Is Nitrogen the Next Carbon?

William Battye and Viney P. Aneja
North Carolina State University
Raleigh, NC 27695
&
William H. Schlesinger
Duke University
Durham, NC 27708

http://www.meas.ncsu.edu/airquality

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NC STATE UNIVERSITY

In key ways the next 20 years are already determined

The global community will have to contend with a number of significant global grand challenges

Climate change: GHG now in the atmosphere will drive changes up to 2030.

Urbanization: 2010 first year urban population exceeded the rural population,
Will reach ~55% by 2025.

Population increase:
An extra billion people by 2025.

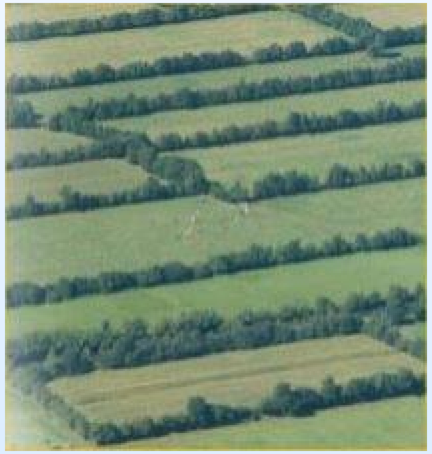
Consumption will increase with prosperity

The consequence of these global challenges will manifest in the environment and global agricultural production

Contents

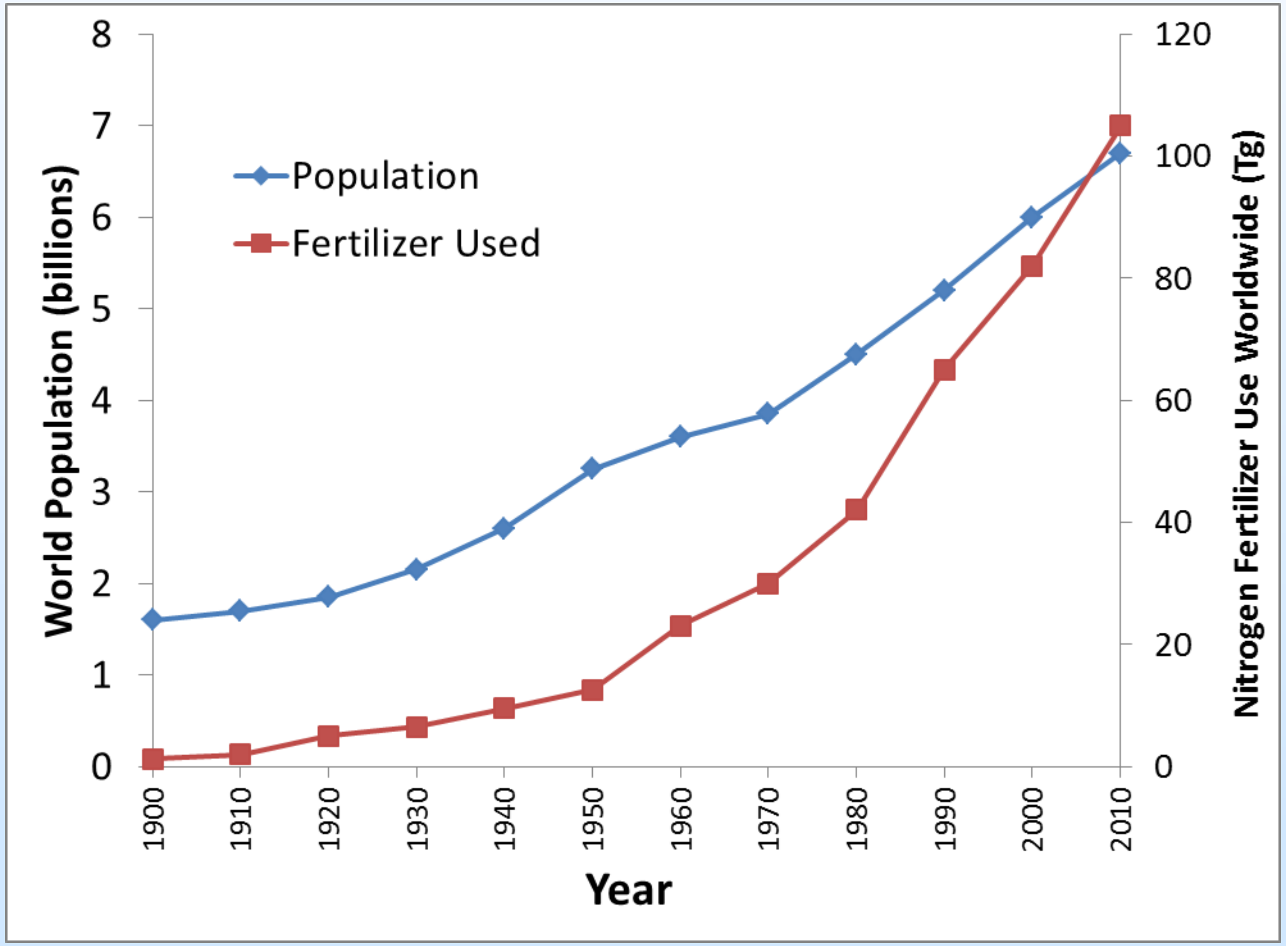
- Background
- Trends in anthropogenic production of reactive N (Nr)
- Comparison with recent estimates of natural Nr fluxes
- Fate and impacts of anthropogenic Nr increment
- Potential mitigation measures
- Conclusions

Intensification of Agriculture





Population increase and use of nitrogen fertilizer (1900 to 2010)



Source: Aneja et al., *Atmospheric Environment*, 2008.
International Fertilizer Industry Association

U.S. Sources of Reactive Nitrogen (Nr)

- **Human Activities introduce ~ five times more Nr into the U.S. environment than natural sources.**
- **The largest anthropogenic sources of Nr are: synthetic fertilizer, nitrogen fixing legumes, and fossil fuel combustion.**

