Nitrogen Acquisition Costs to Plants Reduce Net Primary Production at the Global Scale

Mingjie Shi, Joshua Fisher,
Edward Brzostek, Richard Phillips

CESM Biogeochemistry Working Group
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Motivation

The role of nutrient availability in regulating net ecosystem production and ecosystem C use efficiency

Accurate predictions of the land C sink and nutrient constraints captured by CLM

Improving terrestrial C sinks to associated with nutrient limitation to climate models and Earth system models

Plant NPP allocation for N acquisition: up to 20% of NPP to both symbiotic and free-living microbes at the root surface to increase their access to N

BUT, CLM assumes that N is acquired at no C cost to plants!

Scientific Questions

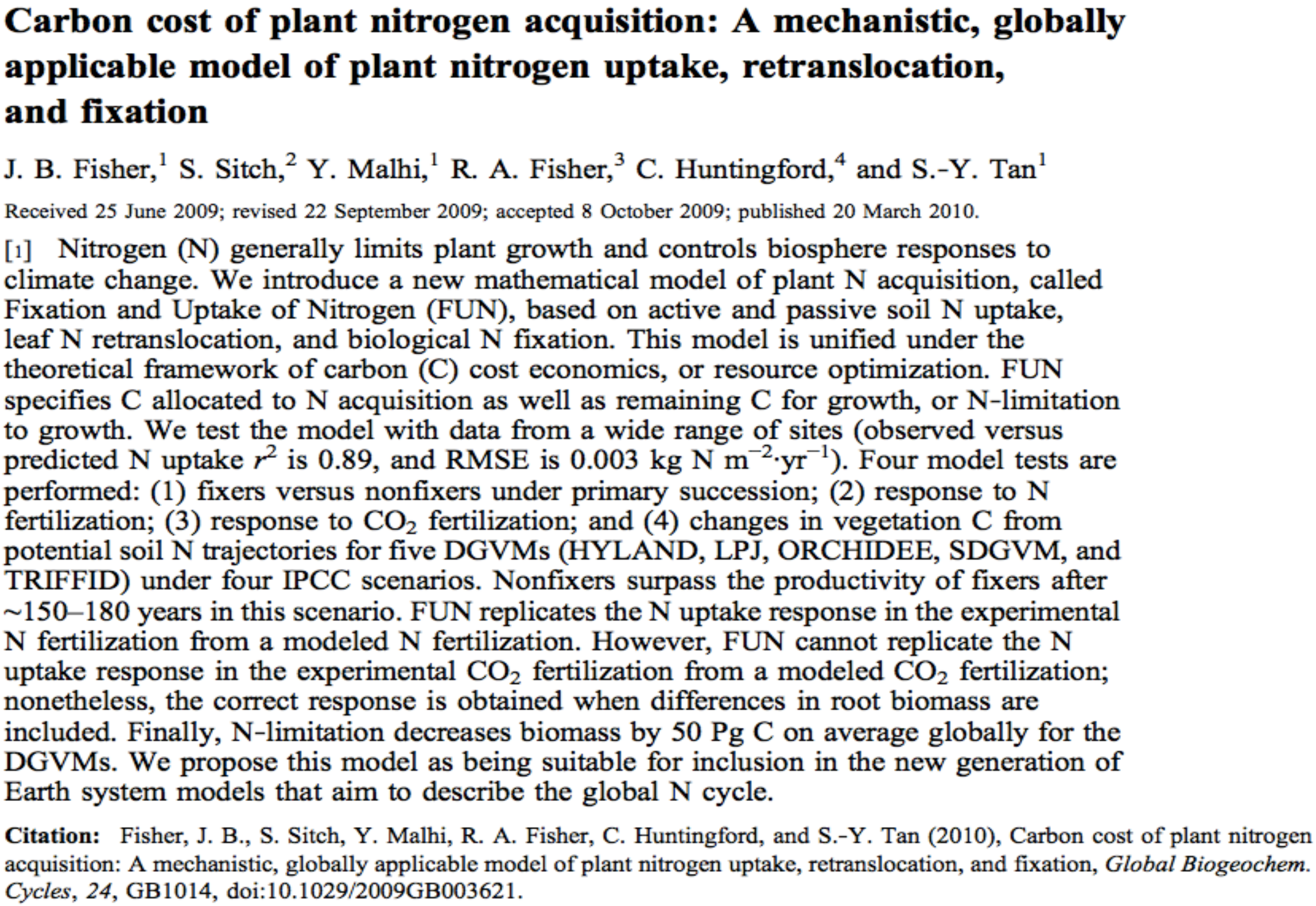
How much N is taken up and what is the global distribution?

How does the C cost of N acquisition vary spatially and temporally?

How sensitive is the land C sink to a dynamic prediction of the C cost of N acquisition?

Methods

The Fixation and Uptake of Nitrogen (FUN) model (Fisher et al., 2010; Brzostek et al., 2014) explicitly includes the C cost for N acquisition.



Carbon cost of plant nitrogen acquisition: A mechanistic, globally applicable model of plant nitrogen uptake, retranslocation, and fixation

J. B. Fisher,[1] S. Sitch,[2] Y. Malhi,[1] R. A. Fisher,[3] C. Huntingford,[4] and S.-Y. Tan[1]

Received 25 June 2009; revised 22 September 2009; accepted 8 October 2009; published 20 March 2010.

[1] Nitrogen (N) generally limits plant growth and controls biosphere responses to climate change. We introduce a new mathematical model of plant N acquisition, called Fixation and Uptake of Nitrogen (FUN), based on active and passive soil N uptake, leaf N retranslocation, and biological N fixation. This model is unified under the theoretical framework of carbon (C) cost economics, or resource optimization. FUN specifies C allocated to N acquisition as well as remaining C for growth, or N-limitation to growth. We test the model with data from a wide range of sites (observed versus predicted N uptake r^2 is 0.89, and RMSE is 0.003 kg N $m^{-2} \cdot yr^{-1}$). Four model tests are performed: (1) fixers versus nonfixers under primary succession; (2) response to N fertilization; (3) response to CO_2 fertilization; and (4) changes in vegetation C from potential soil N trajectories for five DGVMs (HYLAND, LPJ, ORCHIDEE, SDGVM, and TRIFFID) under four IPCC scenarios. Nonfixers surpass the productivity of fixers after ~150–180 years in this scenario. FUN replicates the N uptake response in the experimental N fertilization from a modeled N fertilization. However, FUN cannot replicate the N uptake response in the experimental CO_2 fertilization from a modeled CO_2 fertilization; nonetheless, the correct response is obtained when differences in root biomass are included. Finally, N-limitation decreases biomass by 50 Pg C on average globally for the DGVMs. We propose this model as being suitable for inclusion in the new generation of Earth system models that aim to describe the global N cycle.

Citation: Fisher, J. B., S. Sitch, Y. Malhi, R. A. Fisher, C. Huntingford, and S.-Y. Tan (2010), Carbon cost of plant nitrogen acquisition: A mechanistic, globally applicable model of plant nitrogen uptake, retranslocation, and fixation, *Global Biogeochem. Cycles*, *24*, GB1014, doi:10.1029/2009GB003621.

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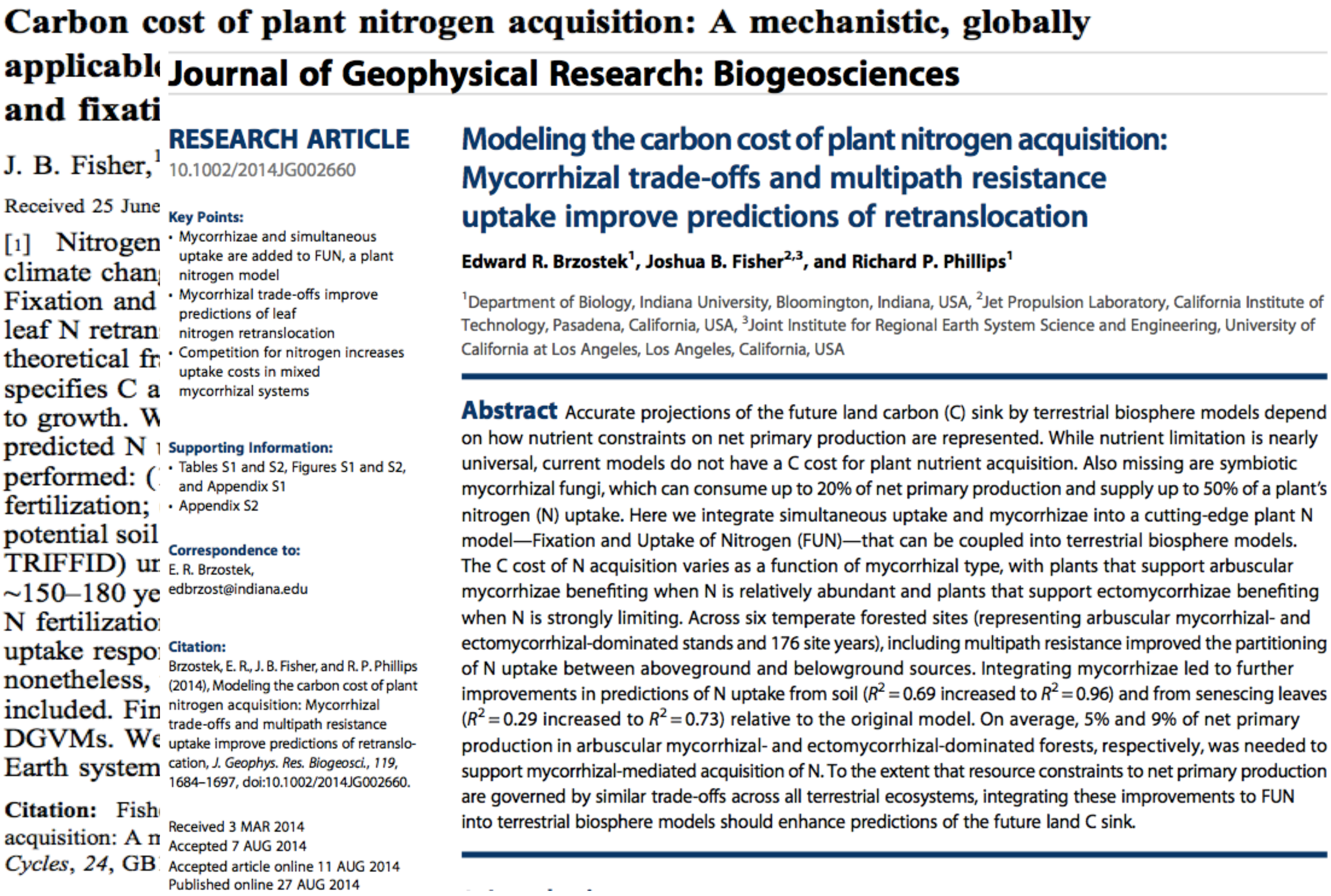

