Nitrogen cycling in the Hadley Centre land surface model (JULES)

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Vial of glowing ultrapure nitrogen, N_2

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California Institute of Technology
Pasadena, California

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The Software Architecture of Global Climate Models

UNIVERSITY OF MANITOBA

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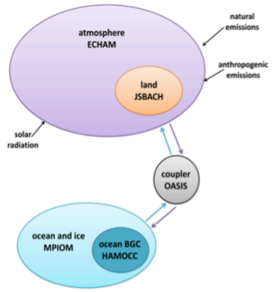
IN41A-1394

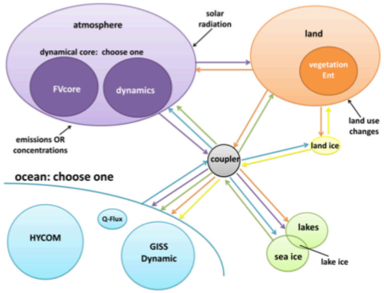
COSMOS 1.2.1

Max-Planck-Institut für Meteorologie, Germany



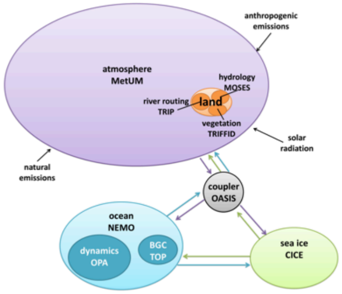
Model E October 11, 2011 revision

NASA Goddard Institute for Space Studies, USA



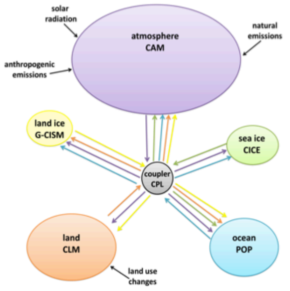
HadGEM3

Met Office, UK



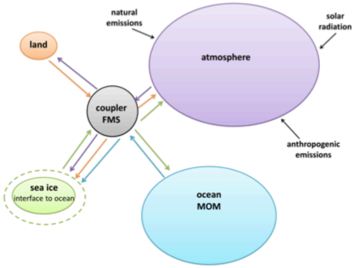
CESM 1.0.3

National Center for Atmospheric Research, USA



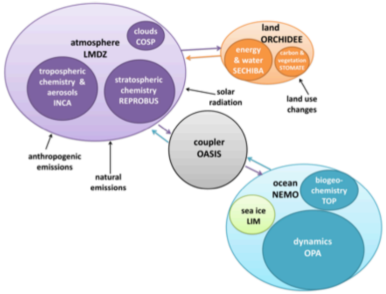
GFDL Climate Model 2.1 (coupled to MOM 4.1)

Geophysical Fluid Dynamics Laboratory, USA



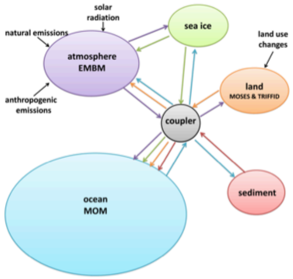
IPSL Climate Model 5A

Institut Pierre Simon Laplace, France



UVic Earth System Climate Model 2.9

University of Victoria, Canada



Key to Diagrams

Each component of the climate system has been assigned a colour:

atmosphere ocean land sea ice land ice sediment

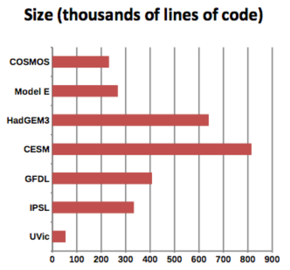
Model code for a component is represented with a bubble. ⬭ Fluxes are represented with arrows, in a colour showing where they originated.

Couplers are grey. ○ Components can pass fluxes either directly to each other or through the coupler.

The area of a bubble represents the size of its code base, relative to other components in the same model.

A smaller bubble within a larger one ◉ represents a small, highly encapsulated model of a system (eg clouds) that is used by the component.

Radiative forcings are passed to components with plain arrows.



Generated using David A. Wheeler's "SLOCCount".

Introduction

It has become common to compare and contrast the output of multiple global climate models (GCMs), such as in the Climate Model Intercomparison Project Phase 5 (CMIP5). However, intercomparisons of the software architecture of GCMs are almost nonexistent. In this qualitative study of seven GCMs from Canada, the United States and Europe, we attempted to fill this gap in research. By examining the model source code, reading documentation, and interviewing developers, we created diagrams of software structure and compared metrics such as encapsulation, coupler design, and complexity.

Component-Based Software Engineering

A global climate model is really a *collection* of models (components), each representing a major realm of the climate system, such as the atmosphere or the land surface. They are highly encapsulated, for stand-alone use as well as a mix-and-match approach that facilitates code sharing between institutions.

This strategy, known as component-based software engineering (CBSE), pools resources to create high-quality components that are used by many GCMs. For example,

- **UVic** uses a modified version of GFDL's ocean model, MOM.
- **HadGEM3** and **CESM** both use CICE, a sea ice model developed a third institution (Los Alamos).

Contrary to CBSE goals, there is no universal interface for climate models, so components need to be modified when they are passed between institutions. Furthermore, the right to edit the *master* copy of a component's source code is generally restricted to the development team at the hosting institution. As a result, many different branches of the software develop.

A drawback to CBSE is the fact that, in the real world, components of the climate system are not encapsulated. For example, how does one represent the relationship between sea ice and the ocean? Many different strategies exist:

- **CESM**: sea ice and ocean are completely separate components.
- **IPSL**: sea ice is a sub-component of the ocean.
- **GFDL**: sea ice is an interface to the ocean. All fluxes to and from the ocean must pass through the sea ice region, even if no ice is actually present.

Acknowledgements

Gavin Schmidt (NASA GISS); Tim Johns (Met Office); Gary Strand (NCAR); Arnaud Caubel, Marie-Alice Foujols, and Anne Cozic (IPSL); Reinhard Budich (MPI); and Michael Eby (University of Victoria) answered questions about their work developing GCMs and helped to verify our observations. Additionally, Michael Eby from the University of Victoria was instrumental in improving the diagram design.

This project was funded by NSERC and the Centre for Global Change Science at the University of Toronto.

The Coupling Process

Since the climate system is highly interconnected, a CBSE approach requires code to tie the components together - interpolating fluxes between grids and controlling interactions between components. These tasks are performed by the coupler. While all GCMs contain some form of coupler, the extent to which it is used varies widely:

- **CESM**: Every interaction is managed by the coupler.
- **IPSL**: Only the atmosphere and the ocean are connected to the coupler. The land component is directly called by the atmosphere.
- **HadGEM3**: all components are connected to the coupler, but ocean-ice fluxes are passed directly, since NEMO and CICE have similar grids.

A CBSE approach has even affected coupling. OASIS, a coupler used by many models (including COSMOS, HadGEM3, and IPSL) is built to handle any number and any type of components, as well as the flux fields within.

Complexity and Focus

A simple line count of GCM source code serves as a reasonable proxy for relative complexity. A model that represents many processes will generally have a larger code base than one that represents only a few. Between models, complexity varies widely. Within models, the bulk of a GCM's complexity is often concentrated in a single component, due to the origin of the model and the institution's goals:

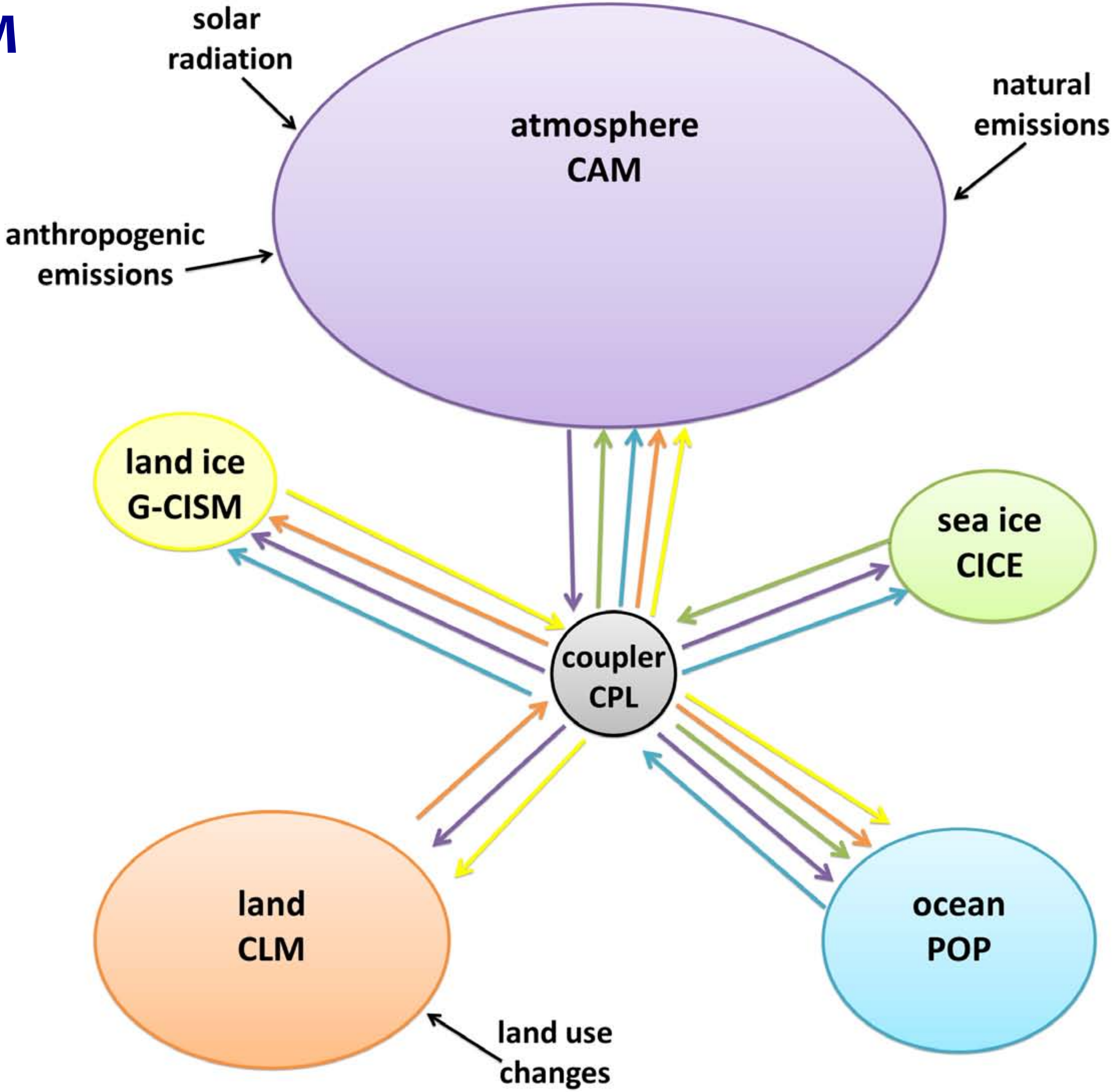
- **HadGEM3**: atmosphere-centric. It grew out of the atmospheric model MetUM, which is also used for weather forecasting, requiring high atmospheric complexity.
- **UVic**: ocean-centric. It began as a branch of MOM, and kept the combination of a complex ocean and a simple atmosphere due to its speed and suitability to very long simulations.
- **CESM**: atmosphere-centric, but land is catching up, having even surpassed the ocean. It is embracing the "Earth System Model" frontier of terrestrial complexity, particularly feedbacks in the carbon cycle.

Conclusions

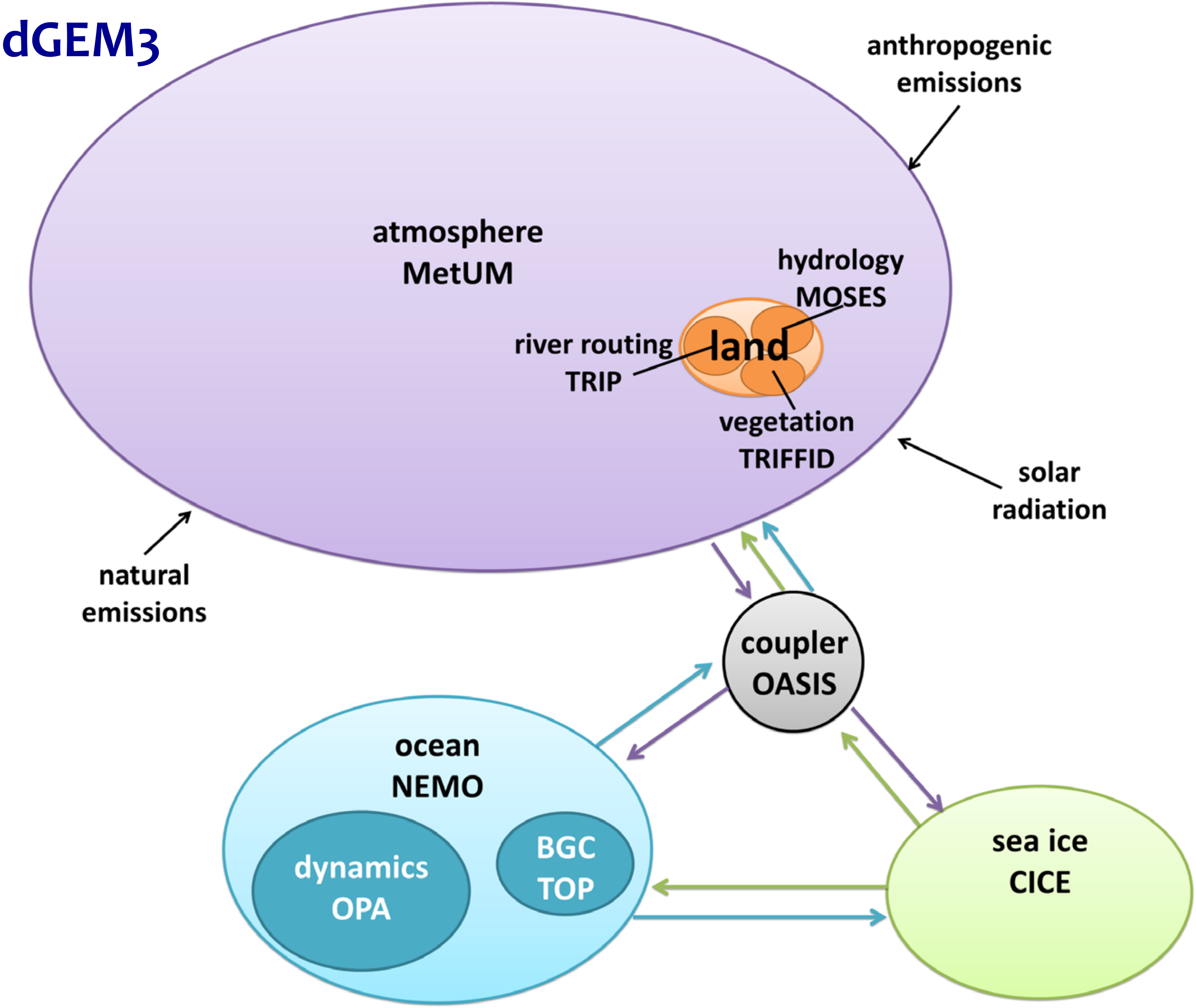
While every GCM we studied shares a common basic design, a wide range of structural diversity exists in areas such as coupler structure, relative complexity between components, and levels of component encapsulation. This diversity can complicate model development, particularly when components are passed between institutions. However, the range of design choices is arguably beneficial for model output, as it inadvertently produces the software engineering equivalent of perturbed physics (although not in a systematic manner).

