N_2O emissions from agricultural soils
-
Mitigation options and opportunities

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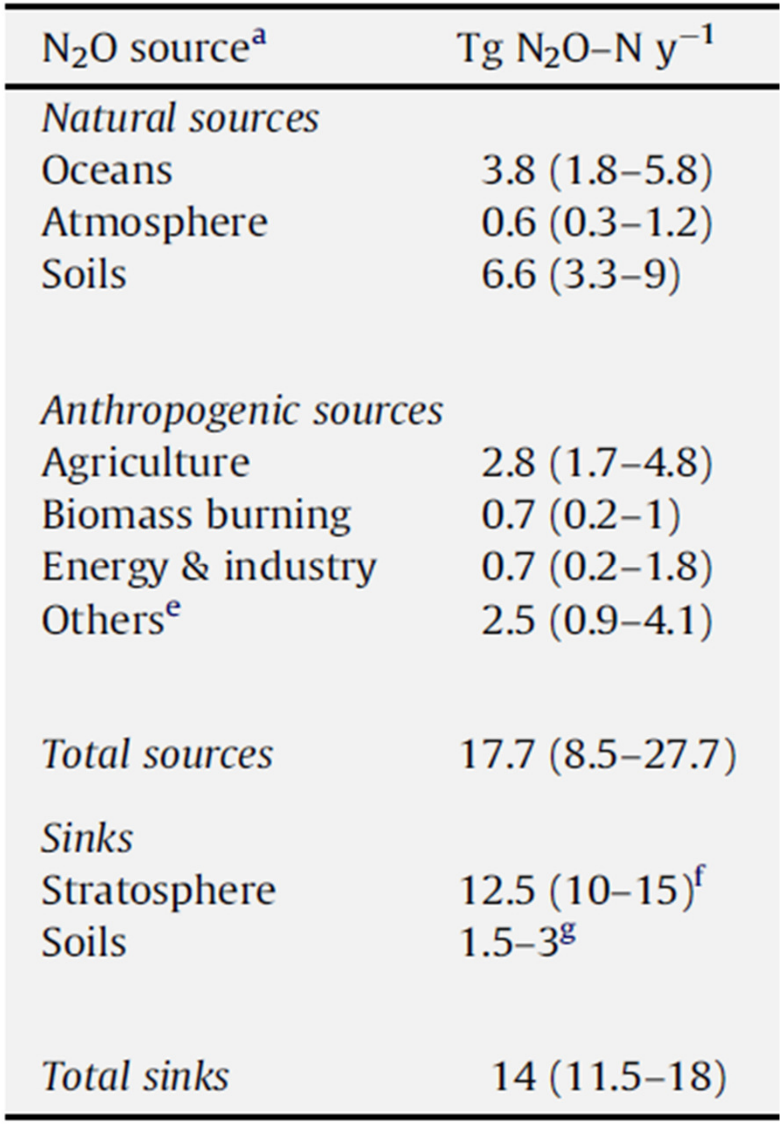
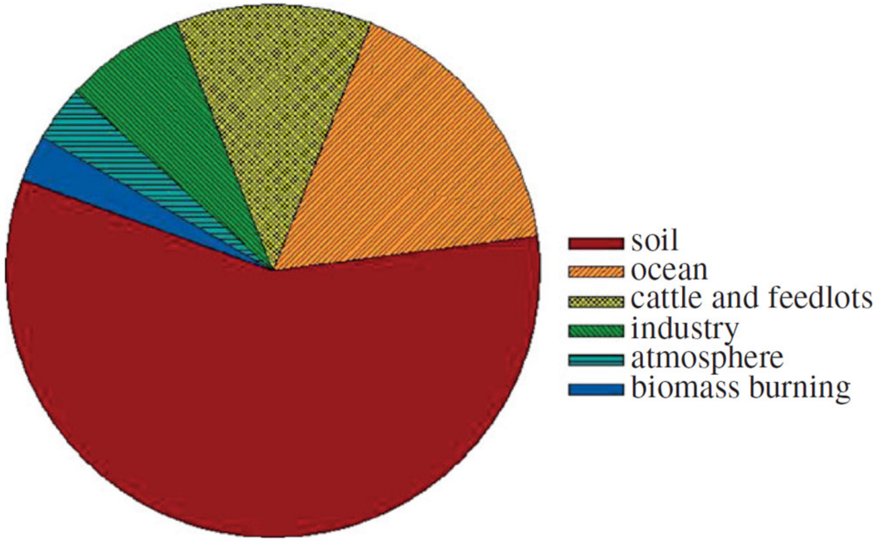
Soils are the dominant source for atmospheric N_2O



N_2O source[a]	Tg N_2O–N y^{-1}
Natural sources	
Oceans	3.8 (1.8–5.8)
Atmosphere	0.6 (0.3–1.2)
Soils	6.6 (3.3–9)
Anthropogenic sources	
Agriculture	2.8 (1.7–4.8)
Biomass burning	0.7 (0.2–1)
Energy & industry	0.7 (0.2–1.8)
Others[e]	2.5 (0.9–4.1)
Total sources	17.7 (8.5–27.7)
Sinks	
Stratosphere	12.5 (10–15)[f]
Soils	1.5–3[g]
Total sinks	14 (11.5–18)

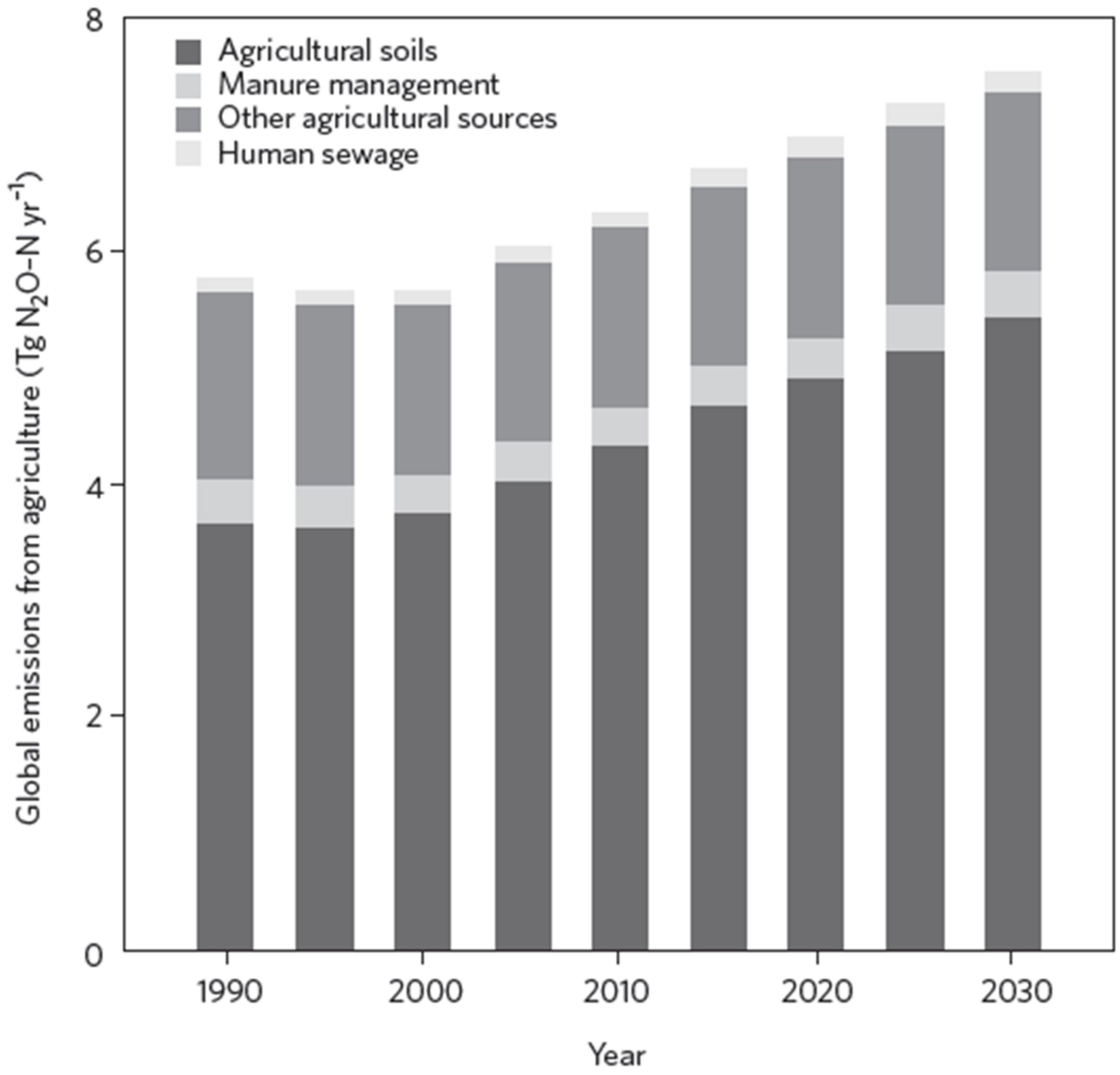
Fowler et al. 2009, Atm. Environm.



Proportions of total global nitrous oxide emitted by various sources and human activities

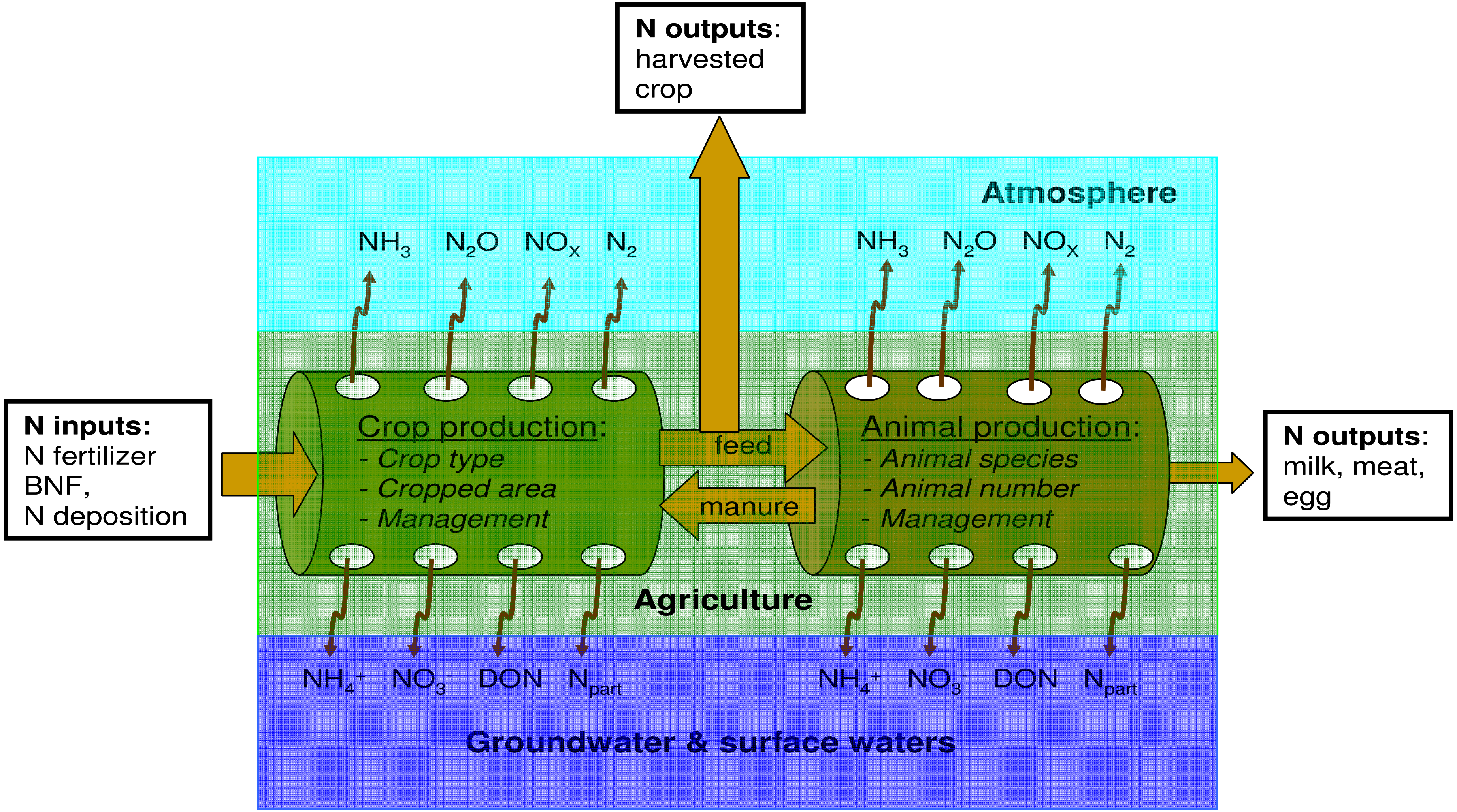
[Thomson et al., 2012; Phil. Trans. R. Soc. B]

Emissions from agricultural soils and due to manure management are driving increases in atmospheric N_2O concentrations



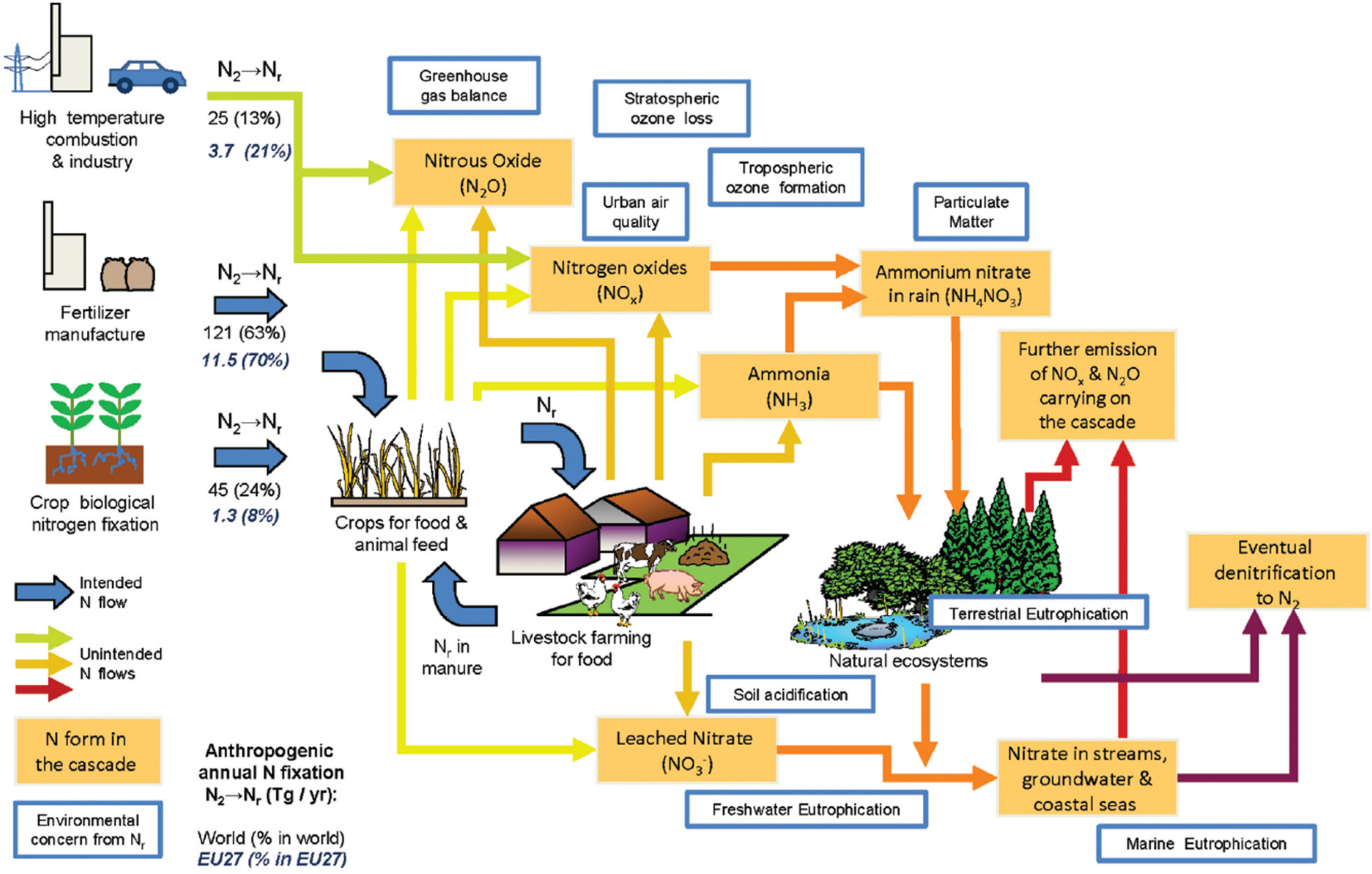
Reya et al. 2012, Nature Geoscience

Nitrogen losses to the environment due to crop and animal production



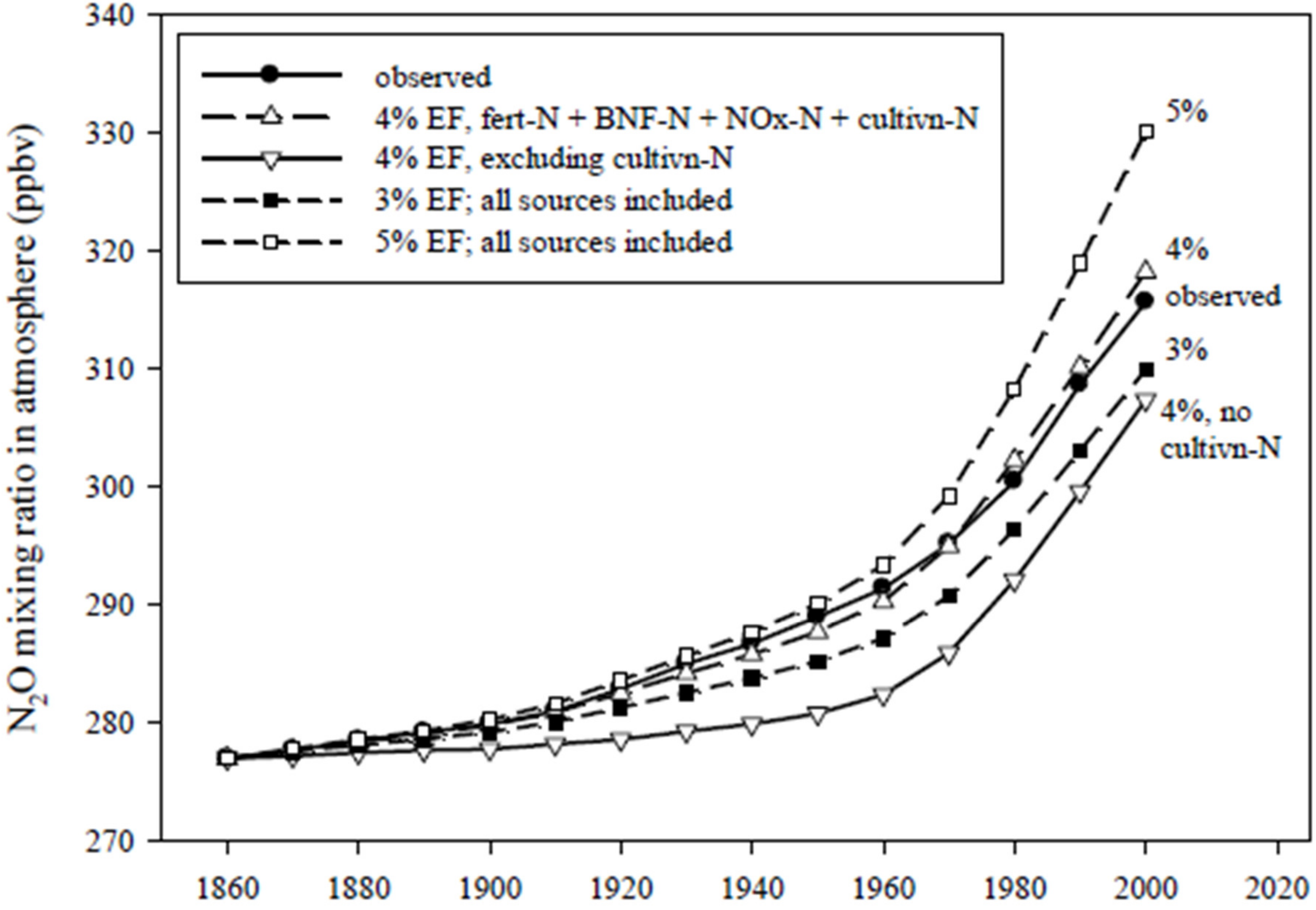
Oenema et al., 2009; AGEE

„Indirect“ emissions are a major source for N_2O



Sutton et al. 2011, European Nitrogen Assessment

Towards a global EF for N_r use (direct+indirect)



