Nitrogen Cycling
and
Soil modeling

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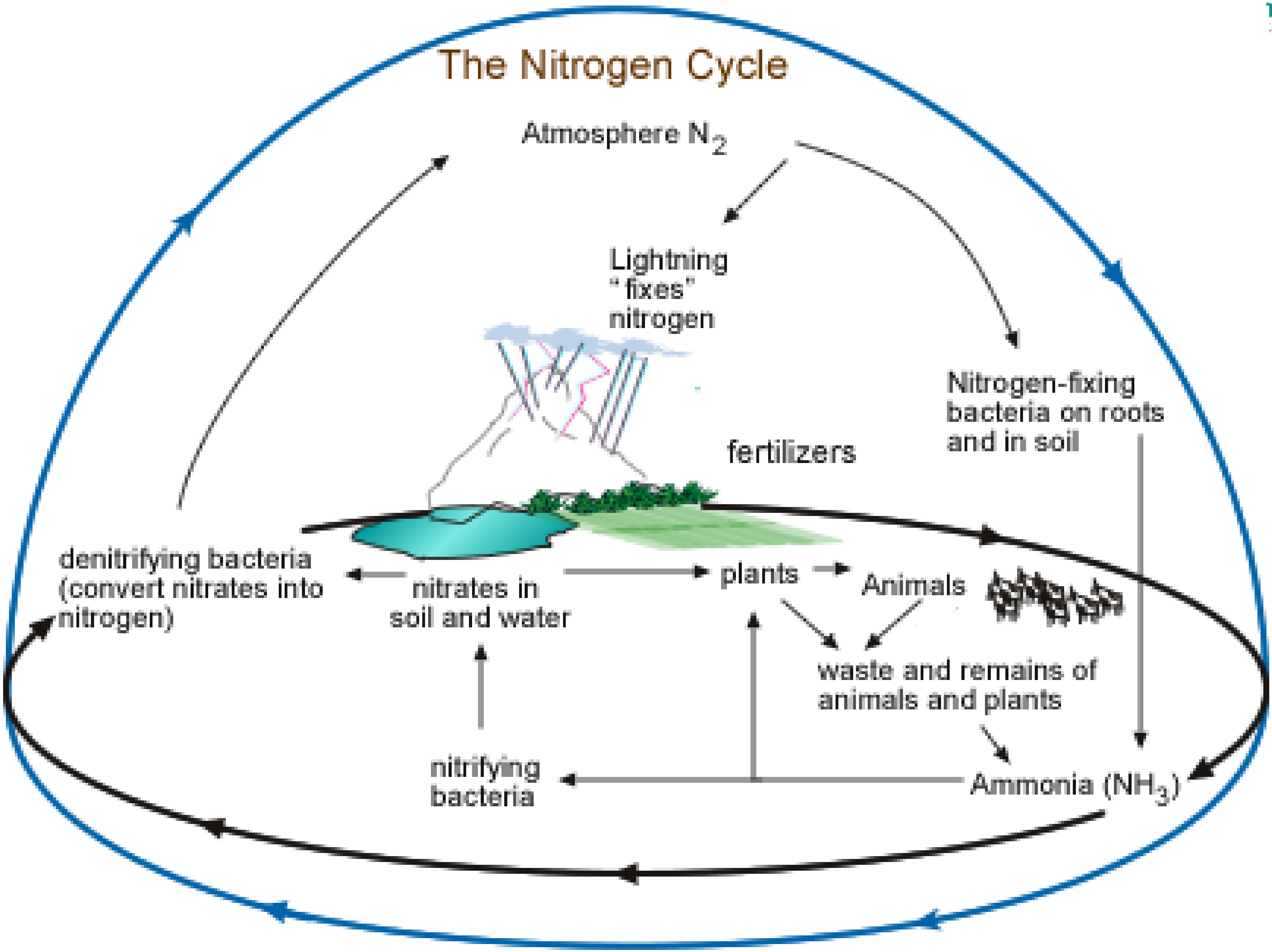
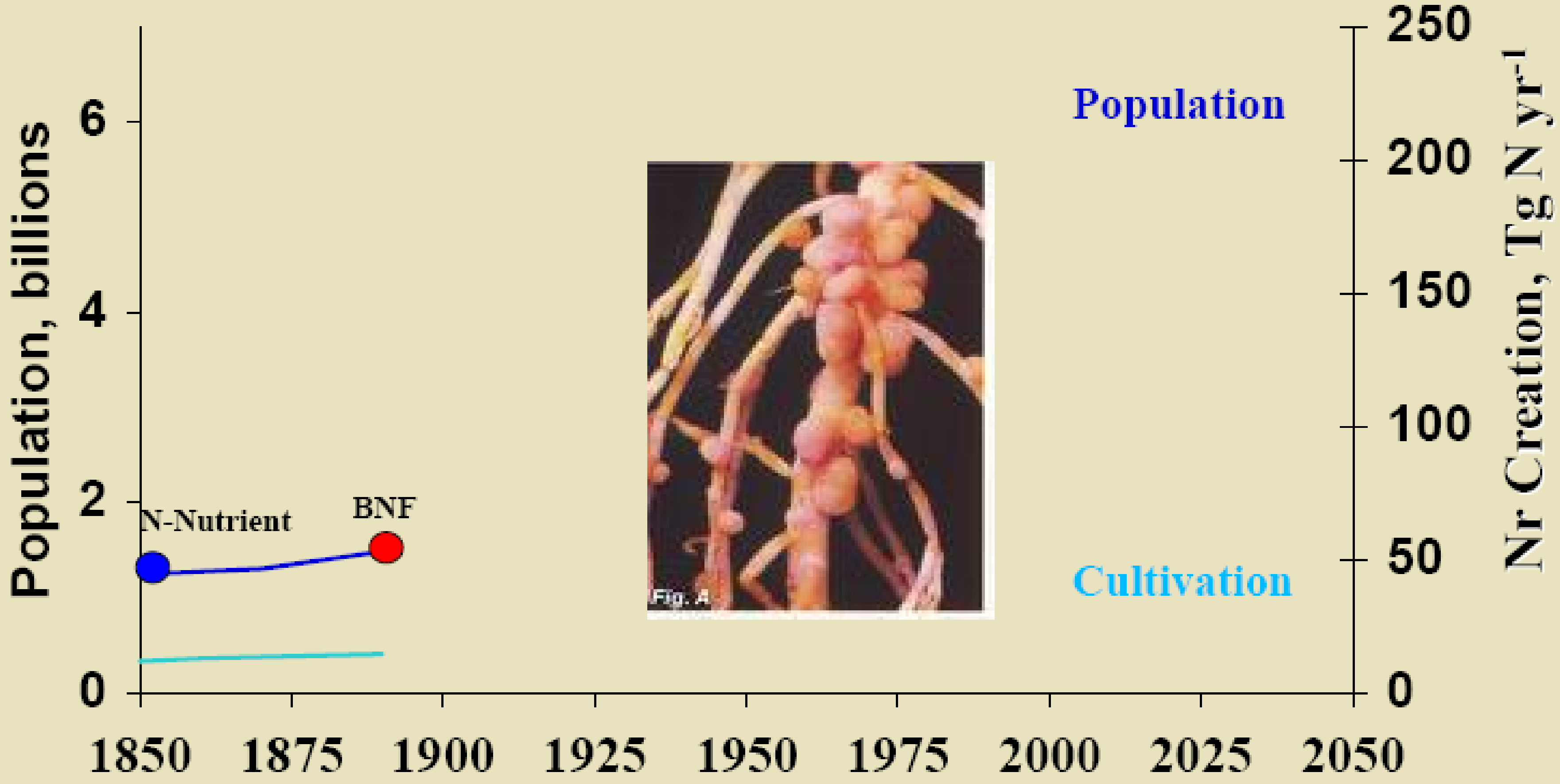
The Nitrogen Cycle



Timeline of Global Reactive N Creation by Human Activity
1850 to 2000



Galloway et al., 2003

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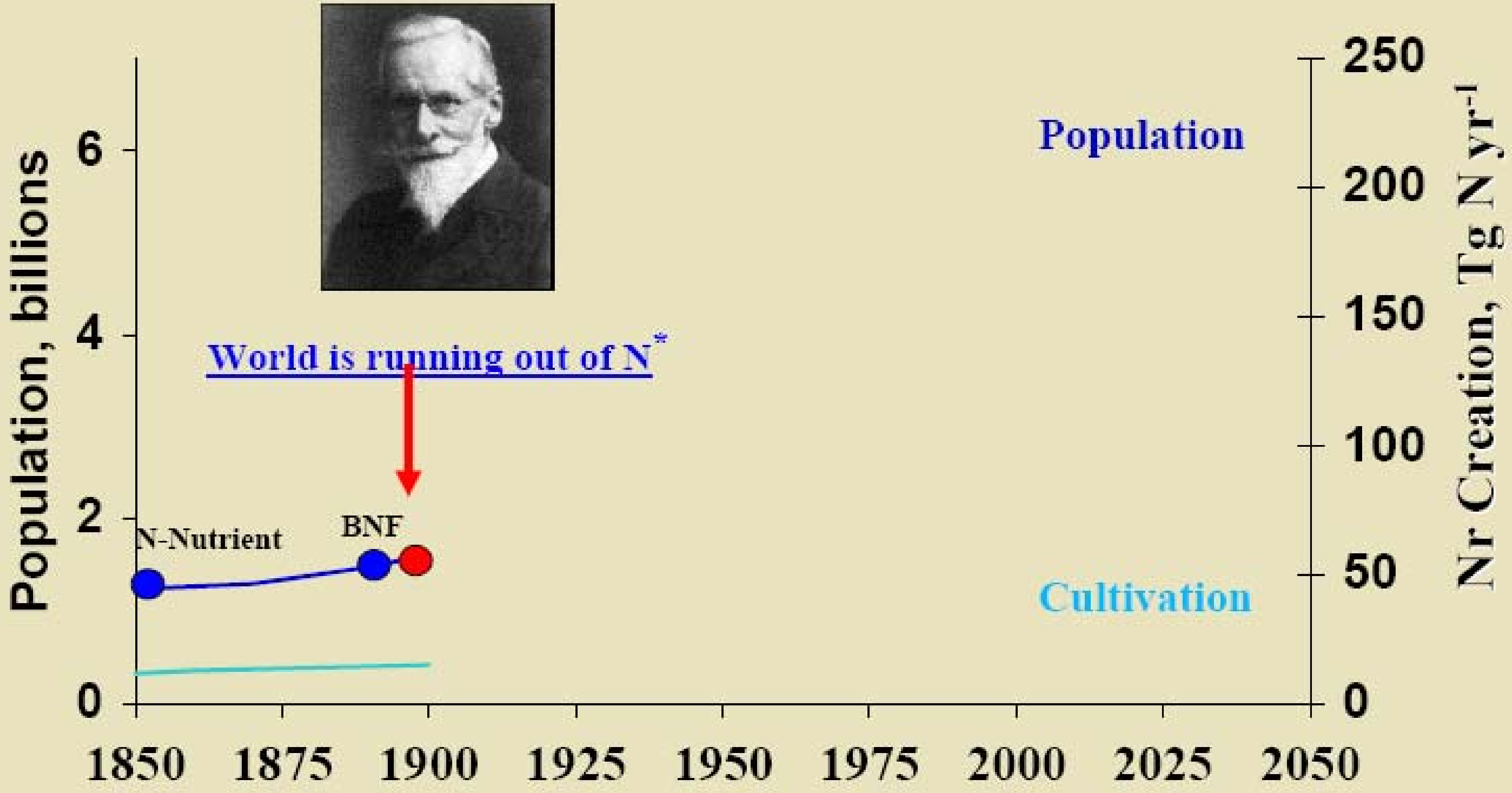

*1898, Sir William Crookes, president of the British Association for the Advancement of Science

Galloway et al., 2003

Timeline of Global Reactive N Creation by Human Activity
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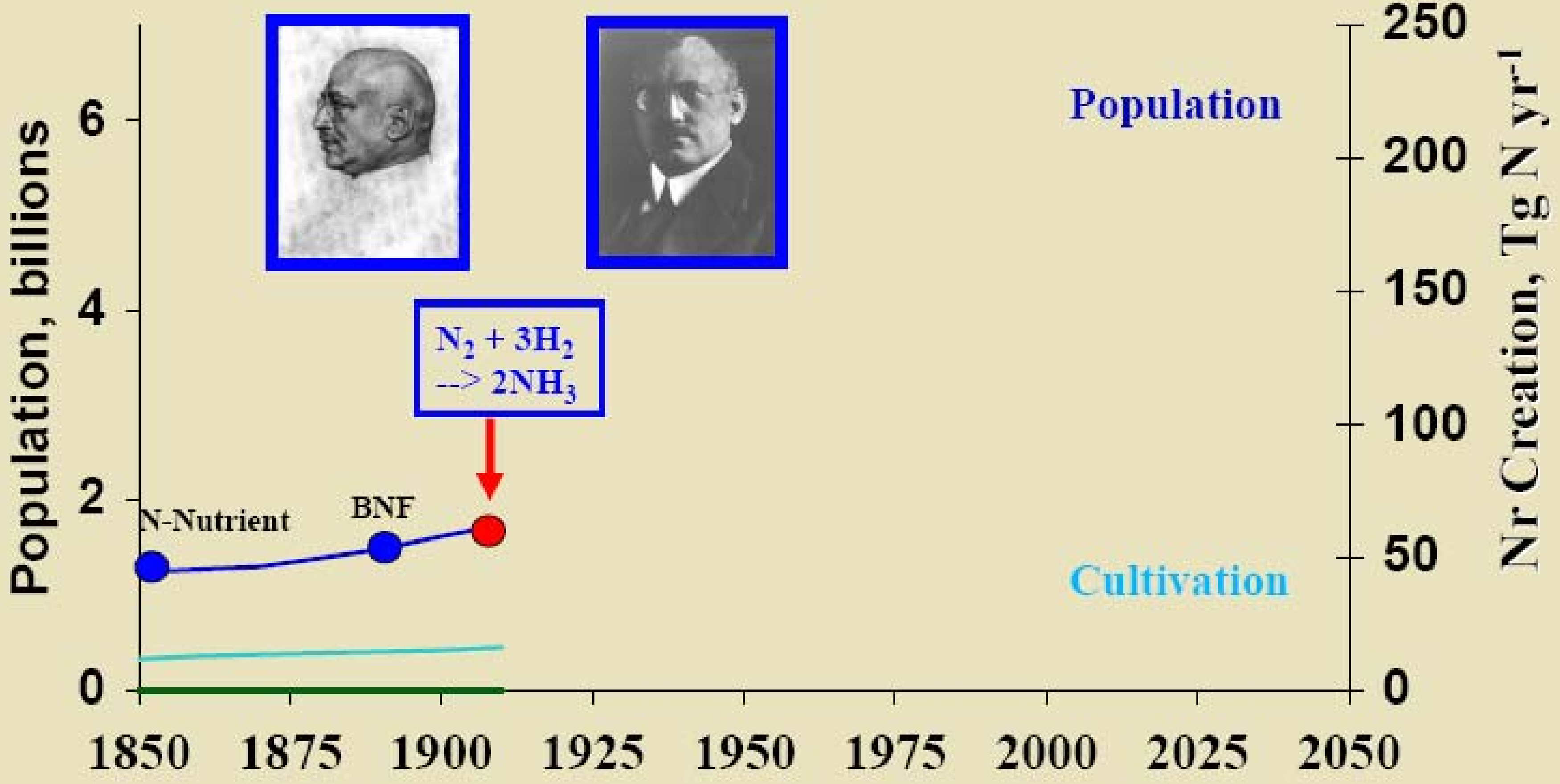
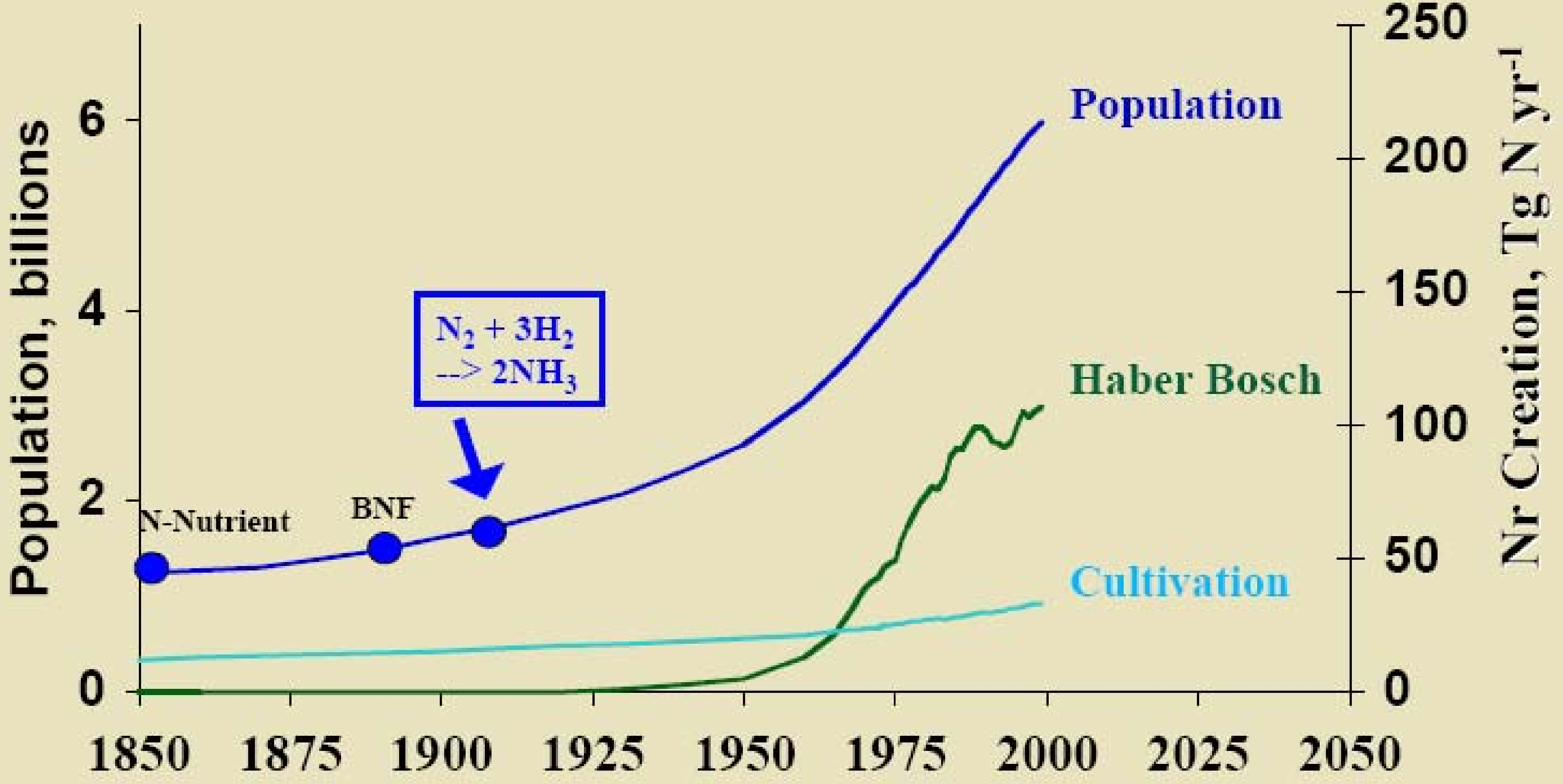


$N_2 + 3H_2 \rightarrow 2NH_3$

Galloway et al., 2003

Timeline of Global Reactive N Creation by Human Activity
1850 to 2000



Galloway et al., 2003

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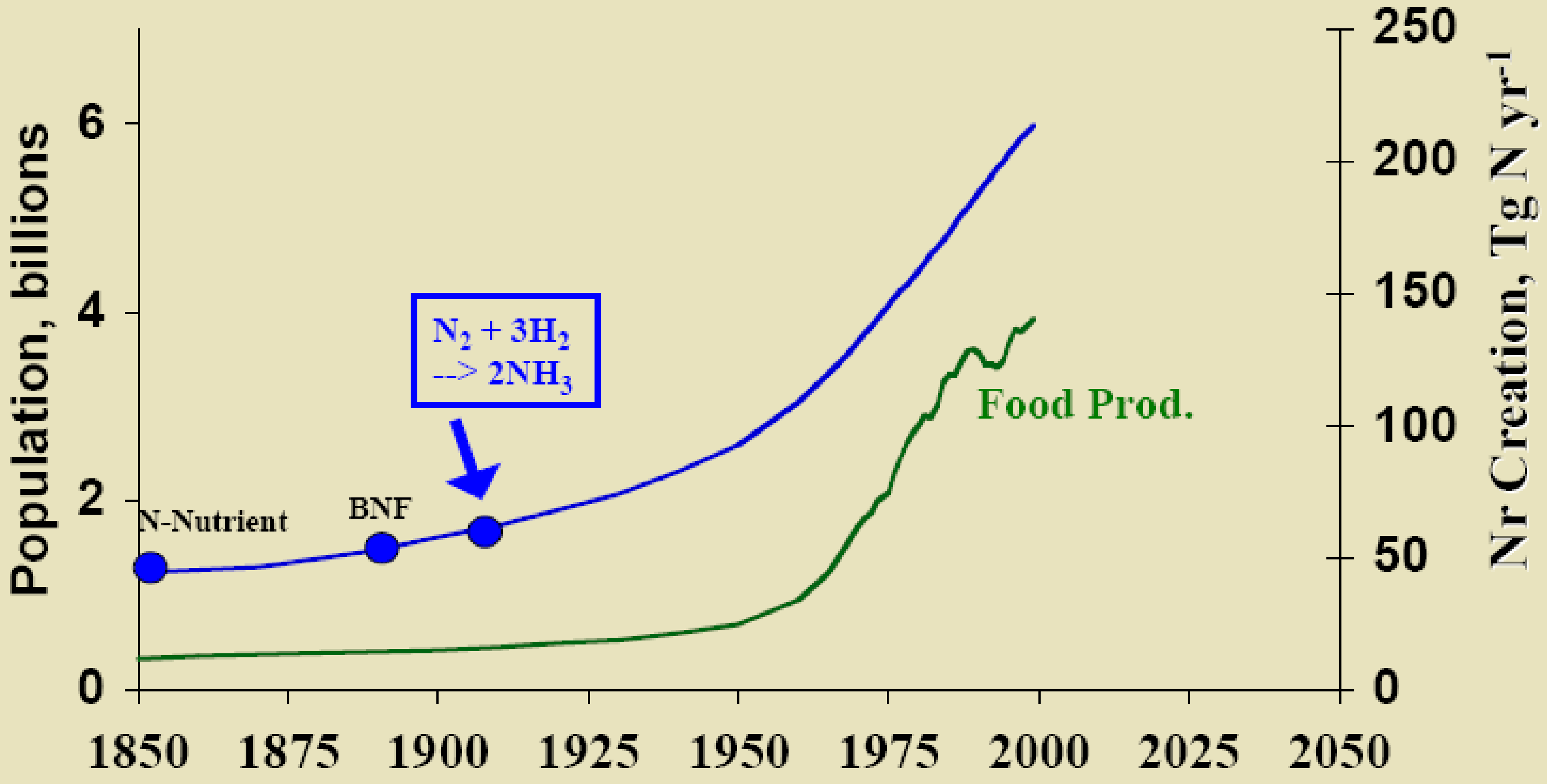


Galloway et al., 2003

The fate of nitrogen

N Fertilizer Produced

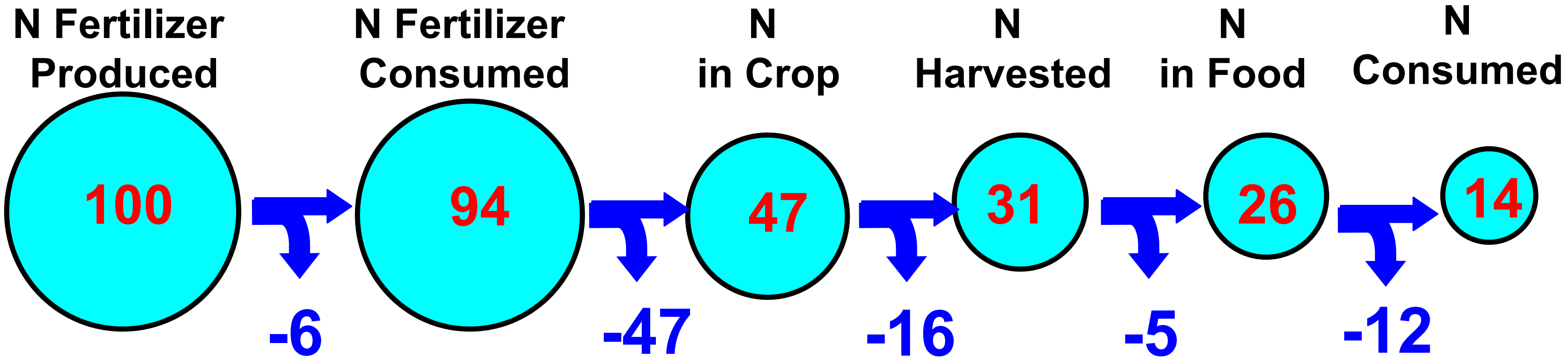
100

The fate of nitrogen

14% of the N produced in the Haber-Bosch process enters the human mouth……….

Galloway JN and Cowling EB. 2002

The fate of nitrogen



N Fertilizer Produced 100

-6

N Fertilizer Consumed 94

-47

N in Crop 47

-16

N Harvested 31

-5

N in Food 26

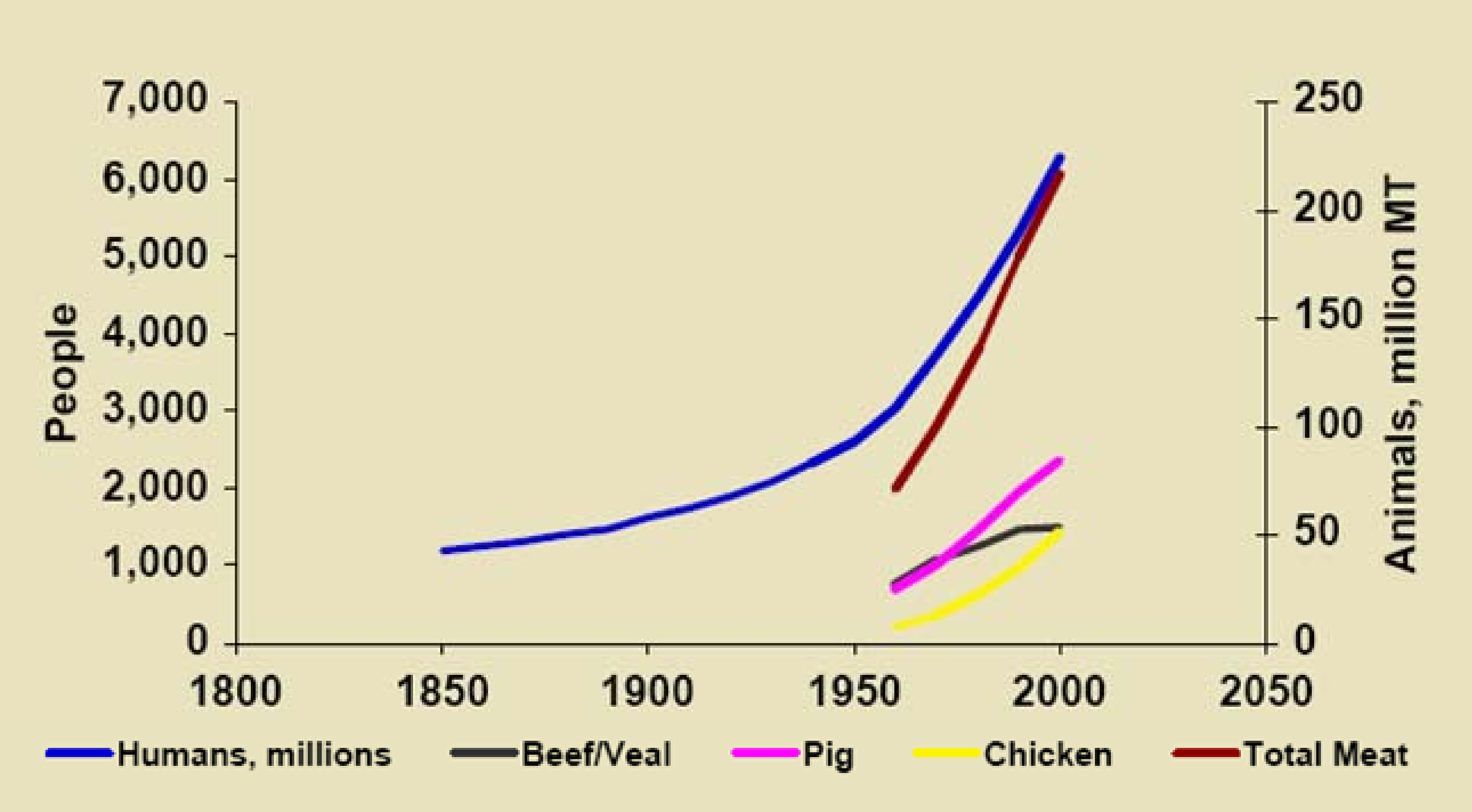
-12

N Consumed 14

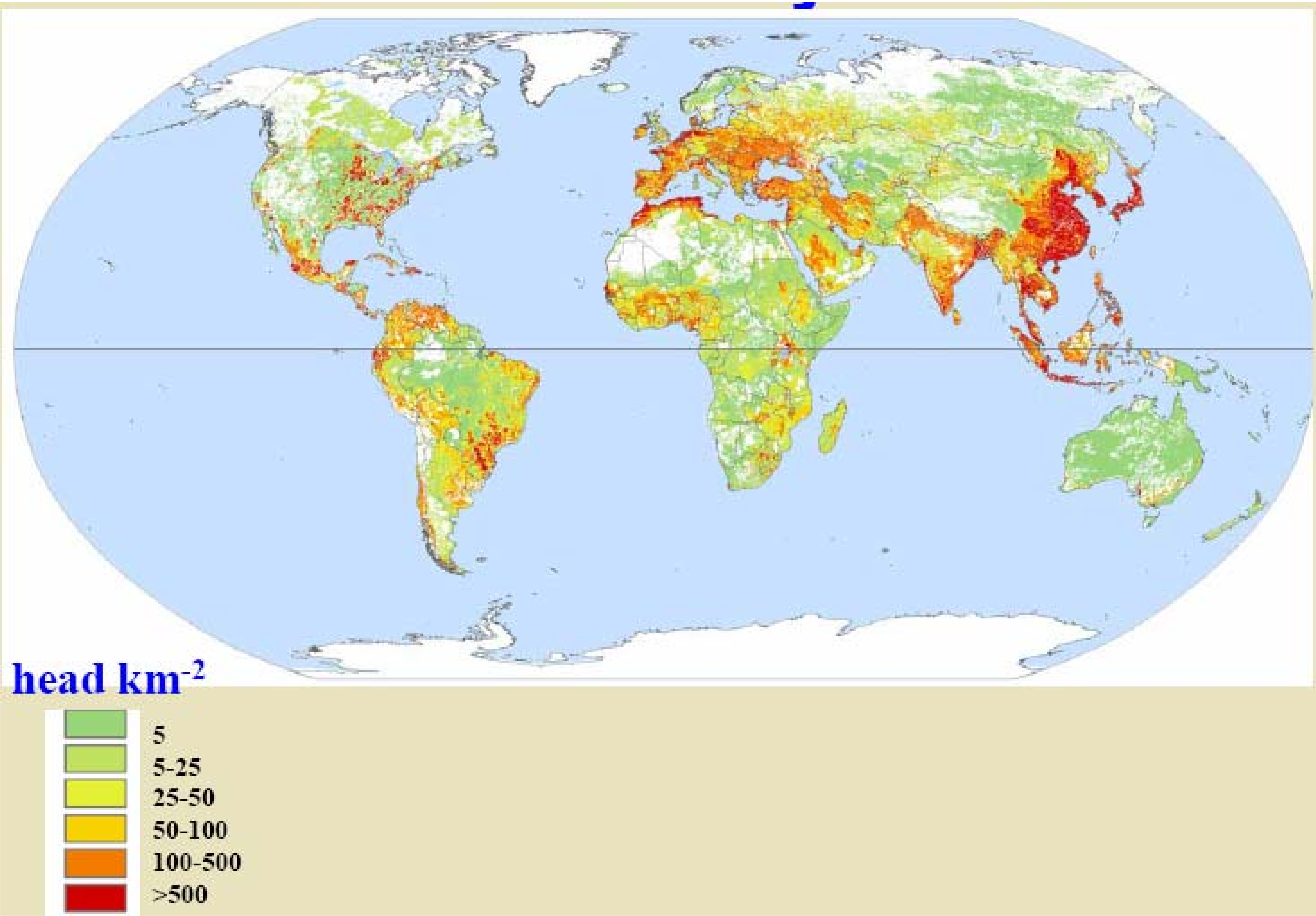
14% of the N produced in the Haber-Bosch process enters the human mouth……….if you are a vegetarian.