Additionally, architectural differences may provide new insights into variability and spread between model results. By examining software variations, as well as scientific variations, we can better understand discrepancies in GCM output.

CESM


solar radiation
atmosphere
CAM
natural emissions
anthropogenic emissions
land ice
G-CISM
sea ice
CICE
coupler
CPL
land
CLM
ocean
POP
land use changes

HadGEM3



anthropogenic
emissions

atmosphere
MetUM

hydrology
MOSES

river routing
TRIP

land

vegetation
TRIFFID

solar
radiation

natural
emissions

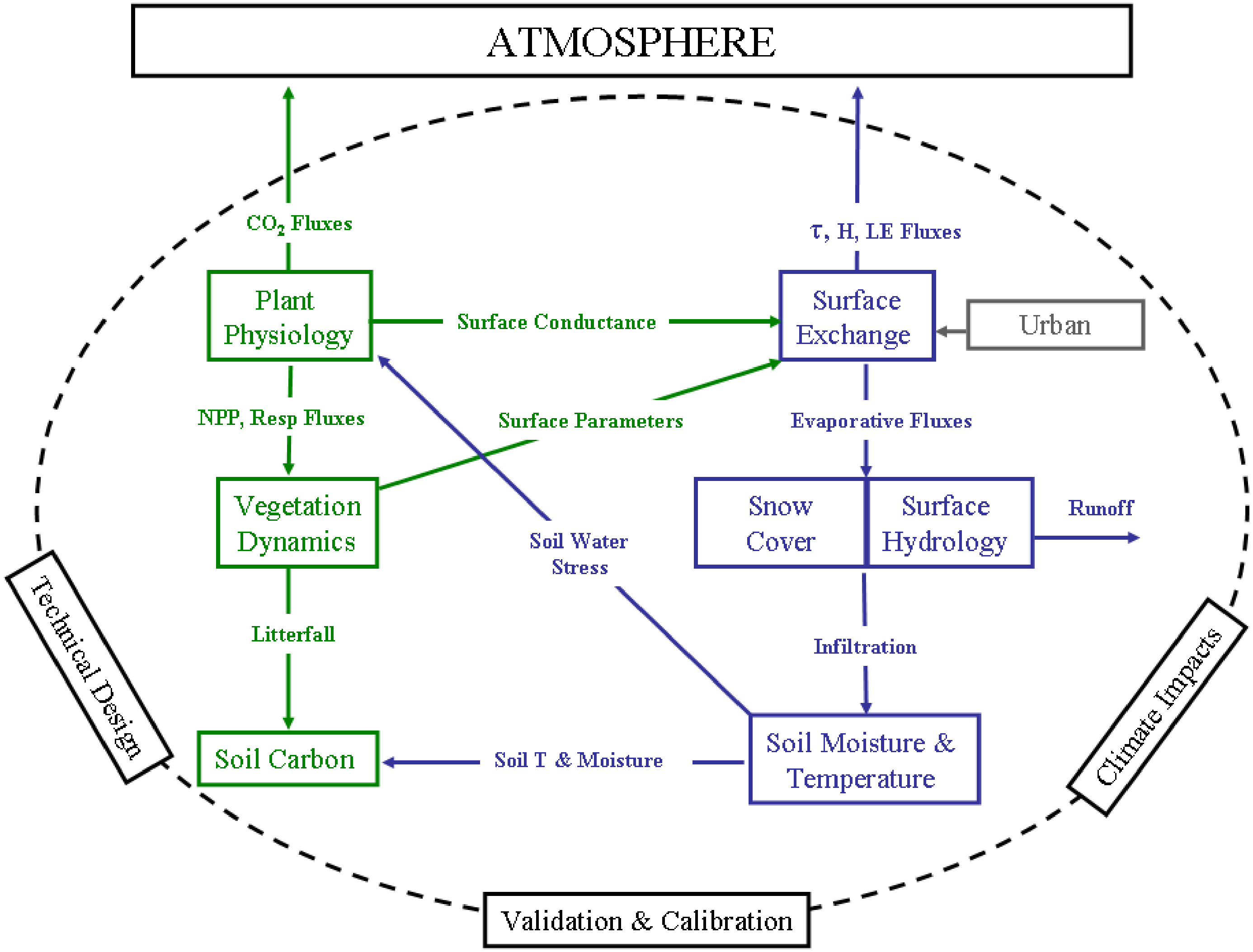
coupler
OASIS

ocean
NEMO

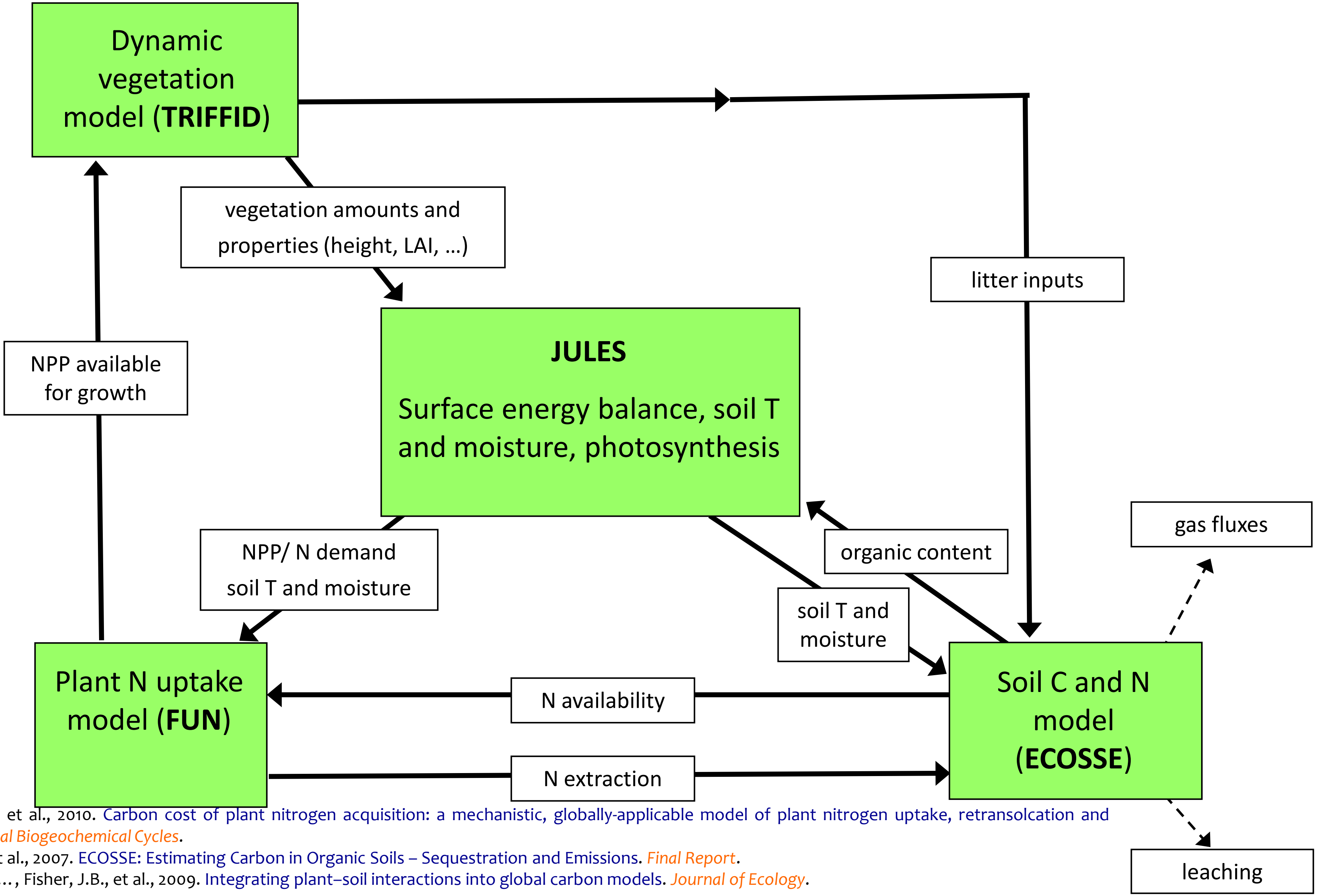
dynamics
OPA

BGC
TOP

sea ice
CICE


ATMOSPHERE
CO_2 Fluxes
τ, H, LE Fluxes
Plant Physiology
Surface Conductance
Surface Exchange
Urban
NPP, Resp Fluxes
Surface Parameters
Evaporative Fluxes
Vegetation Dynamics
Soil Water Stress
Snow Cover
Surface Hydrology
Runoff
Litterfall
Infiltration
Soil Carbon
Soil T & Moisture
Soil Moisture & Temperature
Technical Design
Climate Impacts
Validation & Calibration

JULES-ECOSSE-FUN



Dynamic vegetation model (**TRIFFID**)

vegetation amounts and properties (height, LAI, …)

litter inputs

NPP available for growth

JULES

Surface energy balance, soil T and moisture, photosynthesis

NPP/ N demand soil T and moisture

organic content

soil T and moisture

gas fluxes

Plant N uptake model (**FUN**)

N availability

N extraction

Soil C and N model (**ECOSSE**)

leaching

- Fisher, J.B., et al., 2010. Carbon cost of plant nitrogen acquisition: a mechanistic, globally-applicable model of plant nitrogen uptake, retransolcation and fixation. *Global Biogeochemical Cycles*.
- Smith, P., et al., 2007. ECOSSE: Estimating Carbon in Organic Soils – Sequestration and Emissions. *Final Report*.
- Ostle, N.J., … , Fisher, J.B., et al., 2009. Integrating plant–soil interactions into global carbon models. *Journal of Ecology*.

JULES-ECOSSE-FUN: inputs & outputs

Inputs from JULES-TRIFFID to ECOSSE:

- Litterfall C and N amounts;
- Soil temperature and moisture;
- Soil water flux;
- Root distribution;
- N deposition.

Outputs from ECOSSE:

- Soil C and N stores;
- CO_2, CH_4, N_2O, NO, N_2, NH_3;
- Leaching DOC, NO^-_3, DON.

Inputs from JULES, ECOSSE to FUN:

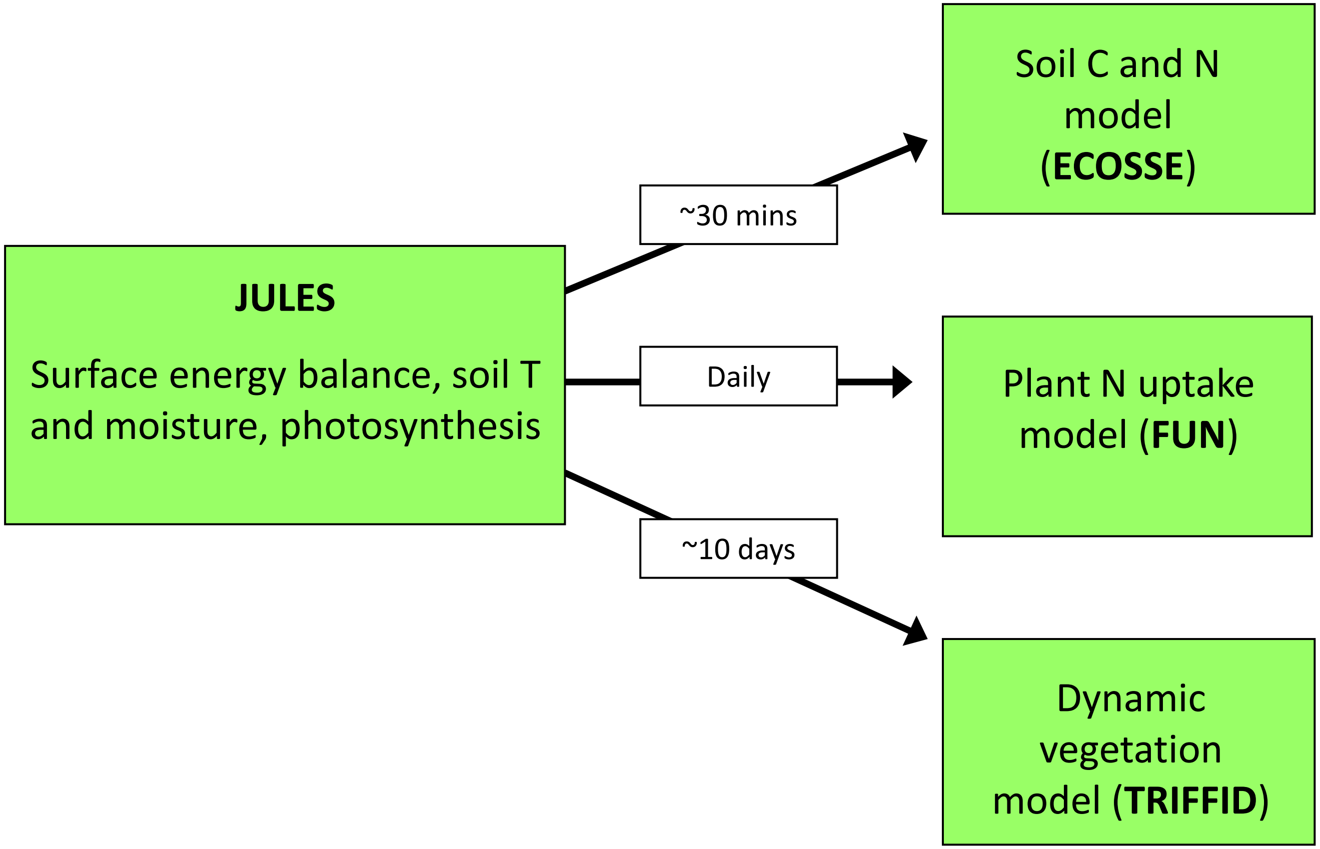
- Soil N stores;
- NPP;
- Transpiration rate;
- Root distribution;
- Leaf turnover;
- Vegetation C and N amounts.