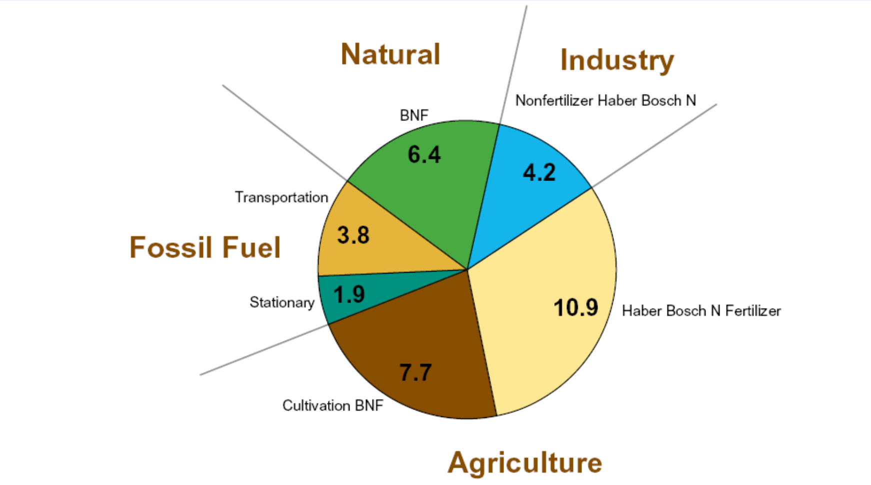
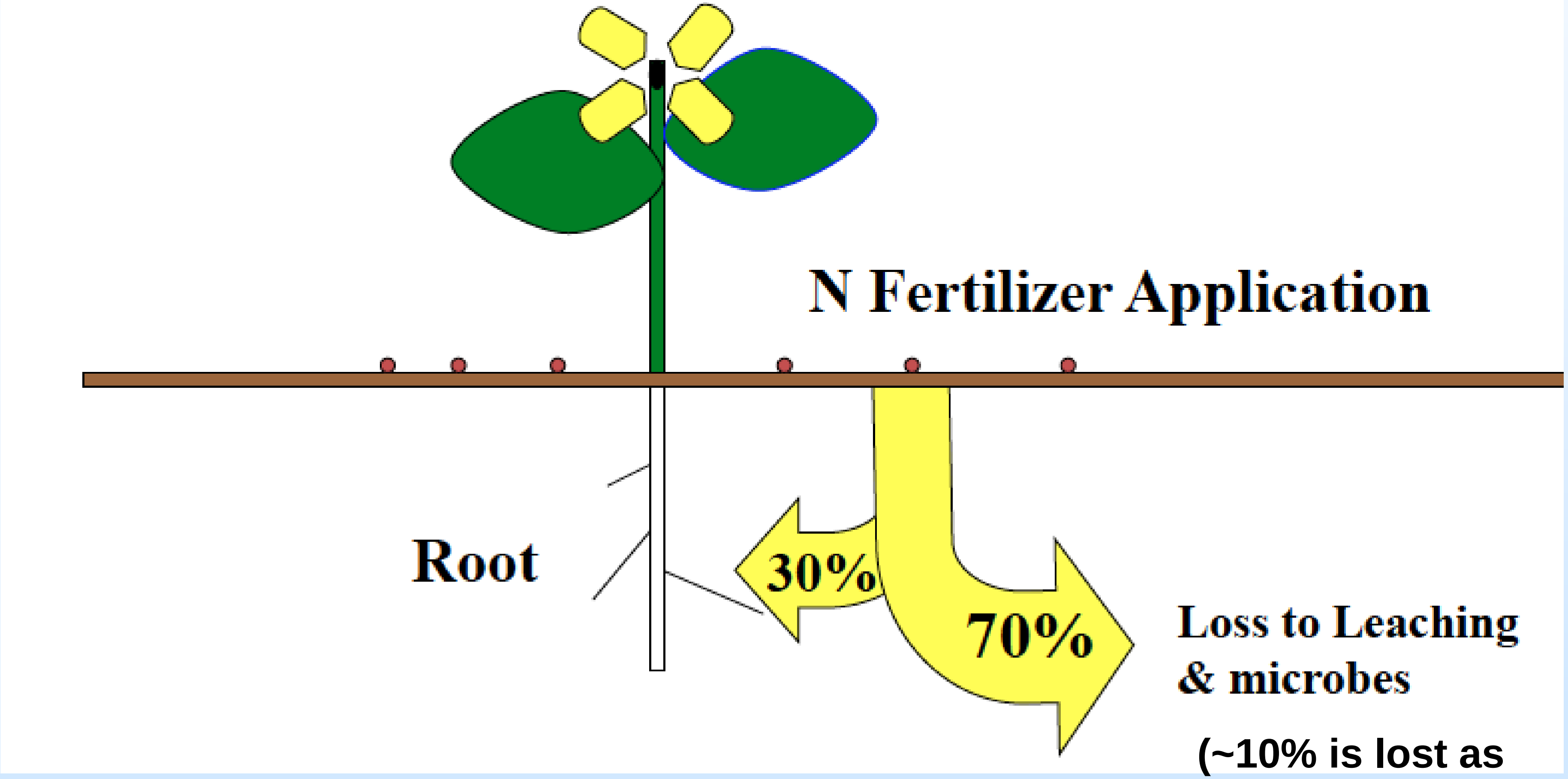


Figure ES-2: Sources of reactive nitrogen (Nr) introduced into the United States in 2002 (Tg N/yr).

Figure ES-2 explanatory notes:
Numerical units: teragram of reactive nitrogen (Nr) per year (Tg N/yr)

Source: EPA-SAB-11-013, 2011.

