annual Anomalies of NDVI

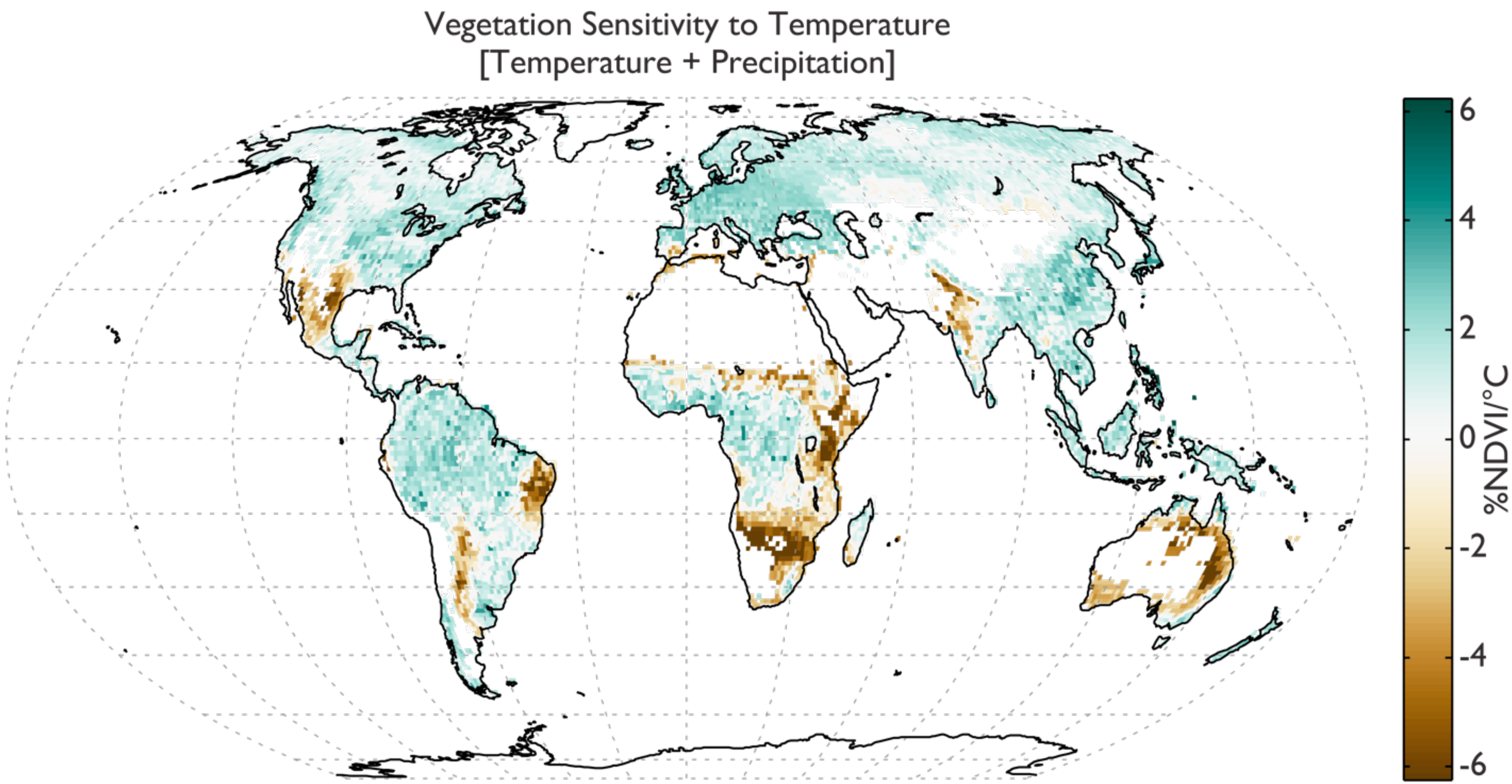


1983 to 2012 (only Temp regression)

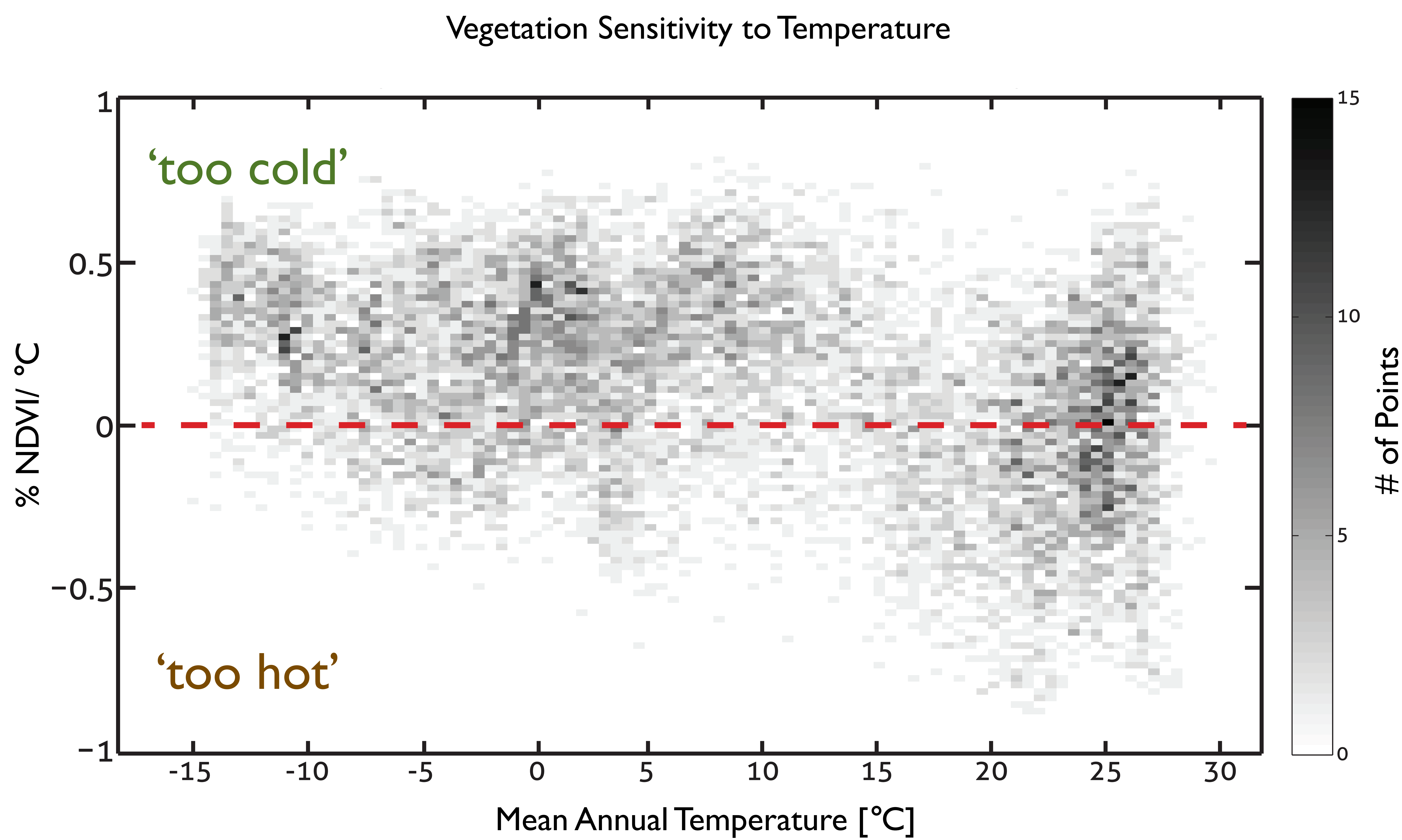


5-15-2015

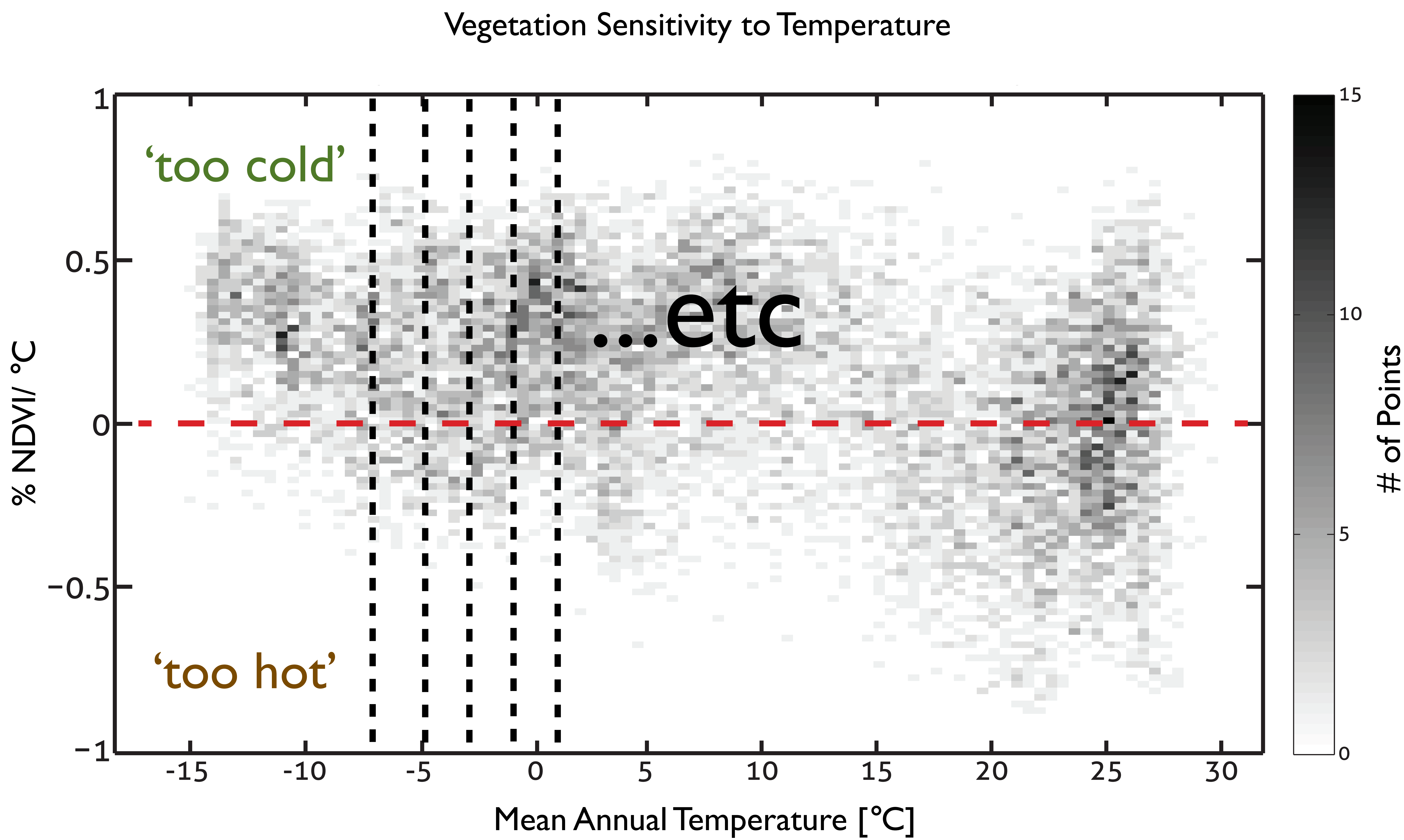
Temperature and Water Availability



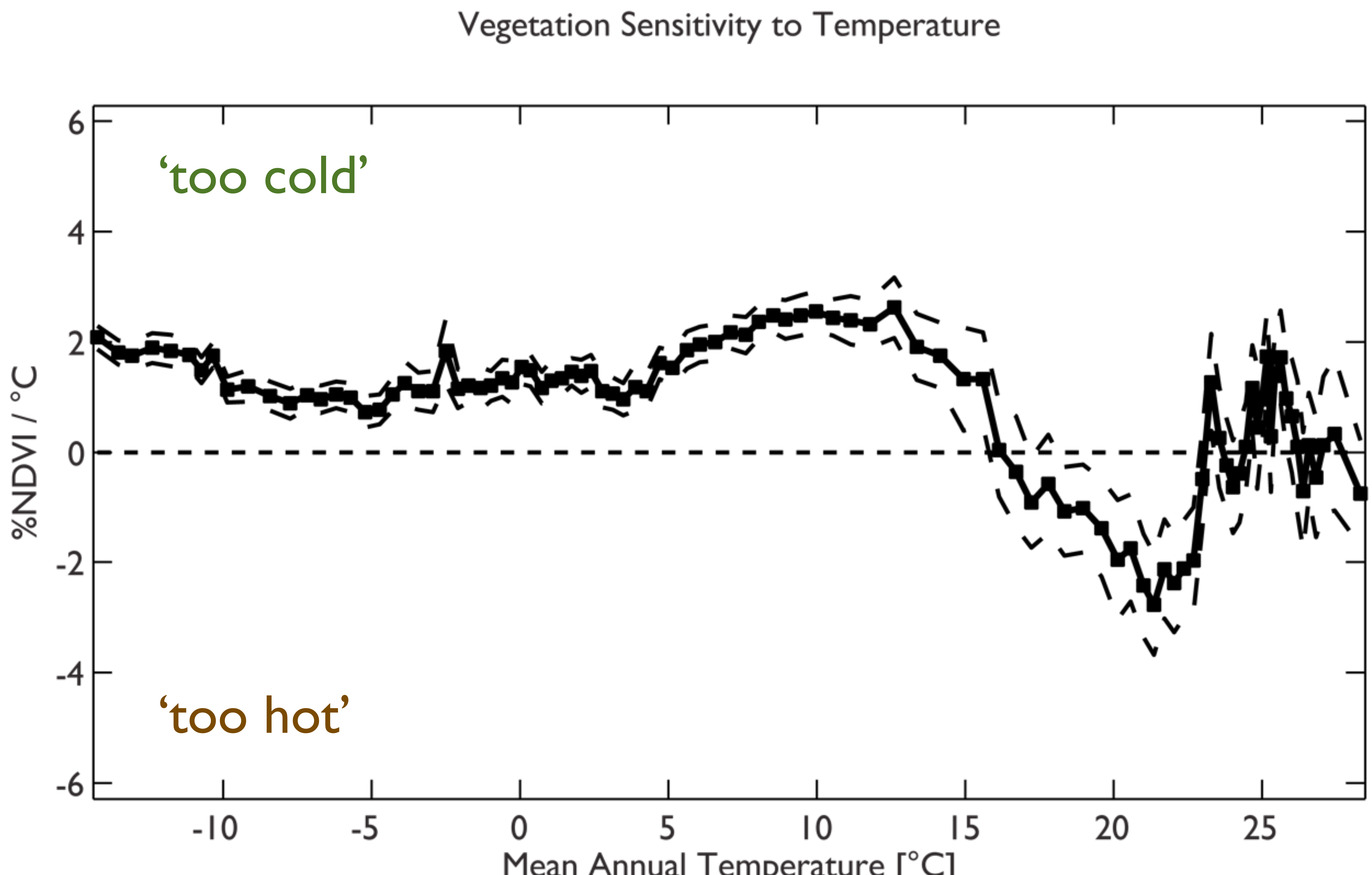
Mean sensitivity of each temperature bin