Galloway JN and Cowling EB. 2002

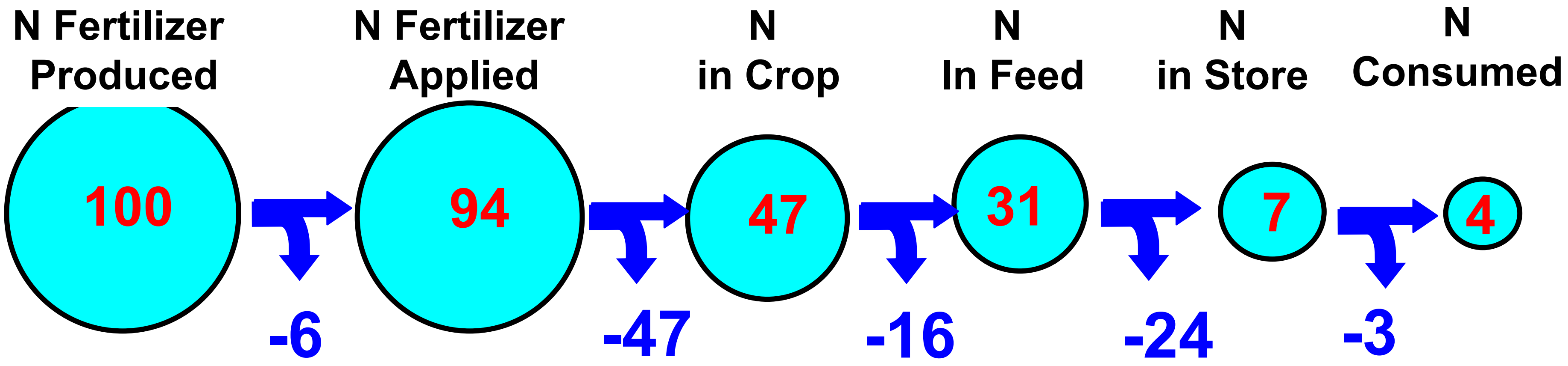
Global human population and meat production



Poultry density



The fate of nitrogen



N Fertilizer Produced

N Fertilizer Applied

N in Crop

N In Feed

N in Store

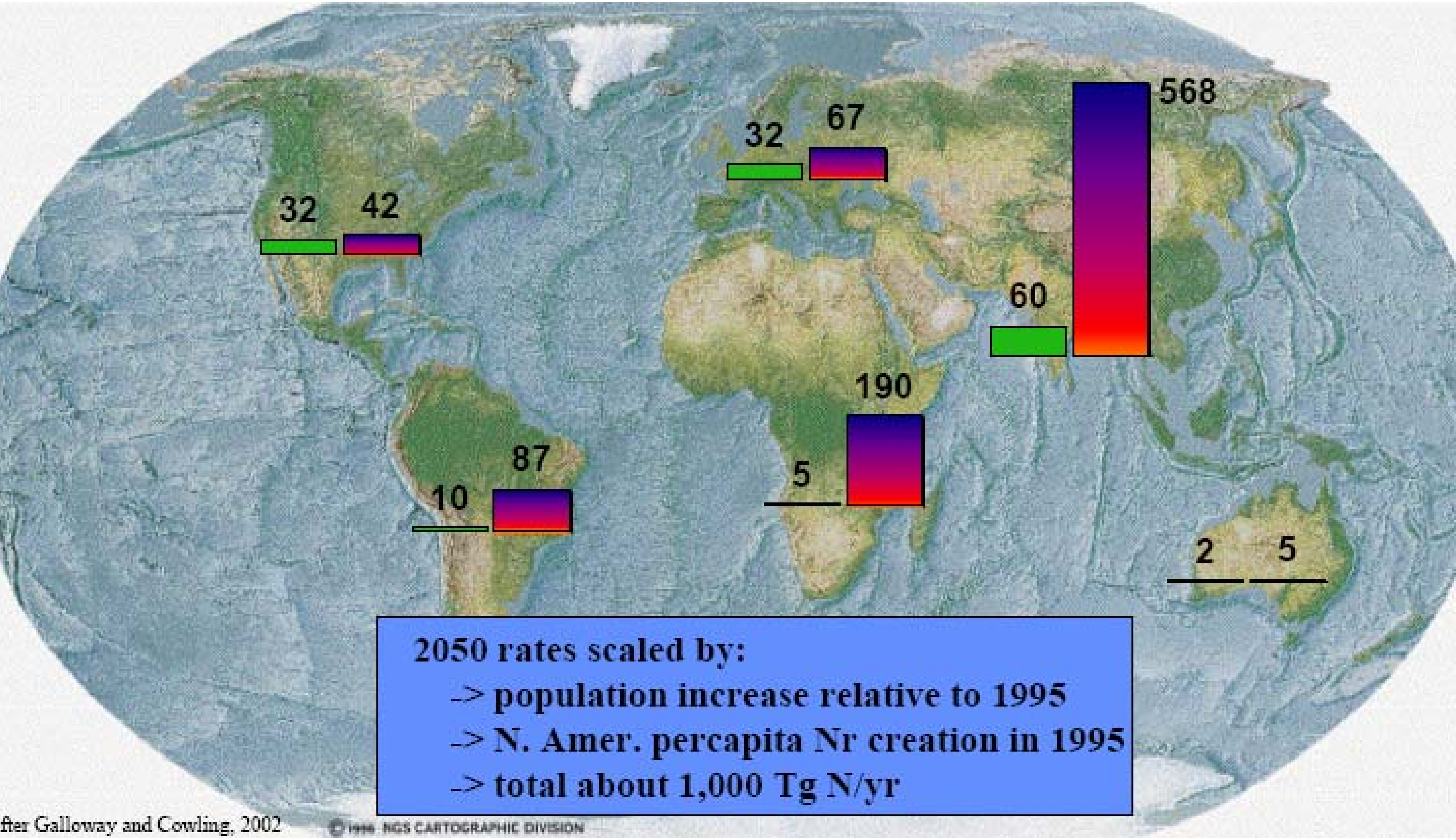
N Consumed

4% of the N produced in the Haber-Bosch process and used for animal production enters the human mouth.

Galloway JN and Cowling EB. 2002

The global nitrogen cycle

Nr creation 1995 (left) and 2050 (right) [Tg N yr^{-1}]



2050 rates scaled by:

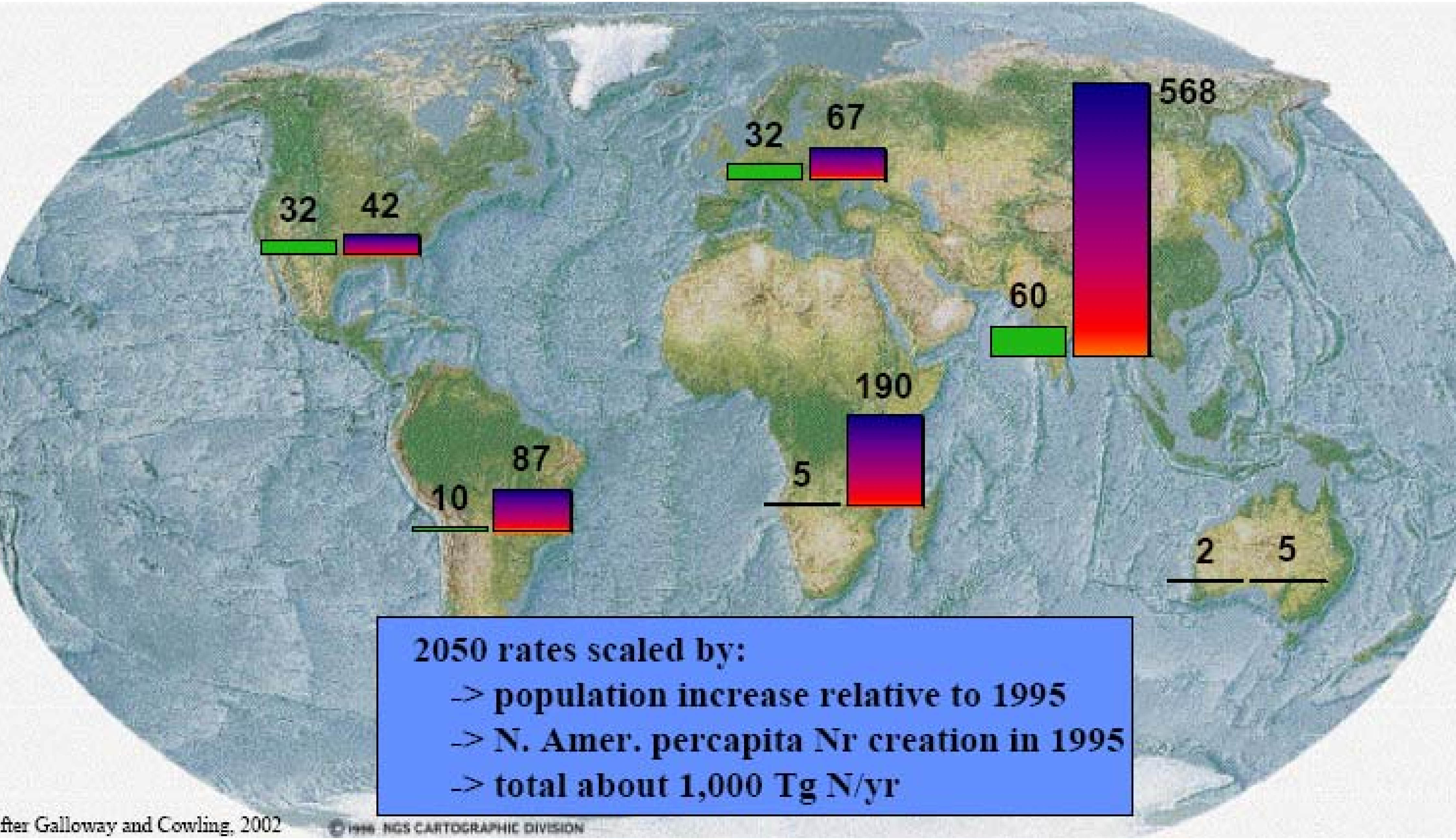
-> population increase relative to 1995

-> N. Amer. percapita Nr creation in 1995

-> total about 1,000 Tg N/yr

fter Galloway and Cowling, 2002

Nr creation 1995 (left) and 2050 (right) [Tg N yr^{-1}]



2050 rates scaled by:

-> population increase relative to 1995

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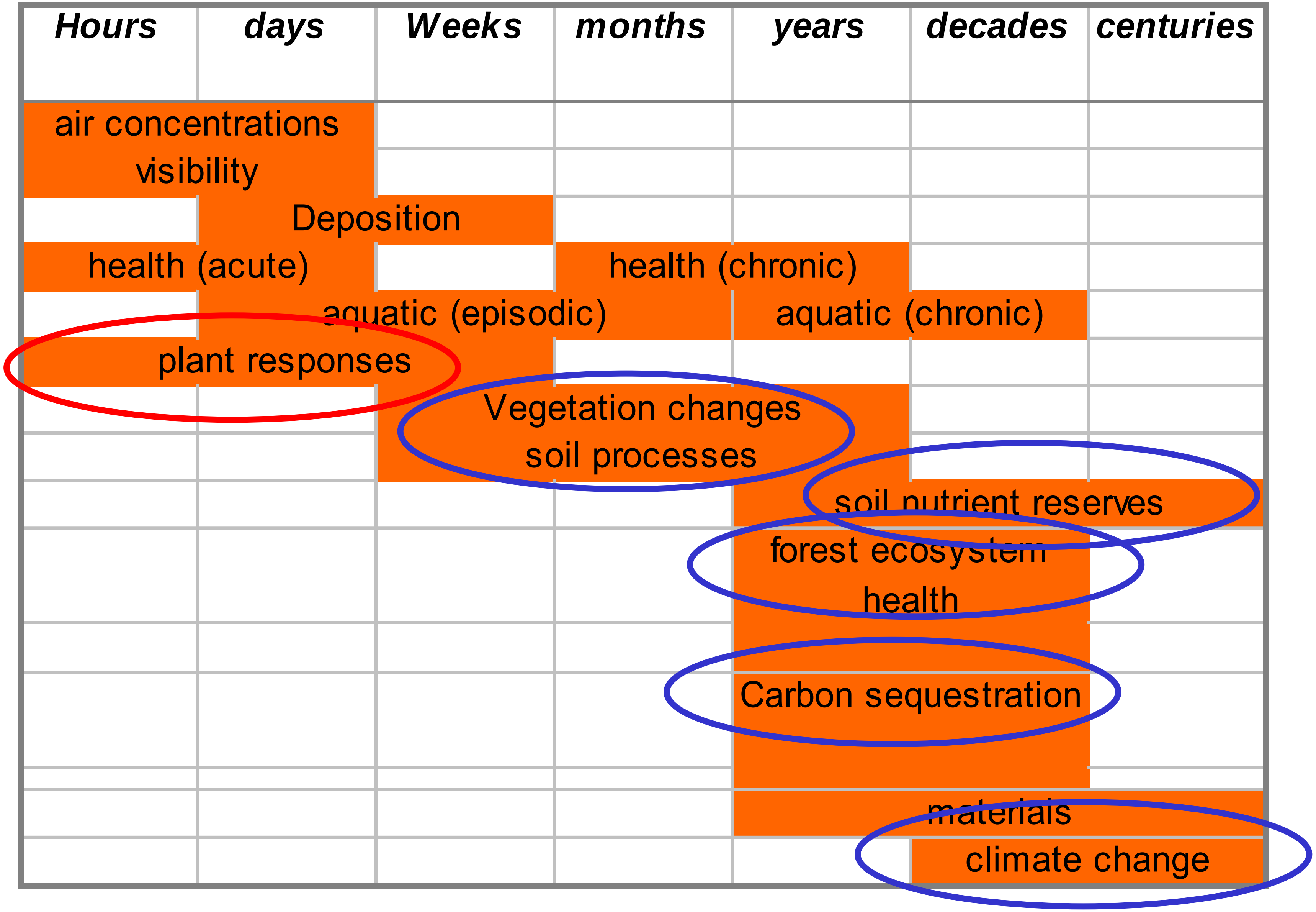
-> total about 1,000 Tg N/yr

fter Galloway and Cowling, 2002

Ecological and social consequences of Nr



Hours | *days* | *Weeks* | *months* | *years* | *decades* | *centuries*

air concentrations visibility

Deposition

health (acute)

health (chronic)

aquatic (episodic)

aquatic (chronic)

plant responses

Vegetation changes soil processes

soil nutrient reserves

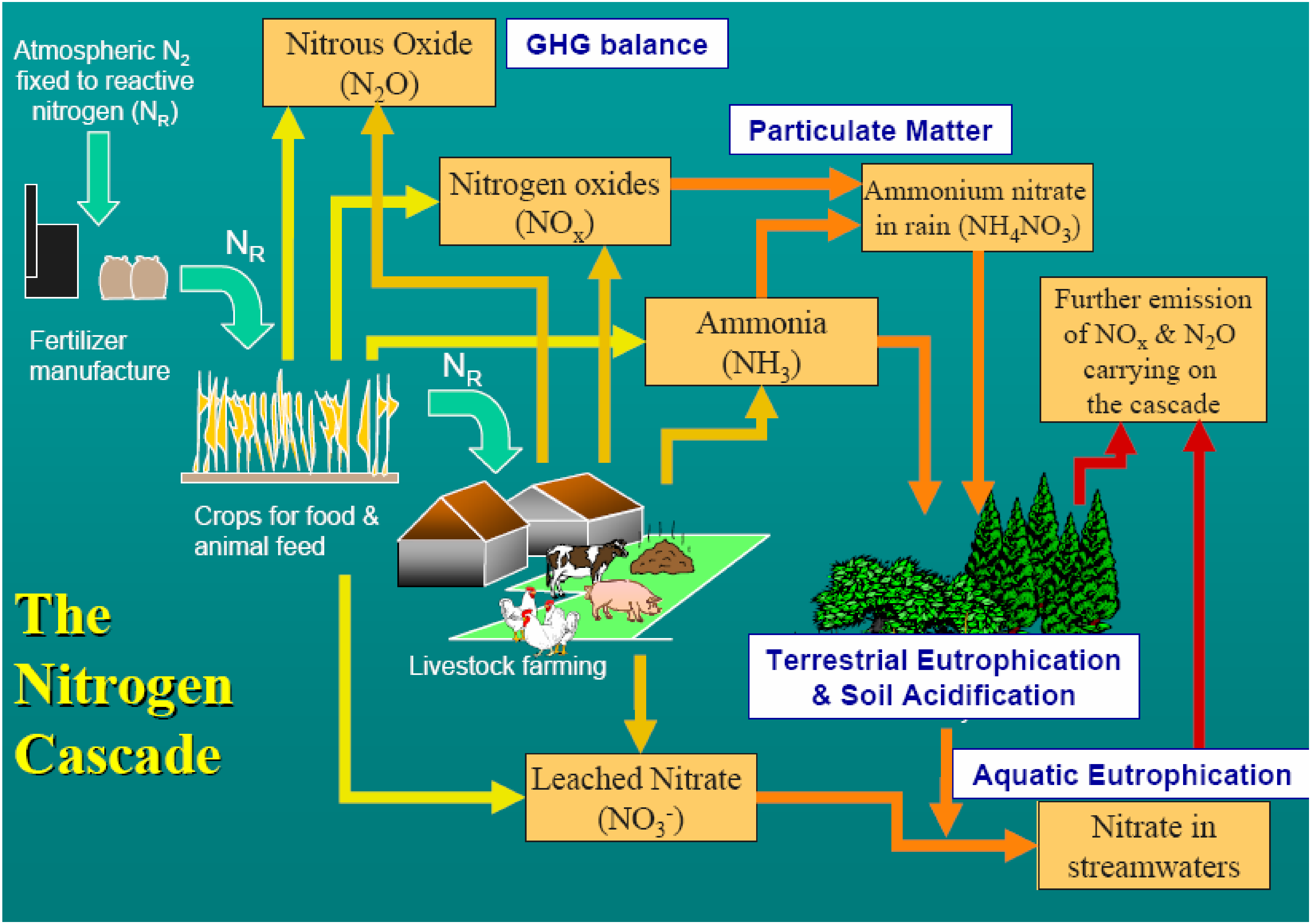
forest ecosystem health

Carbon sequestration

materials

climate change

The Nr cascade



Atmospheric N_2 fixed to reactive nitrogen (N_R)

Fertilizer manufacture

N_R

Crops for food & animal feed

Nitrous Oxide (N_2O)

GHG balance

Nitrogen oxides (NO_x)

Particulate Matter

Ammonium nitrate in rain (NH_4NO_3)

Ammonia (NH_3)

N_R

Livestock farming

Further emission of NO_x & N_2O carrying on the cascade

Terrestrial Eutrophication & Soil Acidification

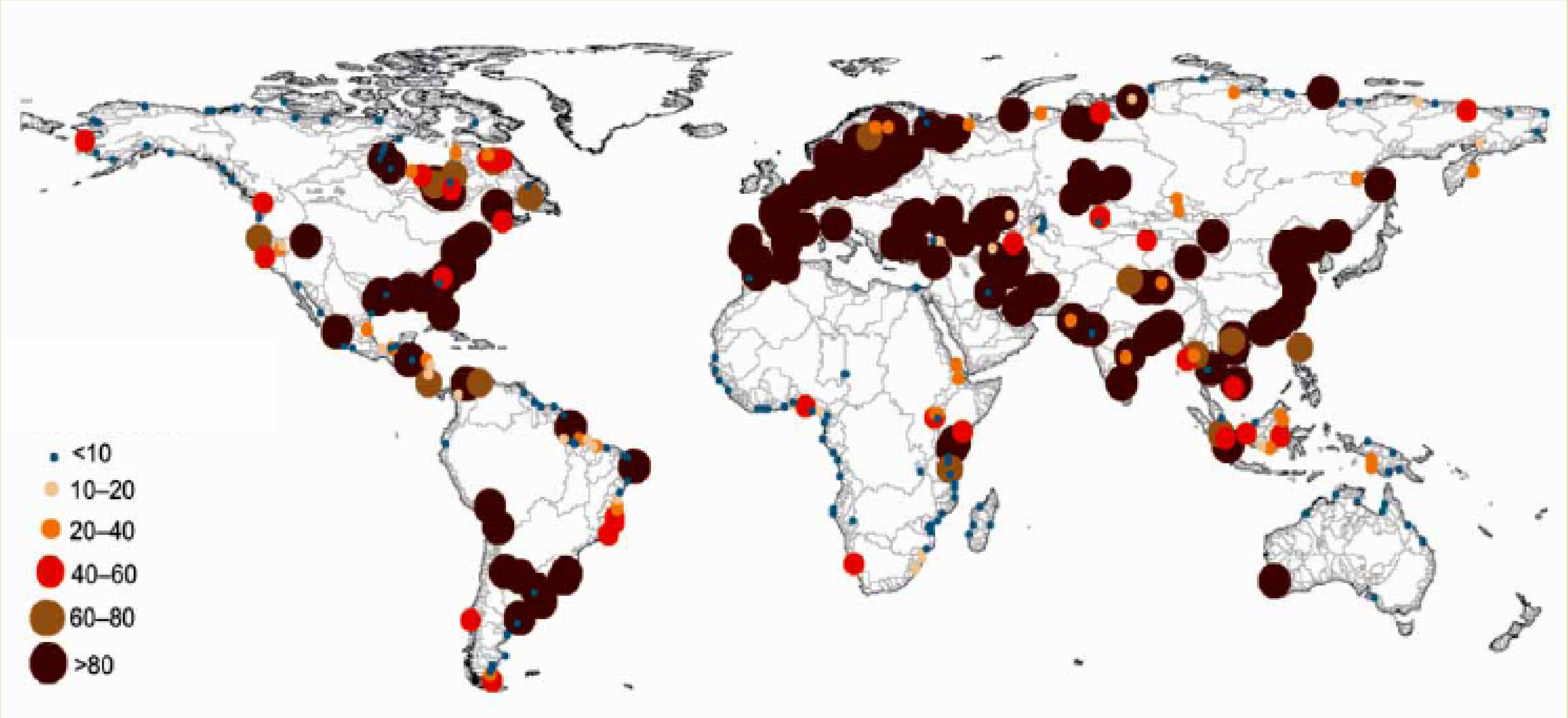
Aquatic Eutrophication

Leached Nitrate (NO_3^-)

Nitrate in streamwaters

The Nitrogen Cascade

Increase in nitrogen flows in rivers

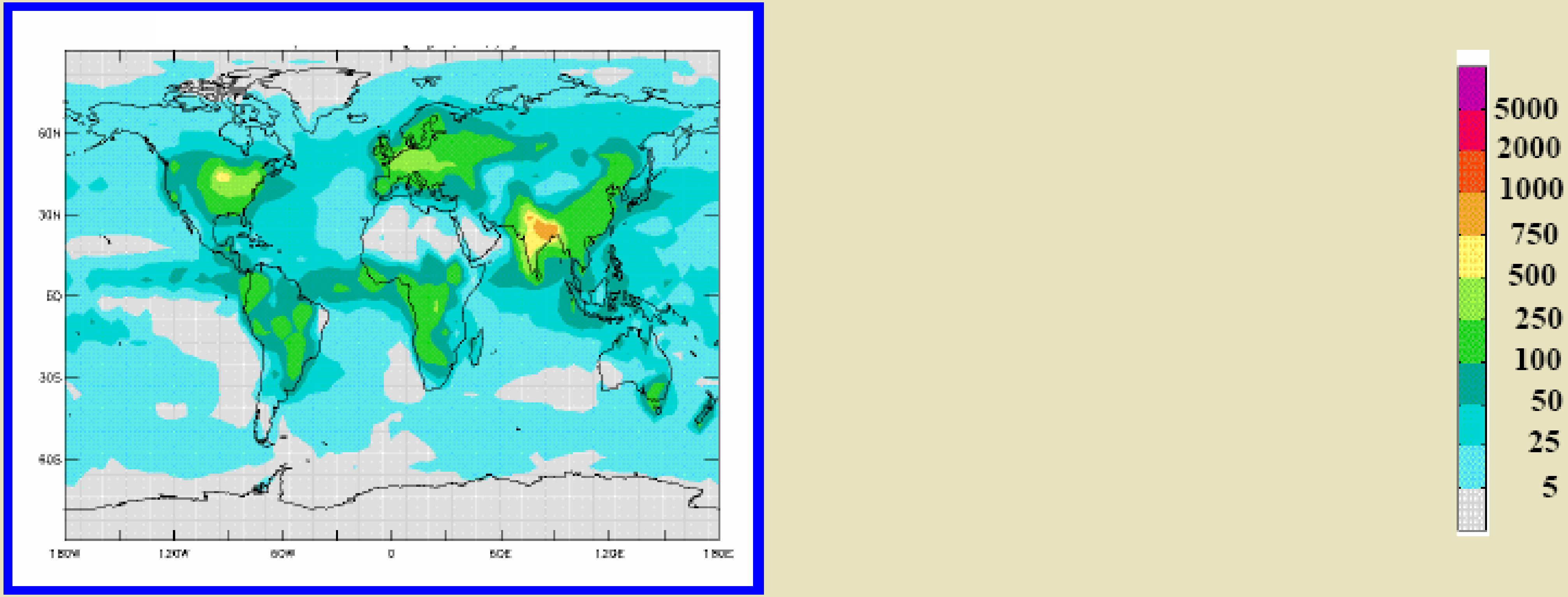


◆Most of the Nr created for food production, is released to the environment

◆About 25% is discharged to the coast via rivers

Source: Millennium Ecosystem Assessment

Nr deposition in 1860 and 1993 [mg m^{-2} yr^{-1}]

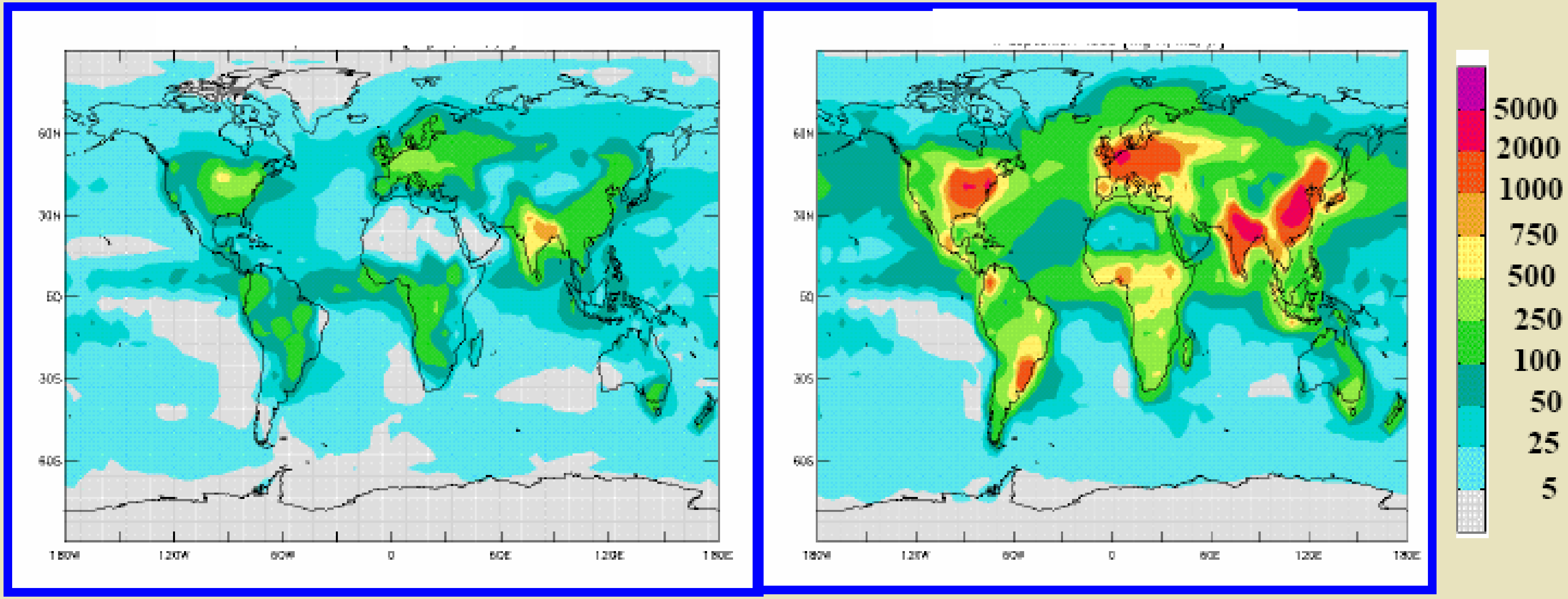


1860

- Nitrogen is emitted as NOx to the atmosphere by fossil fuel combustion
- Nitrogen is emitted as NH_3 and NOx from food production.
- Once emitted, it is transported and deposited to ecosystems.
- In 1860, human activities had limited influence on N deposition.