Outputs from FUN:

- Updated NPP (available for growth) to JULES-TRIFFID;
- Updated plant respiration to JULES-TRIFFID ;
- N uptake amounts (to update soil N) to ECOSSE.

JULES-ECOSSE-FUN

Coupling frequencies between components



JULES

Surface energy balance, soil T and moisture, photosynthesis

~30 mins

Daily

~10 days

Soil C and N model (**ECOSSE**)

Plant N uptake model (**FUN**)

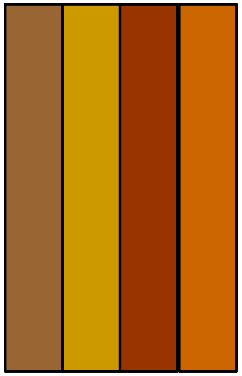
Dynamic vegetation model (**TRIFFID**)

J U L E S - E C O S S E - F U N

JULES with and without ECOSSE and FUN

JULES v3.2 (and before)

RothC



4 soil carbon pools

- Decomposable plant material
- Resistant plant material
- Biomass
- Humus

- No structure with depth.

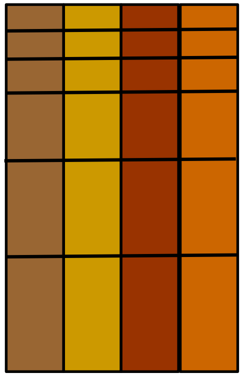
Plant N uptake: **None**

- Plant growth assumes no restriction by soil N.

JULES v(next) – ECOSSE and FUN additions

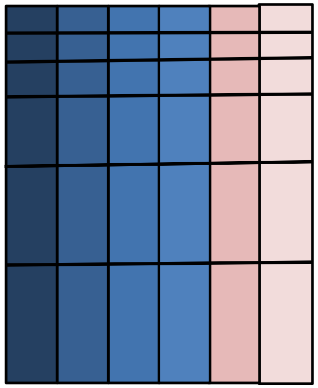
ECOSSE

- ECOSSE is (essentially) a layered combination of RothC and a soil N model: **RothC → SUNDIAL → ECOSSE**



4 soil carbon pools - layered

- Decomposable plant material
- Resistant plant material
- Biomass
- Humus



6 soil nitrogen pools

- Nitrate, ammonium + 4 pools as for C

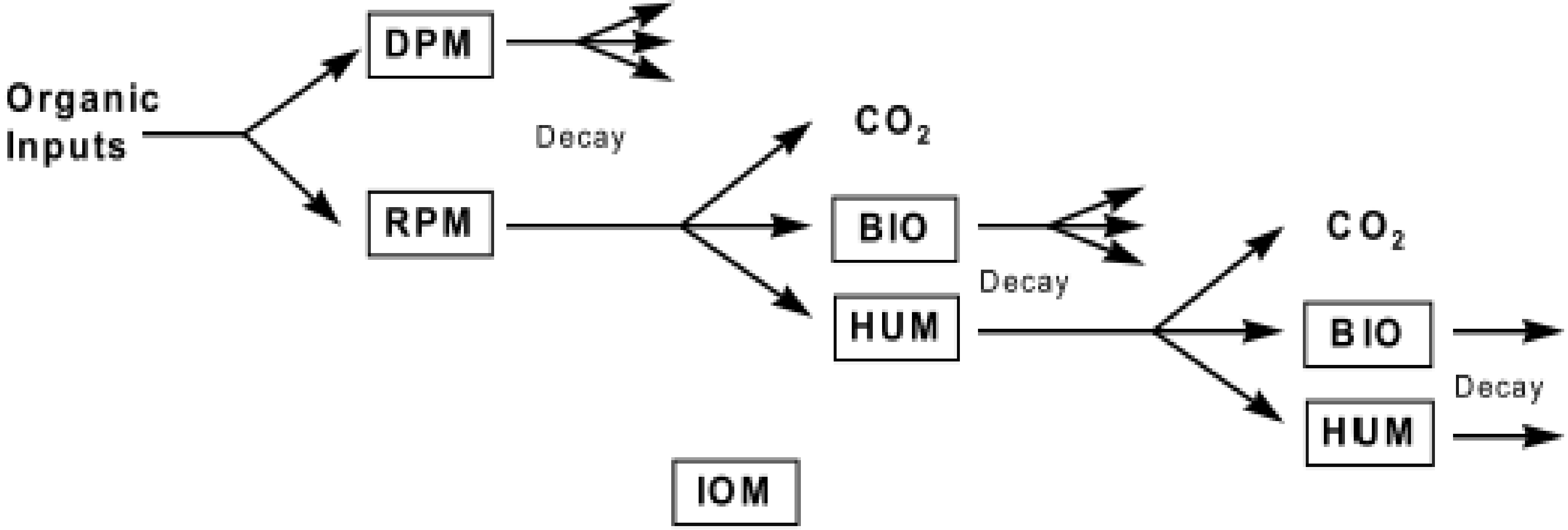
Plant N uptake: **FUN**

- Plants acquire N via passive and active mechanisms.
- Active uptake reduces NPP ➔ reduced plant growth.

ECOSSE

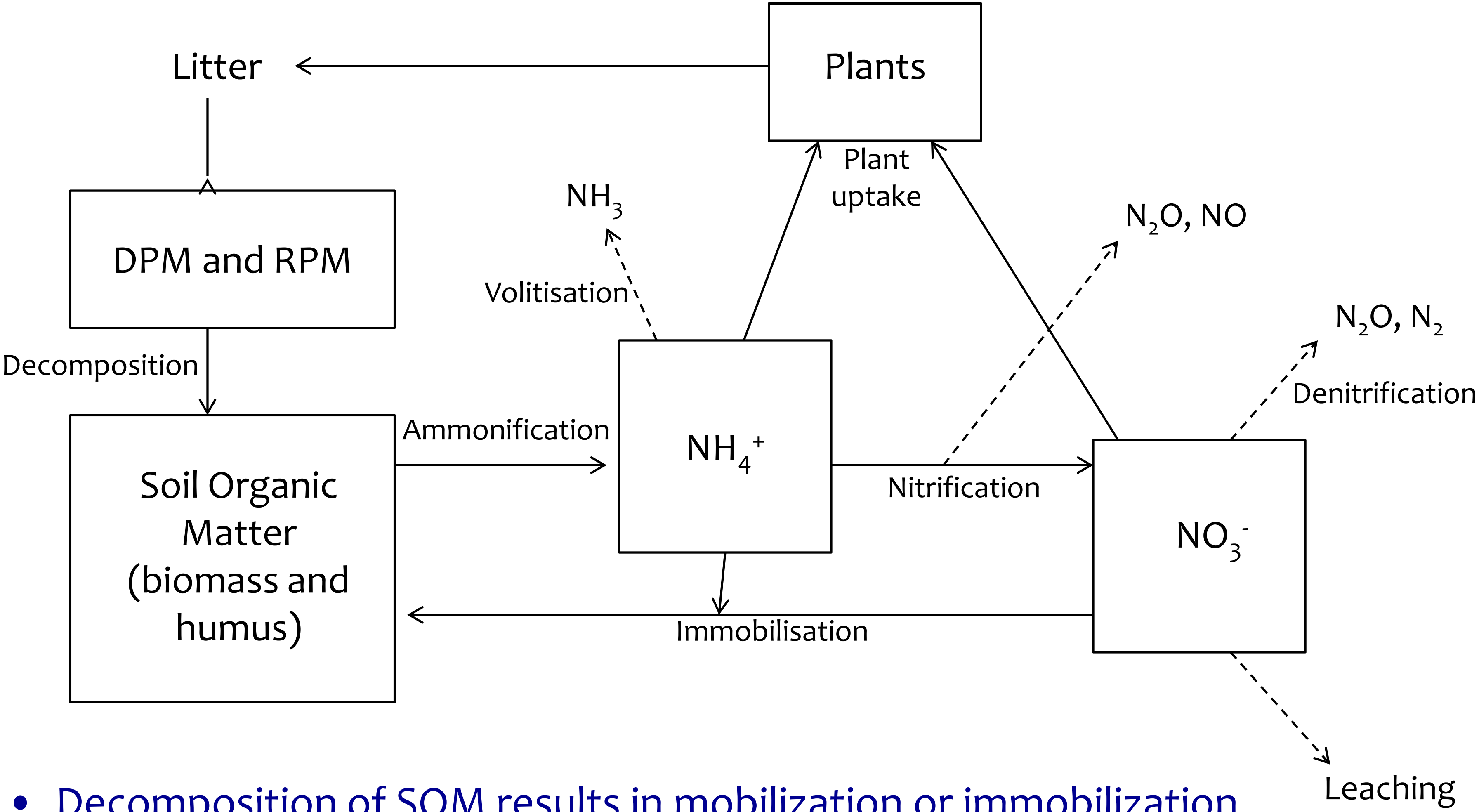
1^{st} order reactions

- Rates modified by soil T and moisture, and pH.
- Also anaerobic decomposition (CH_4).



RPM : Resistant Plant Material
DPM : Decomposable Plant Material
BIO : Microbial Biomass
HUM : Humified OM
IOM : Inert Organic Matter

ECOSSE



Litter

Plants

DPM and RPM

Decomposition

Soil Organic Matter (biomass and humus)

Ammonification

NH_4^+

NH_3

Volitisation

Plant uptake

N_2O, NO

Nitrification

NO_3^-

N_2O, N_2

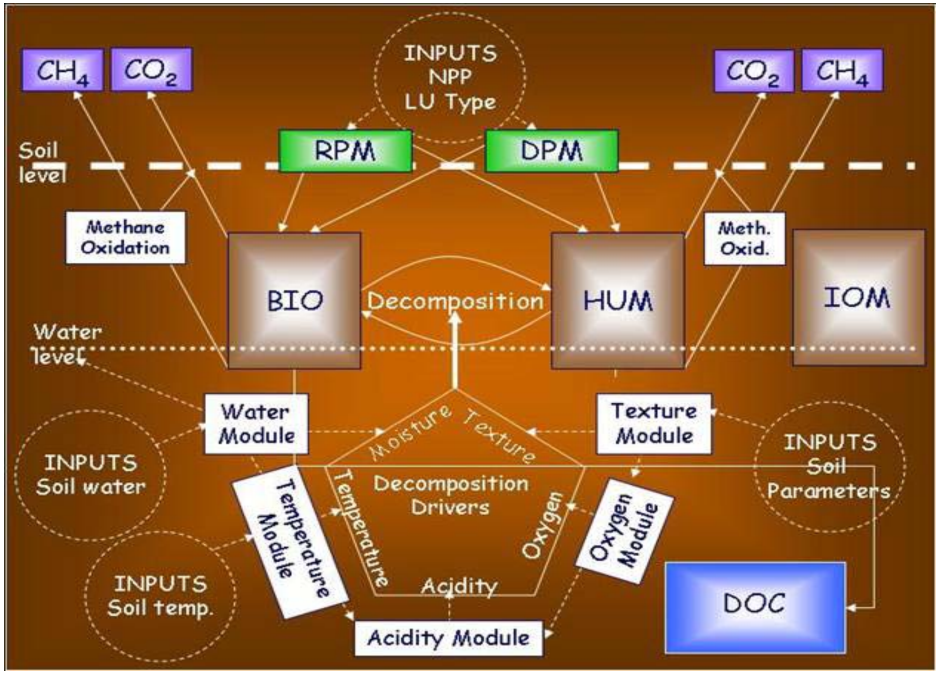
Denitrification

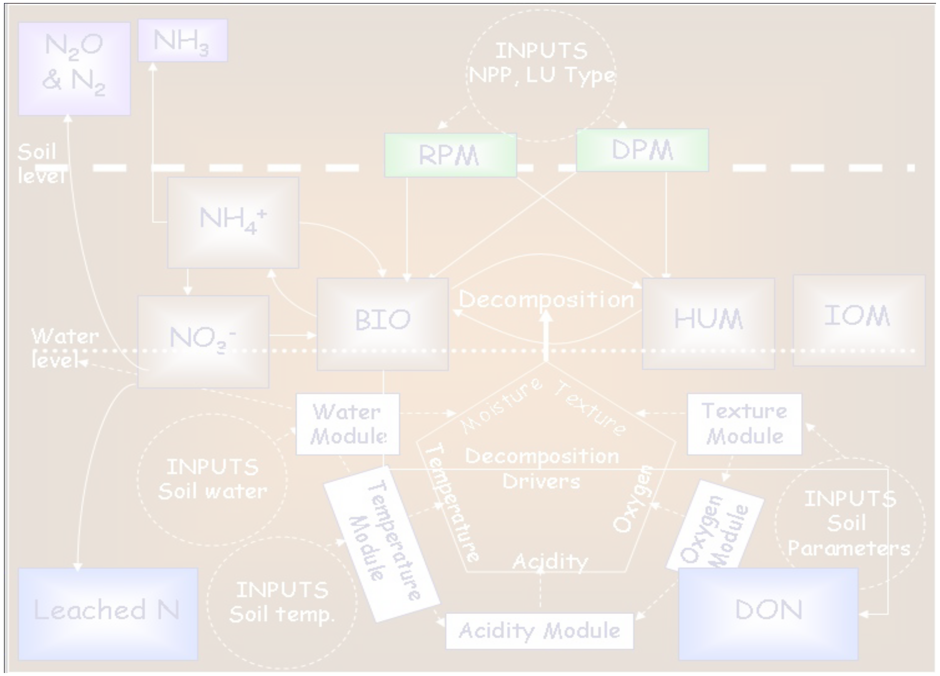
Immobilisation

Leaching

- Decomposition of SOM results in mobilization or immobilization of inorganic N (NO_3^- and NH_4^+) to maintain C:N.
- If insufficient N, decomposition is slowed and produces more CO_2.