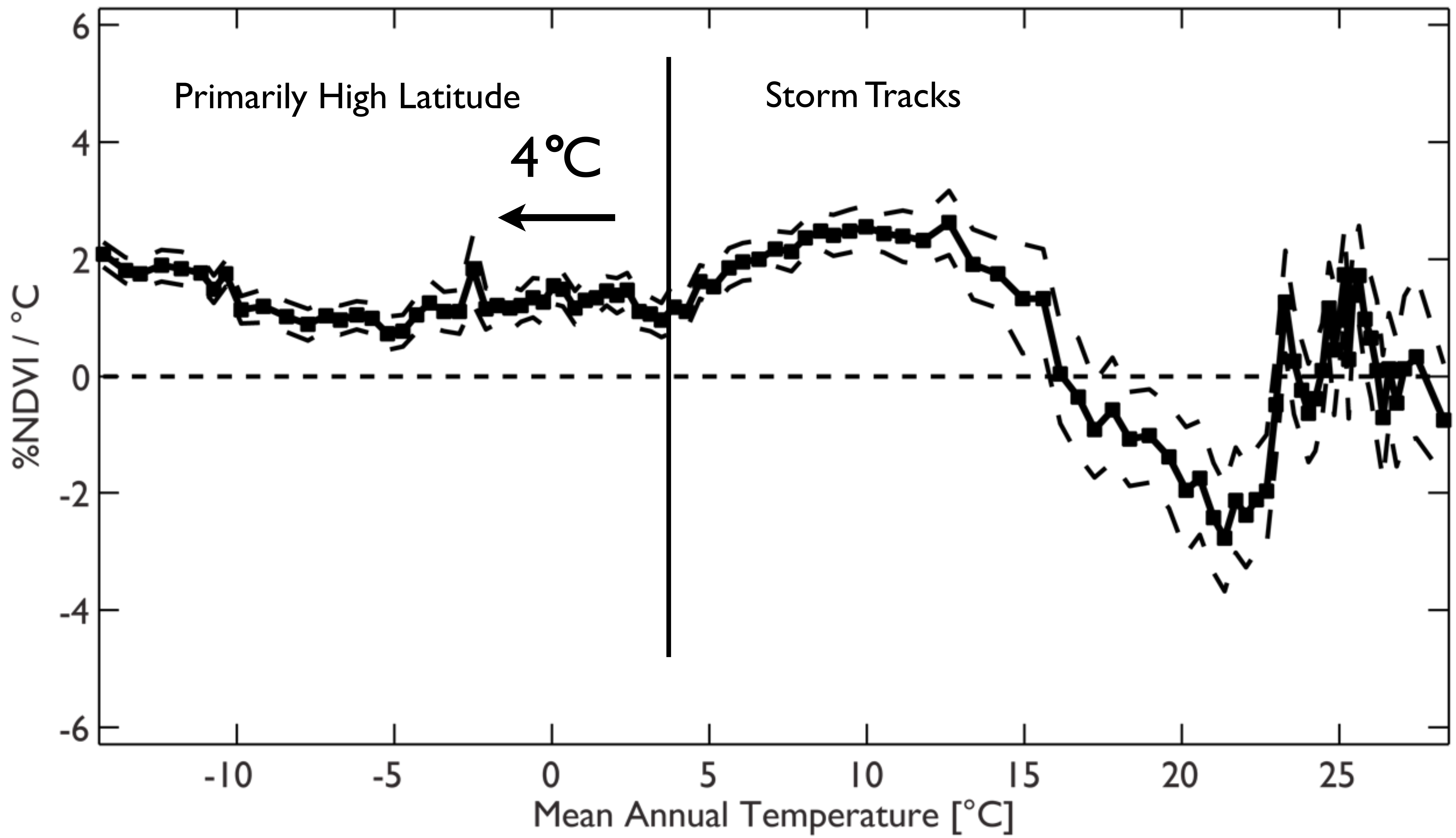
Split data into bins across temperature



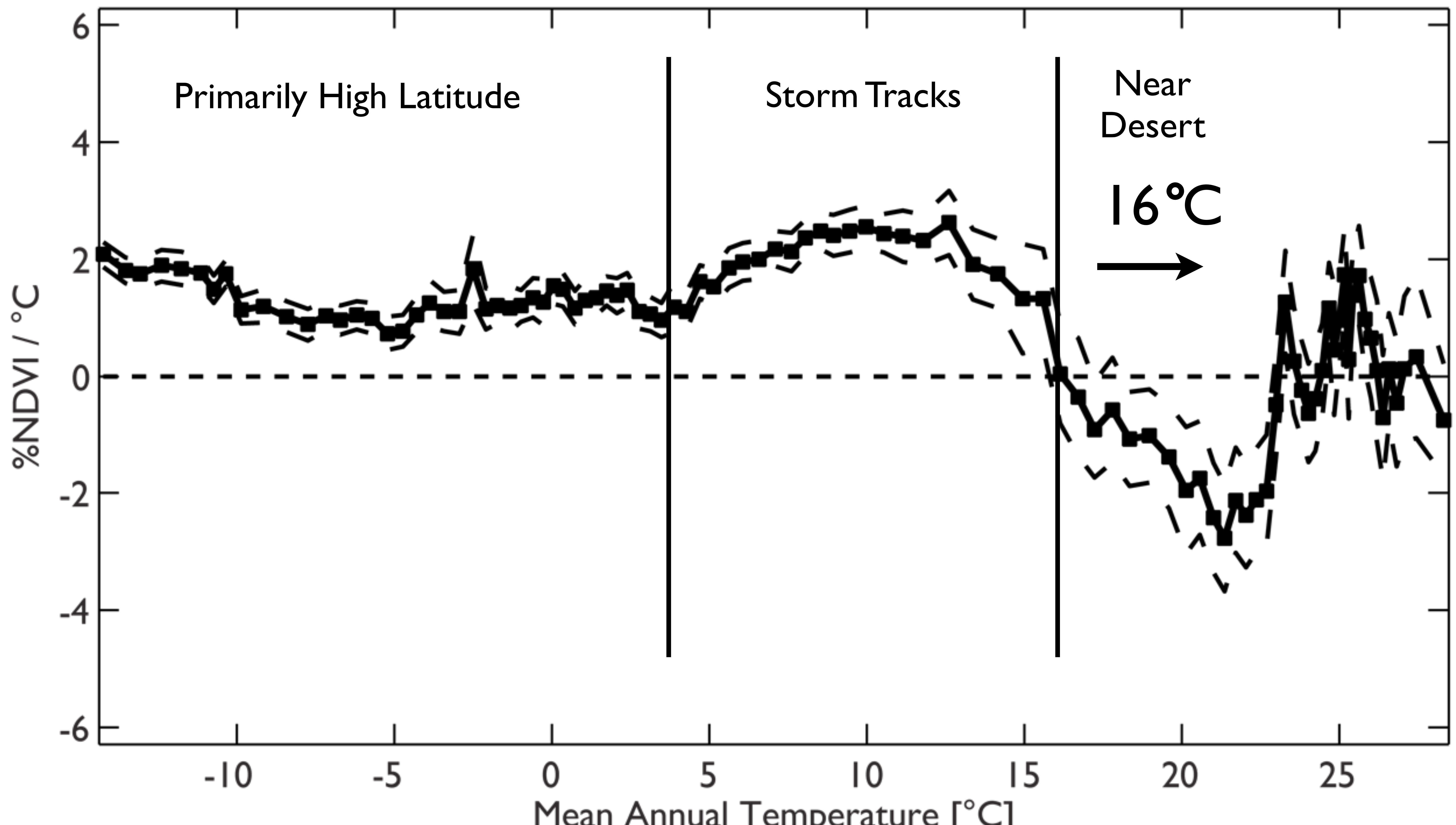
Vegetation sensitivity across temperature



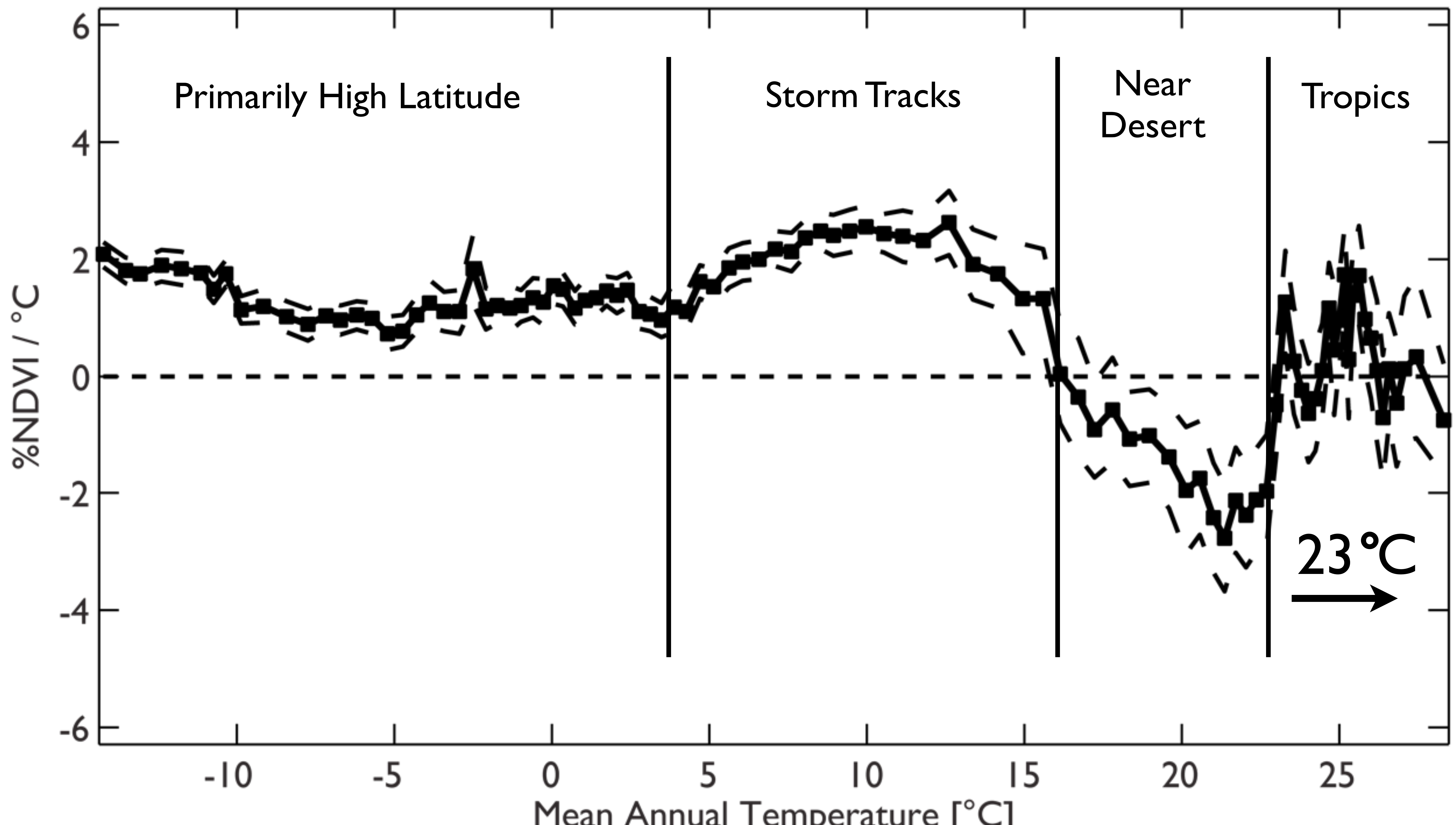
Highest positive sensitivity not at coldest



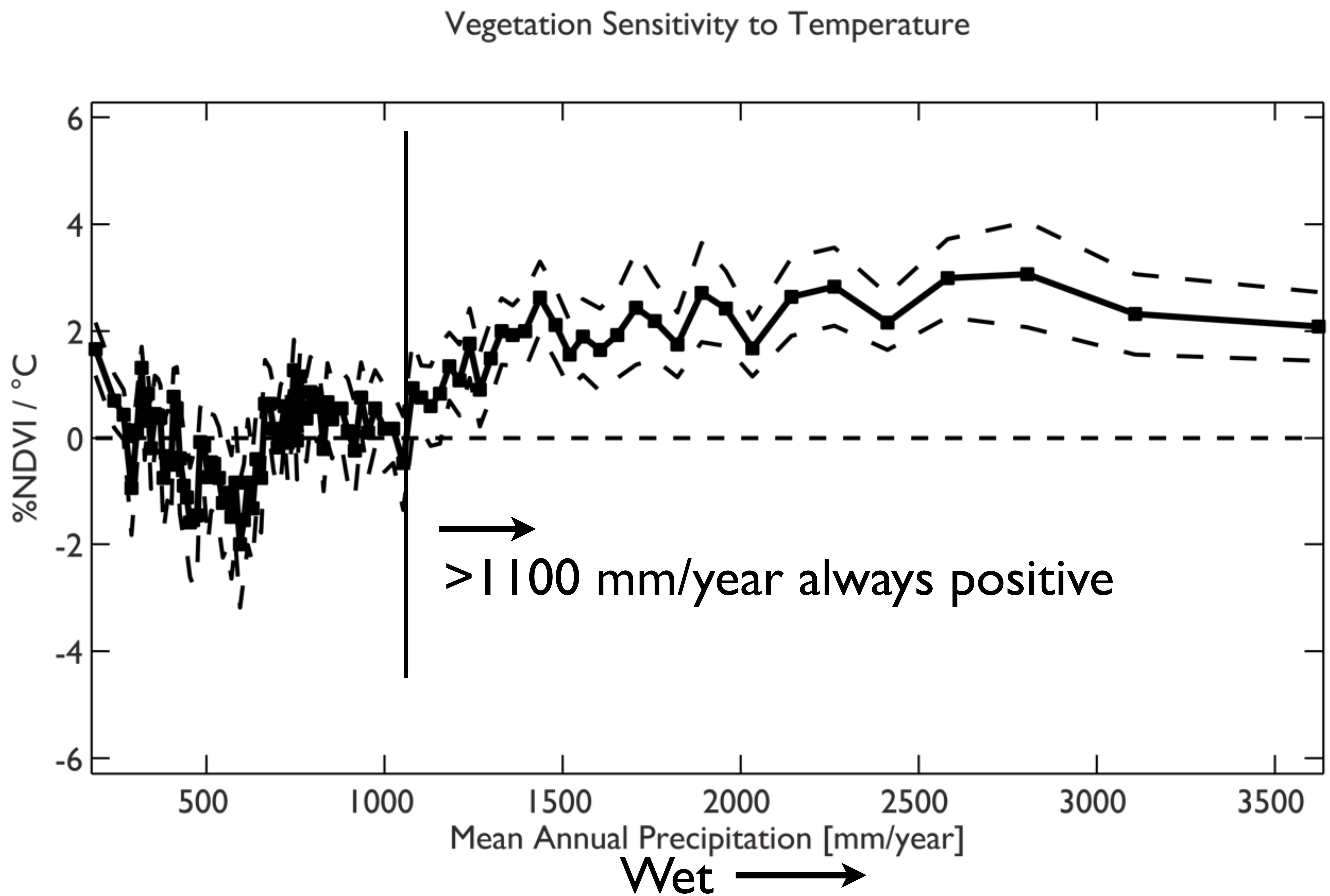
Switch from 'too cold' to 'too hot' at 16°C



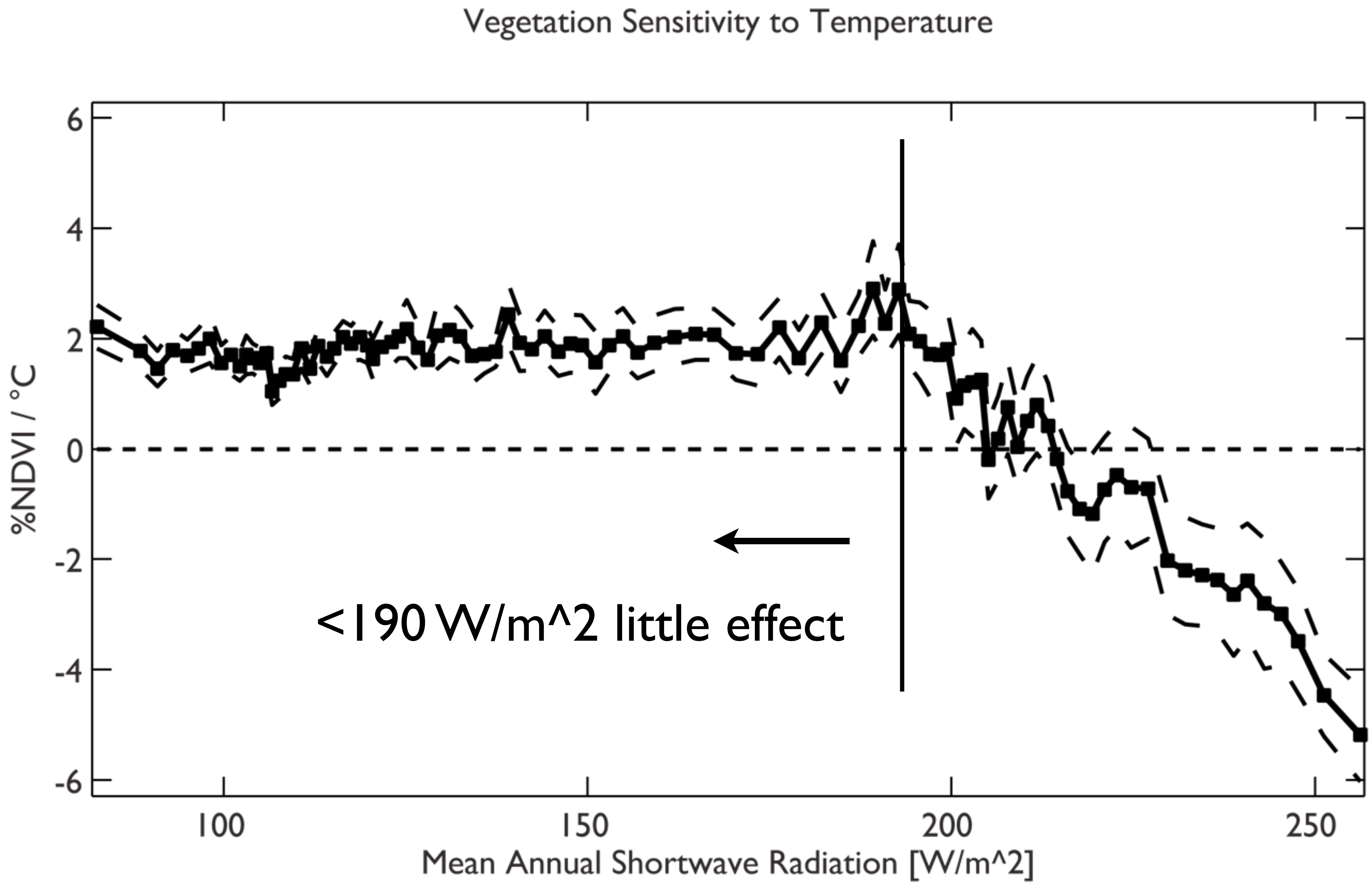
Hot places that are 'greener when hotter'



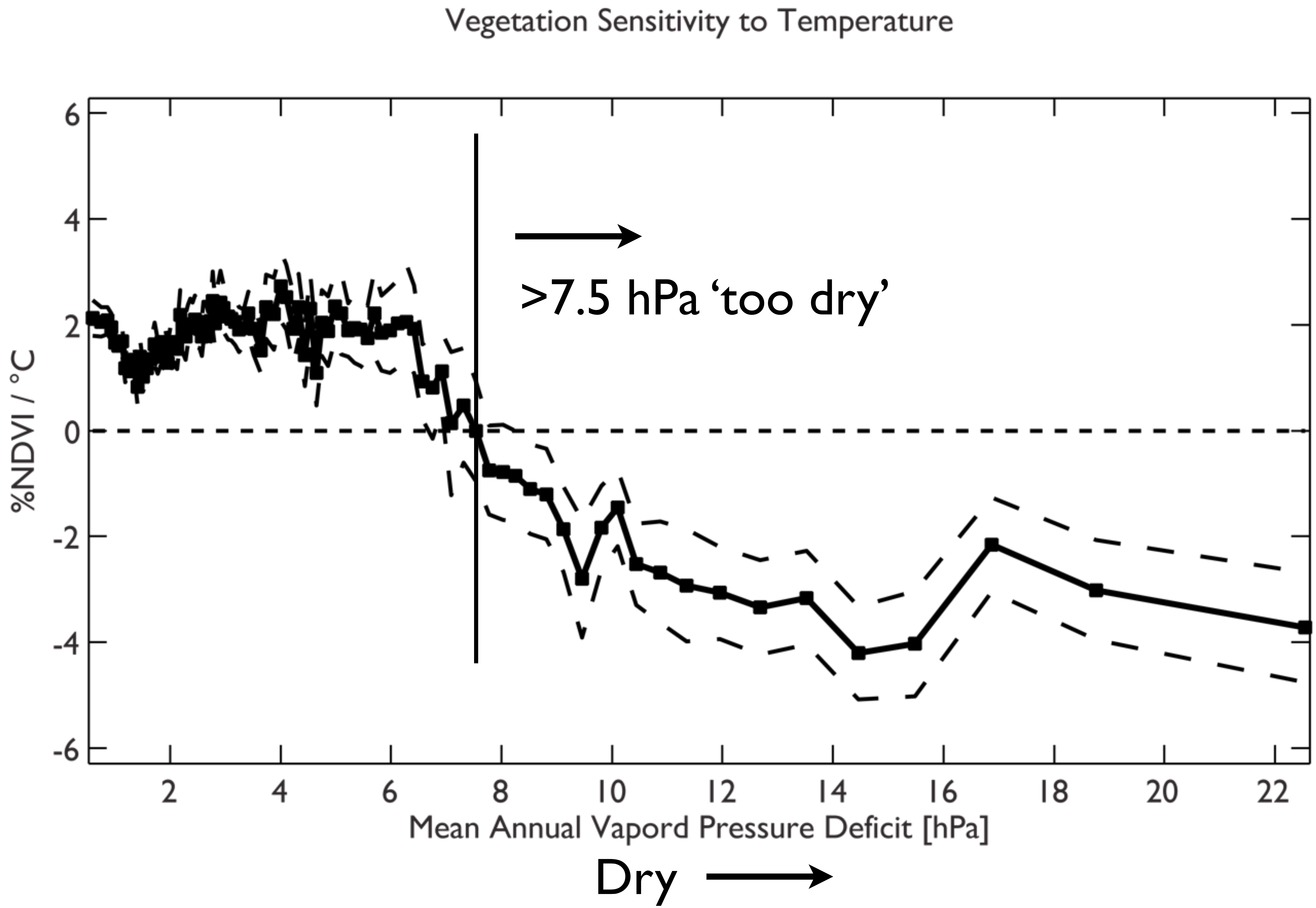
Sensitivity across mean annual precipitation