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Journal of Geophysical Research: Biogeosciences

RESEARCH ARTICLE
10.1002/2014JG002660

Key Points:
- Mycorrhizae and simultaneous uptake are added to FUN, a plant nitrogen model
- Mycorrhizal trade-offs improve predictions of leaf nitrogen retranslocation
- Competition for nitrogen increases uptake costs in mixed mycorrhizal systems

Supporting Information:
- Tables S1 and S2, Figures S1 and S2, and Appendix S1
- Appendix S2

Correspondence to:
E. R. Brzostek,
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Citation:
Brzostek, E. R., J. B. Fisher, and R. P. Phillips (2014), Modeling the carbon cost of plant nitrogen acquisition: Mycorrhizal trade-offs and multipath resistance uptake improve predictions of retranslocation, *J. Geophys. Res. Biogeosci.*, *119*, 1684–1697, doi:10.1002/2014JG002660.

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Modeling the carbon cost of plant nitrogen acquisition: Mycorrhizal trade-offs and multipath resistance uptake improve predictions of retranslocation

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Abstract Accurate projections of the future land carbon (C) sink by terrestrial biosphere models depend on how nutrient constraints on net primary production are represented. While nutrient limitation is nearly universal, current models do not have a C cost for plant nutrient acquisition. Also missing are symbiotic mycorrhizal fungi, which can consume up to 20% of net primary production and supply up to 50% of a plant's nitrogen (N) uptake. Here we integrate simultaneous uptake and mycorrhizae into a cutting-edge plant N model—Fixation and Uptake of Nitrogen (FUN)—that can be coupled into terrestrial biosphere models. The C cost of N acquisition varies as a function of mycorrhizal type, with plants that support arbuscular mycorrhizae benefiting when N is relatively abundant and plants that support ectomycorrhizae benefiting when N is strongly limiting. Across six temperate forested sites (representing arbuscular mycorrhizal- and ectomycorrhizal-dominated stands and 176 site years), including multipath resistance improved the partitioning of N uptake between aboveground and belowground sources. Integrating mycorrhizae led to further improvements in predictions of N uptake from soil ($R^2 = 0.69$ increased to $R^2 = 0.96$) and from senescing leaves ($R^2 = 0.29$ increased to $R^2 = 0.73$) relative to the original model. On average, 5% and 9% of net primary production in arbuscular mycorrhizal- and ectomycorrhizal-dominated forests, respectively, was needed to support mycorrhizal-mediated acquisition of N. To the extent that resource constraints to net primary production are governed by similar trade-offs across all terrestrial ecosystems, integrating these improvements to FUN into terrestrial biosphere models should enhance predictions of the future land C sink.

Methods

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Modeling the carbon cost of plant nitrogen acquisition:

Integration of nitrogen dynamics into the Noah-MP land model v1.1 for climate and environmental predictions

Review Status
This discussion paper is under review for the journal Geoscientific Model Development (GMD).

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[2]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, USA
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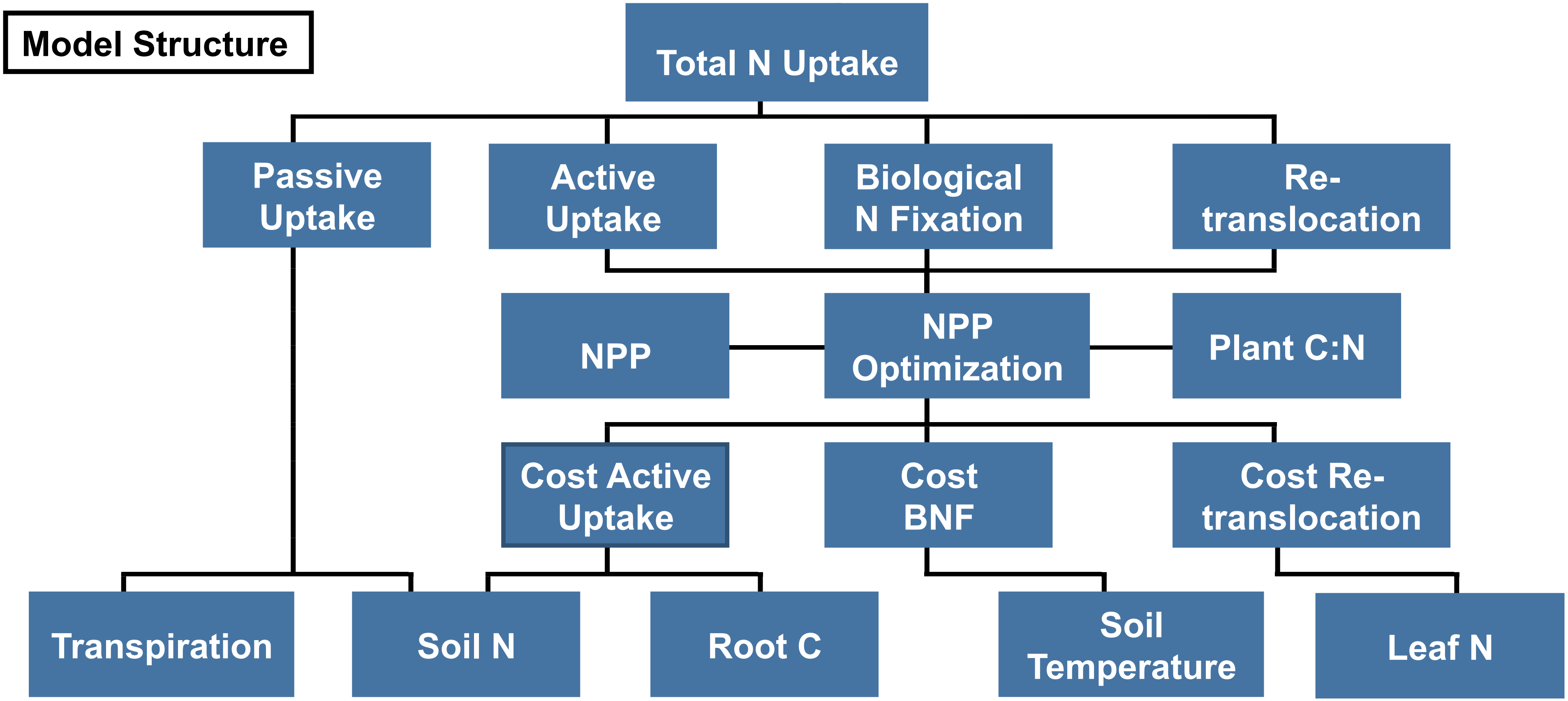
Abstract. Climate and terrestrial biosphere models consider nitrogen an important factor in limiting plant carbon uptake, while operational environmental models view nitrogen as the leading pollutant causing eutrophication in water bodies. The community Noah land surface model with multi-parameterization options (Noah-MP) is unique in that it is the next generation land surface model for the Weather Research and Forecasting meteorological model and for the operational weather/climate models in the National Centers for Environmental Prediction. In this study, we add capability to Noah-MP to simulate nitrogen dynamics by coupling the Fixation and Uptake of Nitrogen (FUN) plant model and the Soil and Water Assessment Tool (SWAT) soil nitrogen dynamics. This incorporates FUN's state-of-the-art concept of carbon cost theory and SWAT's strength in representing the impacts of agricultural management on the nitrogen cycle. Parameterizations for direct root and mycorrhizal-associated nitrogen uptake, leaf retranslocation, and symbiotic biological nitrogen fixation are employed from FUN, while parameterizations for nitrogen mineralization, nitrification, immobilization, volatilization, atmospheric deposition, and leaching are based on SWAT. The coupled model is then evaluated at the Kellogg Biological Station – a Long-term Ecological Research site within the U.S. Corn Belt. Results show that the model performs well in capturing the major nitrogen state/flux variables (e.g., soil nitrate and nitrate leaching). Furthermore, the addition of nitrogen dynamics improves the modeling of the carbon and water cycles (e.g., net primary productivity and evapotranspiration). The model improvement is expected to advance the capability of Noah-MP to simultaneously predict weather and water quality in fully coupled Earth system models.

Citation: Cai, X., Yang, Z.-L., Fisher, J. B., Zhang, X., Barlage, M., and Chen, F.: Integration of nitrogen dynamics into the Noah-MP land model v1.1 for climate and environmental predictions, Geosci. Model Dev. Discuss., 8, 4113-4153, doi:10.5194/gmdd-8-4113-2015, 2015.