ECOSSE: SOIL C & N





ECOSSE

Computational time

Based on tests with JULES2.0-ECOSSE at single site (ECOSSE called for each JULES timestep):

Number of ECOSSE layers	Relative CPU (wall clock) time	
0	1.0	
4	1.44	JULES default
10	1.67	
20	2.00	
60	2.89	Stand-alone ECOSSE

Notes:

- These were tests of run time; the results were clearly different.
- Simple tests, with moderate optimisation by compiler.
- Coupling less often (e.g. once every 1-2 hours) would be important in reducing CPU requirements.

PLANT N UPTAKE: FUN

Parameter	Notation	Units
Ability to fix	A_{fix}	TRUE or FALSE
Available soil N	N_{soil}	kg N m^{-2}
Total root biomass	C_{root}	kg C m^{-2}
Leaf N before senescence	N_{leaf}	kg N m^{-2}
Net primary production	C_{NPP}	kg C·m^{-2}·s^{-1}
Plant C:N ratio	$r_{C:N}$	kg C kg N^{-1}
Soil water depth	s_d	M
Soil temperature	T_{soil}	°C
Transpiration	E_T	M s^{-1}

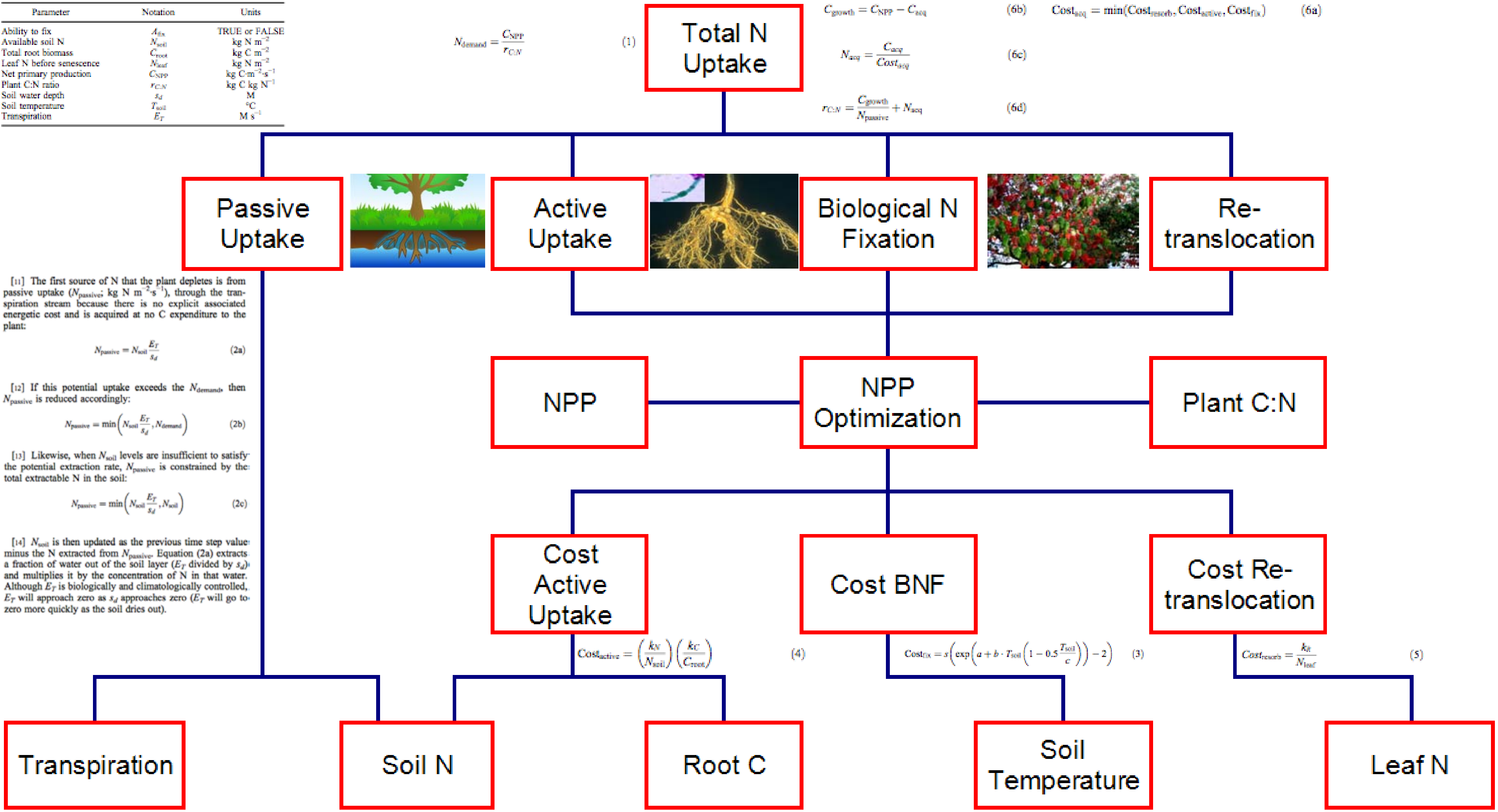
$$N_{\mathrm{demand}} = \frac{C_{\mathrm{NPP}}}{r_{C:N}} \qquad (1)$$

$$C_{\mathrm{growth}} = C_{\mathrm{NPP}} - C_{\mathrm{acq}} \qquad (6b)$$

$$\mathrm{Cost}_{\mathrm{acq}} = \min(\mathrm{Cost}_{\mathrm{resorb}}, \mathrm{Cost}_{\mathrm{active}}, \mathrm{Cost}_{\mathrm{fix}}) \qquad (6a)$$

$$N_{\mathrm{acq}} = \frac{C_{\mathrm{acq}}}{Cost_{\mathrm{acq}}} \qquad (6c)$$

$$r_{C:N} = \frac{C_{\mathrm{growth}}}{N_{\mathrm{passive}}} + N_{\mathrm{acq}} \qquad (6d)$$



$$\mathrm{Cost}_{\mathrm{active}} = \left(\frac{k_N}{N_{\mathrm{soil}}}\right)\left(\frac{k_C}{C_{\mathrm{root}}}\right) \qquad (4)$$

$$\mathrm{Cost}_{\mathrm{fix}} = s\left(\exp\left(a + b \cdot T_{\mathrm{soil}}\left(1 - 0.5\frac{T_{\mathrm{soil}}}{c}\right)\right) - 2\right) \qquad (3)$$

$$Cost_{\mathrm{resorb}} = \frac{k_R}{N_{\mathrm{leaf}}} \qquad (5)$$

[11] The first source of N that the plant depletes is from passive uptake (N_{passive}; kg N m^{-2}·s^{-1}), through the transpiration stream because there is no explicit associated energetic cost and is acquired at no C expenditure to the plant:

$$N_{\mathrm{passive}} = N_{\mathrm{soil}}\frac{E_T}{s_d} \qquad (2a)$$

[12] If this potential uptake exceeds the N_{demand}, then N_{passive} is reduced accordingly:

$$N_{\mathrm{passive}} = \min\left(N_{\mathrm{soil}}\frac{E_T}{s_d}, N_{\mathrm{demand}}\right) \qquad (2b)$$

[13] Likewise, when N_{soil} levels are insufficient to satisfy the potential extraction rate, N_{passive} is constrained by the total extractable N in the soil:

$$N_{\mathrm{passive}} = \min\left(N_{\mathrm{soil}}\frac{E_T}{s_d}, N_{\mathrm{soil}}\right) \qquad (2c)$$

[14] N_{soil} is then updated as the previous time step value minus the N extracted from N_{passive}. Equation (2a) extracts a fraction of water out of the soil layer (E_T divided by s_d) and multiplies it by the concentration of N in that water. Although E_T is biologically and climatologically controlled, E_T will approach zero as s_d approaches zero (E_T will go to zero more quickly as the soil dries out).

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

PLANT N UPTAKE: FUN

Carbon costs

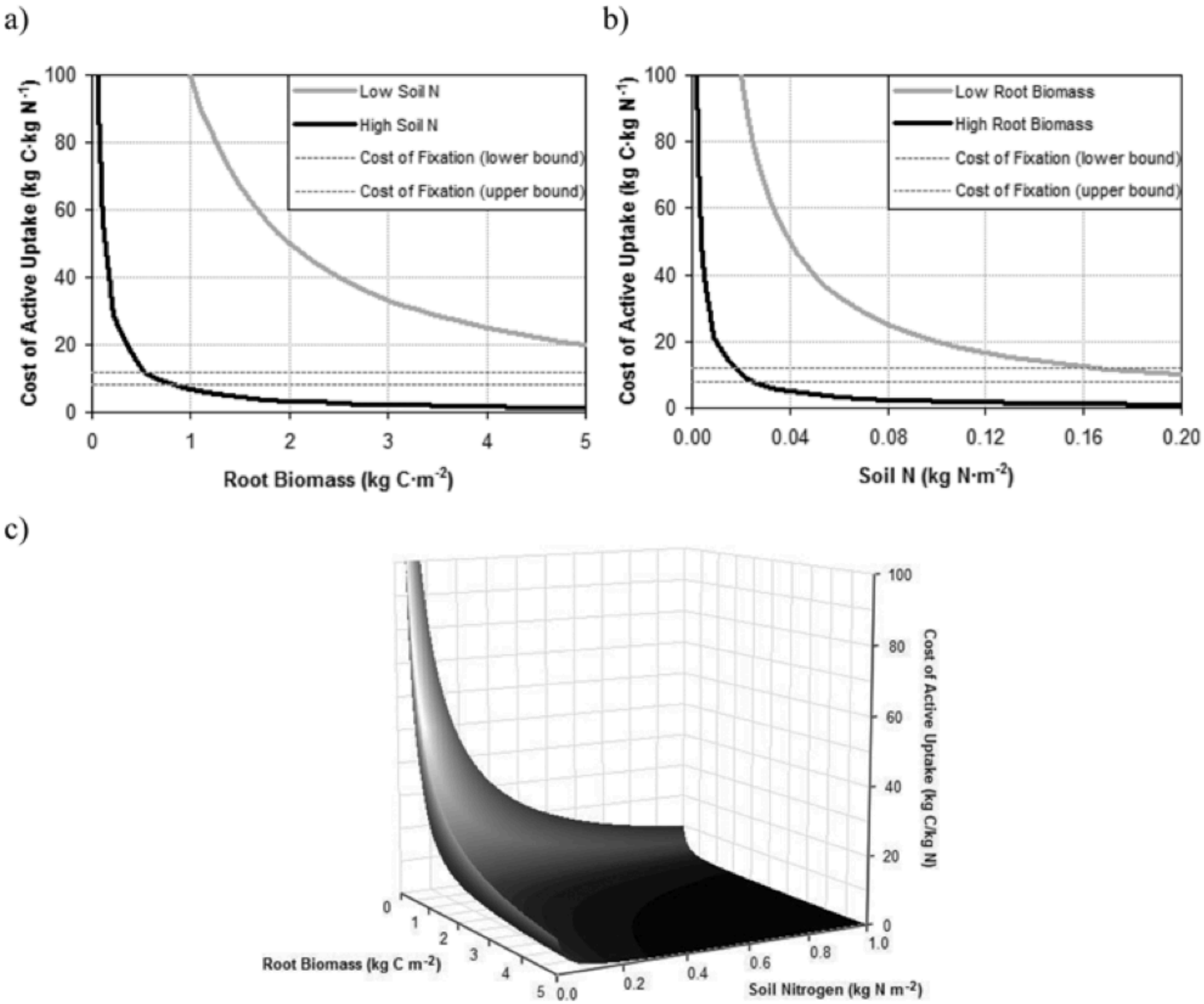
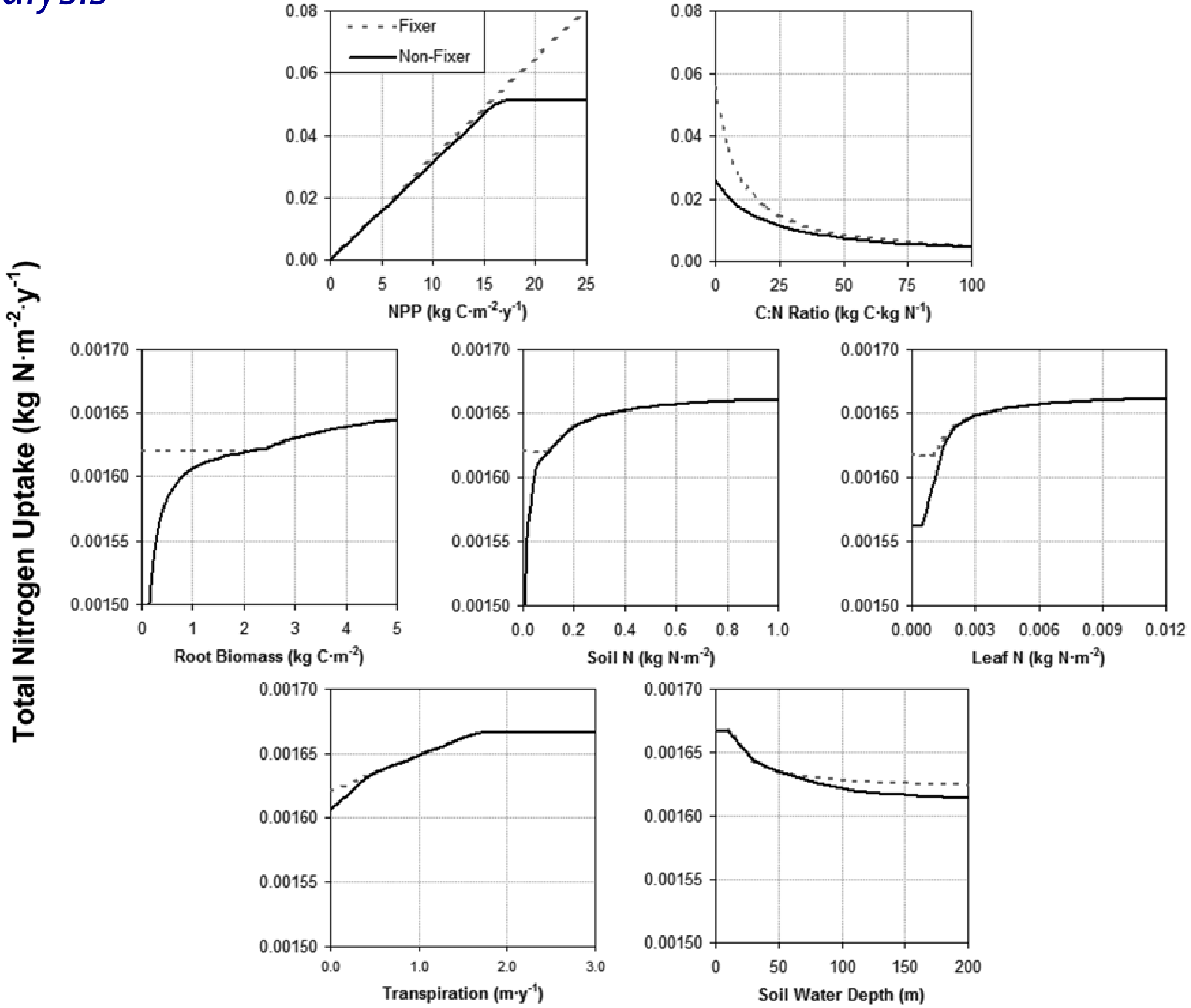


Figure 3. Cost of active nitrogen uptake ($\mathrm{Cost}_{\mathrm{active}}$) with range of cost of biological nitrogen fixation ($\mathrm{Cost}_{\mathrm{fix}}$) versus (a) soil nitrogen with low and high root biomass, (b) root biomass with low and high soil nitrogen, and (c) both soil nitrogen and root biomass.