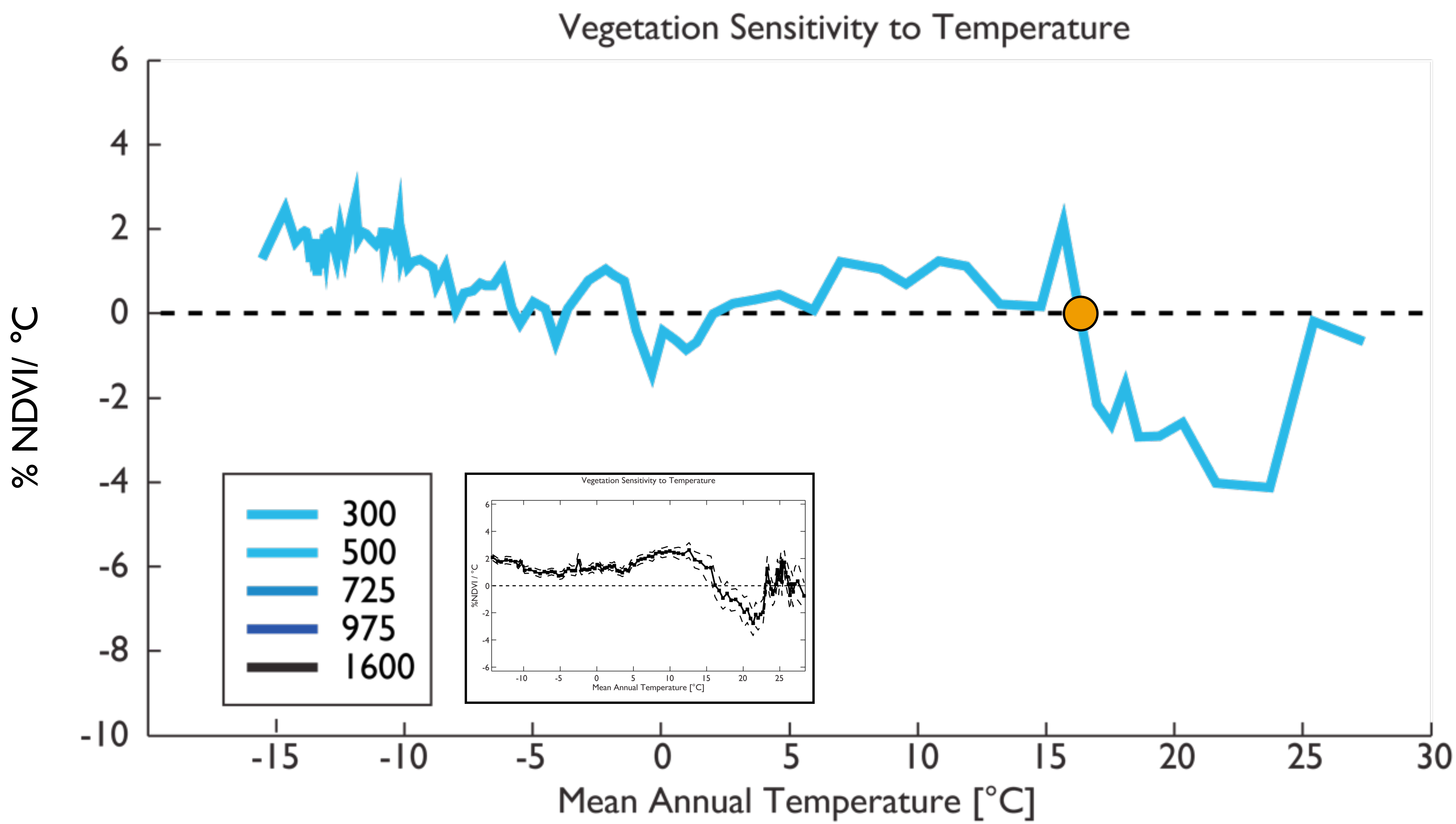
Sensitivity across shortwave radiation



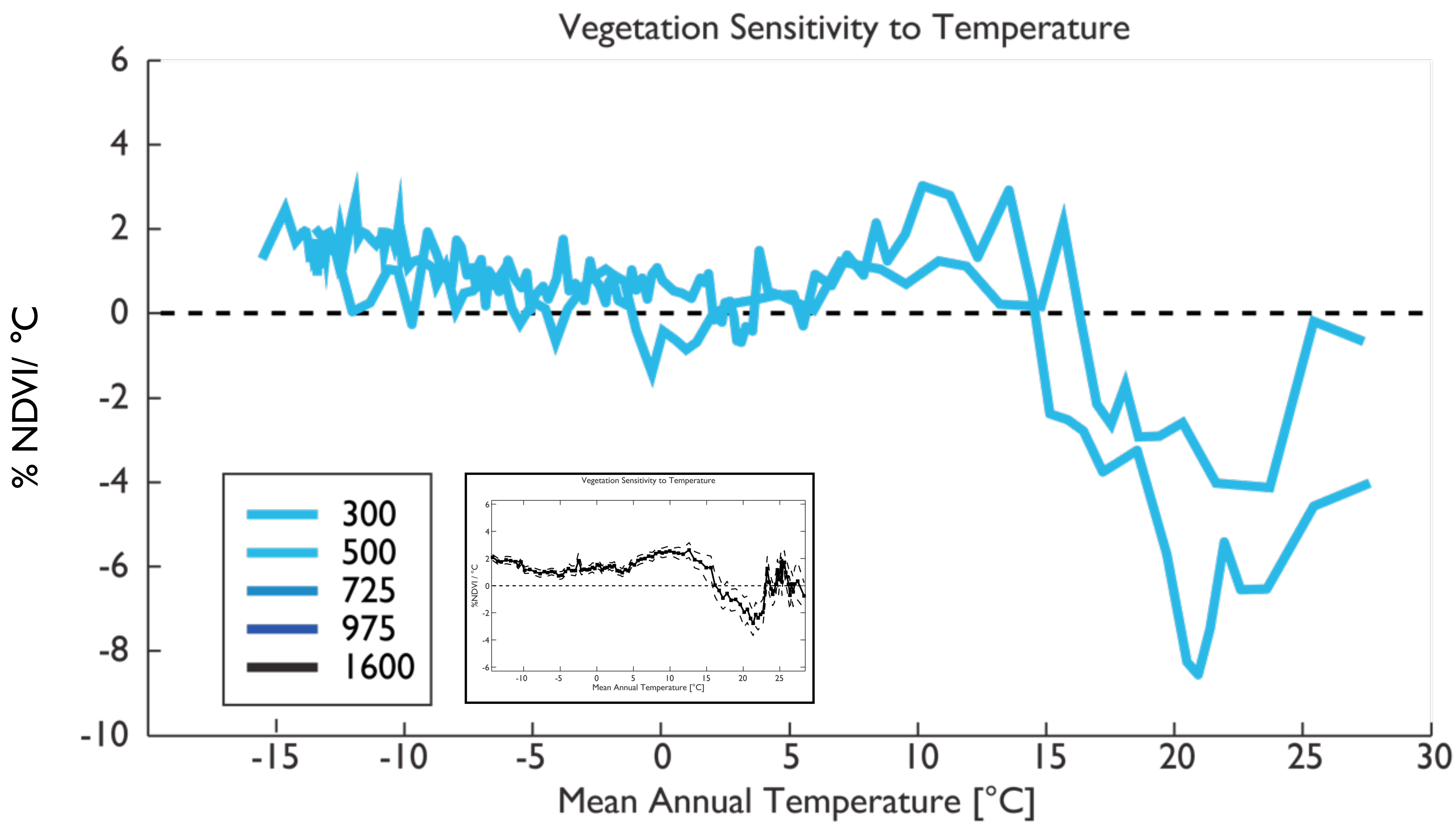
Sensitivity across vapor pressure deficit



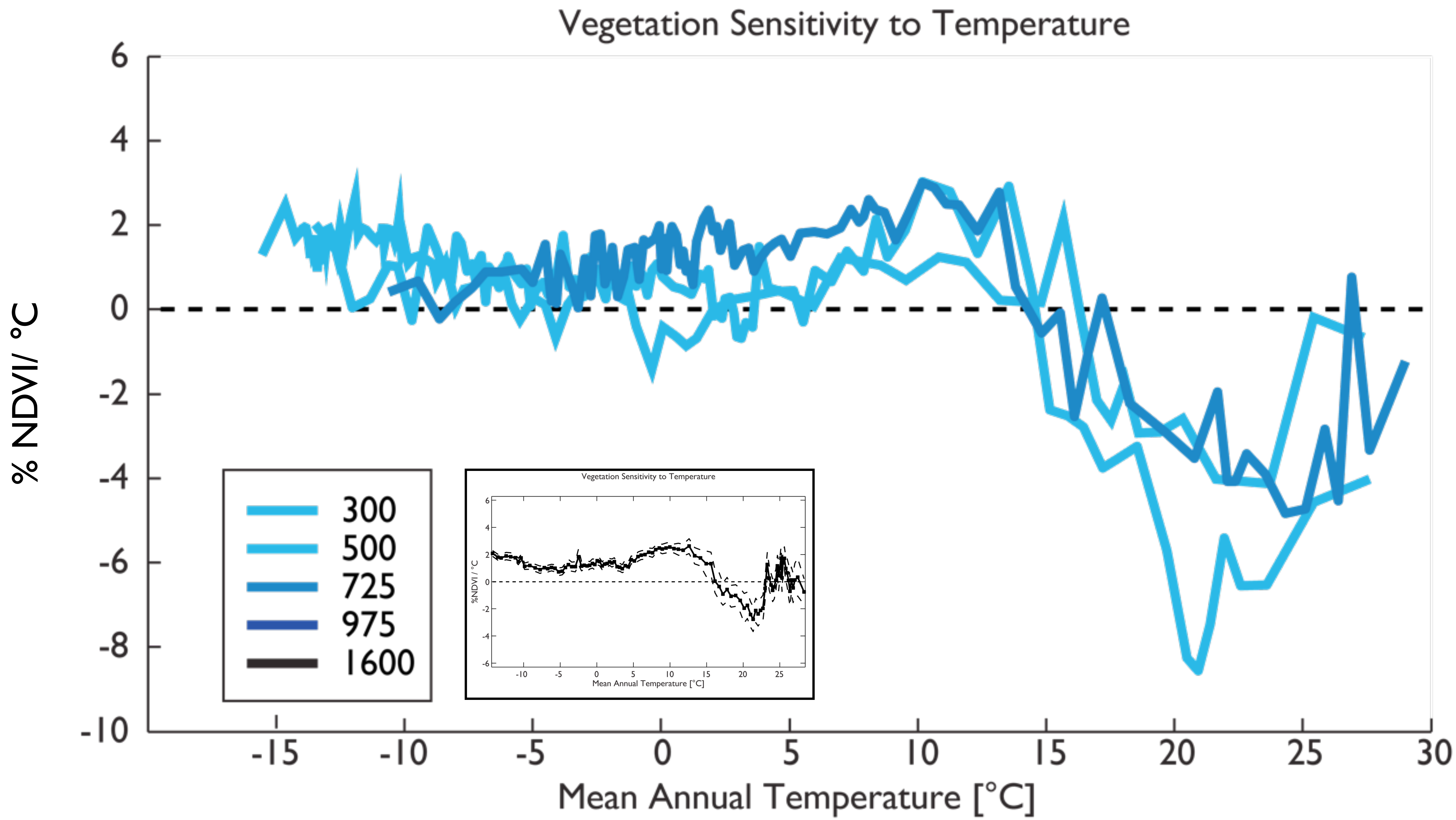
Sensitivity to temperature at 300 mm/year



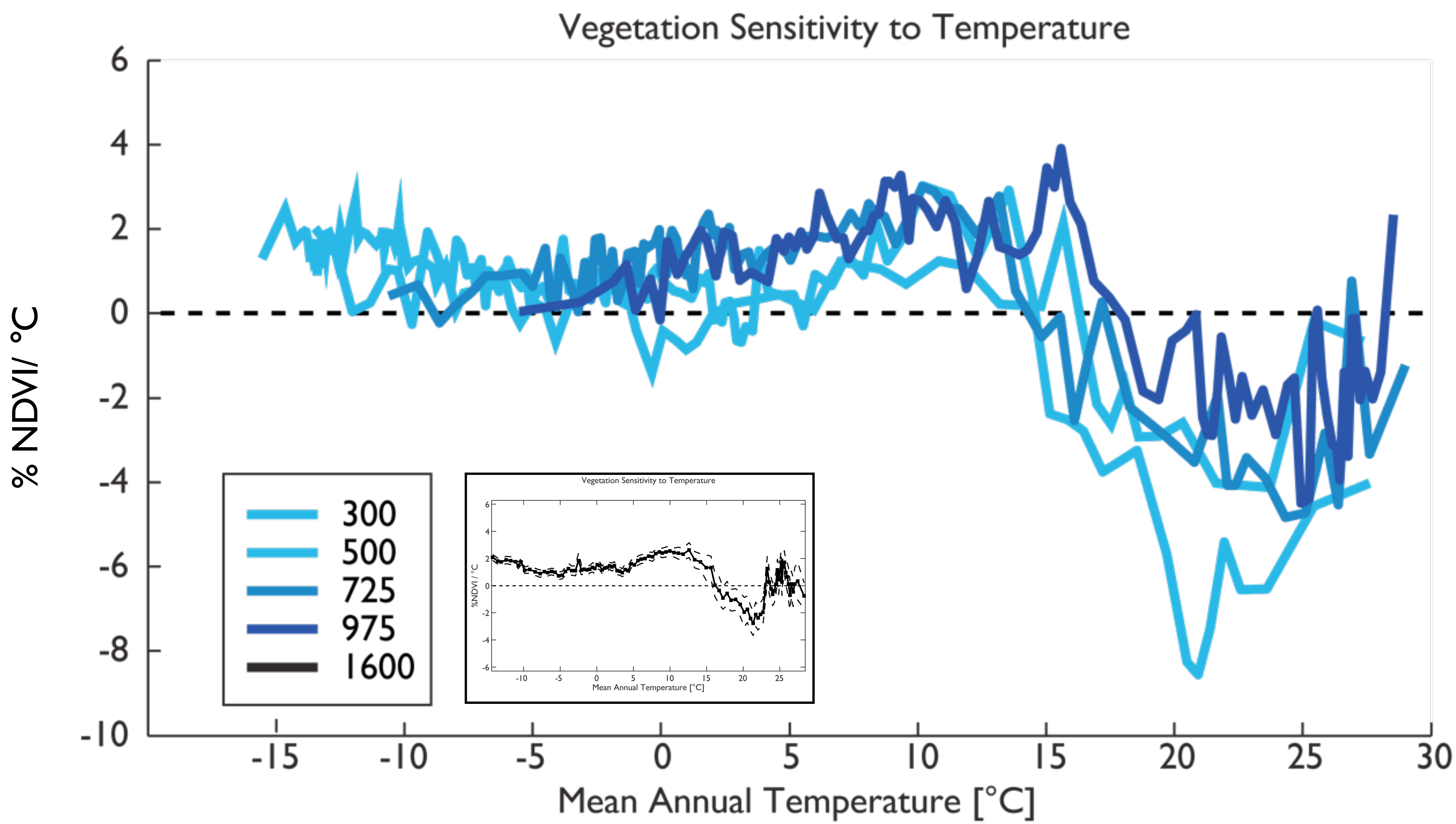
Sensitivity to temperature at 500 mm/year