Methods

Model Structure

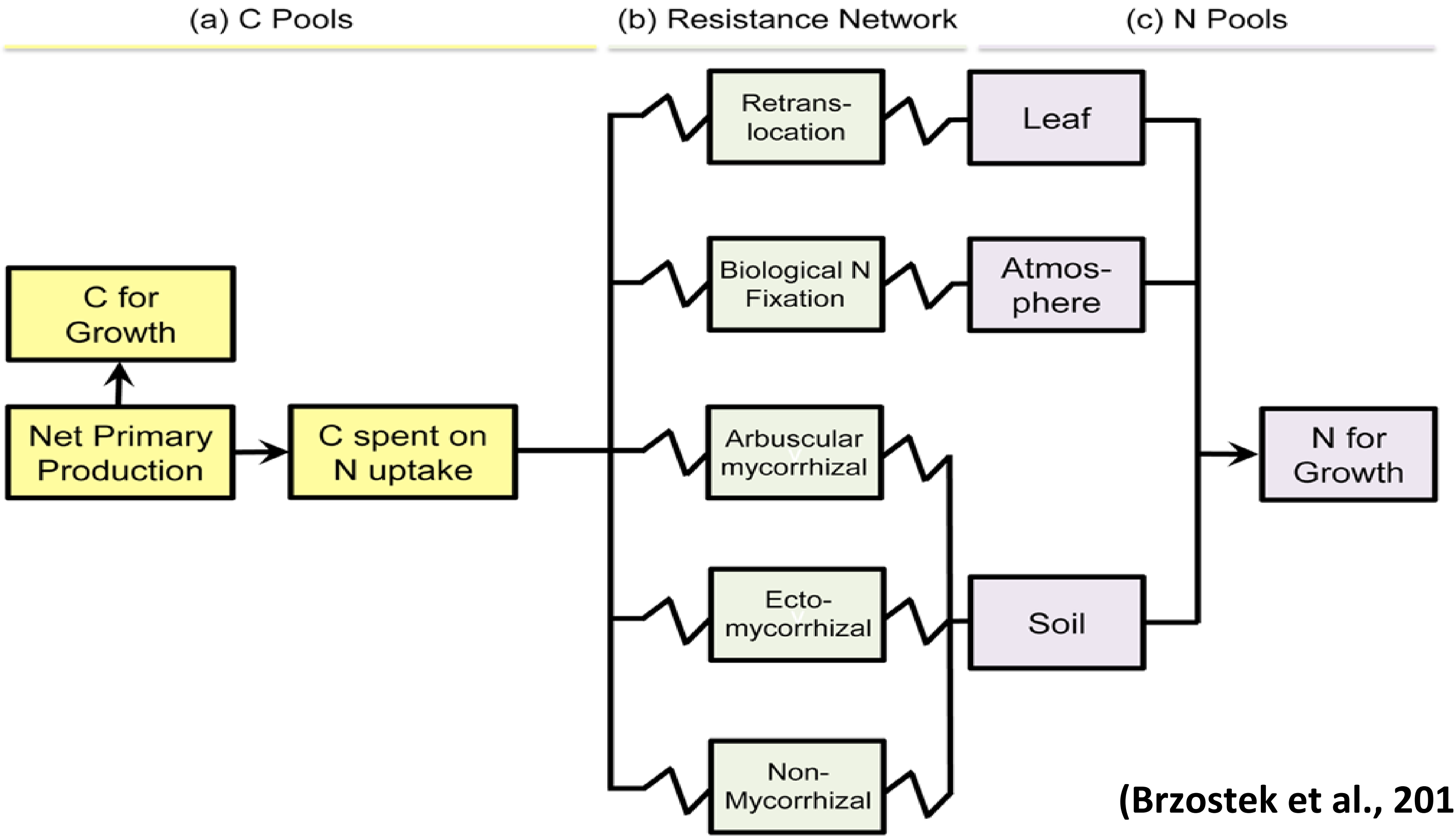


(Fisher et al., 2010)

CLM provides FUN:

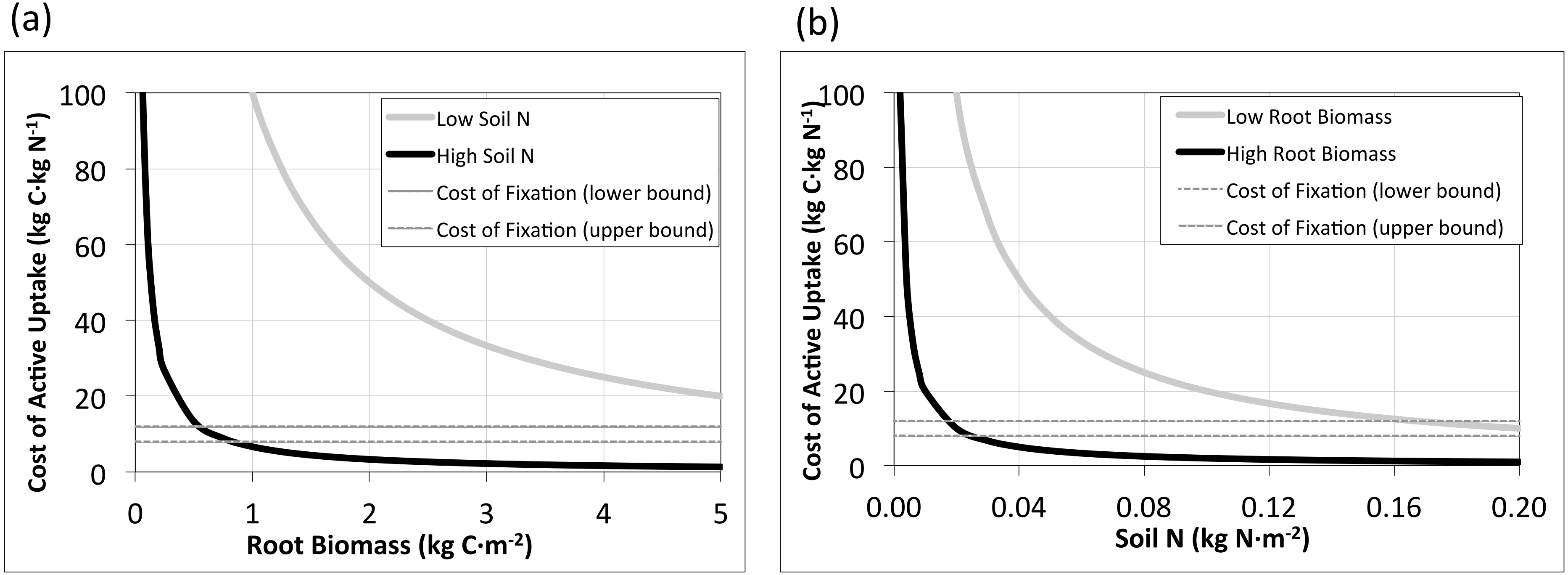
1) Available C
2) Soil mineral N
3) Root Biomass
4) Leaf N
5) Plant C:N ratio
6) Soil layer depth
7) Soil temperature
8) Transpiration

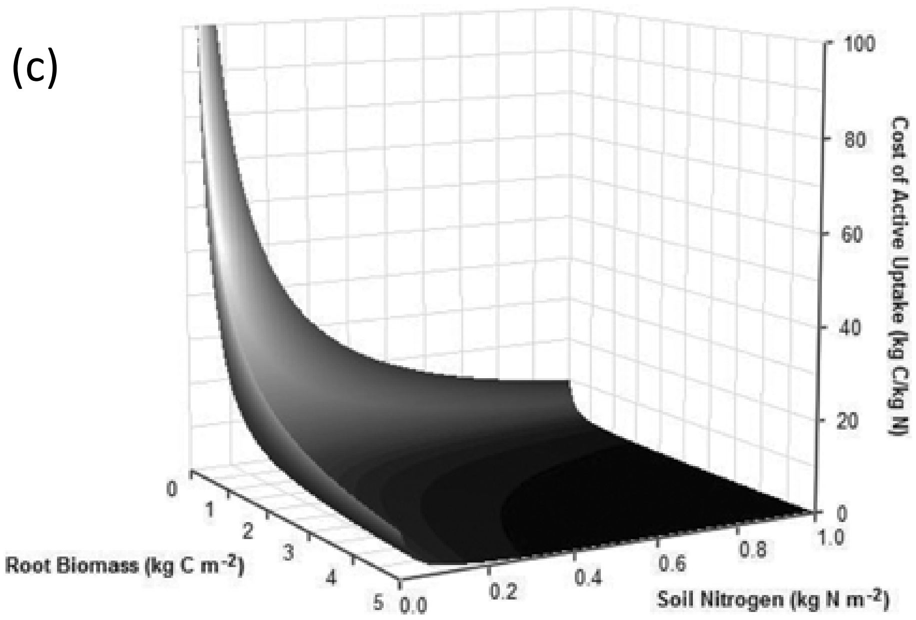
Methods



(Brzostek et al., 2014)

FUN optimally allocates C to growth and to N uptake as a function of the N needed to support NPP and the integrated C costs across all of the pathways in the resistor network.

