Temperature response of nitrogen fixation: A model intercomparison project incorporating physiological measurements into land models

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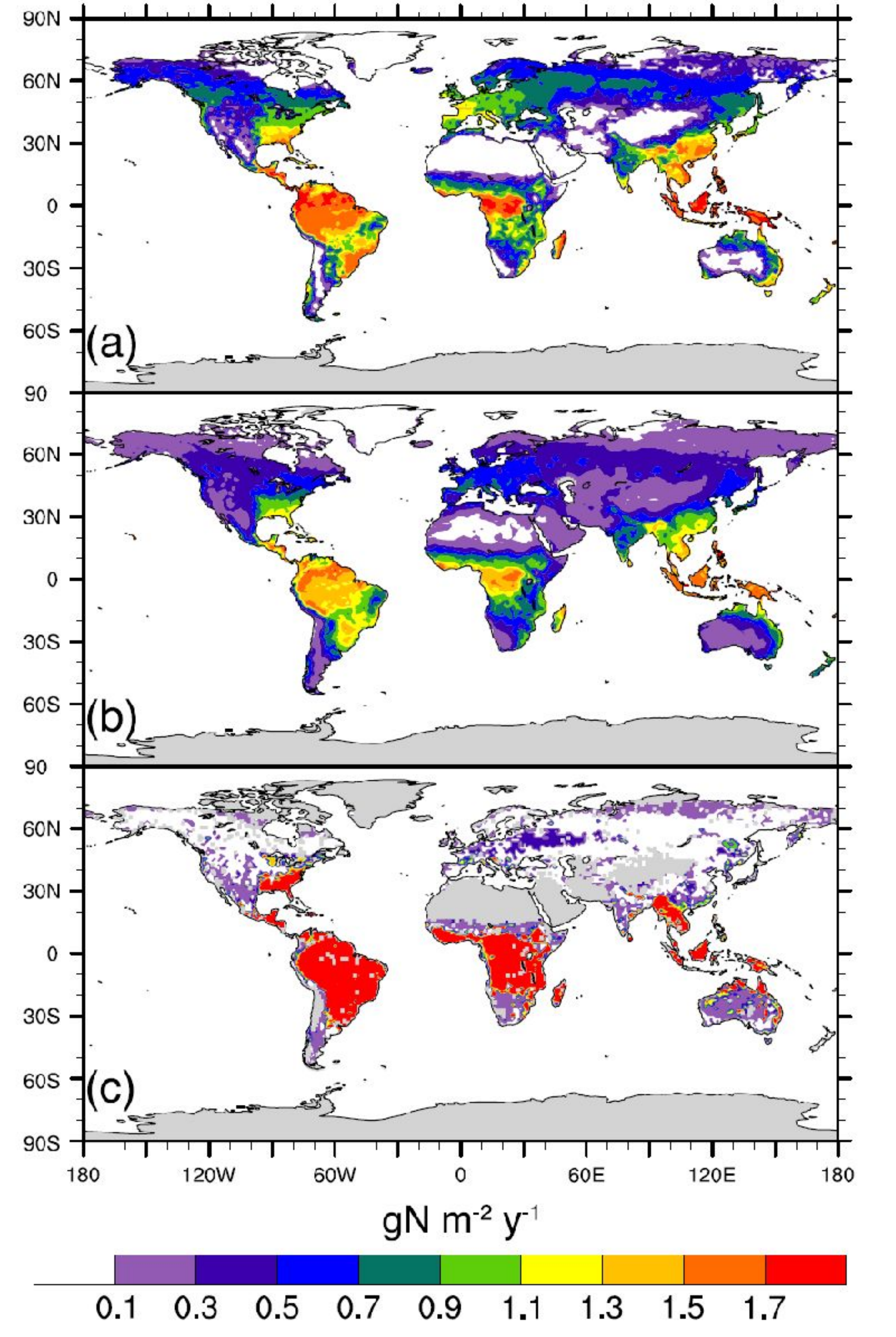
CESM Land Working Group Meeting

TEXAS
The University of Texas at Austin

Biological N fixation dominant natural input of N into terrestrial biosphere

Vitousek *et al.* 2013 *Phil. Trans. R. Soc. B*;
Fowler *et al.* 2013 *Phil. Trans. R. Soc. B*

Multiple approaches to modelling BNF



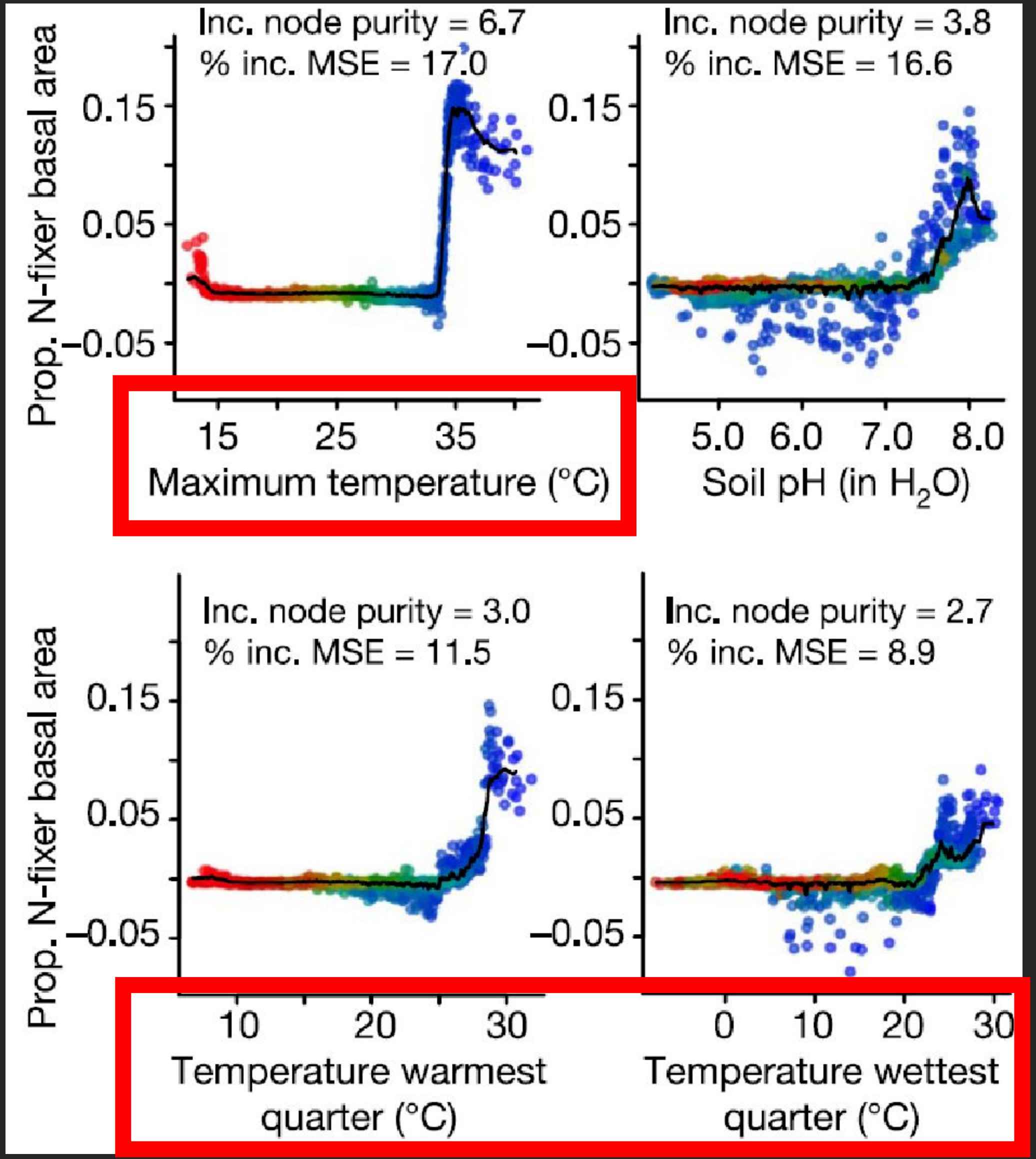
BNF = *f*(NPP)

BNF = *f*(ET)

Process based:
BNF = *f*(temperature, …)

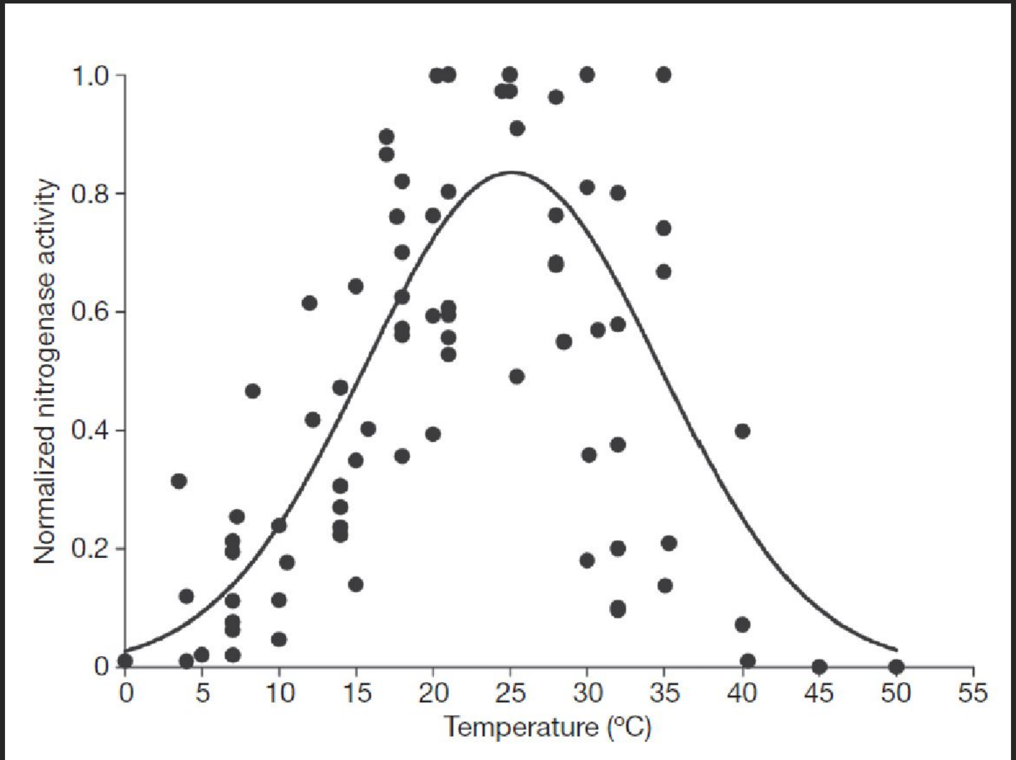
Wieder *et al.* 2015.
Environ. Res. Lett.

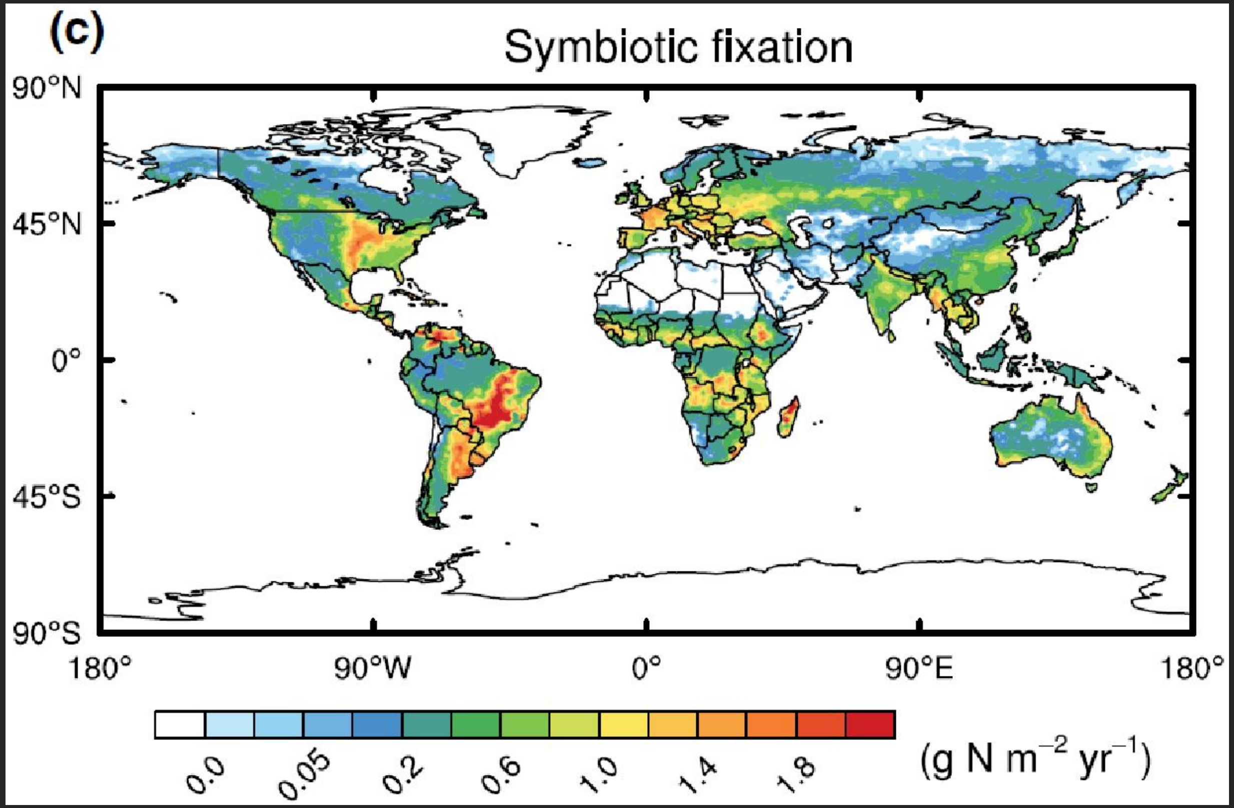
Temperature indices 1st, 3rd, 4th best predictors of global N-fixing tree % basal area



Steidinger *et al.* 2019 *Nature*

Typical N fixation temperature function in land models





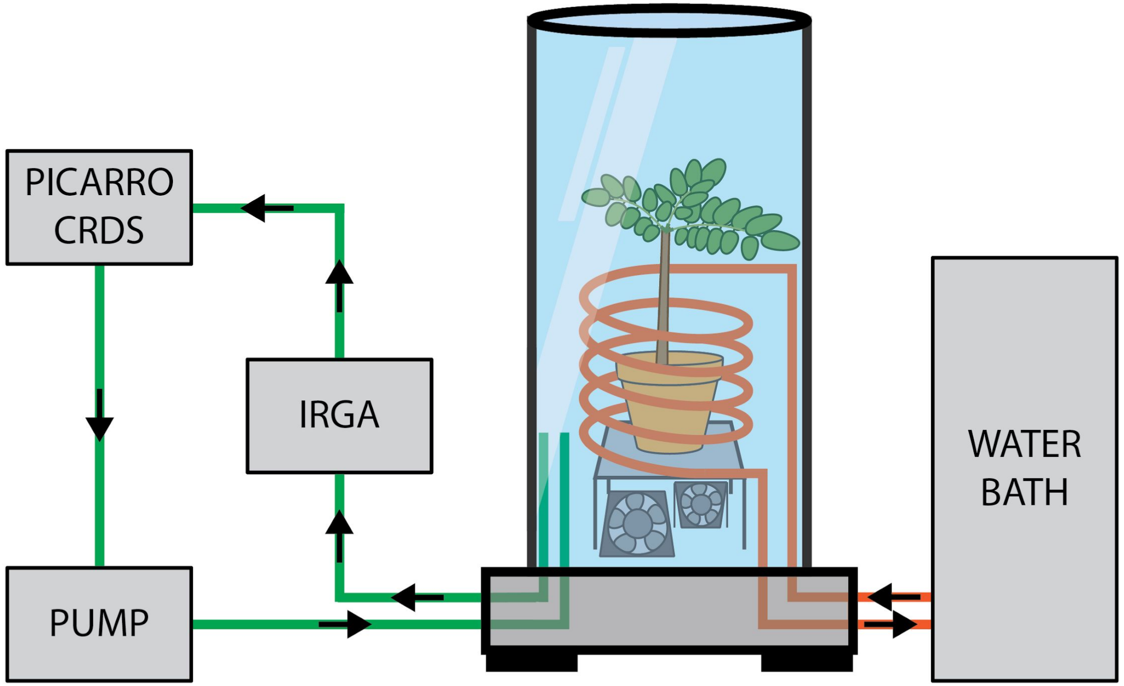
Houlton *et al.* 2008 *Nature;* Shi *et al*. 2016 *Global Change Biology*