Smith et al. 2012 Phil. Trans. R. Soc. B

Strategies for reducing GHG (and N_2O?) emissions from agricultural soils

(1) Reducing N application rates and increasing plant N use efficiencies

(2) Employing lower emissions fertilizers

(3) Conversion from conventional to reduced tillage

(4) Increased soil C inputs

(5) Including legumes in crop rotations

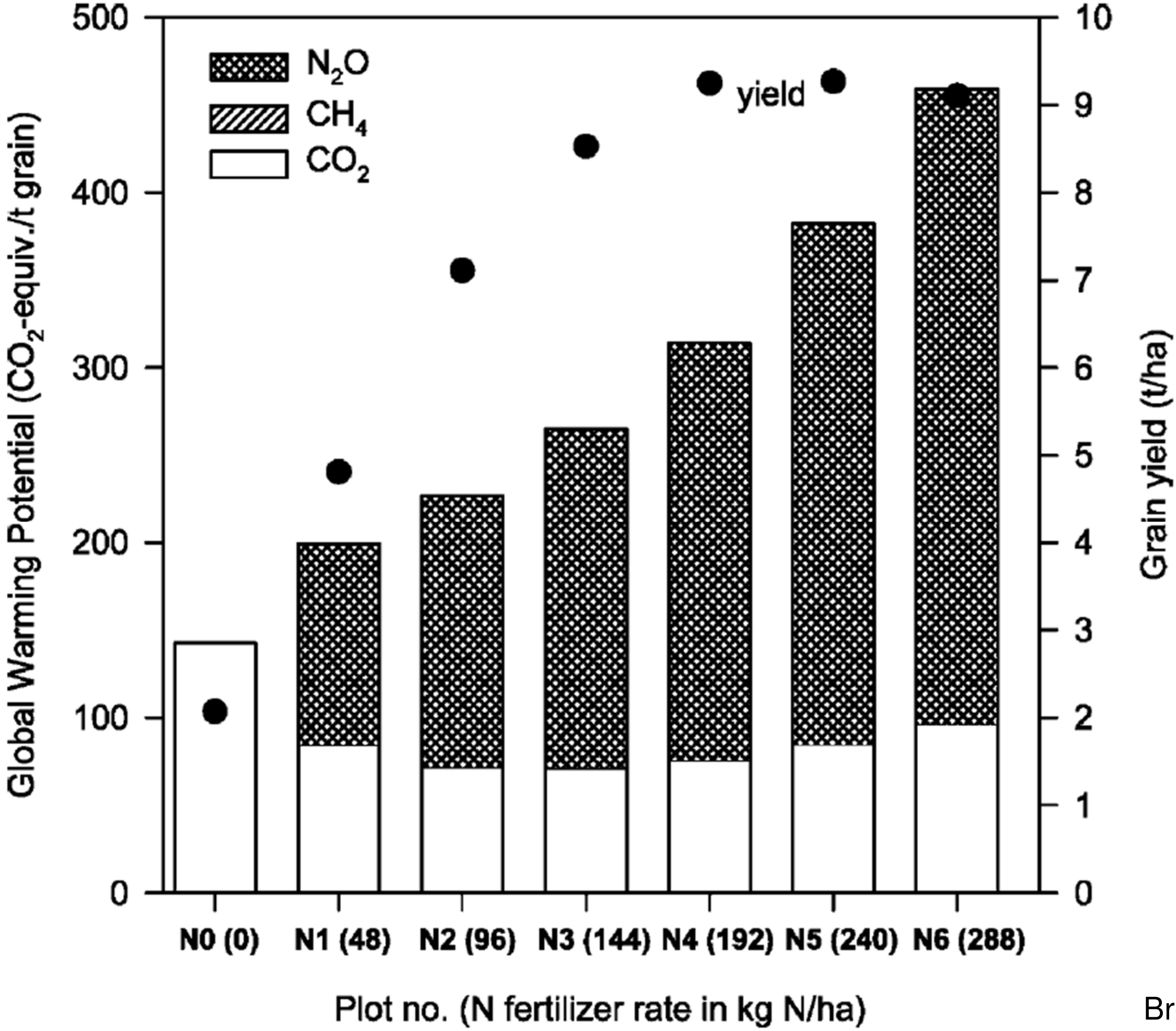
(6) Use of inhibitors (urease/nitrification/denitrification?)

(7) Microbial ecology and genetic engineering

(8) Sustainable agricultural intensification

(1) Reducing N fertilization rates

(Wheat Broadbalk Experiment, Rothamsted)



Brentrup et al. 2004; Eur J Agron.

N fertilizer use and associated N_2O emissions in China

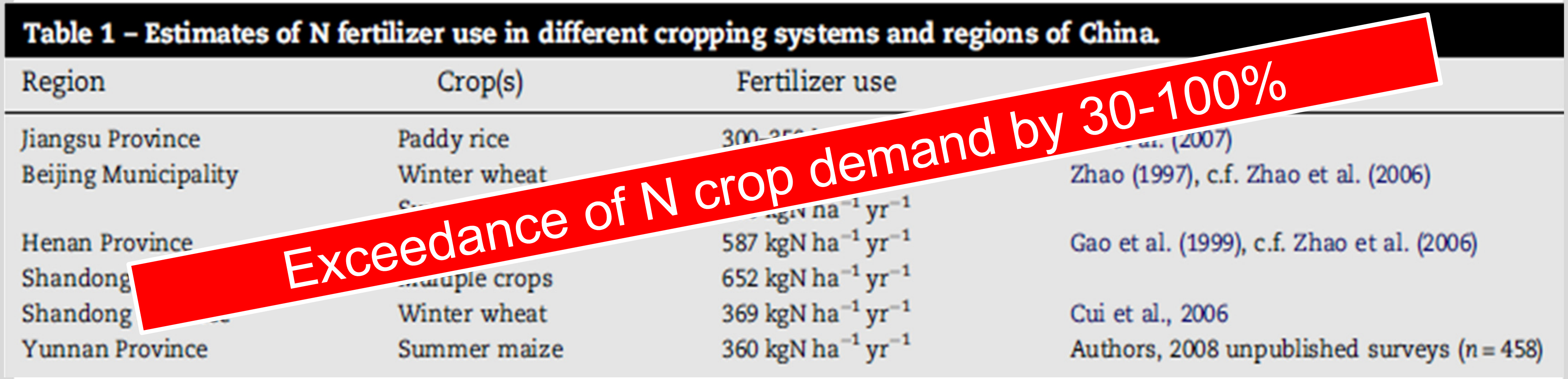
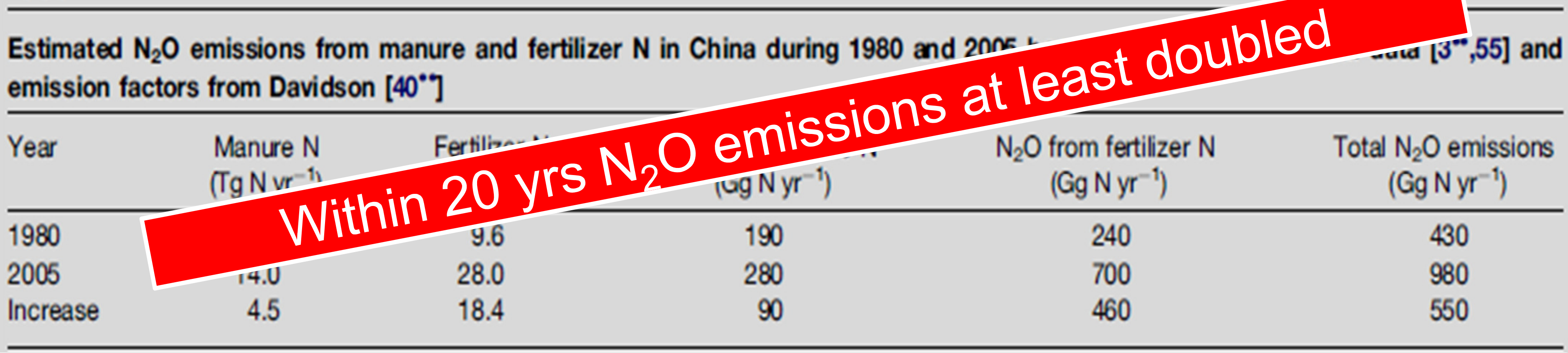


Table 1 – Estimates of N fertilizer use in different cropping systems and regions of China.

Region	Crop(s)	Fertilizer use	
Jiangsu Province	Paddy rice	300– [illegible]	[illegible] al. (2007)
Beijing Municipality	Winter wheat	[illegible]	Zhao (1997), c.f. Zhao et al. (2006)
	S[illegible]	[illegible] kgN ha^{-1} yr^{-1}	
Henan Province	[illegible]	587 kgN ha^{-1} yr^{-1}	Gao et al. (1999), c.f. Zhao et al. (2006)
Shandong [illegible]	[illegible]uple crops	652 kgN ha^{-1} yr^{-1}	
Shandong [illegible]	Winter wheat	369 kgN ha^{-1} yr^{-1}	Cui et al., 2006
Yunnan Province	Summer maize	360 kgN ha^{-1} yr^{-1}	Authors, 2008 unpublished surveys ($n = 458$)

Exceedance of N crop demand by 30-100%

Kahrl et al. 2010 Environm Sci Pol.



Estimated N_2O emissions from manure and fertilizer N in China during 1980 and 200[illegible] [illegible] data [3••,55] and emission factors from Davidson [40••]

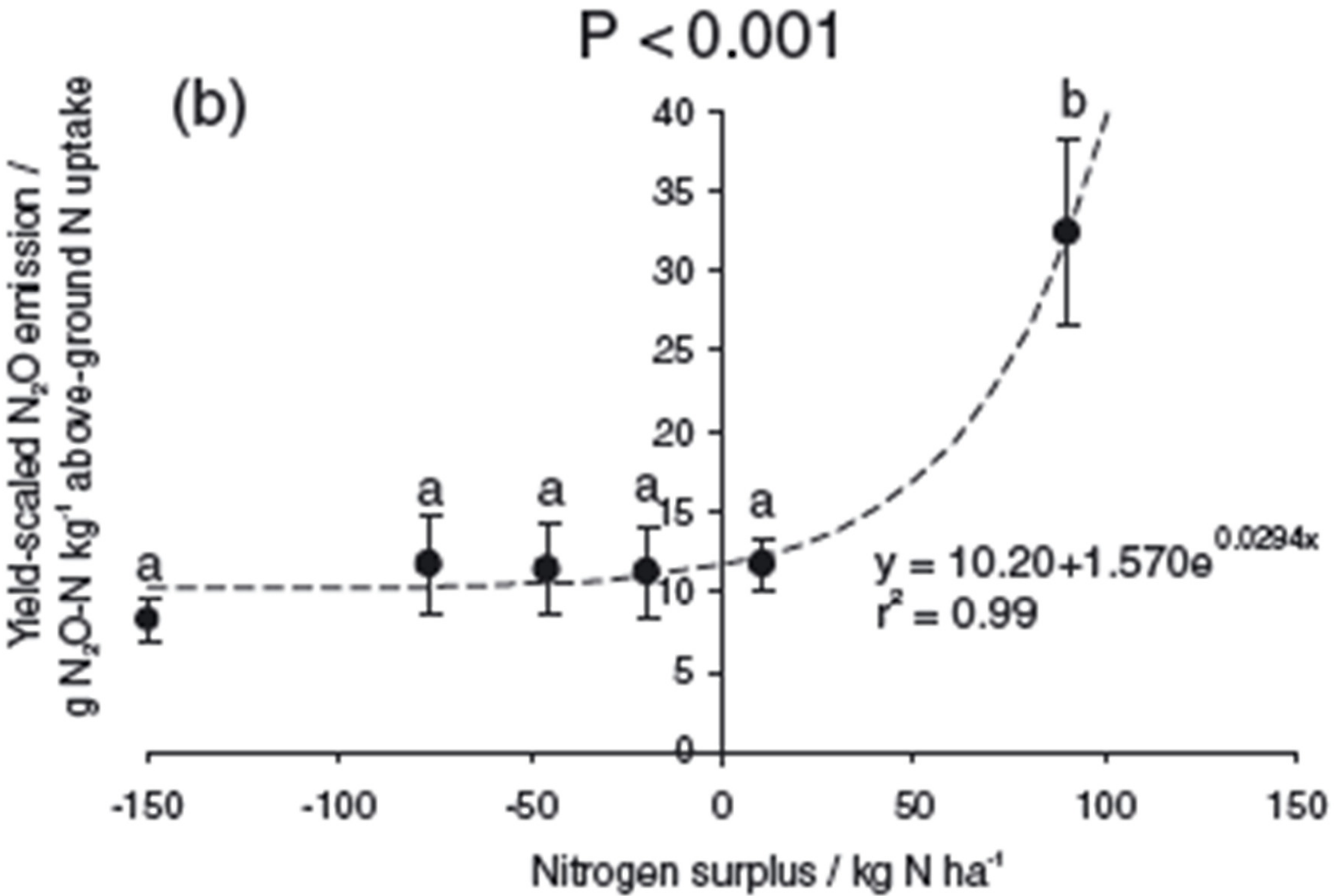
Year	Manure N (Tg N yr^{-1})	Fertiliz[illegible]	[illegible] (Gg N yr^{-1})	N_2O from fertilizer N (Gg N yr^{-1})	Total N_2O emissions (Gg N yr^{-1})
1980	[illegible]	9.6	190	240	430
2005	14.0	28.0	280	700	980
Increase	4.5	18.4	90	460	550

Within 20 yrs N_2O emissions at least doubled

Liu & Zhang 2011 Curr Opin Environm Sust

And this is likely an underestimation, since …

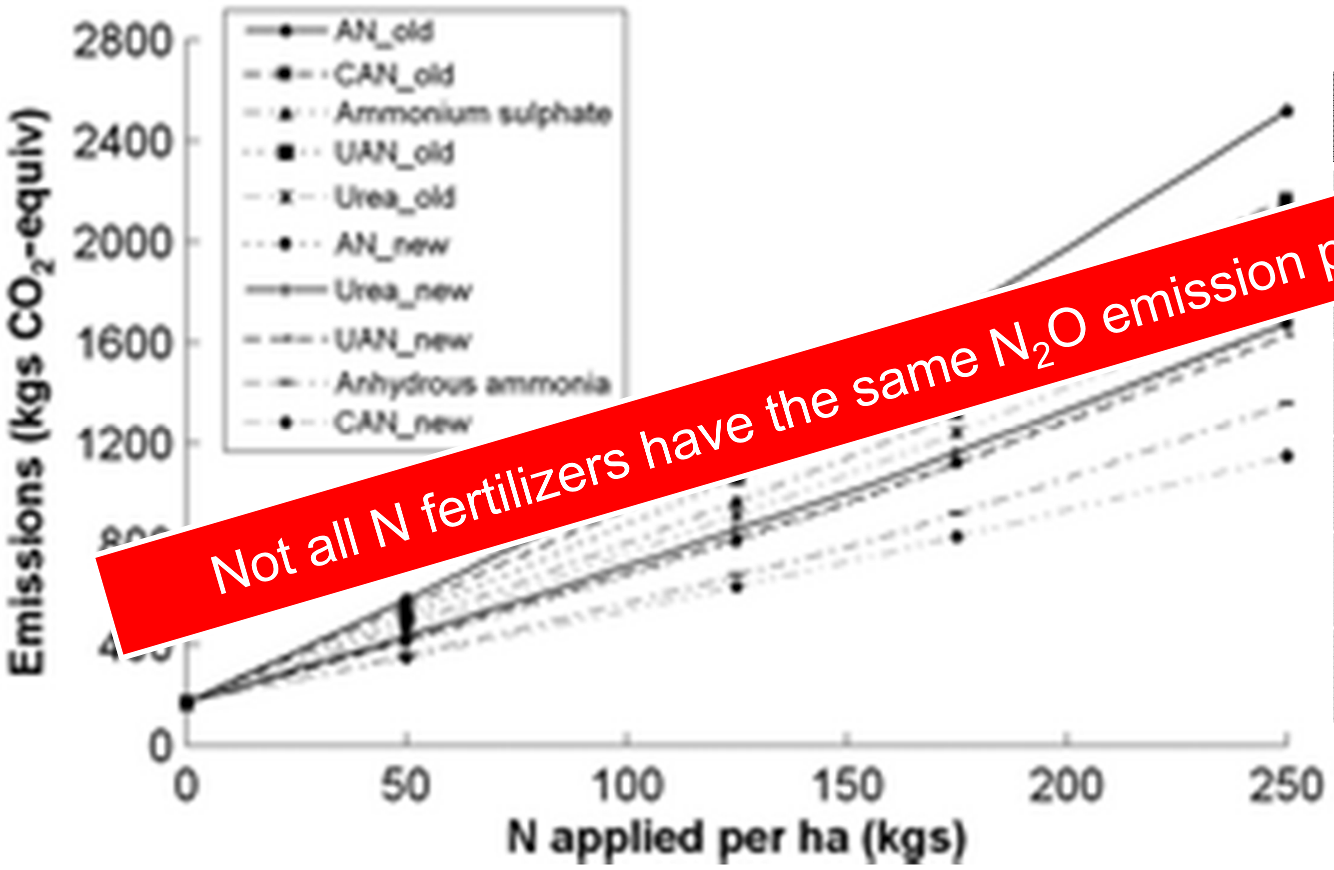
…N_2O emissions are likely to increase exponentially with increasing nitrogen surplus



Van Groeningen et al. 2010, Eur J Soil Sci

(2) Employing lower emissions fertilizers

GHG from N application (production, hydrolysis, direct and and indirect N_2O)



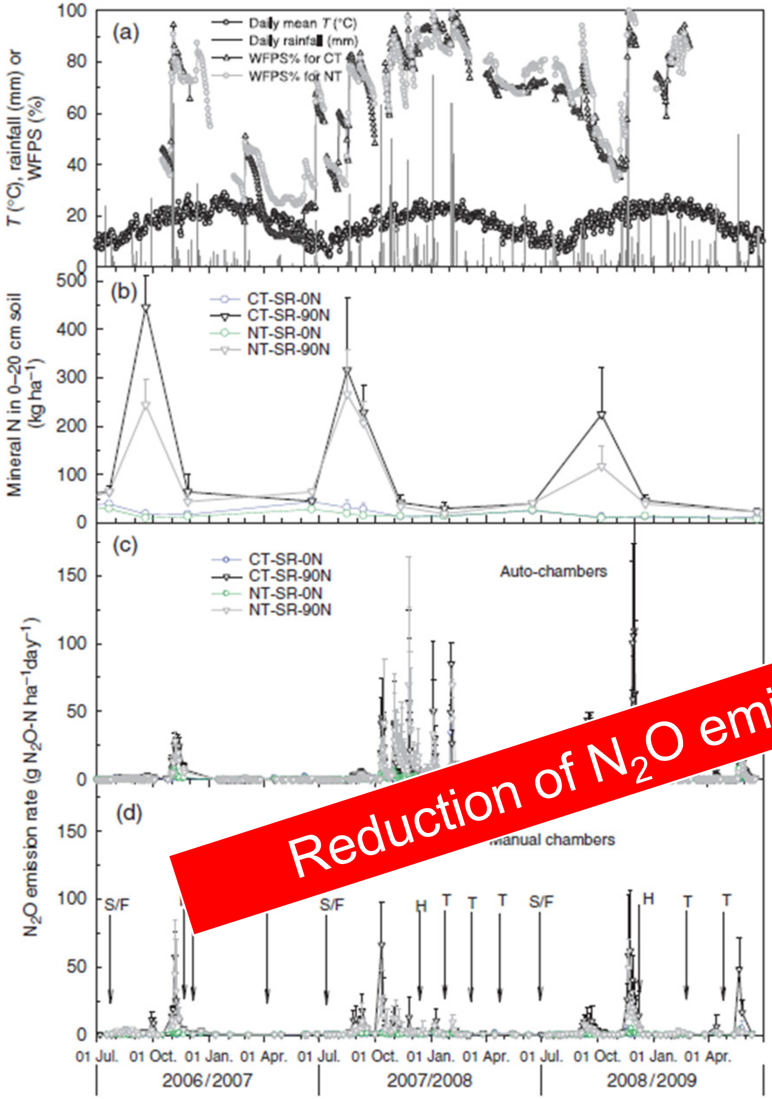
Not all N fertilizers have the same N_2O emission potential

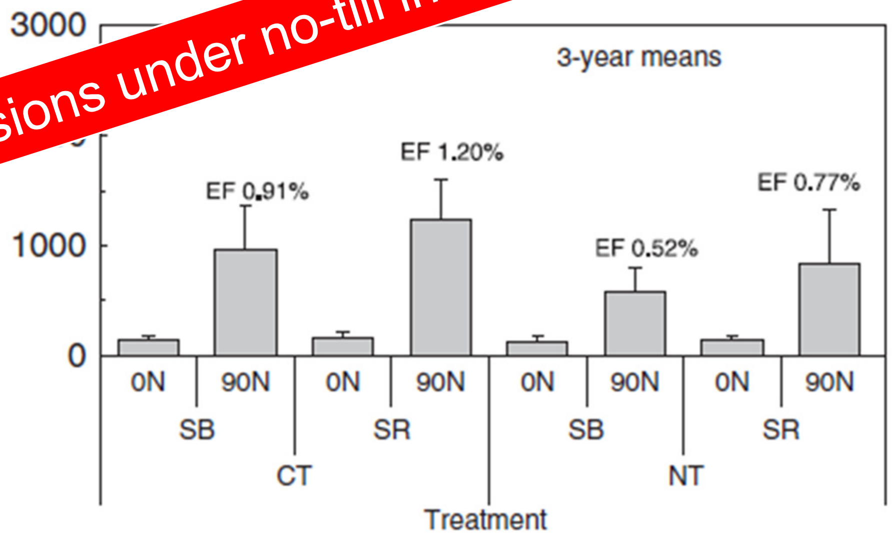
Acronym	Fertilizer
[illegible]	[illegible] nitrate
[illegible]	Urea ammonium nitrate
CAN	Calcium ammonium nitrate
AS	Ammonium sulphate
_old	e.g. +N_2O during fertilizer production
_new	N_2O abated during fertilizer production

Hillier et al. 2012, Global Change Biol.