PLANT N UPTAKE: FUN

GB1014 FISHER ET AL.: CARBON COST OF PLANT N ACQUISITION GB1014

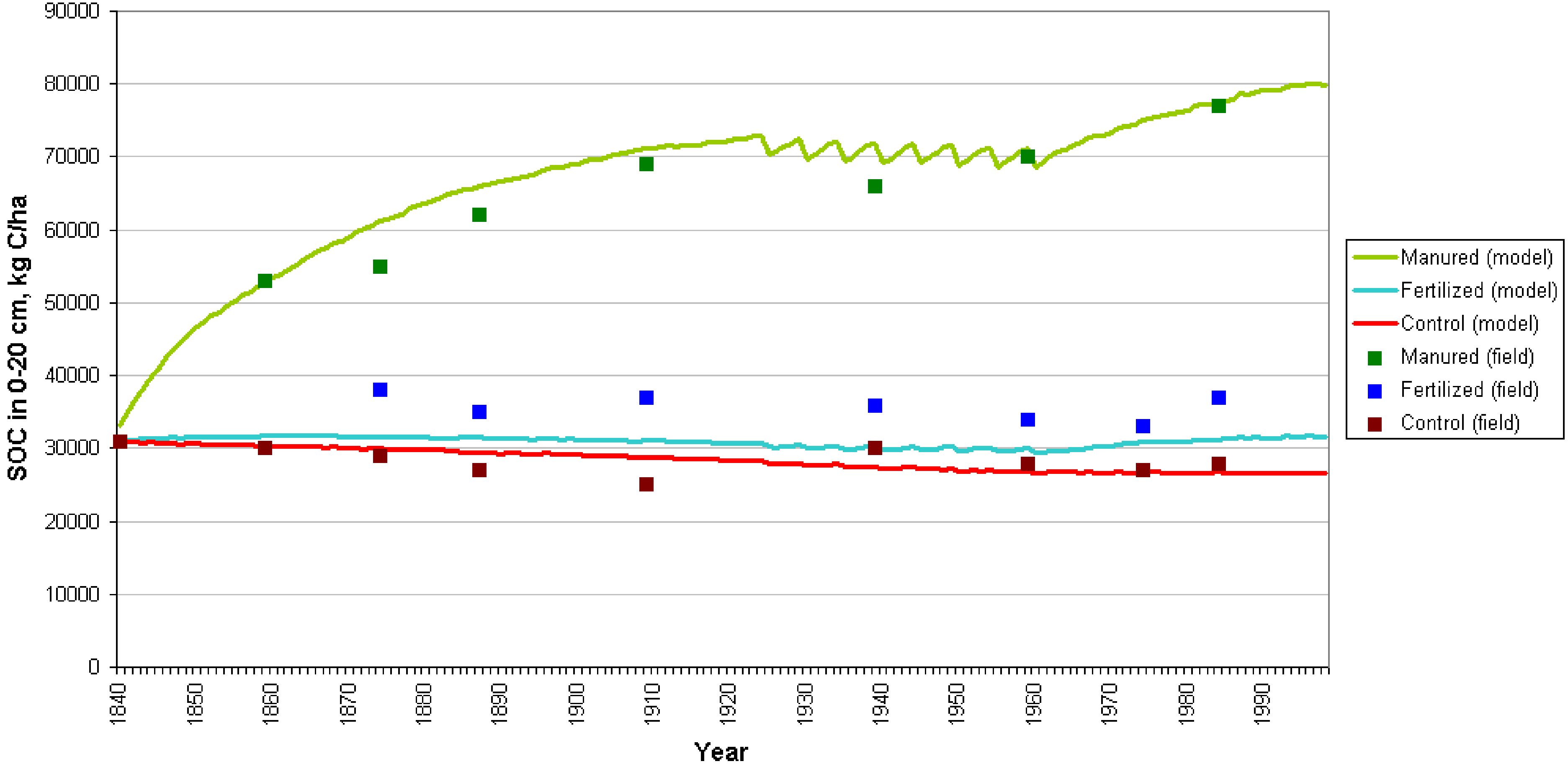
Sensitivity Analysis



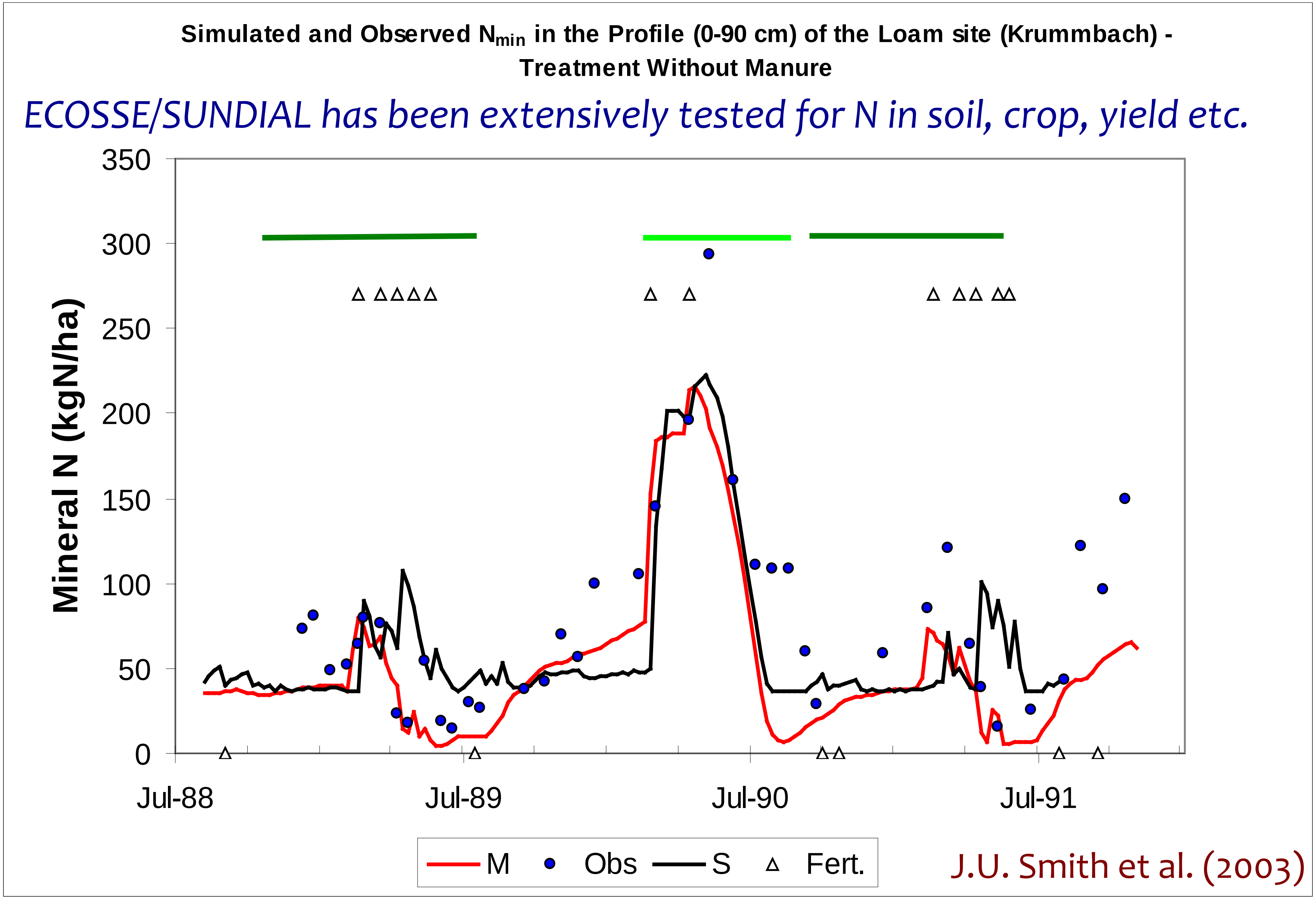
RESULTS: ECOSSE

160 years of SOC at Rothamsted

160-year soil organic carbon dynamics at a winter wheat field with different treatments in Rothamsted Agricultural Station in UK from 1840-1990



ECOSSE: MINERAL N



Simulated and Observed N_{min} in the Profile (0-90 cm) of the Loam site (Krummbach) - Treatment Without Manure

ECOSSE/SUNDIAL has been extensively tested for N in soil, crop, yield etc.

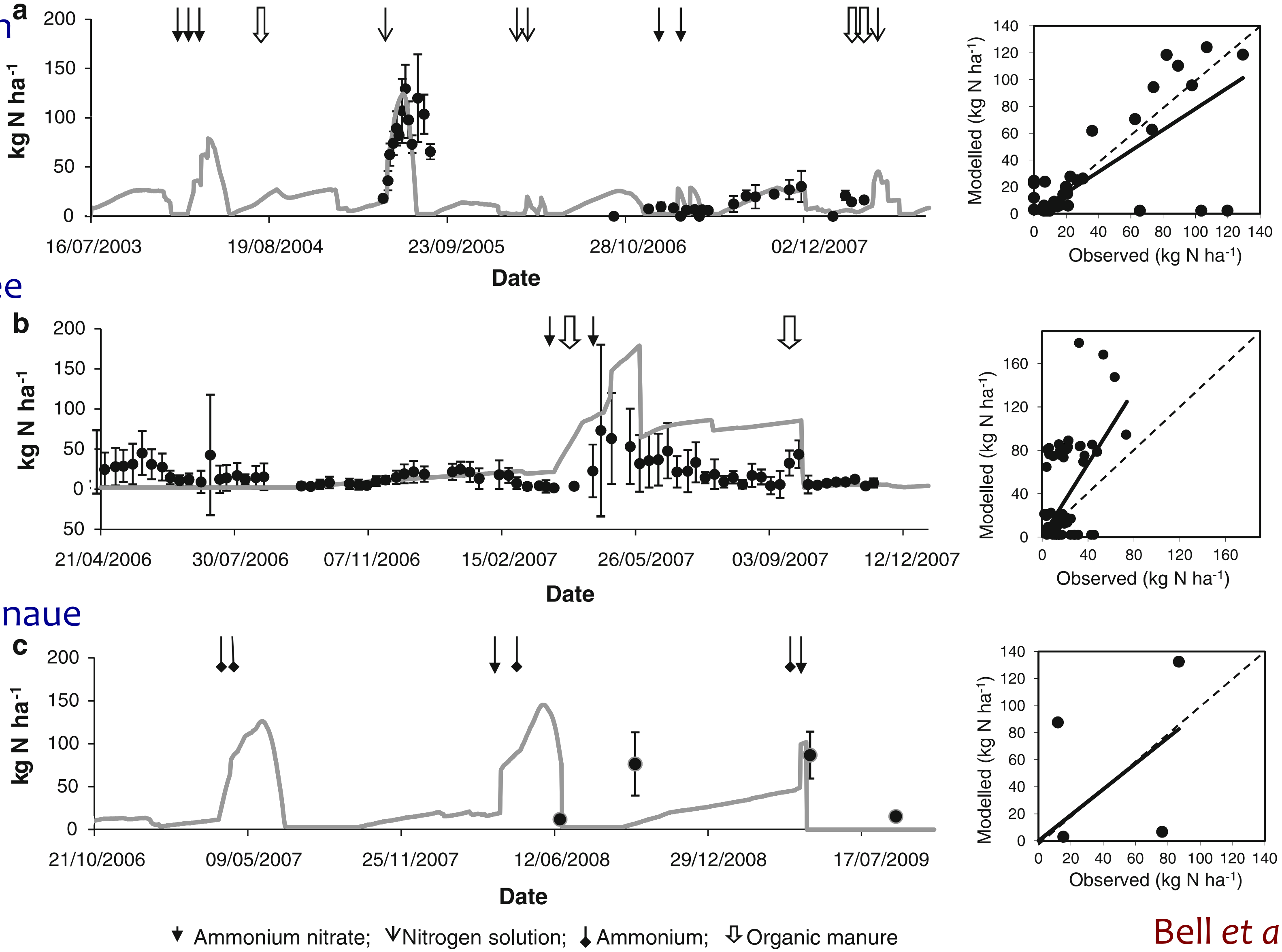
J.U. Smith et al. (2003)

ECOSSE: NO_3^-

Grignon

Gebesee

Paulinenaue



Bell *et al.* (2012)