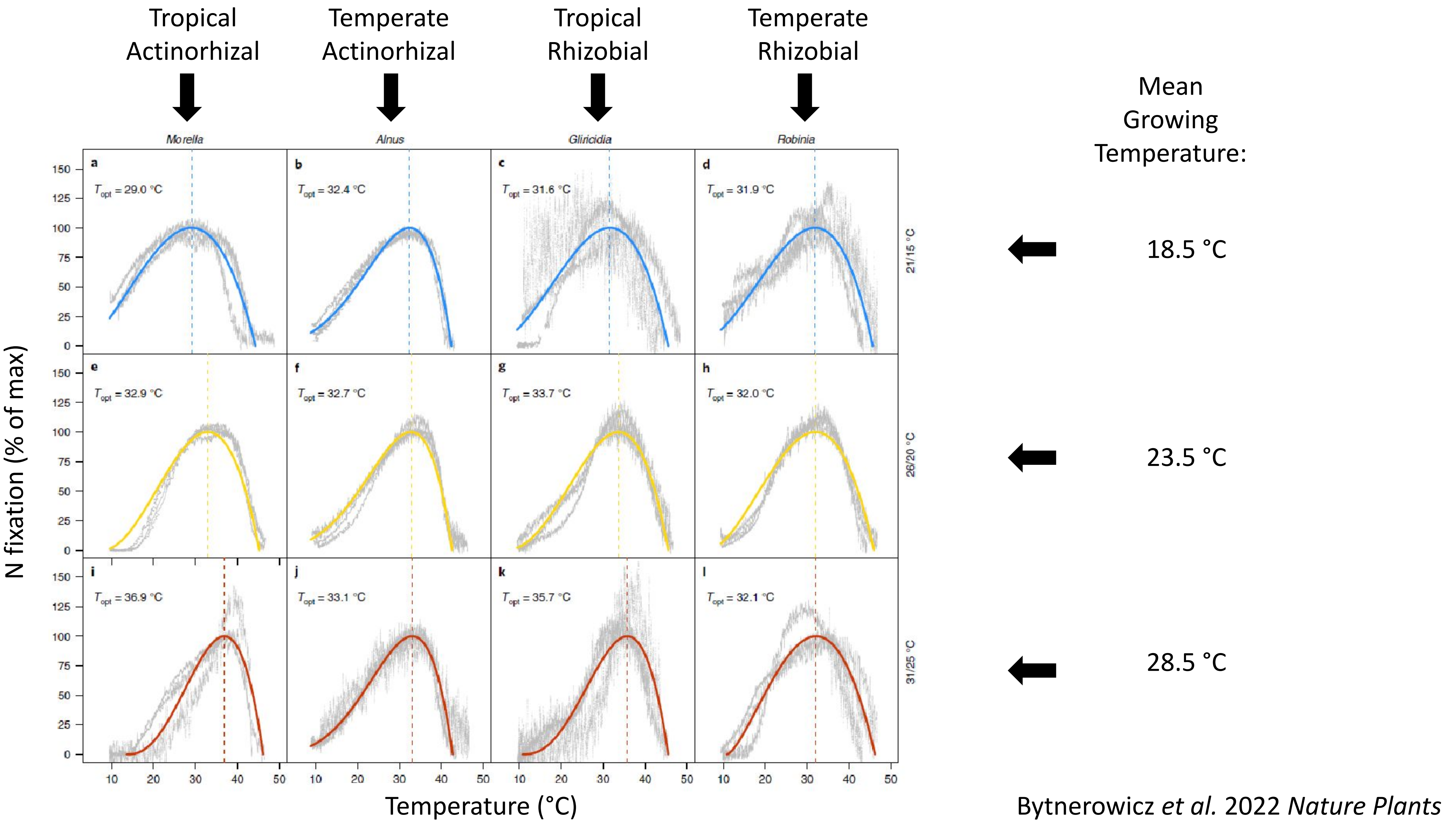
RESEARCH ARTICLE

Methods in Ecology and Evolution BRITISH ECOLOGICAL SOCIETY

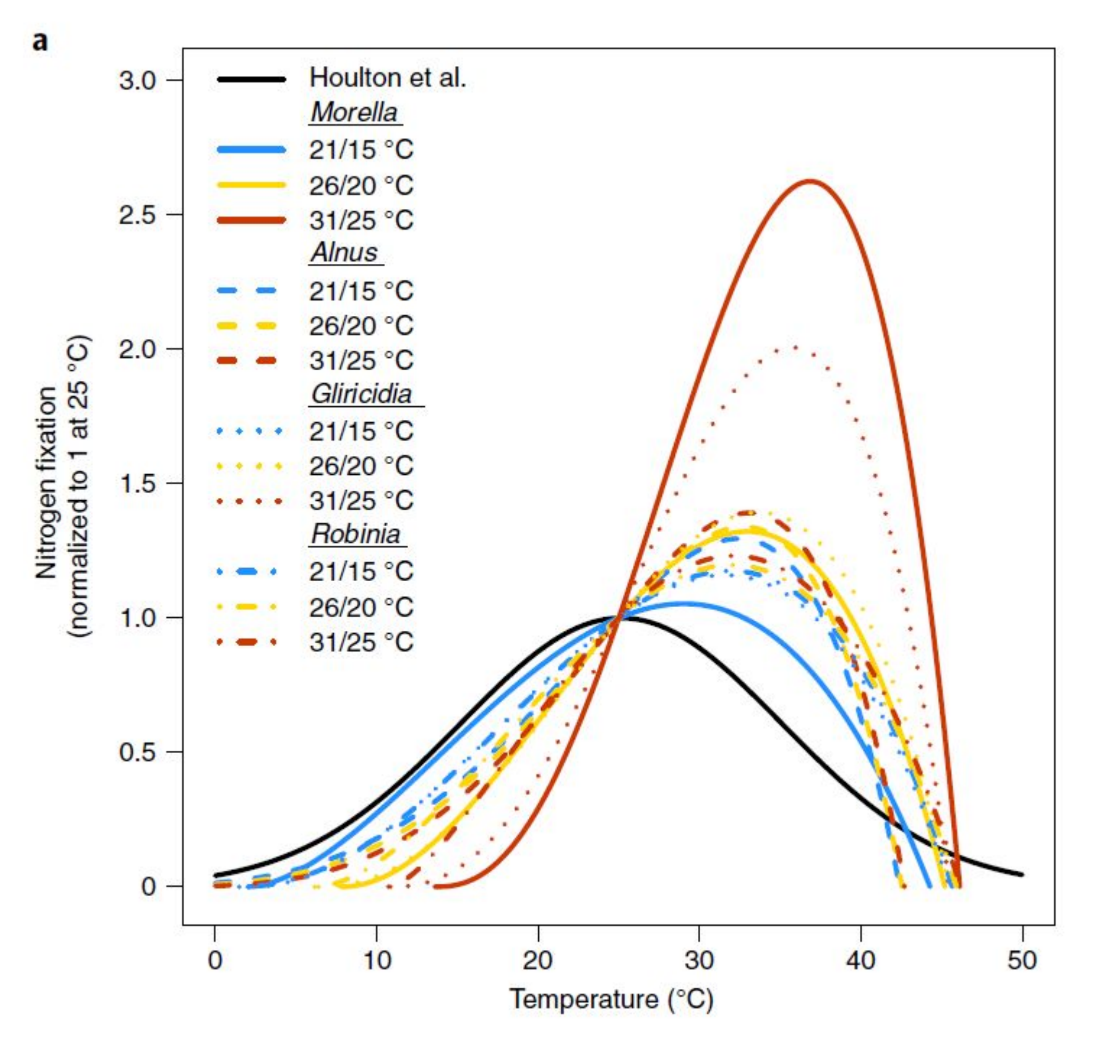
Repeatable, continuous and real-time estimates of coupled nitrogenase activity and carbon exchange at the whole-plant scale

Thomas A. Bytnerowicz[1] | Elizabeth Min[2] | Kevin L. Griffin[1,2] | Duncan N. L. Menge[1]





Bytnerowicz *et al.* 2022 *Nature Plants*

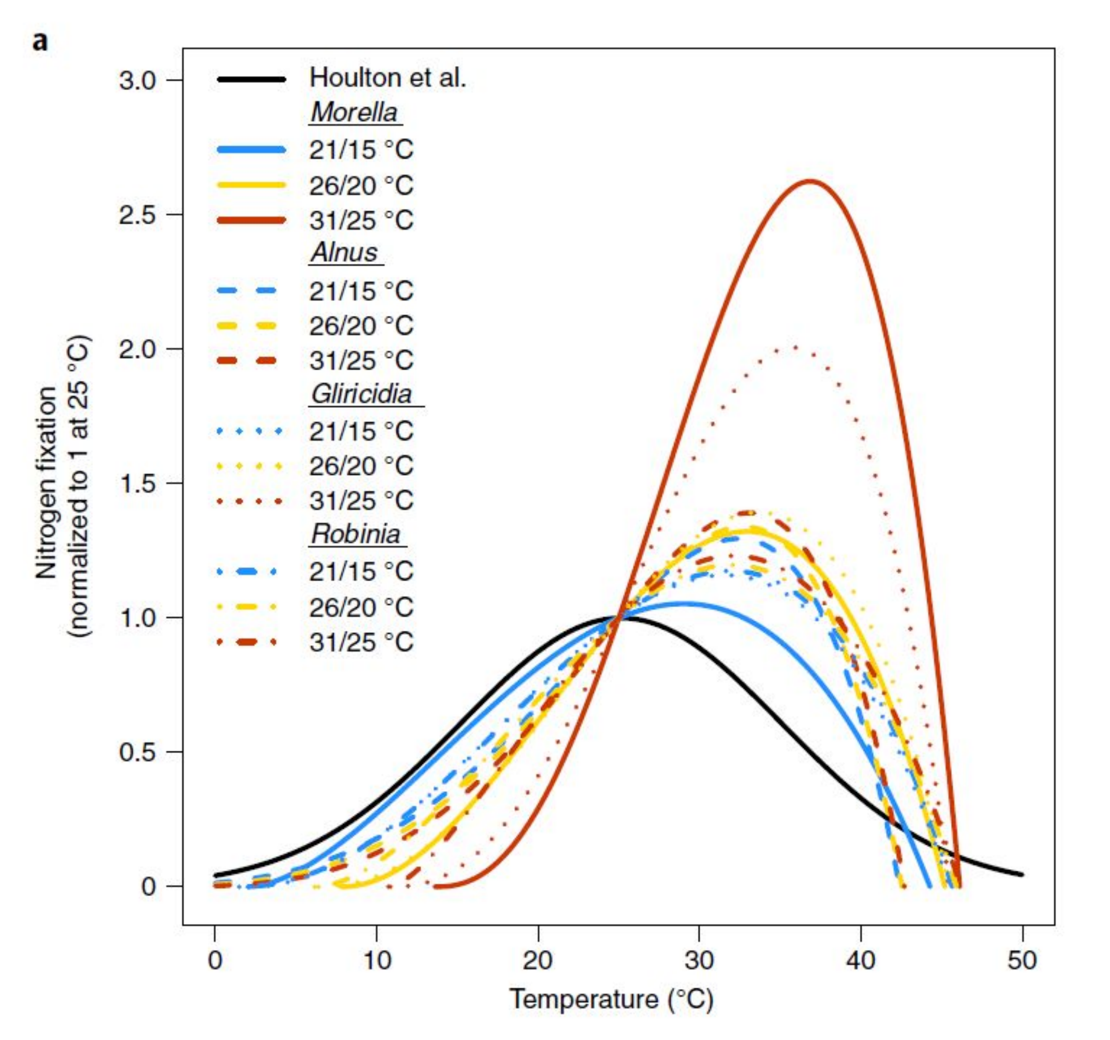


Optimal temperatures for N fixation are

- 3.9-11.7 °C higher than Houlton *et al.*
    - Houlton *et al.* – asymbiotic and high latitudes (mean 57 °, range 32-79 °)