(3) Conversion from conventional to reduced tillage

(Southern Queensland, Australia)



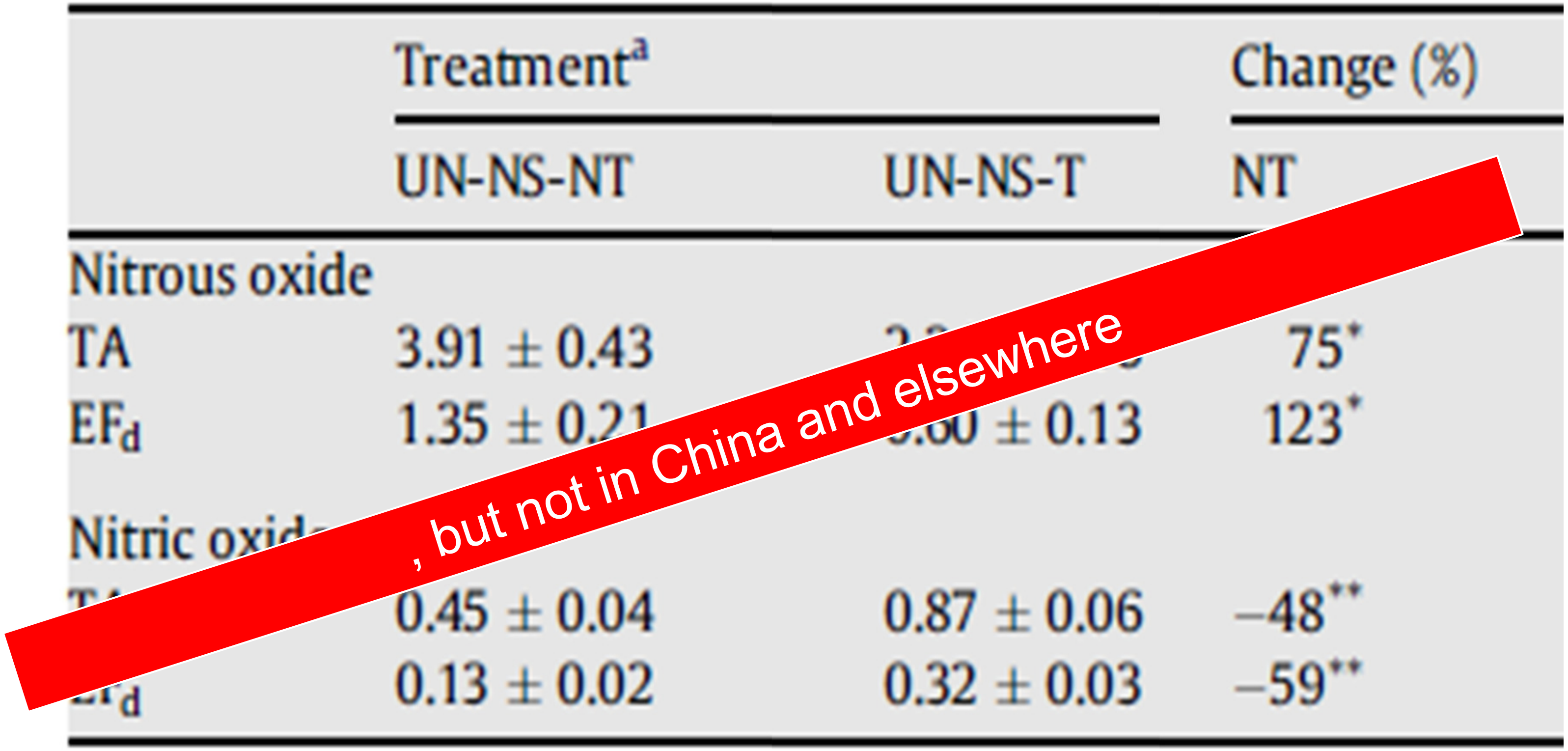


Reduction of N_2O emissions under no-till in Australia, but..

Wang et al. 2011, Global Change Biol.

Conversion from conventional to reduced tillage

(Yangtze river delta, China)



	Treatment[a]		Change (%)
	UN-NS-NT	UN-NS-T	NT
Nitrous oxide			
TA	3.91 ± 0.43	[illegible]	75*
EF_d	1.35 ± 0.21	0.60 ± 0.13	123*
Nitric oxide			
TA	0.45 ± 0.04	0.87 ± 0.06	−48**
EF_d	0.13 ± 0.02	0.32 ± 0.03	−59**

, but not in China and elsewhere

Yao et al. 2009 Soil Biol Biochem.

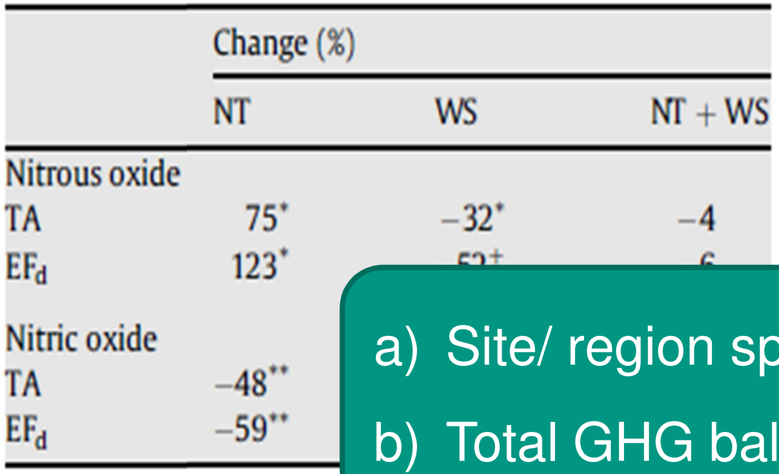
a) Site/ region specific evaluation needed

b) Total GHG balance needs to be considered

(4) Increased soil C inputs ≈ +N_2O emissions?

a) Addition of litter with wide C:N ratios (e.g straw) can lead to an immobilization of N and decreased N_2O emissions

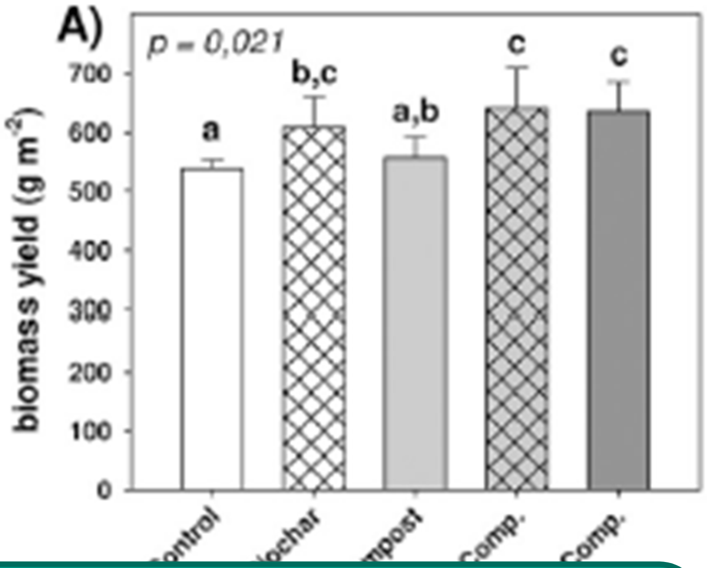
(Yao et al. 2009, Soil Biol Biochem)

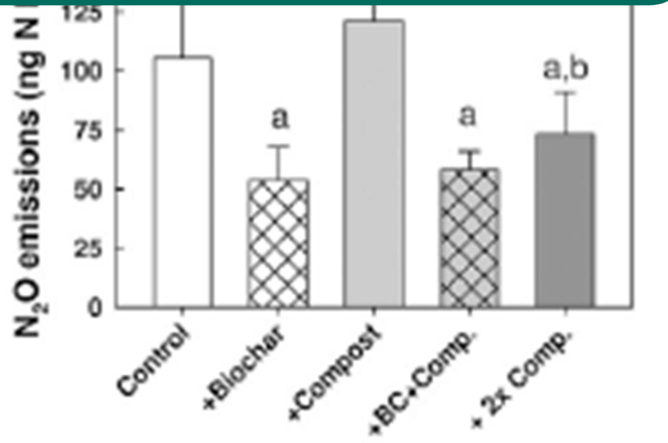


	Change (%)		
	NT	WS	NT + WS
Nitrous oxide			
TA	75*	−32*	−4
EF_d	123*	52†	6
Nitric oxide			
TA	−48**		
EF_d	−59**		

b) Addition of biochar may reduce N_2O emissions due to pH and min N absorption effects

(Kammann et al. 2009, SJ Env Qual)

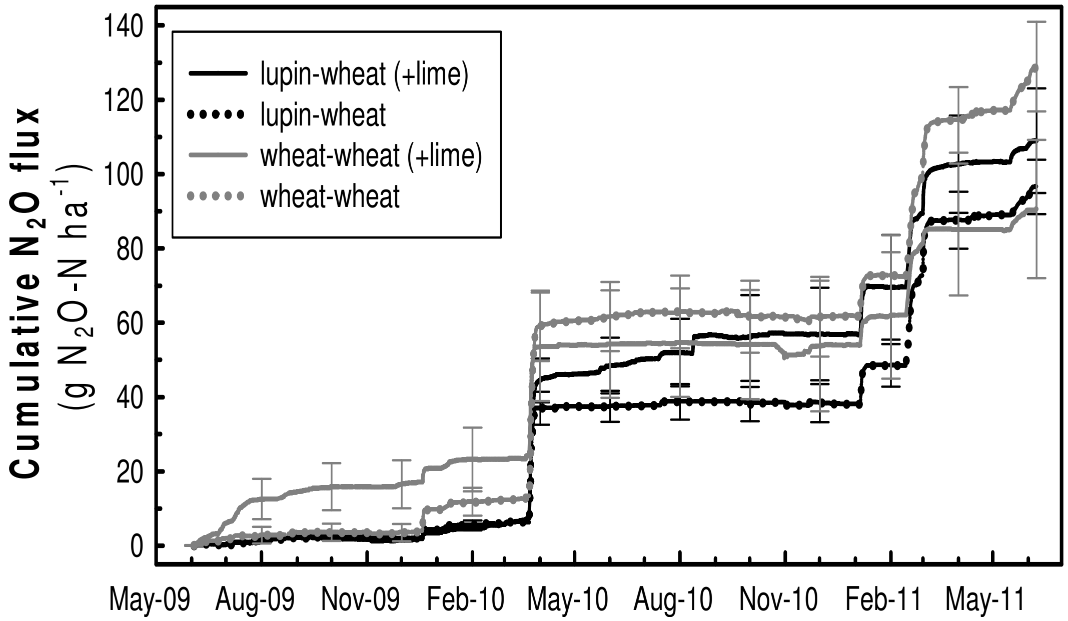




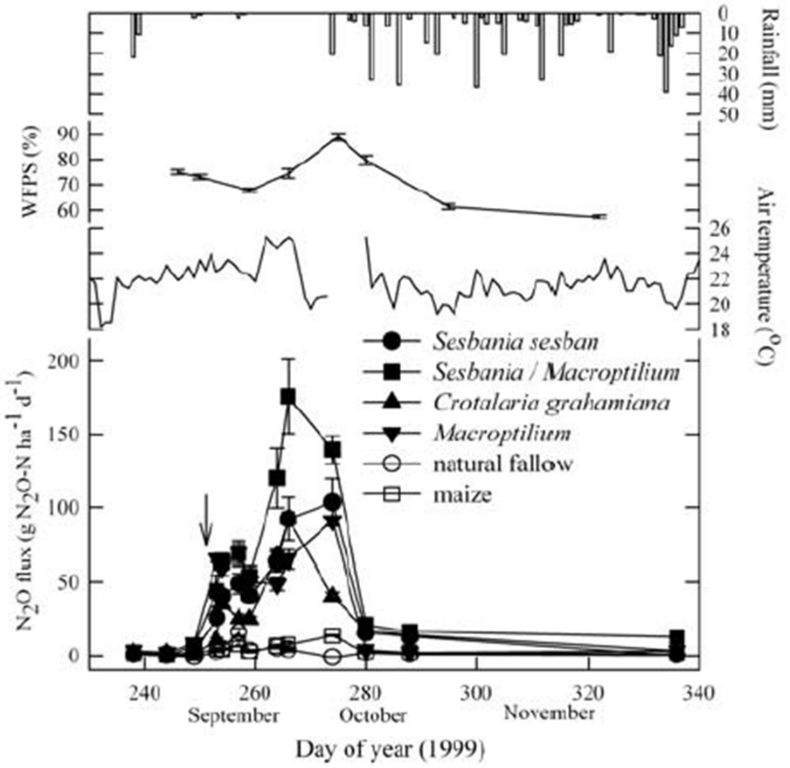
a) Site/ region specific evaluation needed

b) Total GHG balance needs to be considered

(5) Including legumes in crop rotations (2 examples)



Barton et al. 2012,Agric Ecosys Environm, subm.



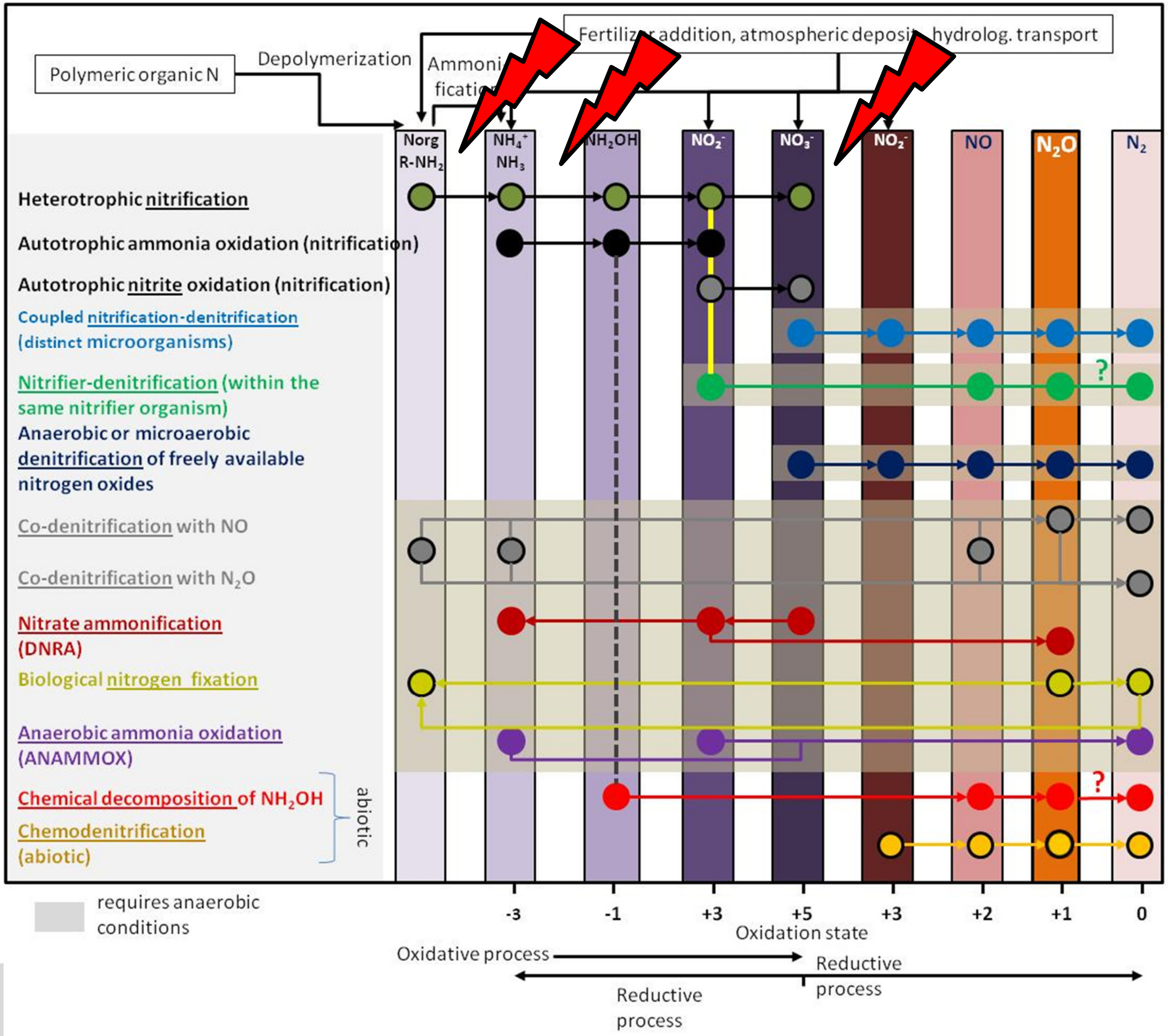
a) Effect of legumes on N_2O emissions depend on climate conditions

b) Yields are comparabel or higher, (scaling with yield)

c) Region specific evaluation needed

(6) Use of inhibitors or slow release fertilizers

Karlsruhe Institute of Technology



Polymeric organic N

Depolymerization

Ammonification

Fertilizer addition, atmospheric deposit., hydrolog. transport

Norg R-NH$_2$

NH_4^+ NH_3

NH_2OH

NO_2^-

NO_3^-

NO_2^-

NO

N_2O

N_2

Heterotrophic nitrification

Autotrophic ammonia oxidation (nitrification)

Autotrophic nitrite oxidation (nitrification)

Coupled nitrification-denitrification (distinct microorganisms)

Nitrifier-denitrification (within the same nitrifier organism)

Anaerobic or microaerobic denitrification of freely available nitrogen oxides

Co-denitrification with NO

Co-denitrification with N_2O

Nitrate ammonification (DNRA)

Biological nitrogen fixation

Anaerobic ammonia oxidation (ANAMMOX)

Chemical decomposition of NH_2OH

Chemodenitrification (abiotic)

abiotic

?