~ 70% of Nitrogen Fertilizer is Lost

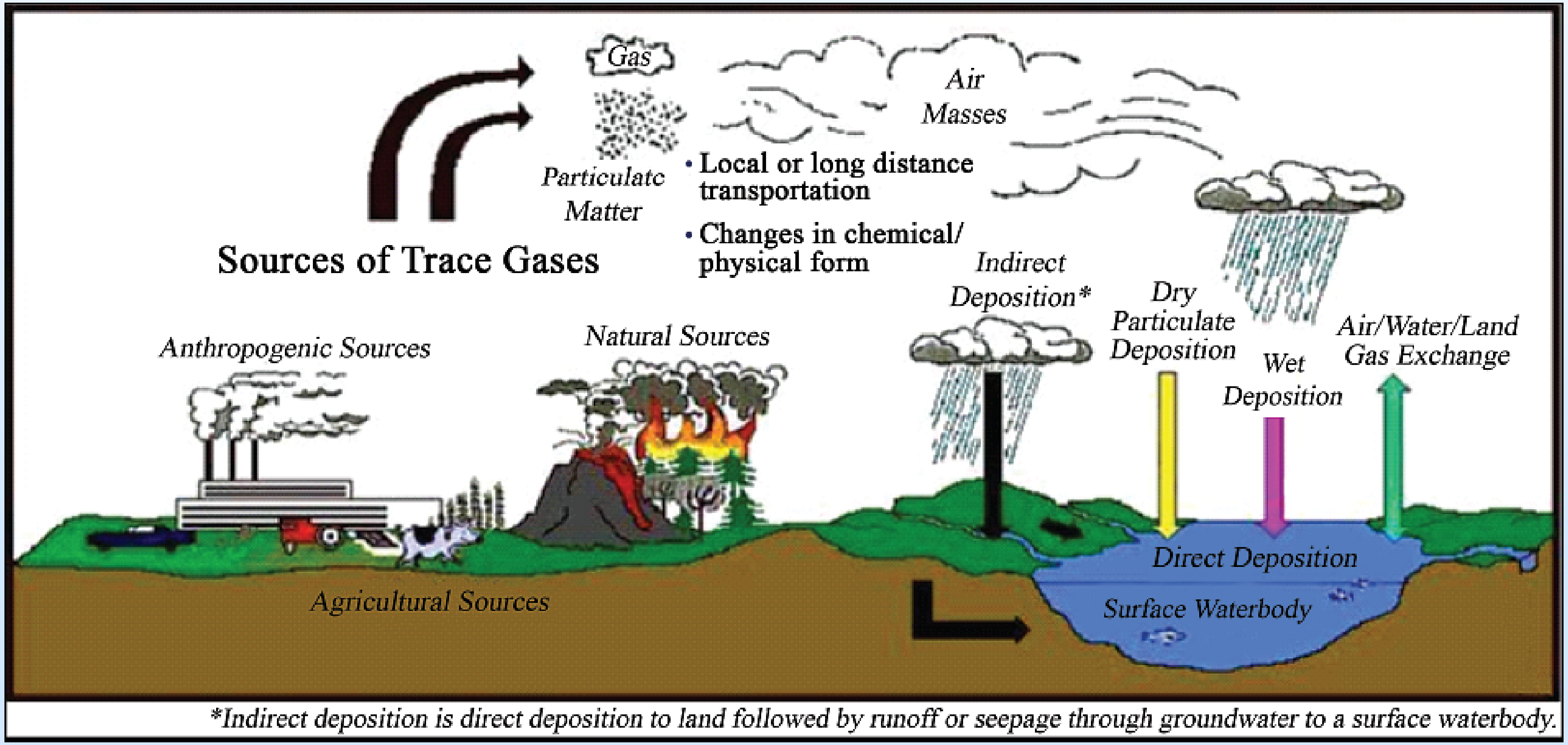


(~10% is lost as ammonia)

(In the production of meat and dairy, ~92% of the reactive nitrogen is lost to the environment)

By capturing more N, yield efficiency can be gained

Emission, Transport, Transformation, and Deposition of Trace Gases

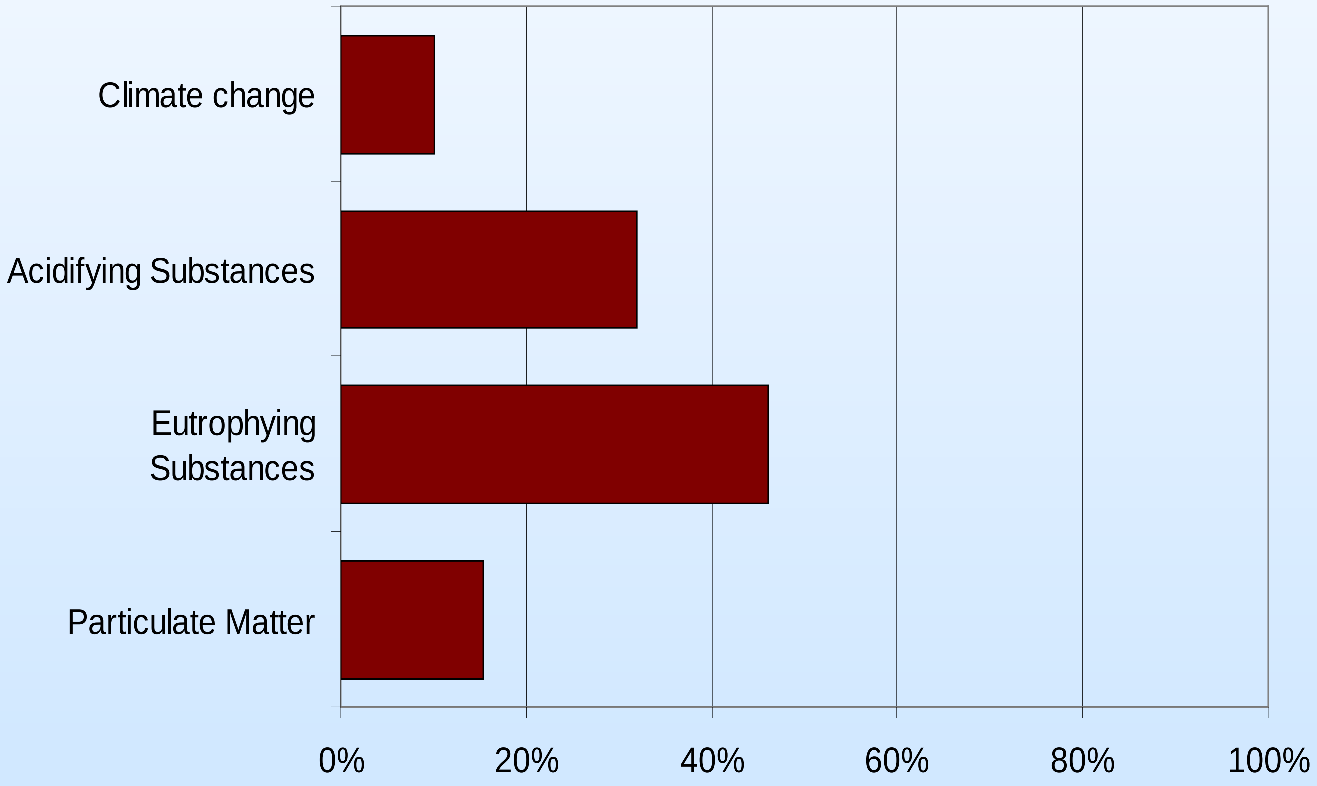


Source: Aneja, Schlesinger and Erisman, *Nature Geoscience*, 2008.

Agriculture, Air Quality and Climate:
Emissions and Issues

Direct:

- NH_3
- NO_y
- *N_2O*
- PM
- *CH_4*
- *CO_2*
- VOCs/HAPs
- SO_2, H_2S
- Odour
- Pesticides



Indirect:

- Secondary PM
- CO_2 sequestration and loss (managed soils)
- Indirect N_2O (N deposition)