Bytnerowicz *et al.* 2022 *Nature Plants*

Model Intercomparison Project

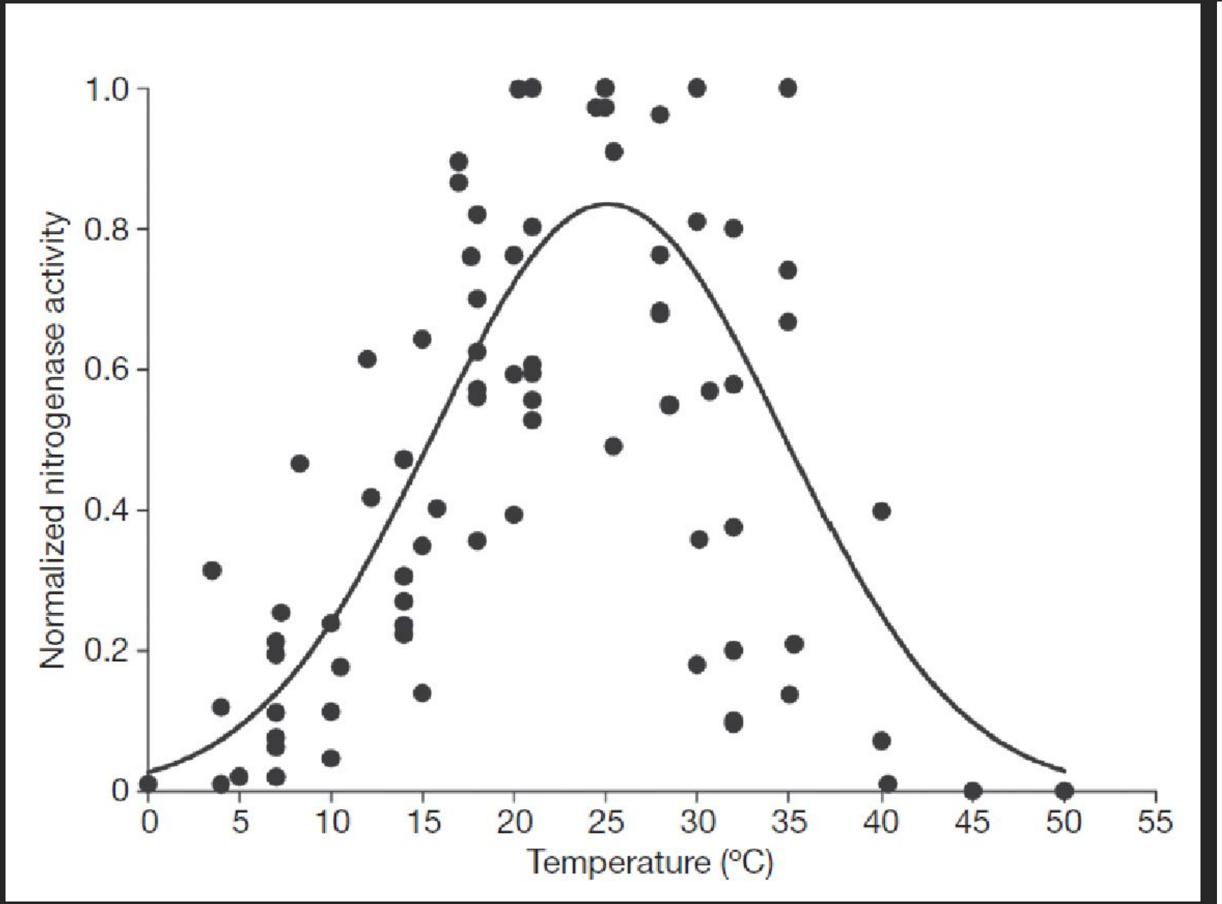


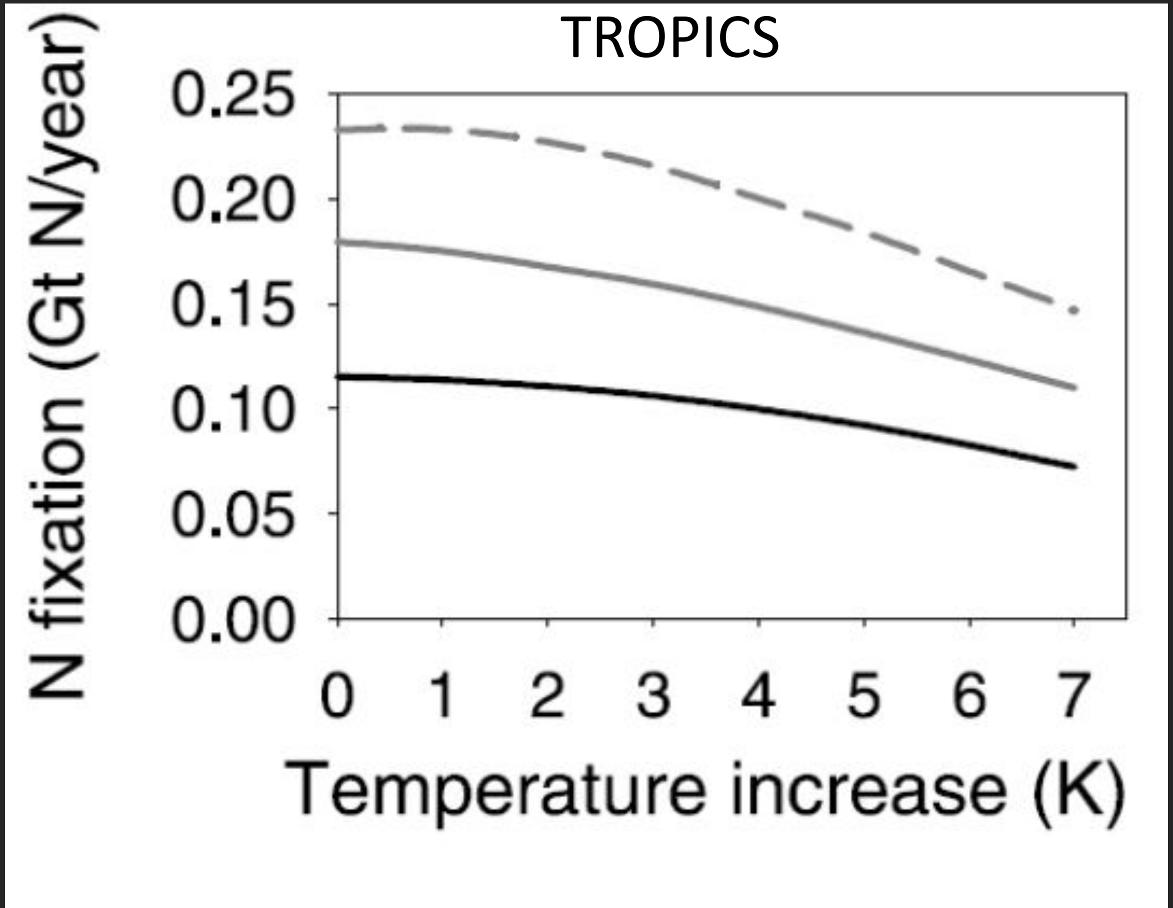
How do the temperature response of BNF and the capacity for acclimation affect predictions of N fixation, NPP, and land carbon storage with climate warming?

Land Models:

- CLASSIC
- CTSM 5.1
- ELM
- LM4-N
- ORCHIDEE-CNP v1.3
- OCN
- QUINCY

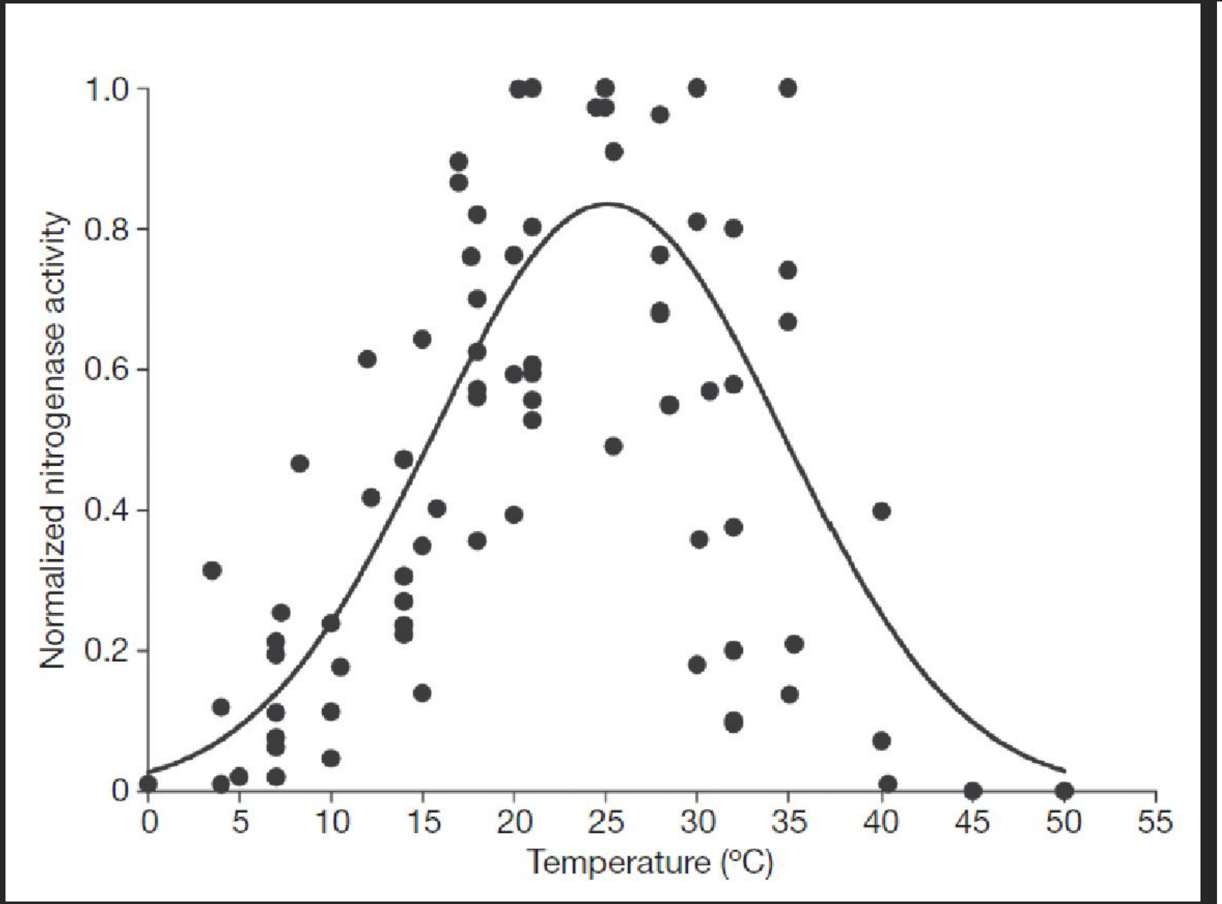
Projected decline in tropical BNF with climate warming??

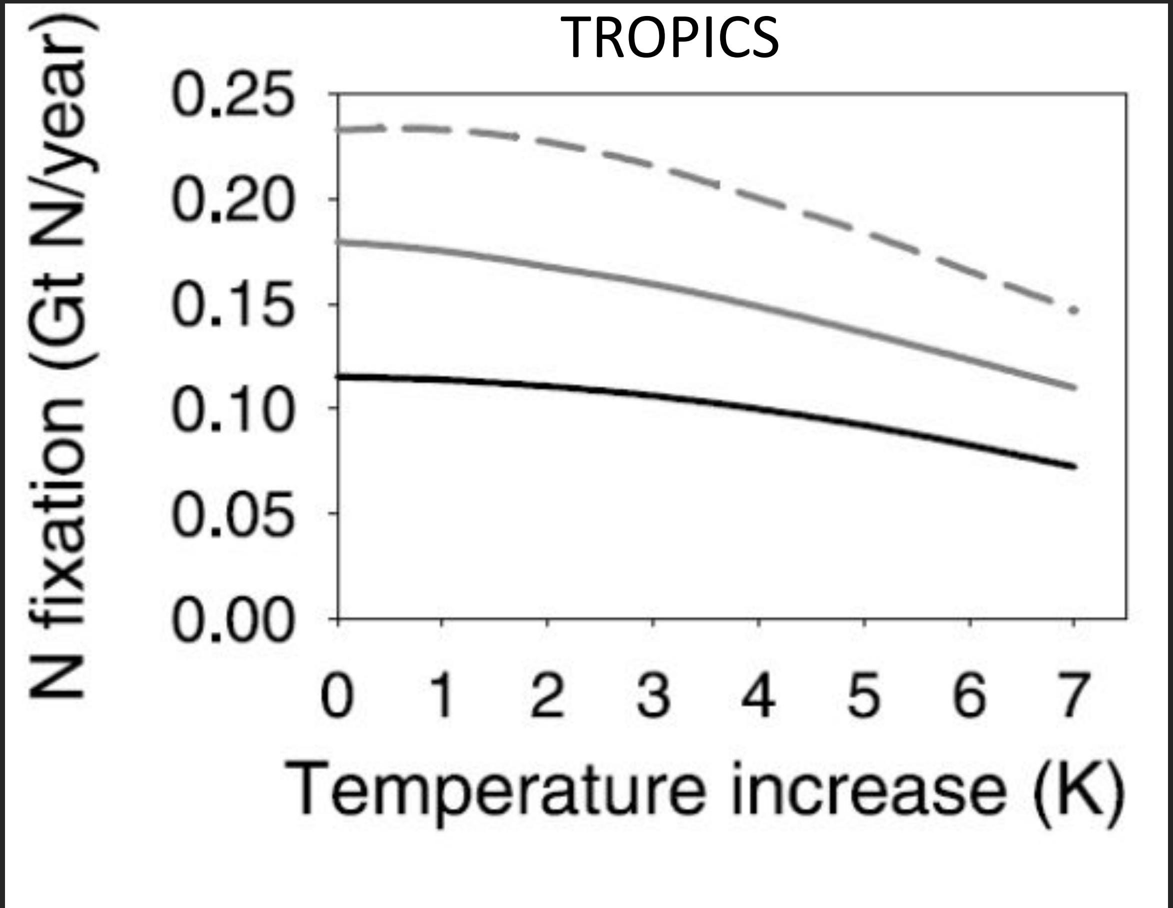




Houlton *et al.* 2008. *Nature*;
Wang & Houlton. 2009. *Geophysical Research Letters*

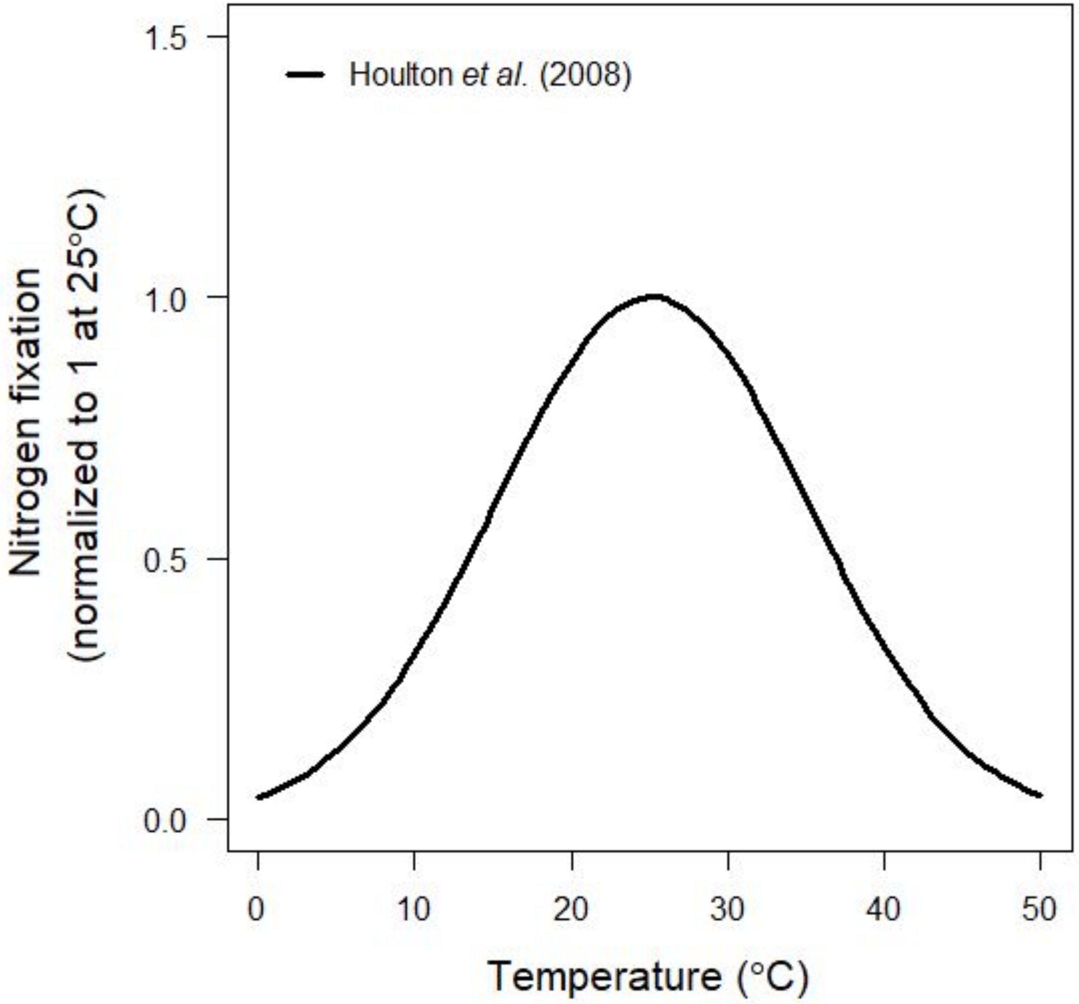
How sensitive is this result to temperature response of BNF?