Galloway et al., 2003b

Nr deposition in 1860 and 1993 [mg m^{-2} yr^{-1}]



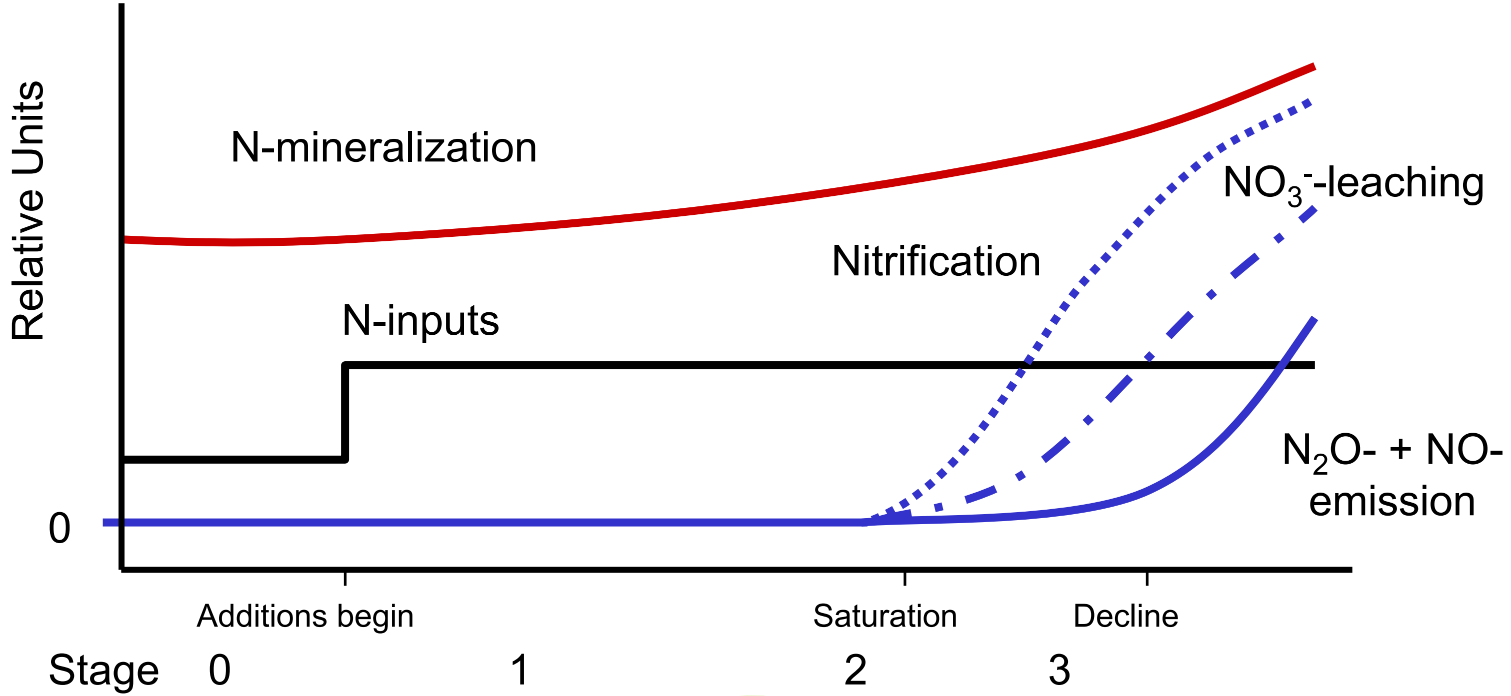
1860

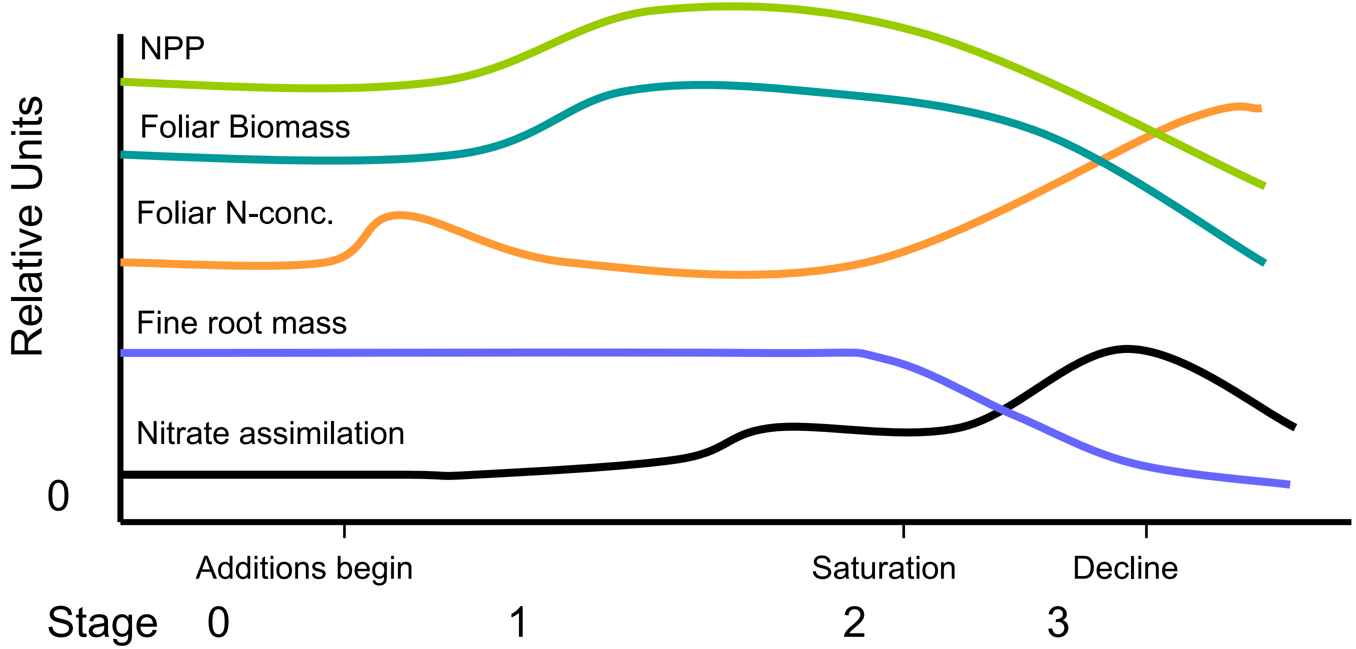
1993

- Nitrogen is emitted as NOx to the atmosphere by fossil fuel combustion
- Nitrogen is emitted as NH_3 and NOx from food production.
- Once emitted, it is transported and deposited to ecosystems.
- In 1860, human activities had limited influence on N deposition.
- By 1993, the picture had changed.

Galloway et al., 2003b

Nr deposition and forest ecosystem health

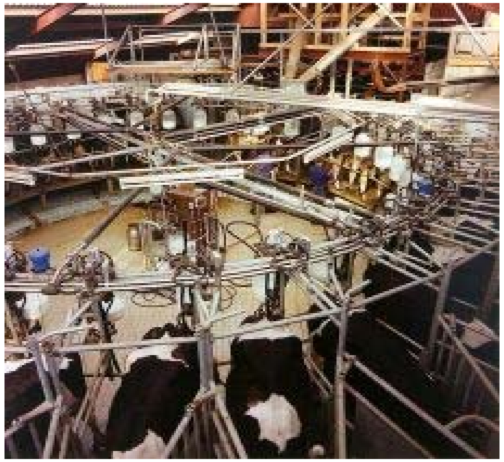




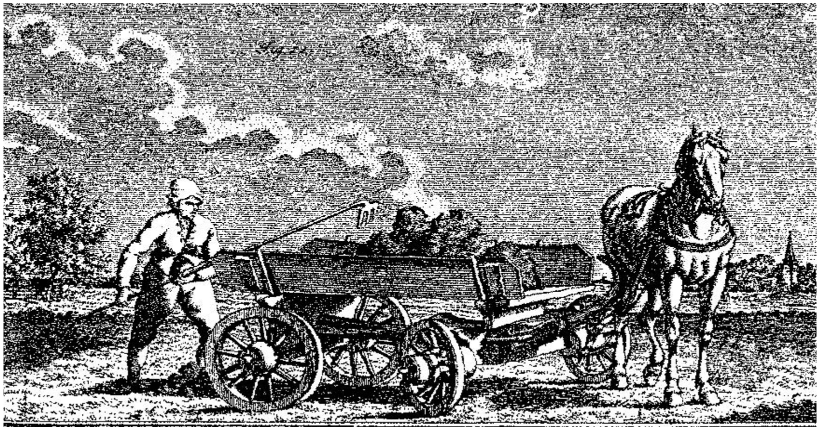
Aber et al., 1998,
BioScience 48, 921-934

Historical development

Closed nutrient cycles



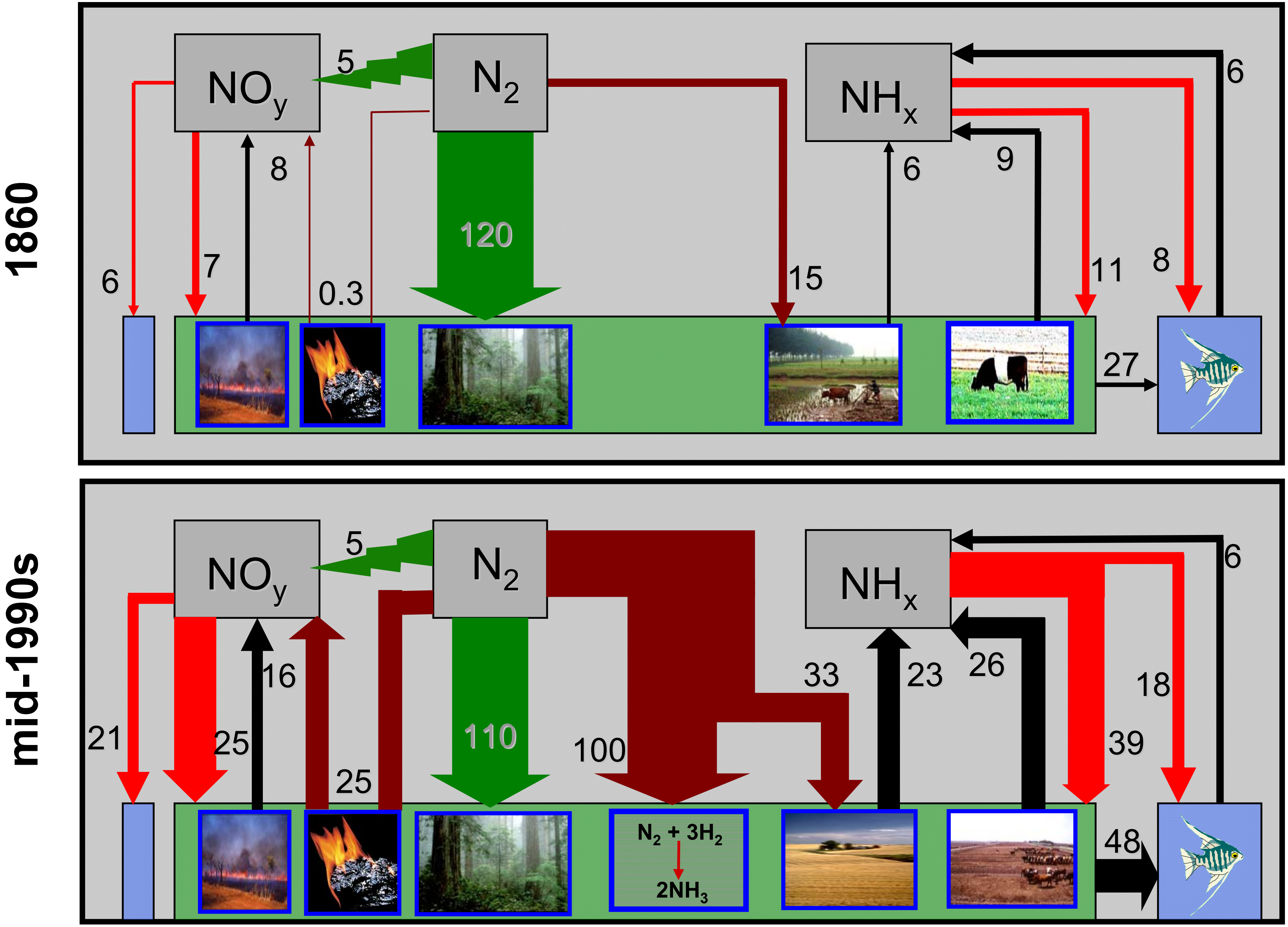
Intensive agriculture



Industrialisation

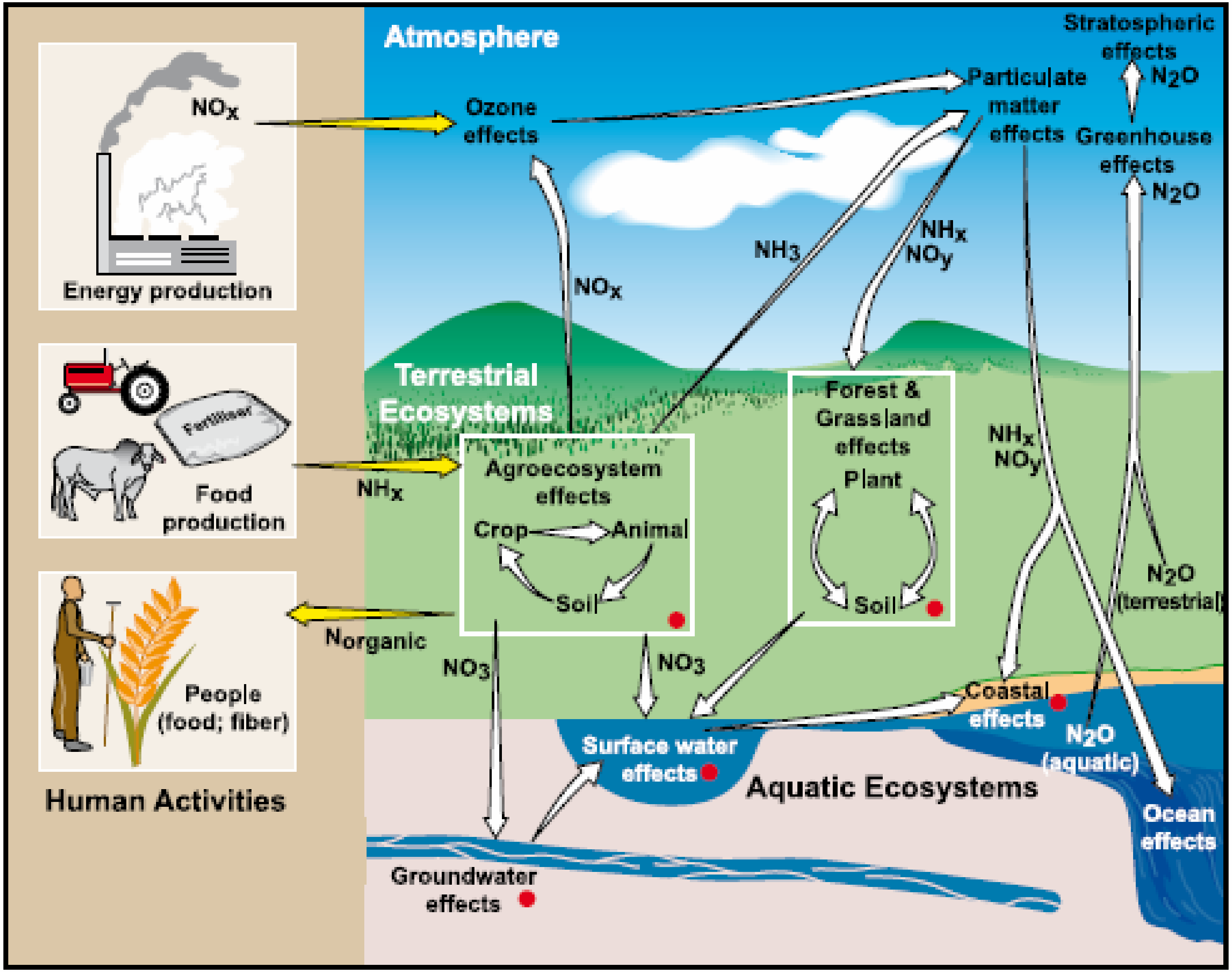
Man labor

The Global Nitrogen Budget in 1860 and mid-1990s, TgN/yr

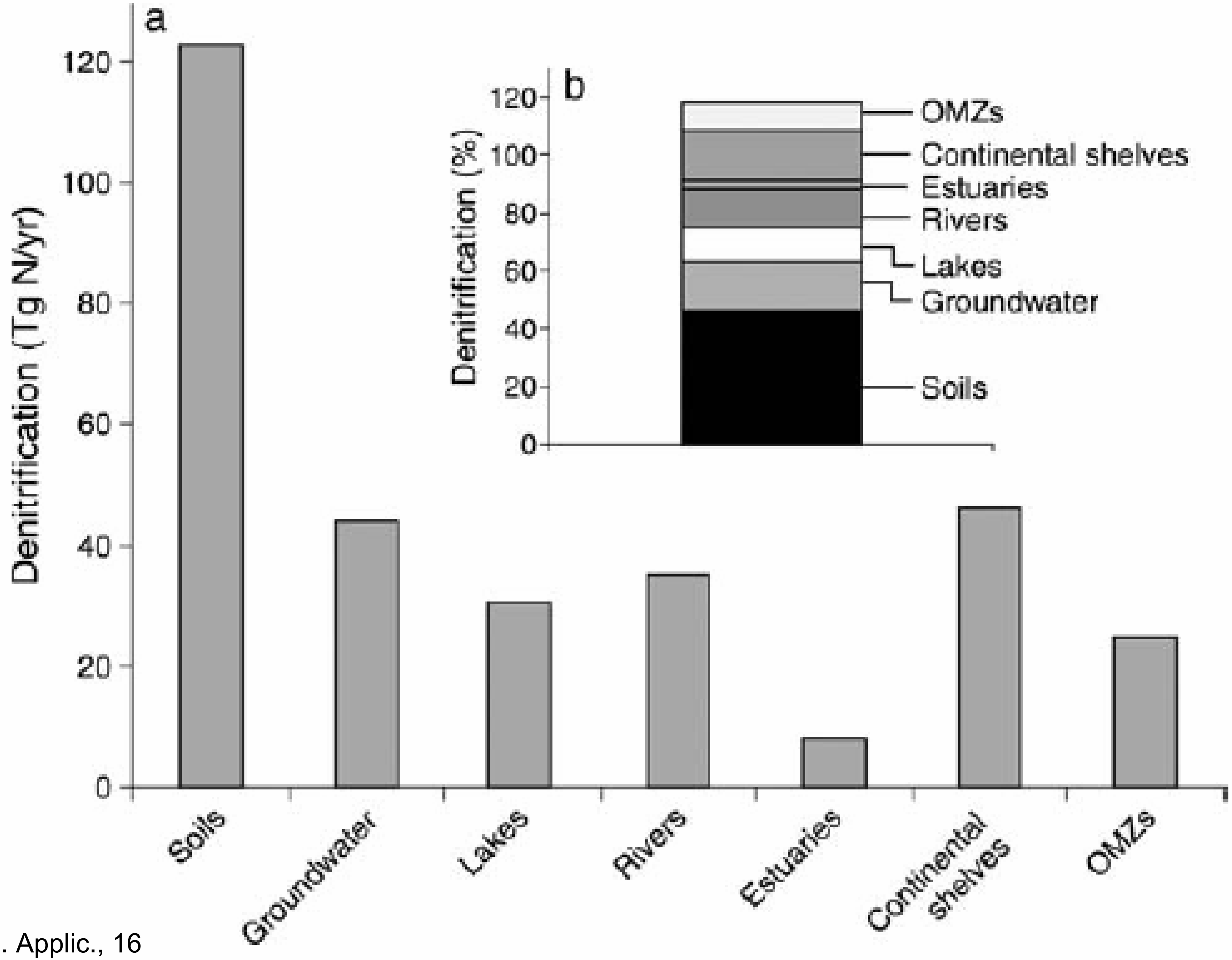


Galloway et al., 2003

Soils as principal receptors and transformators of Nr

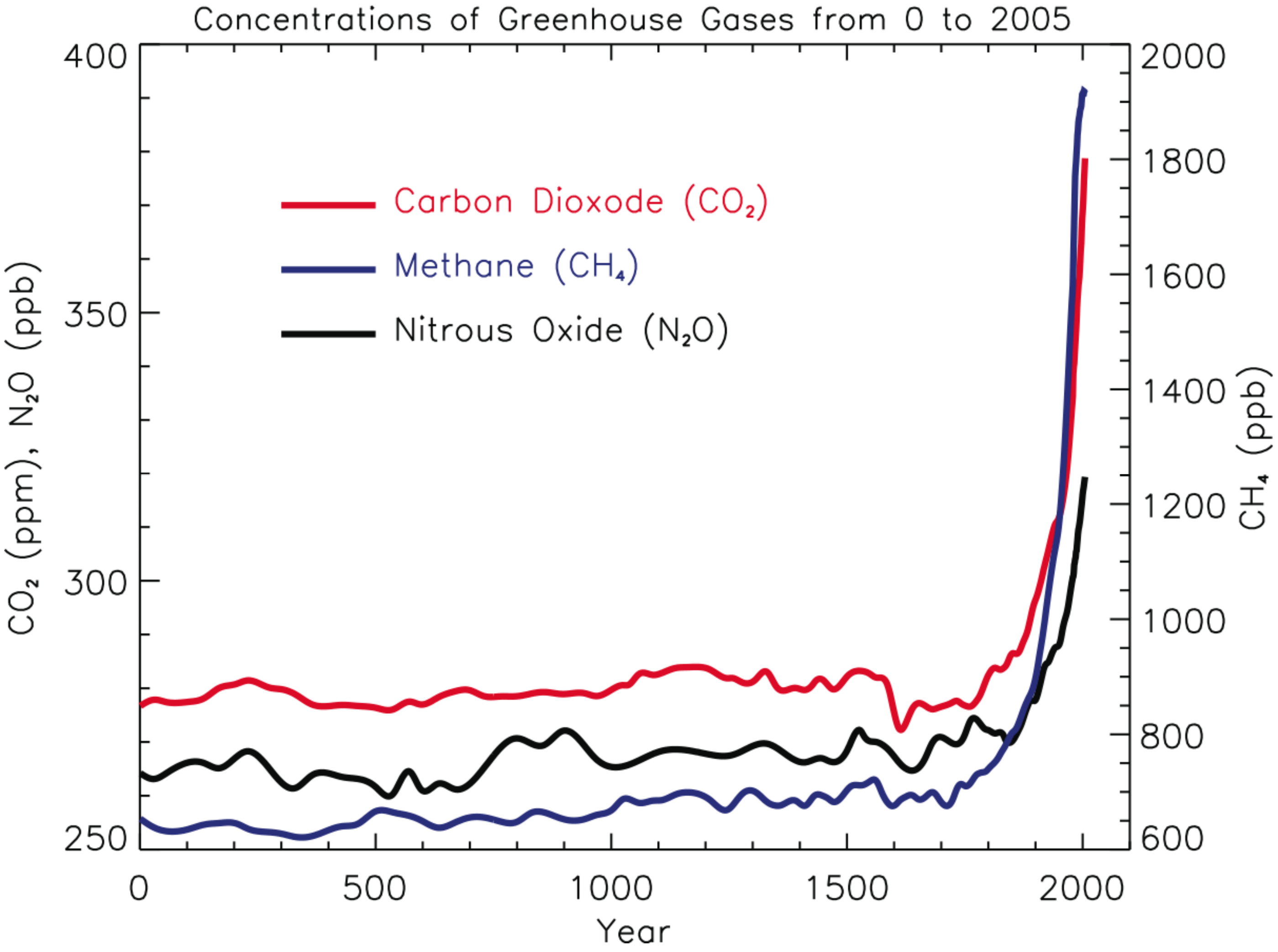


Approx. 270 Tg N_r additions to terrestrial systems

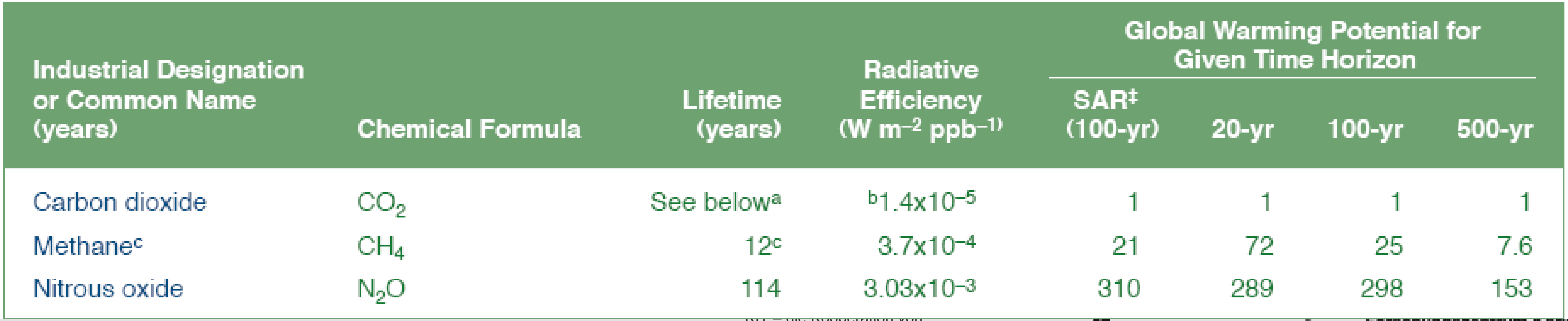


Seitzinger et al., 2006, Ecol. Applic., 16

N_2O

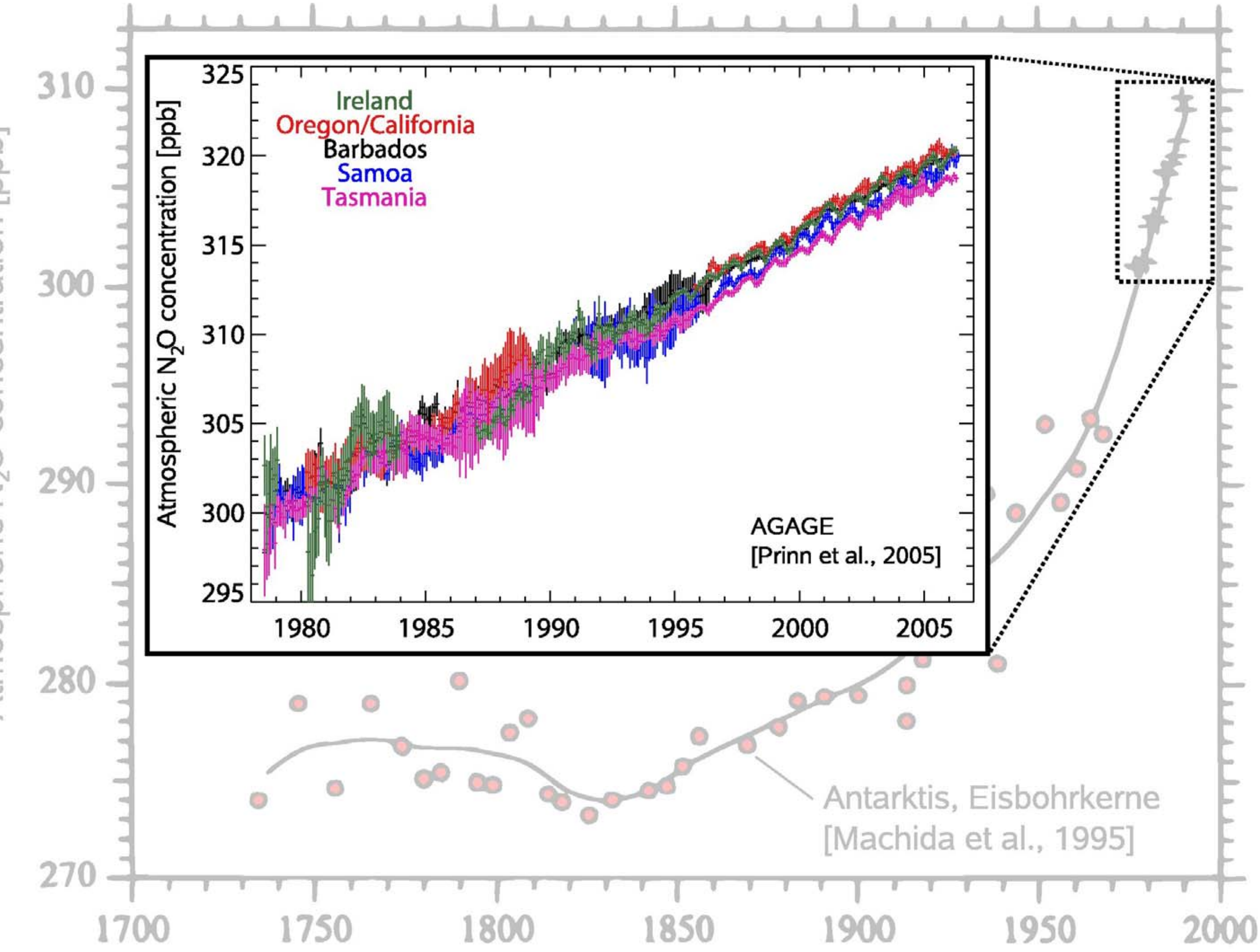


IPCC 2007

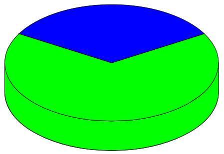


Industrial Designation or Common Name (years)	Chemical Formula	Lifetime (years)	Radiative Efficiency (W m^{-2} ppb^{-1})	Global Warming Potential for Given Time Horizon			
				SAR‡ (100-yr)	20-yr	100-yr	500-yr
Carbon dioxide	CO_2	See below[a]	[b]1.4×10^{-5}	1	1	1	1
Methane[c]	CH_4	12[c]	3.7×10^{-4}	21	72	25	7.6
Nitrous oxide	N_2O	114	3.03×10^{-3}	310	289	298	153