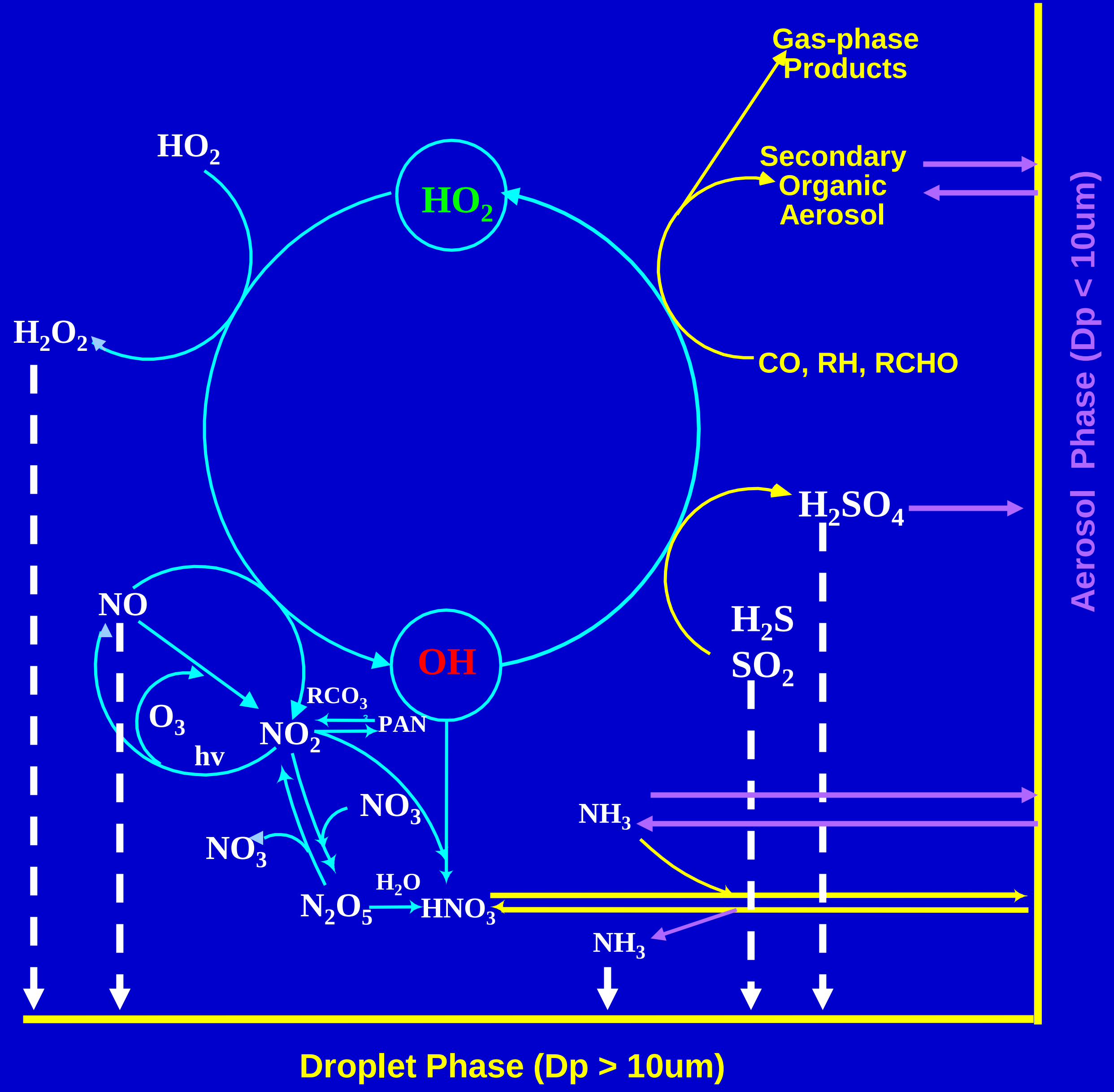
U.S. Agricultural Emissions

(compared with all sources)

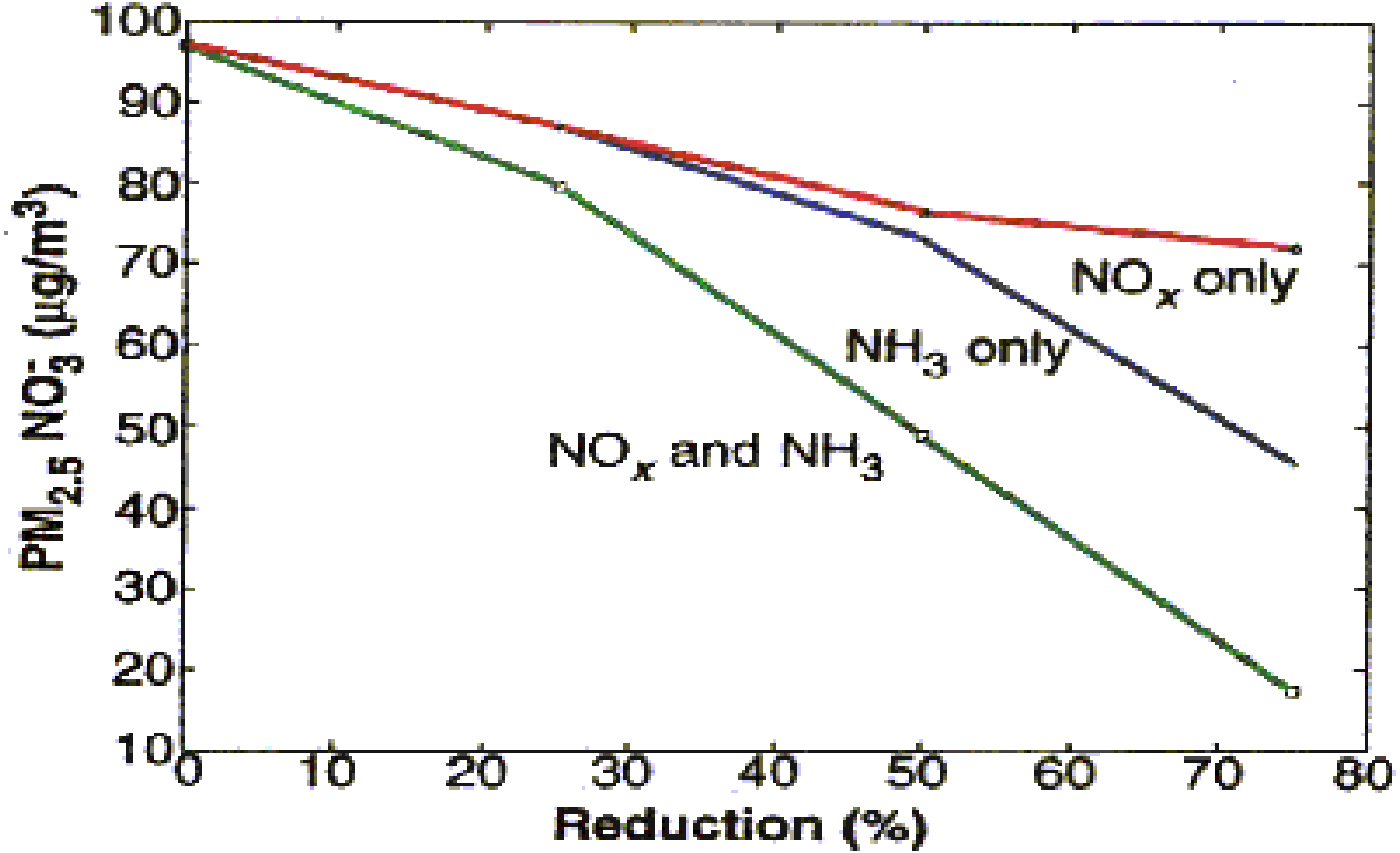
• Ammonia	~ 80%
• Nitrogen Oxides	~ 20%
• Reduced Sulfur	unquantified
• $PM_{2.5}$	~ 16%
• PM_{10}	~ 18%
• VOCs/HAPS	unquantified
• Methane	~ 29%
• Nitrous Oxide	~ 72%
• Odor	unquantified
• Pathogens	unquantified

Source: Aneja, Schlesinger, and Erisman, *ES&T*, 2009.