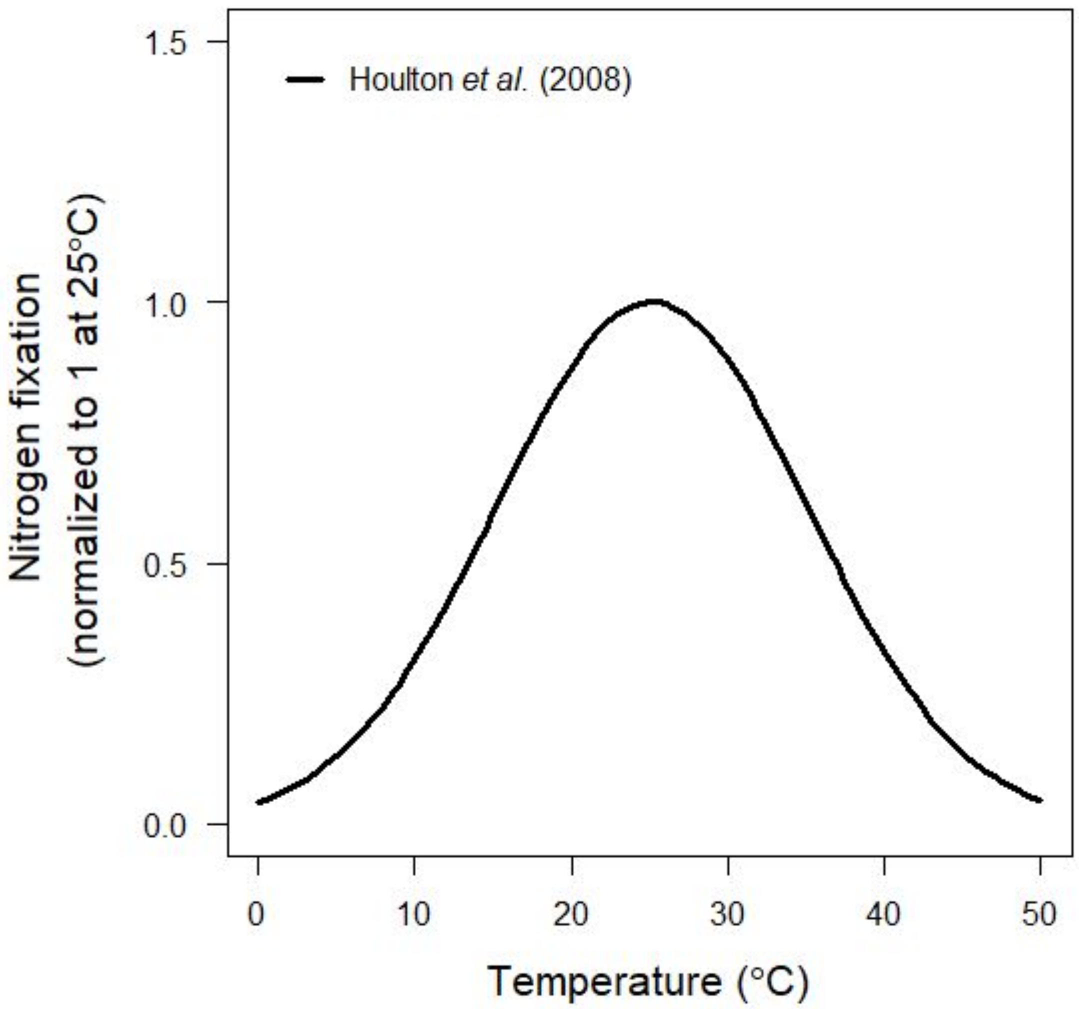
Houlton *et al.* 2008. *Nature*;
Wang & Houlton. 2009. *Geophysical Research Letters*

Global function; T_{opt} = 25.2 °C

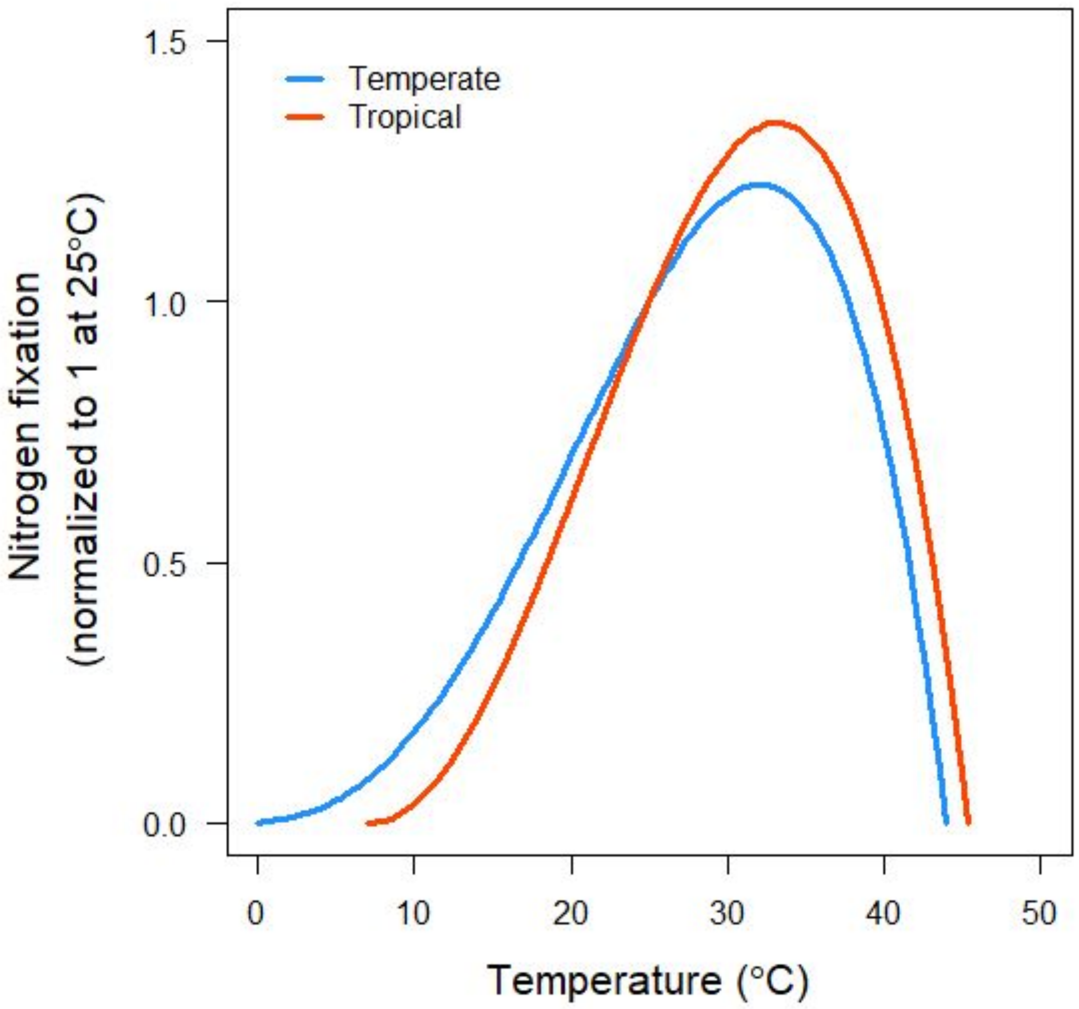


Houlton *et al.* 2008 *Nature*

Global function; T_{opt} = 25.2 °C

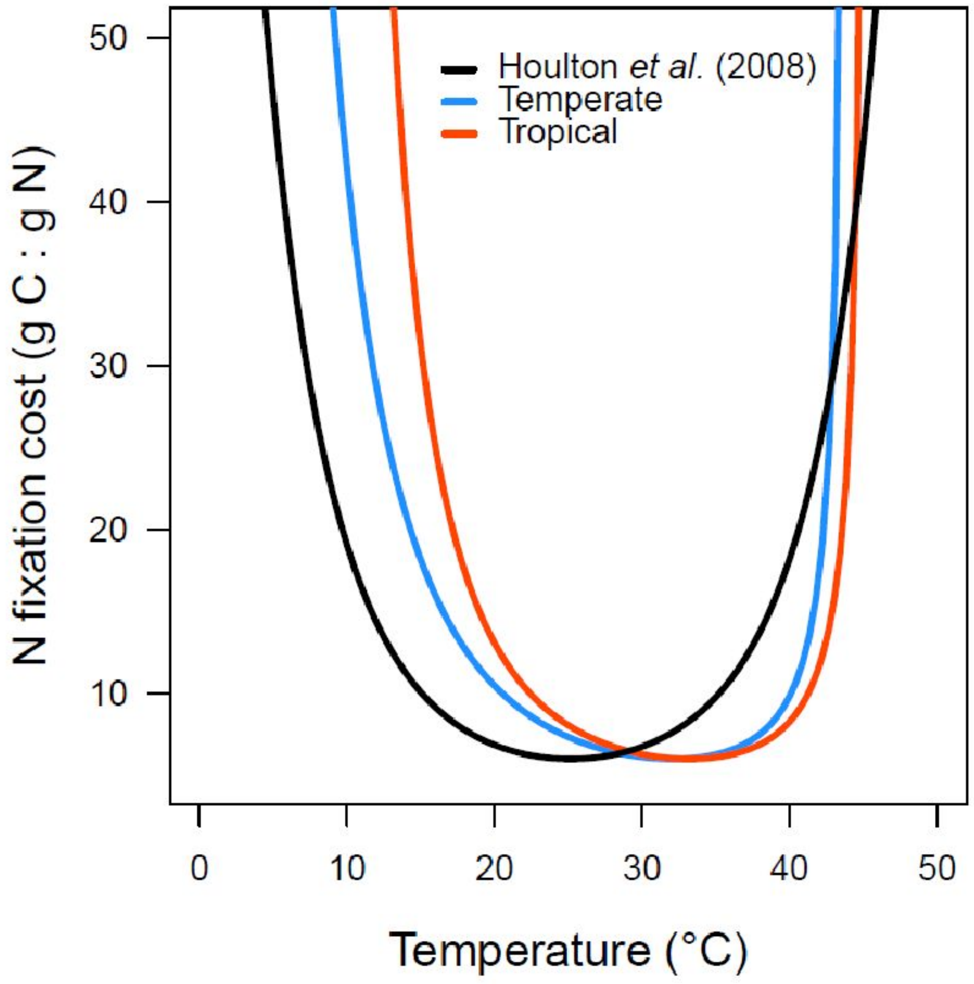


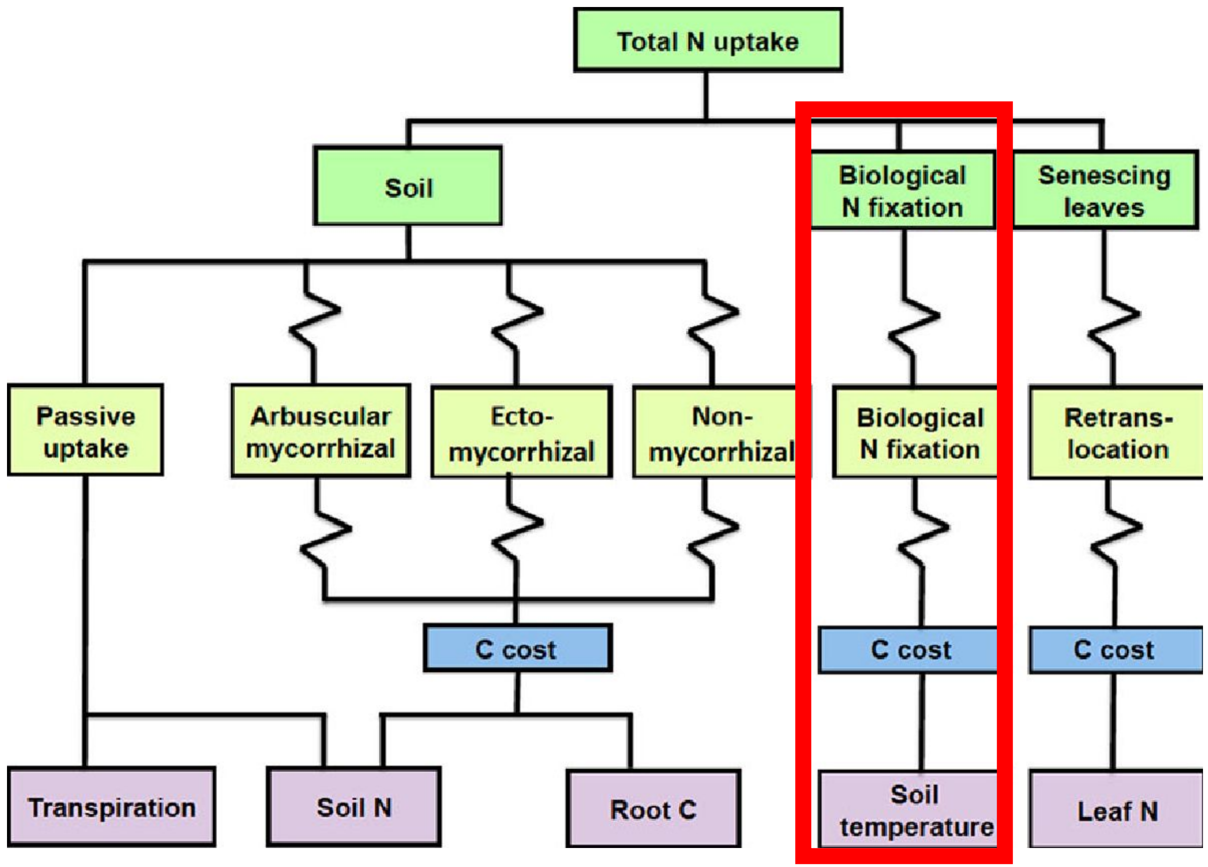
Separate temperate/tropical function; T_{opt} = 32.1 and 33.2 °C



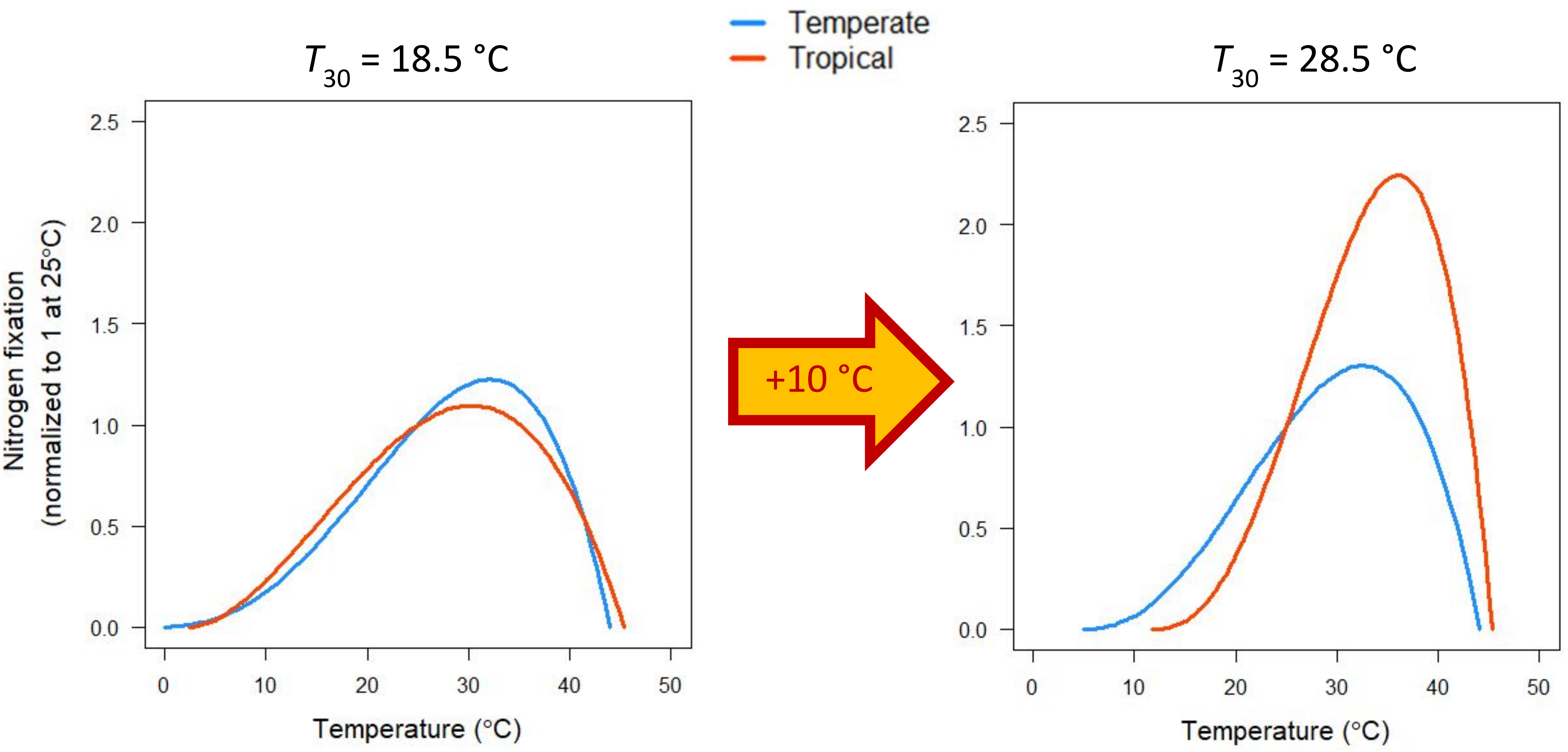
Houlton *et al.* 2008 *Nature*; Bytnerowicz *et al.* 2022 *Nature Plants*

Fixation and Uptake of Nitrogen (FUN) model





Fisher *et al*. 2010 *Global Biogeochemical Cycles*;
Shi *et al.* 2016 *Global Change Biology*


Temperate
Tropical
T_{30} = 18.5 °C
T_{30} = 28.5 °C
+10 °C
Nitrogen fixation
(normalized to 1 at 25°C)
Temperature (°C)
Temperature (°C)
0.0
0.5
1.0
1.5
2.0
2.5
0
10
20
30
40
50

- Three approaches for representing BNF temperature response
  - One global function (Houlton *et al*. 2008)
  - Separate temperate & tropical functions (no acclimation; Bytnerowicz *et al*. 2022)
  - Separate temperate & tropical functions (acclimation; Bytnerowicz *et al*. 2022)
  - Plus model default, if different, e.g., ORCHIDEE was *f*(NPP) scaled by plant N:P