Atmospheric N_2O concentrations



Industrial sources



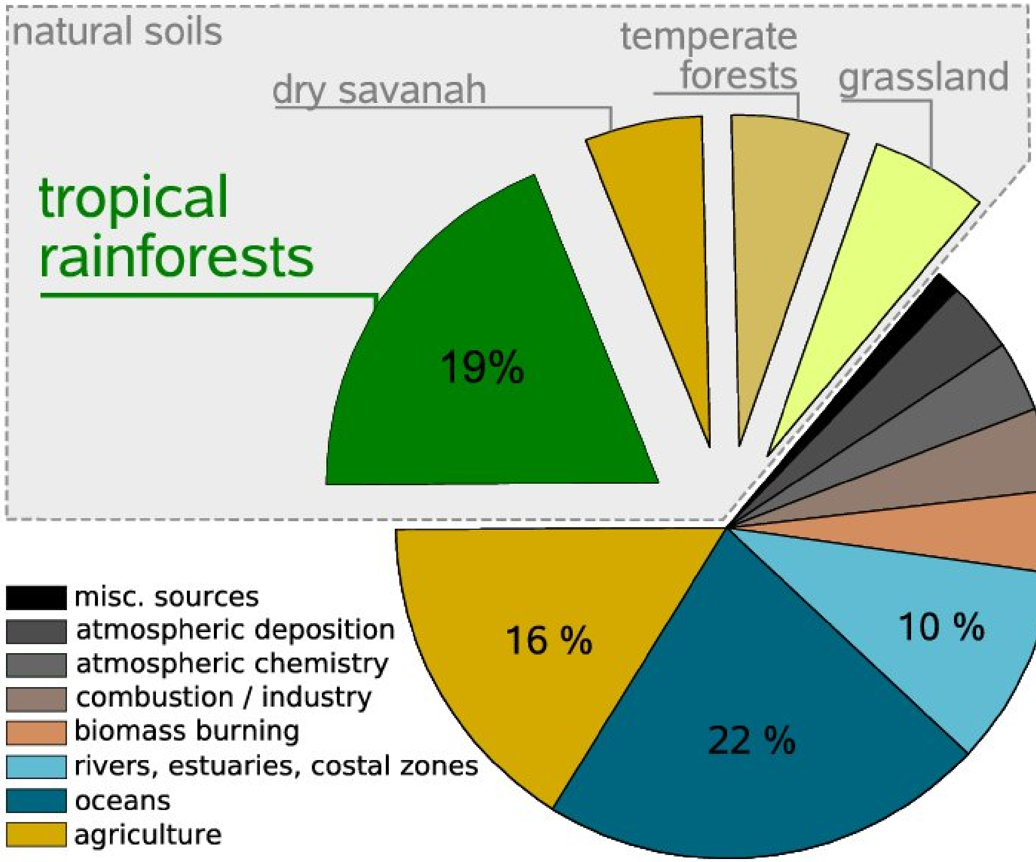
Agriculture, forests, ozeans

N_2O

Soils: 60-70%

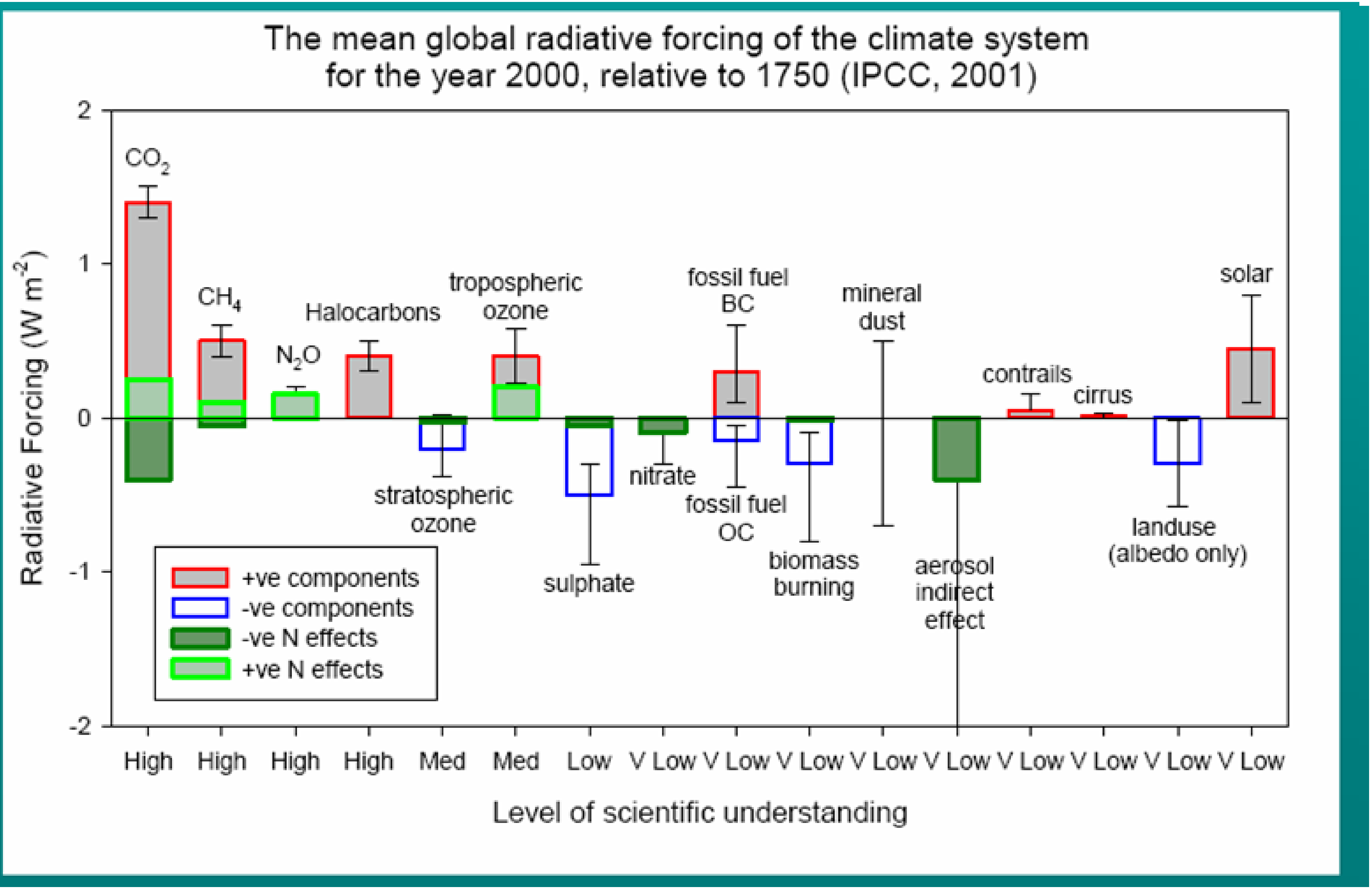
Sources and sinks of N_2O

N_2O-sources	Relative contribution to all identified sources [%]	Tg (10^{12} g) N_2O-N a^{-1}	
Natural N_2O sources			
Ocean	18.5	3.0	(1.0-5.0)
Tropical soils			
Wet forests	**18.5**	**3.0**	**(2.2-3.7)**
Dry savannas	**6.2**	**1.0**	**(0.5-2.0)**
Temperate soils			
Forests	**6.2**	**1.0**	**(0.1-2.0)**
Grasslands	**6.2**	**1.0**	**(0.5-2.0)**
Anthropogenic N_2O sources			
Agricultural soils	**20.4**	**3.3**	**(0.6-14.8)**
Biomass burning	3.1	0.5	(0.2-1.0)
Industrial sources	8.0	1.3	(0.7-1.8)
Cattle and feedlots	13.0	2.1	(0.6-3.1)
Total N_2O sources		16.2	(6.4-34.4)
N_2O sinks and atmospheric increase			
Stratospheric destruction		12.3	(9.0-16.0)
Removal by soil microbes		**?**	**(?)**
Atmospheric increase		**3.9**	**(3.1-4.7)**

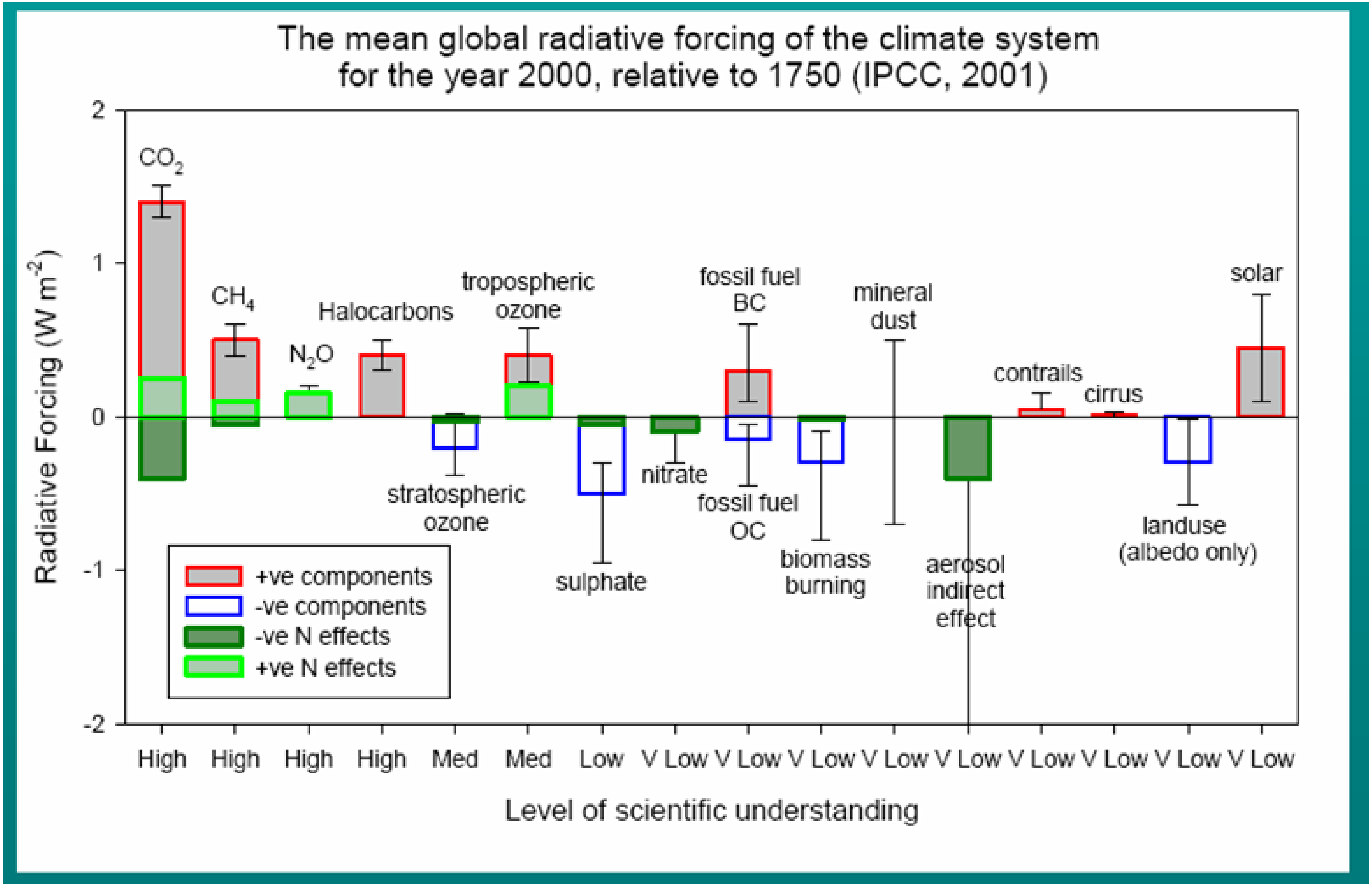


IPCC 2001, 2007

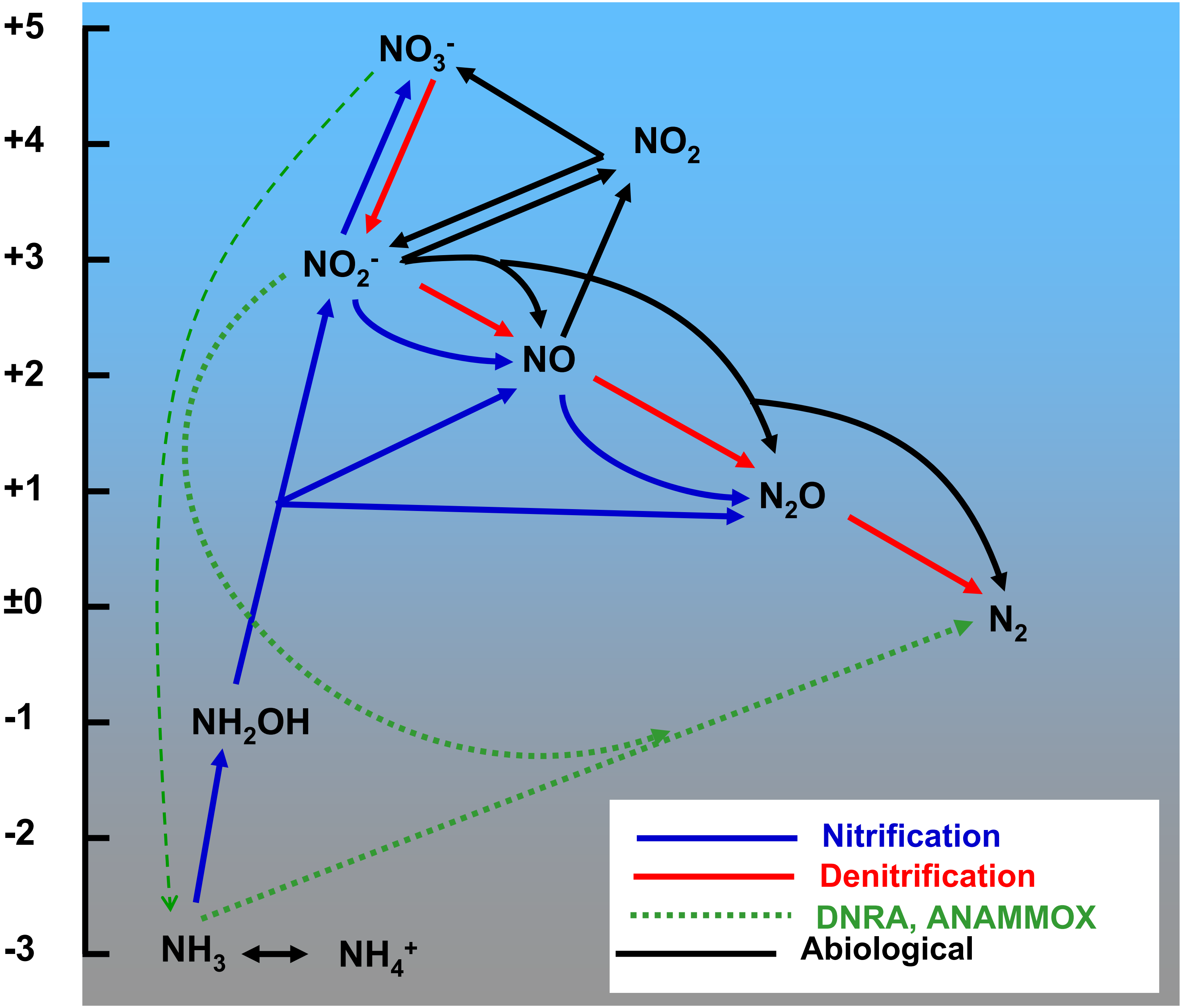
The effect of N on the GHG balance



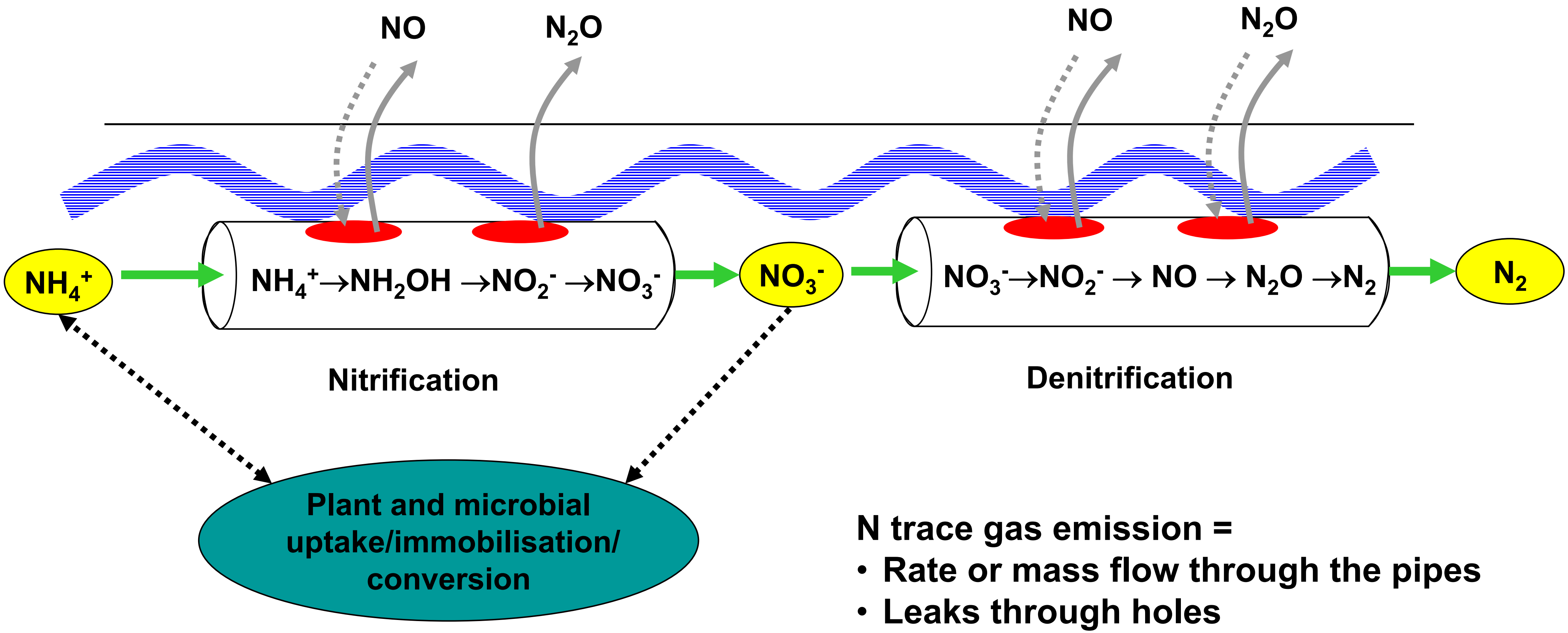
The effect of N on the GHG balance



Complexity of Nr reactions in soils



N trace gas production in soils

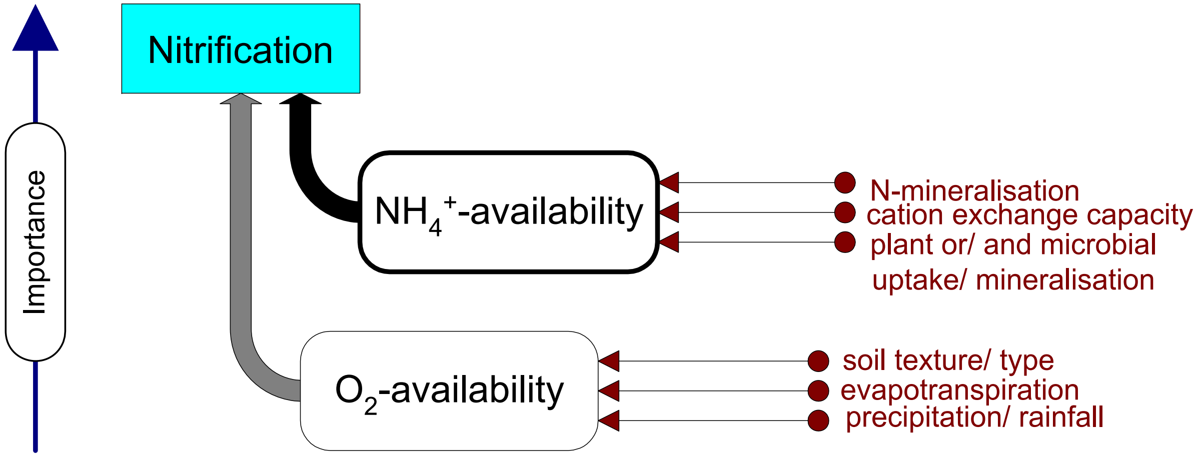


N trace gas emission =

- **Rate or mass flow through the pipes**
- **Leaks through holes**

Davidson et al., 1993, 2000

Controlling factors of N trace gas production in soils



Importance

Nitrification

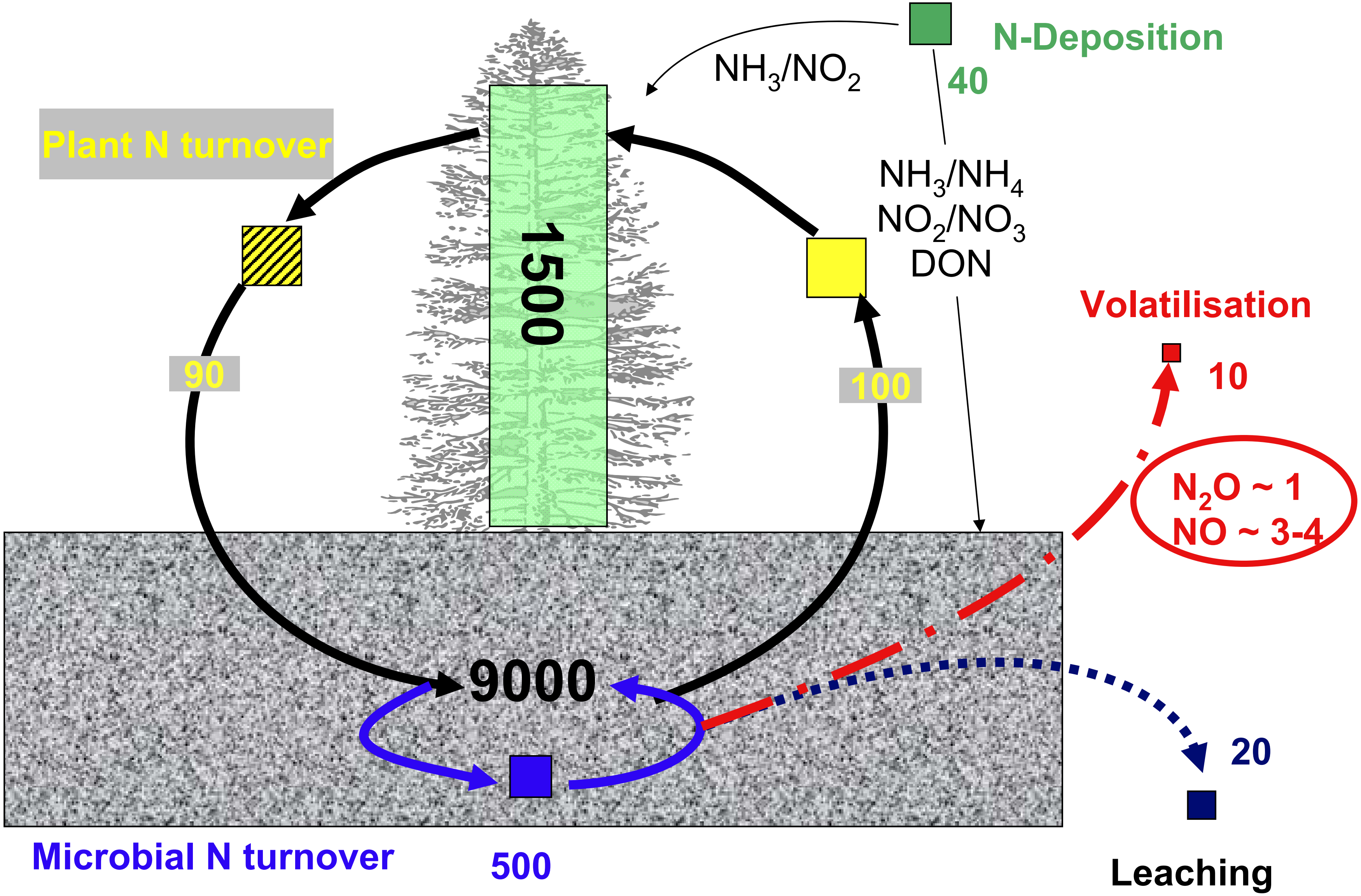
NH_4^+-availability

- N-mineralisation
- cation exchange capacity
- plant or/ and microbial uptake/ mineralisation

O_2-availability

- soil texture/ type
- evapotranspiration
- precipitation/ rainfall

N trace gases and ecosystem N cycling



N-Deposition

NH_3/NO_2

40

NH_3/NH_4
NO_2/NO_3
DON

Plant N turnover

1500

90

100

Volatilisation

10

N_2O ~ 1
NO ~ 3-4

9000

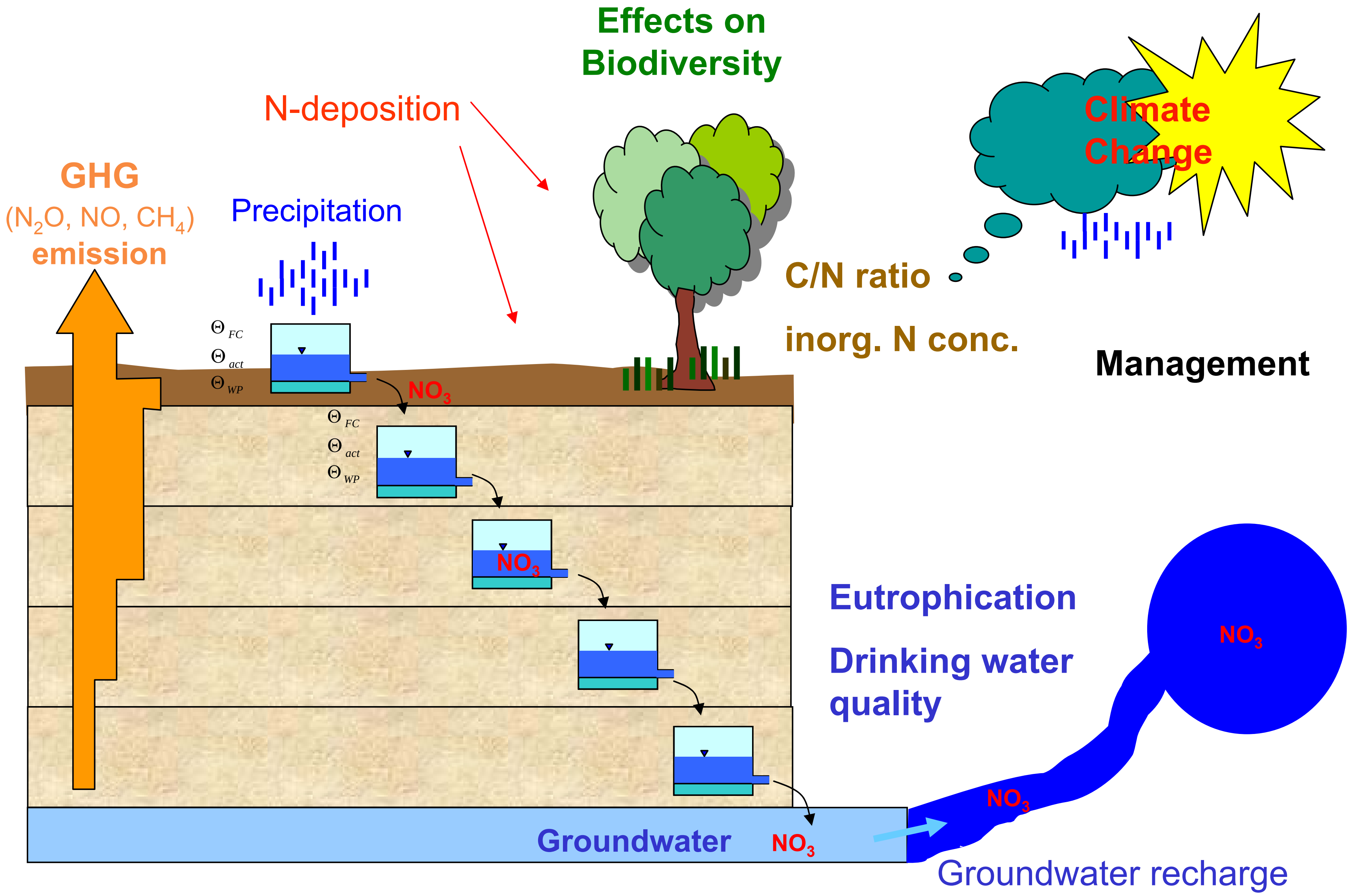
20

Microbial N turnover

500

Leaching

What is needed?