?

requires anaerobic conditions

-3 -1 +3 +5 +3 +2 +1 0

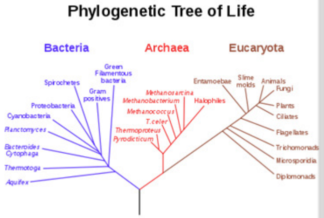
Oxidation state

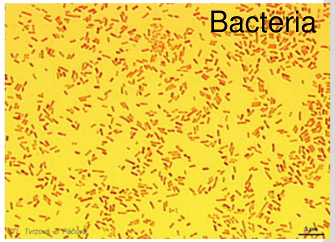
Oxidative process

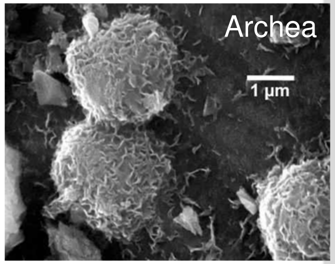
Reductive process

Reductive process

Butterbach-Bahl et al. 2013, Phil. Trans. R. Soc. B







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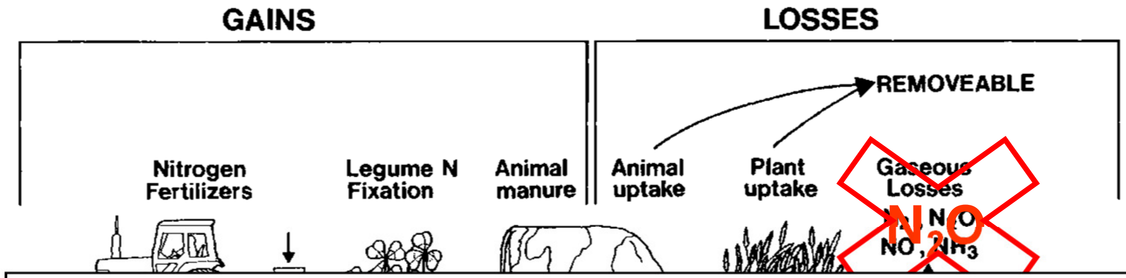
Use of inhibitors or slow release fertilizers



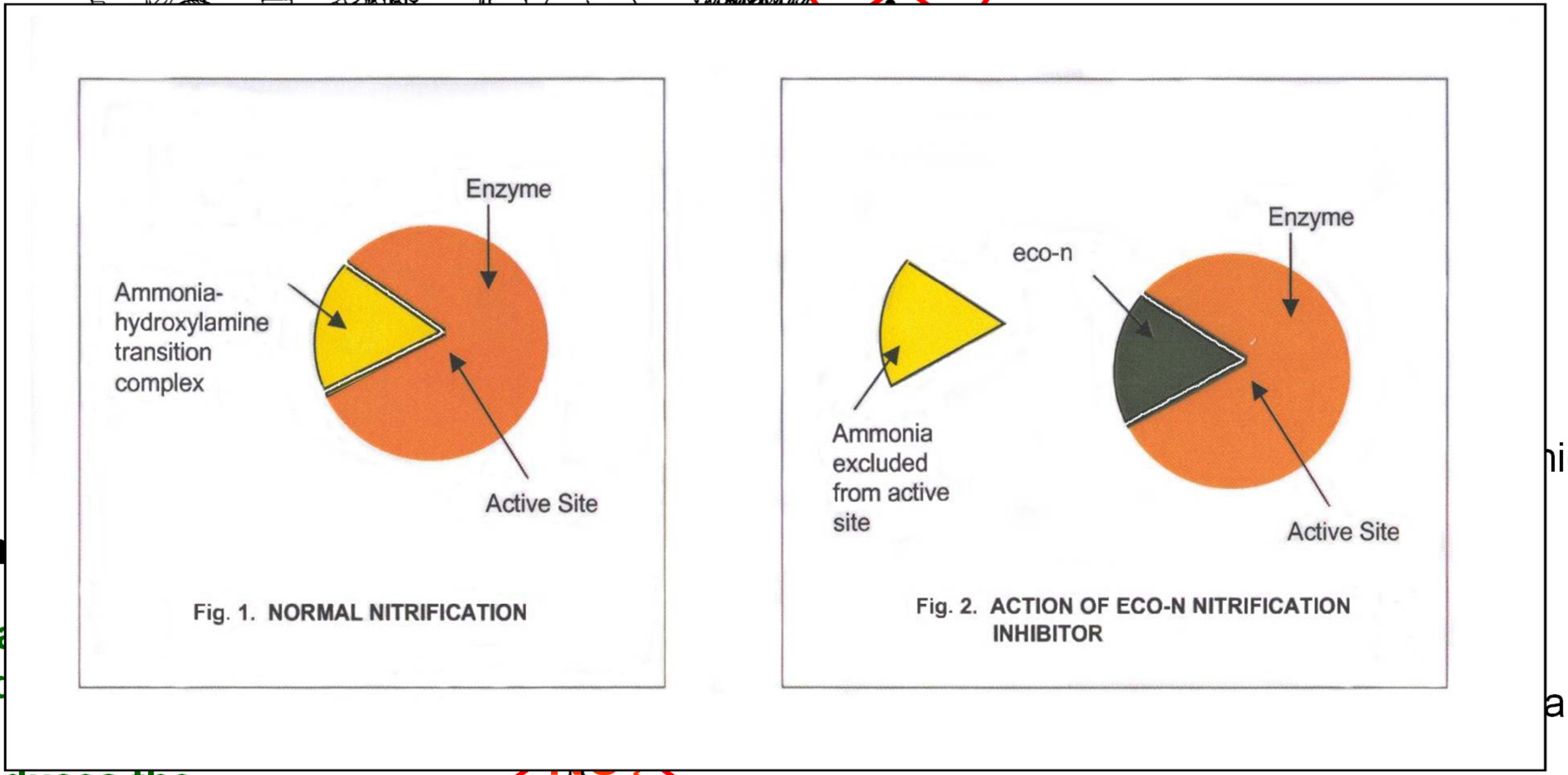


Fig. 1. NORMAL NITRIFICATION

Fig. 2. ACTION OF ECO-N NITRIFICATION INHIBITOR

Cation exchan

nic

a

Nitrifica slows c nitrate thus reduces the nitrogen losses

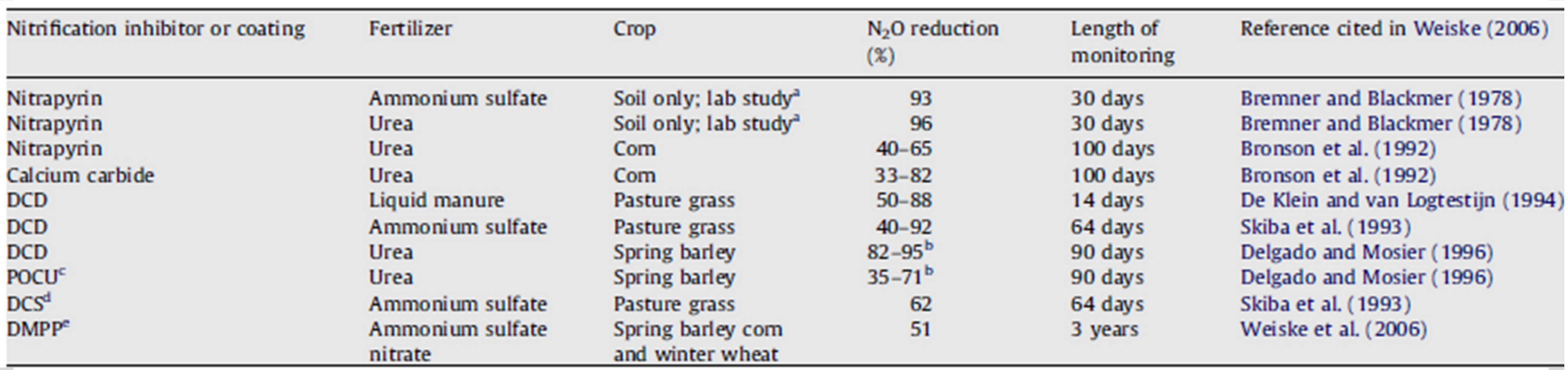
In grazed pastures urine patches are the main sources of nitrous oxide emissions and nitrate leaching

(courtesy T. Clough)

1,000 kg N/ha in urine patch (= 2 t Urea/ha) **Urea fertiliser only applied at 30 kg N/ha**

Use of inhibitors or slow release fertilizers

Inhibitors have been widely tested and based on data from field measurements



Nitrification inhibitor or coating	Fertilizer	Crop	N_2O reduction (%)	Length of monitoring	Reference cited in Weiske (2006)
Nitrapyrin	Ammonium sulfate	Soil only; lab study[a]	93	30 days	Bremner and Blackmer (1978)
Nitrapyrin	Urea	Soil only; lab study[a]	96	30 days	Bremner and Blackmer (1978)
Nitrapyrin	Urea	Corn	40–65	100 days	Bronson et al. (1992)
Calcium carbide	Urea	Corn	33–82	100 days	Bronson et al. (1992)
DCD	Liquid manure	Pasture grass	50–88	14 days	De Klein and van Logtestijn (1994)
DCD	Ammonium sulfate	Pasture grass	40–92	64 days	Skiba et al. (1993)
DCD	Urea	Spring barley	82–95[b]	90 days	Delgado and Mosier (1996)
POCU[c]	Urea	Spring barley	35–71[b]	90 days	Delgado and Mosier (1996)
DCS[d]	Ammonium sulfate	Pasture grass	62	64 days	Skiba et al. (1993)
DMPP[e]	Ammonium sulfate nitrate	Spring barley corn and winter wheat	51	3 years	Weiske et al. (2006)

Snyder et al.2009, Agric Ecosys Environm

“*The United Nations Framework Convention on Climate Change (UNFCCC) Expert Review Team commended New Zealand for incorporating the effect of the nitrification inhibitor, dicyandiamide (DCD), into its country-specific emissions factors, as DCD represents a potentially significant mitigation option that may gain increased use over time*”

(7) Microbial ecology and genetic engineering

- Approx.1/3 of denitrifying bacteria have a truncated denitrification pathway (Philippot et al., 2011, GCB)
- Fungal denitrification as well as nitrifier-denitrification mostly ends with the production of N_2O (Butterbach-Bahl et al.2013; Phil. Trans Roy.Soc Ser.B; Wrage et al., 2002, Soil Biol.Biochem.)
- Better understanding of N_2O production-consumption processes and linkages to soil microbial ecology may allow to define new mitigation options by e.g. changing pH (liming), residue management, crop species selection (effect via root exudates), aeration, Cu availability, fertilizer regimes…

Microbial ecology and genetic engineering

- Engineering crop plants to fix N_2 (Beaty and Good 2011, Science), coupling of nitrogen supply and carbon metabolism will reduce N_2O emissions

- Introducing the N_2O reductase gene in crops → amplifying the amount of available enzyme catalyst in agri-system environments during crop growth and in post-harvest detritus (Wan et al. 2012, Trends in Biotechnology)

(8) Sustainable agricultural intensification

..producing more output from the same area of land while reducing the negative environmental impacts and at the same time increasing contributions to natural capital and the flow of environmental services (Pretty 2008, Phil Trans Roy Soc B).

E.g. by

- using crop varieties and livestock breeds with a high ratio of productivity to use of externally derived inputs
- growing high-yielding pasture species with a lower nitrogen content
- Close linkage of livestock and crop production systems (mixed systems)
- …..

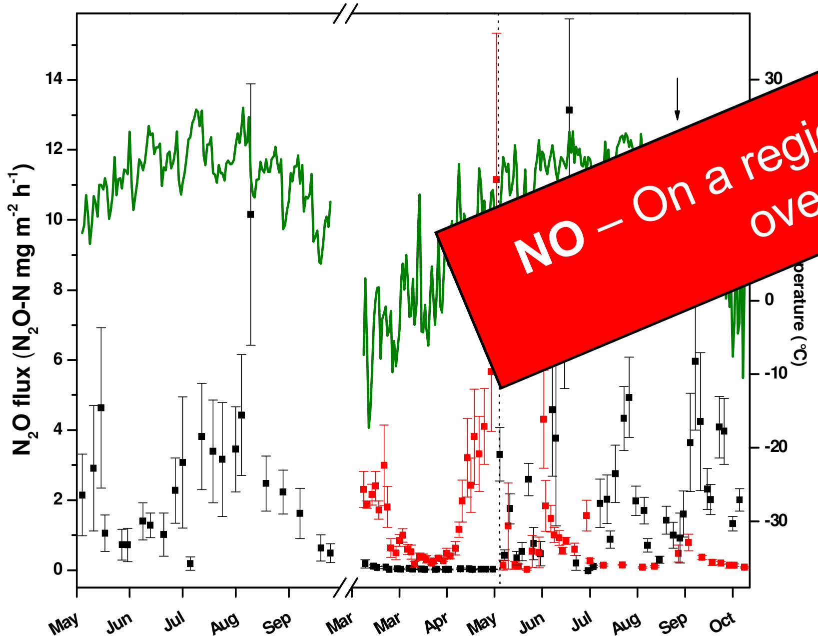
Summary

- Increasing crop nutrient use efficiency
- Intensification of agricultural production
- Inhibitors, slow release fertilizers, crop breeding, genetic engineering as well as a wide variety of management options are established or will become available in the near future as tools/options for reducing N_2O emissions
- Mitigation options need to consider all GHG fluxes
- Consideration of other negative environmental impacts (soil fertility, water quality and quantity, air chemistry, human health) together with socioeconomic consequences
- Region specific assessment of measures using a combination of field trials and modeling studies is needed for evaluating mitigation options and opportunities

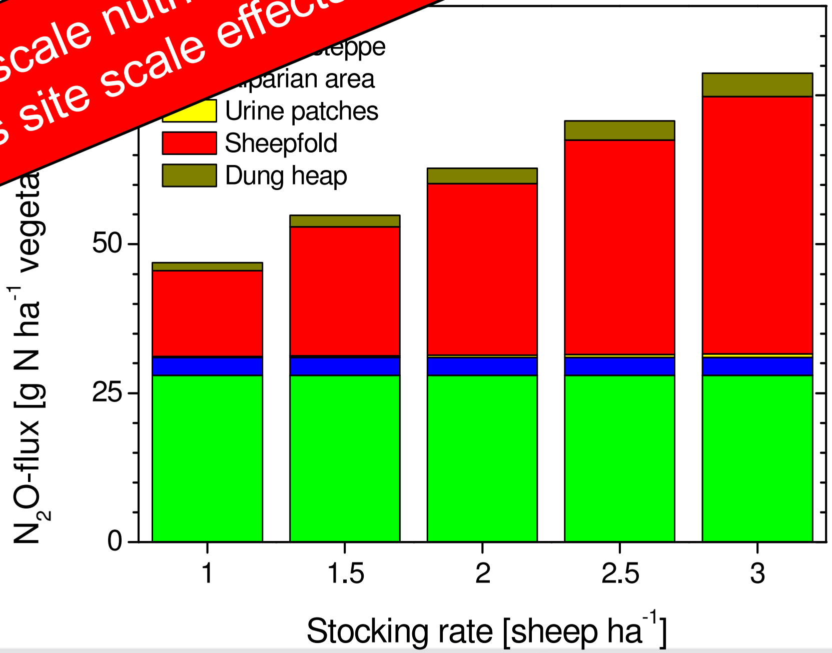
Thank you

Do natural steppe systems emit more N_2O than grazed systems?

NO – On a regional scale nutrient management overrides site scale effects

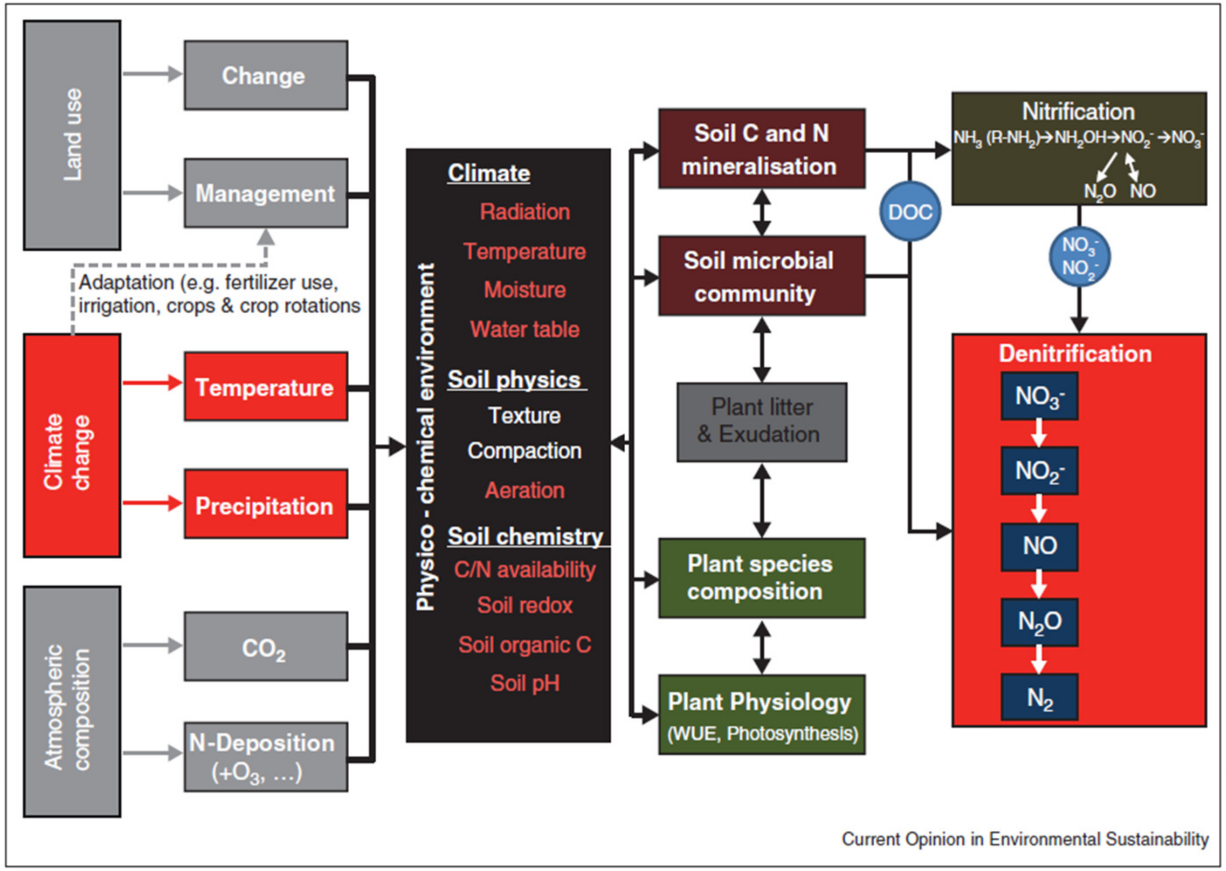


Holst et al., 2007, Plant and Soil



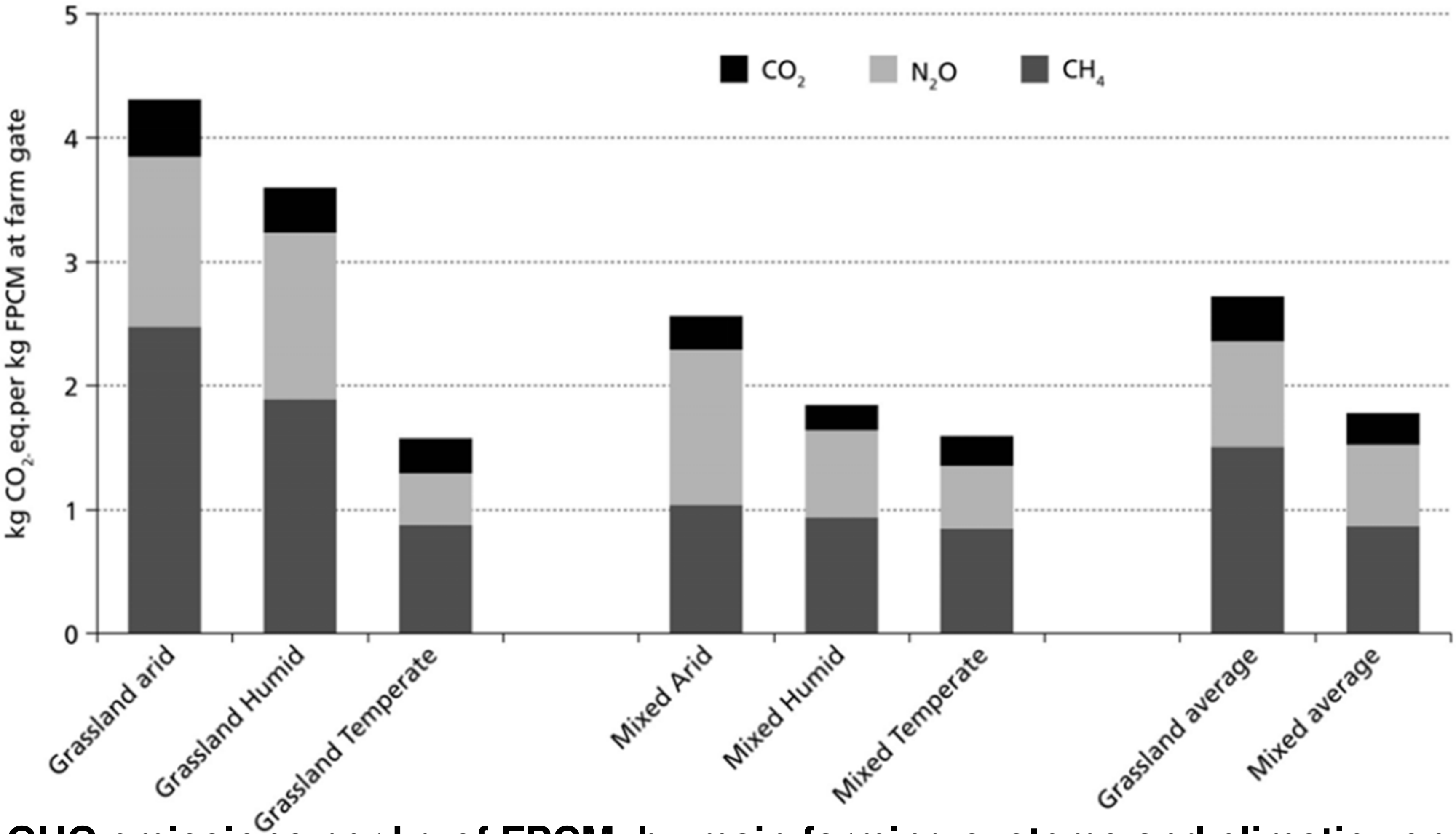
Conversion from conventional to reduced tillage and increased soil C inputs