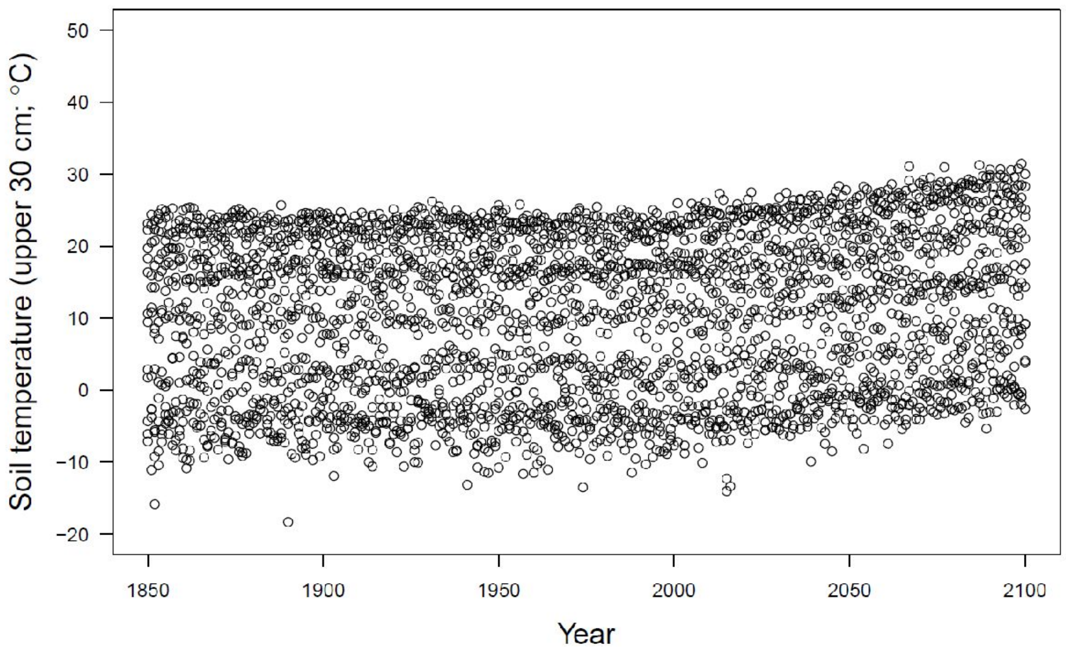
- Site-level simulations
    - Tropical: Manaus, Brazil (3.1190° S, 60.0217° W)
    - Temperate: Harvard Forest, USA (42.5315° N, 72.1900° W)
    - Boreal: Bonanza Creek, USA (64.8585° N, 147.8467° W)
- Next step will be global-level simulations

- Simulations
  - 1850 to 2014 historical simulation
  - Future warming from 2015 to 2100 (fixed CO_2 and N deposition)
  - Future warming from 2015 to 2100 (transient CO_2 and N deposition)
- ISIMIP3b GFLD-ESM4 forcing
  - Pre-industrial for spin-up (1601-1849)
  - Historical (1850-2014)
  - Future with SSP585 (2015-2100)

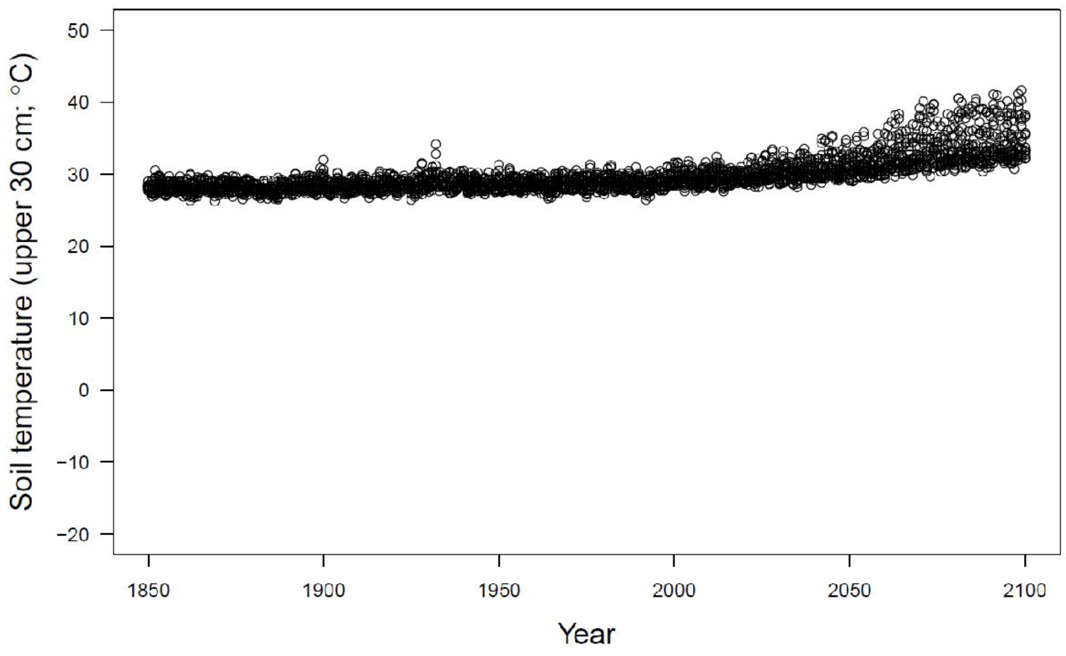
Soil Temperature (ORCHIDEE-CNP v1.3)

- 2015 to 2100: Warming with transient CO_2 and N deposition (SSP585)
- Monthly means

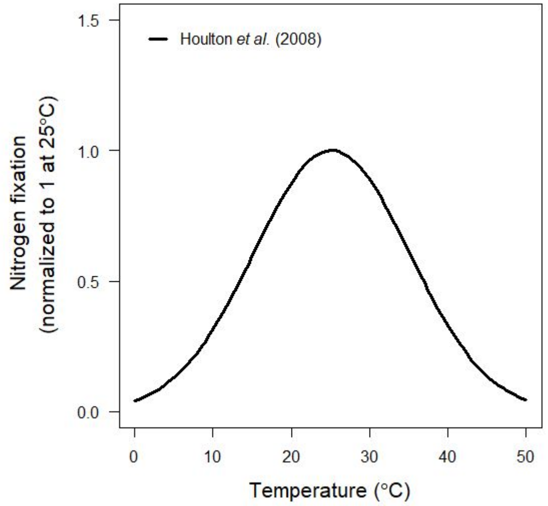
Harvard Forest



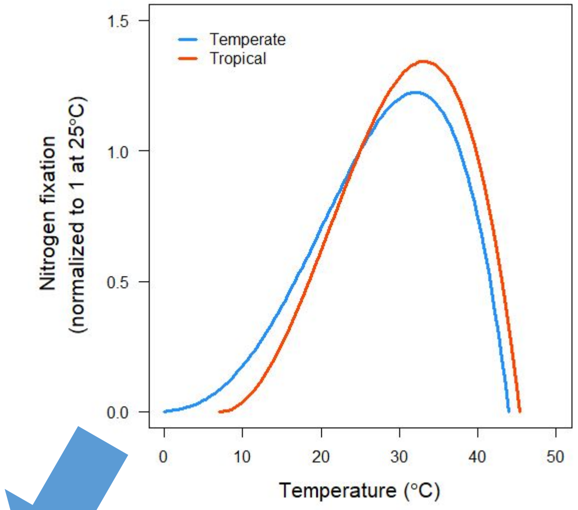
Manaus

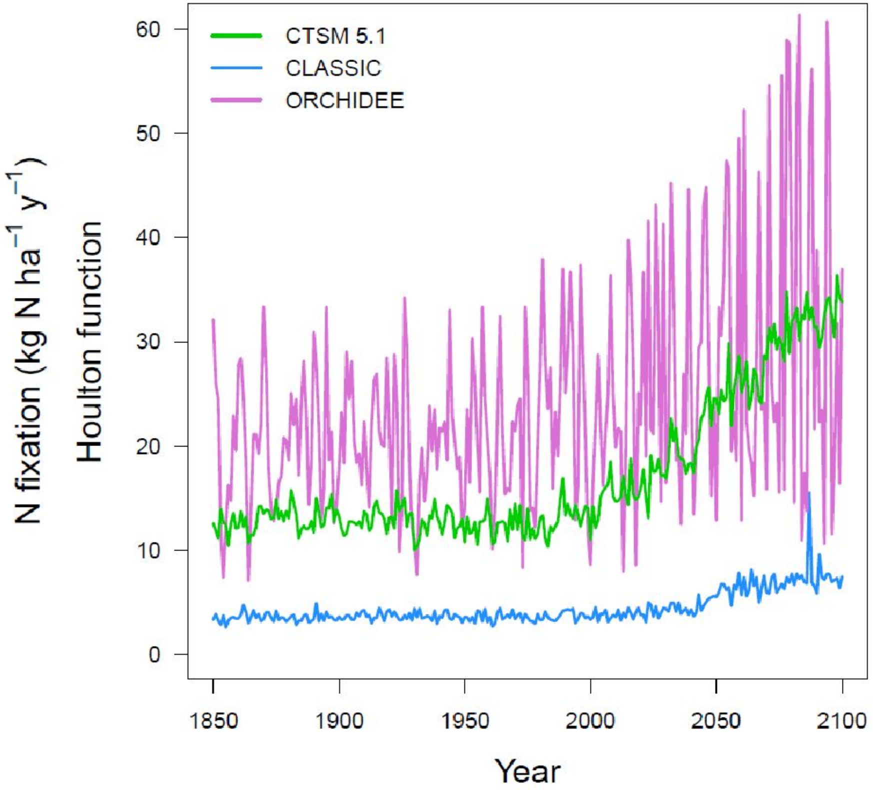


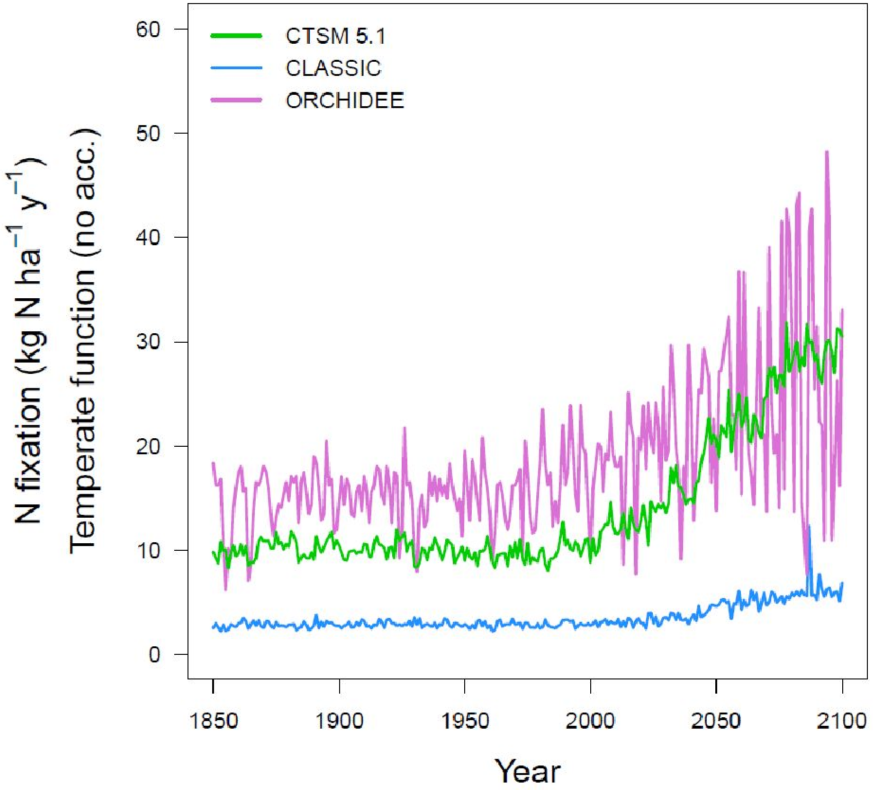
Harvard Forest



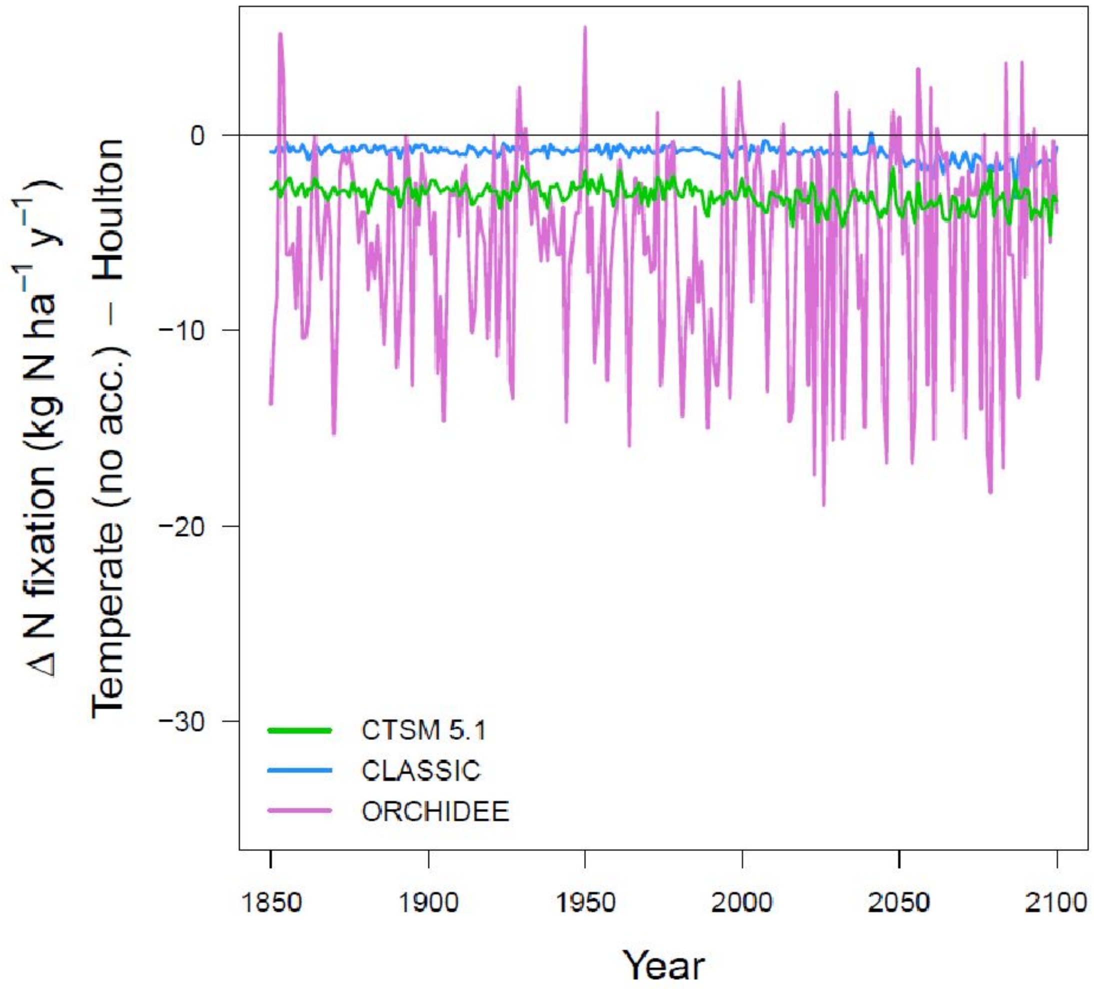
- Transient CO_2 and N deposition
- Total N fixation = (symbiotic + free-living)