Effects on Biodiversity

N-deposition

GHG

(N_2O, NO, CH_4)

emission

Precipitation

Climate Change

C/N ratio

inorg. N conc.

Management

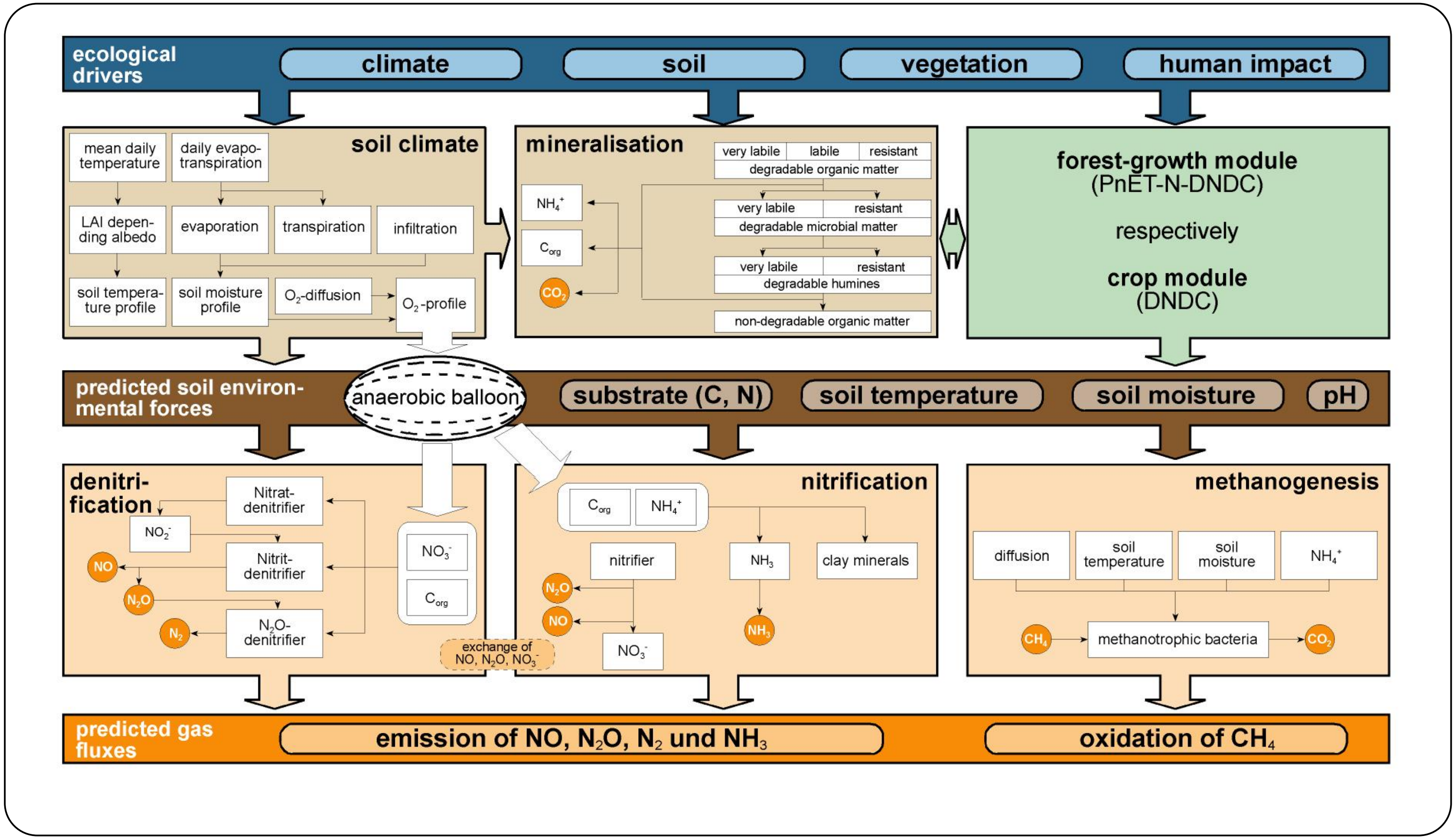
Eutrophication

Drinking water quality

Groundwater

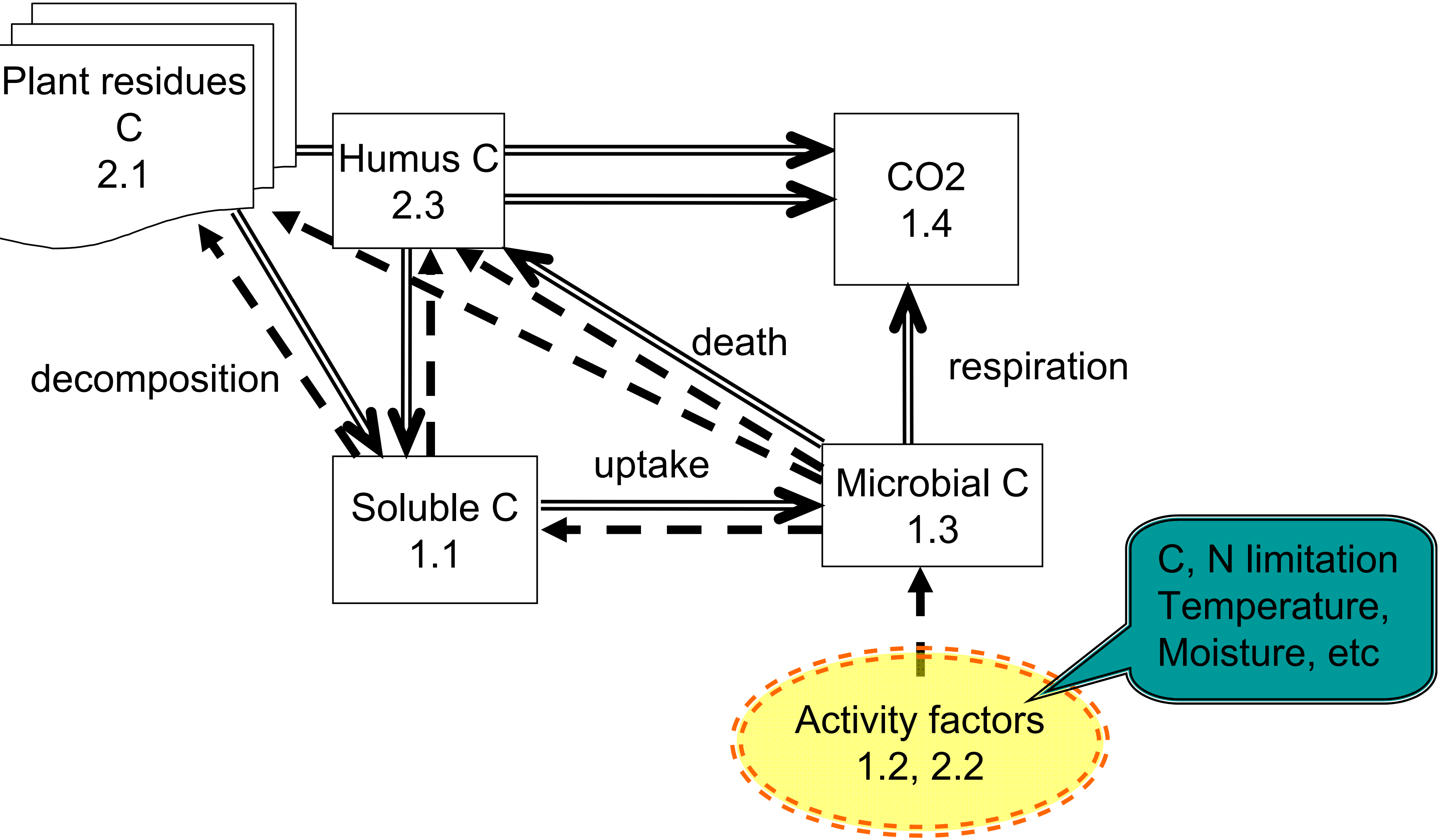
Groundwater recharge

Detailed C and N ecosystem model!



Modeling C mineralisation

Double lines show carbon mass flows and dashed lines show influences described in model



Plant residues C 2.1

Humus C 2.3

CO2 1.4

decomposition

death

respiration

uptake

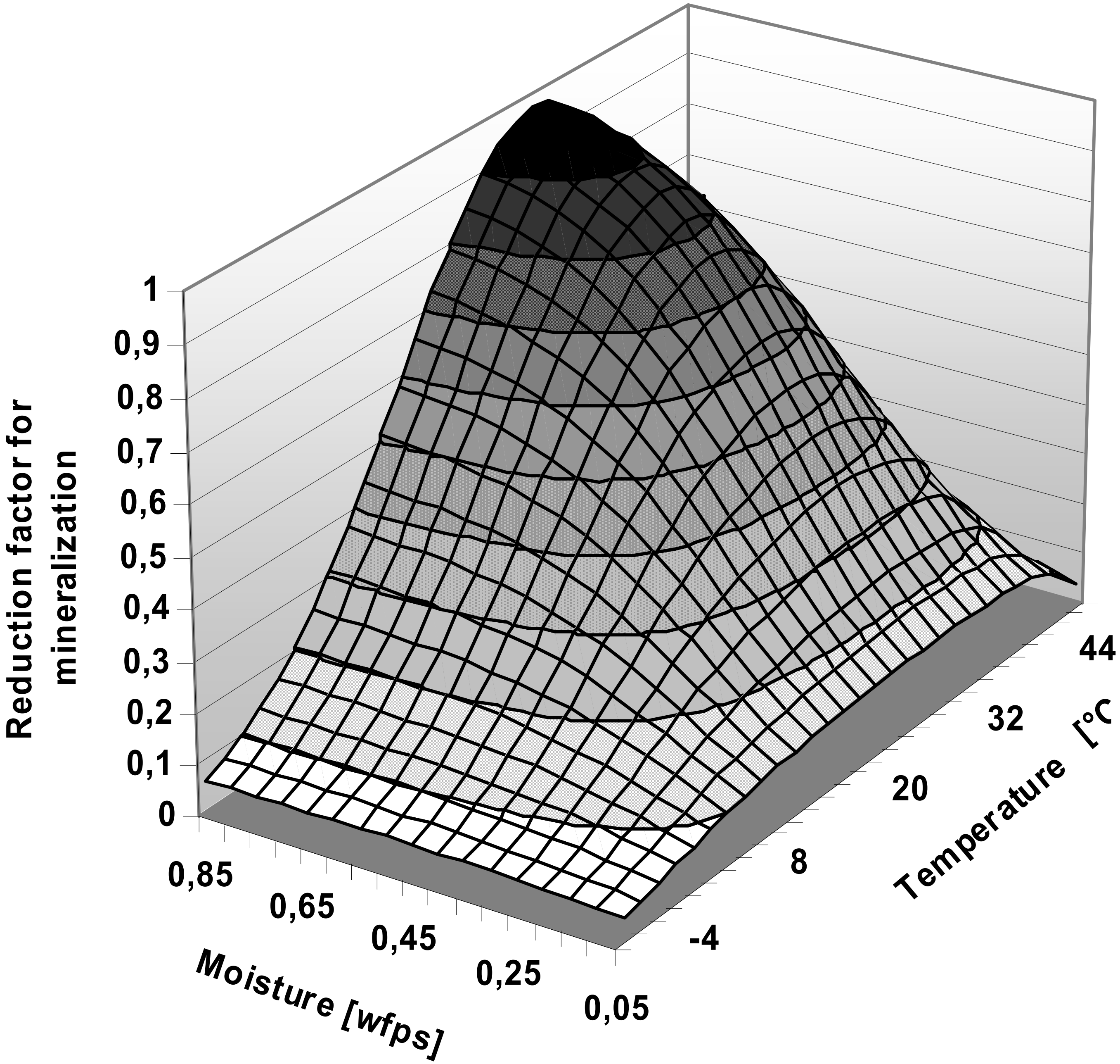
Soluble C 1.1

Microbial C 1.3

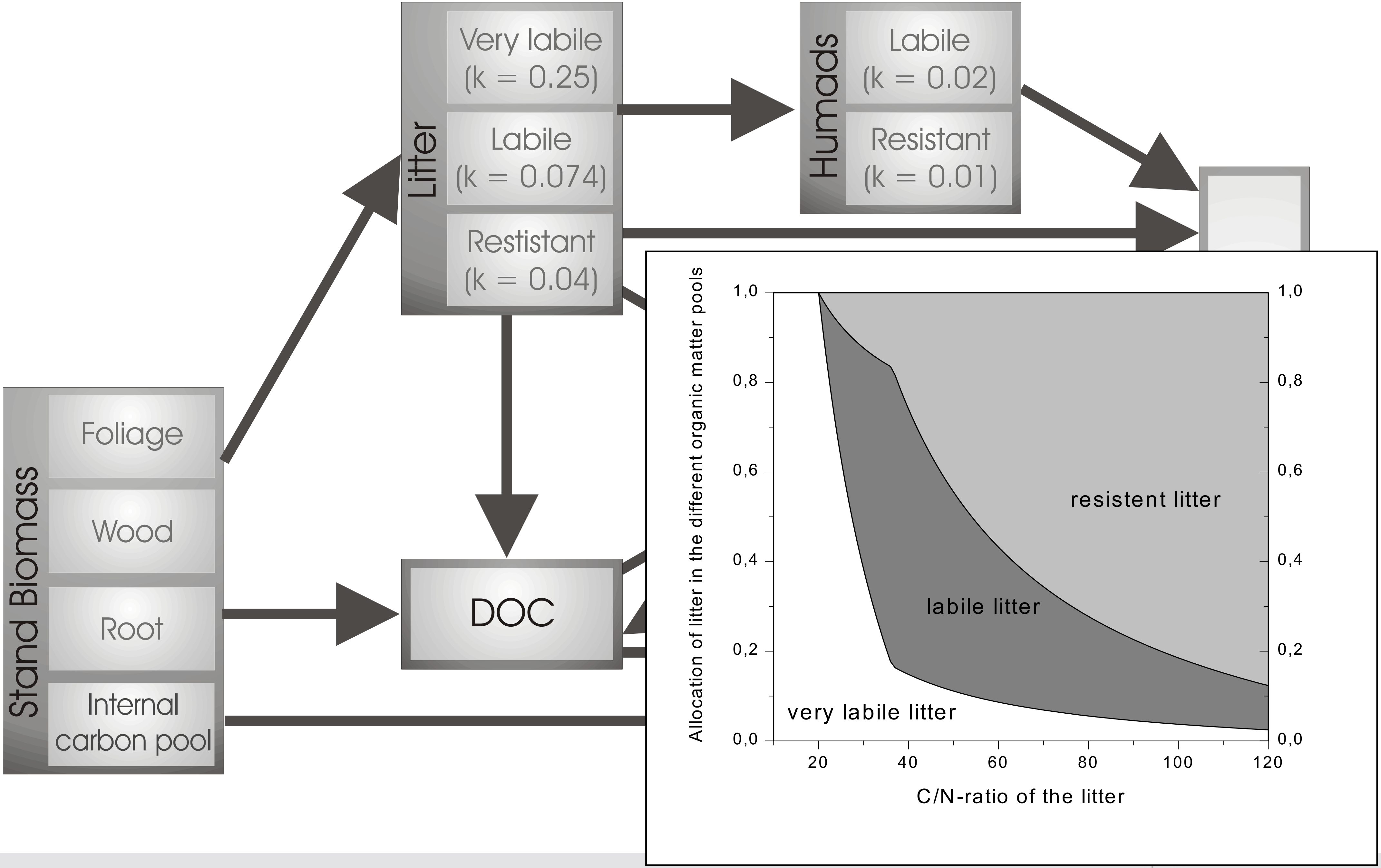
C, N limitation Temperature, Moisture, etc

Activity factors 1.2, 2.2

Moisture/ temperature reduction factors



Modeling C mineralisation



Stand Biomass

Foliage

Wood

Root

Internal carbon pool

Litter

Very labile (k = 0.25)

Labile (k = 0.074)

Restistant (k = 0.04)

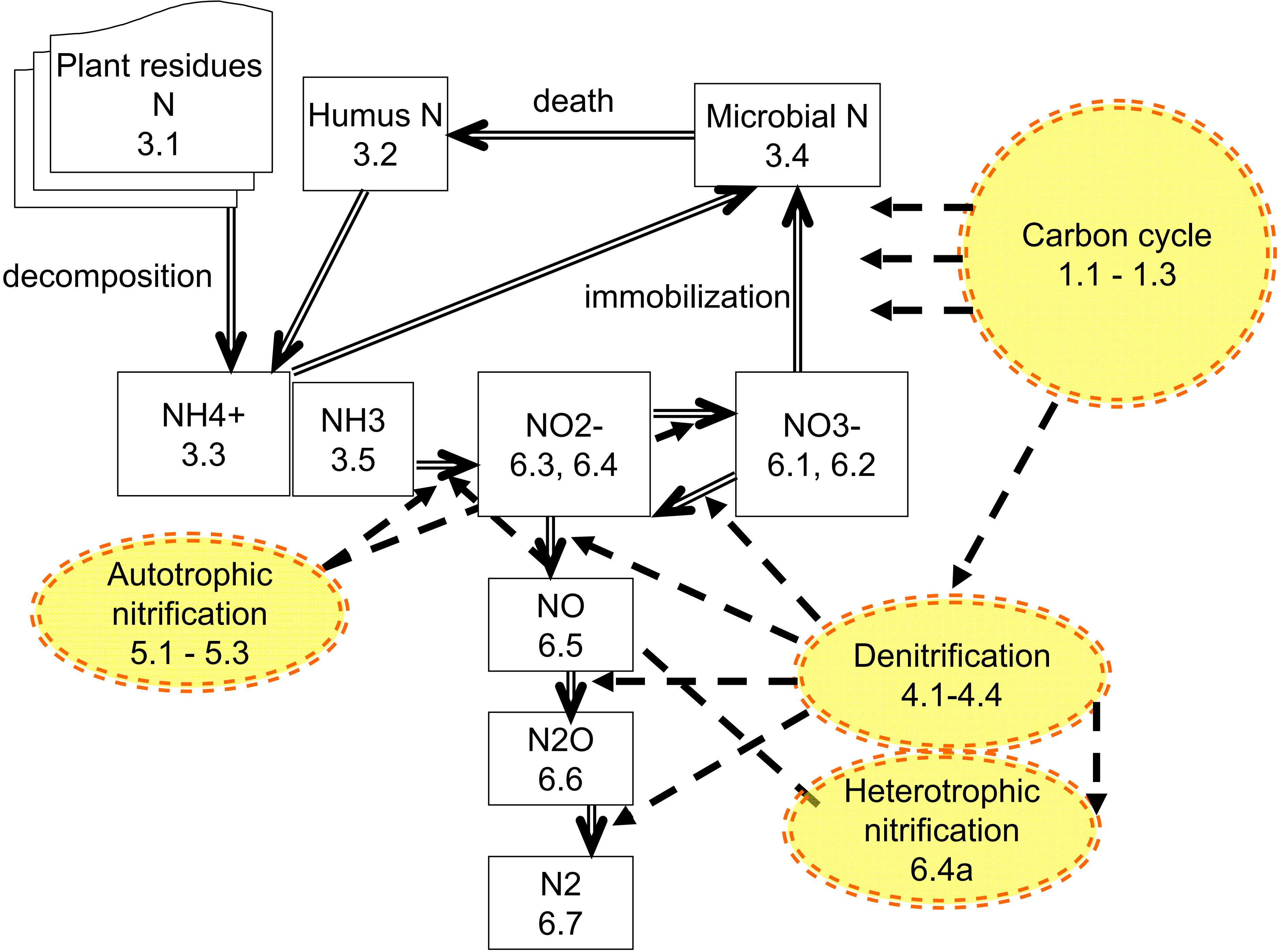
Humads

Labile (k = 0.02)

Resistant (k = 0.01)

DOC

Modeling N turnover



Plant residues N 3.1

Humus N 3.2

death

Microbial N 3.4

decomposition

immobilization

Carbon cycle 1.1 - 1.3

NH4+ 3.3

NH3 3.5

NO2- 6.3, 6.4

NO3- 6.1, 6.2

Autotrophic nitrification 5.1 - 5.3

NO 6.5

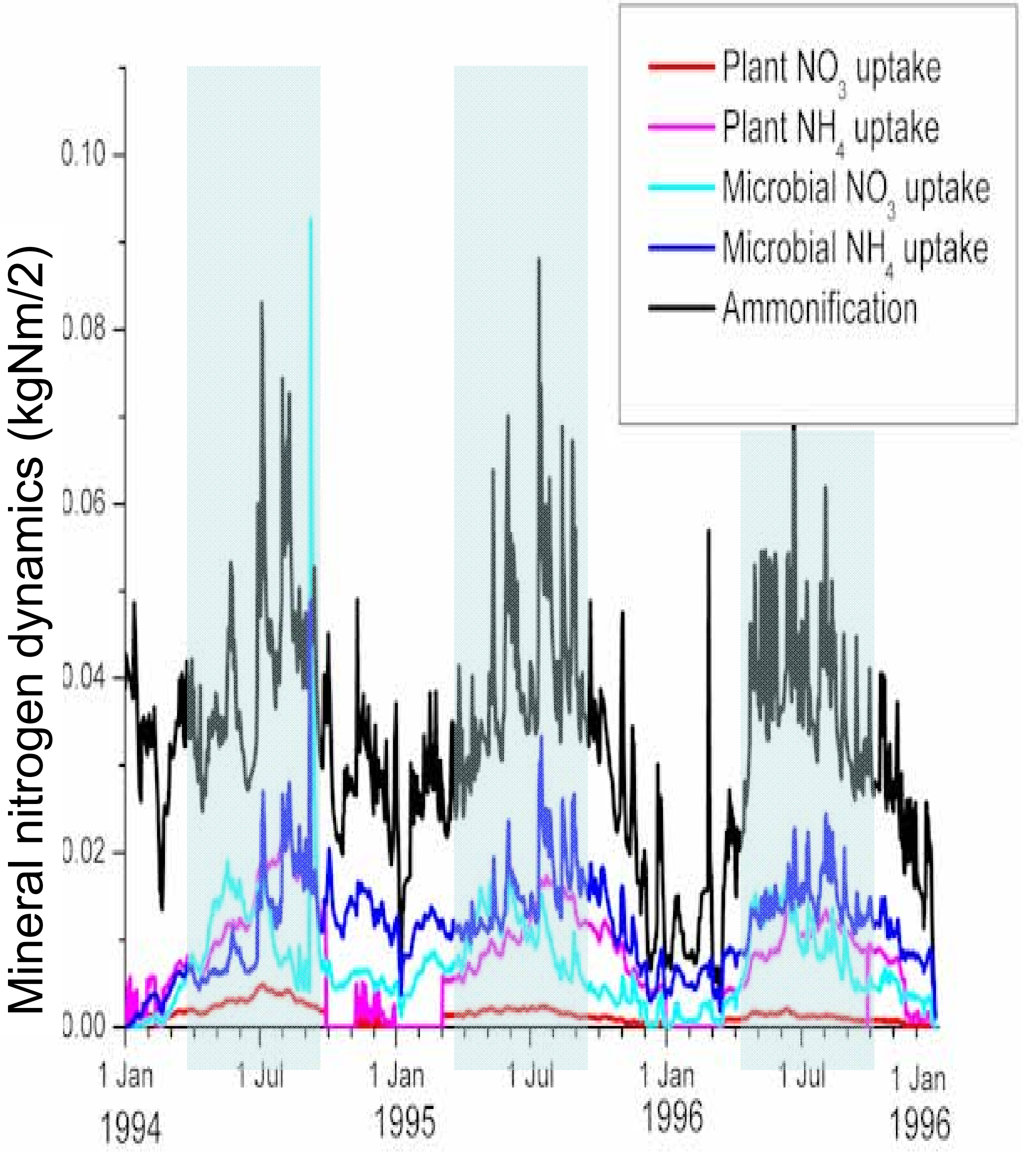
Denitrification 4.1-4.4

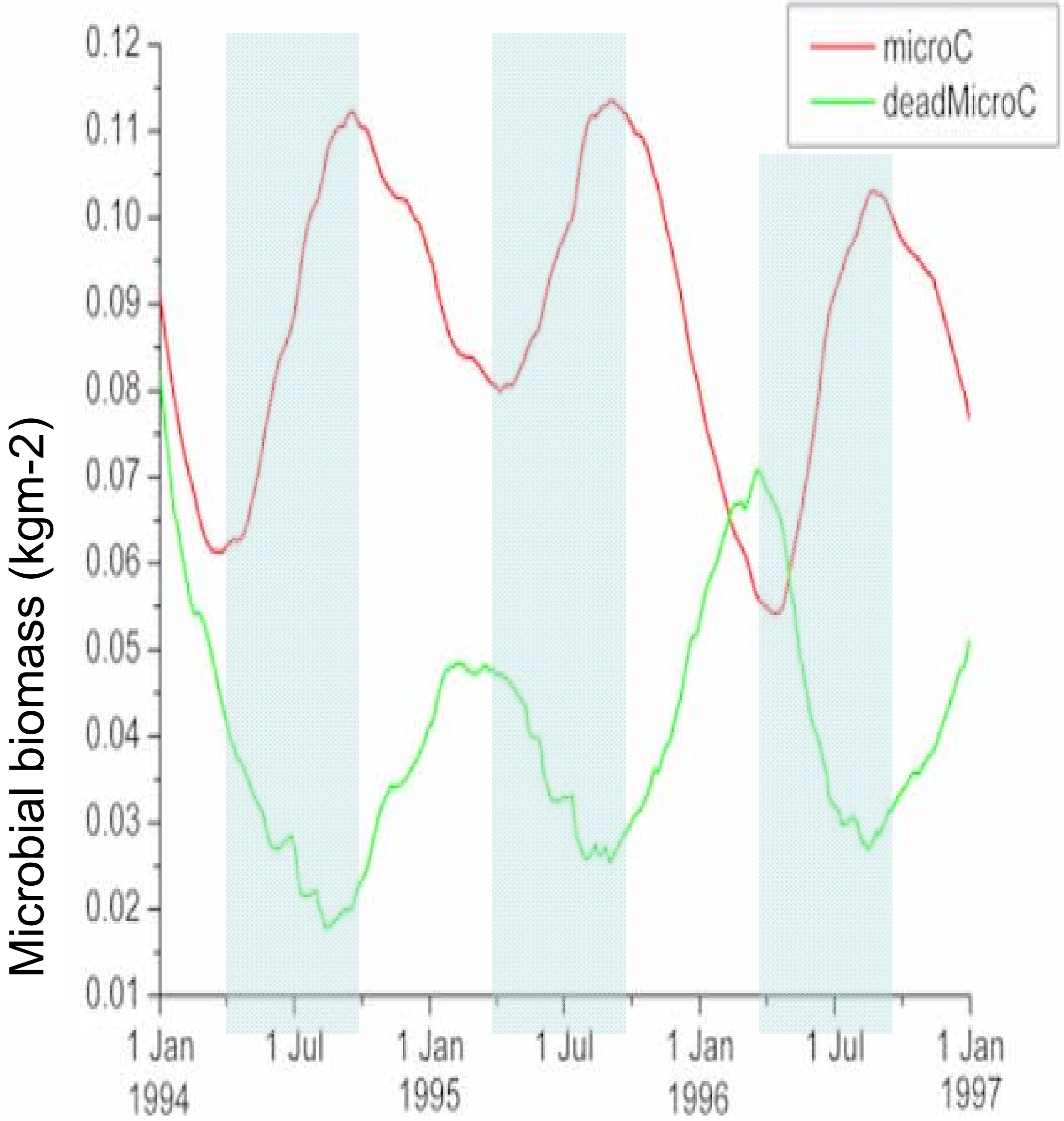
N2O 6.6

Heterotrophic nitrification 6.4a

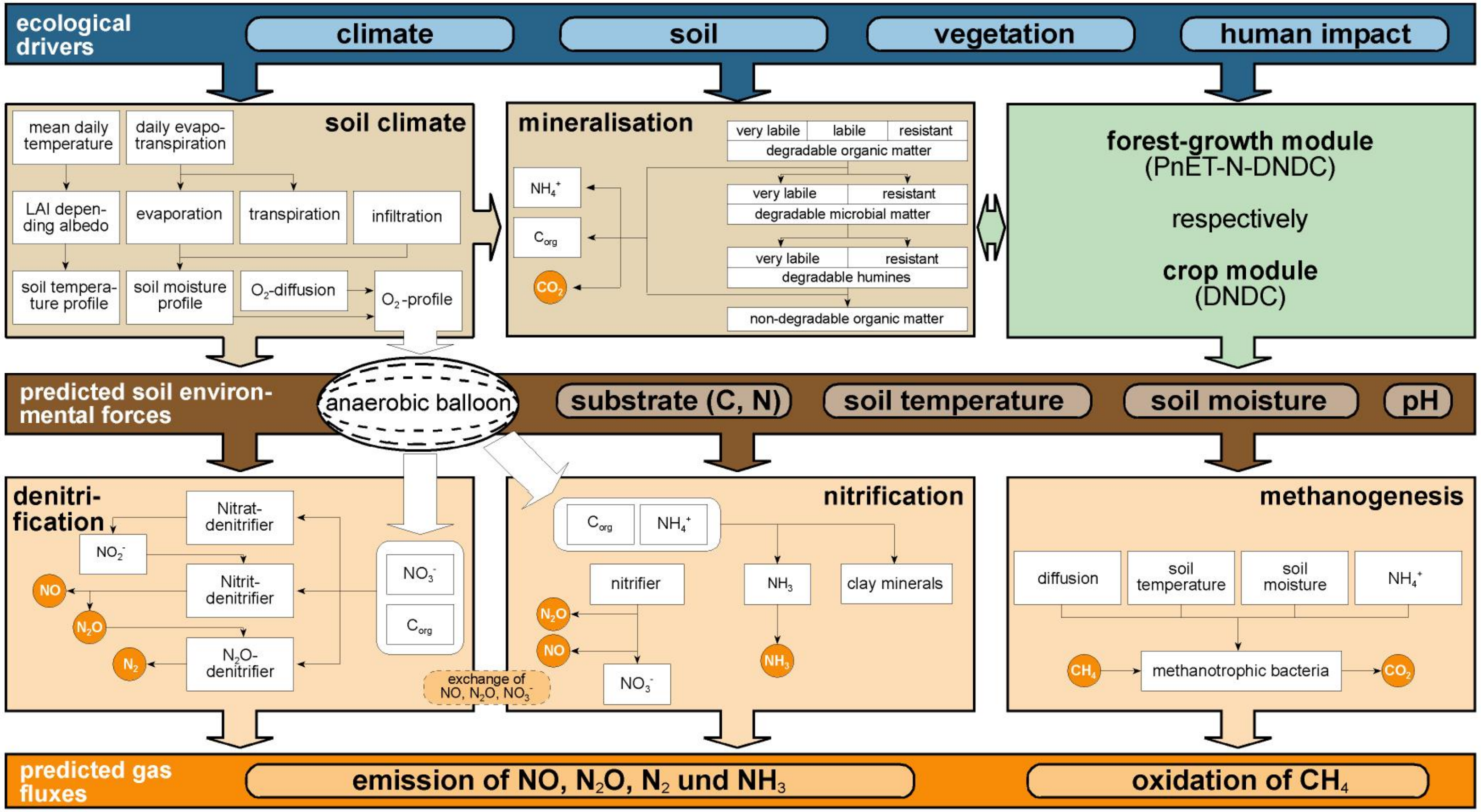
N2 6.7

Modeling N turnover and microbial biomass dynamics





Anaerobic balloon



ecological drivers
climate
soil
vegetation
human impact

soil climate
mean daily temperature
daily evapo-transpiration
LAI depending albedo
evaporation
transpiration
infiltration
soil temperature profile
soil moisture profile
O_2-diffusion
O_2-profile

mineralisation
very labile | labile | resistant
degradable organic matter
very labile | resistant
degradable microbial matter
very labile | resistant
degradable humines
non-degradable organic matter
NH_4^+
C_{org}
CO_2

forest-growth module
(PnET-N-DNDC)
respectively
crop module
(DNDC)

predicted soil environmental forces
anaerobic balloon
substrate (C, N)
soil temperature
soil moisture
pH