- Mixed results for N_2O
- Positive effects (mostly) for soil organic carbon stocks
- Total GHG balance: N_2O effects may in some cases override C stock gains
- Site/ region specific evaluation needed



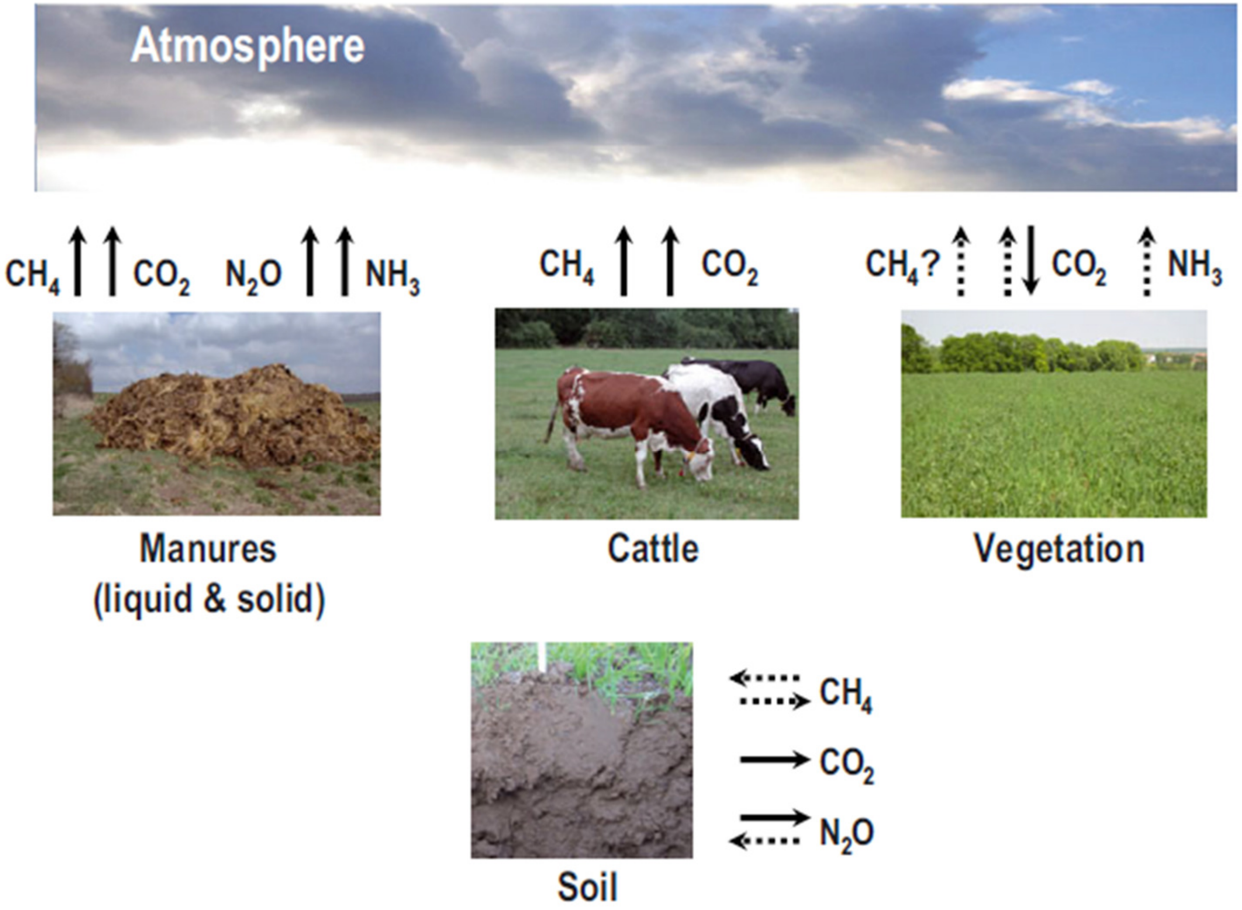
Current Opinion in Environmental Sustainability

GHG-emissions, N2O and milk production



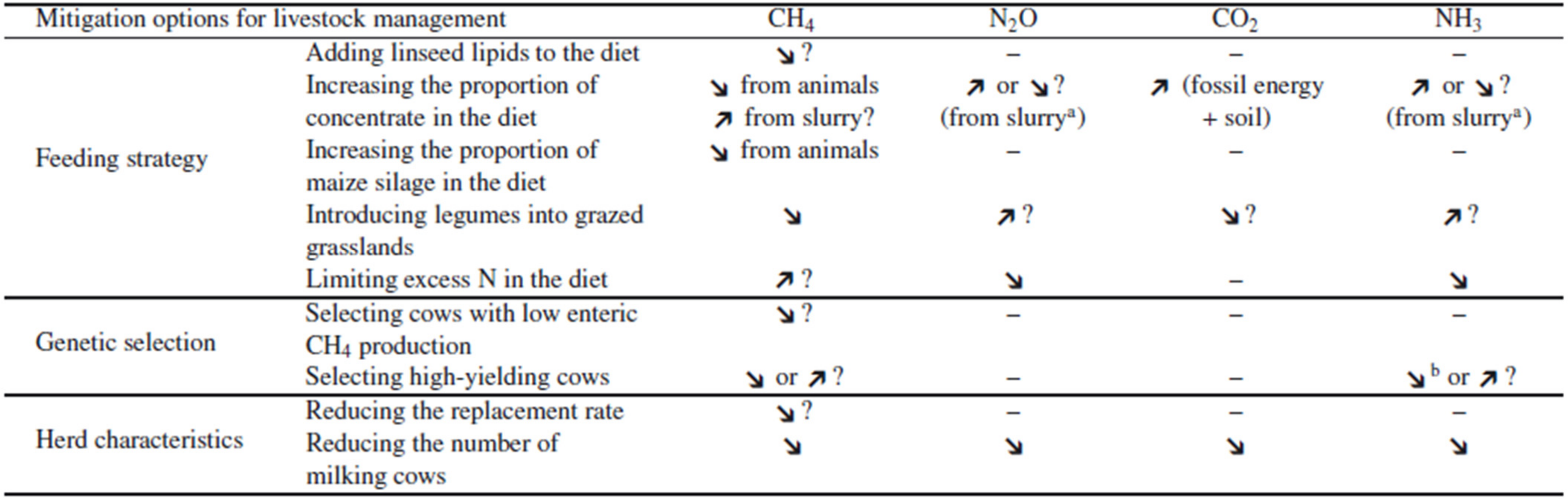
GHG emissions per kg of FPCM, by main farming systems and climatic zones (Emissions related to processing and land use change are omitted) [FAO, **Greenhouse Gas Emissions from the** fat and protein corrected milk (FPCM)

Livestock and GHG emissions



Novak and Fiorelli 2010 Agron. Sustain. Dev.

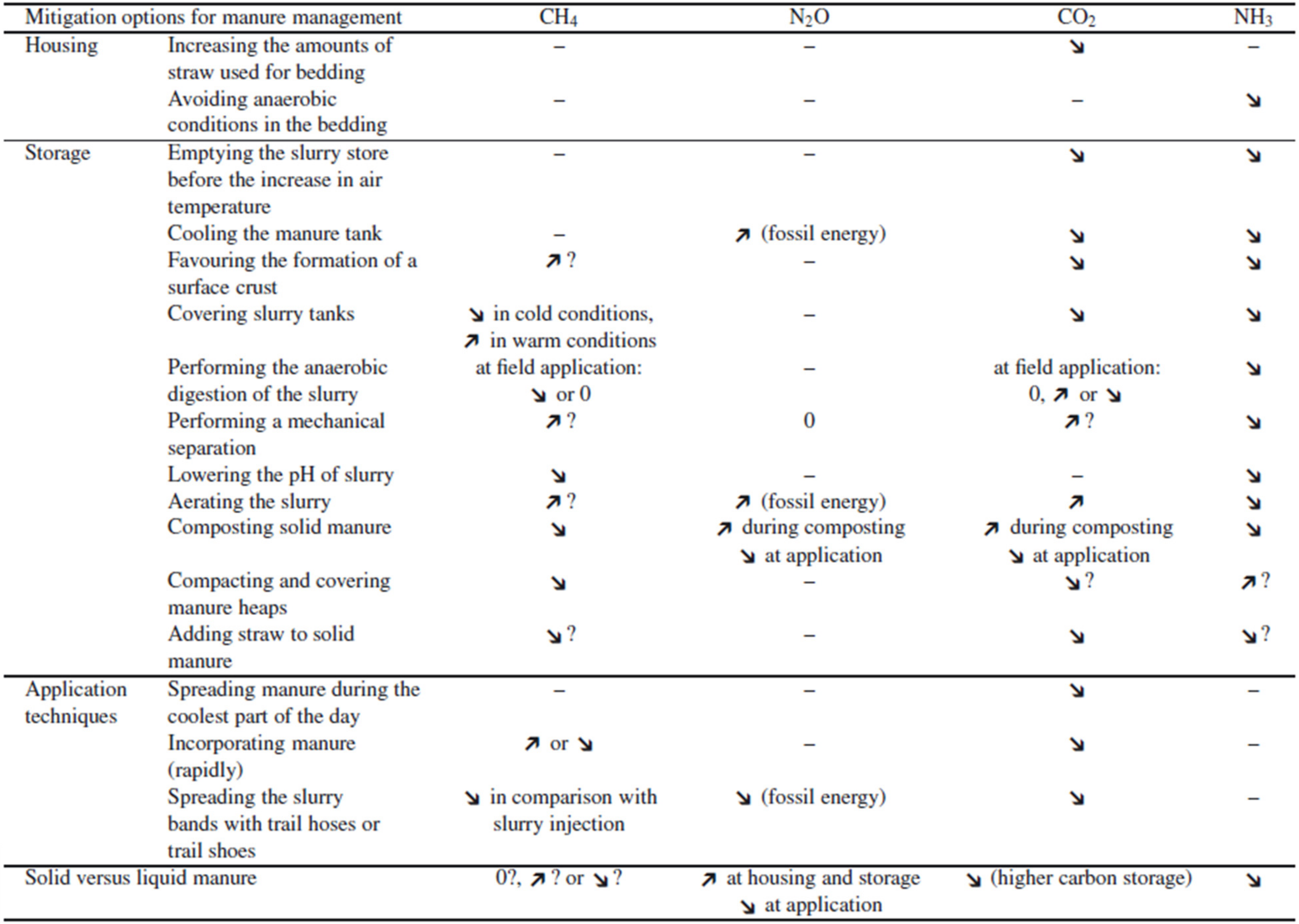
Effects on greenhouse gas and ammonia emissions of mitigation options reported for livestock management



Mitigation options for livestock management		CH_4	N_2O	CO_2	NH_3
Feeding strategy	Adding linseed lipids to the diet	↘ ?	–	–	–
	Increasing the proportion of concentrate in the diet	↘ from animals ↗ from slurry?	↗ or ↘ ? (from slurry[a])	↗ (fossil energy + soil)	↗ or ↘ ? (from slurry[a])
	Increasing the proportion of maize silage in the diet	↘ from animals	–	–	–
	Introducing legumes into grazed grasslands	↘	↗ ?	↘ ?	↗ ?
	Limiting excess N in the diet	↗ ?	↘	–	↘
Genetic selection	Selecting cows with low enteric CH_4 production	↘ ?	–	–	–
	Selecting high-yielding cows	↘ or ↗ ?	–	–	↘[b] or ↗ ?
Herd characteristics	Reducing the replacement rate	↘ ?	–	–	–
	Reducing the number of milking cows	↘	↘	↘	↘

Novak and Fiorelli 2010 Agron. Sustain. Dev.

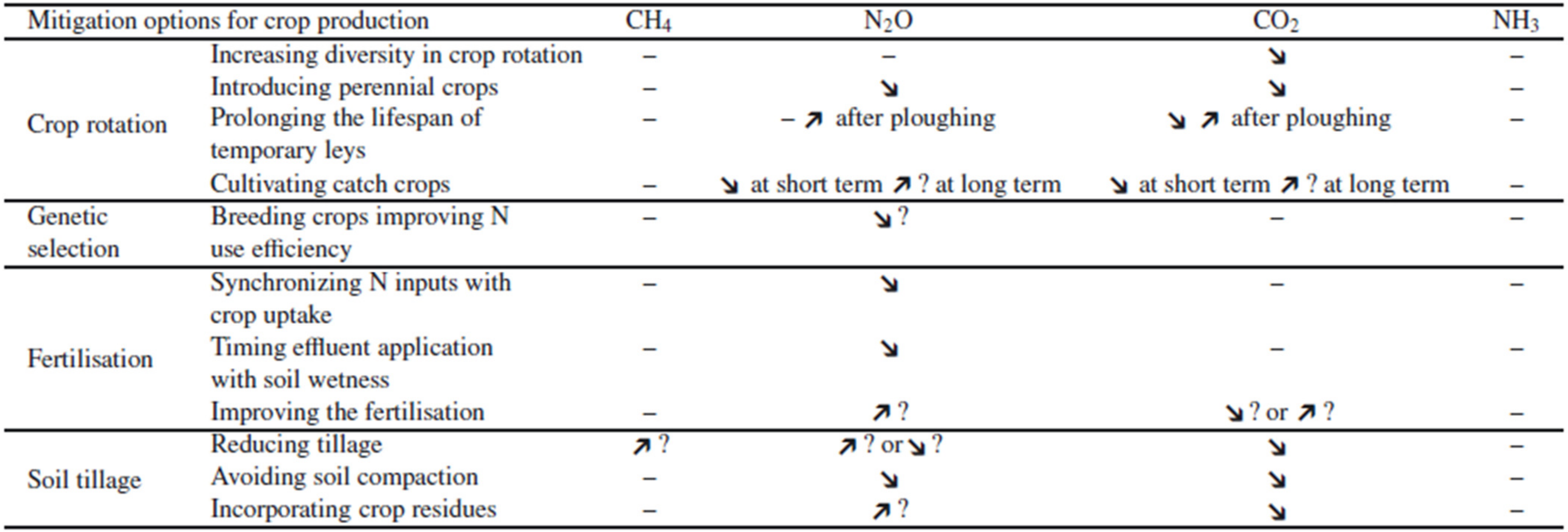
Effects on greenhouse gas and ammonia emissions of mitigation options reported for manure management



Mitigation options for manure management		CH_4	N_2O	CO_2	NH_3
Housing	Increasing the amounts of straw used for bedding	–	–	↘	–
	Avoiding anaerobic conditions in the bedding	–	–	–	↘
Storage	Emptying the slurry store before the increase in air temperature	–	–	↘	↘
	Cooling the manure tank	–	↗ (fossil energy)	↘	↘
	Favouring the formation of a surface crust	↗ ?	–	↘	↘
	Covering slurry tanks	↘ in cold conditions, ↗ in warm conditions	–	↘	↘
	Performing the anaerobic digestion of the slurry	at field application: ↘ or 0	–	at field application: 0, ↗ or ↘	↘
	Performing a mechanical separation	↗ ?	0	↗ ?	↘
	Lowering the pH of slurry	↘	–	–	↘
	Aerating the slurry	↗ ?	↗ (fossil energy)	↗	↘
	Composting solid manure	↘	↗ during composting ↘ at application	↗ during composting ↘ at application	↘
	Compacting and covering manure heaps	↘	–	↘ ?	↗ ?
	Adding straw to solid manure	↘ ?	–	↘	↘ ?
Application techniques	Spreading manure during the coolest part of the day	–	–	↘	–
	Incorporating manure (rapidly)	↗ or ↘	–	↘	–
	Spreading the slurry bands with trail hoses or trail shoes	↘ in comparison with slurry injection	↘ (fossil energy)	↘	–
Solid versus liquid manure		0?, ↗ ? or ↘ ?	↗ at housing and storage ↘ at application	↘ (higher carbon storage)	↘

Novak and Fiorelli 2010 Agron. Sustain. Dev.

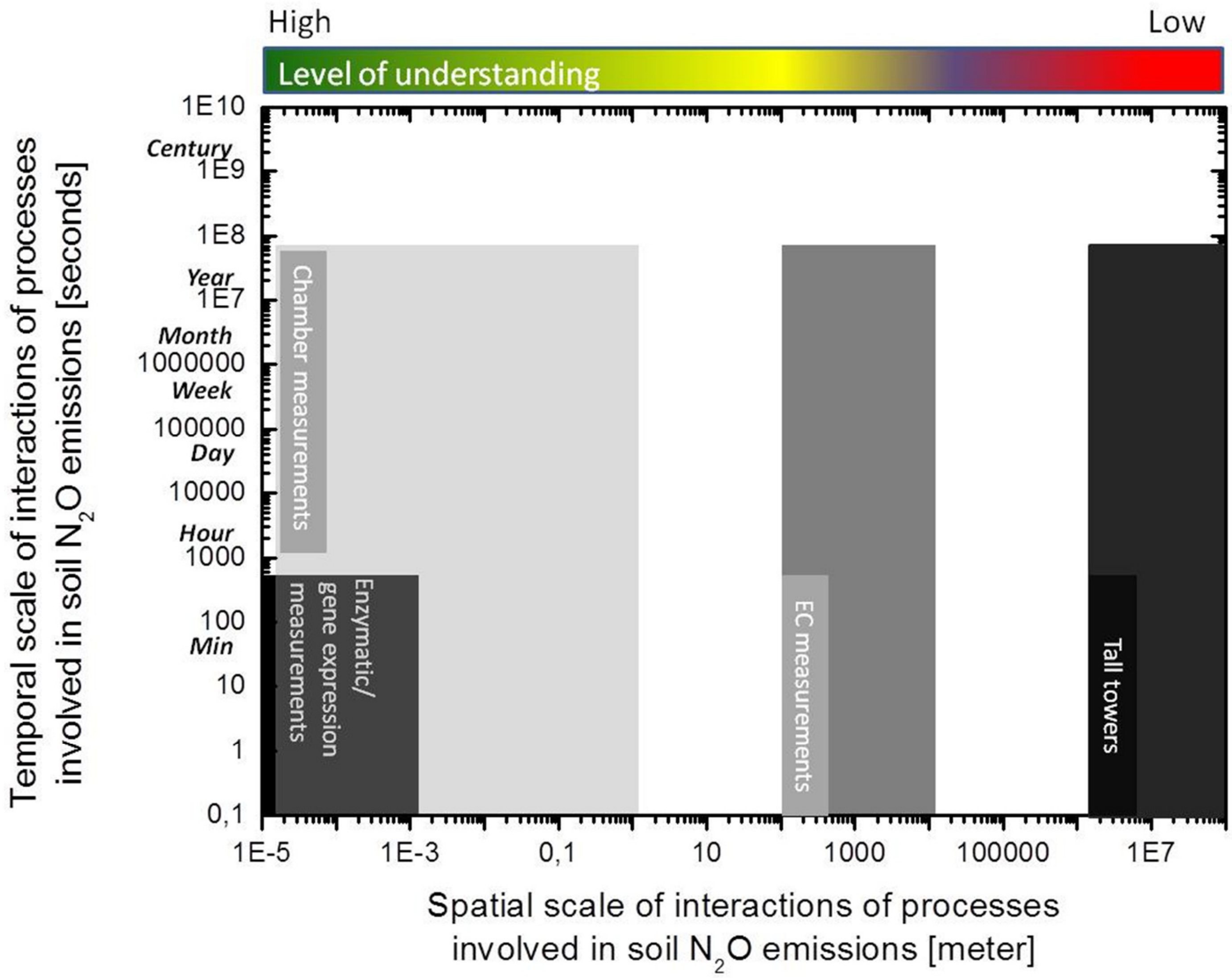
Effects on greenhouse gas and ammonia emissions of mitigation options at the crop production stage