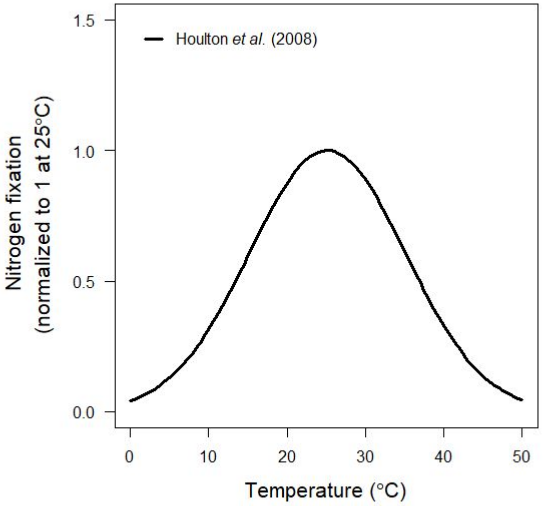






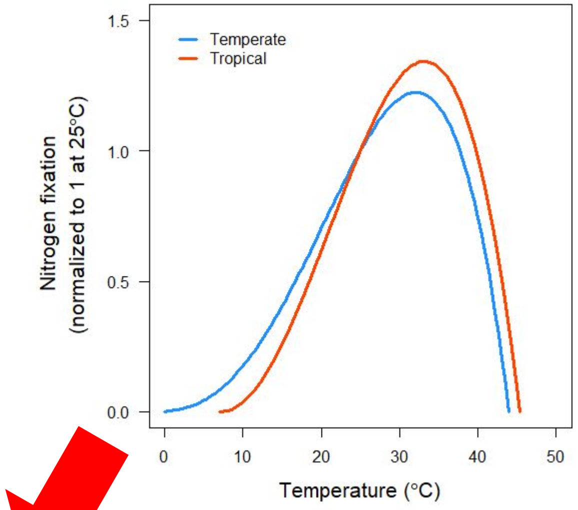
Harvard Forest

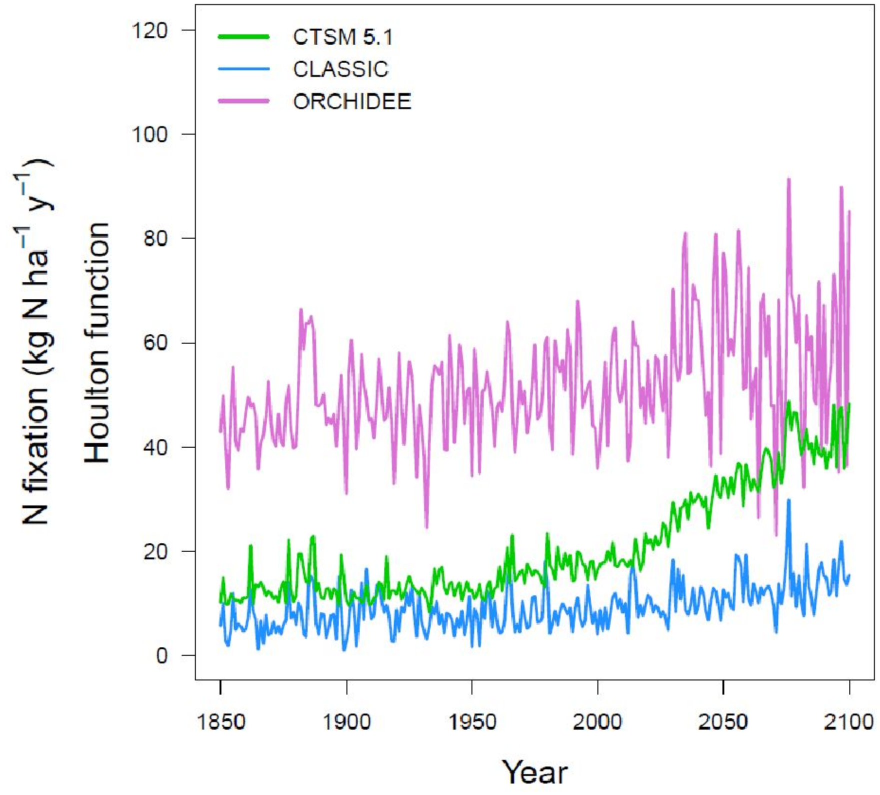


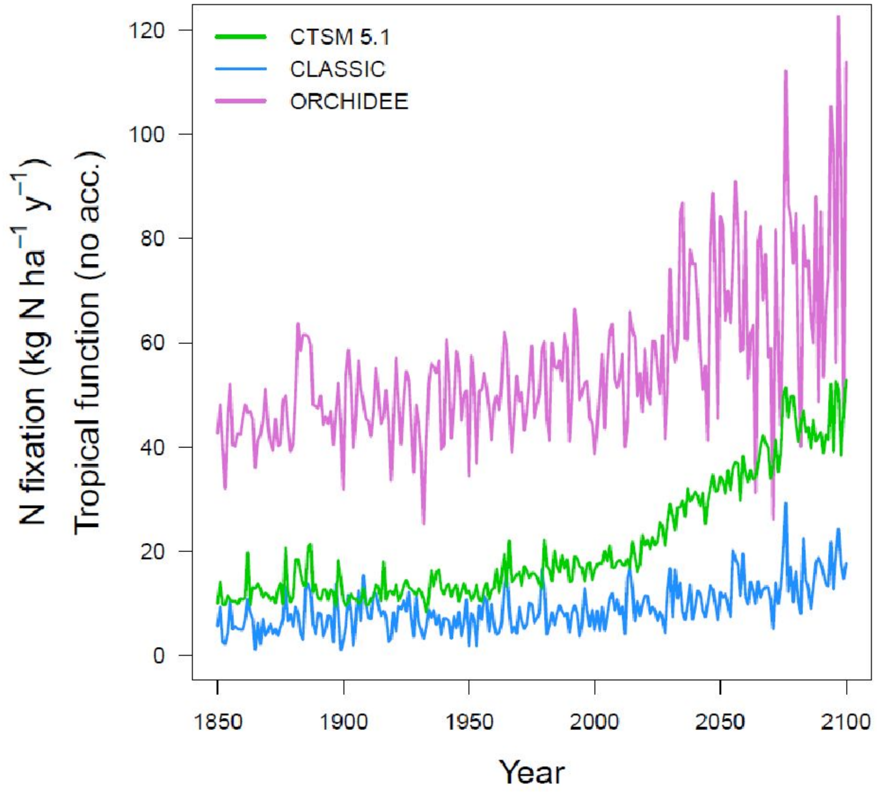


Manaus

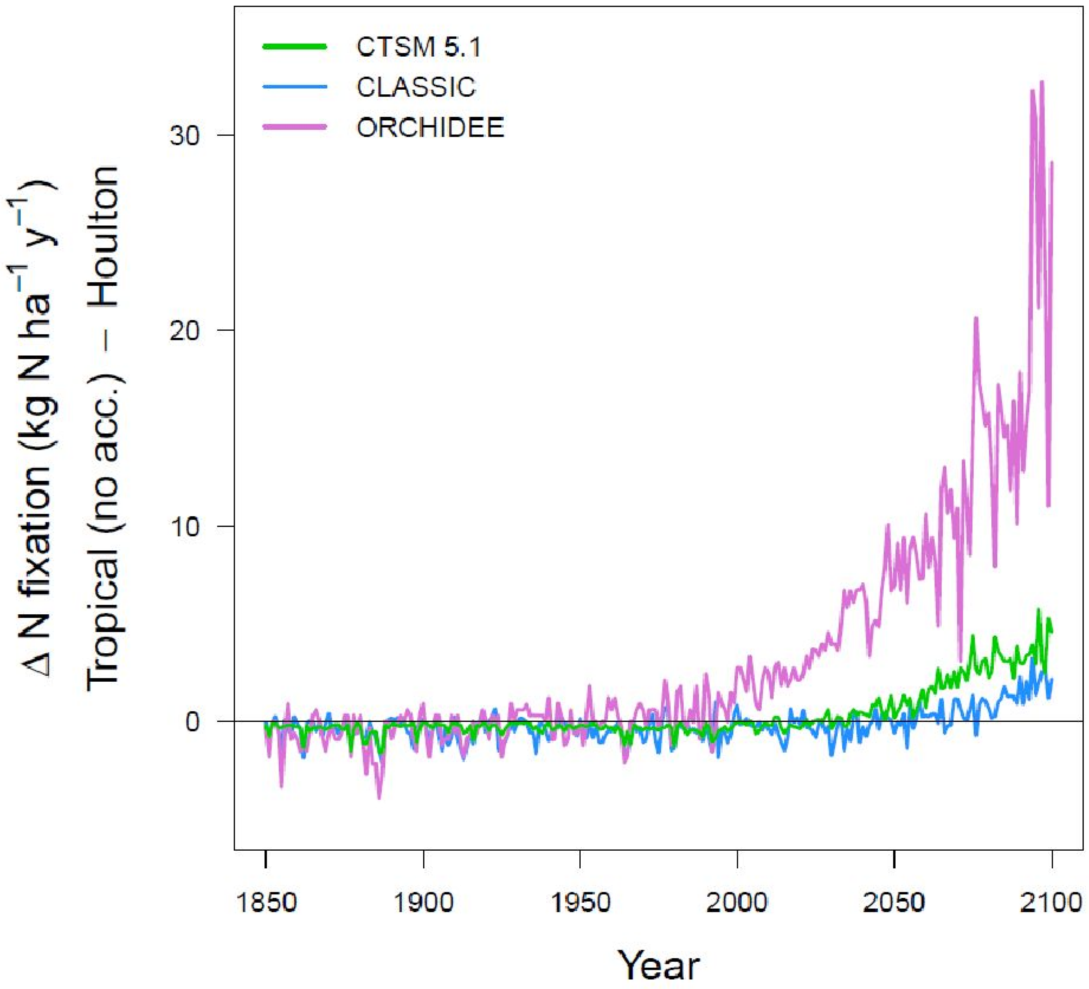
- Transient CO_2 and N deposition
- Total N fixation = (symbiotic + free-living)







Manaus



CTSM 5.1
CLASSIC
ORCHIDEE
30
20
10
0
1850
1900
1950
2000
2050
2100
Year
Δ N fixation (kg N ha⁻¹ y⁻¹)
Tropical (no acc.) – Houlton

Ongoing experimental work

- N fixation temperature response for more species
  - Woody, crop, herbaceous
  - Arctic to tropical
- Temperature response of BNF carbon costs
- Timescale on acclimation response
  - How quick? (1 week, 1 month, 1 year?)
- Bounds on acclimation response
  - Does it saturate?

@bytnerowicz

Modeling Collaborators:
Will Wieder
Sian Kou-Giesbrecht
Sönke Zaehle
Elena Shevliakova
Daniel Goll
Cheng Gong
Xiaojuan Yang

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY
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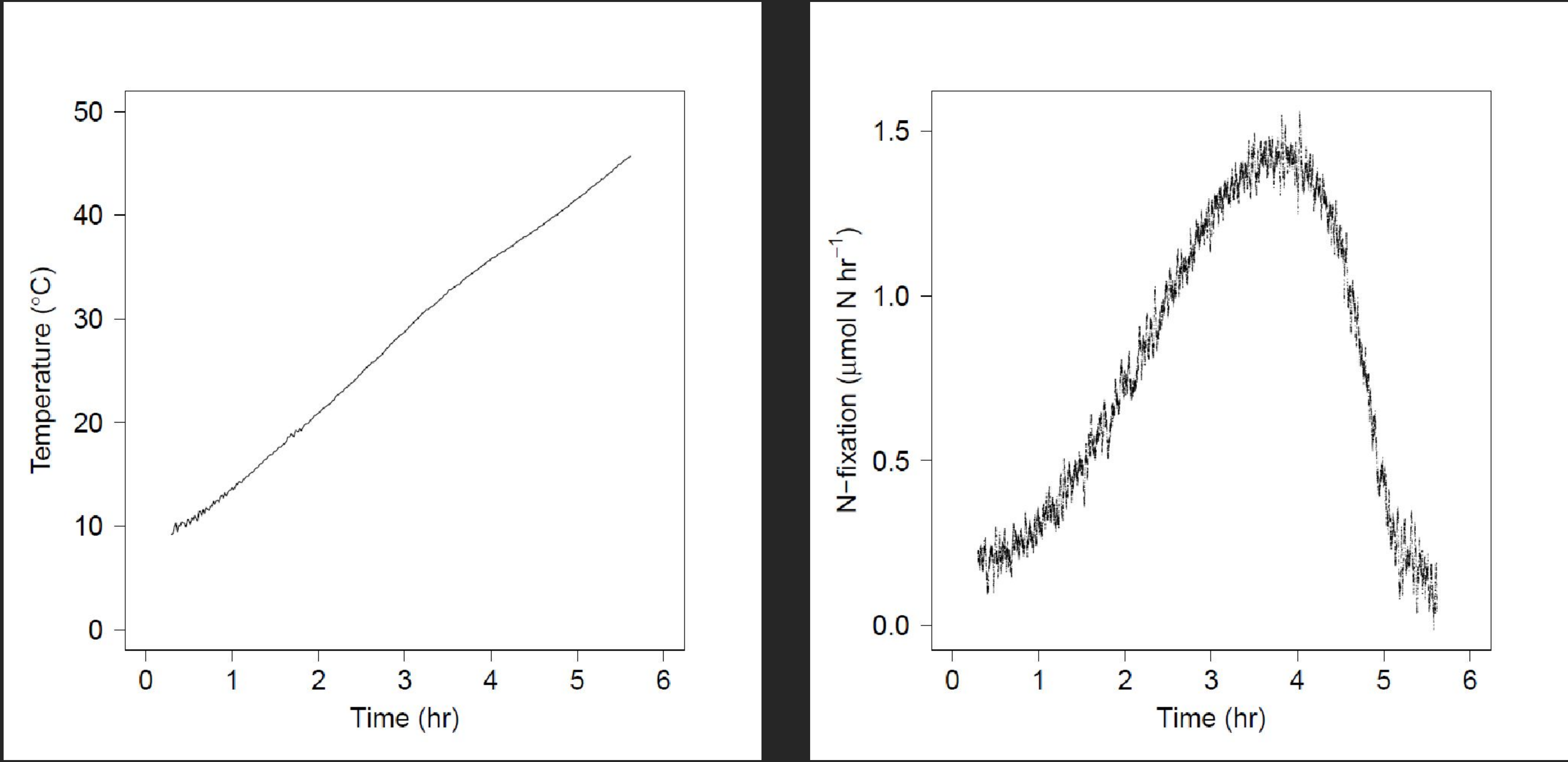
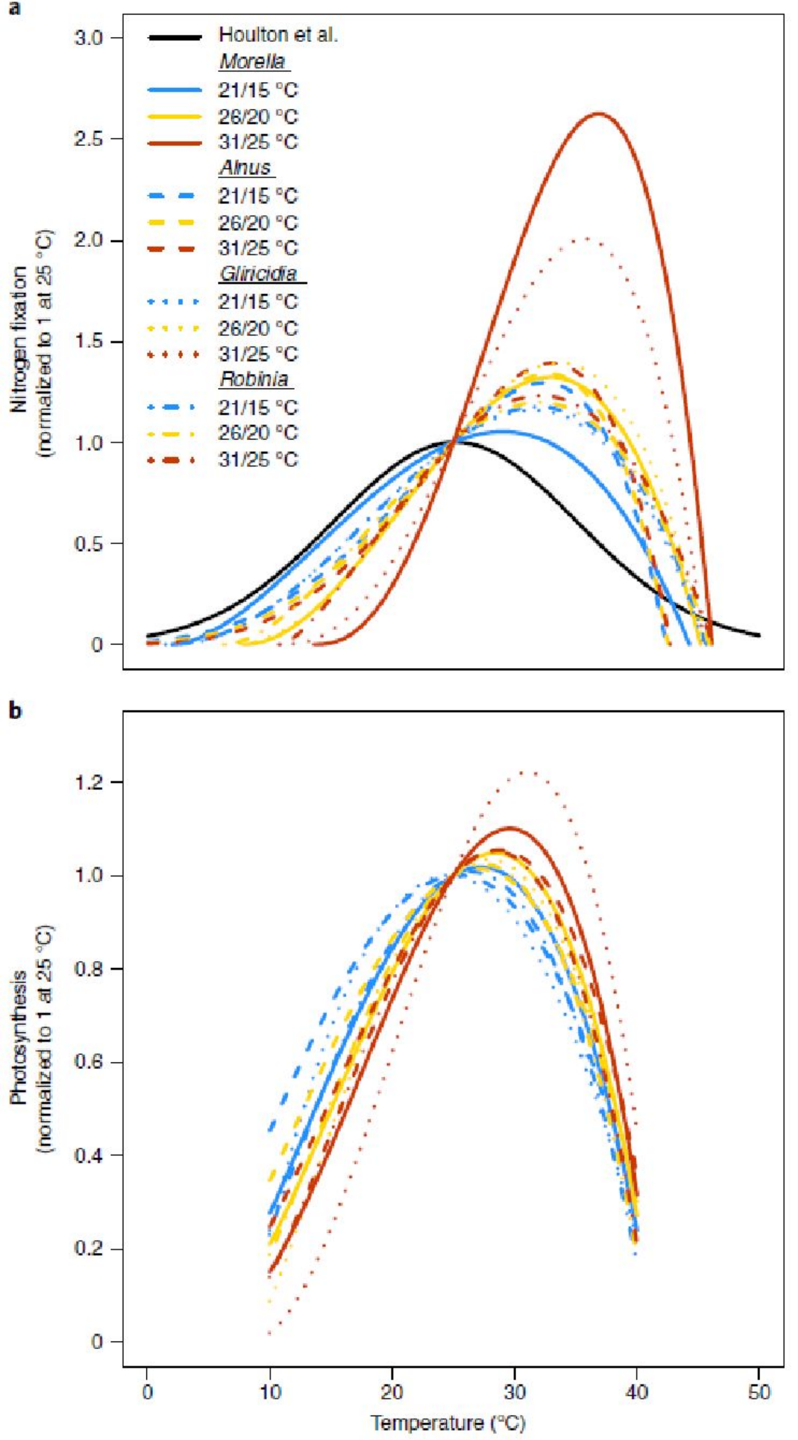
COLUMBIA UNIVERSITY E3B Ecology, Evolution, & Environmental Biology
TEXAS The University of Texas at Austin