Gas-To-Particle Conversion Processes



Chemical coupling in the atmospheric gas, particle, and droplet phases
(Source: Meng, Dabdub, and Seinfeld, *Science*, 1997.)



Peak 1-hour average $PM_{2.5}$ nitrate levels achieved at Riverside, California, on 28 August, 1987 as dependent on the degree of emissions reduction from the base conditions of the episode.

(Source: Meng, Dabdub, and Seinfeld, *Science*, 1997)

Introduction

- Industrial fixation of nitrogen plays a central role in the modern agricultural revolution
- The role of reactive nitrogen (i.e. fixed-N) in agriculture is analogous to role of carbon in the industrial revolution
- Almost 50 years ago the human impact on the natural nitrogen cycle was recognized as larger – on a percentage basis – than the impact on the carbon cycle (Delwiche, 1970, *Scientific American*)
- **Since 1960, human-induced production of reactive-N has increased by almost a factor of 5; while C has increased by about a factor of 3.**

Preamble

- **Nitrogen is necessary to sustain all life and is required to sustain agriculture and the global food supply.**

- **Nitrogen emissions from agricultural (both crop and animal) sources have not been categorized well.**

- **Satellite measurements can now provide spatial and temporal global coverage for ammonia.**

Terminology and definitions

Inert
N_2 gas

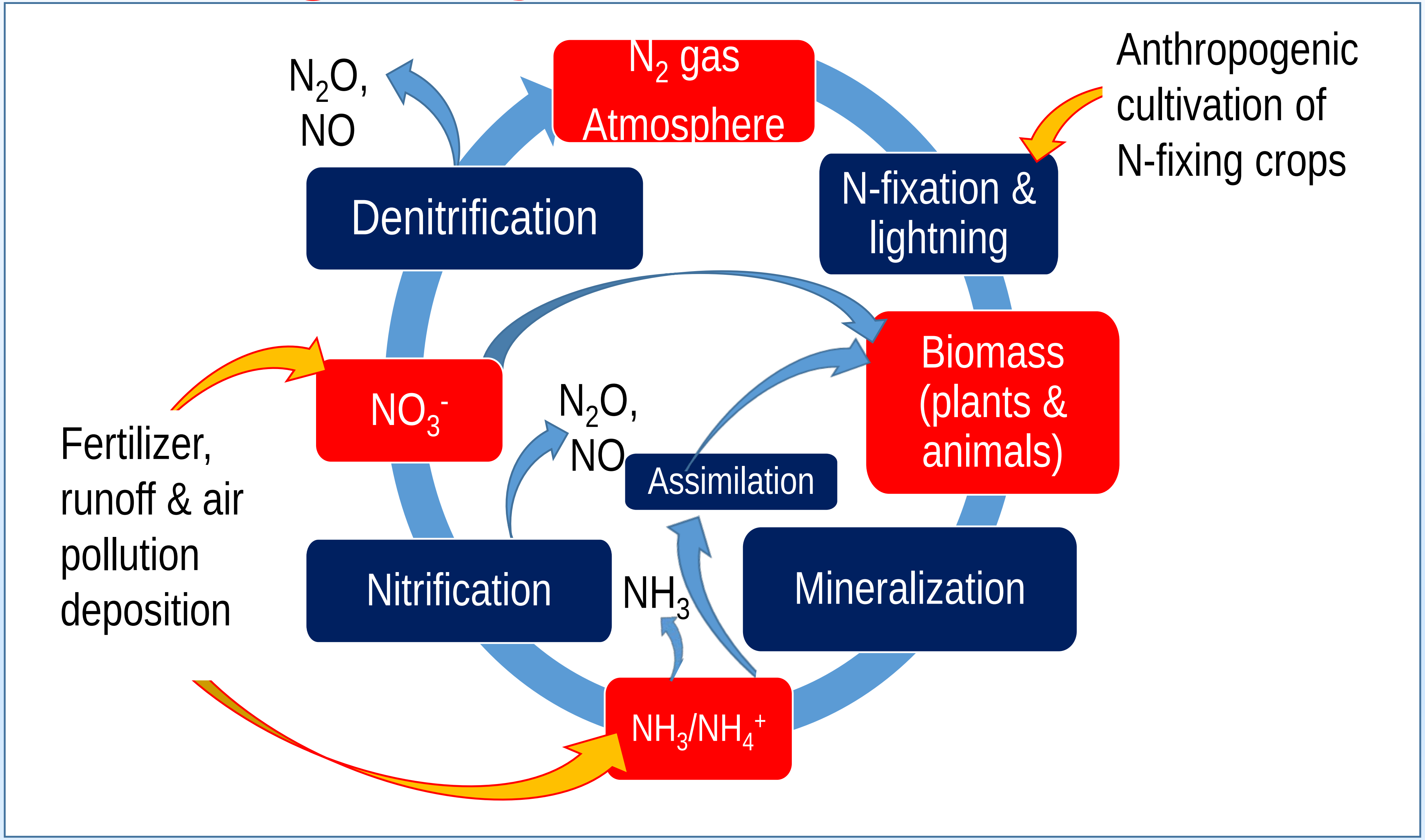
Reactive N includes:

1. Biologically available N compounds
2. Chemically reactive N compounds
3. Radiatively active N compounds

- **Some examples**

1. Important biomolecules containing N: chlorophyll, hemoglobin, all proteins, DNA, …
2. Fertilizers: ammonia (NH_3), ammonium salts (NH_4^+), nitrate salts (NO_3^-), urea [$(NH_4)_2CO$]
3. Nitrous oxide (N_2O) is radiatively active, but chemically and biologically inert