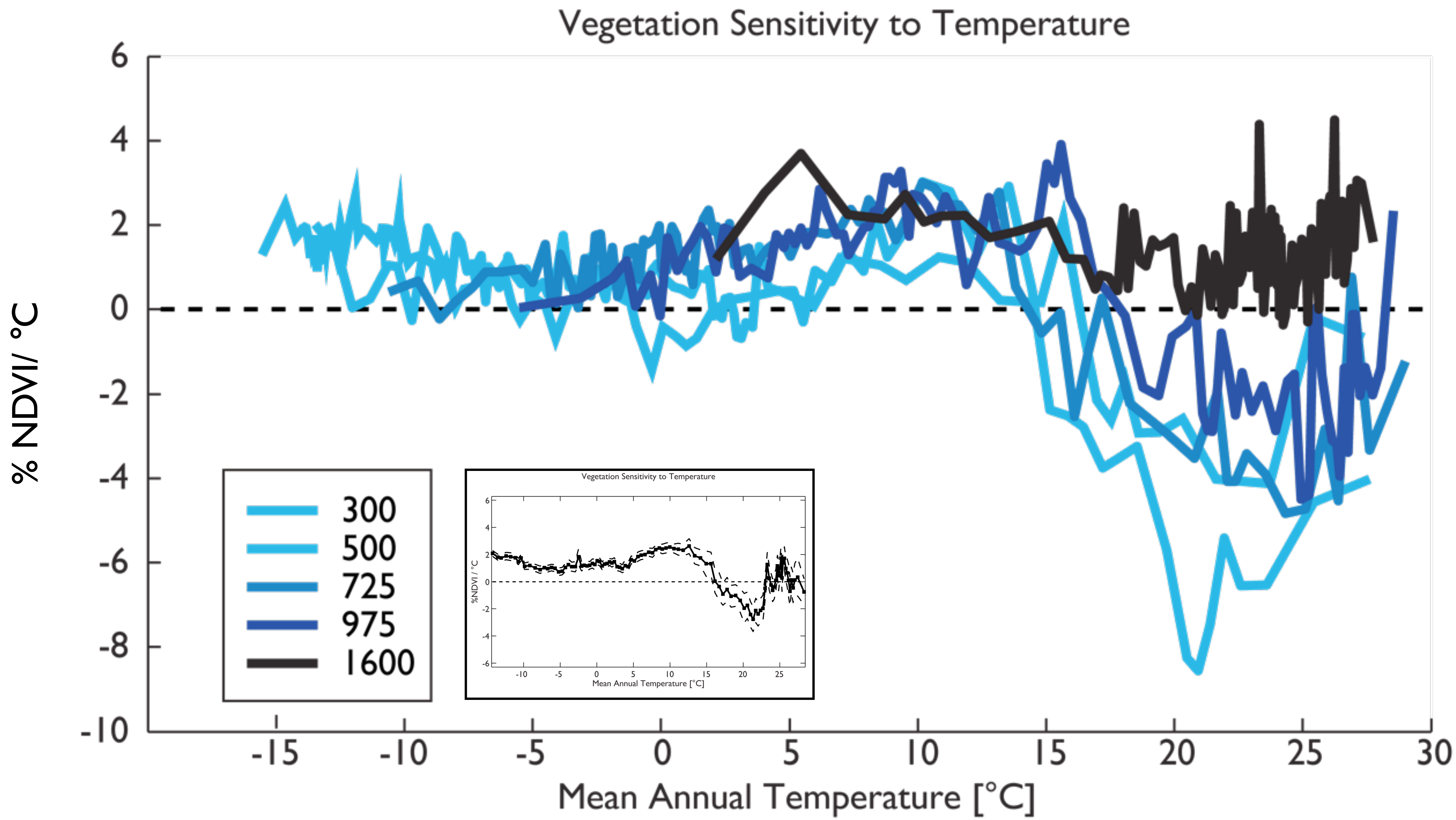
Sensitivity to temperature at 700 mm/year



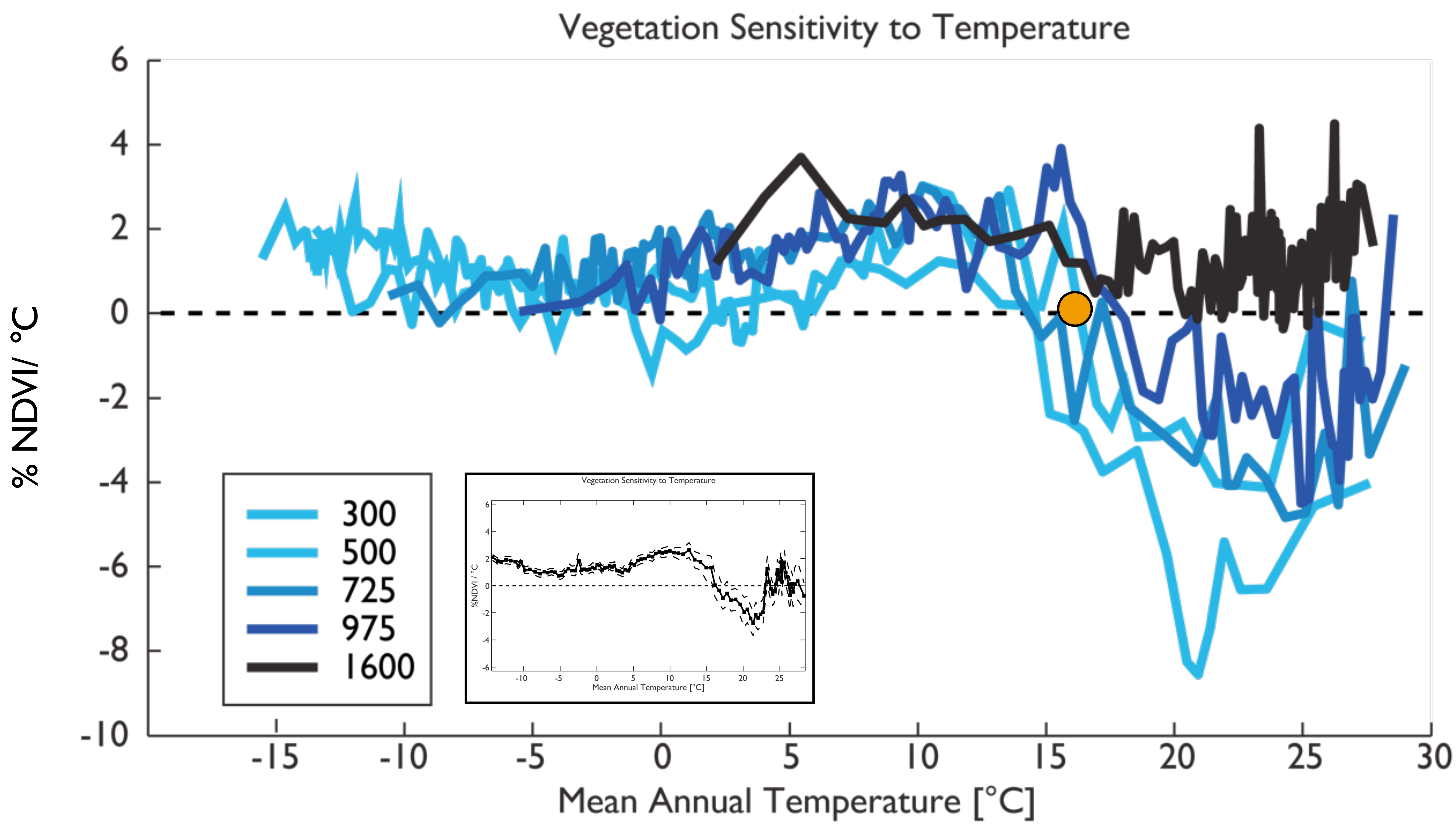
Sensitivity to temperature at 975 mm/year



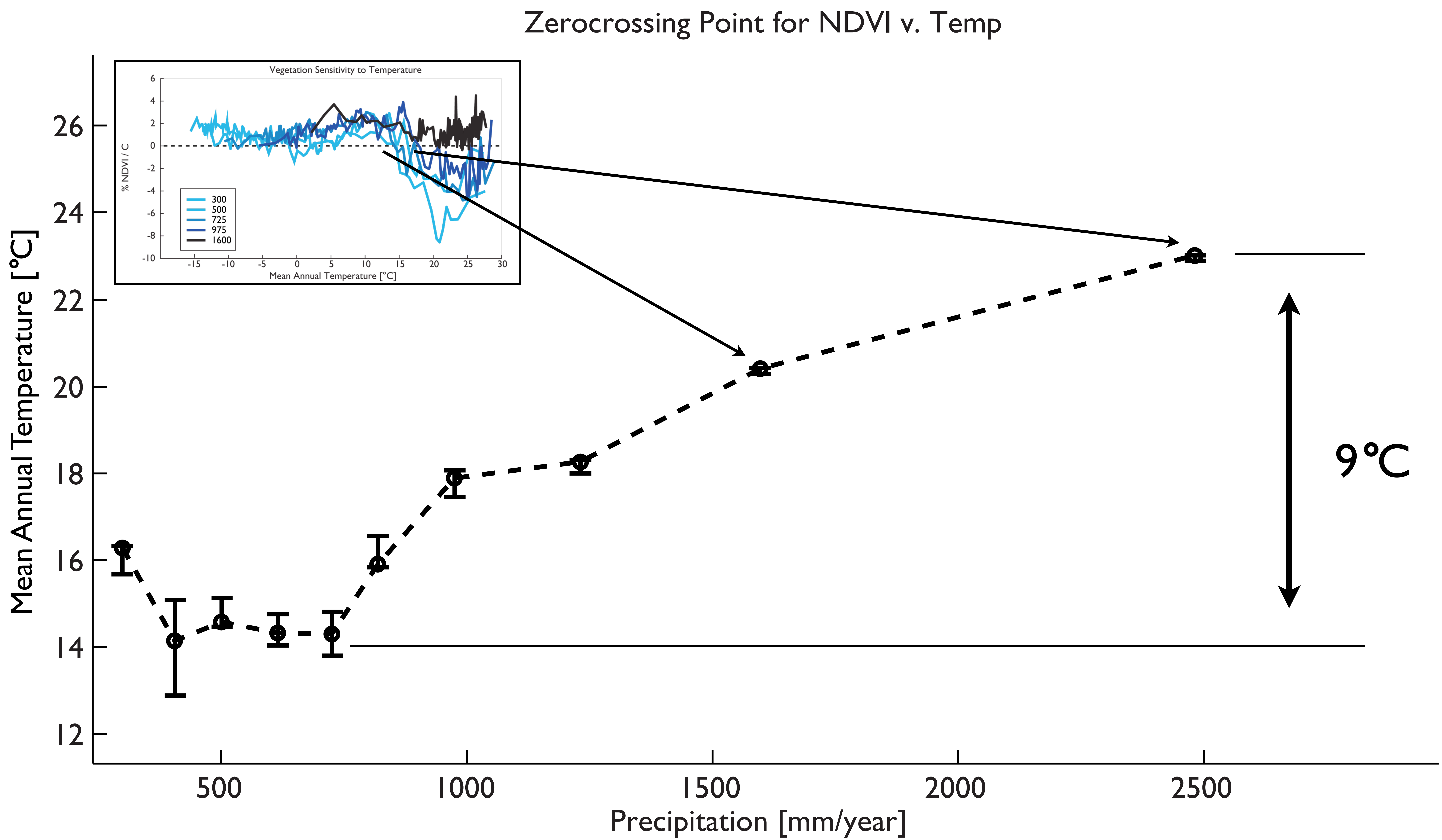
Sensitivity to temperature at 1600 mm/year



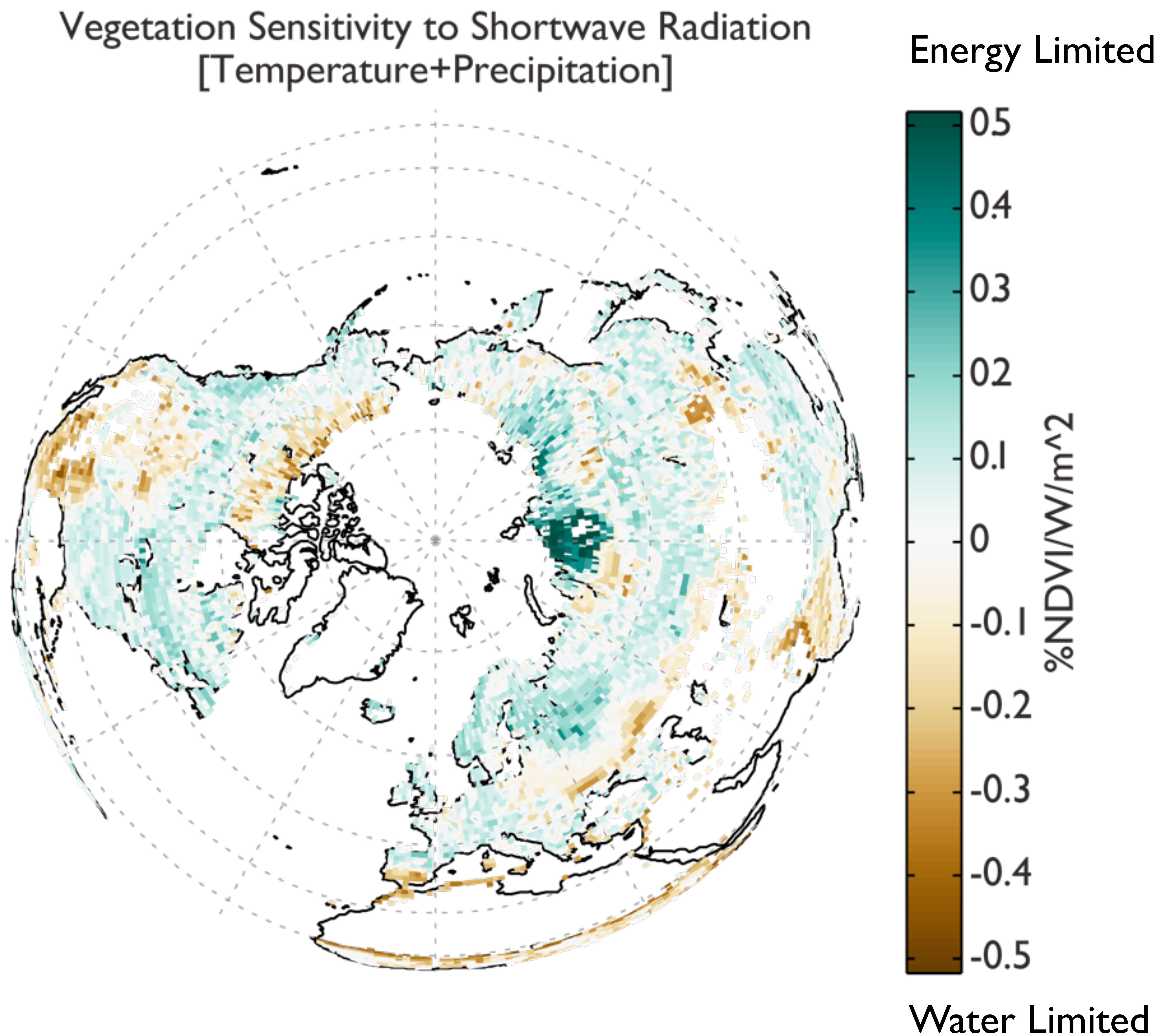
Sensitivity to temperature at 1600 mm/year



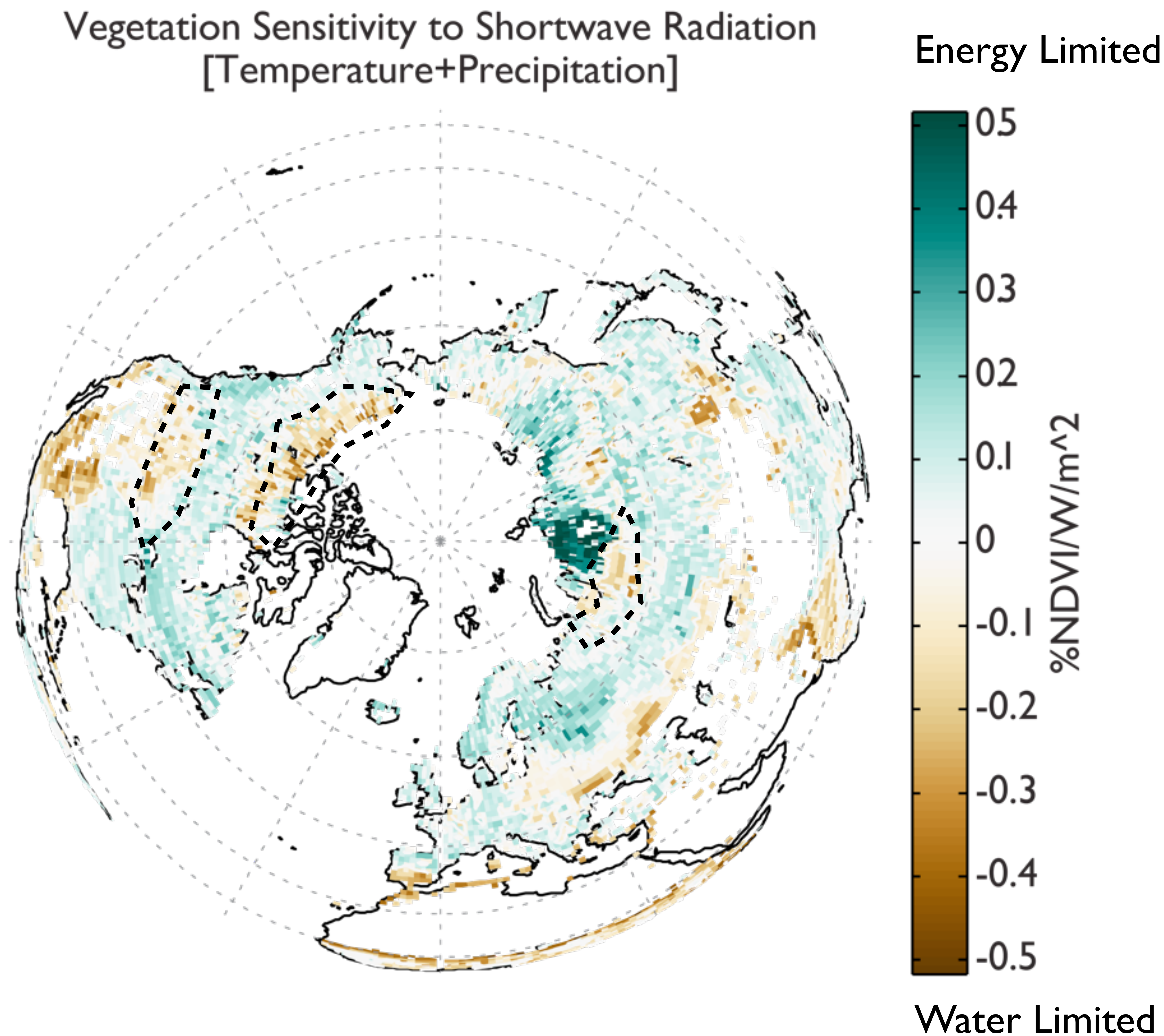
Temperature of ‘too hot’ climate constraint