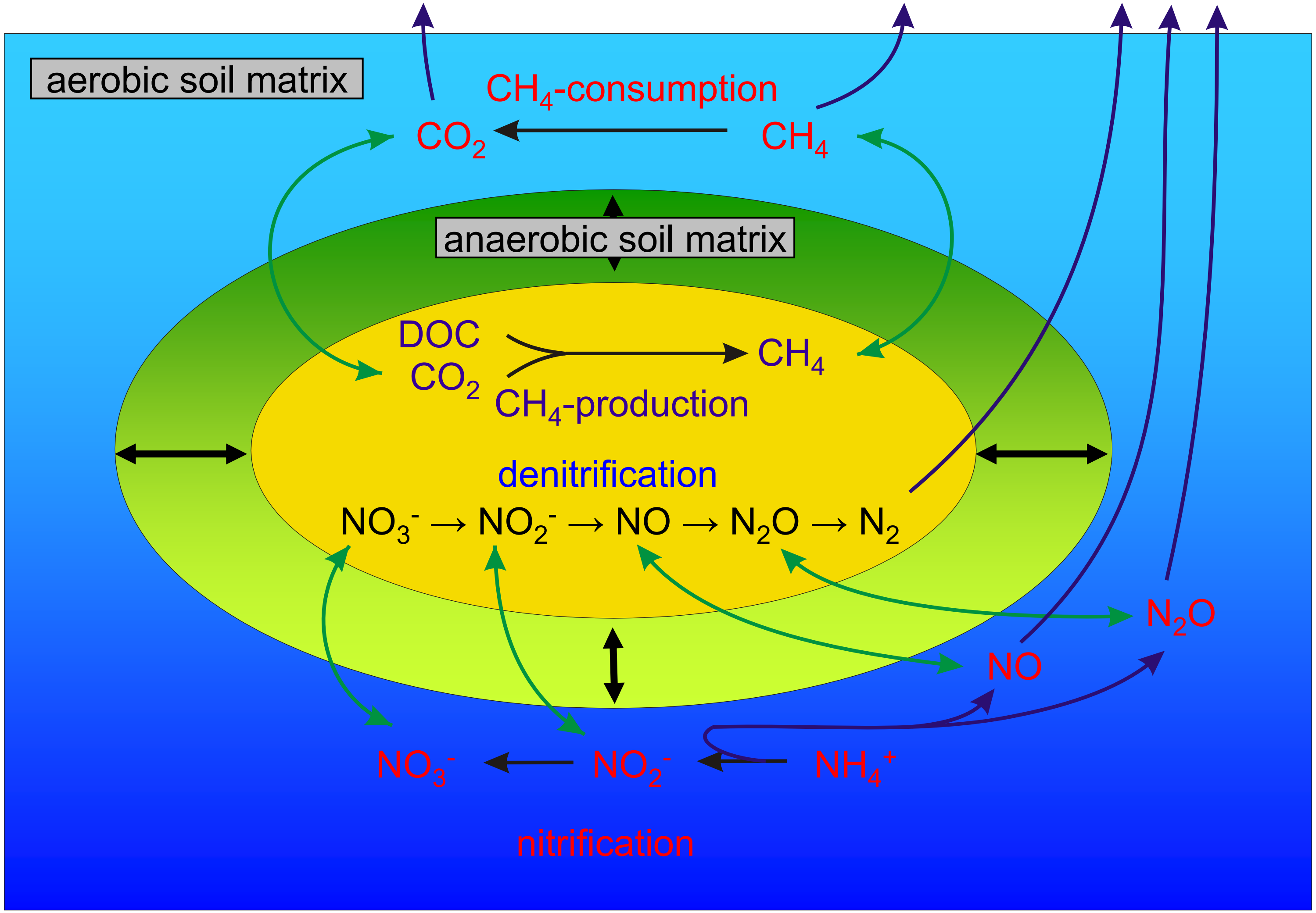
denitrification
Nitrat-denitrifier
NO_2^-
NO
Nitrit-denitrifier
N_2O
N_2O-denitrifier
N_2
NO_3^-
C_{org}
exchange of NO, N_2O, NO_3^-

nitrification
C_{org}
NH_4^+
nitrifier
NH_3
clay minerals
N_2O
NO
NO_3^-
NH_3

methanogenesis
diffusion
soil temperature
soil moisture
NH_4^+
CH_4
methanotrophic bacteria
CO_2

predicted gas fluxes
emission of NO, N_2O, N_2 und NH_3
oxidation of CH_4

Anaerobic balloon

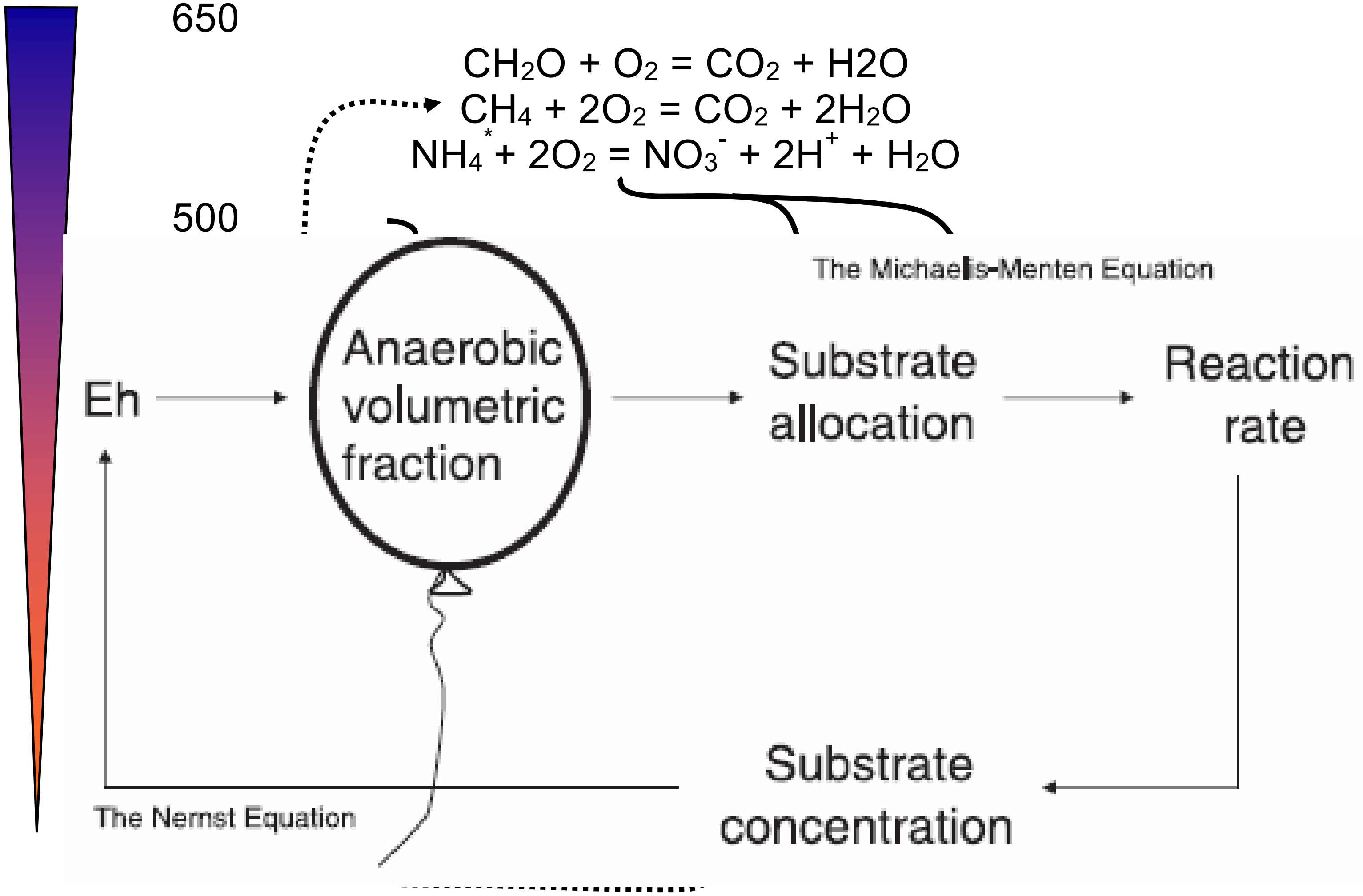


Anaerobic balloon

Dominant oxidant

Eh (mV)

Reactions



650

500

Oxygen (O_2)

$CH_2O + O_2 = CO_2 + H2O$

$CH_4 + 2O_2 = CO_2 + 2H_2O$

$NH_4^{*} + 2O_2 = NO_3^{-} + 2H^{+} + H_2O$

Nitrate (NO_3^{-})
Nitrite (NO_2^{-})
Nitric oxide (NO)
Nitrous oxide (N_2O)

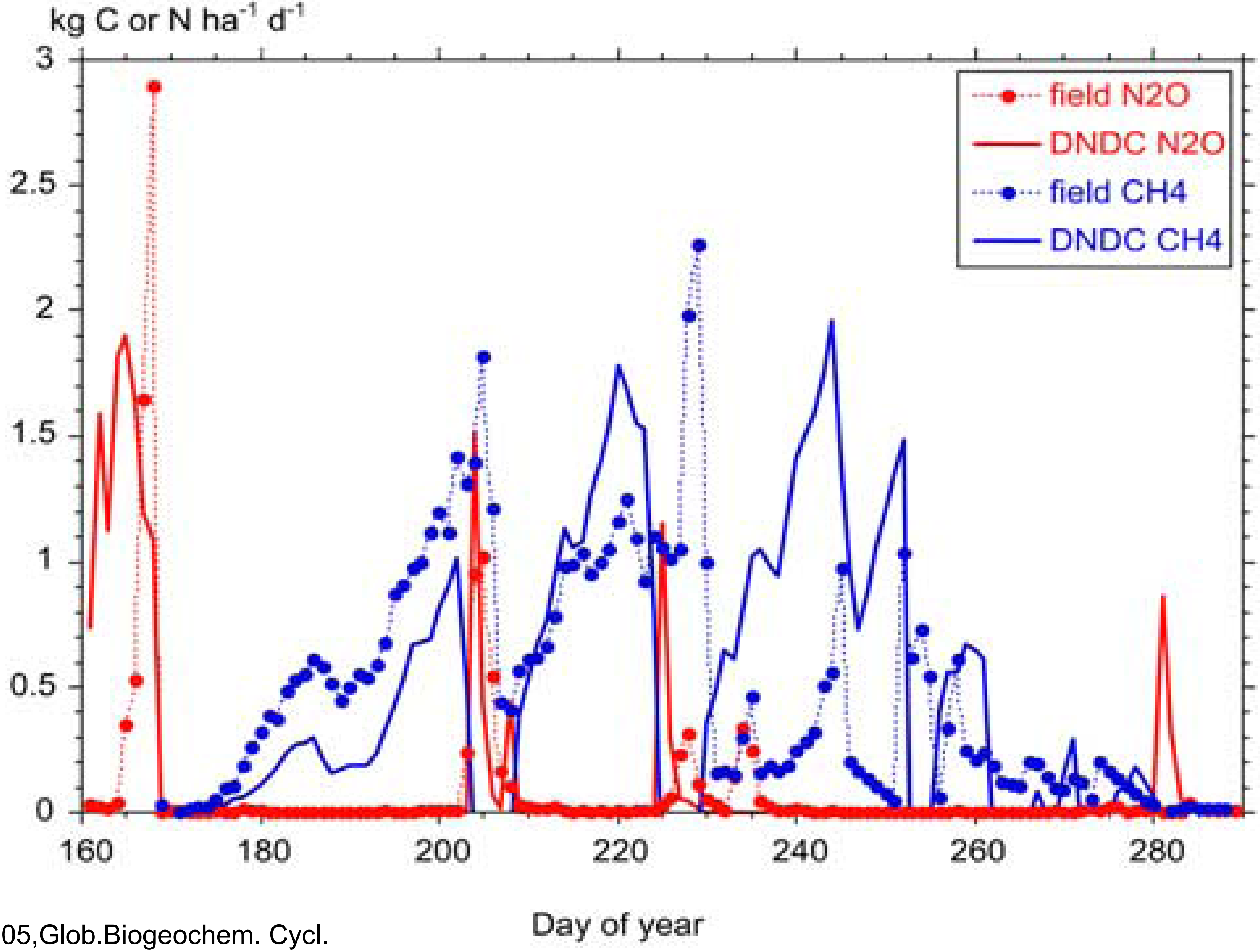
Manganese (Mn^{4+})

Iron (Fe^{3+})

Sulfate (SO_4^{2-})

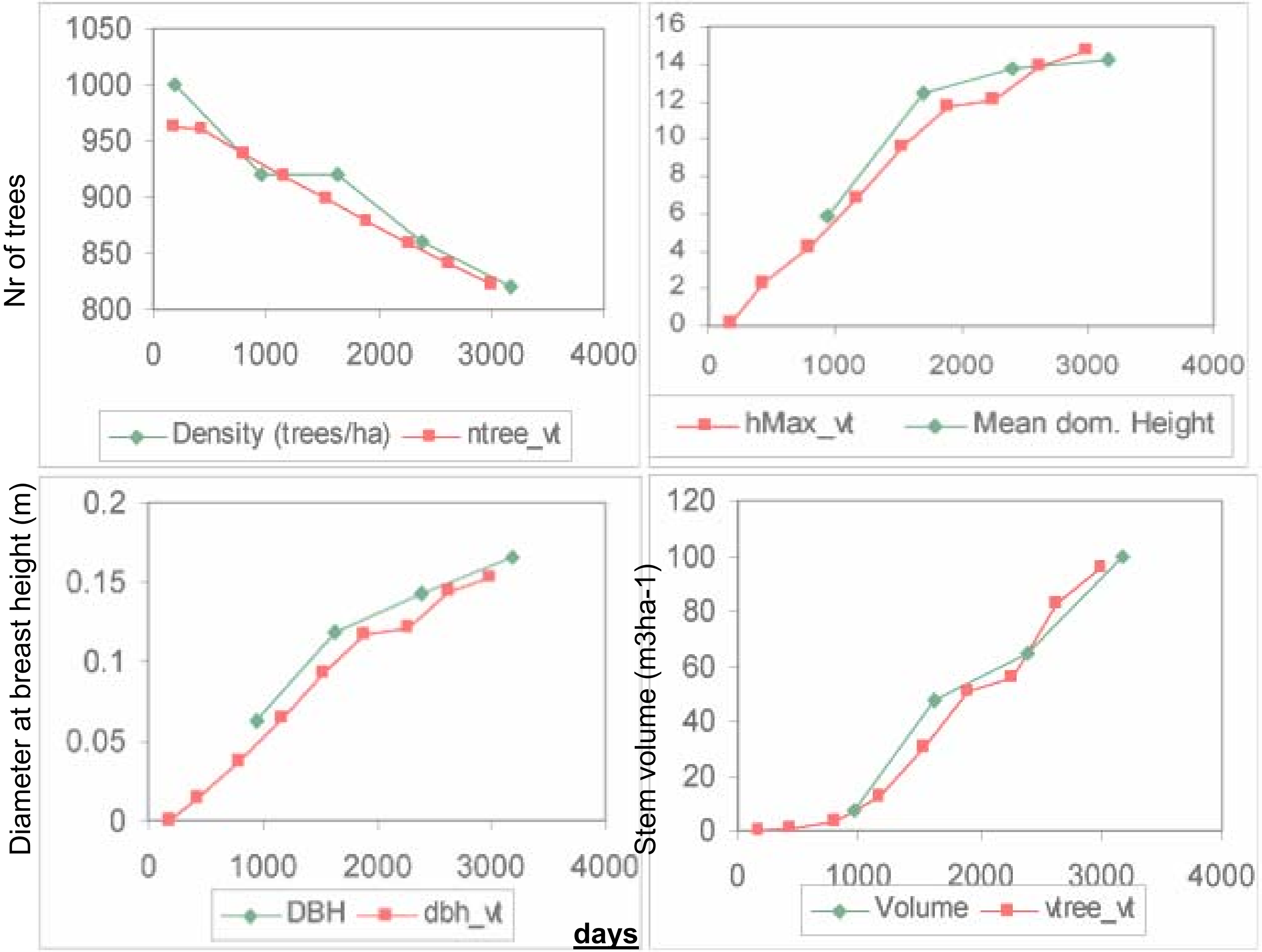
Hydrogen (H_2)

Model evaluation: $N_2O$and CH_4 exchange in rice paddies



Li et al., 2005,Glob.Biogeochem. Cycl.

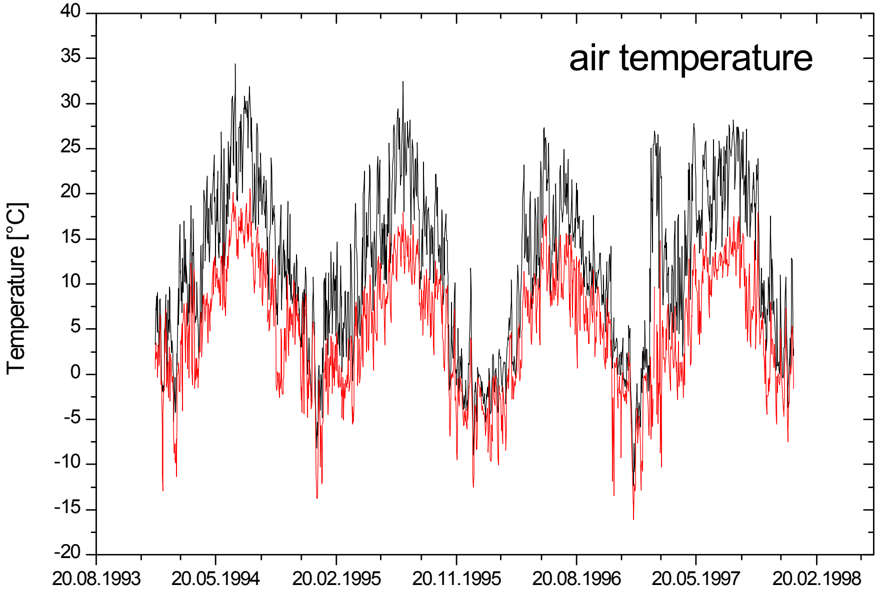
Model evaluation: forest growth

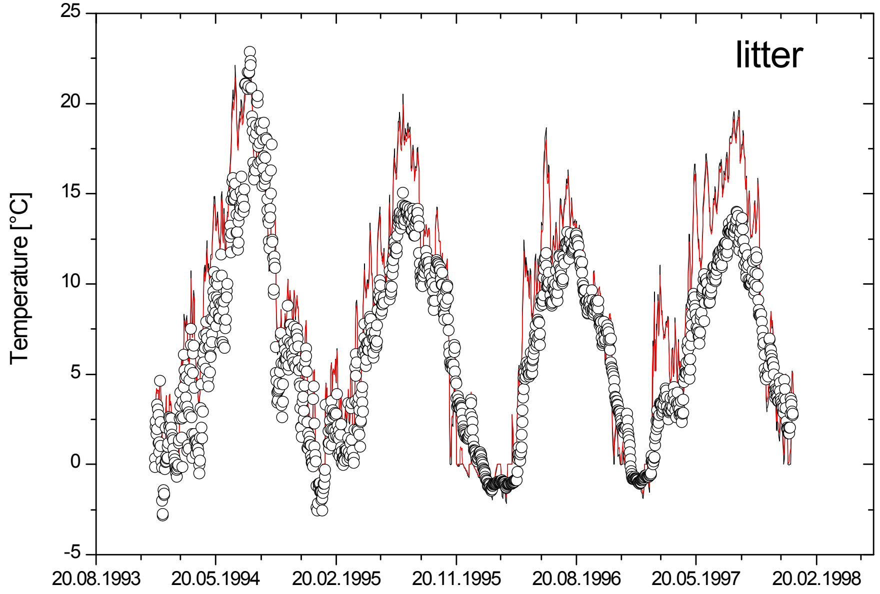


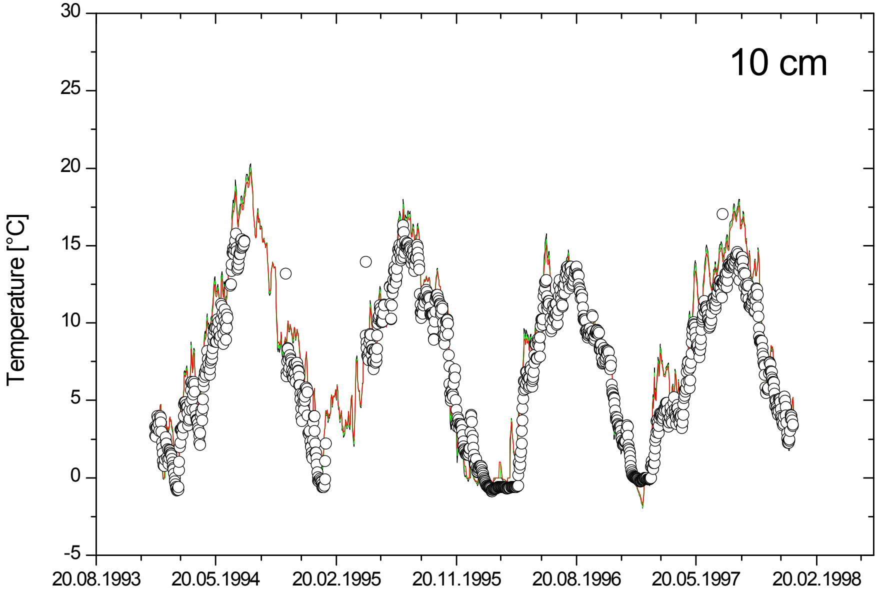
Long-term simulation of biomass development for a Eucalypt plantage using PnET and TREEDYN: nr of trees, average diameter and wood volumes