The nitrogen cycle



Milestones – synthetic nitrogen fertilizer

? (before 70 AD)
Nitrogen-bearing wastes used to promote crop growth

1772
Nitrogen identified as a distinct chemical element.

Mid-1800s
Nitrogen identified as a key plant nutrient

Late-1800s
Markets develop for South Pacific guano

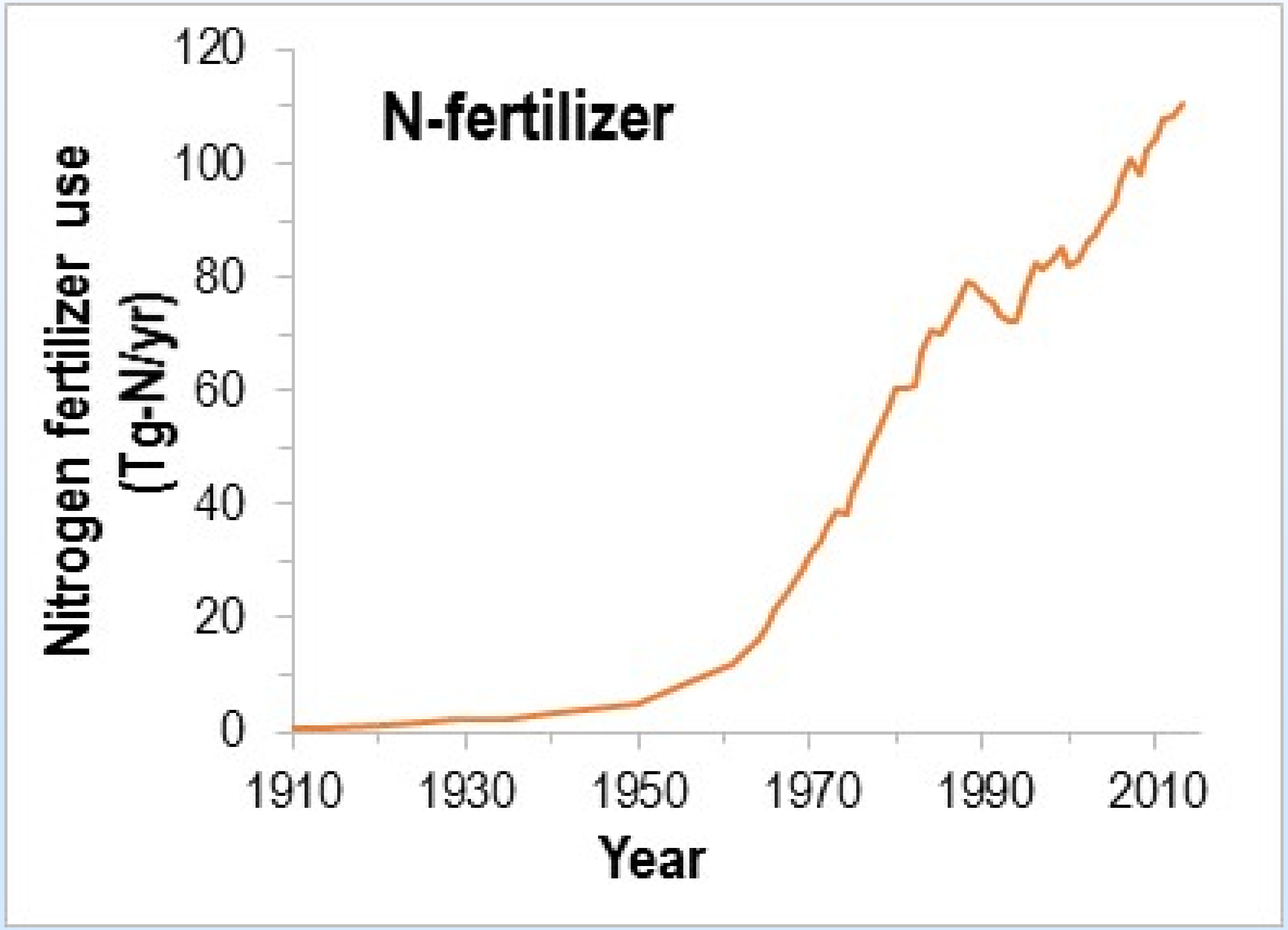
1911
Haber-Bosch process for NH_3

1940s
Fertilizer use becomes routine in the U.S.

1960s
Fertilizer use becomes common worldwide

Timeline

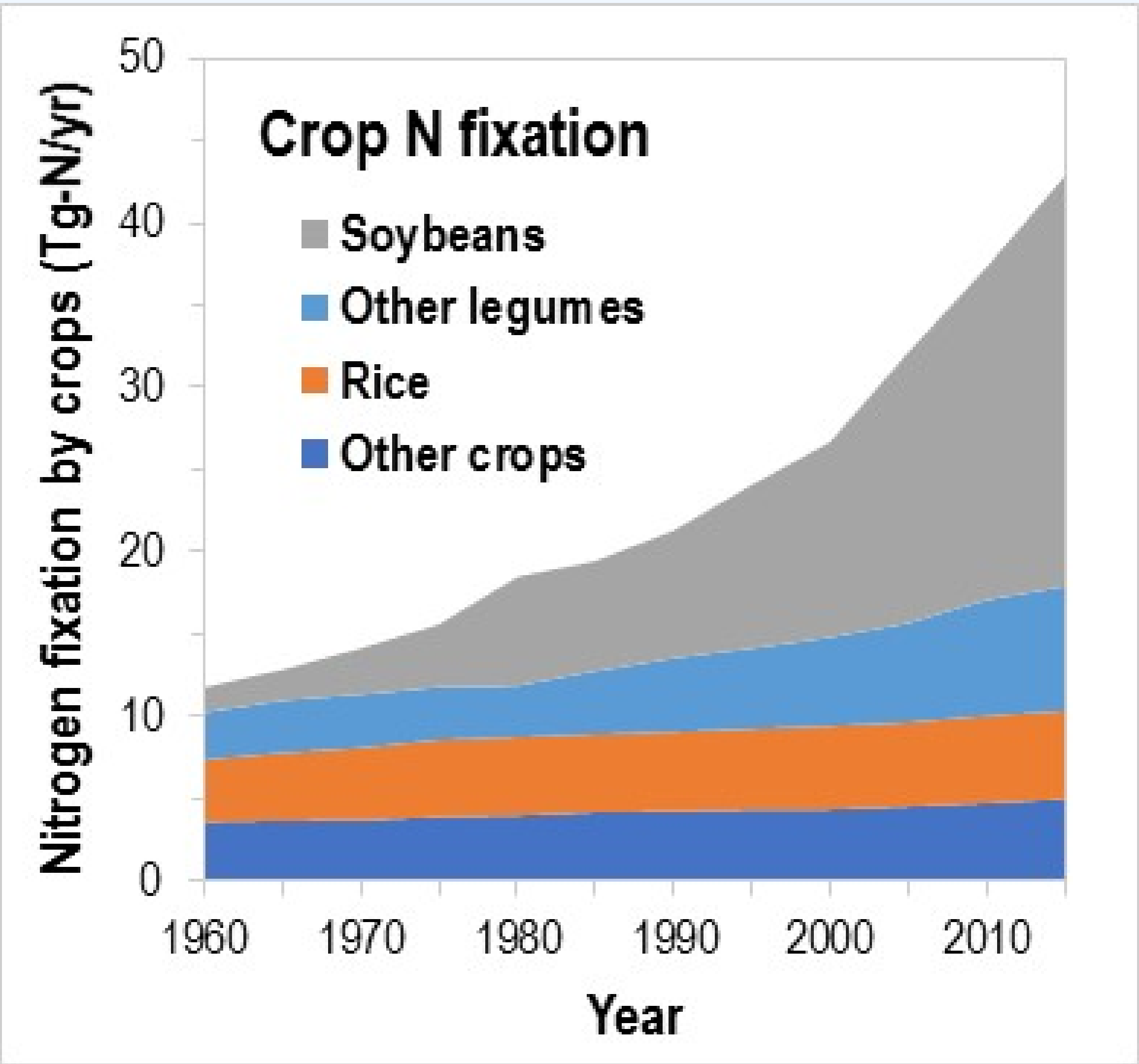
Global Trends – nitrogen fertilizer usage