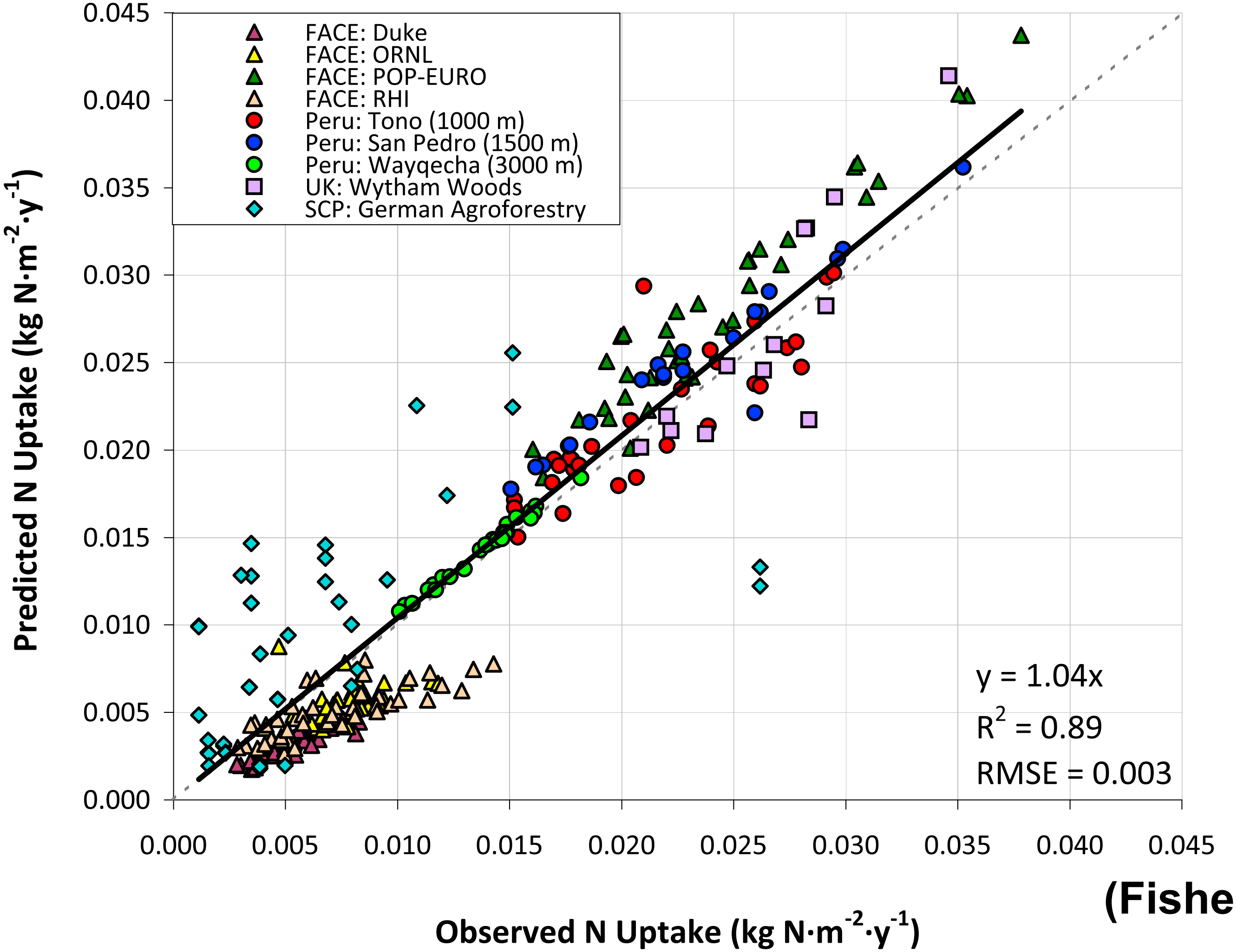




Cost of active nitrogen uptake (Cost$_{active}$) with range of cost of biological nitrogen fixation (Cost$_{fix}$) versus:

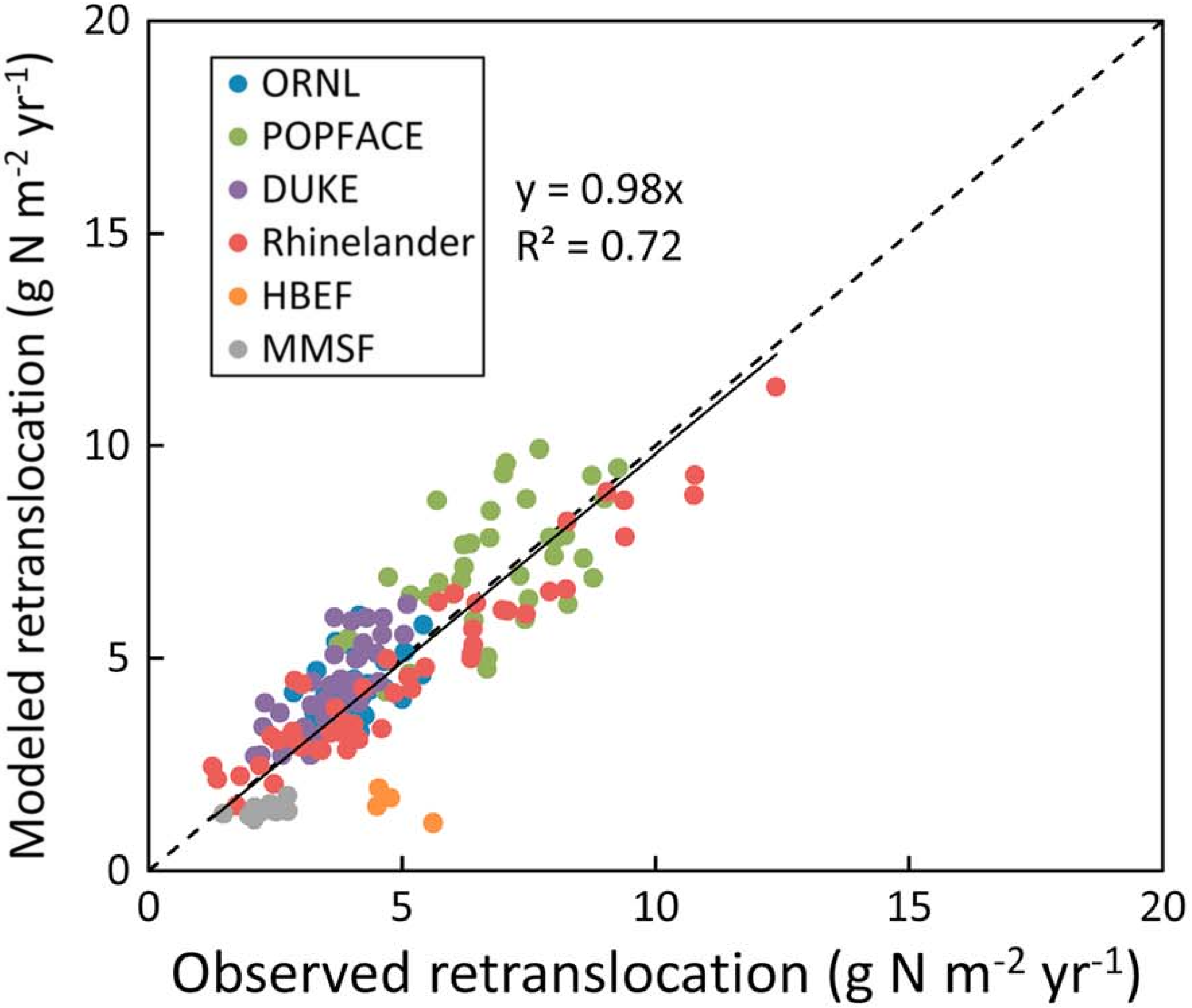
(a) soil nitrogen with low and high root biomass,
(b) root biomass with low and high soil nitrogen
(c) both soil nitrogen and root biomass.

(Fisher et al., 2010)



(Fisher et al., 2010)

Scatterplot of observed versus predicted N uptake FUN from the Free Air CO_2 Enrichment (FACE) experiments (Finzi *et al.*, 2007), three agroecosystem sites from the Special Collaborative Project 179 (SCP179) international workshop data set (McVoy *et al.*, 1995), three tropical montane sites in the Peruvian Andes (Tan, 2008), and an ancient woodland in the United Kingdom (Tan, 2008).



Stepwise improvement in model predictions of total N uptake across six sites that vary in mycorrhizal association from FUN2.0. The dashed line indicates the 1:1 relationship.

(Brzostek et al., 2014)

CLM-Trunk-FUN Coupling

FUN was coupled with CLM4.0-CN, CLM4.5-BGC, and CLM-Trunk-BGC:

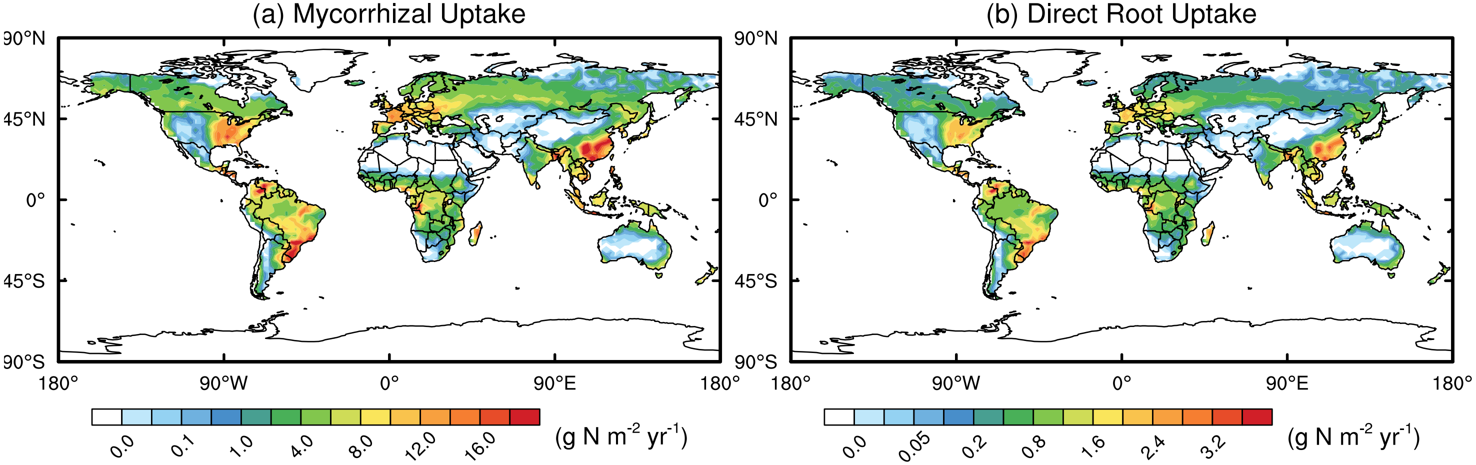
clm_varcon.F90
CNDriverMod.F90
pftconMod.F90
CNFUNMod.F90
CNVegStateType.F90
CNPhenologyFlagMod.F90

CNVegCarbonFluxType.F90
CNVegCarbonStateType.F90
readParamsMod.F90
CNVegNitrogenFluxType.F90
CNPhenologyMod.F90
CNVegNitrogenStateType.F90

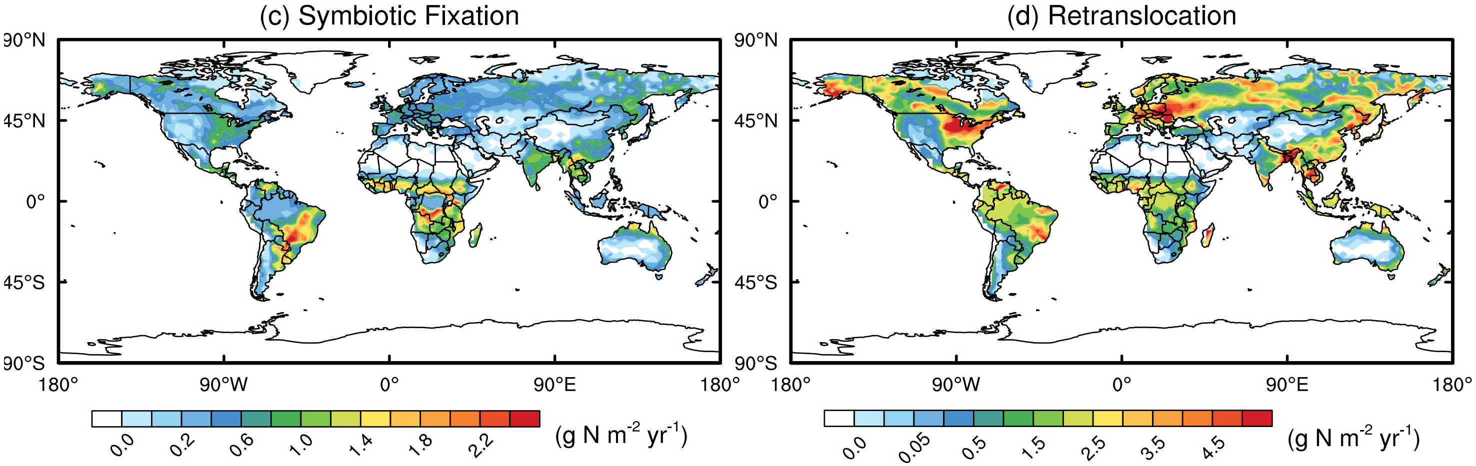
SoilBiogeochemNStateUpdate1Mod.F90
SoilBiogeochemCarbonFluxType.F90
NutrientCompetitionCLM45defaultMod.F90
SoilBiogeochemNitrogenFluxType.F9
SoilBiogeochemCompetitionMod.F90

Results

How much N is taken up and what is the global distribution?