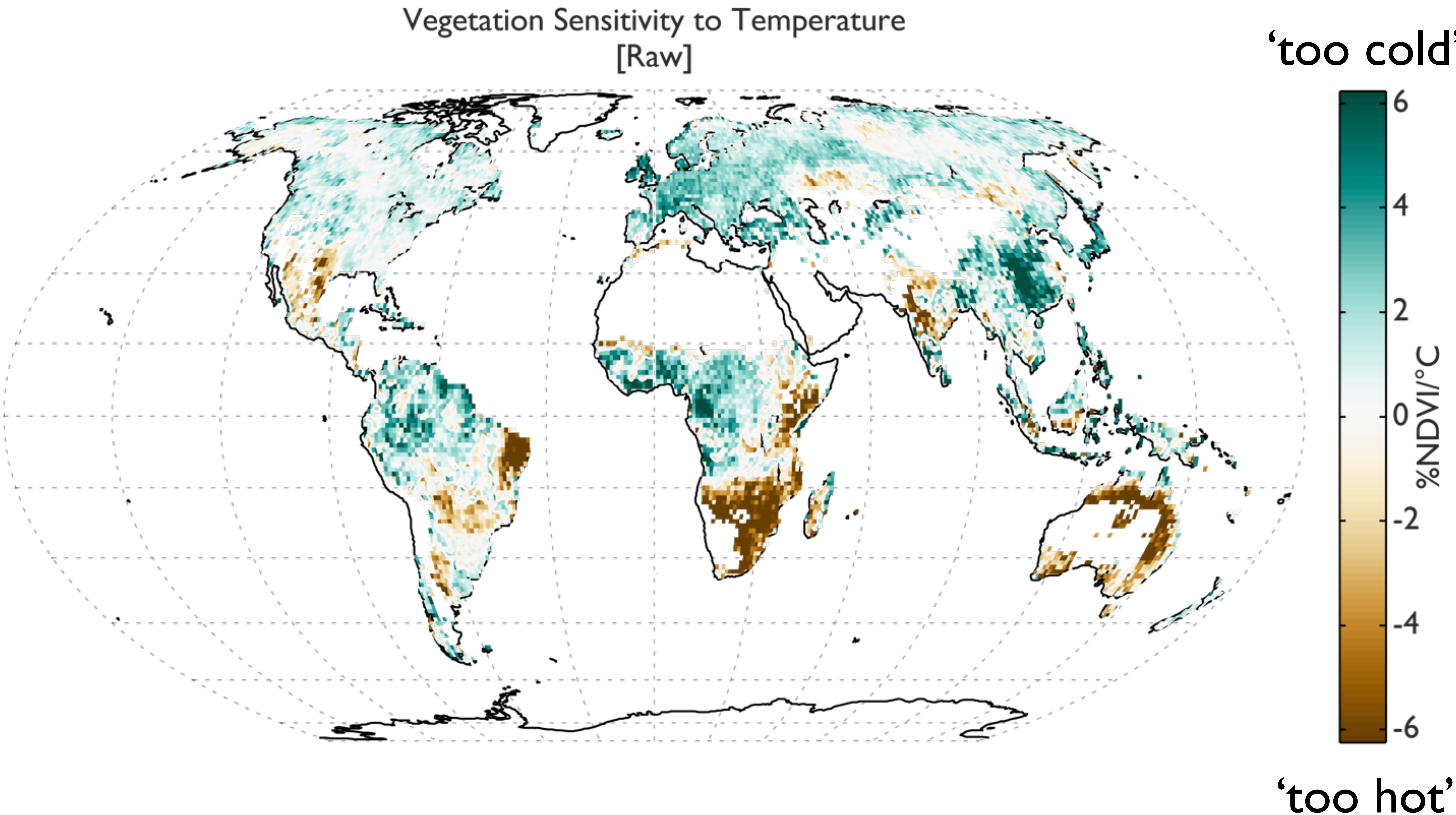
Water limited vegetation in cold places



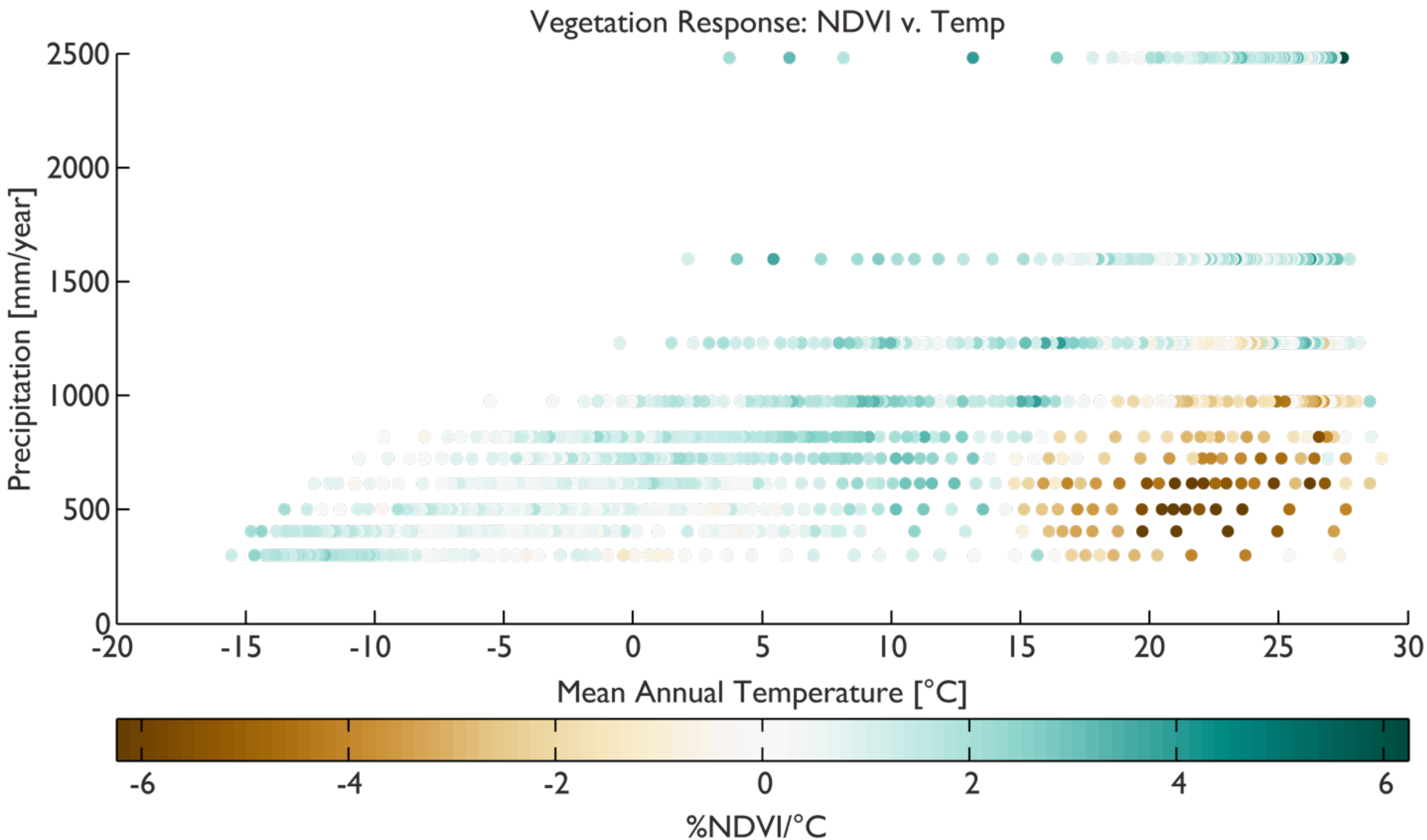
More than cold limits high latitudes



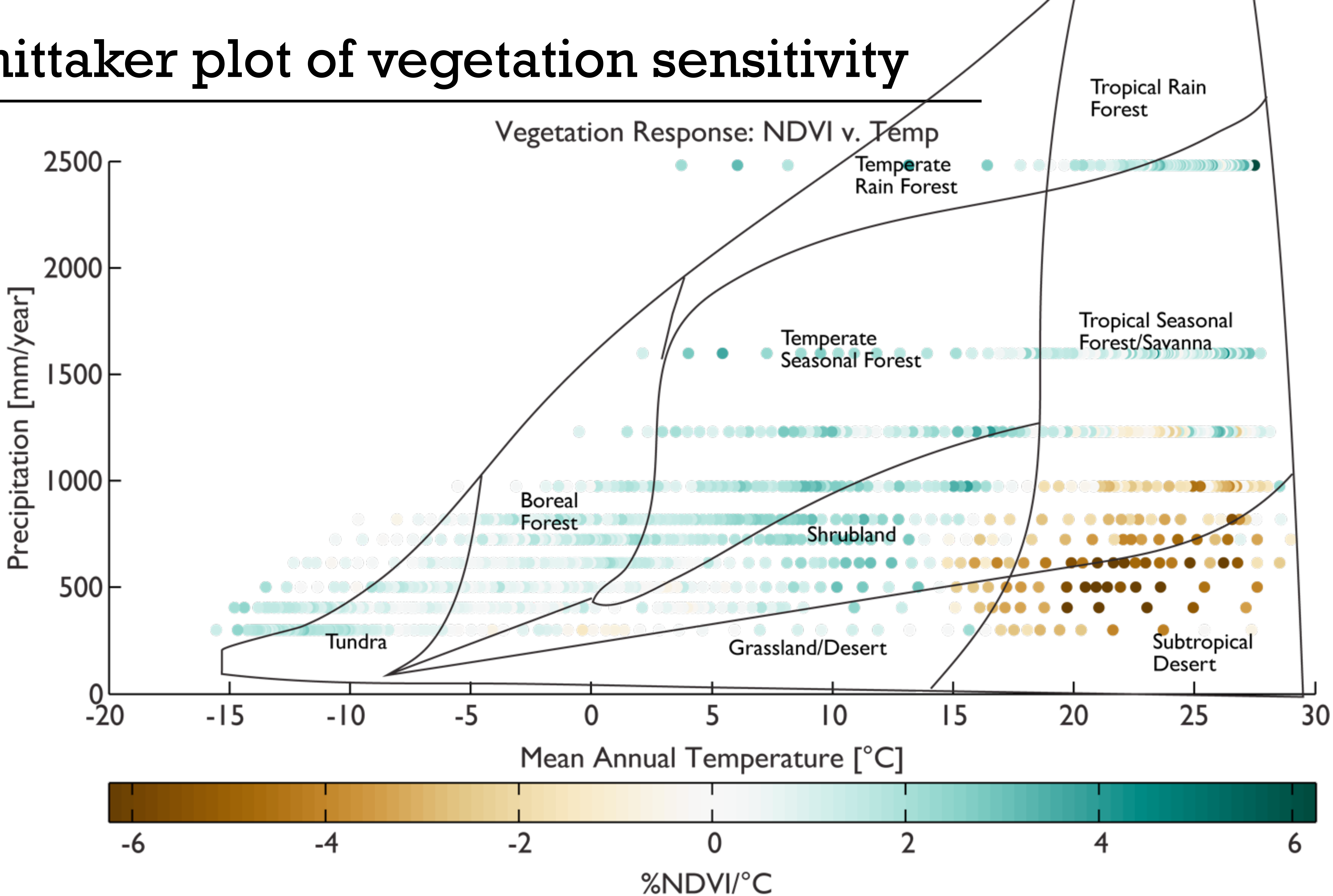
Vegetation sensitivity to temperature



Whittaker plot of vegetation sensitivity



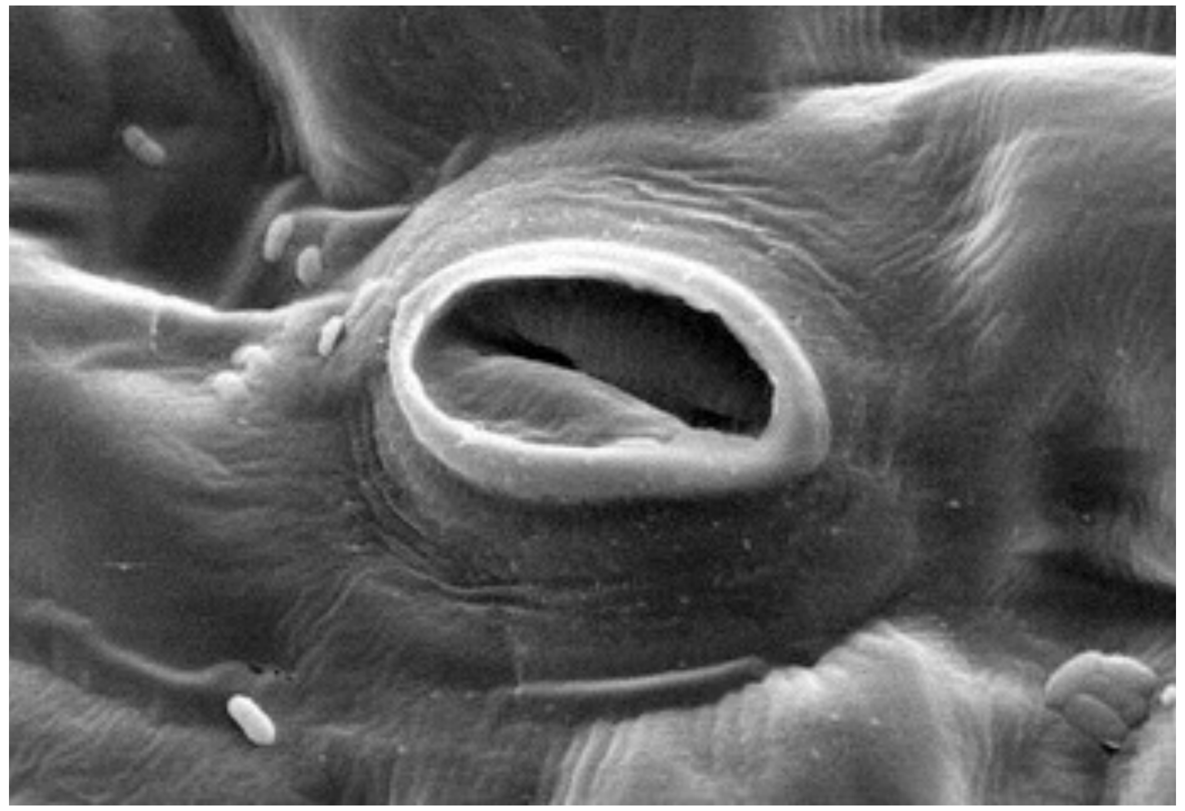
Whittaker plot of vegetation sensitivity