ECOSSE: NH_4^+

Grignon

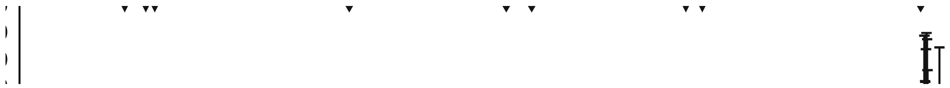
Gebesee

Paulinenaue

Bell *et al.* (2012)

ECOSSE: N_2O

Grignon



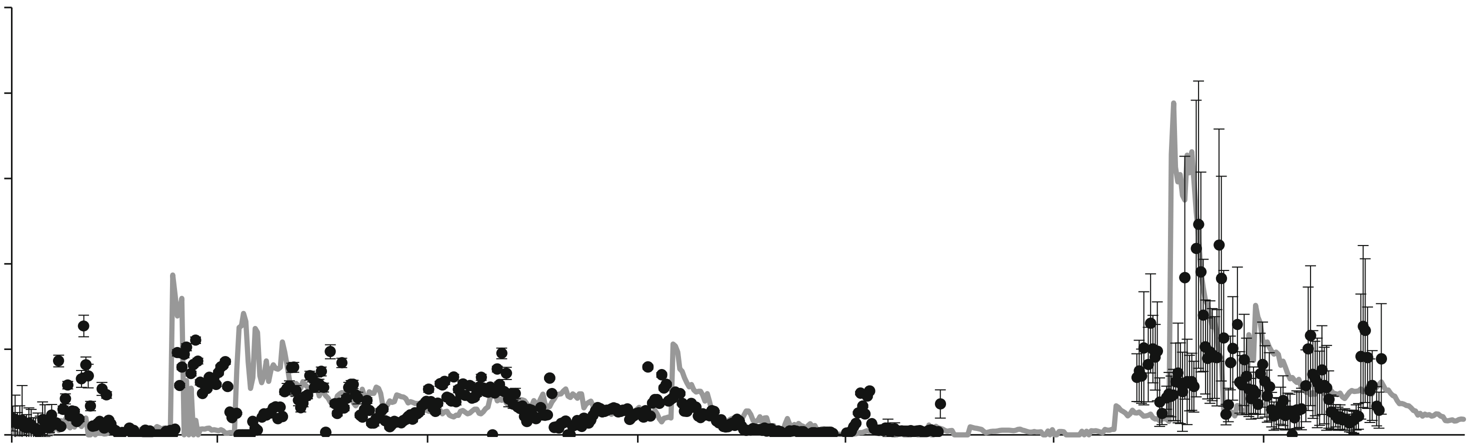
Gebesee

Paulinenaue

Bell *et al.* (2012)

ECOSSE: NO

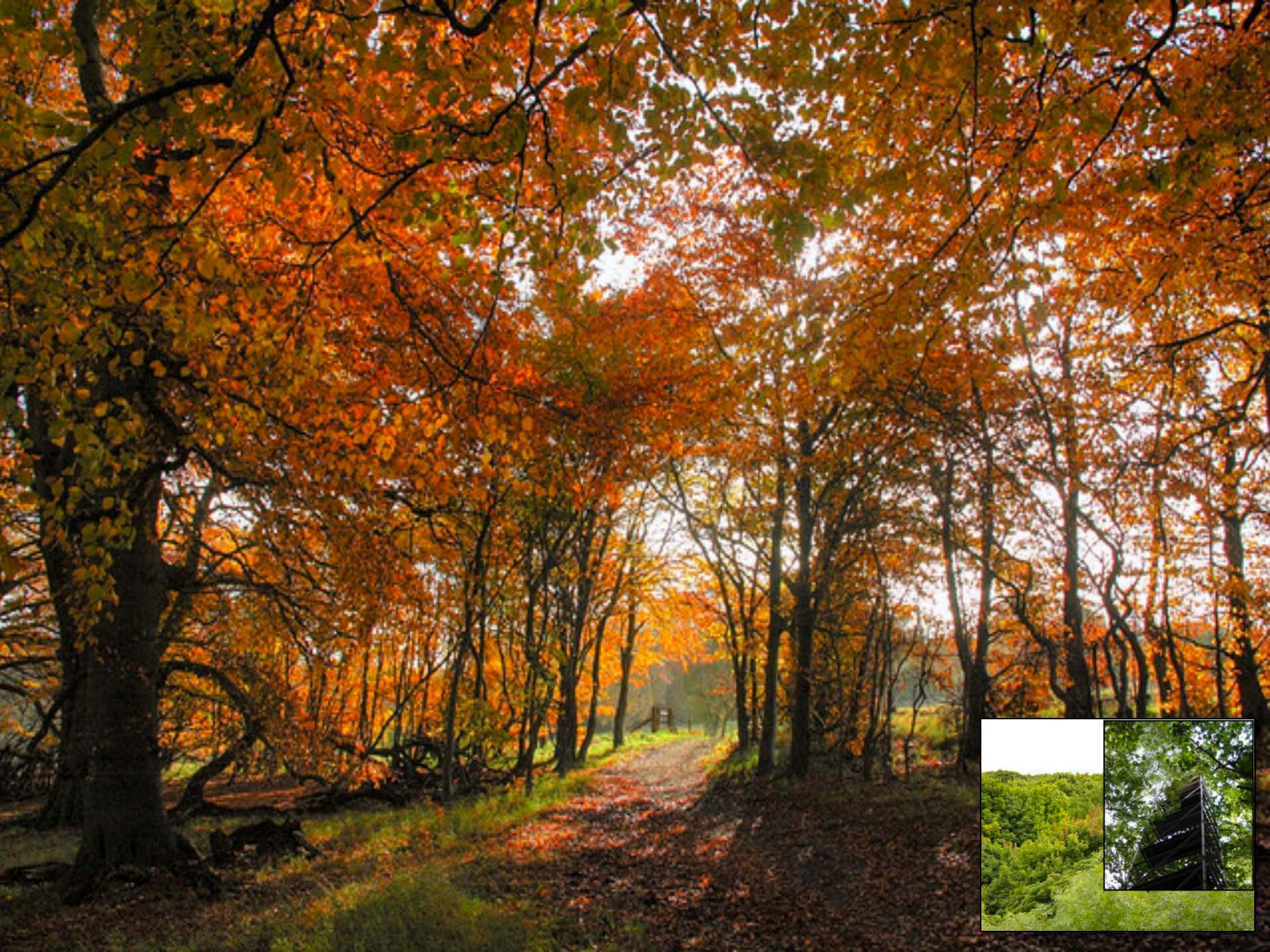
Grignon



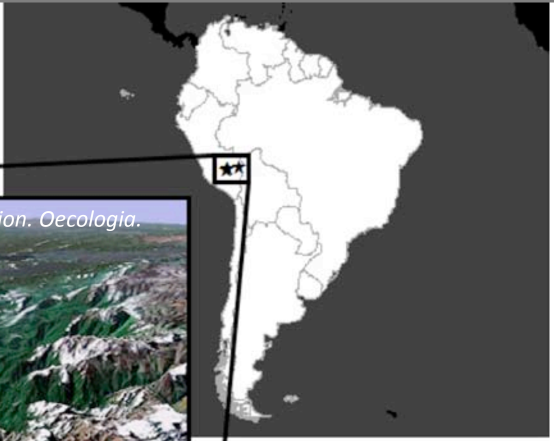
Bell *et al.* (2012)

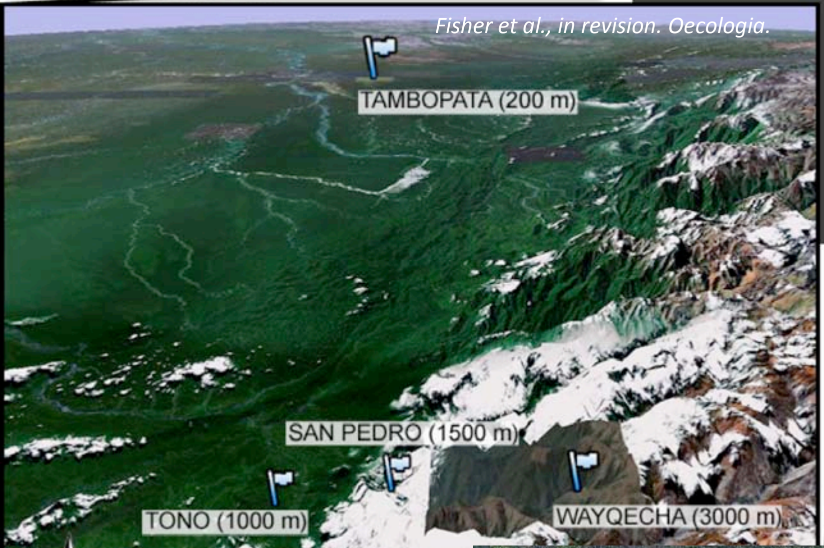
RESULTS: FUN


ORNL5774-2000

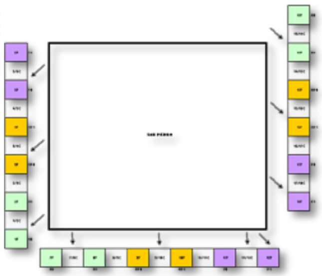


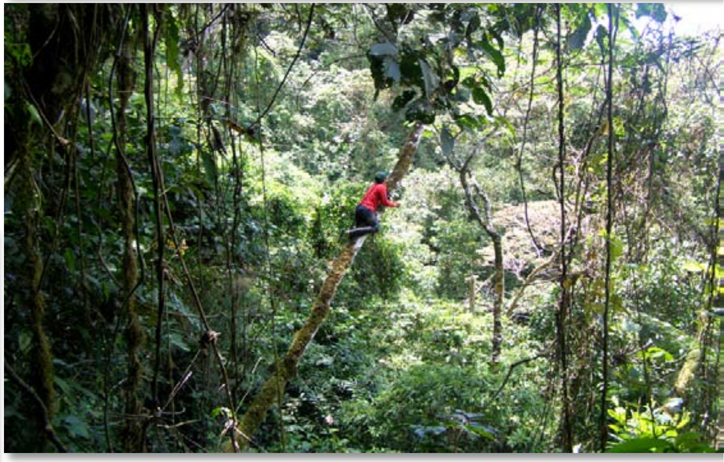
FUN: DATA TEST



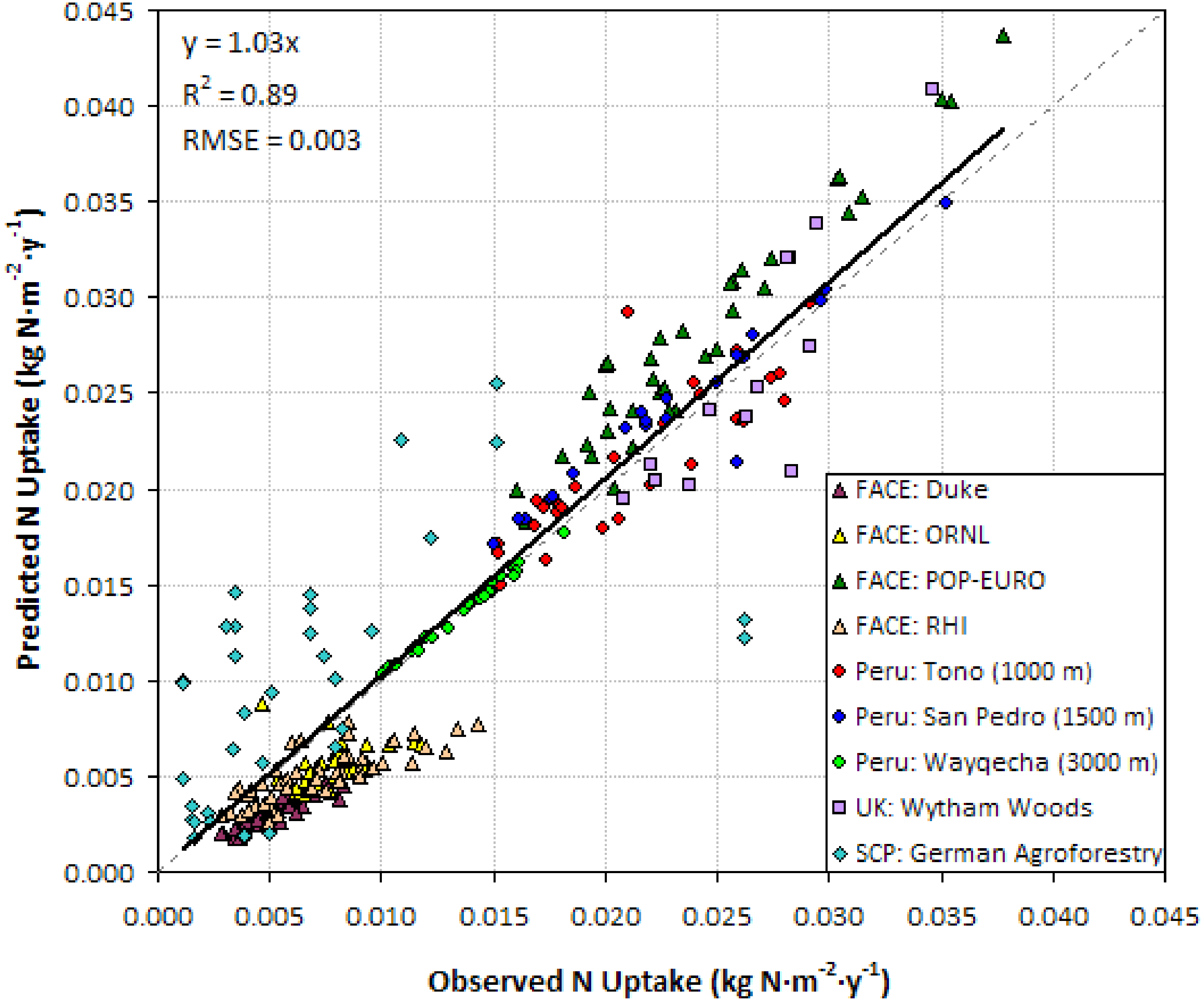


Fisher et al., in revision. Oecologia.