(a) Mycorrhizal Uptake

(b) Direct Root Uptake

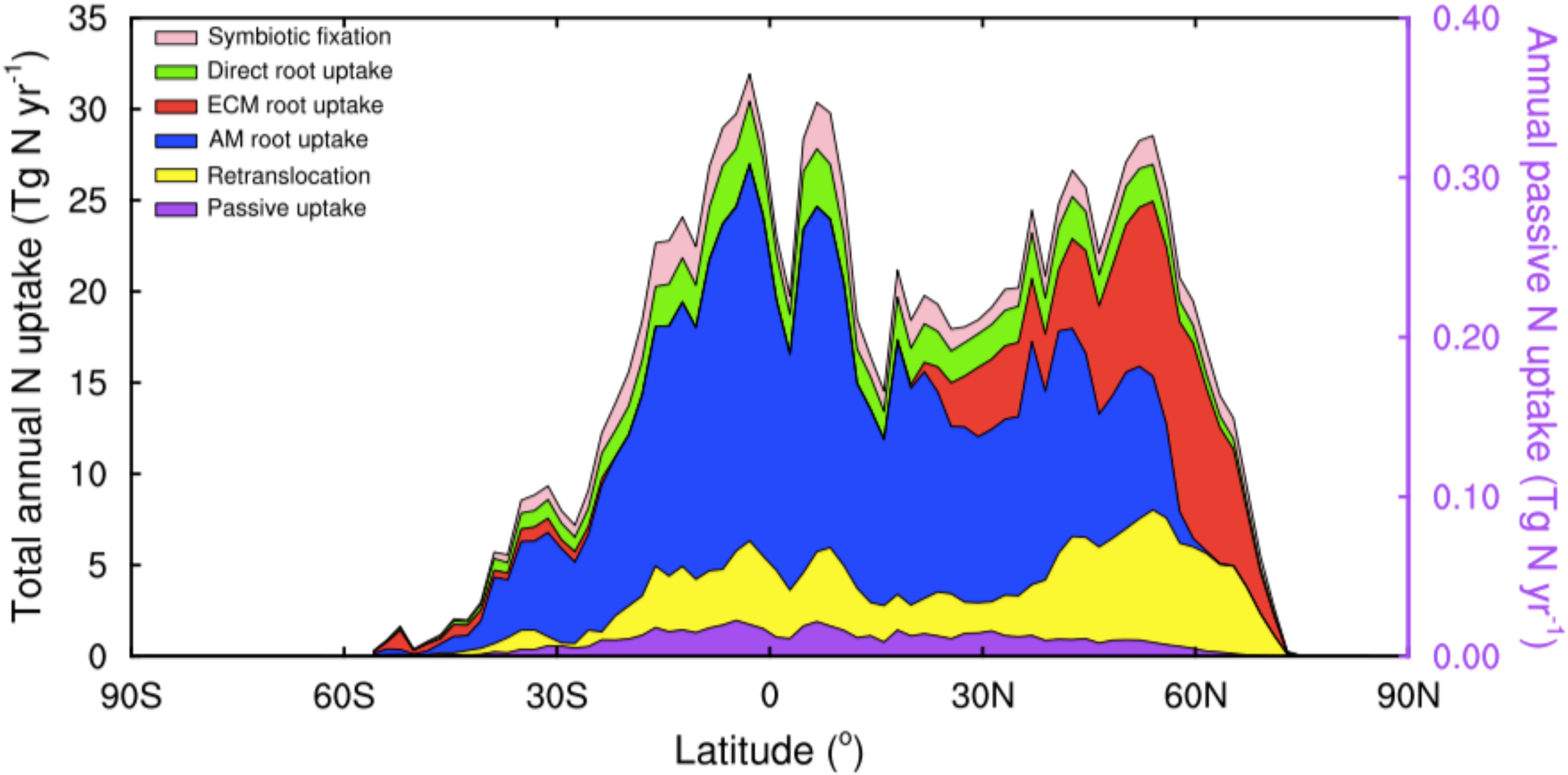

(c) Symbiotic Fixation

(d) Retranslocation

- The global total uptake is 1.2 Pg N yr^{-1}.
- Mycorrhizal represent the dominant pathway followed by retranslocation, direct root uptake, and fixation.

Results

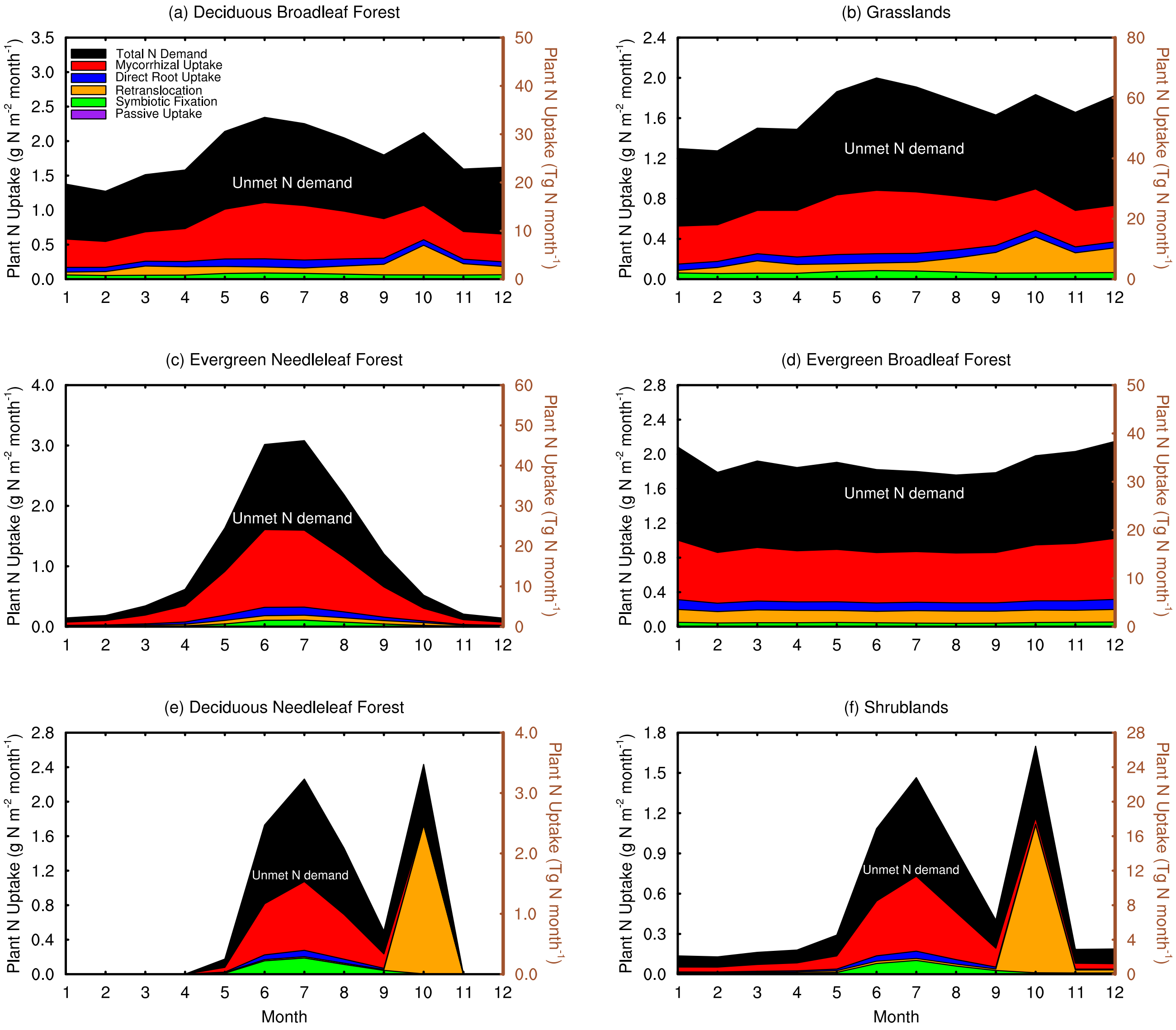
How much N is taken up and what is the global distribution?



- The high N uptake regions are tropics and mid-latitudes in the north hemisphere.
- The fractions of the mycorrhizal uptake, direct root uptake, retranslocation, fixation, and passive uptake amounts are 64%, 10%, 19%, 7%, and 0.1% of the total N uptake amount, respectively.