- **Benchmarks**
  - **1910: ~1 Tg-N**
    (Pacific guano)
  - **1960: ~12 Tg-N**
  - **2013: ~110 Tg-N**
    (synthetic fertilizer)

Sources: Cushman, 2013; International Fertilizer Industry Association, 2016

Global Trends – crop nitrogen fixation



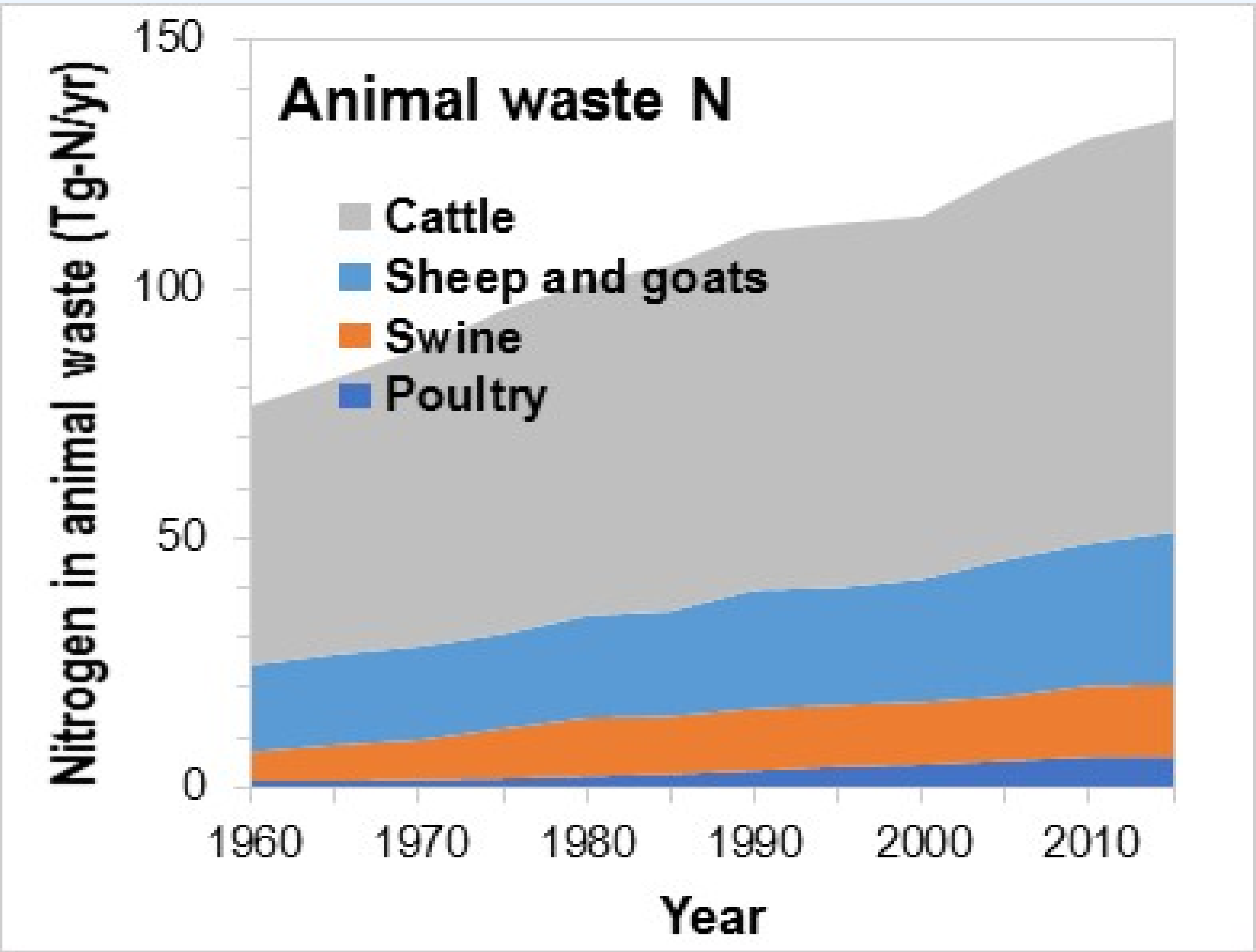
- Breakdown in 2015

Crop	N-fixed (Tg/y)
Soybeans	25
Other beans & legumes	7.5
Rice	5.4
Other	5.0

- Uncertainty: ±20%

Source: Crop trends, FAO; N-fixation rates: Herridge et al, 2008

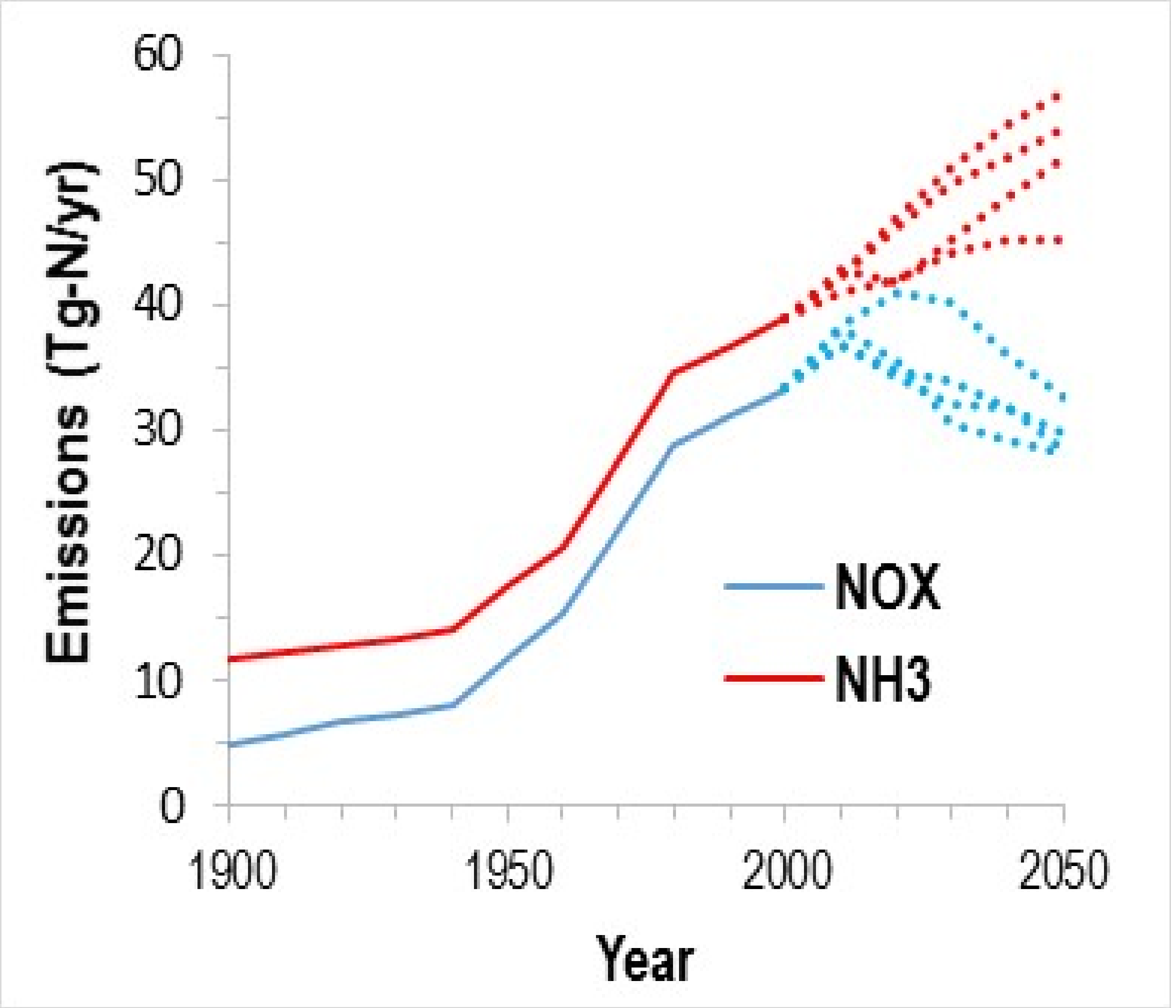
Global Trends – domestic animal waste



- Animal waste does not contribute to new fixed N
- …since it originally derives from plant N
- …but animals concentrate N in their waste, thereby enhancing losses to the environment

Source: Battye, Aneja, and Schlesinger, *Earth's Future*, 2017