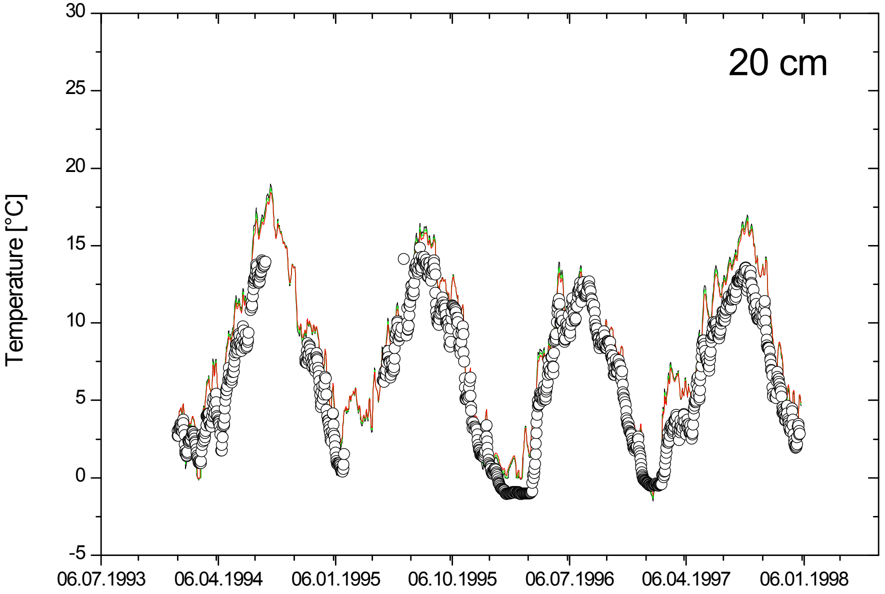
Model evaluation: soil physics

Soil temperature

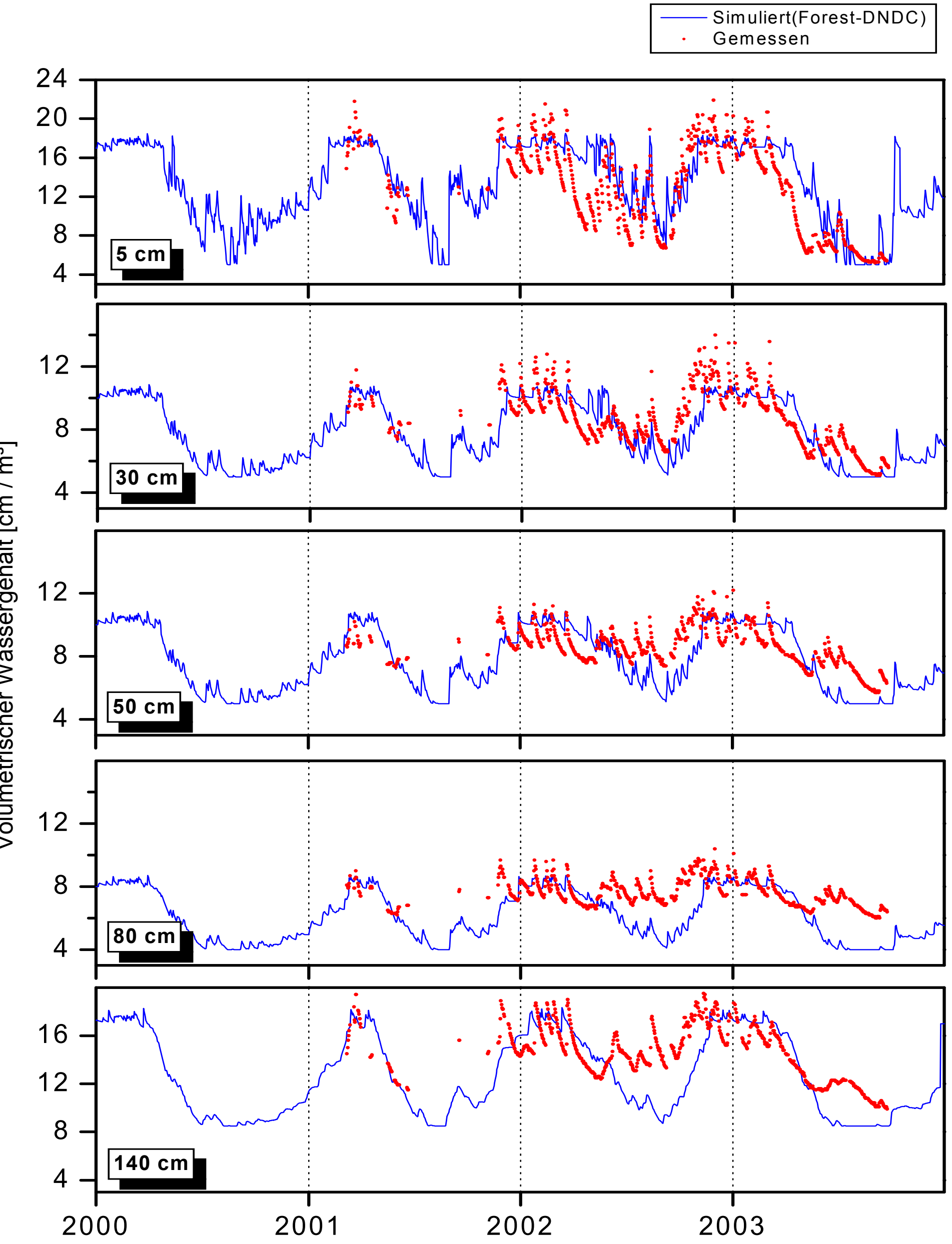




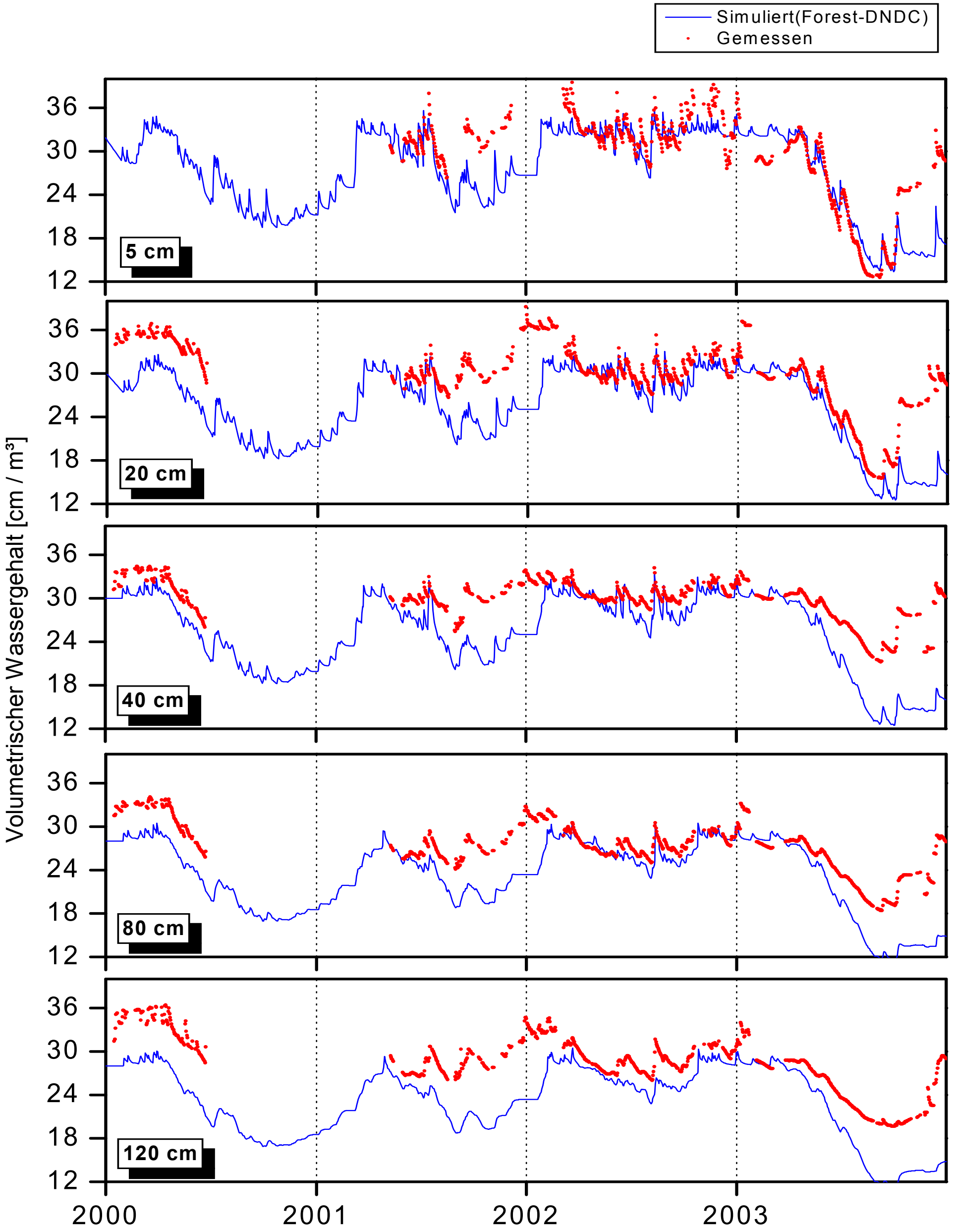




Model evaluation: soil water

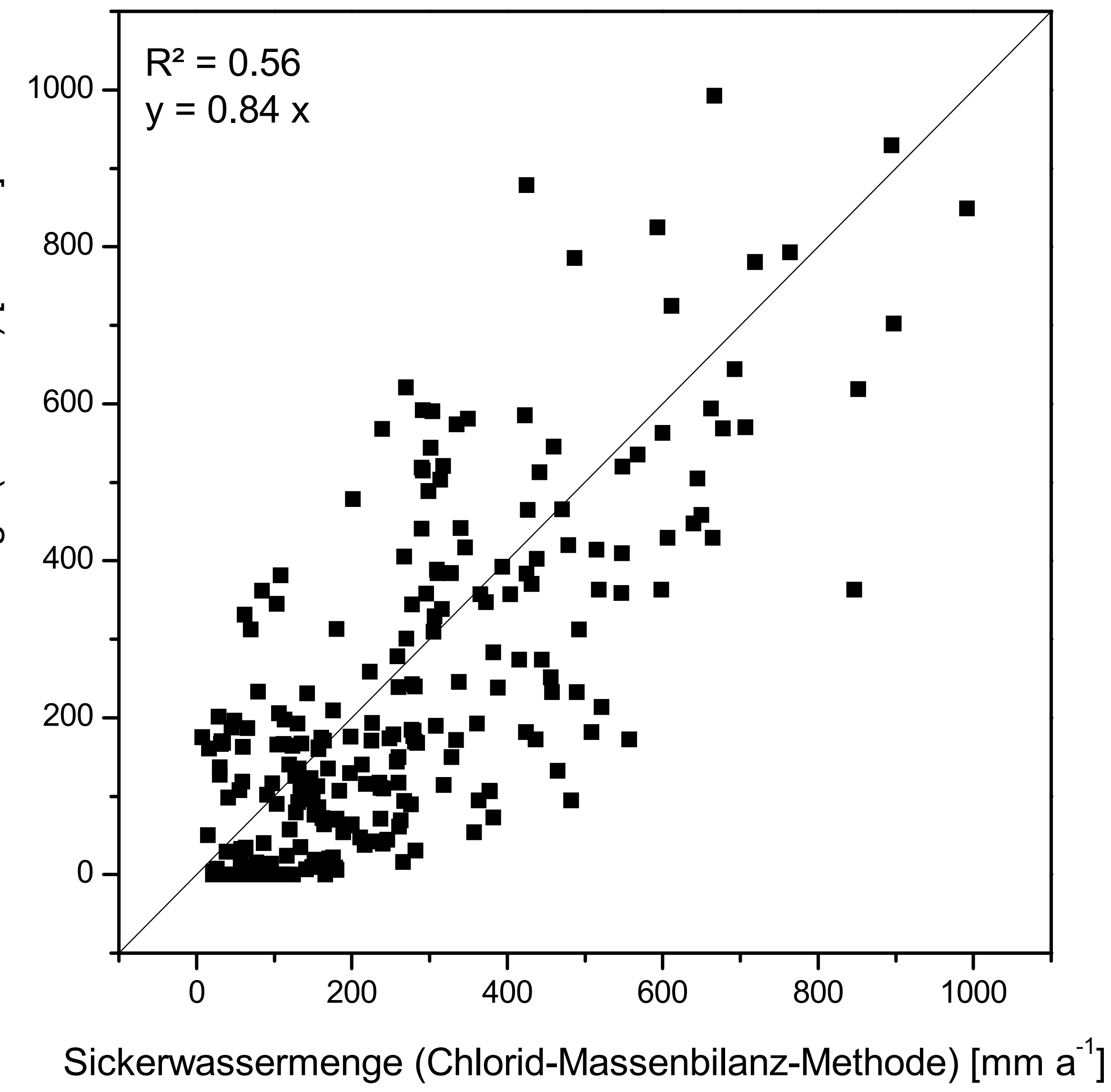


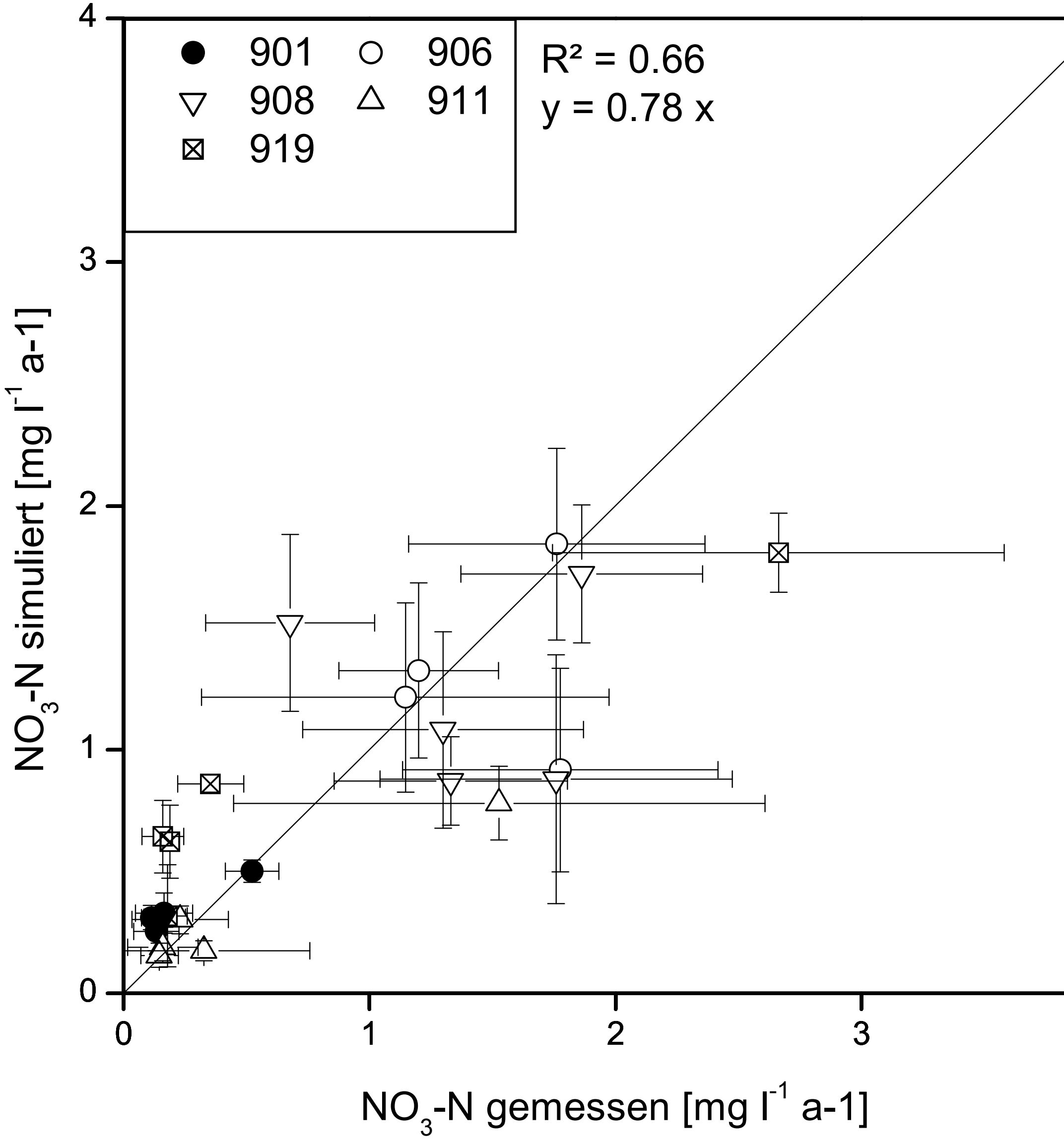
Altdorf



Flossenbürg

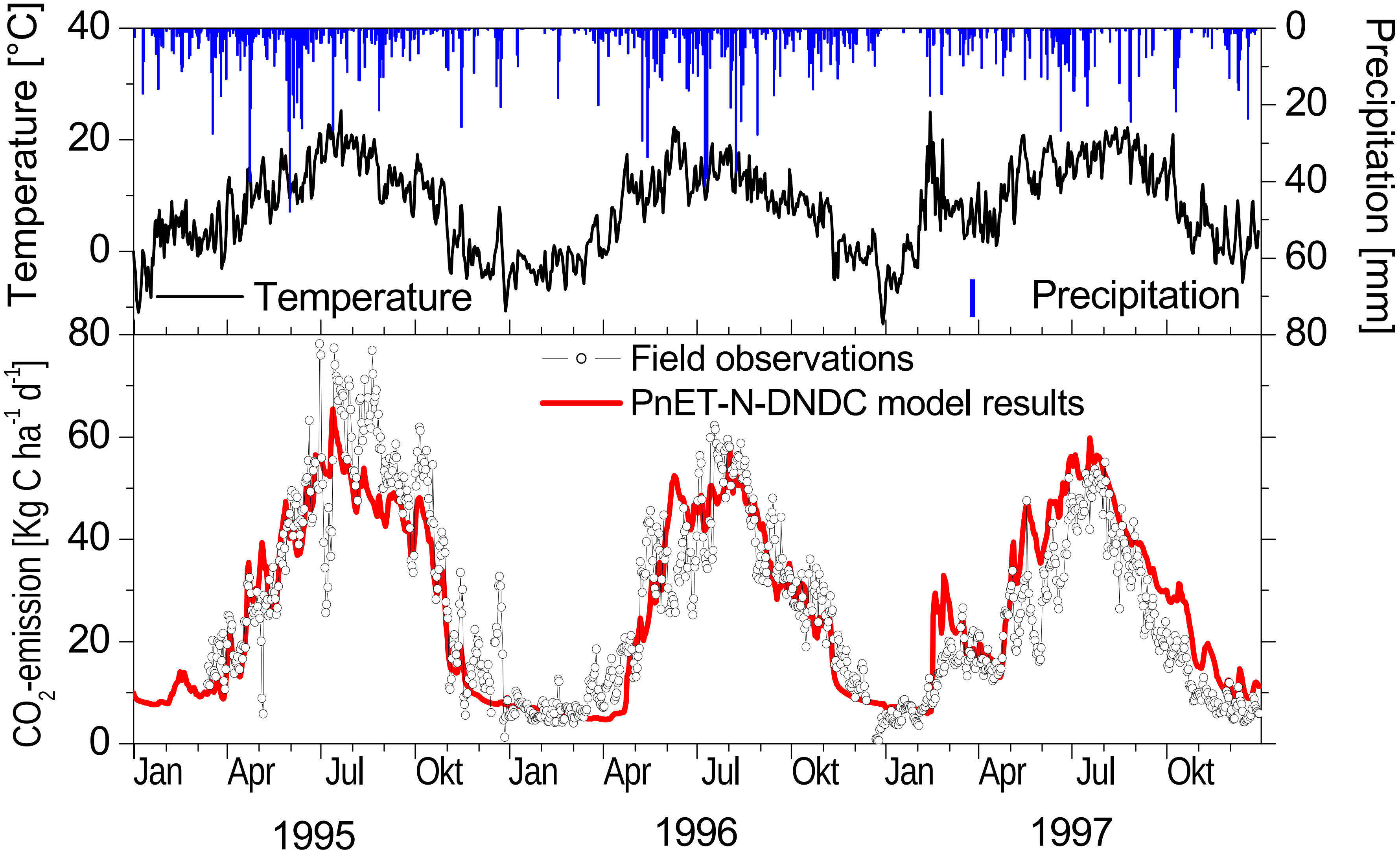
Model evaluation: Nitrate leaching



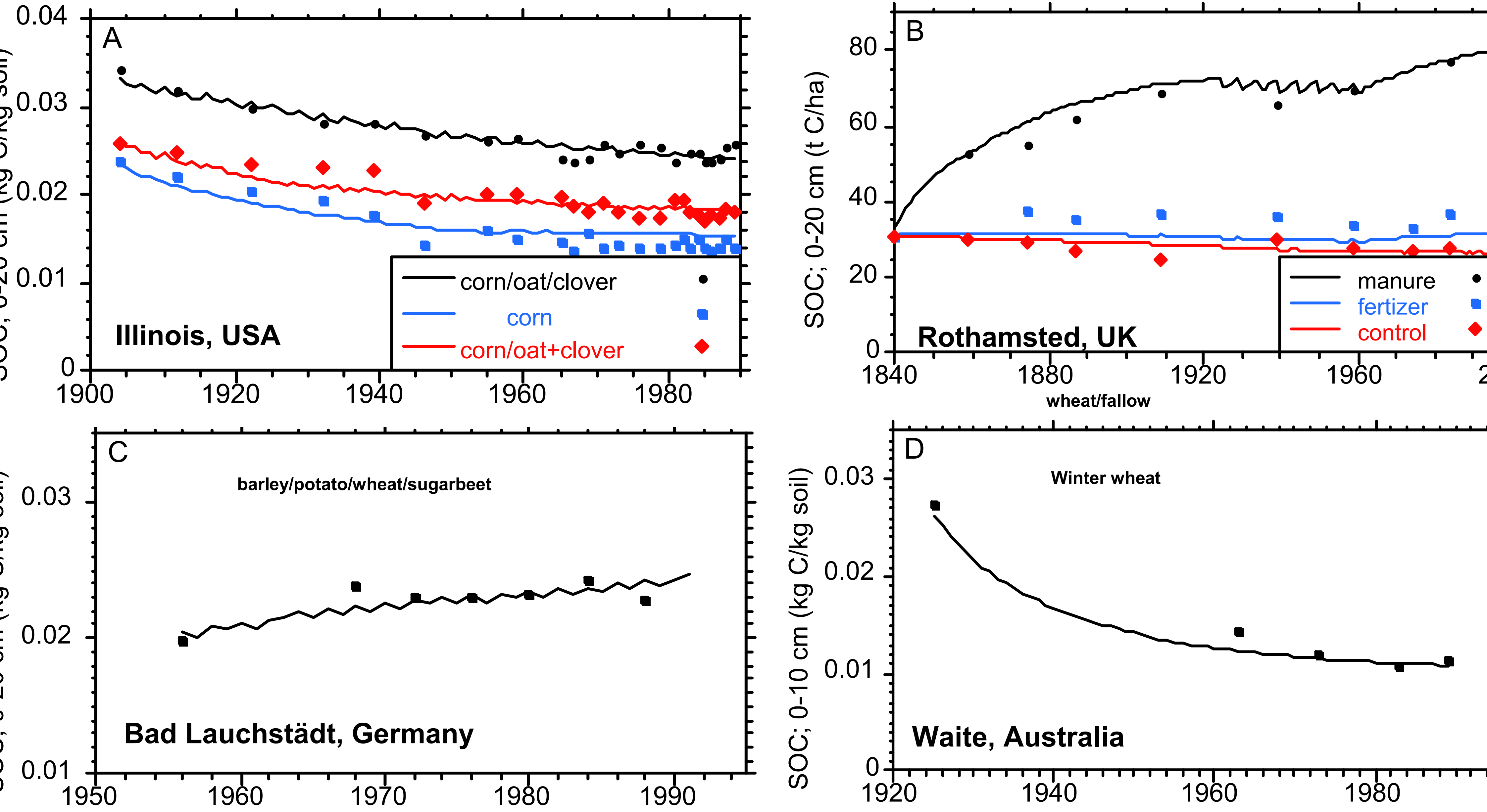


Model evaluation: soil CO_2 emissions

Water balance Soil CO_2 emissions

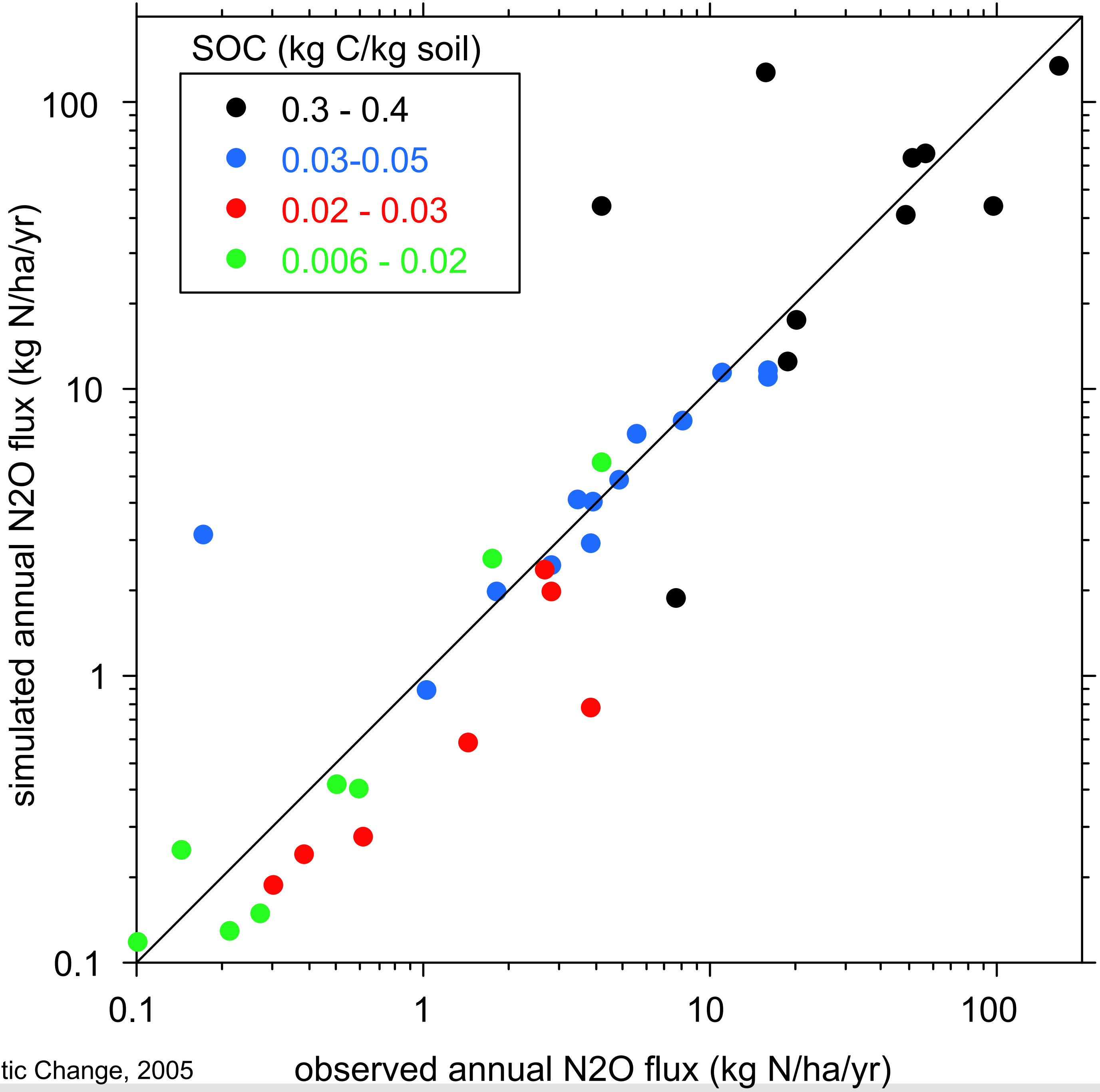


Testing the DNDC model for simulating SOC dynamics



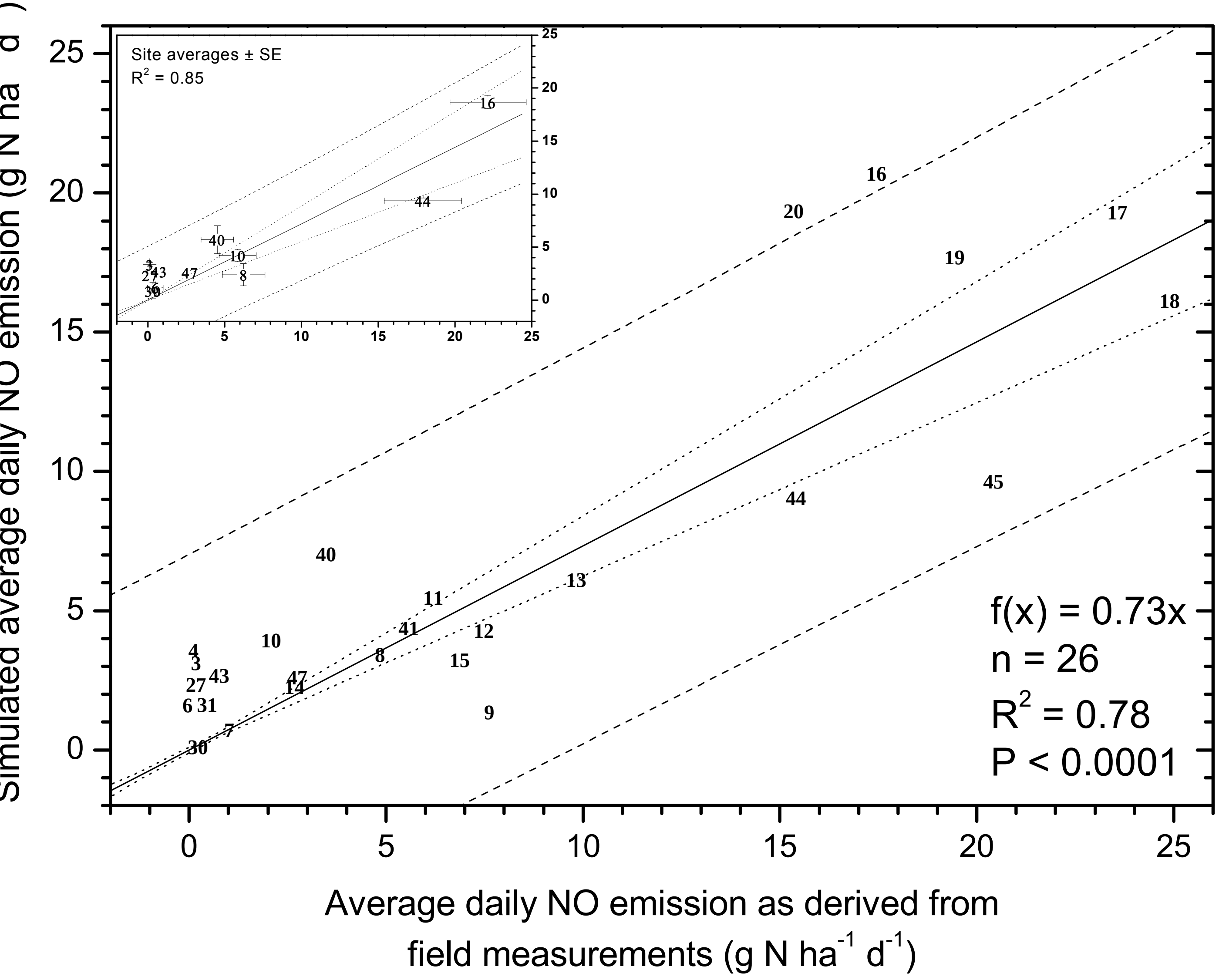
Li, Frolking, Butterbach-Bahl, Climatic Change, 2005

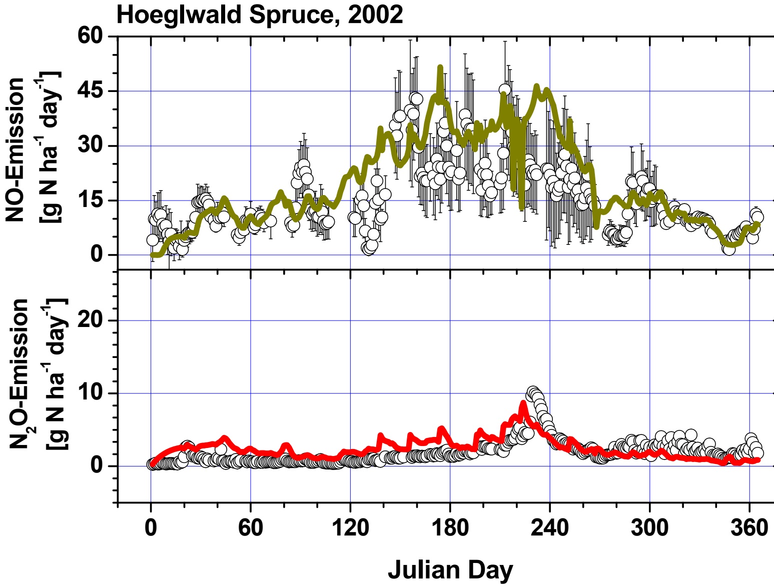
Testing the DNDC model for N_2O emissions