Results

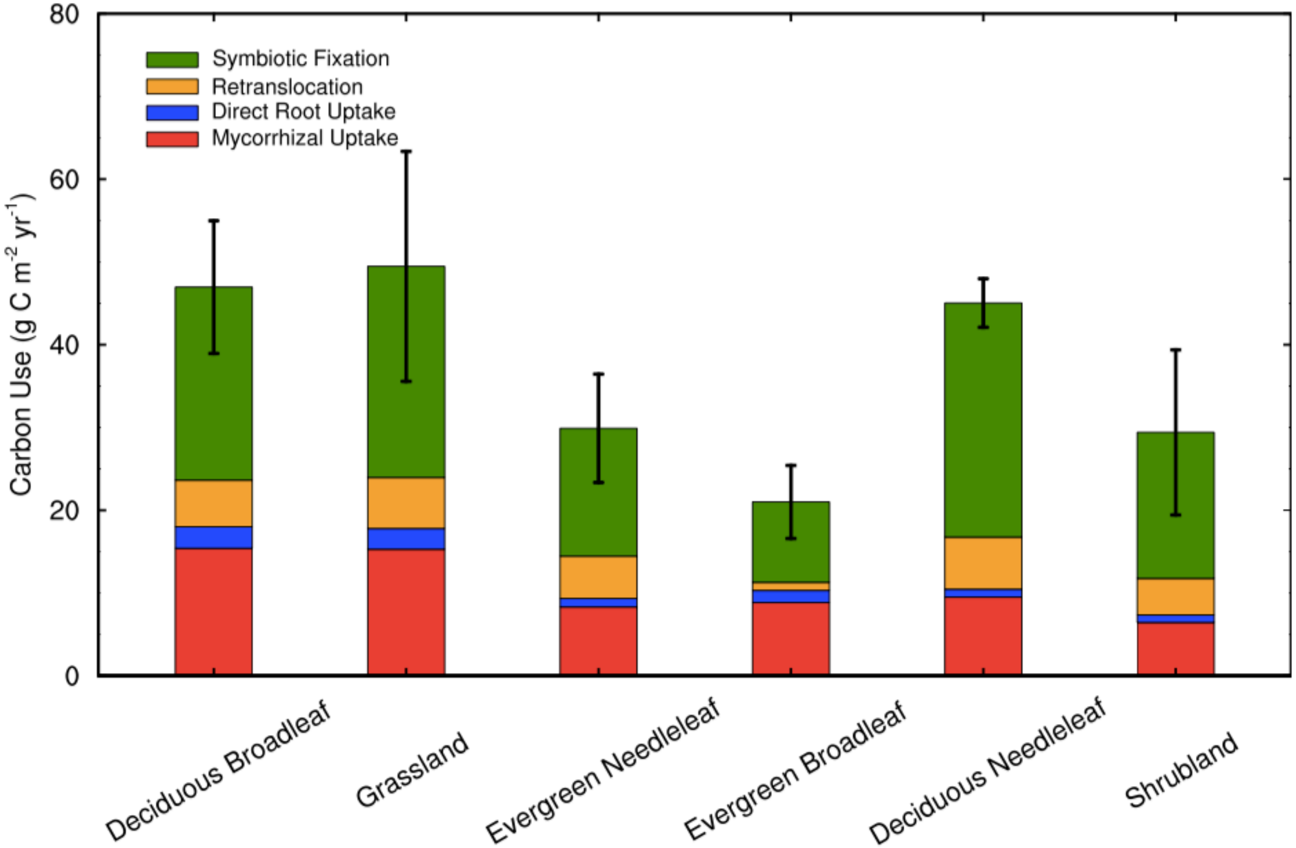
How does the C cost of N acquisition vary spatially and temporally?



- Total N uptake does not meet total N demand for most of the year in all biomes.
- Evergreen broadleaf forest has the largest N uptake rate, which is 11 g N m^{-2} y^{-1}.
- Deciduous needleleaf forest has the most met demand.

Results

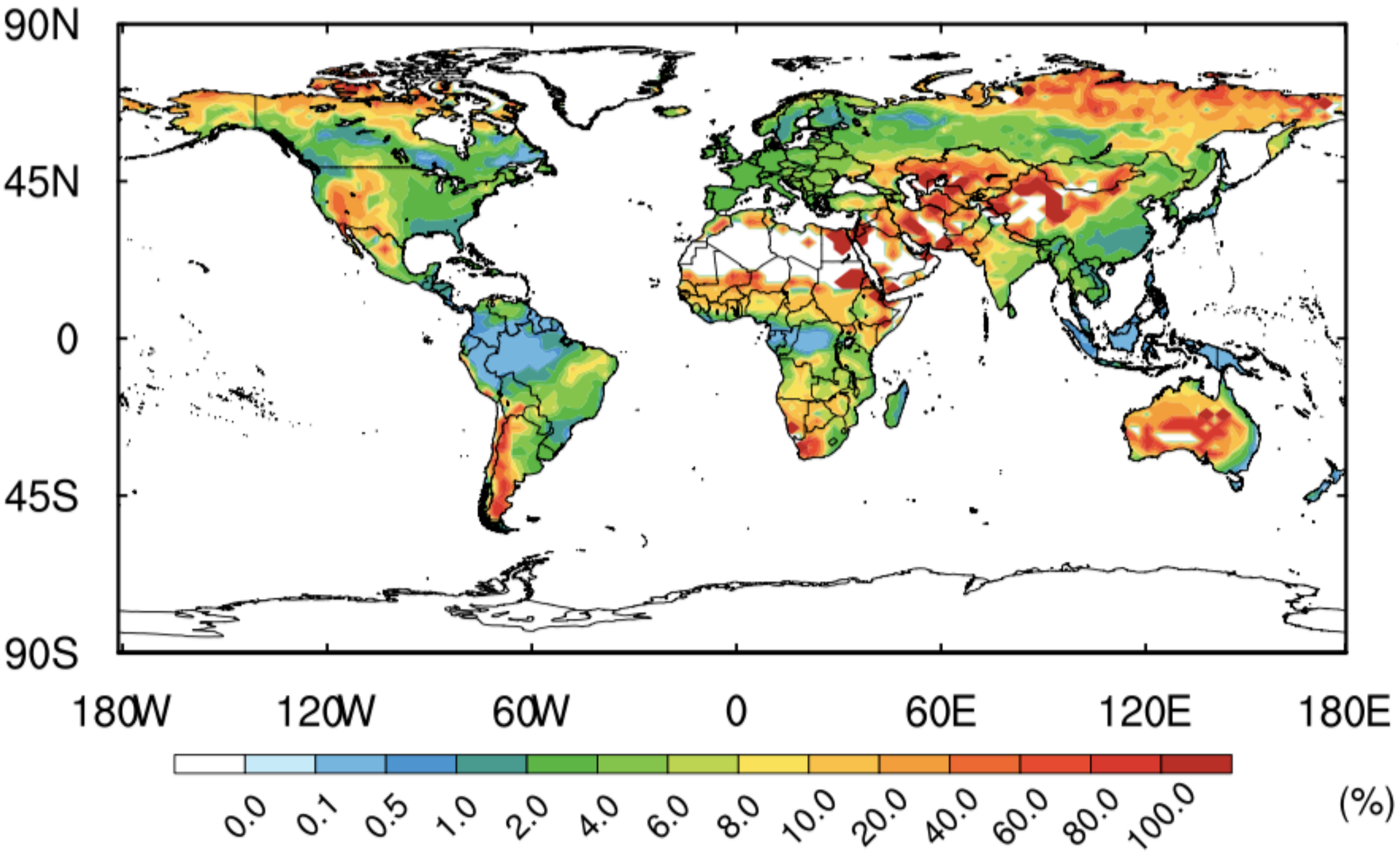
How does the C cost of N acquisition vary spatially and temporally?



- C spent on N acquisition is 5.1 Pg C yr^{-1} globally.
- The mycorrhizal and fixation used C amounts are 1.6 Pg C yr^{-1} and 2.6 Pg C yr^{-1}, respectively; they are 31% and 50% of the global total used C amount, respectively.
- Grassland spends the most C on N acquisition per unit area; evergreen broadleaf forest spends the least C on N acquisition per unit area.

Results

How does the C cost of acquisition vary spatially and temporally?



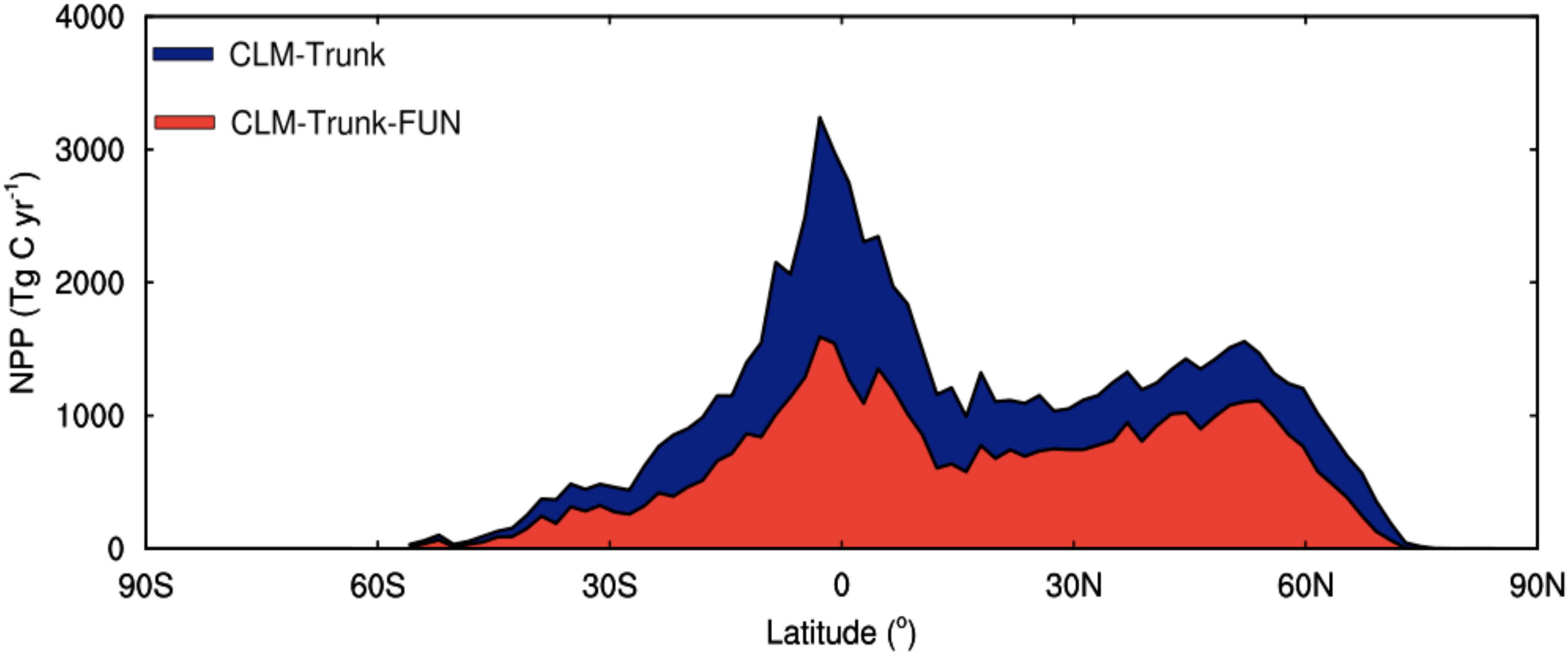
$$C_{use.ratio} = \frac{C_{use,\,acquisition}}{C_{available}}$$

where $C_{use,\ acquisition}$ is the total C used by the four N uptake pathways, and $C_{available}$ is the difference between GPP and maintenance respiration.