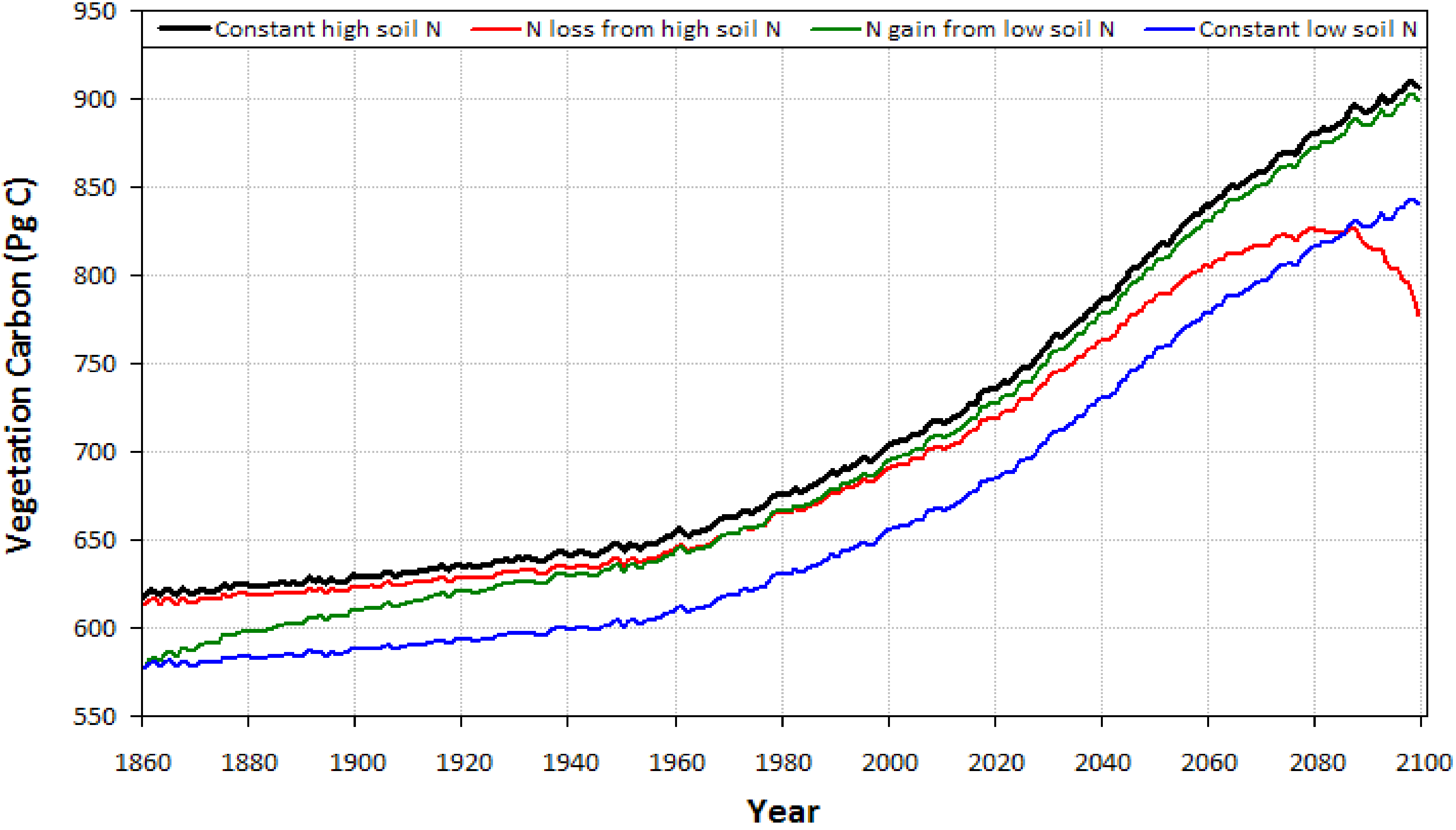




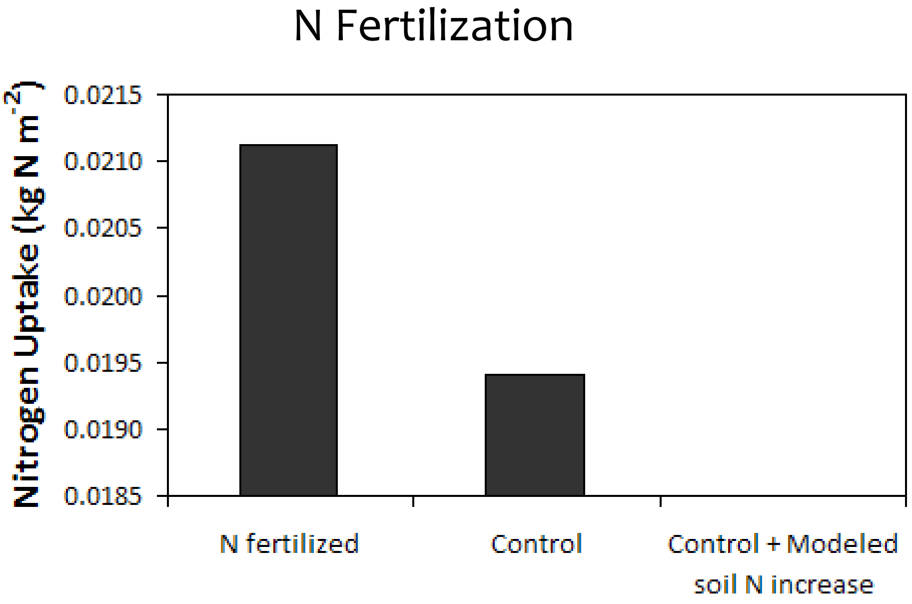
FUN: DATA TEST

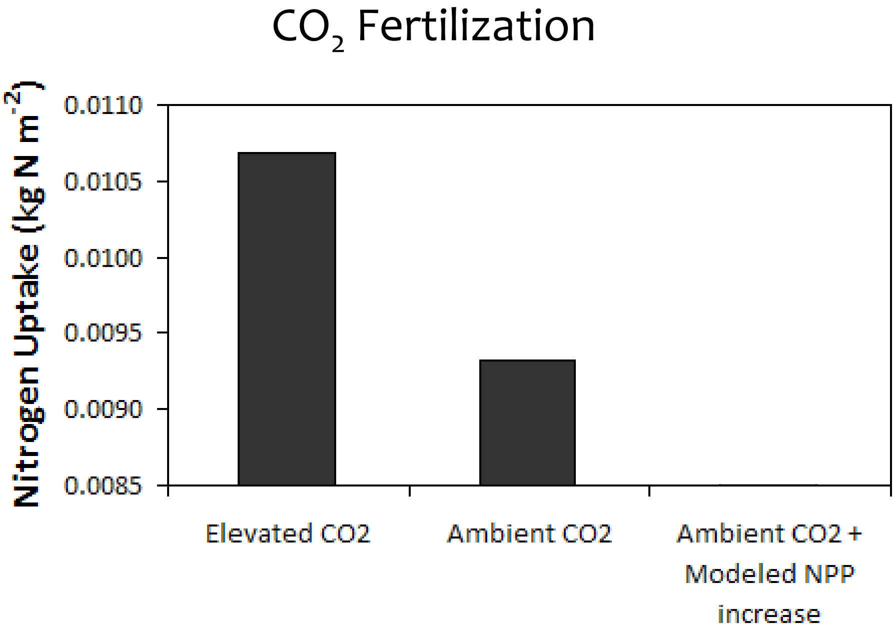


FUN IMPACT ON GLOBAL VEG C

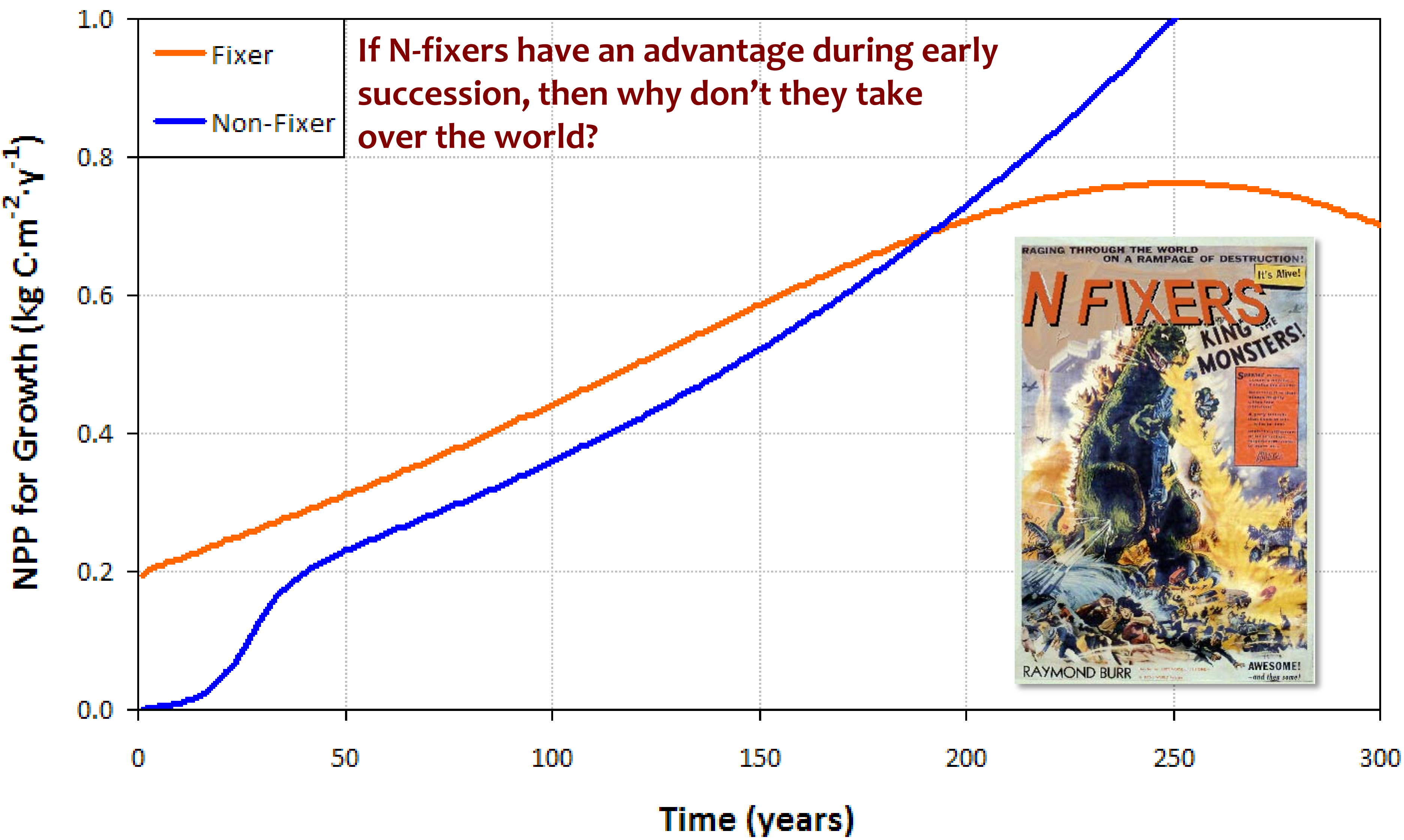


PREDICT EXPERIMENTS





N FIXERS



If N-fixers have an advantage during early succession, then why don't they take over the world?

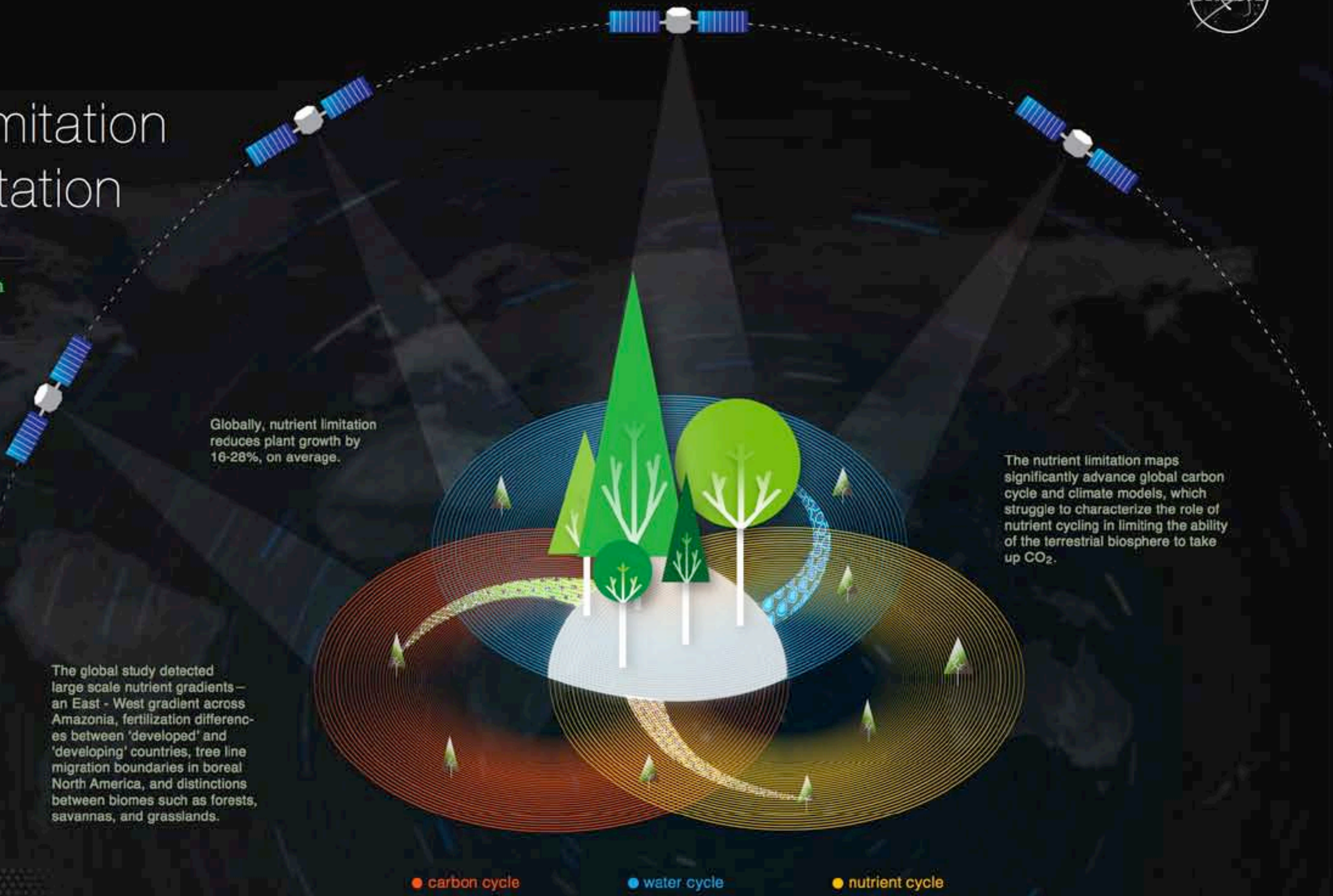
ON-GOING PROJECTS, NEXT STEPS

National Aeronautics and Space Administration

Global Nutrient Limitation In Terrestrial Vegetation

NASA has determined the limits to vegetation growth from soil nutrients availability

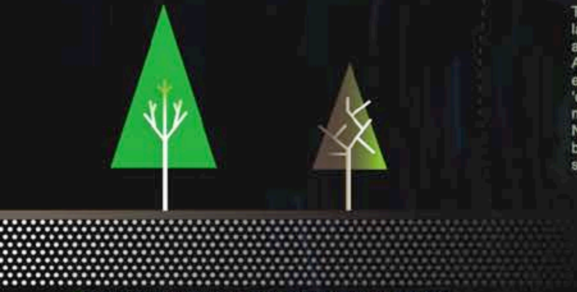
Using 19 years of remote sensing data, a research team led by Dr. Josh Fisher (JPL) calculated maximum possible vegetation productivity – as determined by available water and light – then cross-compared that theoretical maximum with observed vegetation productivity. Where actual vegetation productivity was less than the theoretical maximum, the researchers found vegetation was nutrient limited, after accounting for disturbance.