The Future of Vegetation

Timescales of vegetation dynamics

Stomata



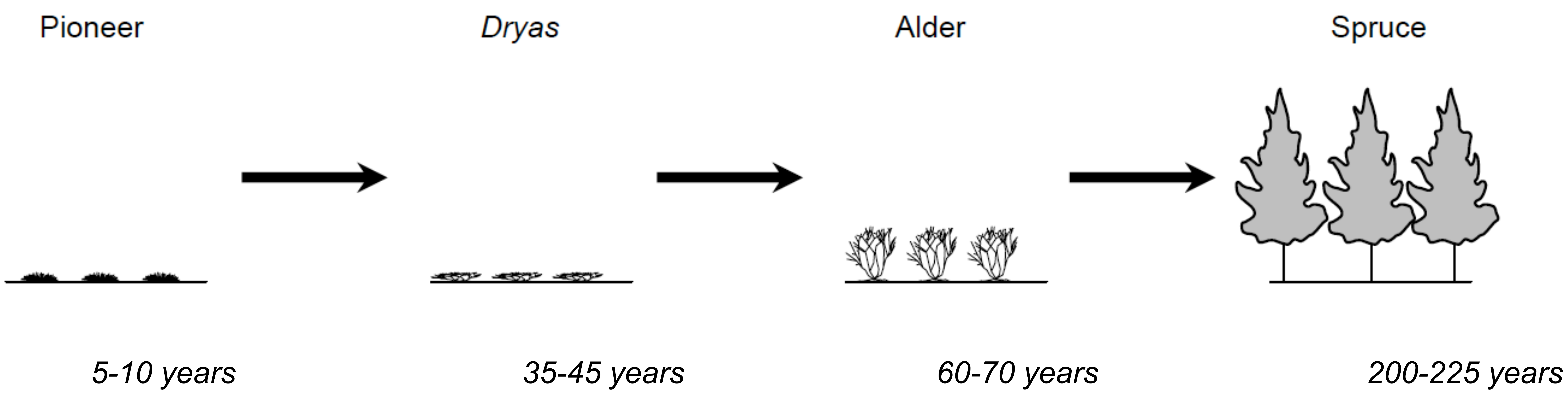
Minutes - Hours

Phenology

Days - Weeks

Inter-annual variation

Years



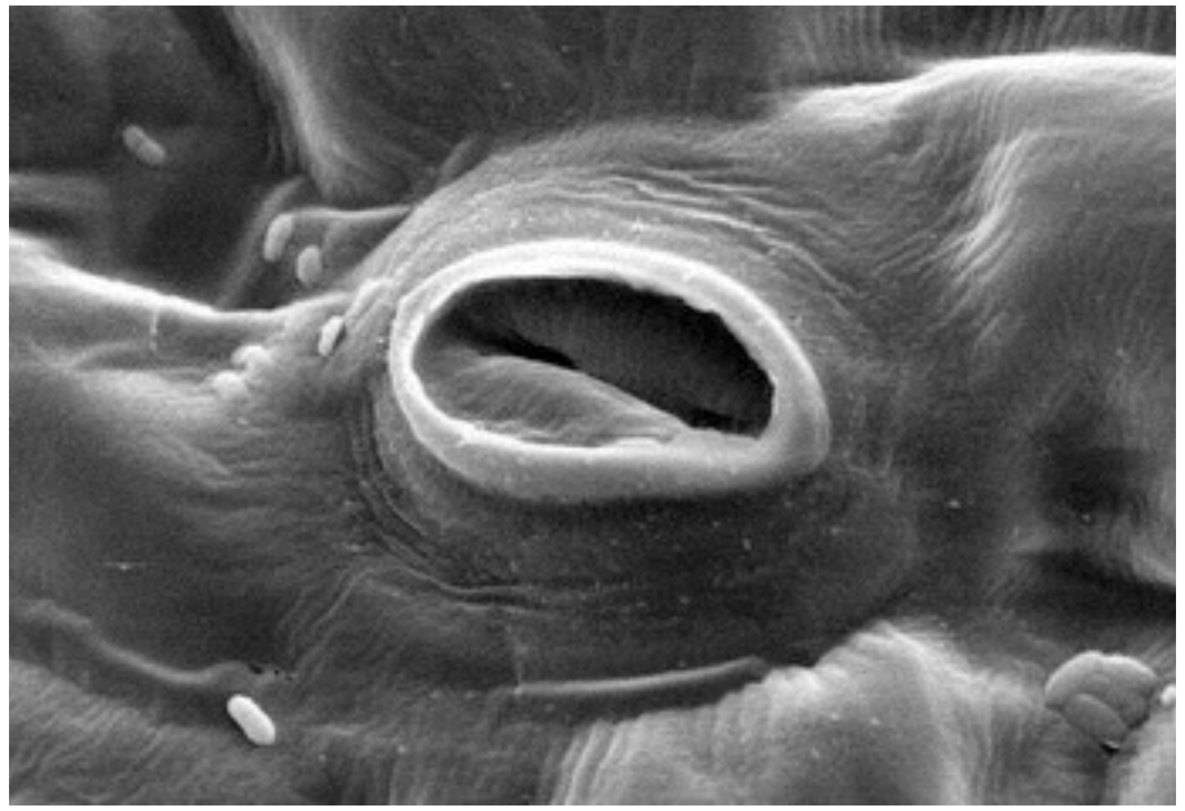
http://media.treehugger.com

http://farm8.staticflickr.com/7042

G. Bonan 2002, Ecological Climatology, Chapter 11

Sensitivity to inter-annual variation

Stomata



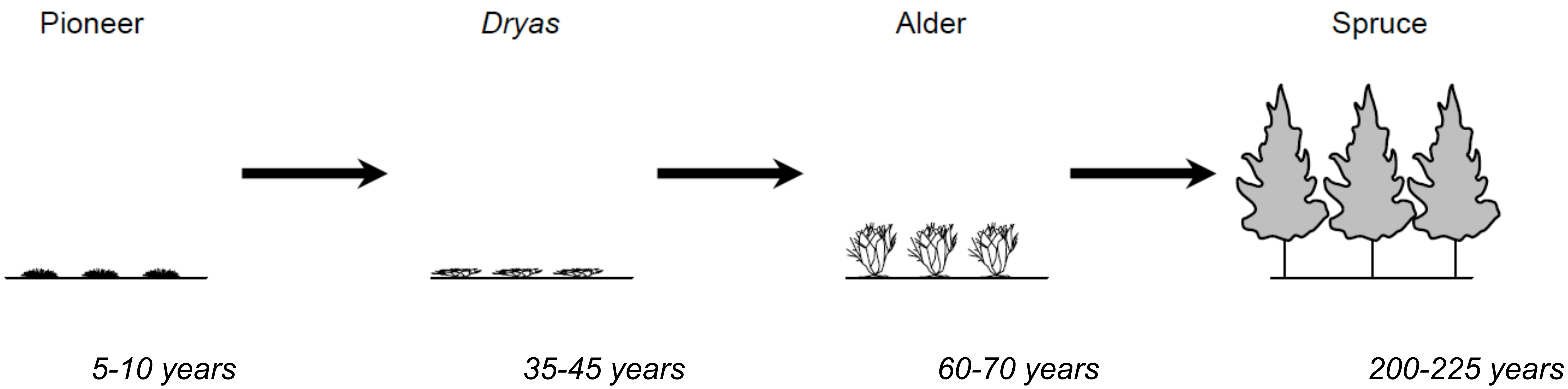
Minutes - Hours

Phenology

Days - Weeks

Inter-annual variation

Years



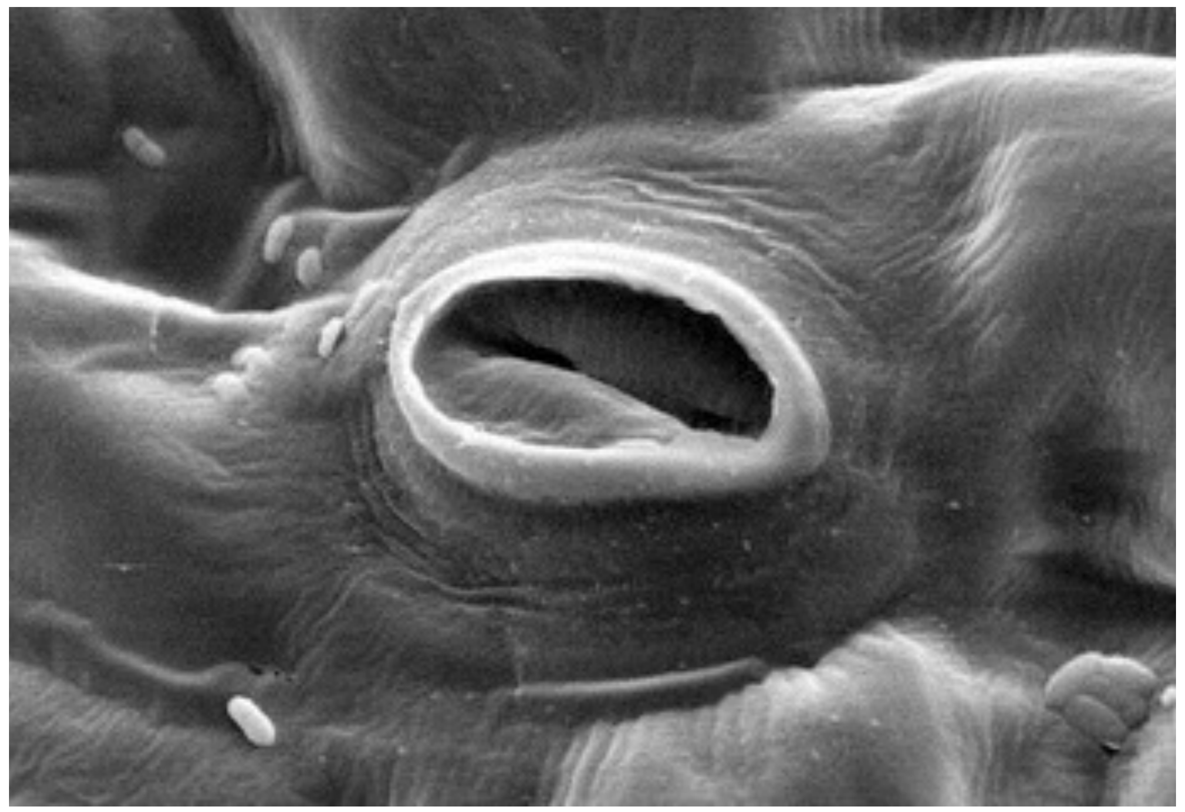
http://media.treehugger.com

http://farm8.staticflickr.com/7042

G. Bonan 2002, Ecological Climatology, Chapter 11

Decades long records of vegetation

Stomata



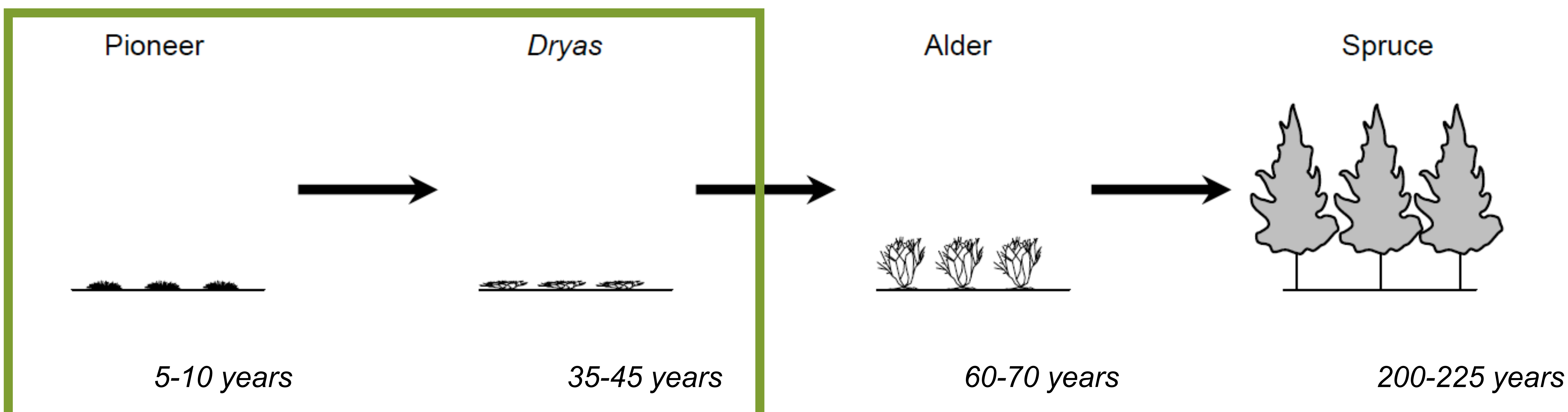
Minutes - Hours

Phenology

Days - Weeks

Inter-annual variation

Years



http://media.treehugger.com

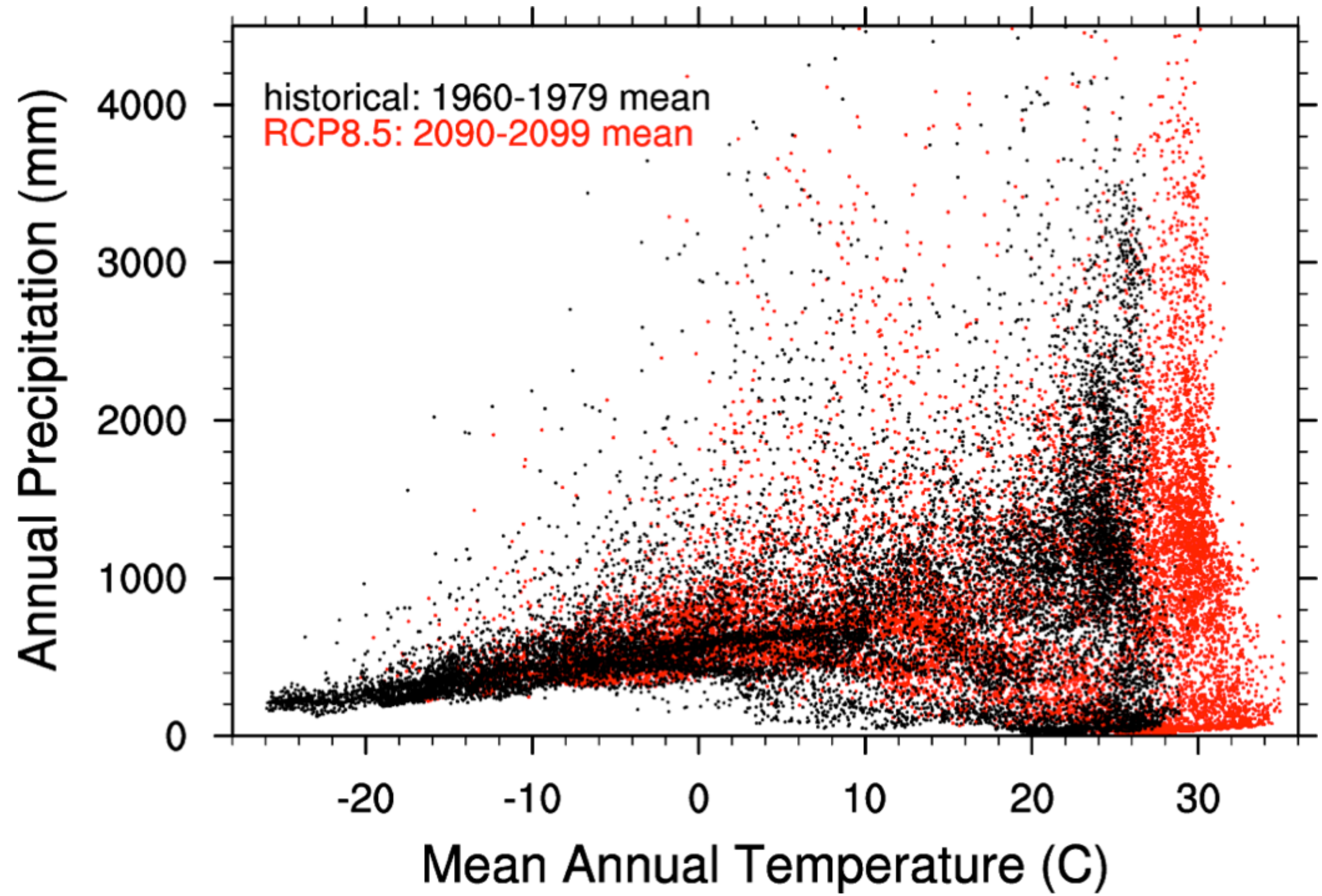
http://farm8.staticflickr.com/7042

G. Bonan 2002, Ecological Climatology, Chapter 11

Project trajectories from climate sensitivity

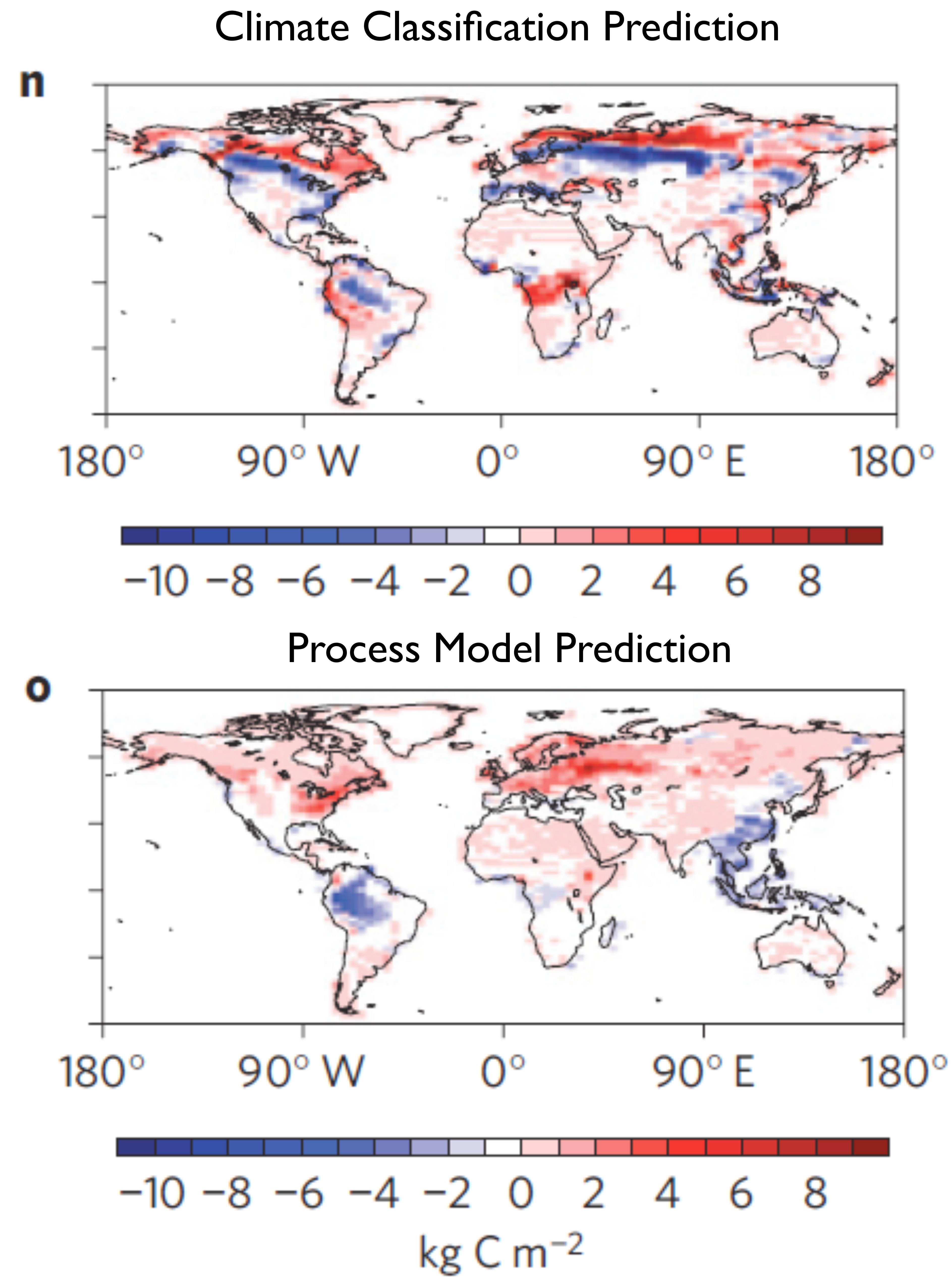
Use anomalies in temperature, shortwave radiation, vapor pressure deficit and precipitation

Where is vegetation going tomorrow? How does it compare to climate classification?



from Charlie Koven

Models and Climate to Predict Land Carbon



Koven 2013

Masking for Vegetation

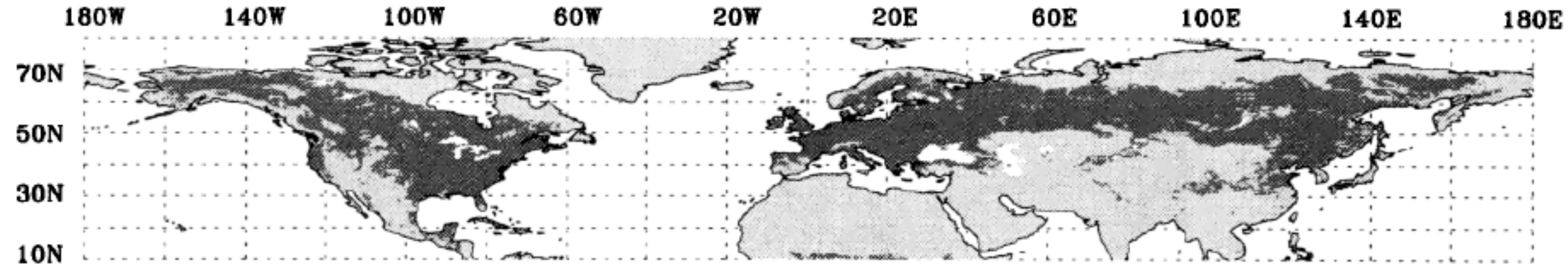


Figure 2. Map of vegetated pixels (solid) used in this study. Vegetated pixels are identified as those with (1) June to August NDVI composite values > 0.1 for all years and (2) June to August average NDVI values > 0.3 for all years.