- Tropical forests have the lowest C use ratio.
- High-latitude shrubland and arid and semi-arid regions have the highest C use ratio.

Results

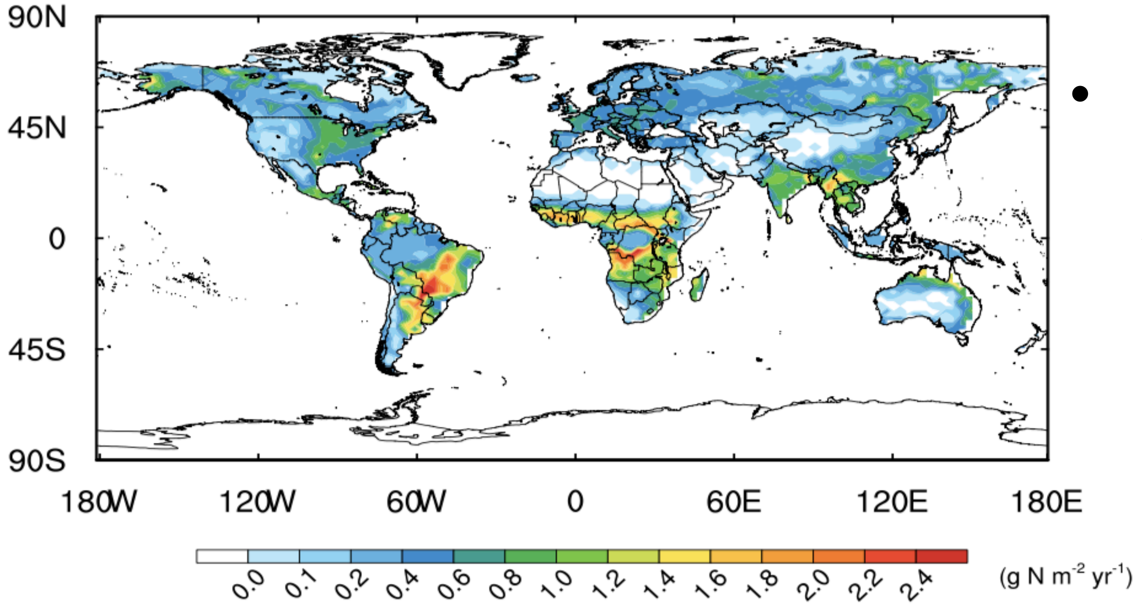
How sensitive is the land C sink to a dynamic prediction of the C cost of N acquisition?



- Global total NPP is down-regulated by 41%.
- The reduced NPP amount peaks at 2°S, and decreases towards the Poles.
- CLM-Trunk-FUN results in NPP decrease in all biomes.

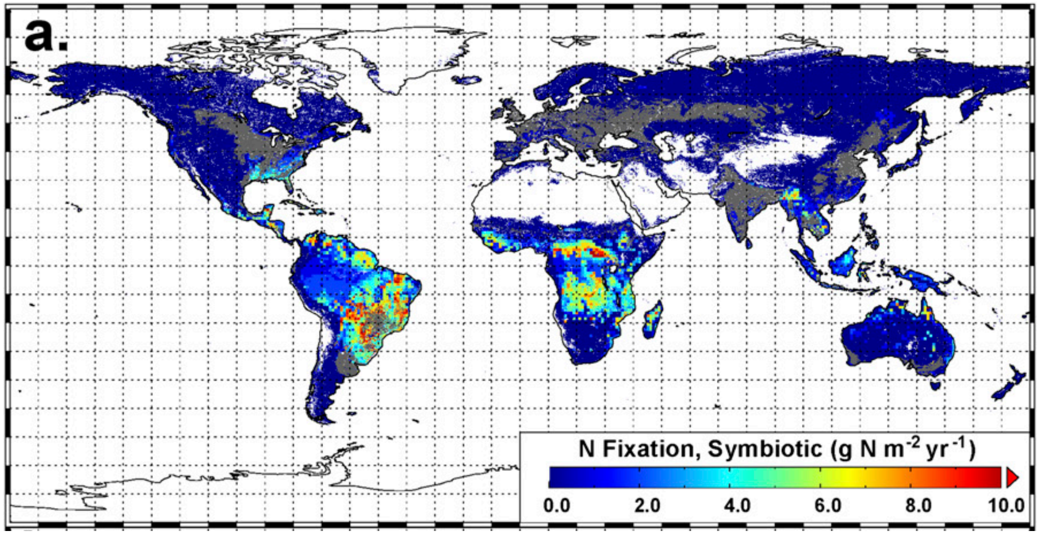
Discussion

CLM-Trunk-FUN simulated symbiotic BNF



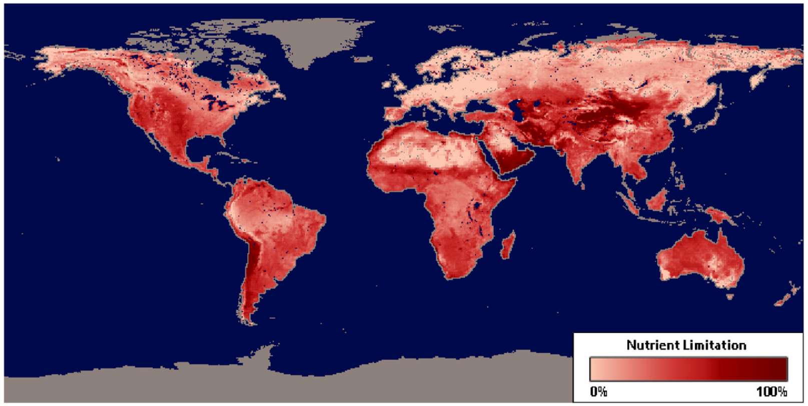
- CLM-Trunk-FUN predicted symbiotic BNF is 81.1 Tg N yr^{-1} and 0.53 g N m^{-2} yr^{-1}.

- Symbiotic BNF is 105.1 Tg N yr^{-1} (Cleveland et al., 2013) and 0.85 g N m^{-2} yr^{-1} on an per unit area basis (Sullivan et al., 2014).

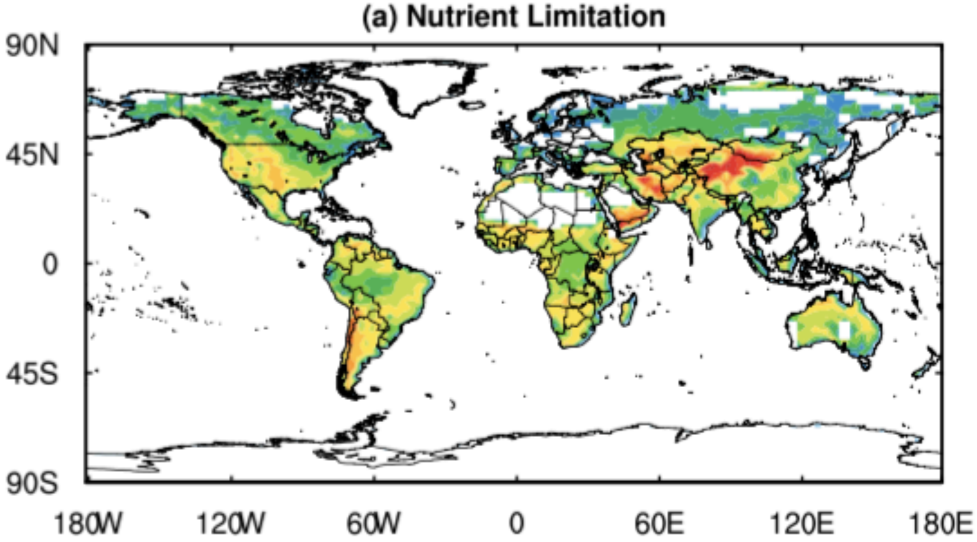


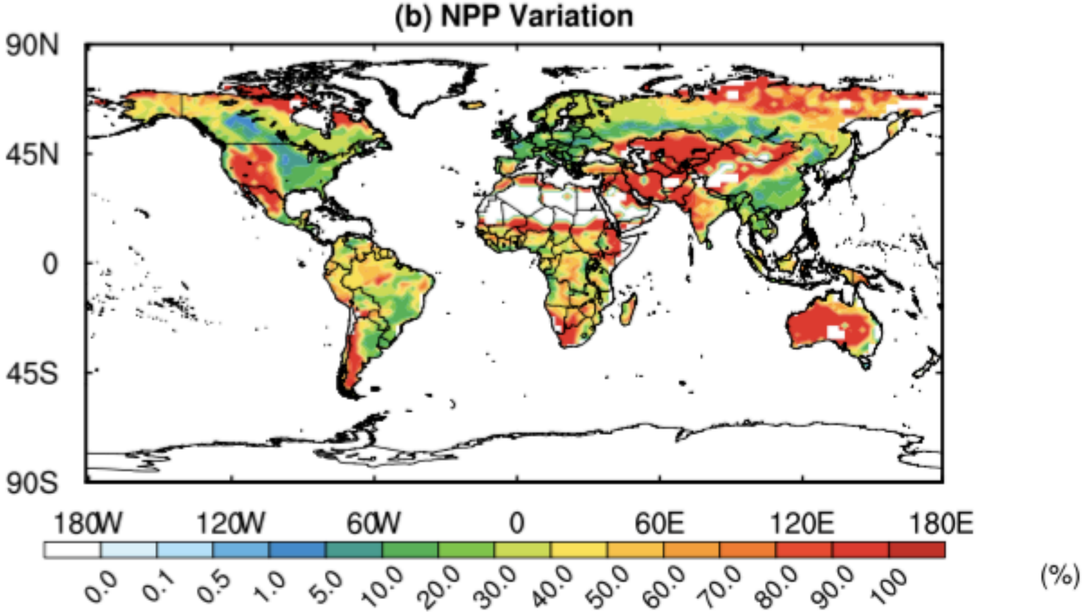
Discussion

Benchmarking CLM-Trunk-FUN



- We used a new global nutrient limitation product developed from remote sensing (Fisher et al., 2012).
- The nutrient limitation and NPP variation patterns at the global scale.