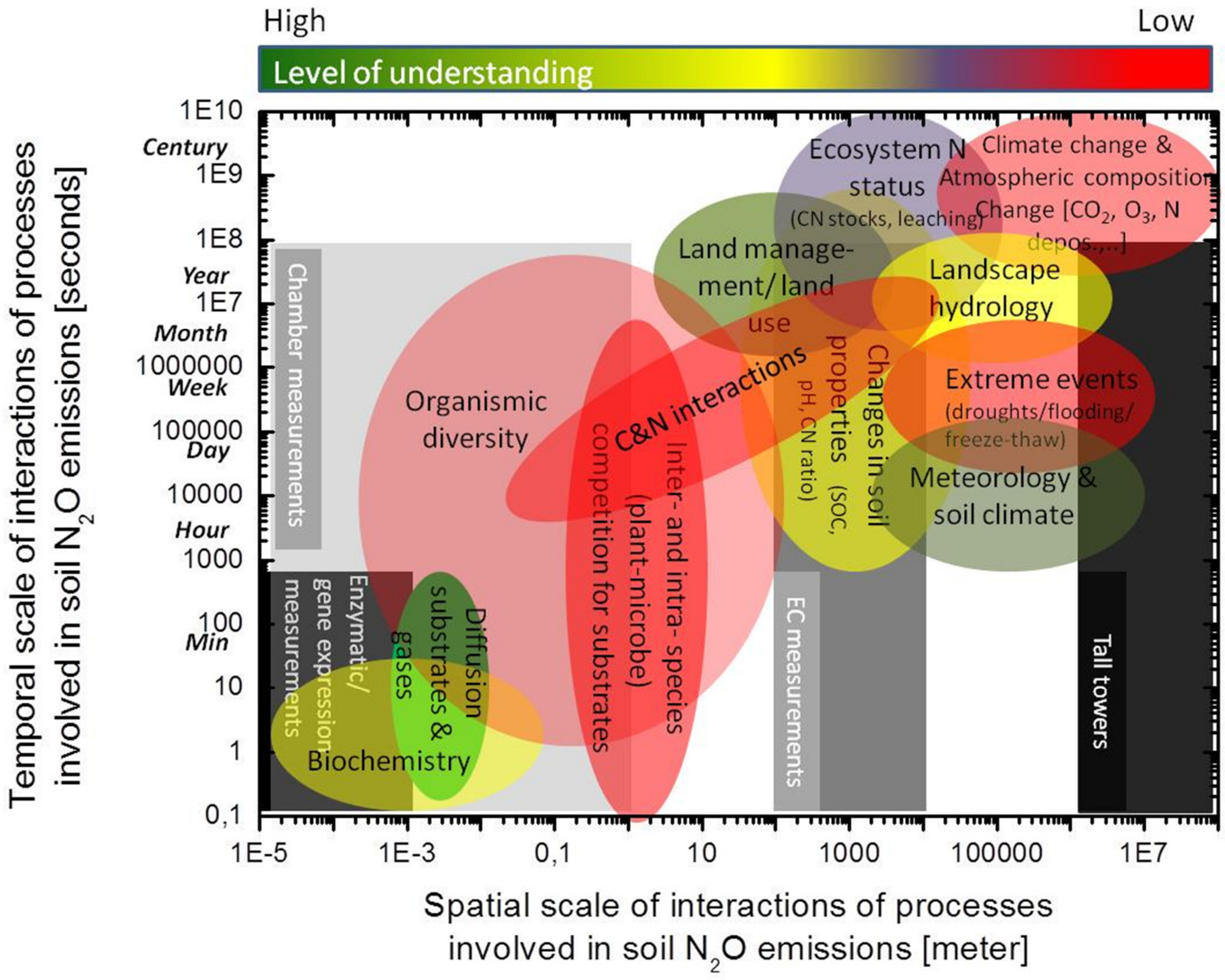
Mitigation options for crop production		CH_4	N_2O	CO_2	NH_3
Crop rotation	Increasing diversity in crop rotation	–	–	↘	–
	Introducing perennial crops	–	↘	↘	–
	Prolonging the lifespan of temporary leys	–	– ↗ after ploughing	↘ ↗ after ploughing	–
	Cultivating catch crops	–	↘ at short term ↗ ? at long term	↘ at short term ↗ ? at long term	–
Genetic selection	Breeding crops improving N use efficiency	–	↘ ?	–	–
Fertilisation	Synchronizing N inputs with crop uptake	–	↘	–	–
	Timing effluent application with soil wetness	–	↘	–	–
	Improving the fertilisation	–	↗ ?	↘ ? or ↗ ?	–
Soil tillage	Reducing tillage	↗ ?	↗ ? or ↘ ?	↘	–
	Avoiding soil compaction	–	↘	↘	–
	Incorporating crop residues	–	↗ ?	↘	–

Novak and Fiorelli 2010 Agron. Sustain. Dev.

Measuring N_2O exchange

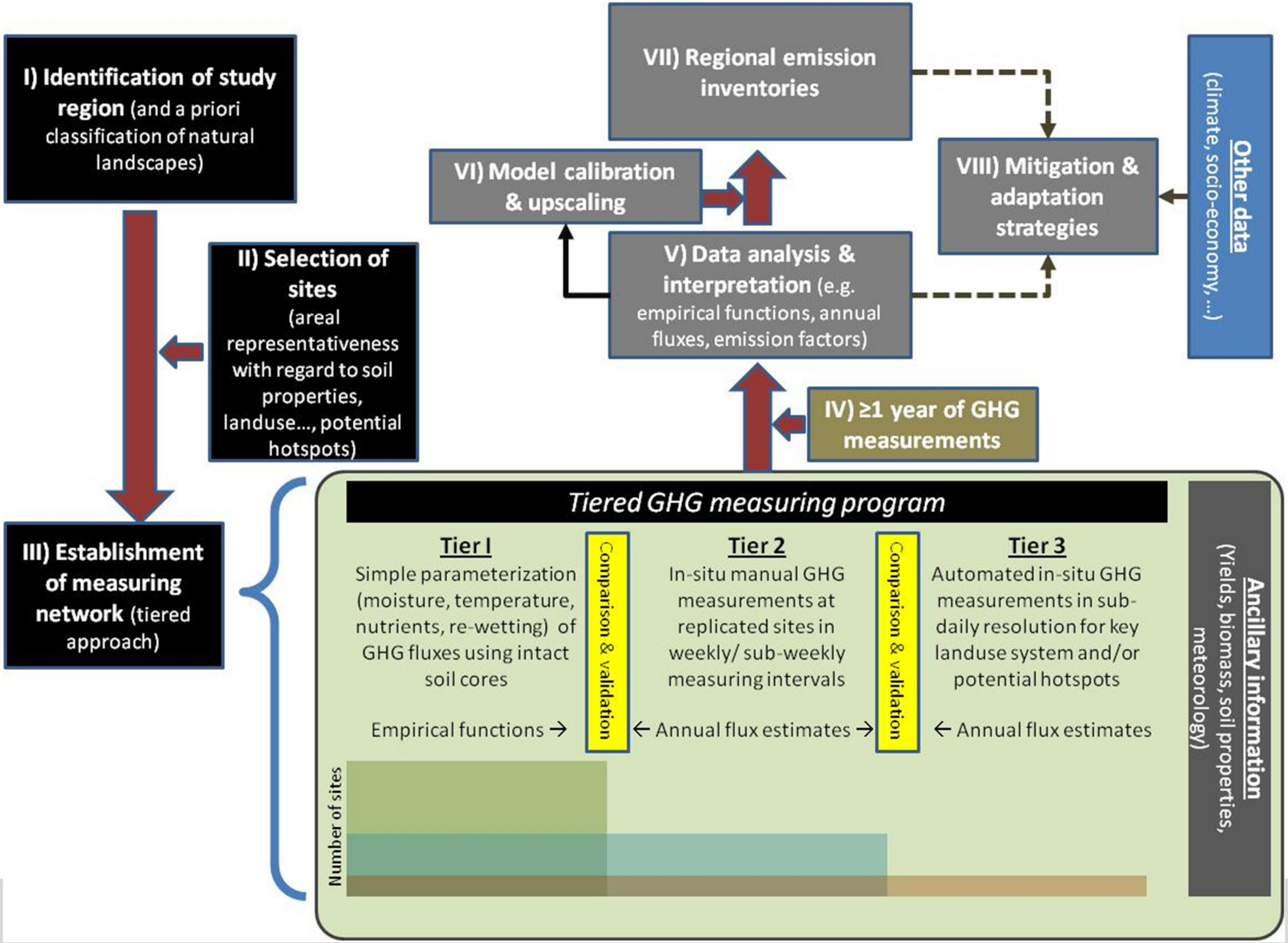


Measuring N_2O exchange



Butterbach-Bahl et al. 2013, Phil. Trans. R. Soc. B

Identifying regional hot spots of emissions



I) Identification of study region (and a priori classification of natural landscapes)

II) Selection of sites (areal representativeness with regard to soil properties, landuse…, potential hotspots)

III) Establishment of measuring network (tiered approach)

IV) ≥1 year of GHG measurements

V) Data analysis & interpretation (e.g. empirical functions, annual fluxes, emission factors)

VI) Model calibration & upscaling

VII) Regional emission inventories

VIII) Mitigation & adaptation strategies

Other data (climate, socio-economy, …)

Tiered GHG measuring program

Tier I
Simple parameterization (moisture, temperature, nutrients, re-wetting) of GHG fluxes using intact soil cores
Empirical functions →

Comparison & validation

Tier 2
In-situ manual GHG measurements at replicated sites in weekly/ sub-weekly measuring intervals
← Annual flux estimates →

Comparison & validation

Tier 3
Automated in-situ GHG measurements in sub-daily resolution for key landuse system and/or potential hotspots
← Annual flux estimates

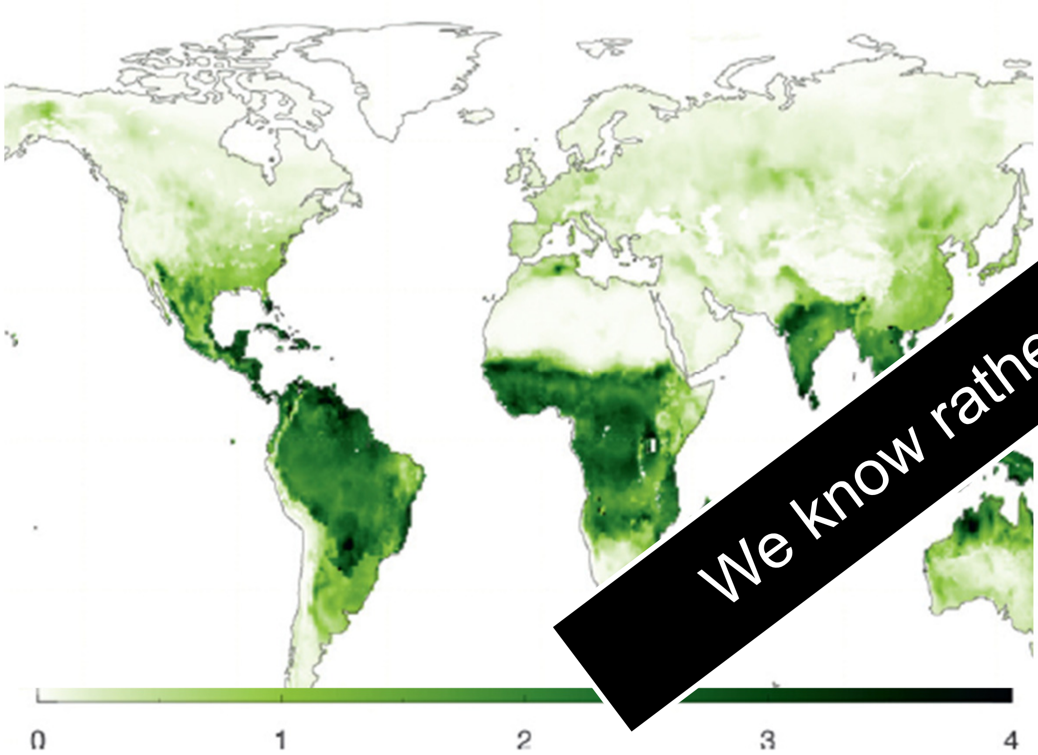
Ancillary information (Yields, biomass, soil properties, meteorology)

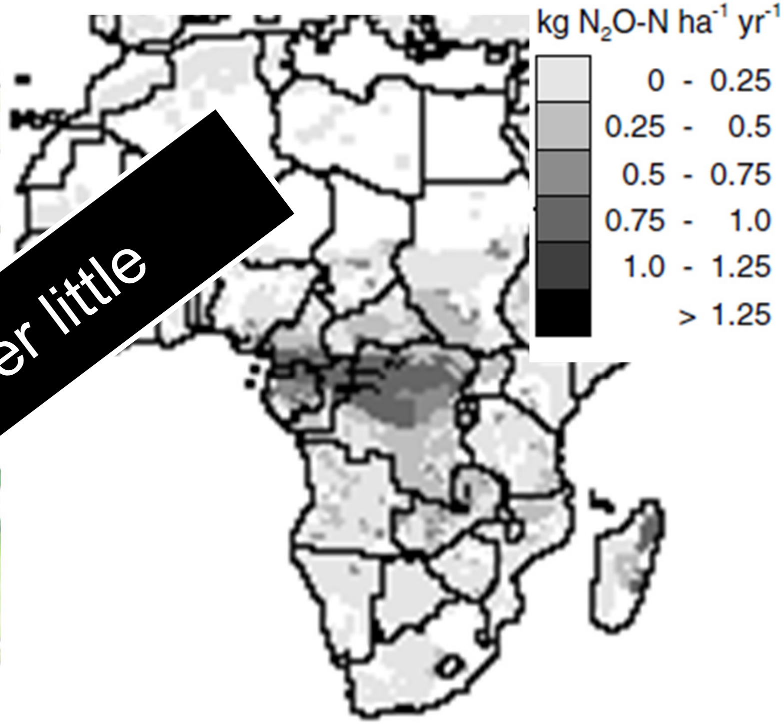
Regional inventories

- Emission factor (EF) approaches → national inventories
- empirical approaches (e.g Stehfest & Bouman, 2006)
- GIS linked biogeochemical model approaches (e.g. Butterbach-Bahl et al., 2004)
- Mass balance and EF approaches (e.g. De Vries et al., 2011)

➢ All approaches still have severe short comes
  - Uncertainty not quantified
  - site validation difficult (e.g. EF approaches)
  - Regional validation missing
  - Severe lack of measurements in many regions
  - ……..

What do we know at global scale?





We know rather little

Simulated spatial pattern of annual non-agricultural soil nitrous oxide (N_2O) emissions for the year 1990 (kg N ha^{-1} yr^{-1})

[Xu-Ri et al., 2012; New. Phytol.]

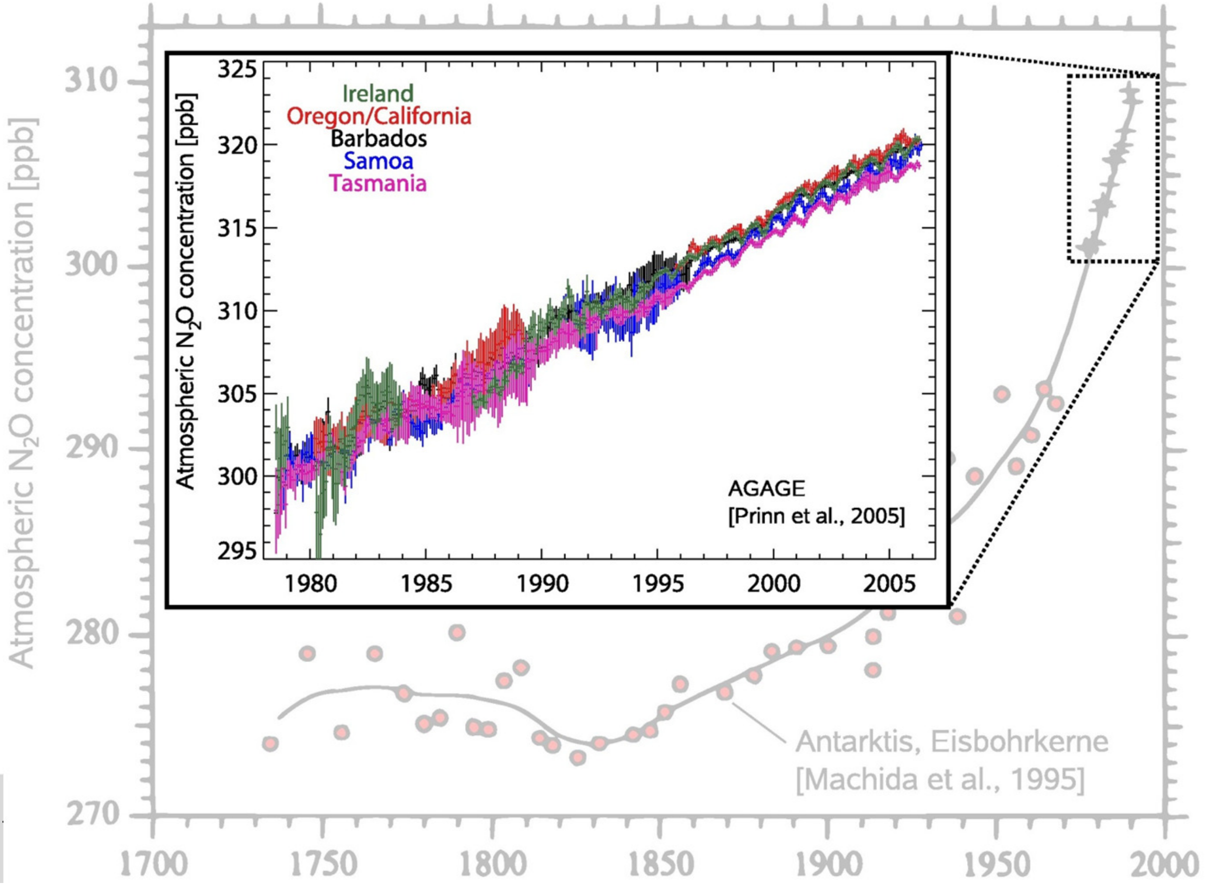
Simulated annual N_2O emission rates for natural ecosystems for 1998 land cover

[Stehfest and Bouman, 2006; Nutr. Cycl Agroecosys.]

Motivation

Why is N_2O of interests?

- Potent GHG (GWP 296), lifetime ca. 130 yrs,5-8% contribution to global warming
- atmospheric concentrations increased from approx. 280 ppbv to 315 ppbv
- Increase continues at 1% yr^{-1}