NDVI Values
Maximum 3 months > .1
Mean of Maximum 3 months > .3

Zhou et al. 2001

Climate Classification

BWh	Arid - Desert - Hot	Pann < 5th Percentile
Af	Tropical - Rainforest	Tmin > +18 C; Pmin (month) > 60 mm
Aw	Tropical - Savannah	Tmin > +18 C; Pmin (month) < 60 mm in winter

Koppen-Geiger Climate Classification

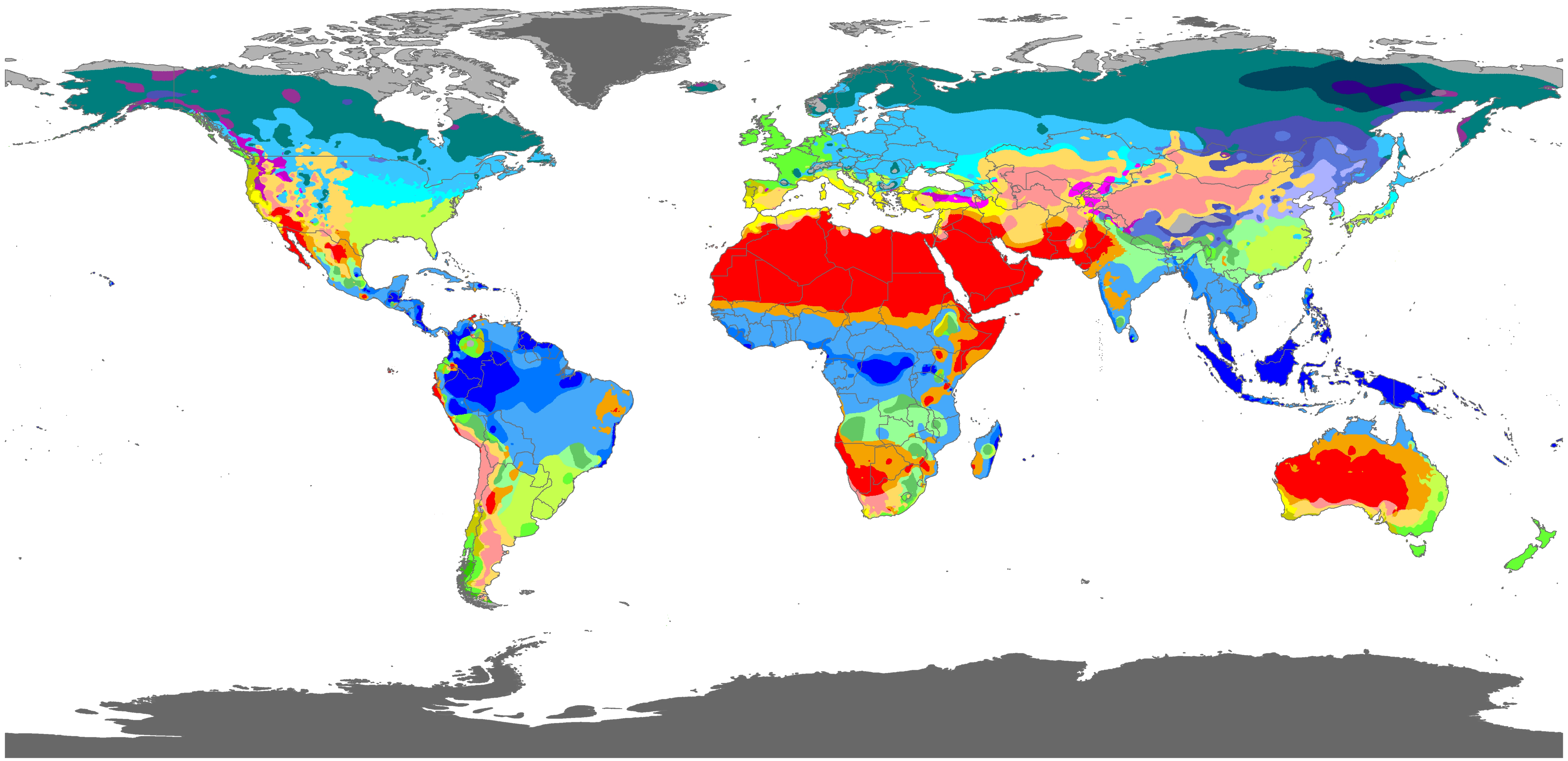
Climate Defined

BWh
Arid - Desert - Hot

Af
Tropical - Rainforest

Aw
Tropical - Savannah

Dfc
Cold - Without dry season - cold summer



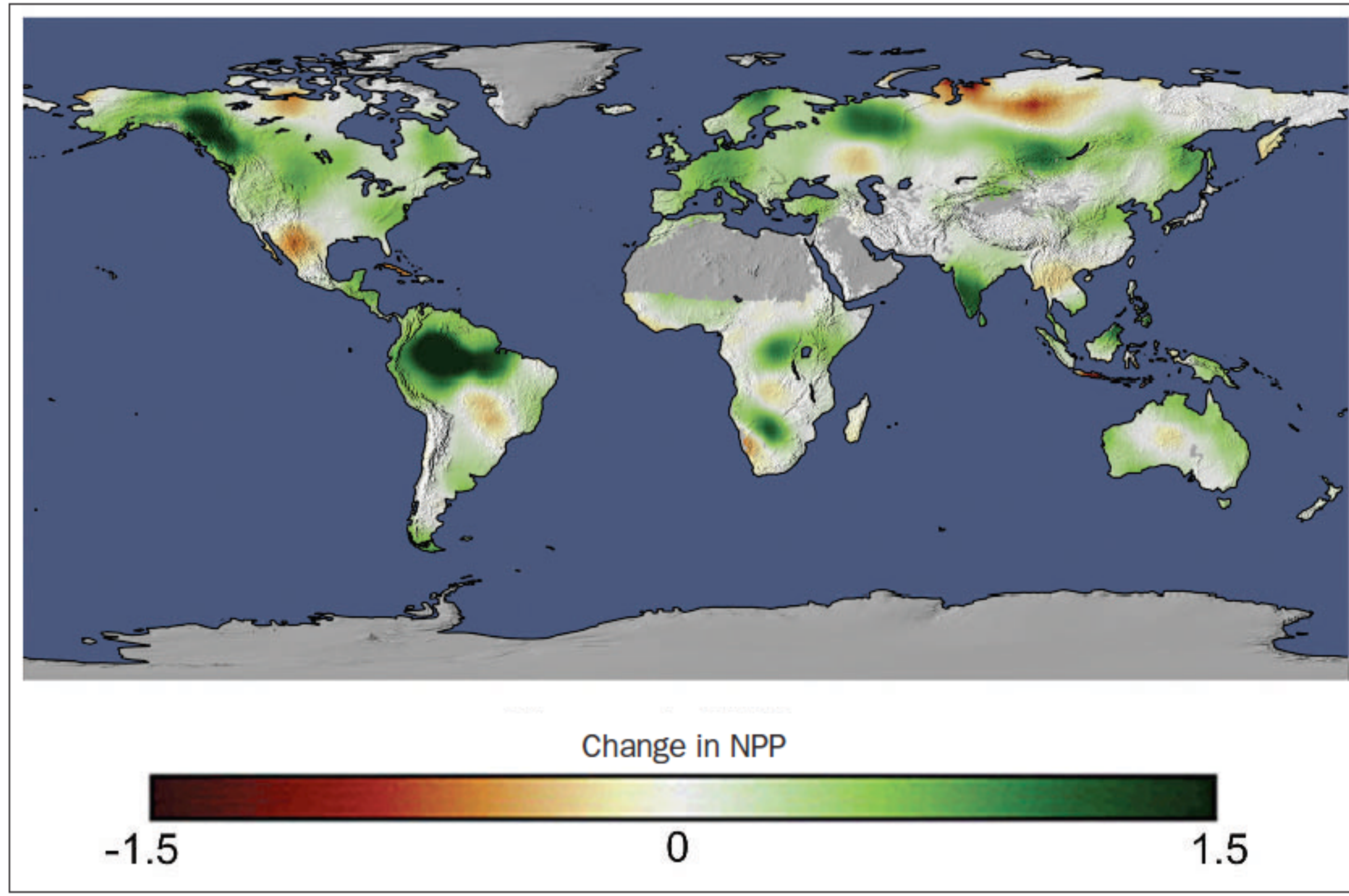
Peel et al., 2007

Table 1: Key to calculate the climate formula of Köppen and Geiger for the main climates and subsequent precipitation conditions, the first two letters of the classification. Note that for the polar climates (E) no precipitation differentiations are given, only temperature conditions are defined. This key implies that the polar climates (E) have to be determined first, followed by the arid climates (B) and subsequent differentiations into the equatorial climates (A) and the warm temperate and snow climates (C) and (D), respectively. The criteria are explained in the text.

Type	Description	Criterion
A	**Equatorial climates**	$T_{min} \geq +18\ ^\circ C$
Af	Equatorial rainforest, fully humid	$P_{min} \geq 60$ mm
Am	Equatorial monsoon	$P_{ann} \geq 25\,(100 - P_{min})$
As	Equatorial savannah with dry summer	$P_{min} < 60$ mm in summer
Aw	Equatorial savannah with dry winter	$P_{min} < 60$ mm in winter
B	**Arid climates**	$P_{ann} < 10\, P_{th}$
BS	Steppe climate	$P_{ann} > 5\, P_{th}$
BW	Desert climate	$P_{ann} \leq 5\, P_{th}$
C	**Warm temperate climates**	$-3\ ^\circ C < T_{min} < +18\ ^\circ C$
Cs	Warm temperate climate with dry summer	$P_{smin} < P_{wmin}, P_{wmax} > 3\, P_{smin}$ and $P_{smin} < 40$ mm
Cw	Warm temperate climate with dry winter	$P_{wmin} < P_{smin}$ and $P_{smax} > 10\, P_{wmin}$
Cf	Warm temperate climate, fully humid	neither Cs nor Cw
D	**Snow climates**	$T_{min} \leq -3\ ^\circ C$
Ds	Snow climate with dry summer	$P_{smin} < P_{wmin}, P_{wmax} > 3\, P_{smin}$ and $P_{smin} < 40$ mm
Dw	Snow climate with dry winter	$P_{wmin} < P_{smin}$ and $P_{smax} > 10\, P_{wmin}$
Df	Snow climate, fully humid	neither Ds nor Dw
E	**Polar climates**	$T_{max} < +10\ ^\circ C$
ET	Tundra climate	$0\ ^\circ C \leq T_{max} < +10\ ^\circ C$
EF	Frost climate	$T_{max} < 0\ ^\circ C$

Kottek, Markus, Jürgen Grieser, Christoph Beck, Bruno Rudolf, and Franz Rubel. 2006. "World Map of the Koppen-Geiger Climate Classification Updated." *Meteorologische Zeitschrift* 15 (3): 259–64.

Trends in NPP
1981 - 1999



Running, Steven W., Ramakrishna R. Nemani, Faith Ann Heinsch, Maosheng Zhao, Matt Reeves, and Hirofumi Hashimoto. 2004. "A Continuous Satellite-Derived Measure of Global Terrestrial Primary Production." *BioScience* 54 (6): 547–60. doi:10.1641/0006-3568(2004)054[0547:ACSMOG]2.0.CO;2.

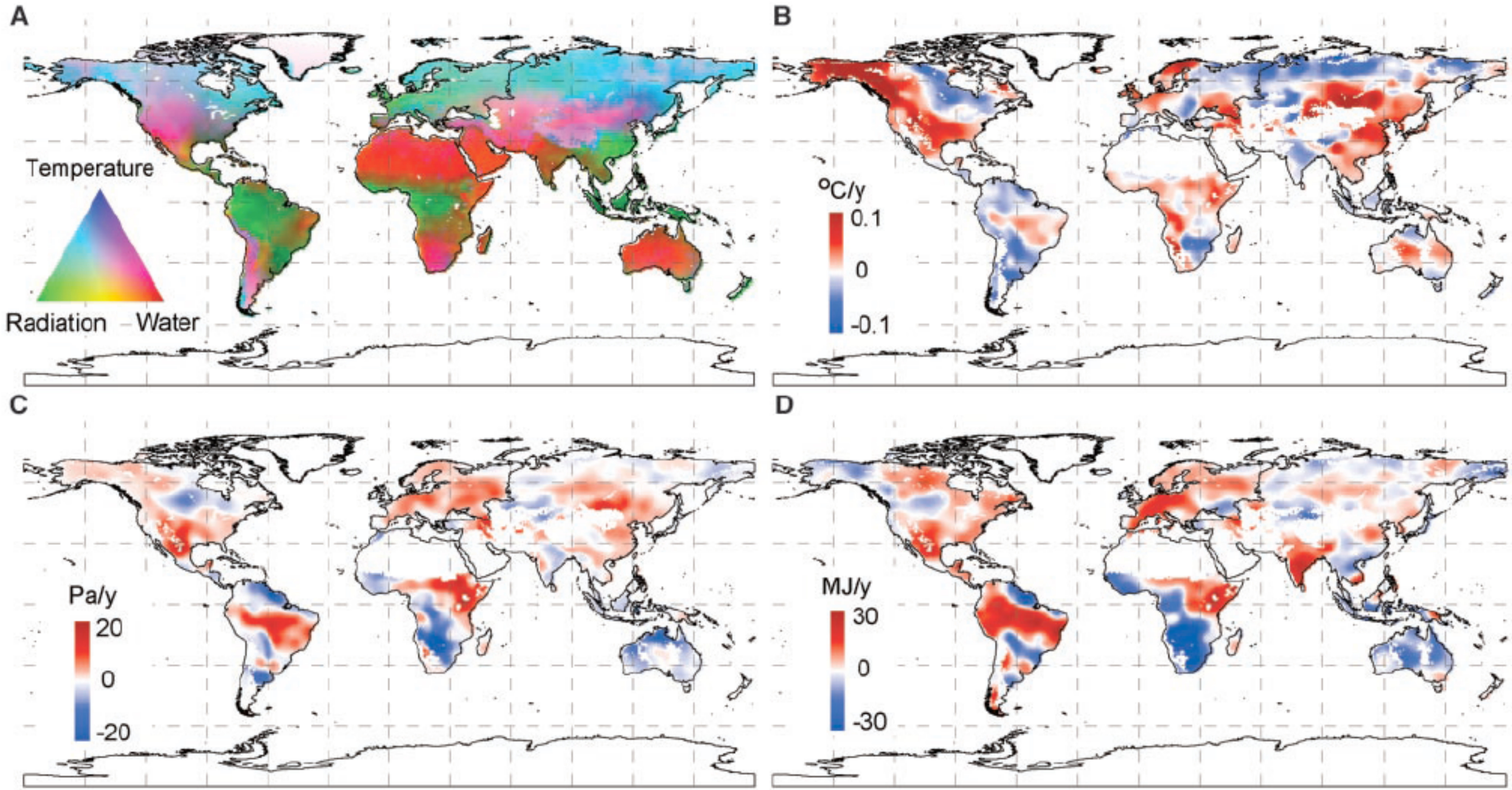


Fig. 1. (**A**) Geographic distribution of potential climatic constraints to plant growth derived from long-term climate statistics. (**B** to **D**) Recent climatic changes, estimated from reanalysis data from 1982 to 1999, in the growing season average temperature (B), vapor pressure deficit (VPD) (C), and solar radiation (D). Reductions in VPD are indicative of increased water availability (C). The growing season is defined as those months with 1982 to 1999 average air temperatures above 0°C.

Nemani, R. R., C. D. Keeling, H. Hashimoto, W. M. Jolly, S. C. Piper, C. J. Tucker, R. B. Myneni, and S. W. Running. 2003. "Climate-Driven Increases in Global Terrestrial Net Primary Production from 1982 to 1999." *Science* 300 (5625): 1560–63.