Globally, nutrient limitation reduces plant growth by 16-28%, on average.

The global study detected large scale nutrient gradients – an East - West gradient across Amazonia, fertilization differences between 'developed' and 'developing' countries, tree line migration boundaries in boreal North America, and distinctions between biomes such as forests, savannas, and grasslands.

The nutrient limitation maps significantly advance global carbon cycle and climate models, which struggle to characterize the role of nutrient cycling in limiting the ability of the terrestrial biosphere to take up CO_2.



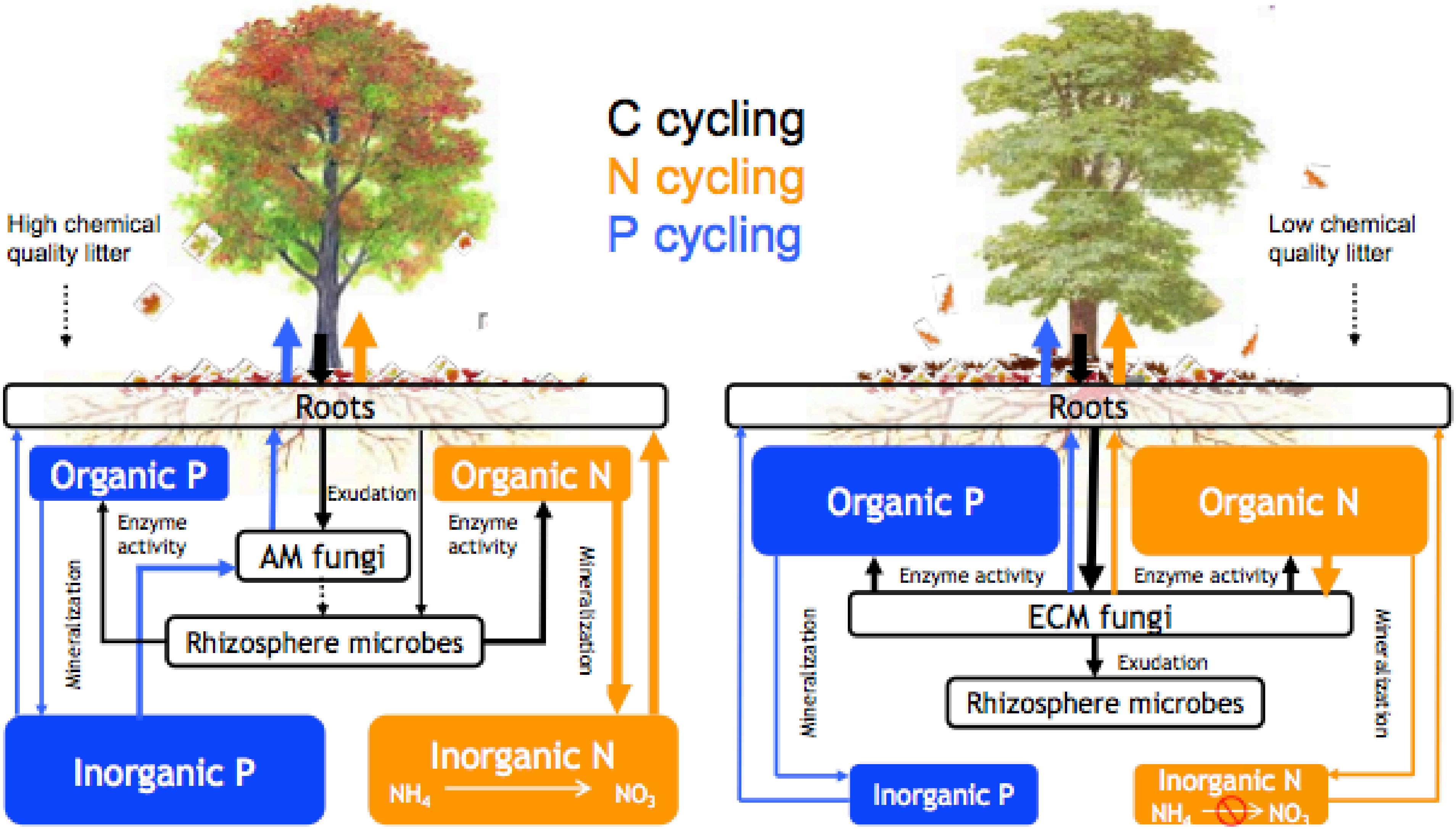
Plant growth is enhanced or limited by the amounts of nutrients in the soil.

Joshua B. Fisher | Jet Propulsion Laboratory
Grayson Badgley | Stanford University
Eleanor Blyth | UK Centre for Ecology & Hydrology

www.nasa.gov

AM tree species
Inorganic nutrient economy; *fast* RAMP

ECM tree species
Organic nutrient economy; *slow* RAMP


C cycling
N cycling
P cycling

High chemical quality litter
Roots
Exudation
Organic P
Organic N
Enzyme activity
Enzyme activity
AM fungi
Mineralization
Mineralization
Rhizosphere microbes
Inorganic P
Inorganic N
NH_4 → NO_3

Low chemical quality litter
Roots
Organic P
Organic N
Enzyme activity
Enzyme activity
ECM fungi
Exudation
Rhizosphere microbes
Mineralization
Mineralization
Inorganic P
Inorganic N
NH_4 → NO_3

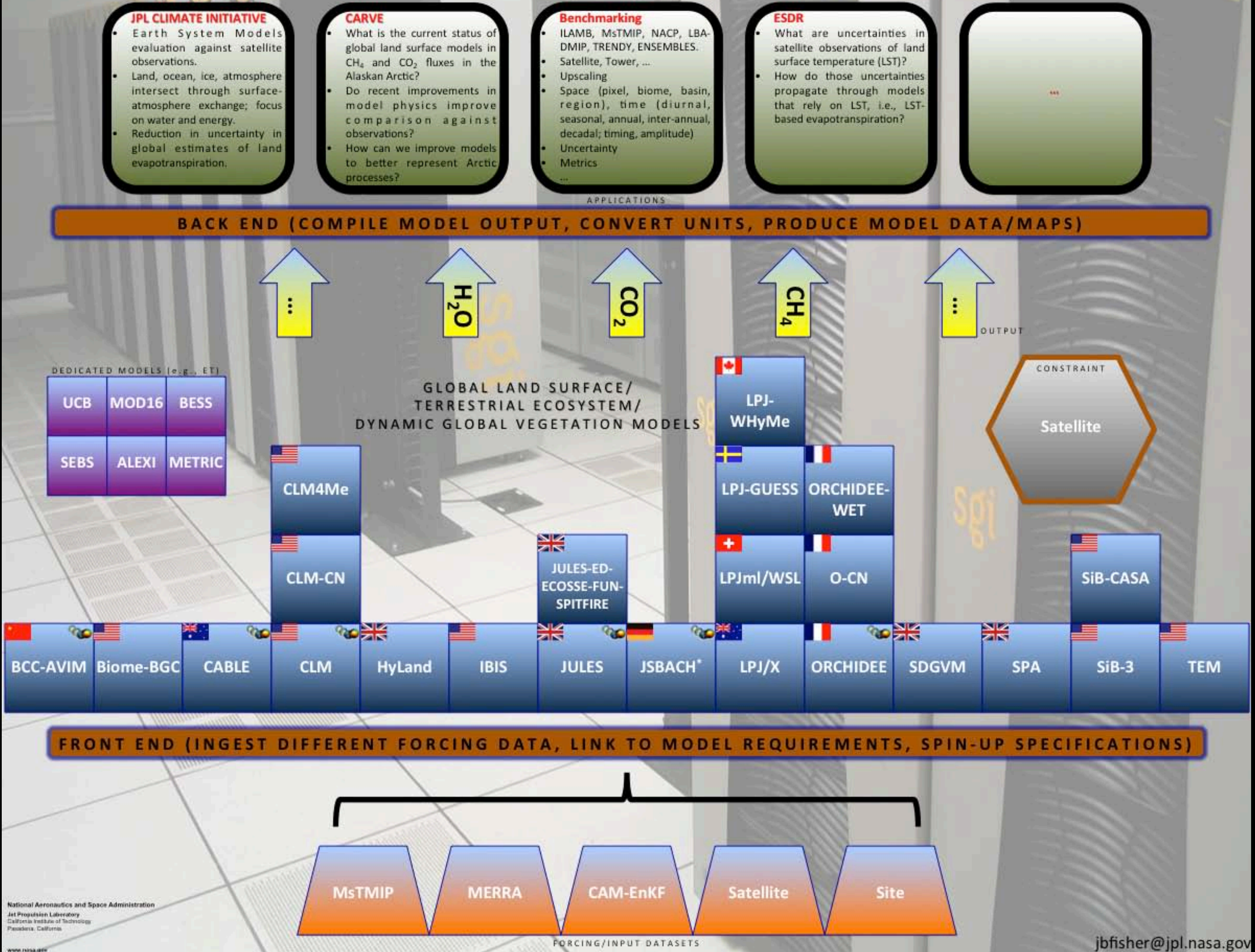
Met Office

National Aeronautics and Space Administration

ENSEMBLE LAND SURFACE MODELING AT JPL

JOSHUA B. FISHER, GARY BLOCK, ALEXANDRE GUILLAUME, KANISKA MALLICK,
JUNG-EUN LEE, JUNJIE LIU, KEVIN BOWMAN, CHIP MILLER, GRAEME STEPHENS

ALMUT ARNETH, IAN BAKER, PHILIPPE CIAIS, DOUG CLARK,
JON FOLEY, DEBORAH HUNTZINGER, CHRIS JONES, JOHN KIMBALL, PETER
LEVY, WEIPING LI, MARK LOMAS, BEN POULTER, COLIN PRENTICE, BILL RILEY,
KEVIN SCHAEFER, STEPHEN SITCH, YINGPING WANG, RITA WANIA, MATT WILLIAMS



JPL CLIMATE INITIATIVE

- Earth System Models evaluation against satellite observations.
- Land, ocean, ice, atmosphere intersect through surface-atmosphere exchange; focus on water and energy.
- Reduction in uncertainty in global estimates of land evapotranspiration.

CARVE

- What is the current status of global land surface models in CH_4 and CO_2 fluxes in the Alaskan Arctic?
- Do recent improvements in model physics improve comparison against observations?
- How can we improve models to better represent Arctic processes?

Benchmarking

- ILAMB, MsTMIP, NACP, LBA-DMIP, TRENDY, ENSEMBLES.
- Satellite, Tower, …
- Upscaling
- Space (pixel, biome, basin, region), time (diurnal, seasonal, annual, inter-annual, decadal; timing, amplitude)
- Uncertainty
- Metrics
- …

ESDR

- What are uncertainties in satellite observations of land surface temperature (LST)?
- How do those uncertainties propagate through models that rely on LST, i.e., LST-based evapotranspiration?

…

APPLICATIONS

BACK END (COMPILE MODEL OUTPUT, CONVERT UNITS, PRODUCE MODEL DATA/MAPS)

…

H_2O

CO_2

CH_4

…

OUTPUT

DEDICATED MODELS (e.g., ET)

UCB	MOD16	BESS
SEBS	ALEXI	METRIC

GLOBAL LAND SURFACE/
TERRESTRIAL ECOSYSTEM/
DYNAMIC GLOBAL VEGETATION MODELS

CLM4Me

CLM-CN

JULES-ED-ECOSSE-FUN-SPITFIRE

LPJ-WHyMe

LPJ-GUESS

ORCHIDEE-WET

LPJml/WSL

O-CN

SiB-CASA

BCC-AVIM | Biome-BGC | CABLE | CLM | HyLand | IBIS | JULES | JSBACH* | LPJ/X | ORCHIDEE | SDGVM | SPA | SiB-3 | TEM

CONSTRAINT

Satellite

FRONT END (INGEST DIFFERENT FORCING DATA, LINK TO MODEL REQUIREMENTS, SPIN-UP SPECIFICATIONS)

MsTMIP

MERRA

CAM-EnKF

Satellite

Site

FORCING/INPUT DATASETS

National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

www.nasa.gov

jbfisher@jpl.nasa.gov

Nitrogen cycling in the Hadley Centre land surface model (JULES)

JOSHUA B. FISHER
DOUGLAS CLARK
TE SMITH

Thank you!

Vial of glowing ultrapure nitrogen, N_2

National Aeronautics and Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

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- *DOE BER Terrestrial Ecosystem Science*
- *NSF Ecosystem Science*
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