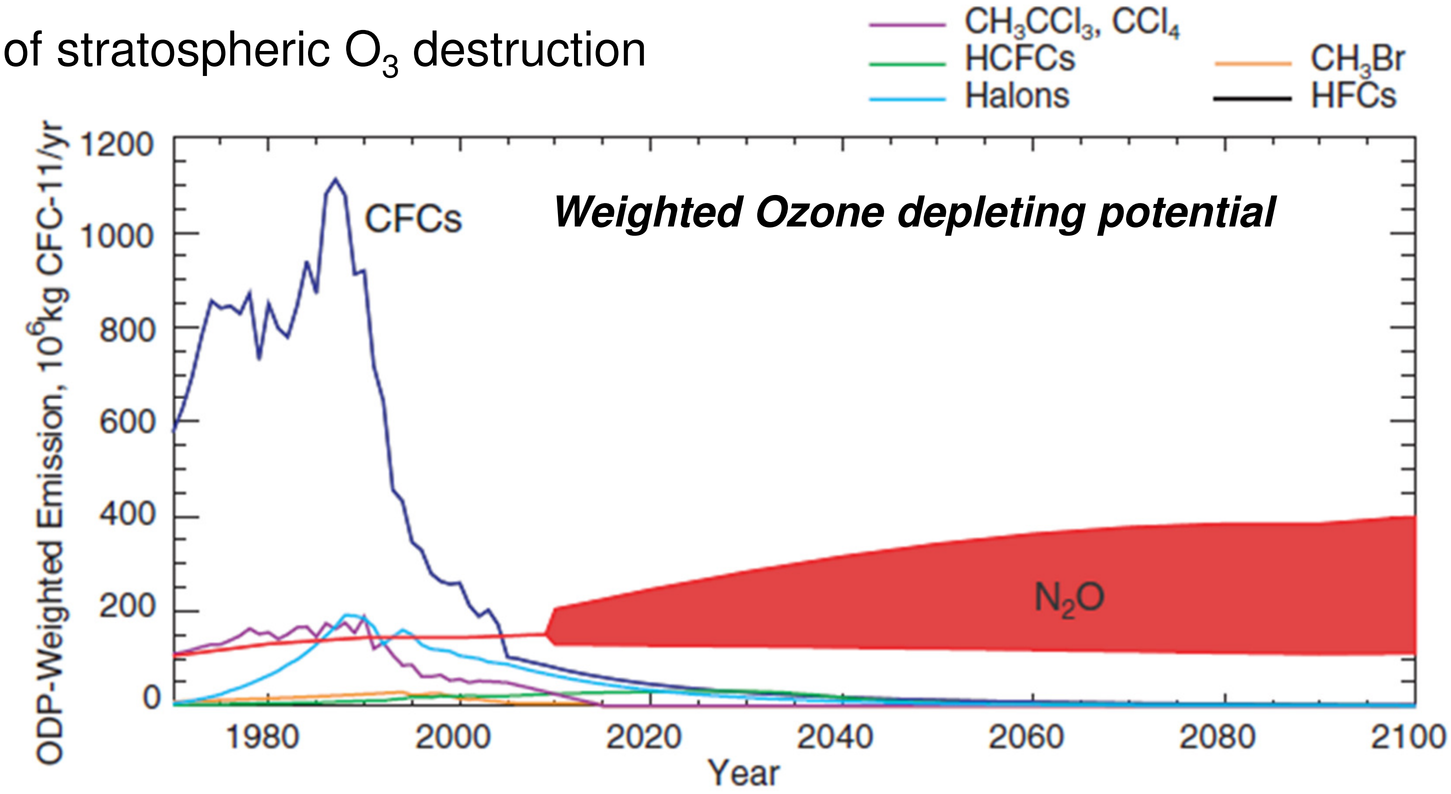


IPCC 2007

Motivation

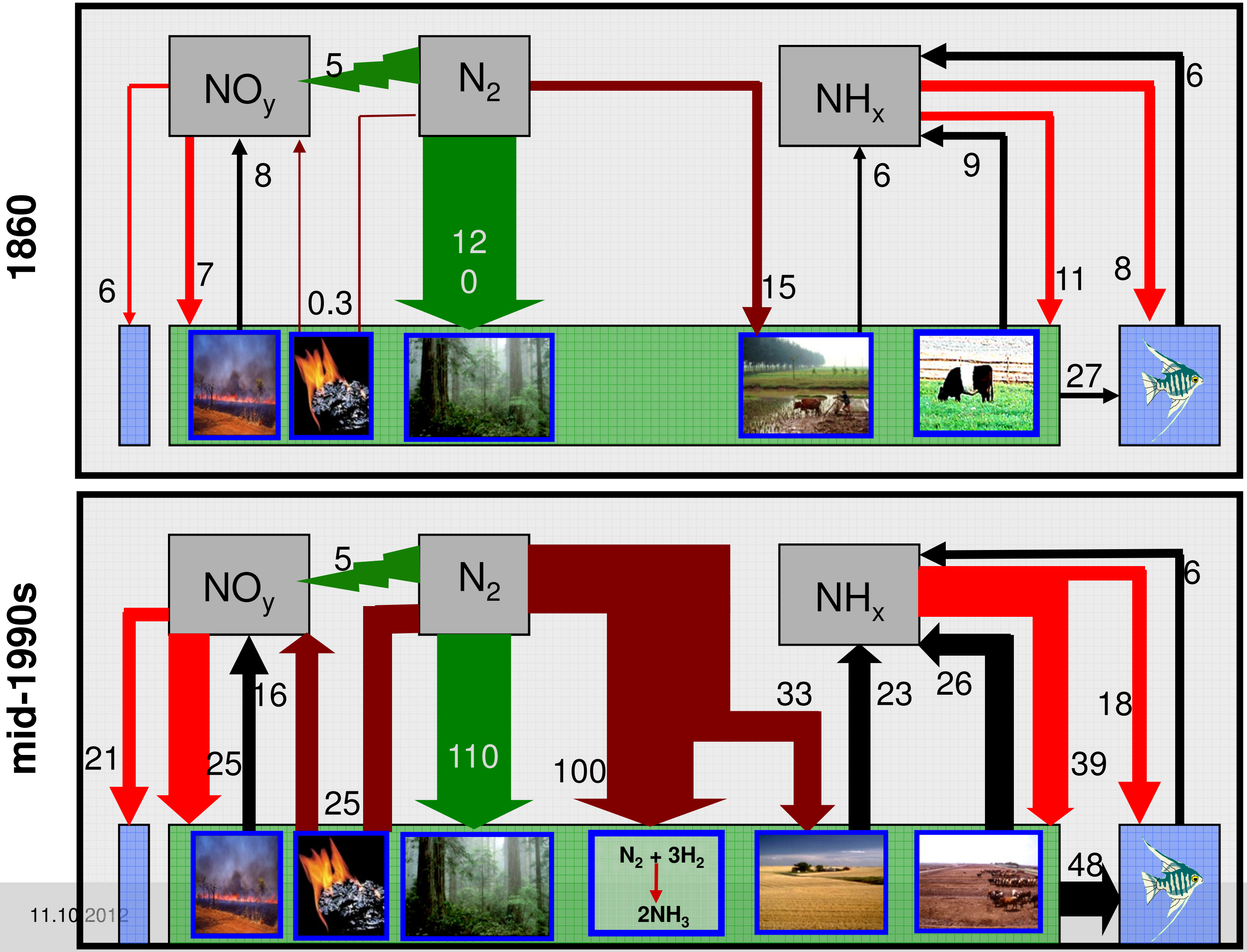
Why is N_2O of interests?

- Potent GHG (GWP 296), lifetime ca. 130 yrs,5-8% contribution to global warming
- atmospheric concentrations increased from approx. 280 ppbv to 315 ppbv
- Increase continues at 1% yr^{-1}
- major driver of stratospheric O_3 destruction



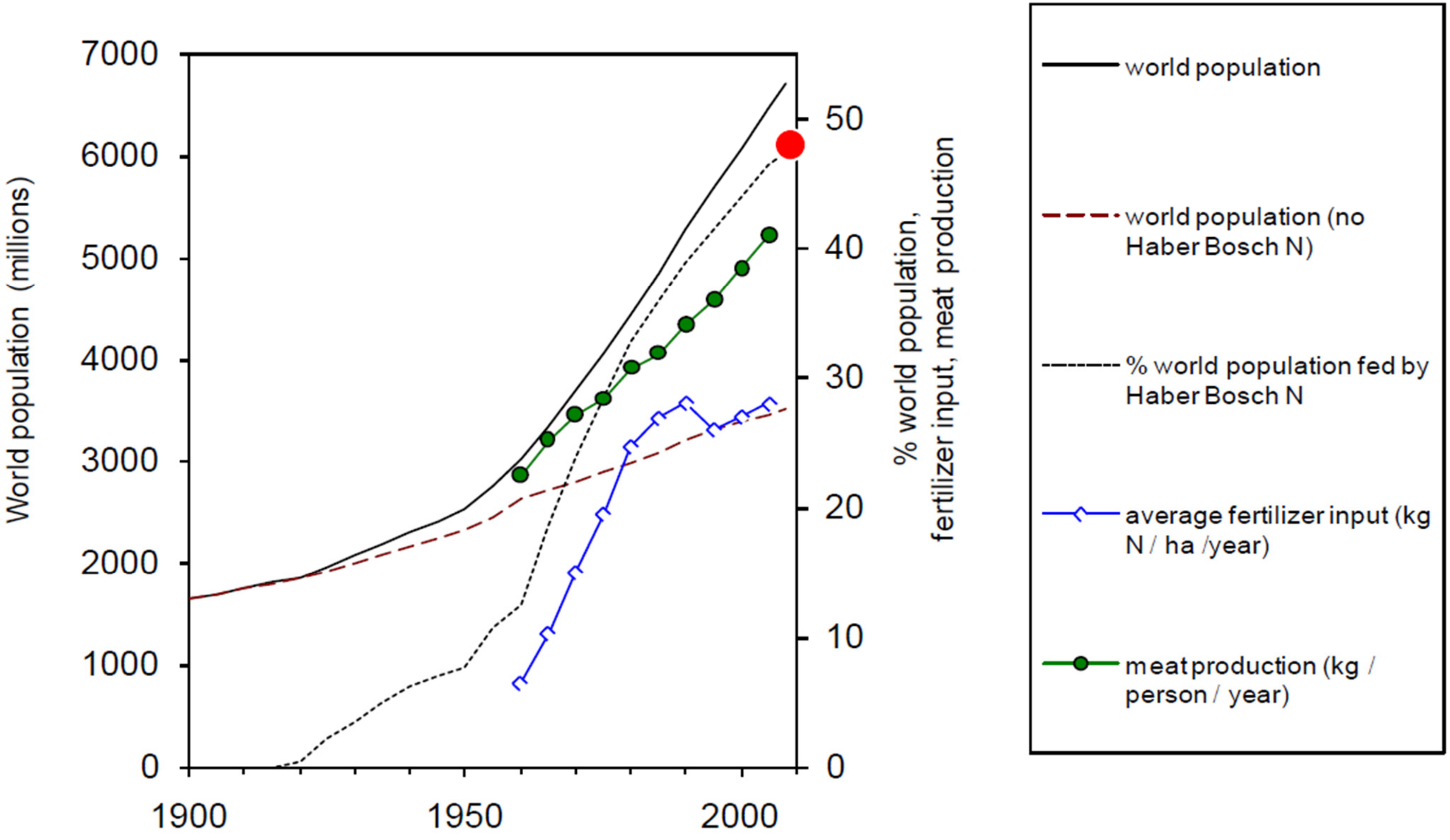
Ravinshankara et al. 2009, Science

Agricultural soils and manure management are driving increases in atmospheric N_2O concentrations;, a consequence of the perturbation of the global N cycle…



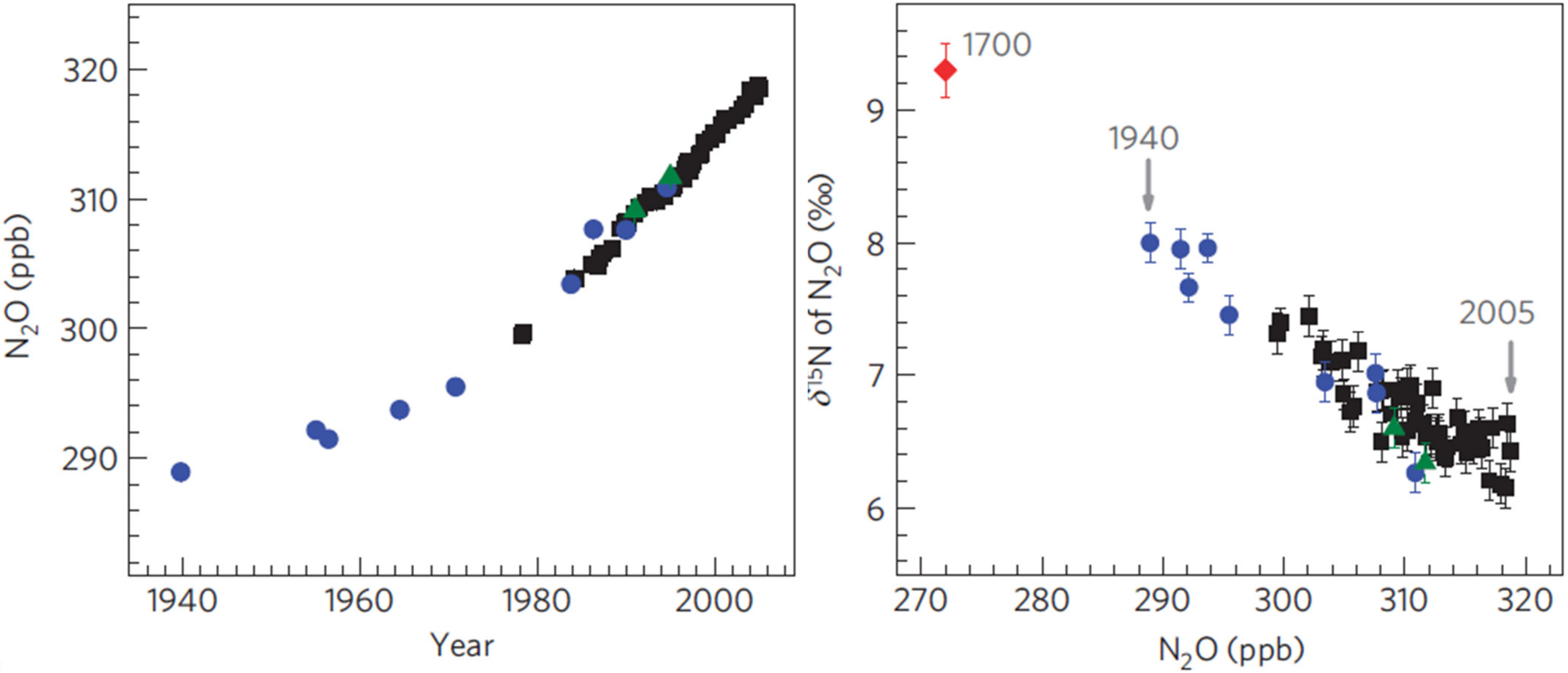
Changed according to Galloway et al., 2003, Biogeochemistry

Agricultural soils and manure management are driving increases in atmospheric N_2O concentrations, a consequence of the perturbation of the global N cycle and the need to feed an increasing world population



Erisman et al., 2008, Nature Geosciences

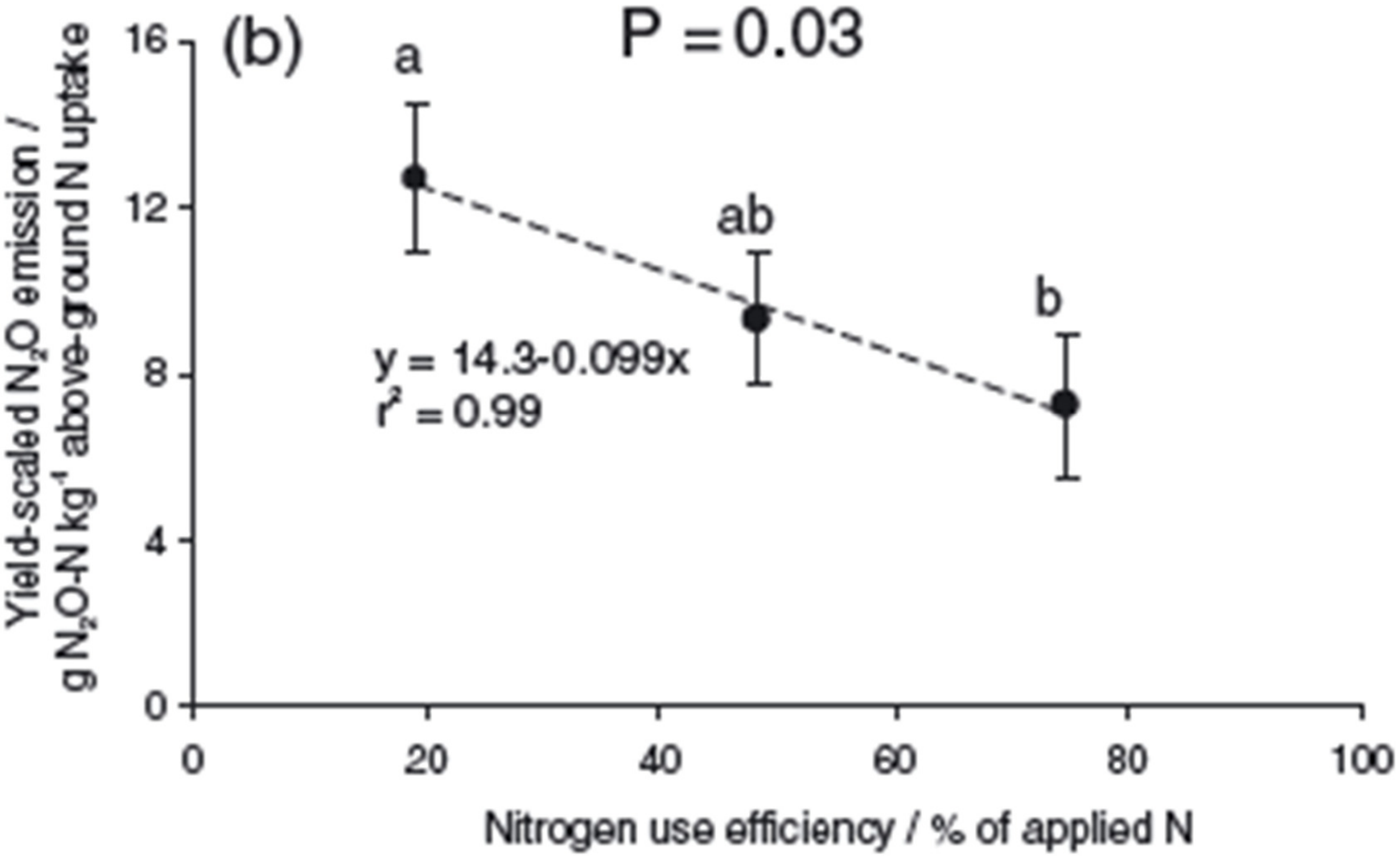
Increase in the atmospheric N_2O burden is largely due to nitrogen-based agricultural fertilizer use



Park et al. 2012, Nature

Under N rich conditions enzyme kinetics of the microbial N_2O production processes favour $_{14}N$

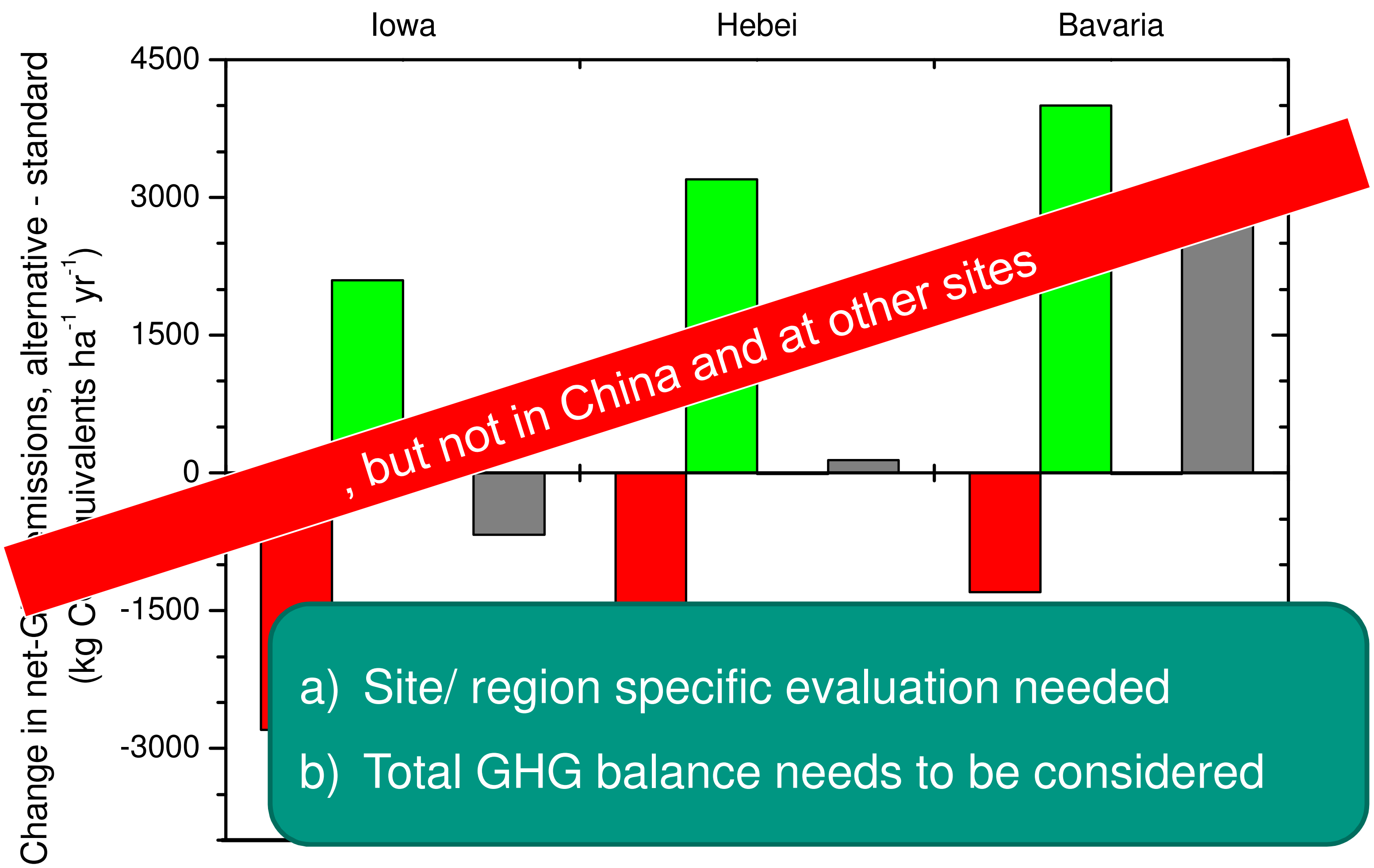
High nitrogen use efficiency ≈ low N_2O emissions



Van Groeningen et al. 2010, Eur J Soil Sci

Conversion from conventional to reduced tillage

(Yangtze river delta, China; Iowa, USA, Hebei, China, Munich, Germany)



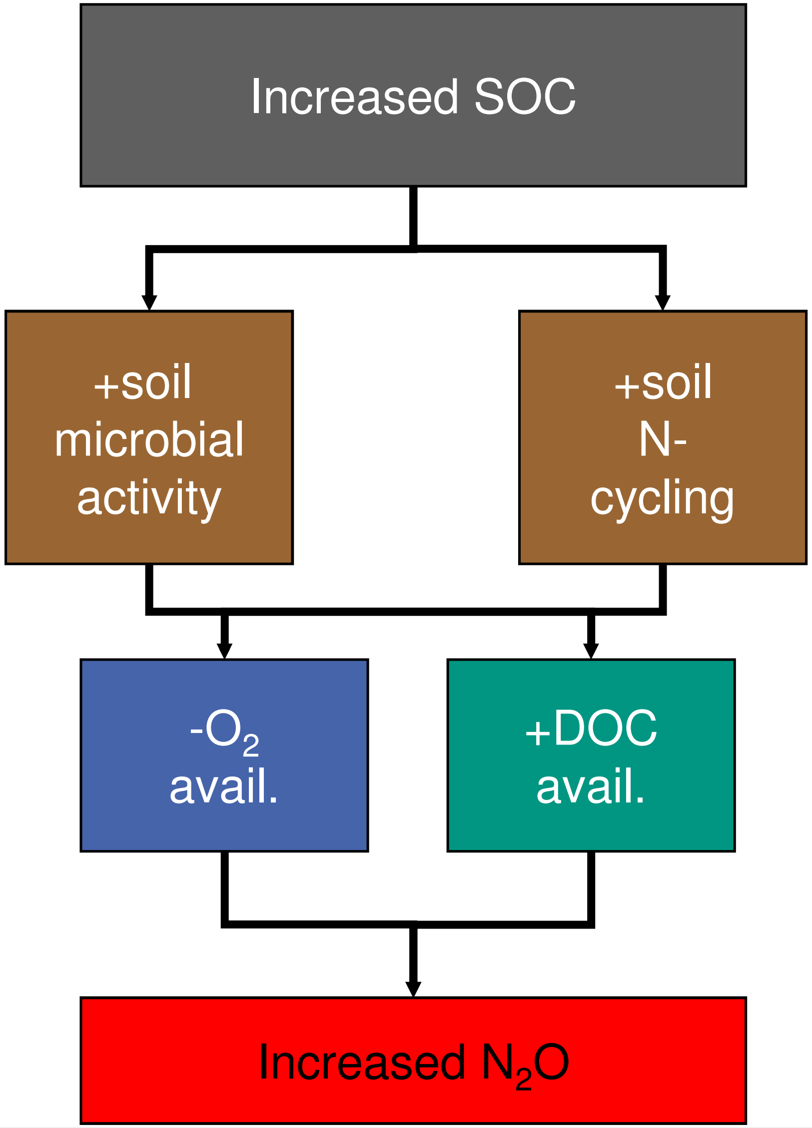
, but not in China and at other sites

a) Site/ region specific evaluation needed

b) Total GHG balance needs to be considered

Li et al. 2005, Climatic Change

(4) Increased soil C inputs ≈ +N_2O emissions?