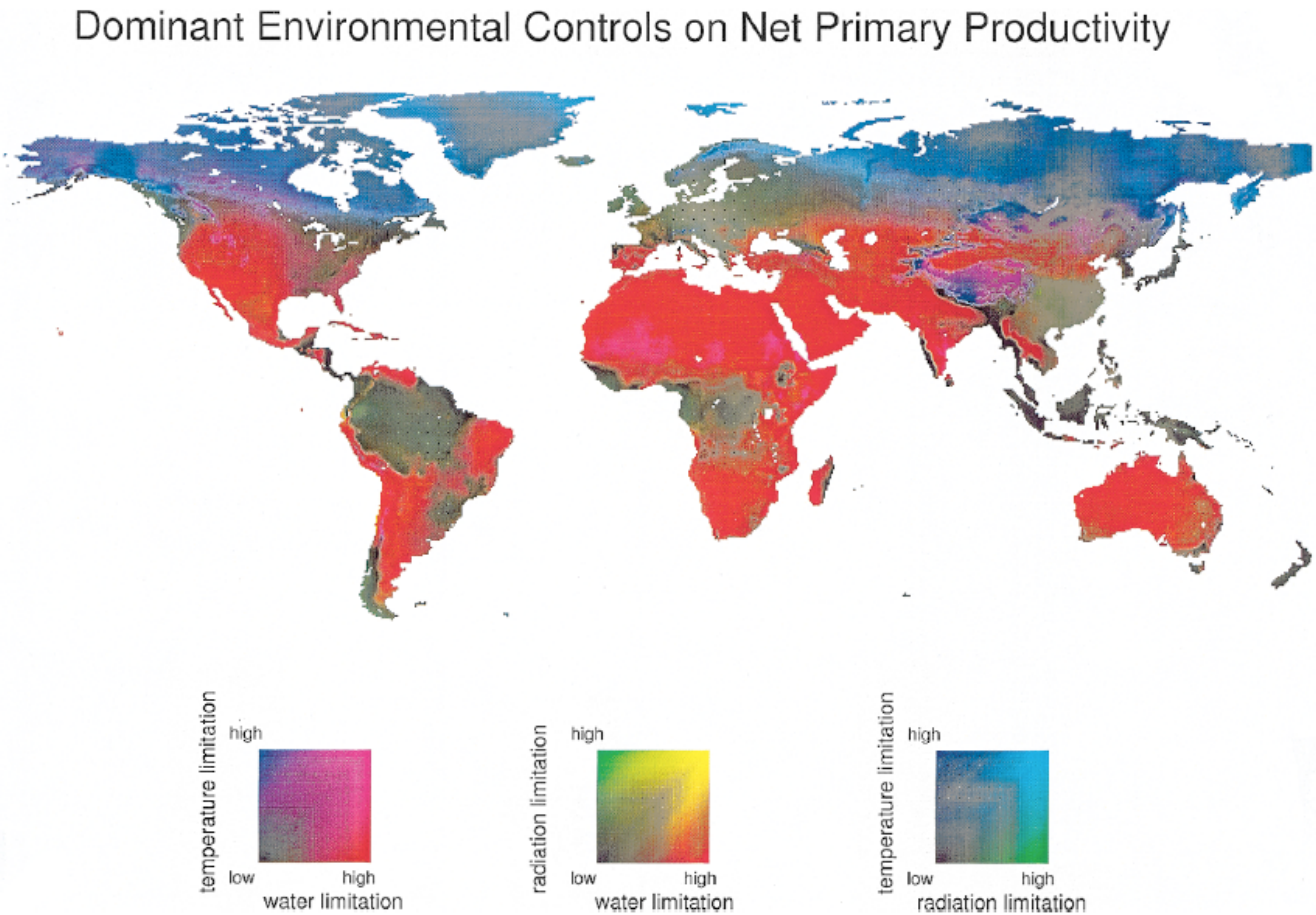


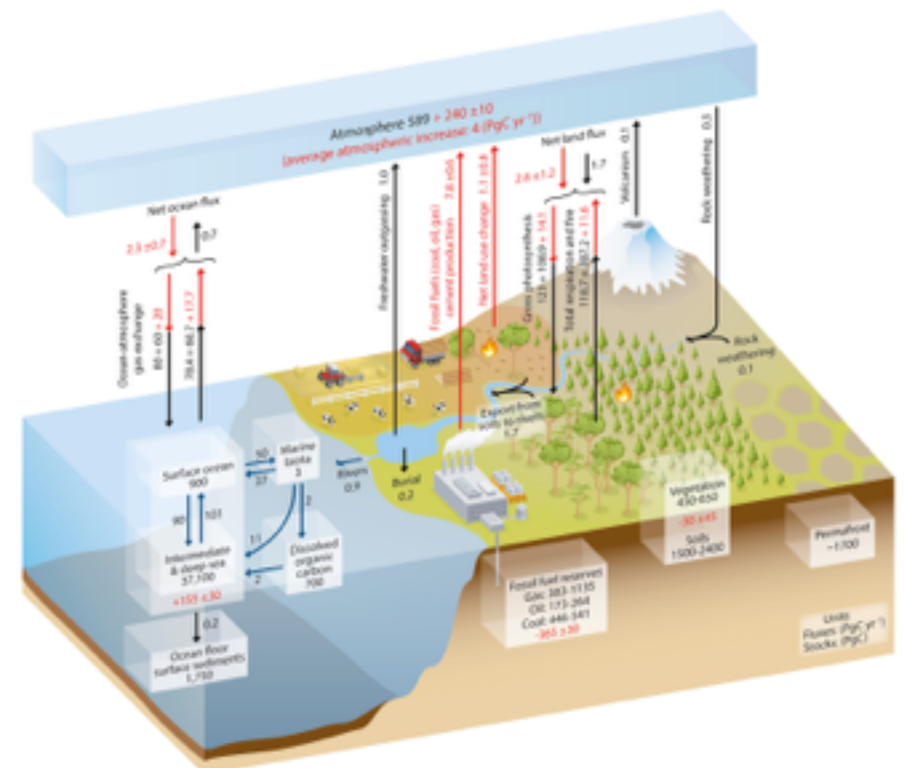
Figure 2. Map of weighted climatic controls on net primary productivity determined from water availability, average temperature, and cloudiness. Each data point represents 3 values of the membership functions based on annual mean temperature, water balance coefficient, and percentage of sunshine hours per year in one 0.5° × 0.5° grid cell.

Churkina, Galina, and Steven W. Running. 1998. "Contrasting Climatic Controls on the Estimated Productivity of Global Terrestrial Biomes." *Ecosystems* 1 (2): 206–15. doi:10.1007/s100219900016.

Above Ground Biomass

MgC/ha

- 0-25
- 76-100
- 251-250
- >400

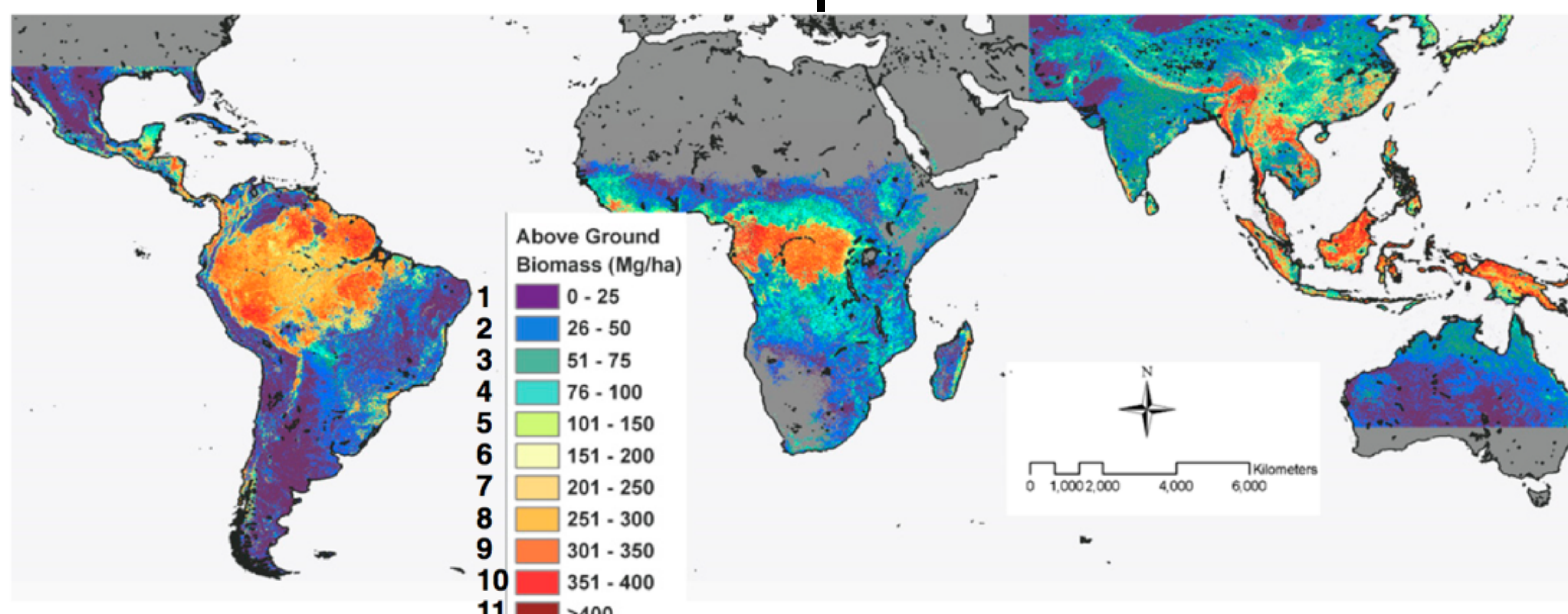


2.6 PgC/yr into land

~550 PgC Vegetation

~2000 PgC Soil

Land + Soil ~3x Atmosphere Carbon

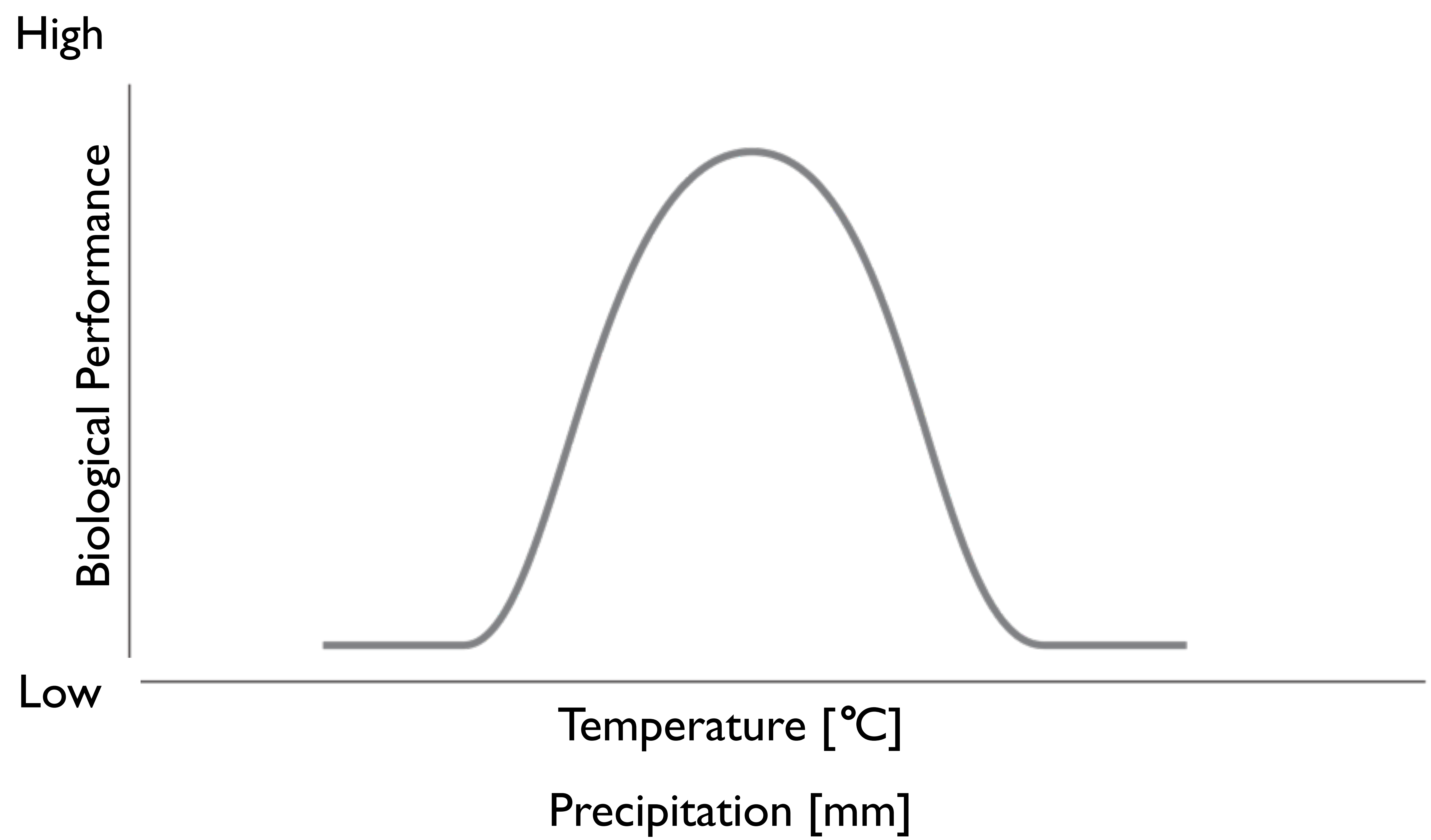


Saatchi et al.2011

Vegetation Performance Curve

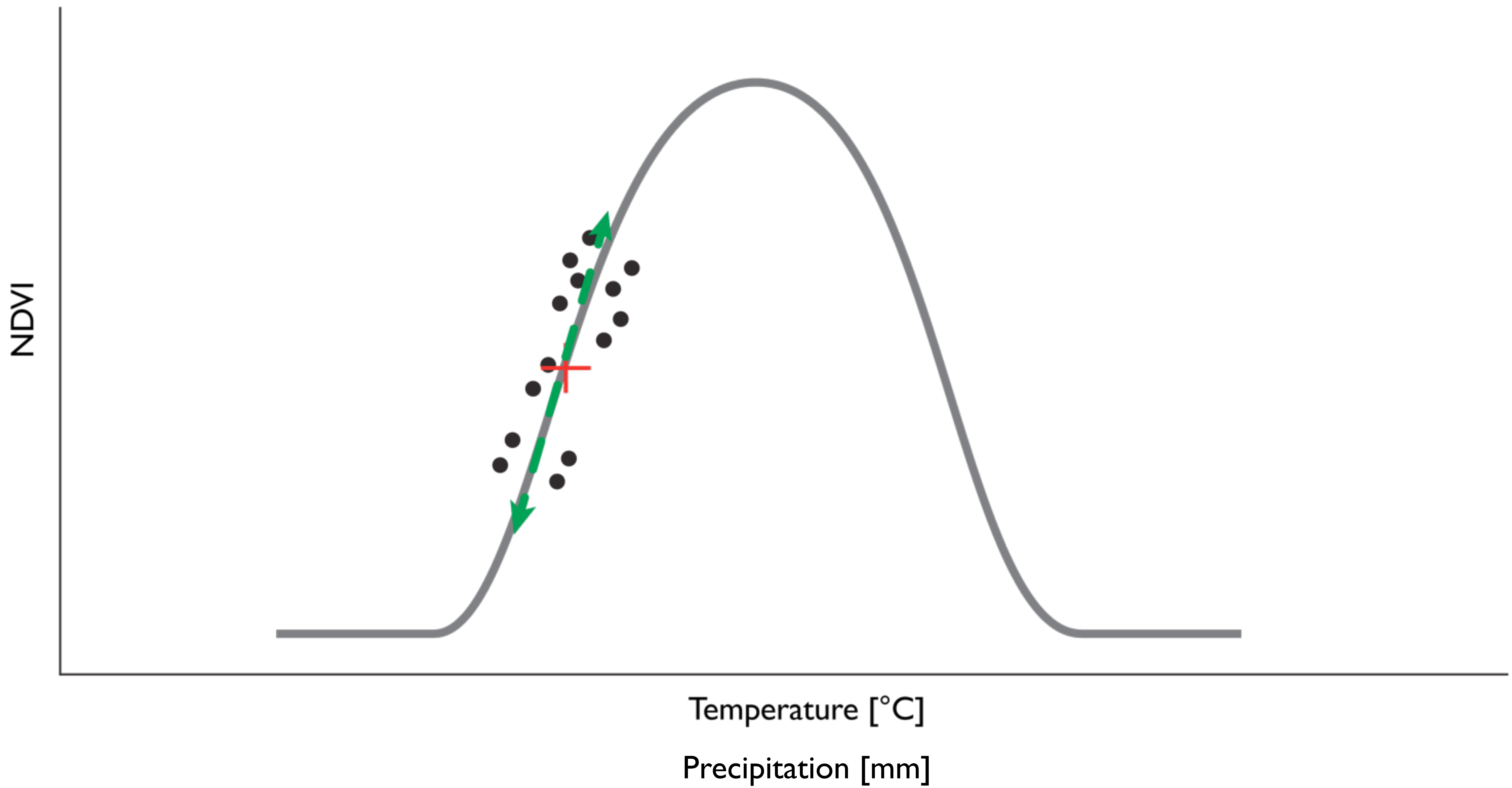
Temperature and precipitation control the performance of vegetation.

Combine gridded data sets to measure a point on this curve.

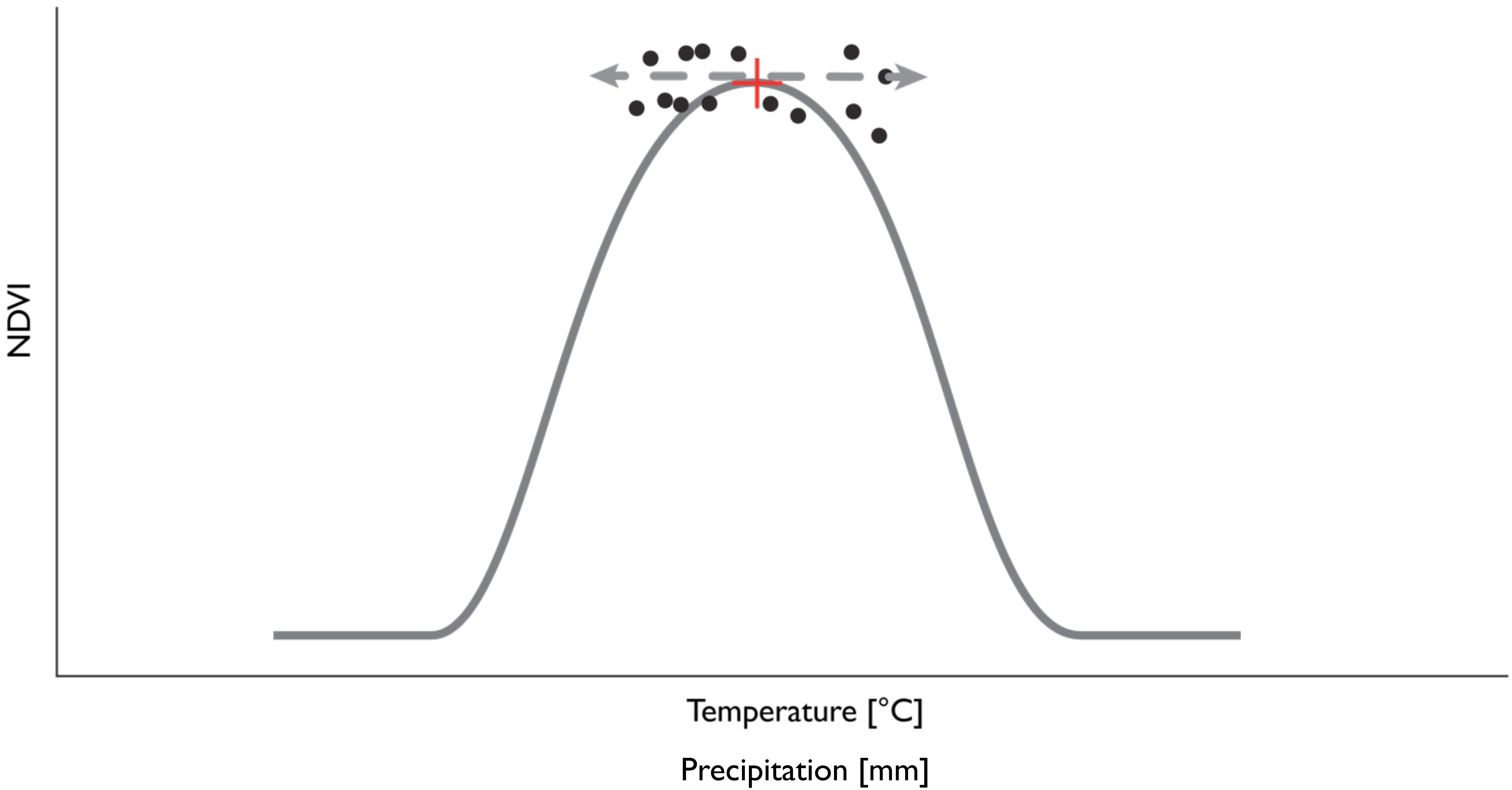


Adapted from Ecological Climatology 2008 G. Bonan Figure 20.1

Positive sensitivity - 'too cold'



Neutral sensitivity - ‘just right’



Negative sensitivity - ‘too hot’