Empirical Collaborators:

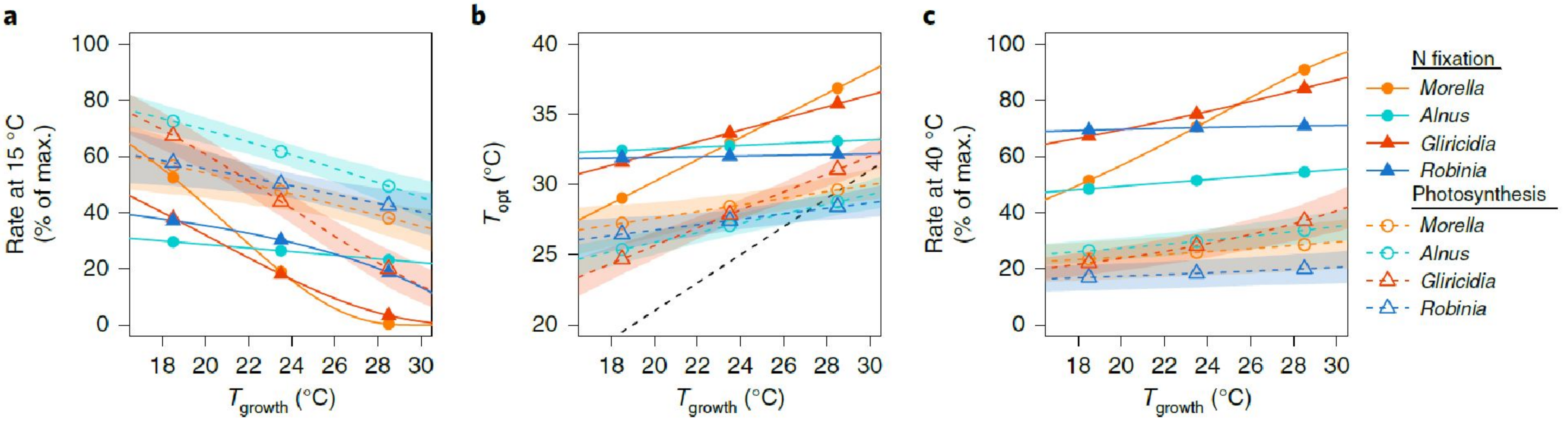


Temperature (°C)
50
40
30
20
10
0
0 1 2 3 4 5 6
Time (hr)
N−fixation (μmol N hr^{-1})
1.5
1.0
0.5
0.0
0 1 2 3 4 5 6
Time (hr)

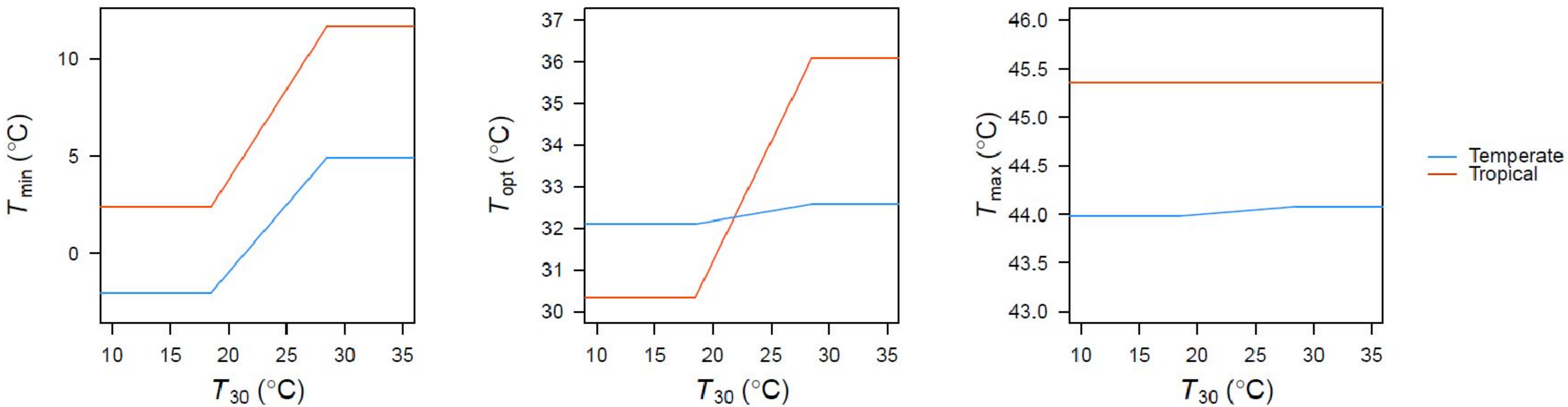


5.2 °C (range of 1.8-7.3 °C) higher than for net photosynthesis

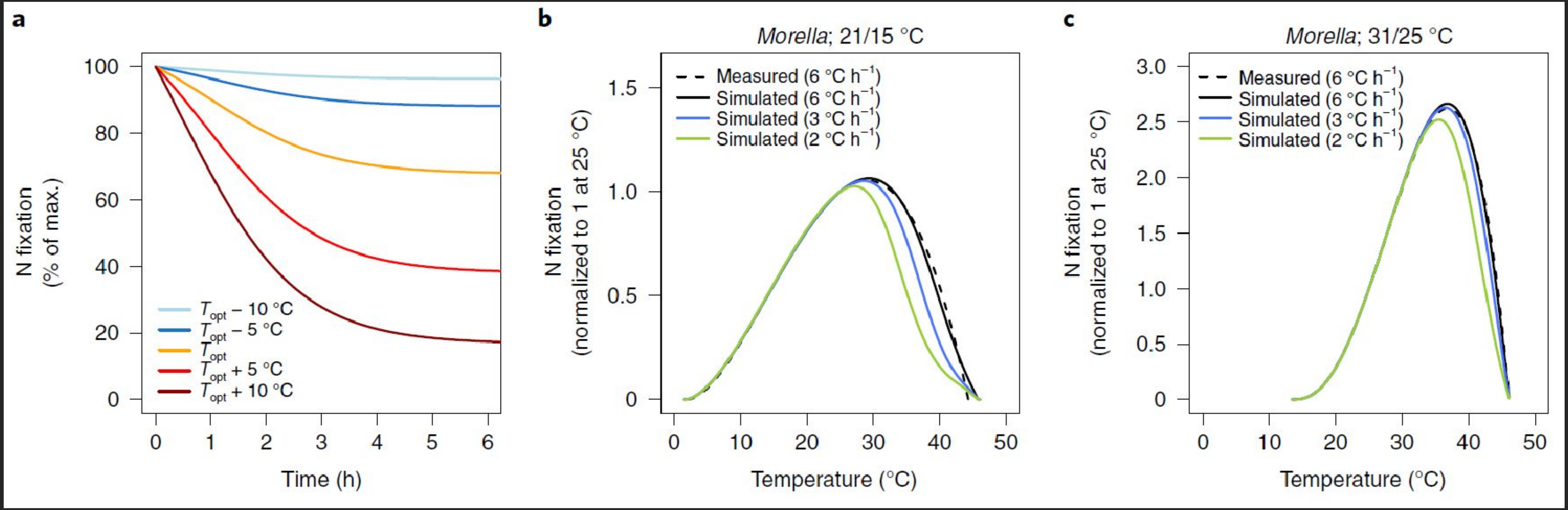
- N limitation more likely at low temperatures
- CO_2 limitation more likely at warm temperatures


a
b
c
Rate at 15 °C
(% of max.)
T_{opt} (°C)
Rate at 40 °C
(% of max.)
T_{growth} (°C)
N fixation
Morella
Alnus
Gliricidia
Robinia
Photosynthesis
Morella
Alnus
Gliricidia
Robinia

$$y = \max\left(0, y_{\max}\left(\frac{T_{\max} - T_s}{T_{\max} - T_{\text{opt}}}\right)\left(\frac{T_s - T_{\min}}{T_{\text{opt}} - T_{\min}}\right)^{\frac{T_{\text{opt}} - T_{\min}}{T_{\max} - T_{\text{opt}}}}\right)$$

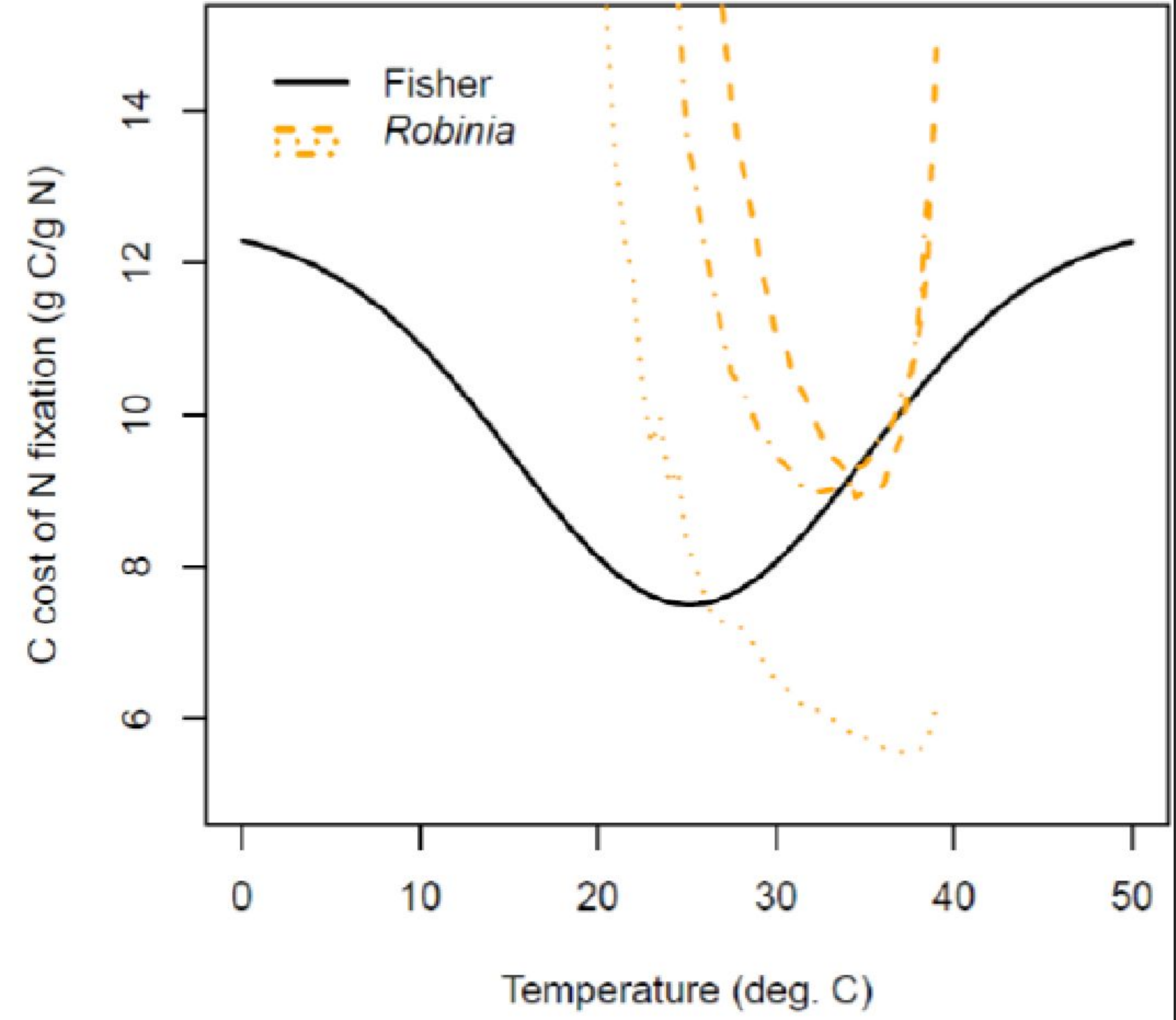


Effect of long exposure to high temperatures on N fixation



Bytnerowicz *et al.* 2022 *Nature Plants*

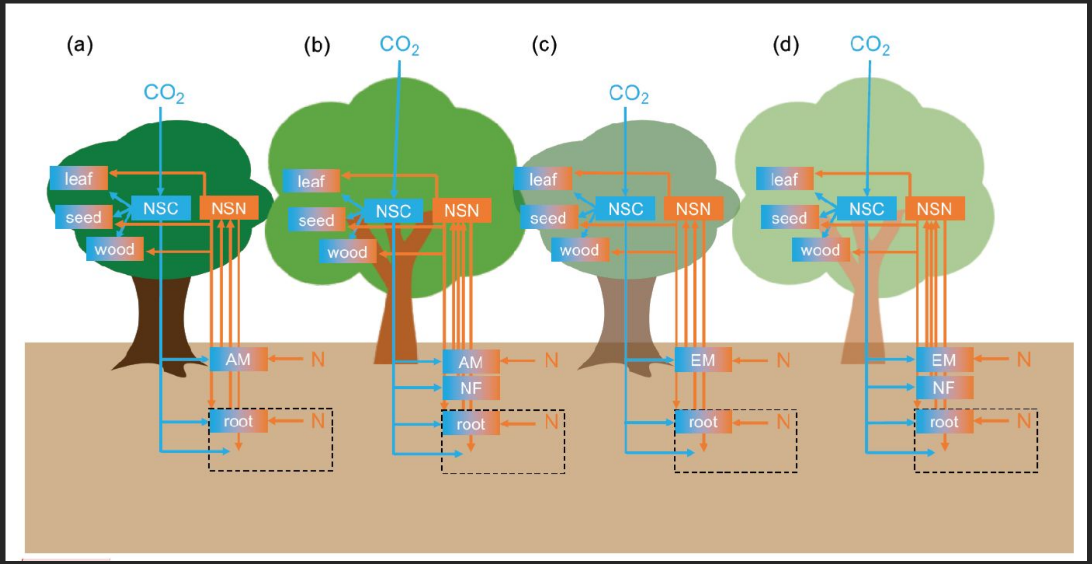
Direct measurement of N fixation cost temperature response