Increased SOC

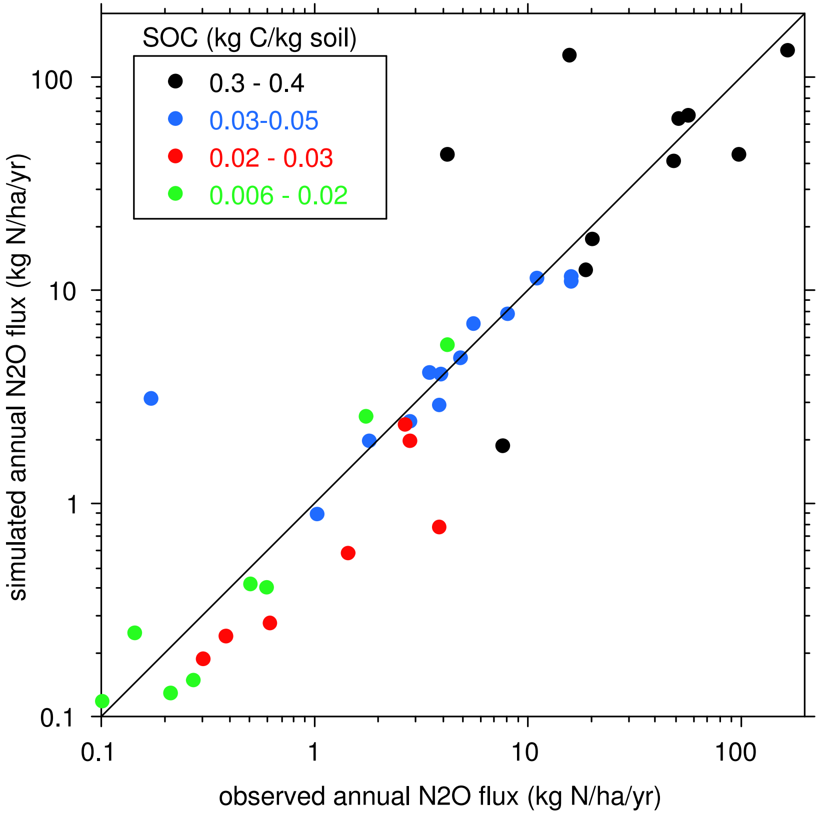
+soil microbial activity

+soil N-cycling

-O_2 avail.

+DOC avail.

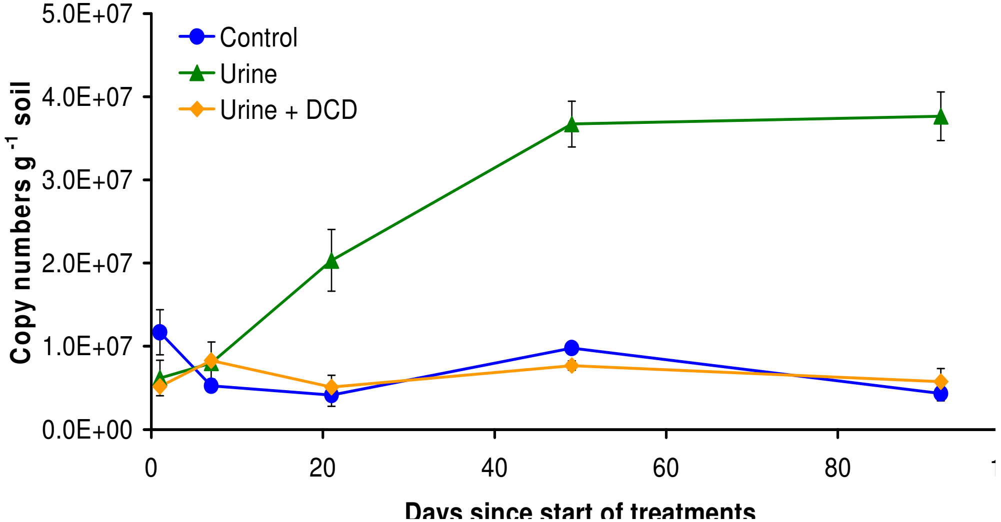
Increased N_2O



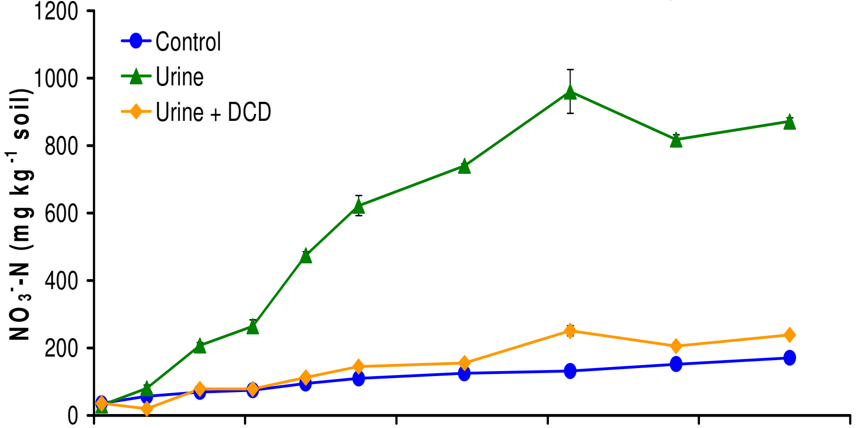
Li et al., 2005, Climatic Change

Use of inhibitors or slow release fertilizers

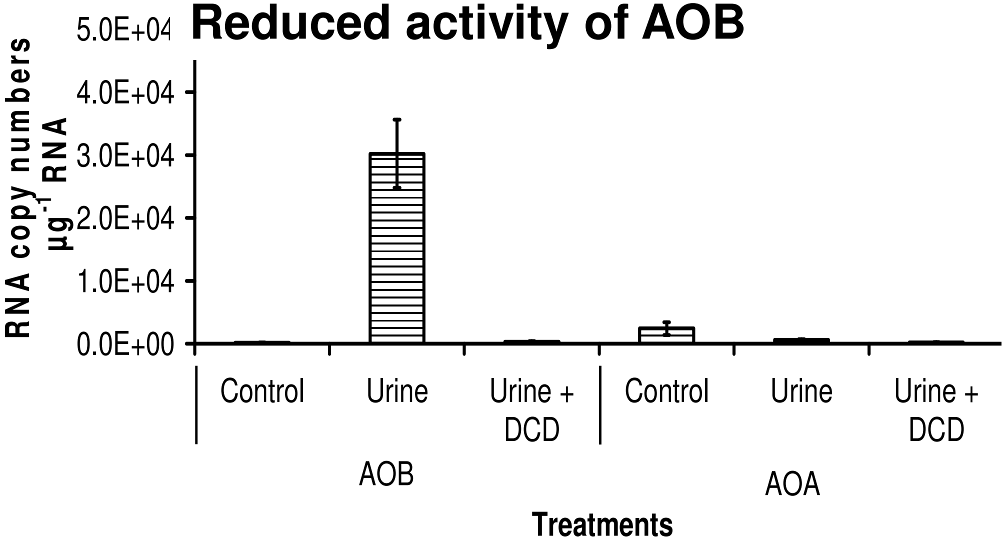
DCD application to Waikato Horotiu soil, New Zealand (Di et al.2009,Nature Geosci.)



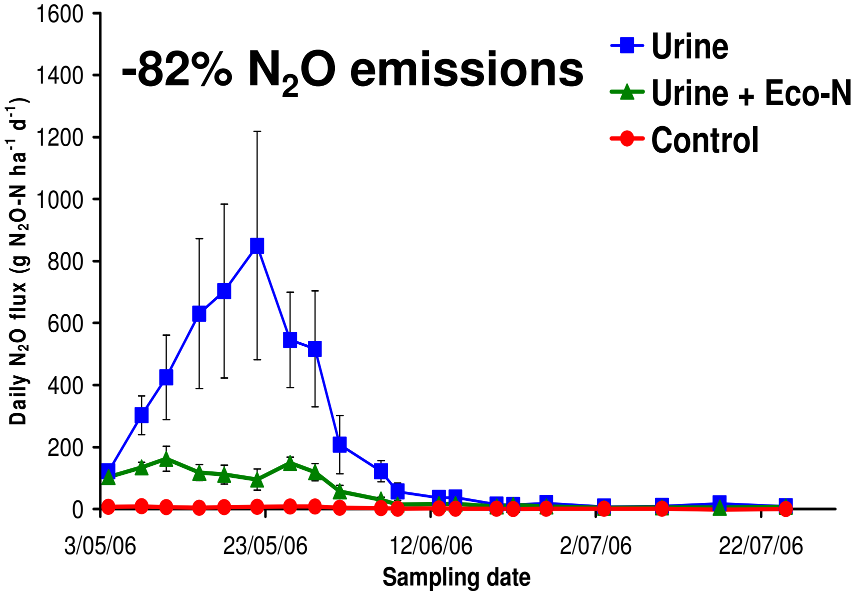
Reduced growth of AOB



Reduced nitrate leaching



Reduced activity of AOB

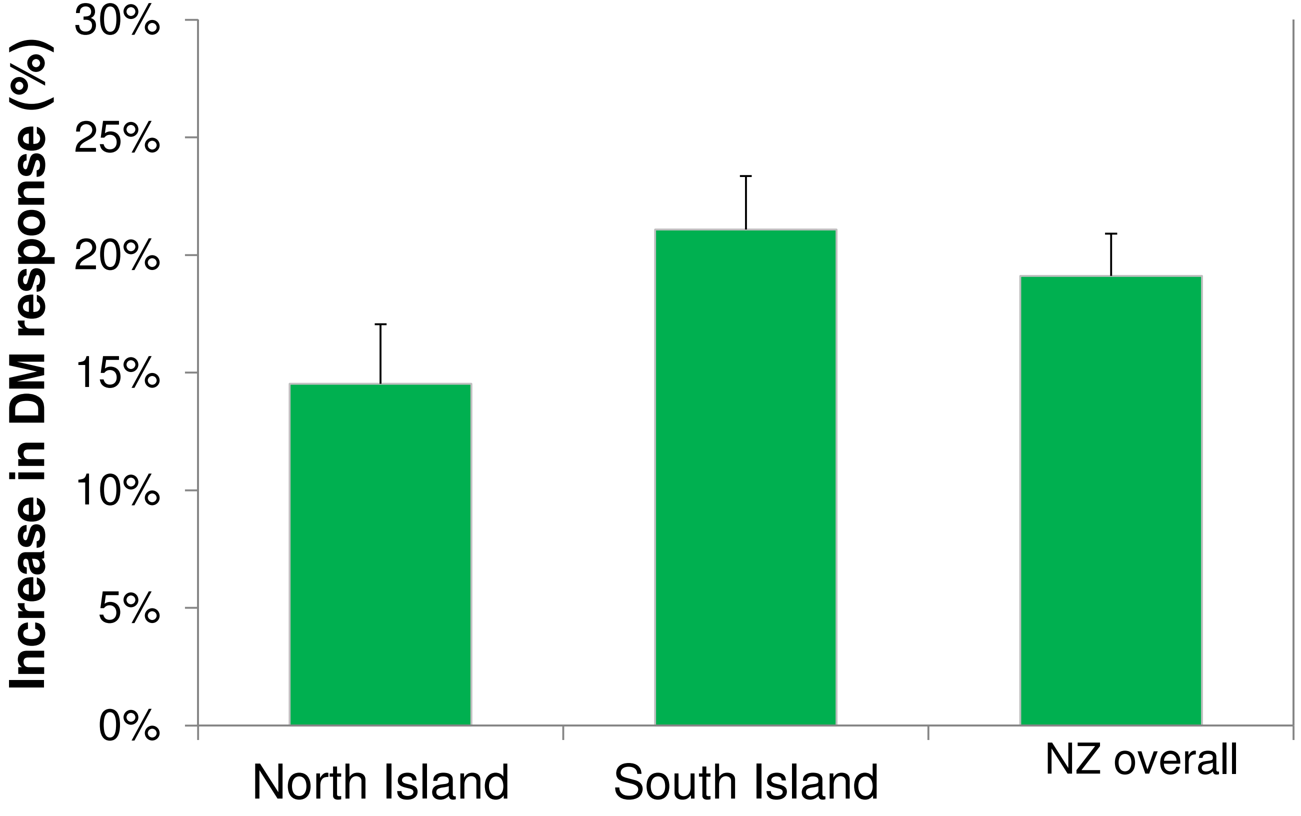


-82% N_2O emissions

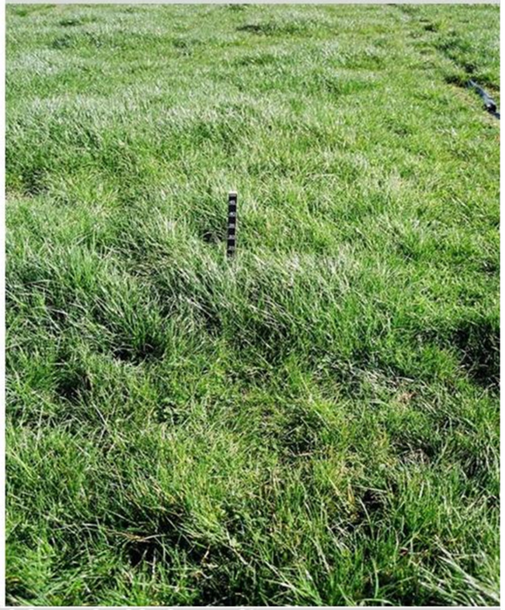
Use of inhibitors or slow release fertilizers

Increased DM production [37 pasture farm trials)

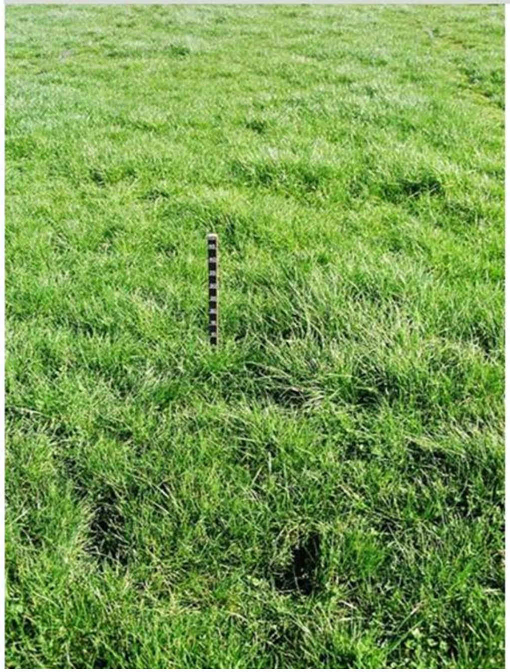
(Carey et al. 2011)



Lincoln University
'eco-n' plot

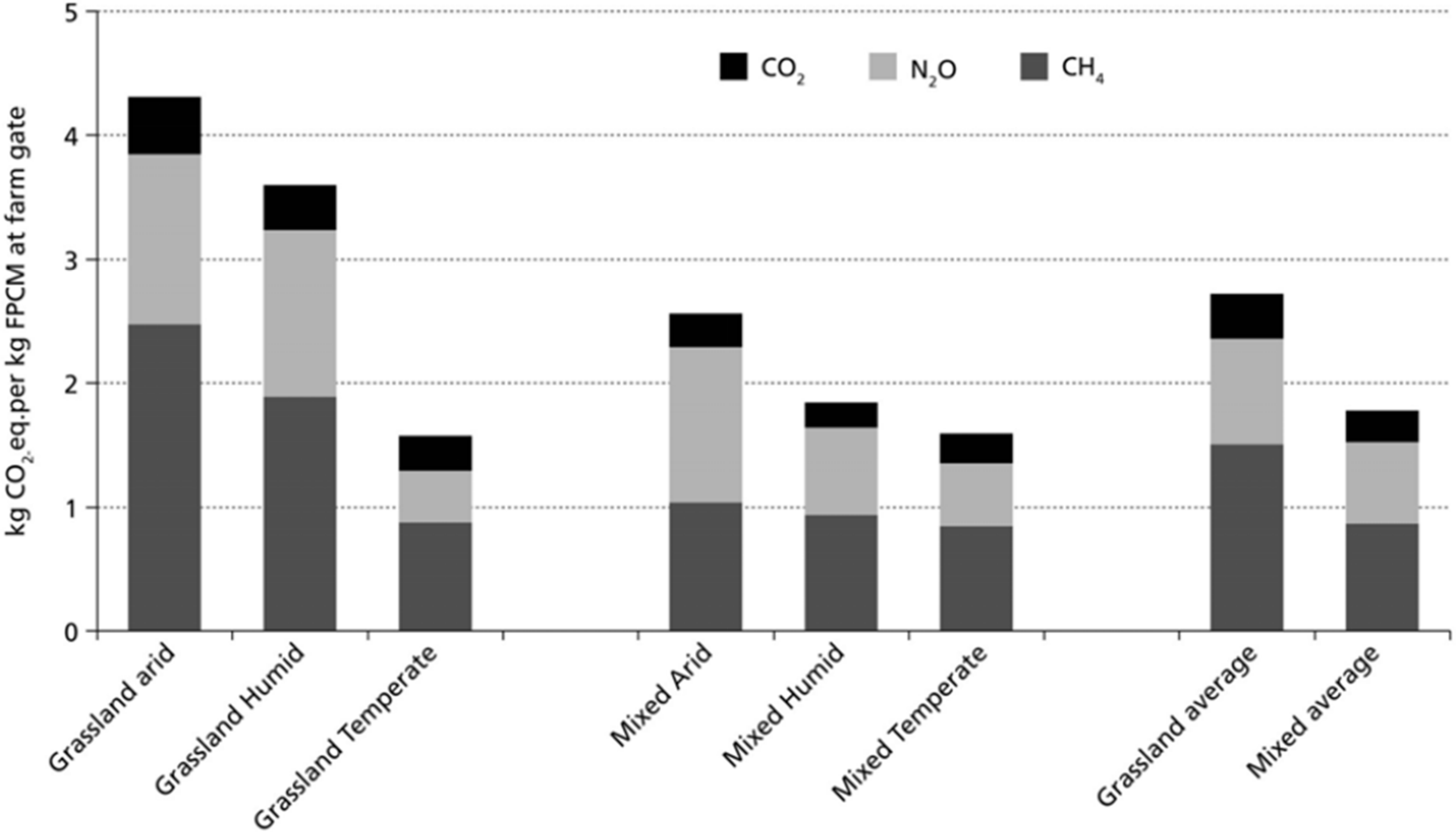


Lincoln University
Control plot: no 'eco-n'



Sustainable agricultural intensification

GHG emissions per kg of Fat and Protein Corrected Milk (FPCM)



FAO 2010 Greenhouse Gas Emissions from the Dairy Sector

(Emissions related to processing and land use change are omitted)