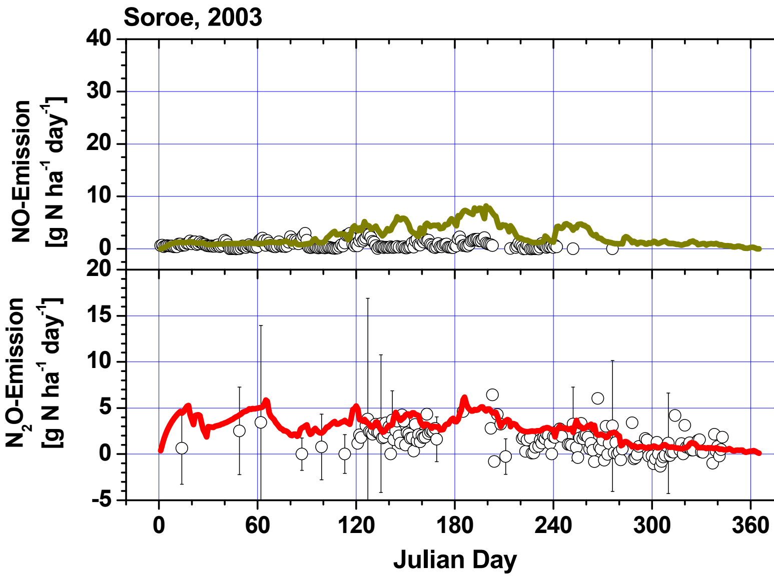


i, Frolking, Butterbach-Bahl, Climatic Change, 2005

Testing the DNDC model for NO emissions



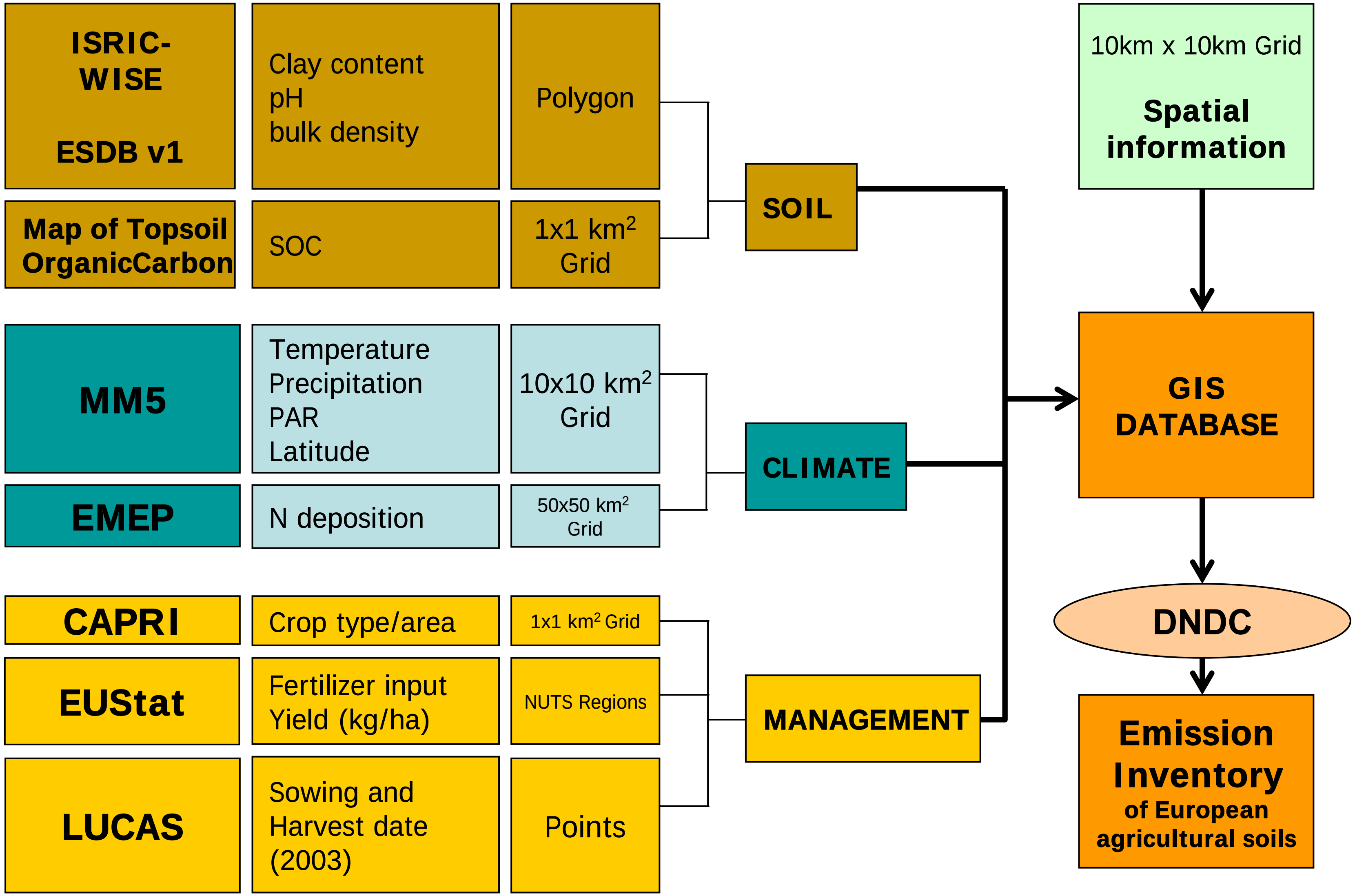




Kesik et al., 2006, Biogeosciences

GIS coupling for GIS – the problem of data

GIS database for DNDC



Data source	Data content	format
ISRIC-WISE **ESDB v1**	Clay content pH bulk density	Polygon
Map of Topsoil OrganicCarbon	SOC	1x1 km^2 Grid
MM5	Temperature Precipitation PAR Latitude	10x10 km^2 Grid
EMEP	N deposition	50x50 km^2 Grid
CAPRI	Crop type/area	1x1 km^2 Grid
EUStat	Fertilizer input Yield (kg/ha)	NUTS Regions
LUCAS	Sowing and Harvest date (2003)	Points

SOIL

CLIMATE

MANAGEMENT

10km x 10km Grid

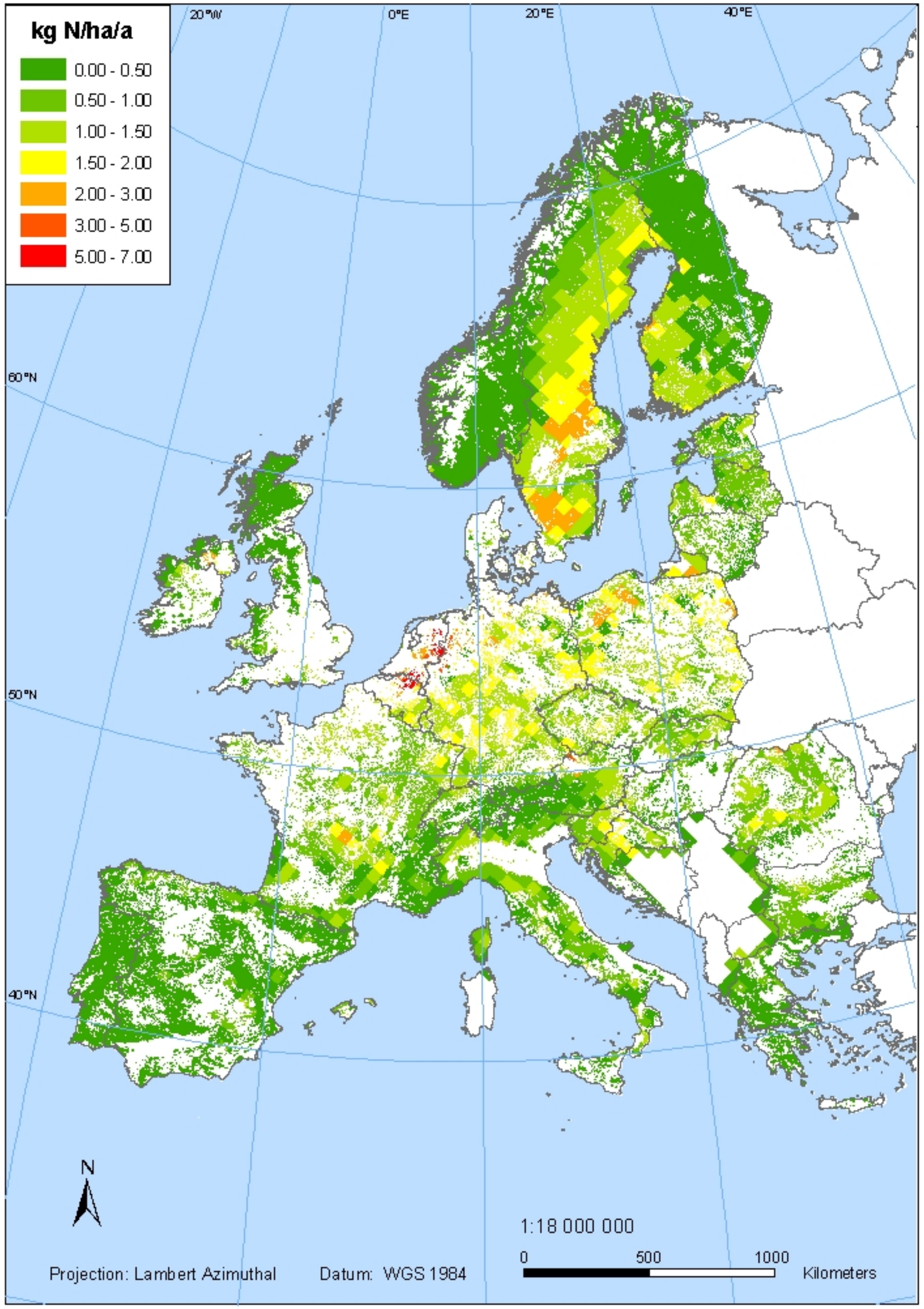
Spatial information

GIS DATABASE

DNDC

Emission Inventory
of European agricultural soils

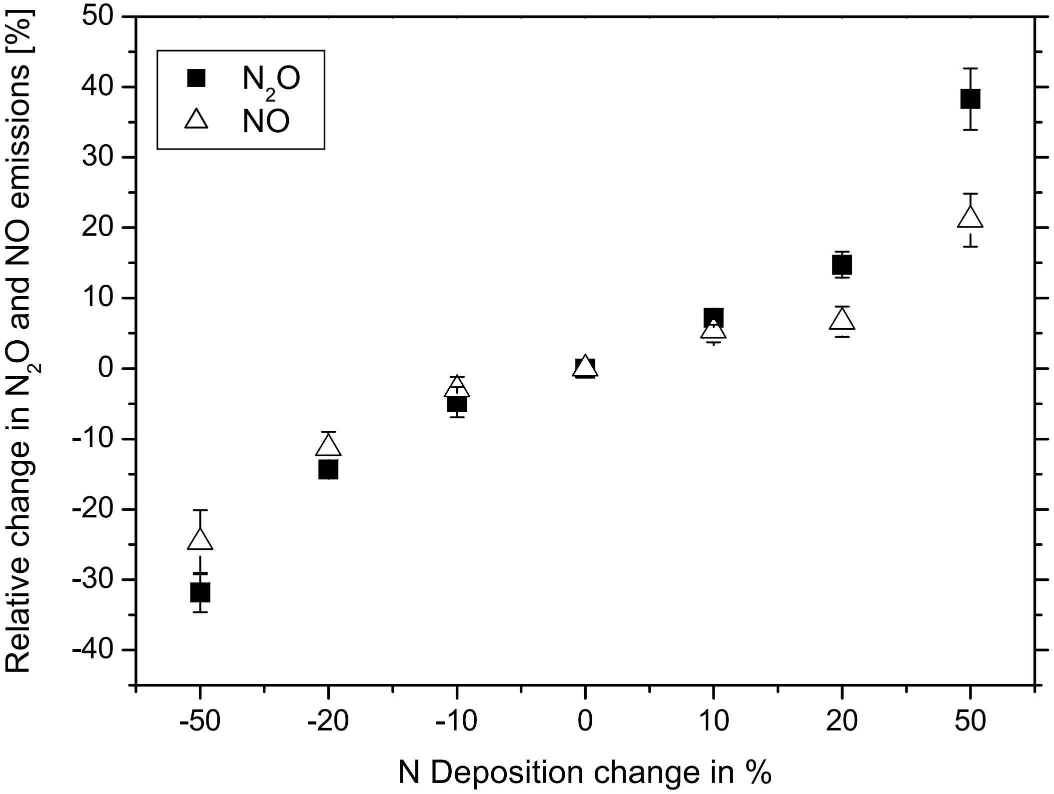
Inventorying soil N trace gas fluxes and identifying feedbacks



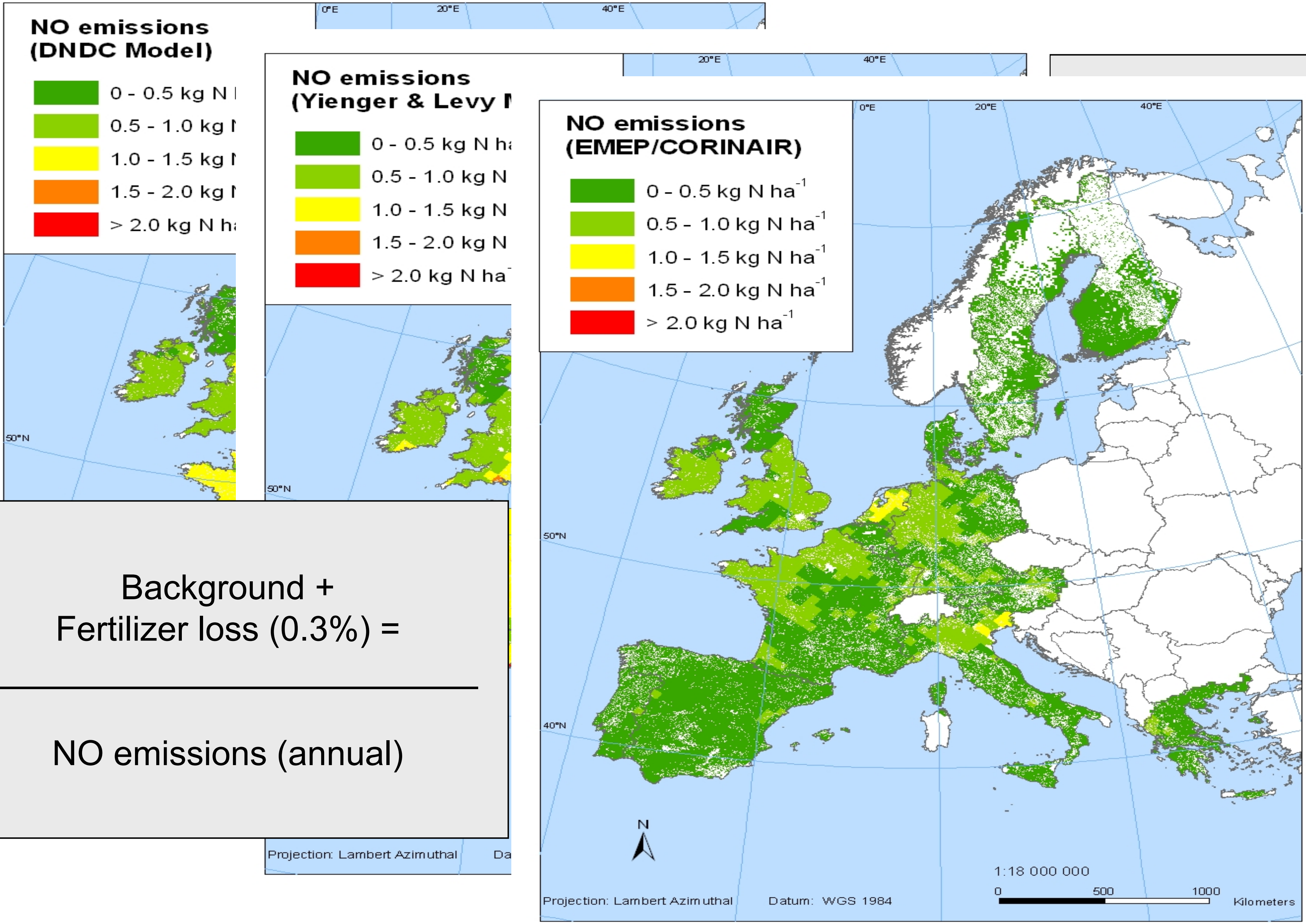
Kesik et al., 2006; Biogeosciences

NO Emissions	Minimum Scenario kt N a^{-1}	Average Scenario kt N a^{-1}	Maximum Scenario kt N a^{-1}
1990	45	98	248
1995	38	85	220
2000	45	99	254

Simulated forest area of Europe: 1 410 477km^2



Simple versus complex



Background +
Fertilizer loss (0.3%) =

NO emissions (annual)

round +
ss (2.5%) +
ects (3 classes) +
ns (4 classes) =

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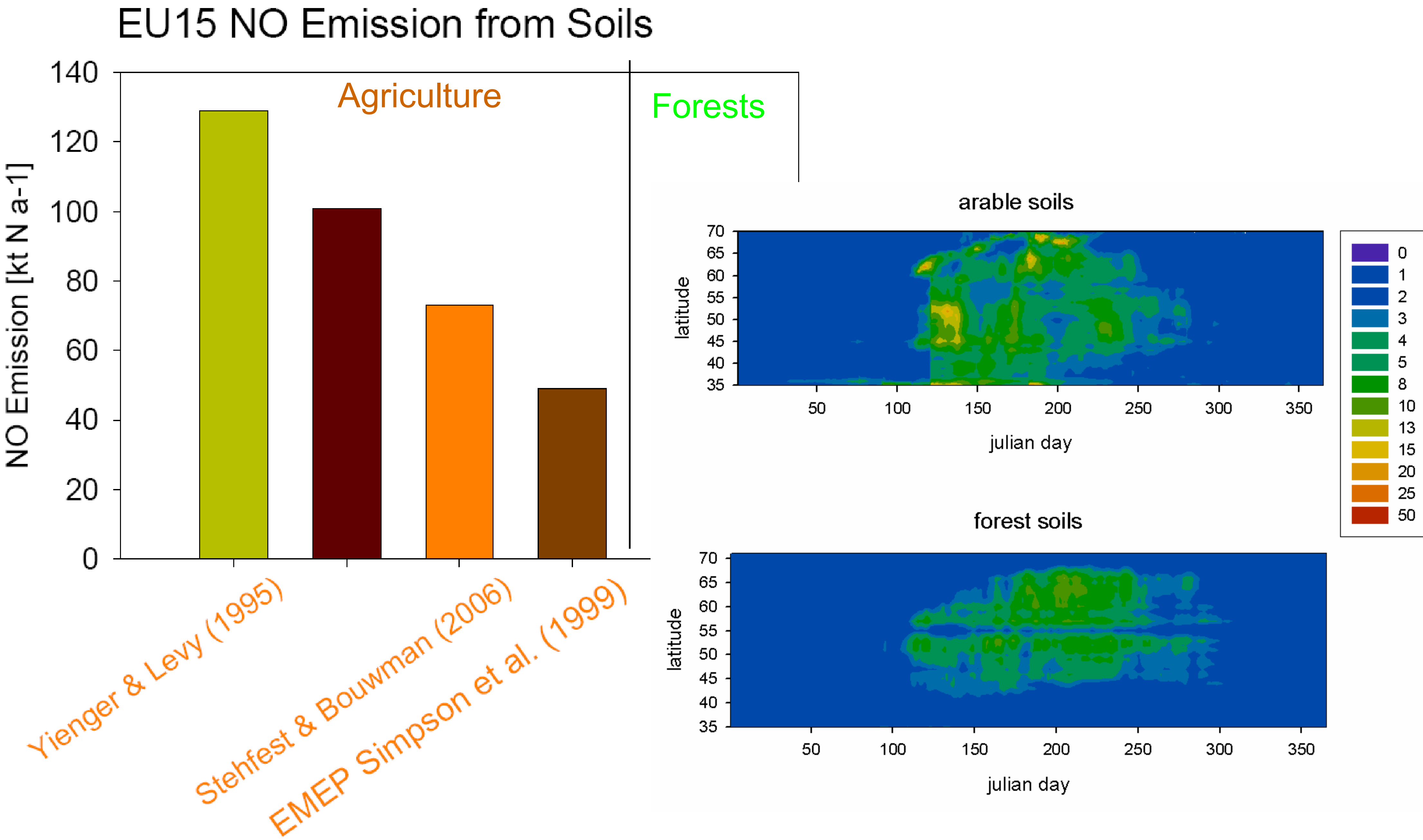
ions (daily)

Butterbach-Bahl et al., 2008; Atm. Environm.

Simple versus complex – daily patterns

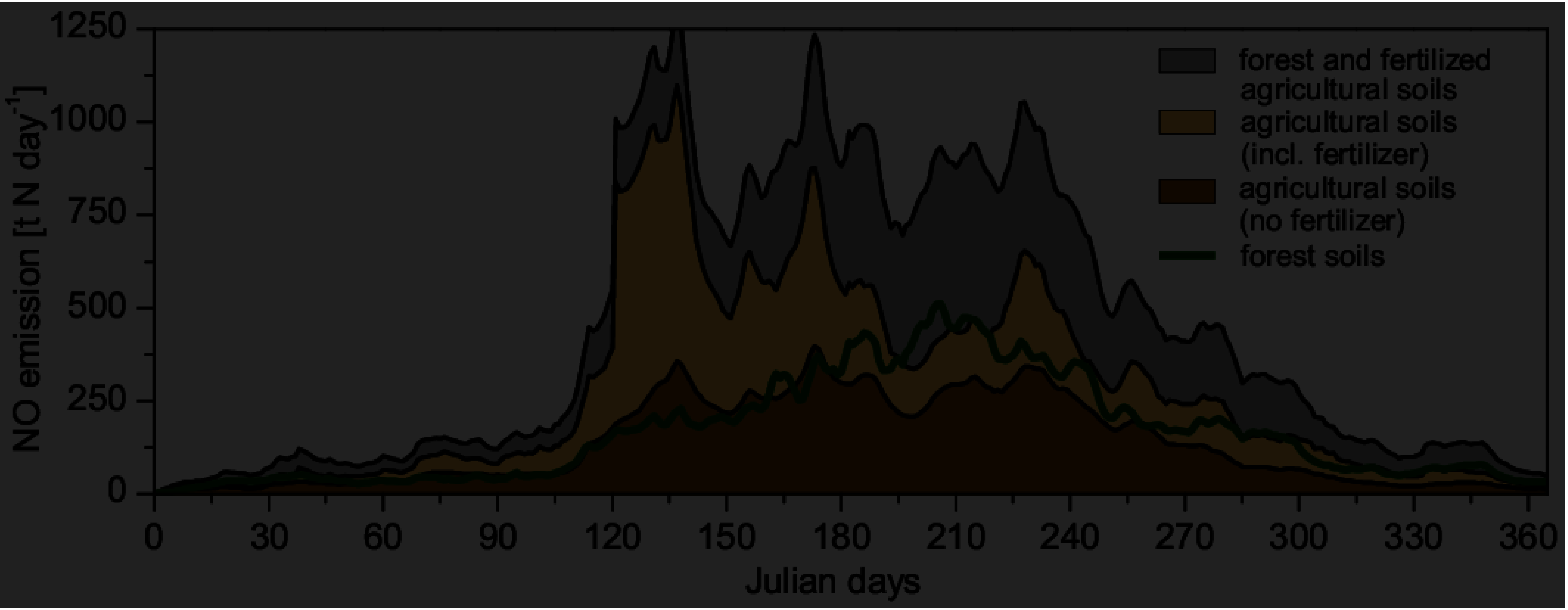


All calculations were done with the activity and meteorological data for the year 2000

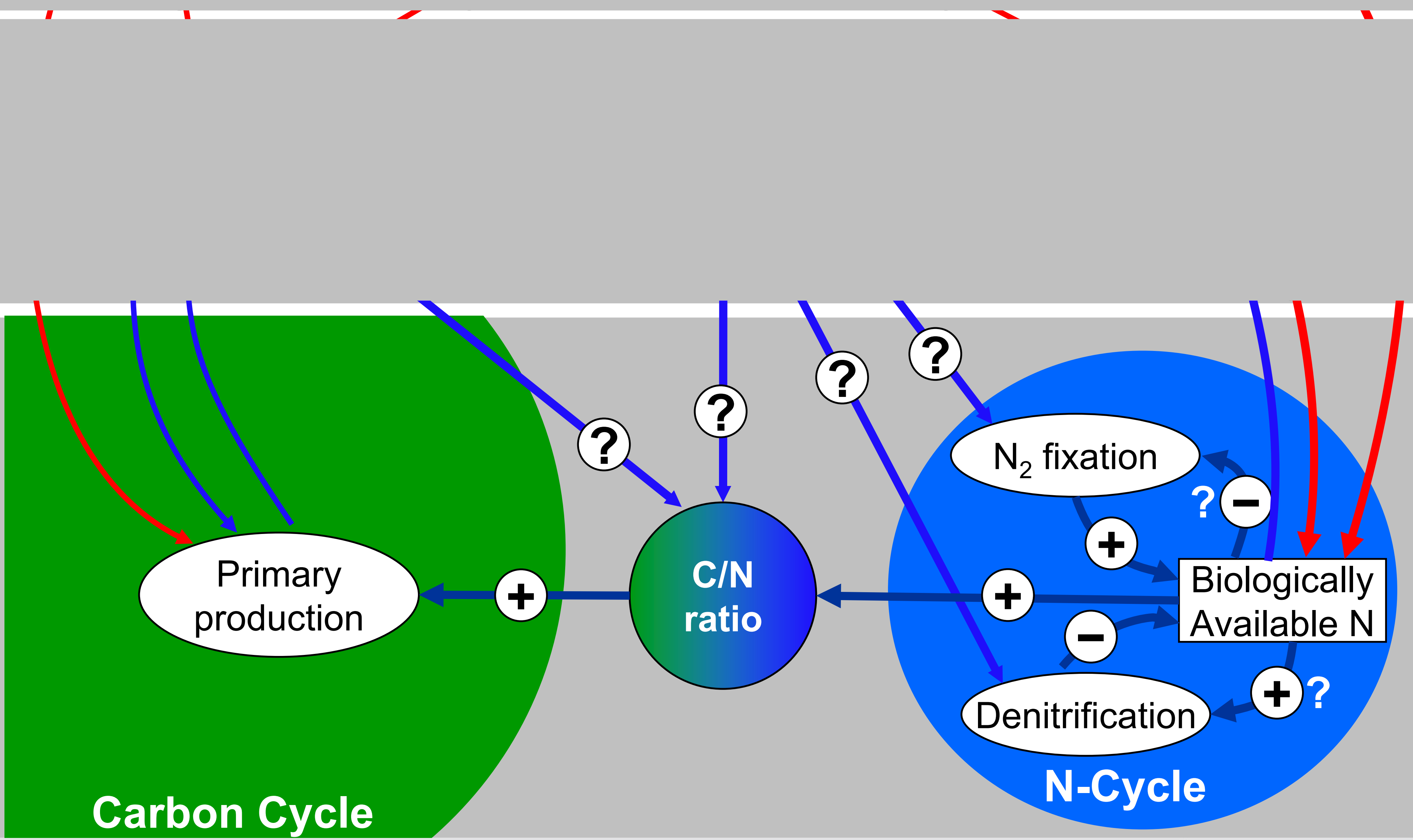
Butterbach-Bahl et al., 2008; Atm. Environm

Soil sources versus industrial sources

Soil agricultural NOx Emissions are contributing in average for entire Europe up to 10% to the tropospheric NO_x burden



Butterbach-Bahl et al., 2008; Atm. Environm

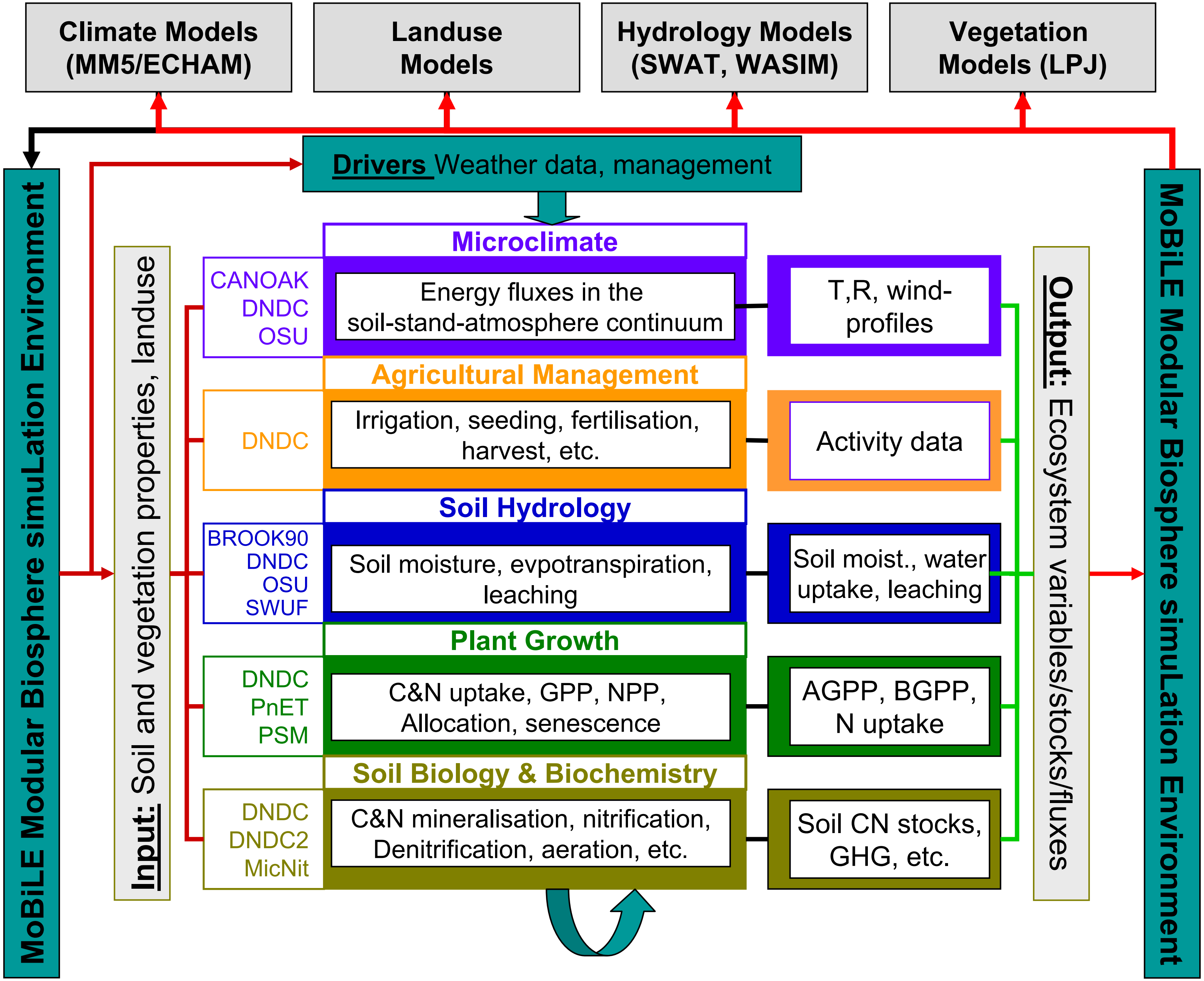


Gruber & Galloway, Nature 2008

The future:

- Improved understanding of global change feedbacks on C and N cycling
- Getting more complex?
- Linking with hydrology
- Development towards a regional earth system model

Karlsruhe Institute of Technology



Climate Models (MM5/ECHAM)

Landuse Models

Hydrology Models (SWAT, WASIM)

Vegetation Models (LPJ)

MoBiLE Modular Biosphere simuLation Environment

Drivers Weather data, management

Input: Soil and vegetation properties, landuse

Microclimate

CANOAK
DNDC
OSU

Energy fluxes in the soil-stand-atmosphere continuum

T,R, wind-profiles

Agricultural Management

DNDC

Irrigation, seeding, fertilisation, harvest, etc.

Activity data

Soil Hydrology

BROOK90
DNDC
OSU
SWUF

Soil moisture, evpotranspiration, leaching

Soil moist., water uptake, leaching

Plant Growth

DNDC
PnET
PSM

C&N uptake, GPP, NPP, Allocation, senescence

AGPP, BGPP, N uptake

Soil Biology & Biochemistry

DNDC
DNDC2
MicNit

C&N mineralisation, nitrification, Denitrification, aeration, etc.

Soil CN stocks, GHG, etc.

Output: Ecosystem variables/stocks/fluxes

MoBiLE Modular Biosphere simuLation Environment