(a) Nutrient Limitation


(b) NPP Variation

Conclusions

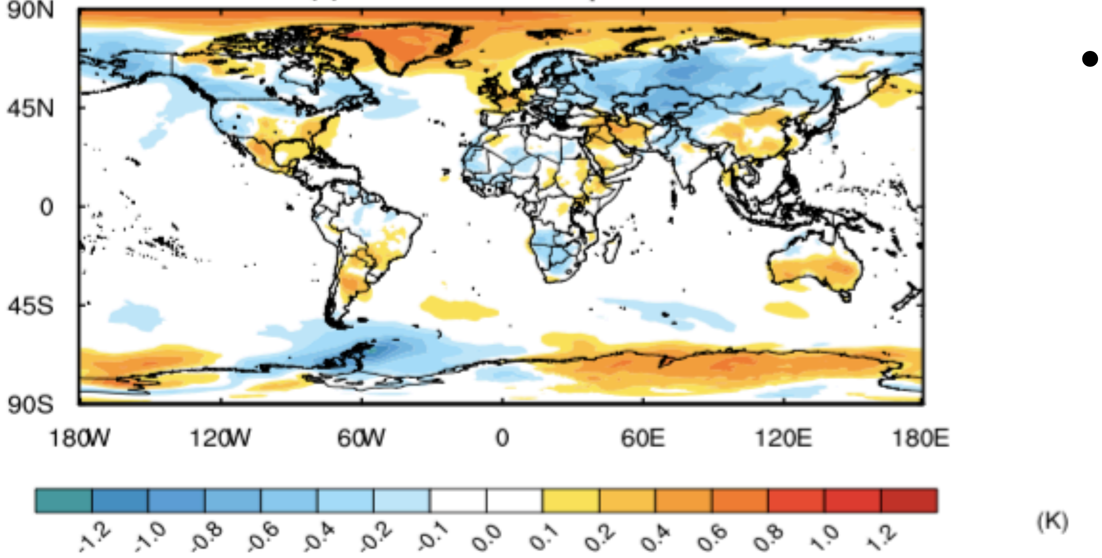
Take Home Messages

- Global total N uptake amount is 1.2 Pg N yr^{-1}.
- N acquisition uses 5.1 Pg C yr^{-1} globally.
- Mycorrhizal N uptake is the dominant N uptake pathway and BNF is the most expensive N uptake pathway.
- Total N uptake reduces NPP globally by 41%.

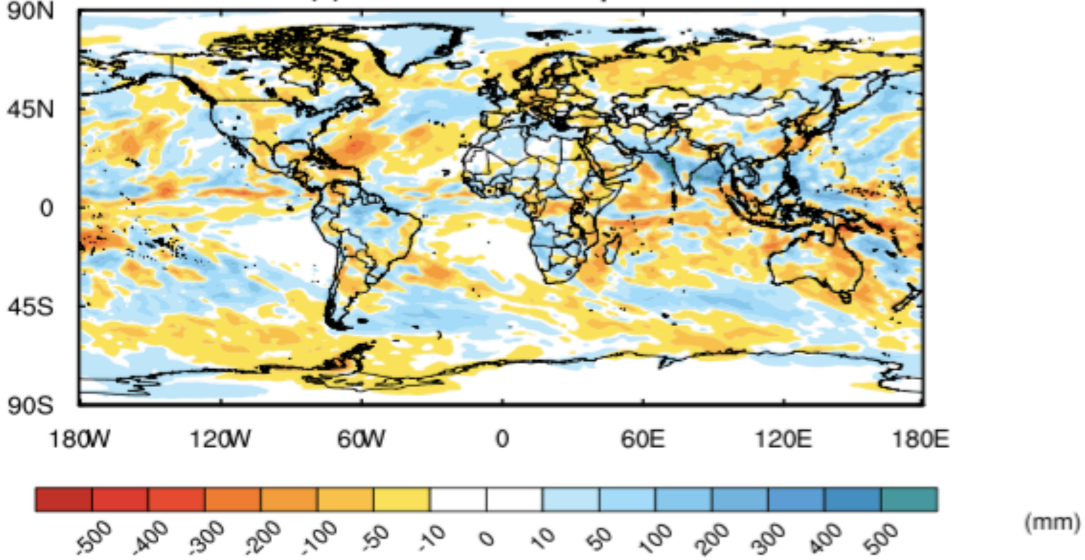
Future Work

- NPP downregulation
- Climate impact

Primary Results From CAM-FUN



(a) CAMFUN-CAM Temperature



(b) CAMFUN-CAM Precipitation

- The C spent on N acquisition results in temperature decrease in mid- and high-latitude areas and increase in polar regions.

- Global precipitation pattern is also changed with FUN coupled into CLM and CAM.

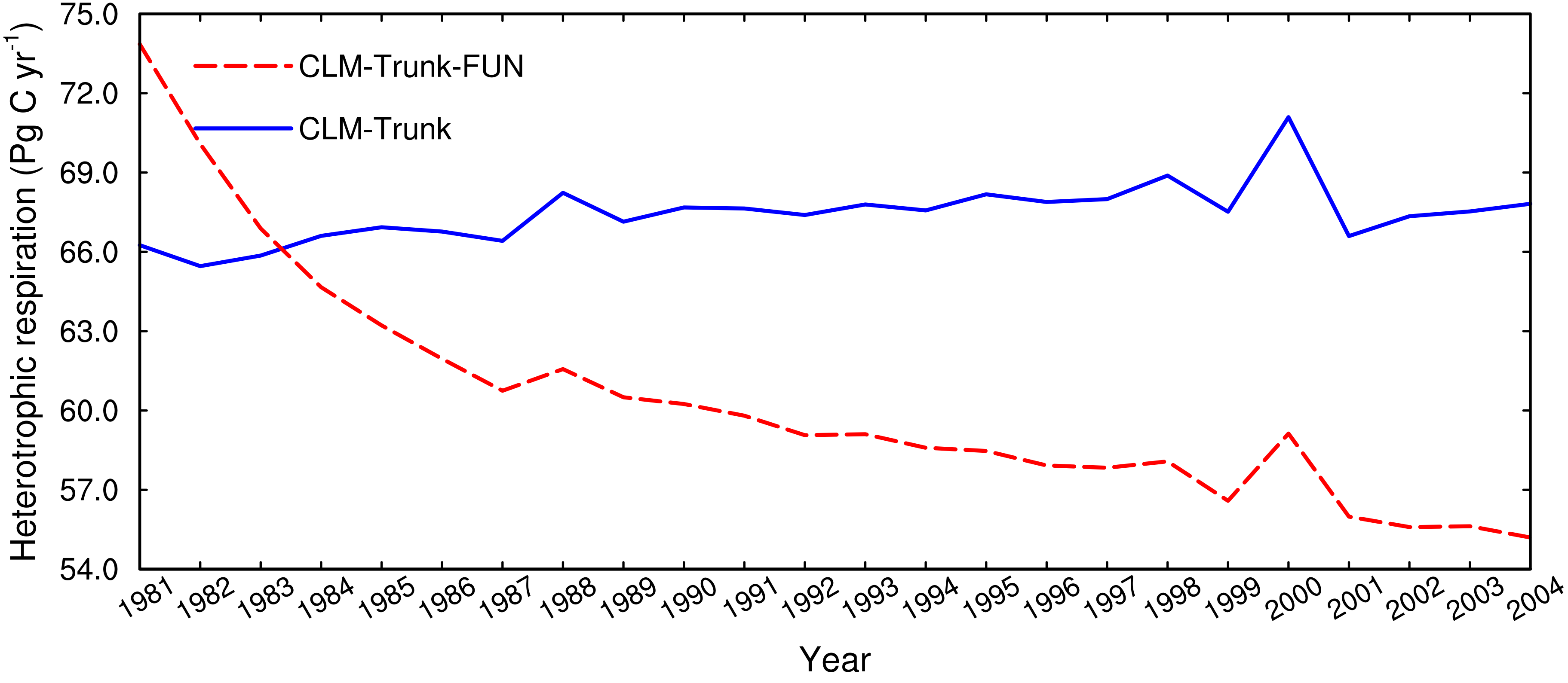
Acknowledgments

- The US Department of Energy Office of Biological and Environmental Research Terrestrial Ecosystem Science Program

- The US National Science Foundation Ecosystem Science Program

- The technical support from Erik Kluzek at NCAR.

Name of the PFTs	**AM (%)**	**ECM (%)**
Bare soil (not vegetated)	0	100
Needleleaf evergreen temperate tree	0	100
Needleleaf evergreen boreal tree	0	100
Needleleaf deciduous boreal tree	0	100
Broadleaf evergreen tropical tree	100	0
Broadleaf evergreen temperate tree	100	0
Broadleaf deciduous tropical tree	100	0
Broadleaf deciduous temperate tree	50	50
Broadleaf deciduous boreal tree	0	100
Broadleaf evergreen shrub	0	100
Broadleaf deciduous temperate shrub	0	100
Broadleaf deciduous boreal shrub	0	100
C3 arctic grass	0	100
C3 non-arctic grass	100	0
C4 grass	100	0


CLM-Trunk-FUN
CLM-Trunk
Heterotrophic respiration (Pg C yr-1)
75.0
72.0
69.0
66.0
63.0
60.0
57.0
54.0
1981
1982
1983
1984
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