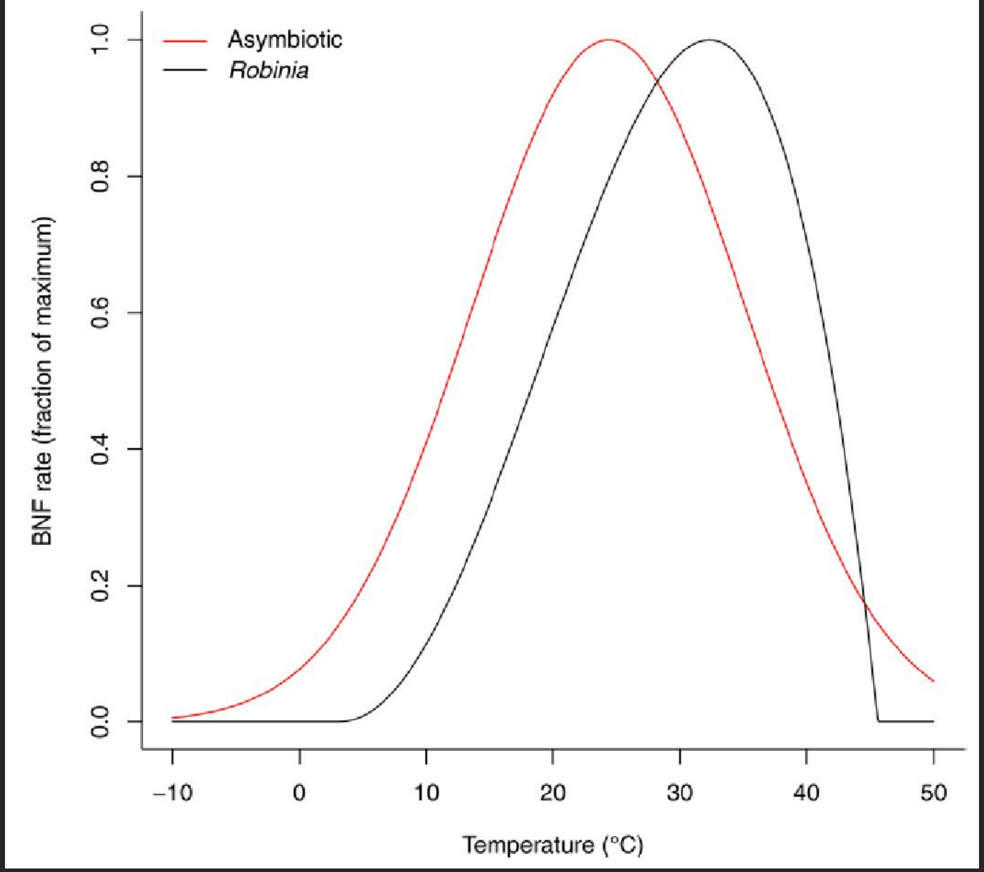


Preliminary data:

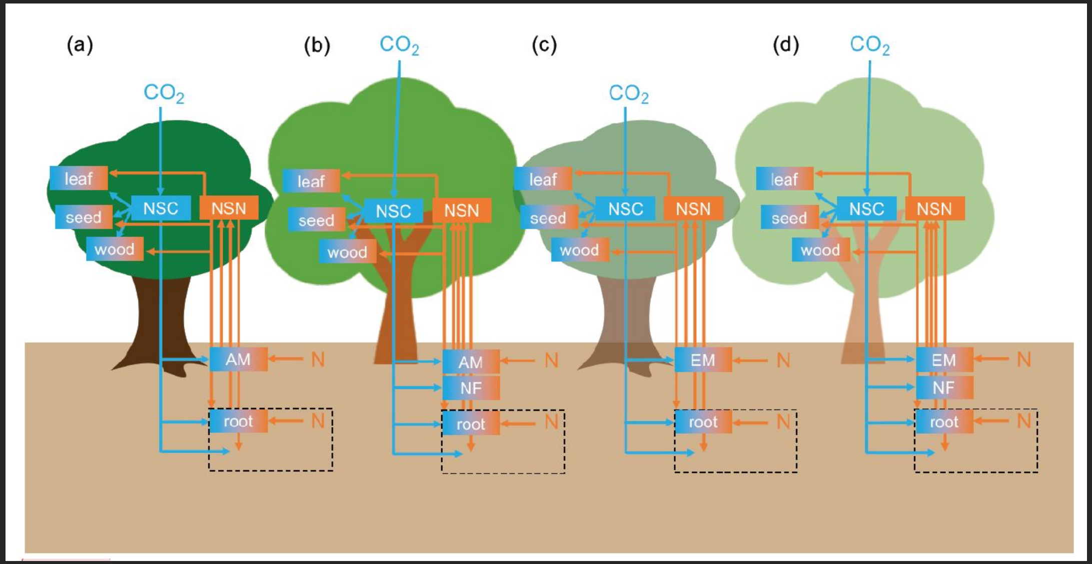
- Costs peak > 150 g C g N^{-1}
- T_{opt} very similar for N fixation rates and costs

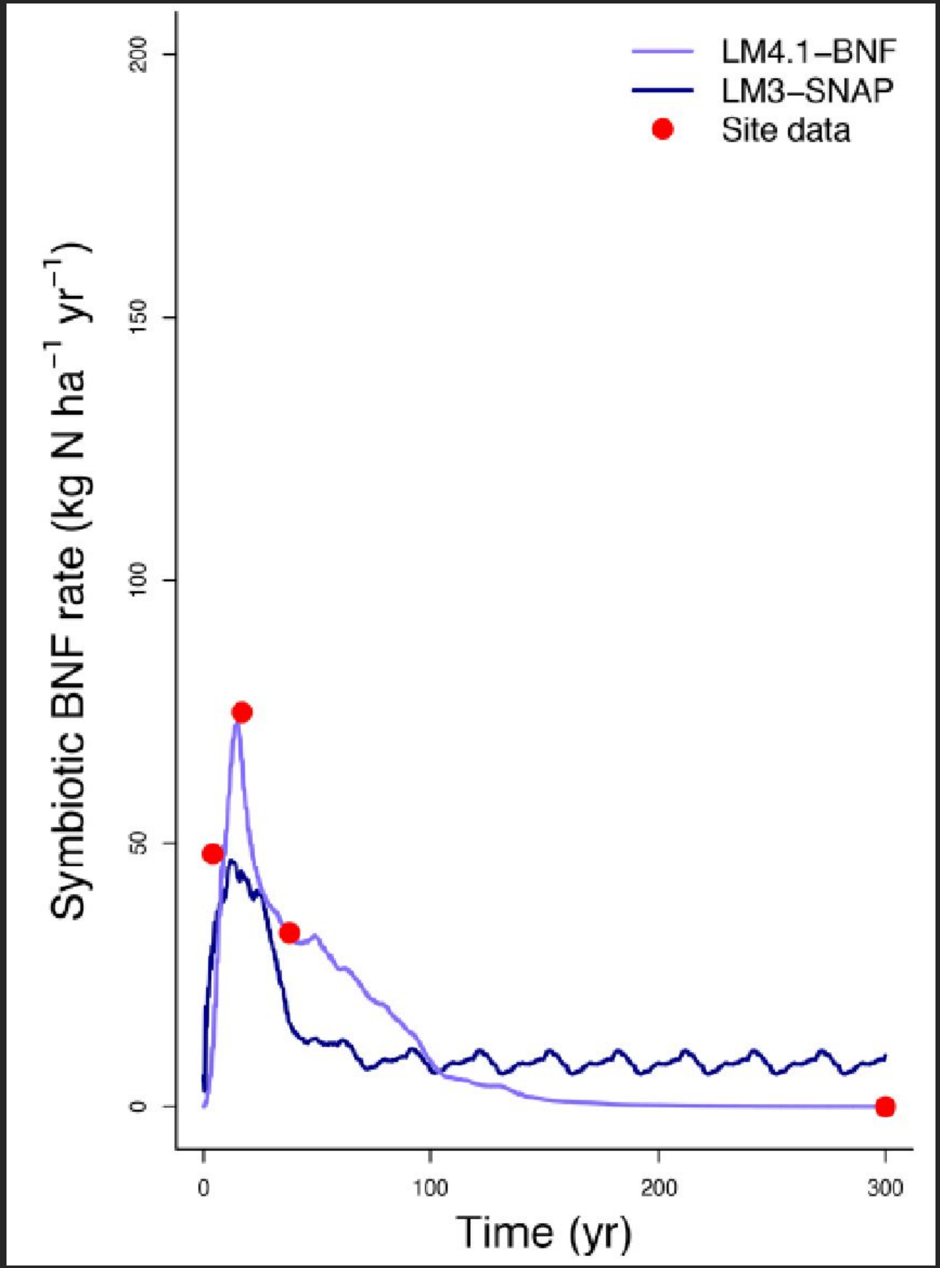
GFDL LM4.1-BNF





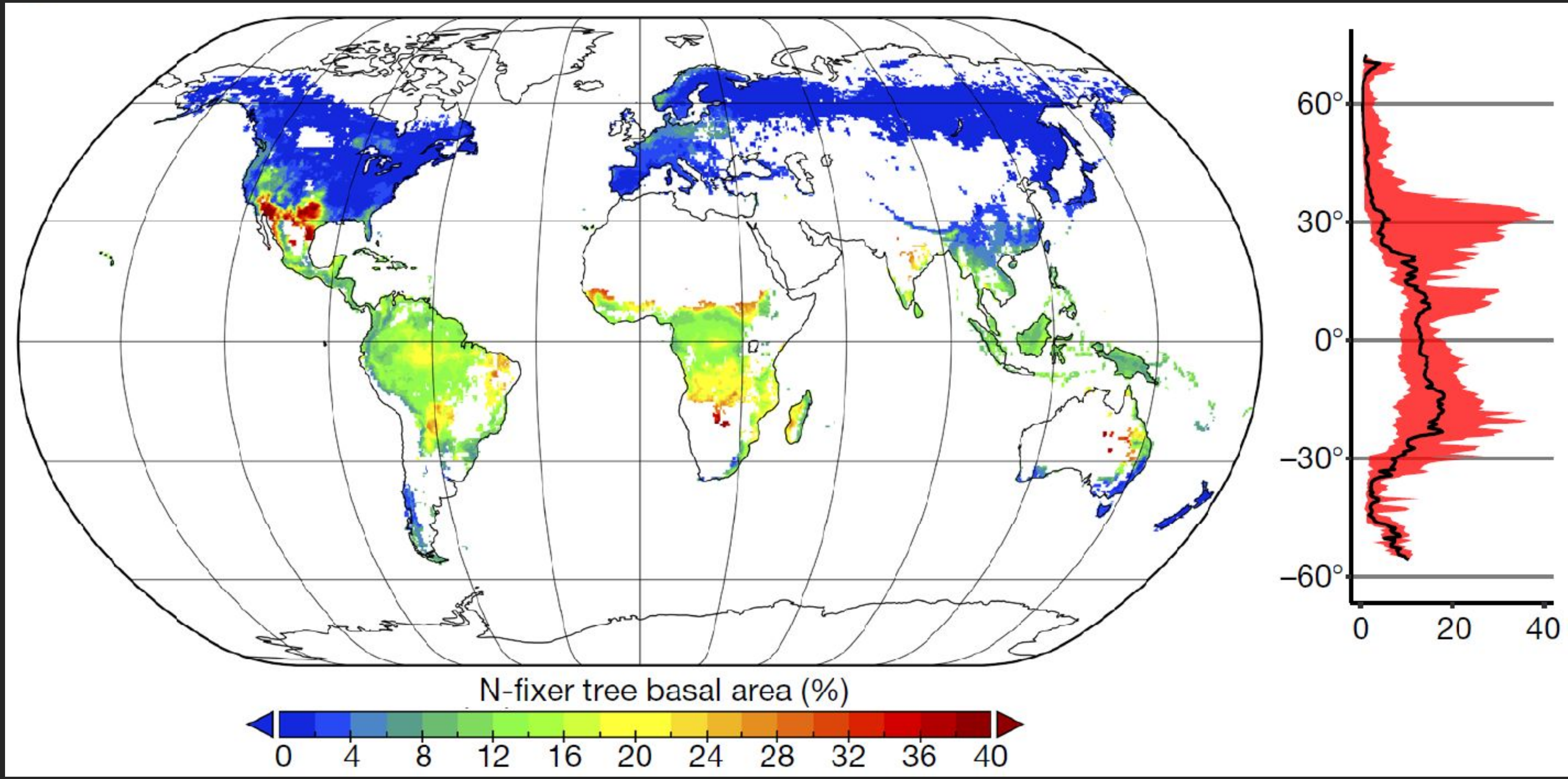
Kou-Giesbrecht *et al.* 2021 *Biogeosciences*





Kou-Giesbrecht *et al.* 2021 *Biogeosciences*

Global N-fixing tree abundance



Steidinger *et al.* 2019 *Nature*

#	Variable Description	Type
1	Mean Annual Temp. (°C)	Bioclimatic
2	Mean Diurnal Temp. Range (°C)	Bioclimatic
3	Isothermality (#2/#7 * 100)	Bioclimatic
4	Temp. Seasonality (St. Dev of Monthly Temp.)	Bioclimatic
5	Max Temp. Hottest Month (°C)	Bioclimatic
6	Min Temp. Coldest Month (°C)	Bioclimatic
7	Temperature Range (#5-#6)	Bioclimatic
8	Mean Temp. Wettest Quarter (°C)	Bioclimatic
9	Mean Temp. Driest Quarter (°C)	Bioclimatic
10	Mean Temp. Warmest Quarter (°C)	Bioclimatic
11	Mean Temp. Coldest Quarter (°C)	Bioclimatic
12	Mean Annual Precipitation (mm)	Bioclimatic
13	Precipitation Wettest Month (mm)	Bioclimatic
14	Precipitation Driest Month (mm)	Bioclimatic
15	Precipitation Seasonality (Coefficient of variation of monthly precipitation)	Bioclimatic
16	Precipitation Wettest Month (mm)	Bioclimatic
17	Precipitation Driest Quarter (mm)	Bioclimatic
18	Precipitation Warmest Quarter (mm)	Bioclimatic
19	Precipitation Coldest Quarter (mm)	Bioclimatic
20	Soil Bulk Density (kg / m^3)	Soil Physical
21	Cation Exchange Capacity ($cmol_c$/kg)	Soil Chemical
22	% Clay (0-2 µm mass fraction)	Soil Physical
23	% Coarse Fragments (volumetric)	Soil Physical
24	Soil Organic C concentration (g kg-1)	Soil Chemical
25	Soil Organic C content (tonnes per ha)	Soil Chemical
26	pH in H2O	Soil Chemical
27	pH in KCl	Soil Chemical
28	% Silt (2-50 µm mass fraction)	Soil Physical
29	% Sand (50-2000 µm mass fraction)	Soil Physical
30	Coefficient of variation of Enhanced Vegetation Index (EVI)	Process
31	Evenness EVI	Process
32	Range EVI	Process
33	Shannon Diversity EVI	Process
34	Simpson Diversity EVI	Process
35	St. Dev. EVI	Process
36	Contrast EVI (exponentially weighted difference between adjacent pixels)	Process
37	Correlation EVI (linear dependency of EVI on adjacent pixels)	Process
38	Dissimilarity EVI (difference in EVI between adjacent pixels)	Process
39	Entropy of EVI	Process
40	Homogeneity EVI (Similarity of EVI between adjacent pixels)	Process
41	Maximum EVI (dominance of EVI between adjacent pixels)	Process
42	Uniformity of EVI	Process
43	Variance of EVI	Process
44	Normalized Difference in Vegetation Index (NDVI)	Vegetative
45	EVI	Vegetative
46	Leaf Area Index	Vegetative
47	Fraction of incident photosynthetically active radition (400-700nm) absorbed by vegetation canopy (Fpar)	Vegetative
48 - 54	Bidirectional Reflectance Distribution Function (BRDF) (7 bands of reflectance)	Vegetative
55	Woody stem density (# of tree stems)	Vegetative
56	Elevation (m)	Topographic
57	Slope (degrees)	Topographic
58	Hillshade (grayscale value)	Topographic
59	Northness (-1 to 1)	Topographic
60	Eastness (-1 to 1)	Topographic
61	Total Phosphorus (P) (g /m^2)	Soil Nutrient
62	Labile P (g /m^2)	Soil Nutrient
63	Organic P (g /m^2)	Soil Nutrient
64	Occluded P (g /m^2)	Soil Nutrient
65	Secondary Mineral P (g /m^2)	Soil Nutrient
66	Apatite P (g /m^2)	Soil Nutrient
67	Soil Carbon : Nitrogen (C:N) ratio	Soil Nutrient
68	Microbial N pool (g N/m^2)	Soil Nutrient
69	Microbial C pool (g C/m^2)	Soil Nutrient
70	Total N density (g /m^2)	Soil Nutrient
71	Mean Annual Decomposition Coefficient (a^{-1}), f(#1, #12)	Decomposition
72	Decomposition Coefficient of Warmest Quarter (a^{-1}), f(#10, #18)	Decomposition
73	Decomposition Coefficient of Wettest Quarter (a^{-1}), f(#8, #16)	Decomposition
74	Decomposition Coefficient of the Coldest Quarter (a^{-1}), f(#11, #19)	Decomposition
75	Decomposition Coefficient of Driest Quarter (a^{-1}), f(#9, #17)	Decomposition