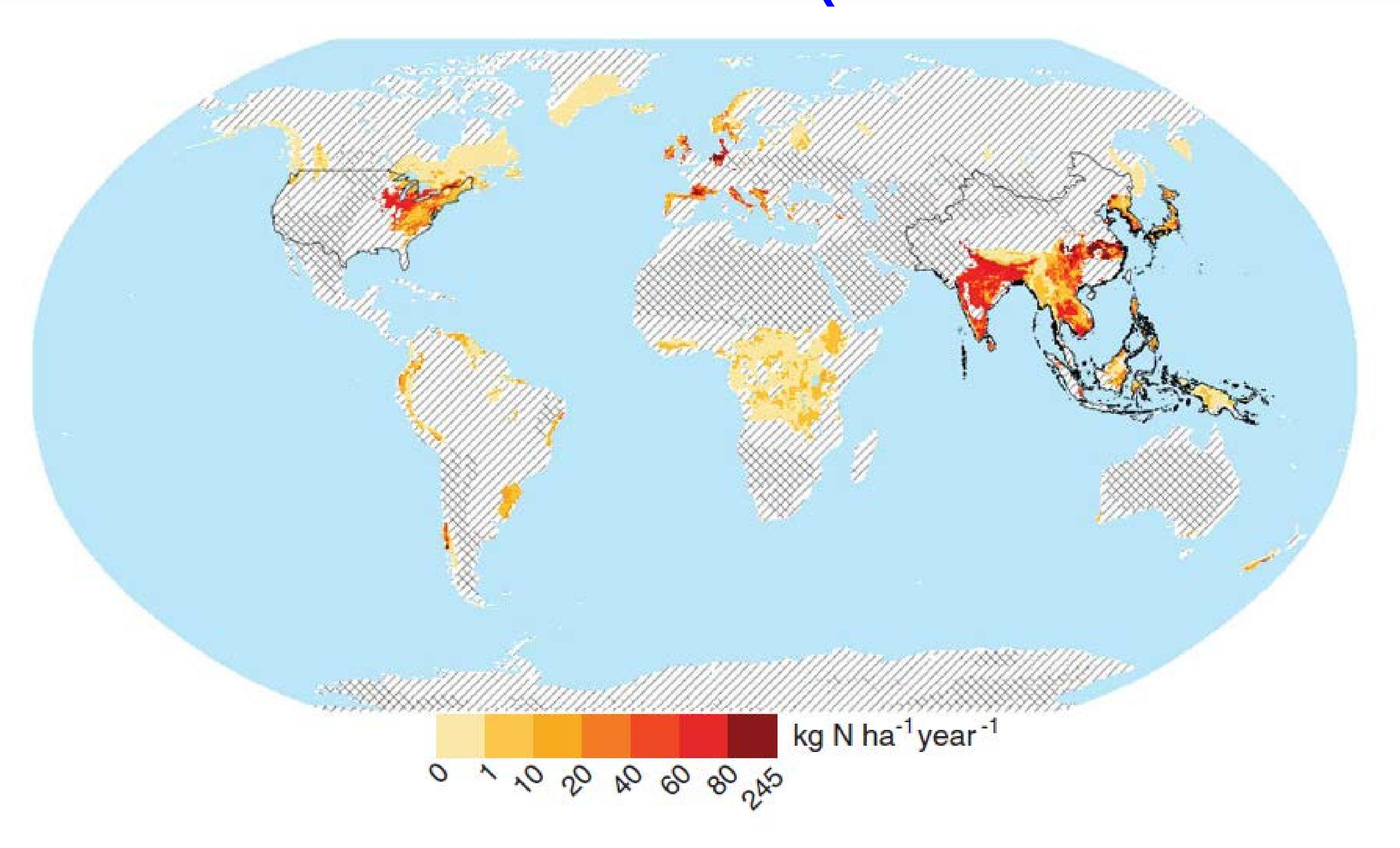
Global Trends – NO_X and NH_3 emissions



- NO_X are believed to be peaking
  - CAAA, 1990; and similar global programs
  - Reduced by fuel switching & post-combustion catalytic controls
- NH_3 emissions from agriculture are projected to continue increasing

Global regions most likely to experience increases in total nitrogen Deposition

(More rain means more pollution)



This map shows 2015 fertilizer application rate for regions with historical (1976–2005) annual precipitation rates above the 75th percentile (averaged over a 30-year period and 21 CMIP5 models) and projected robust increases in annual precipitation by the far future (2071–2100) for the business-as-usual emission scenario

Eutrophication, or excessive nutrient enrichment, threatens water resources across the globe.

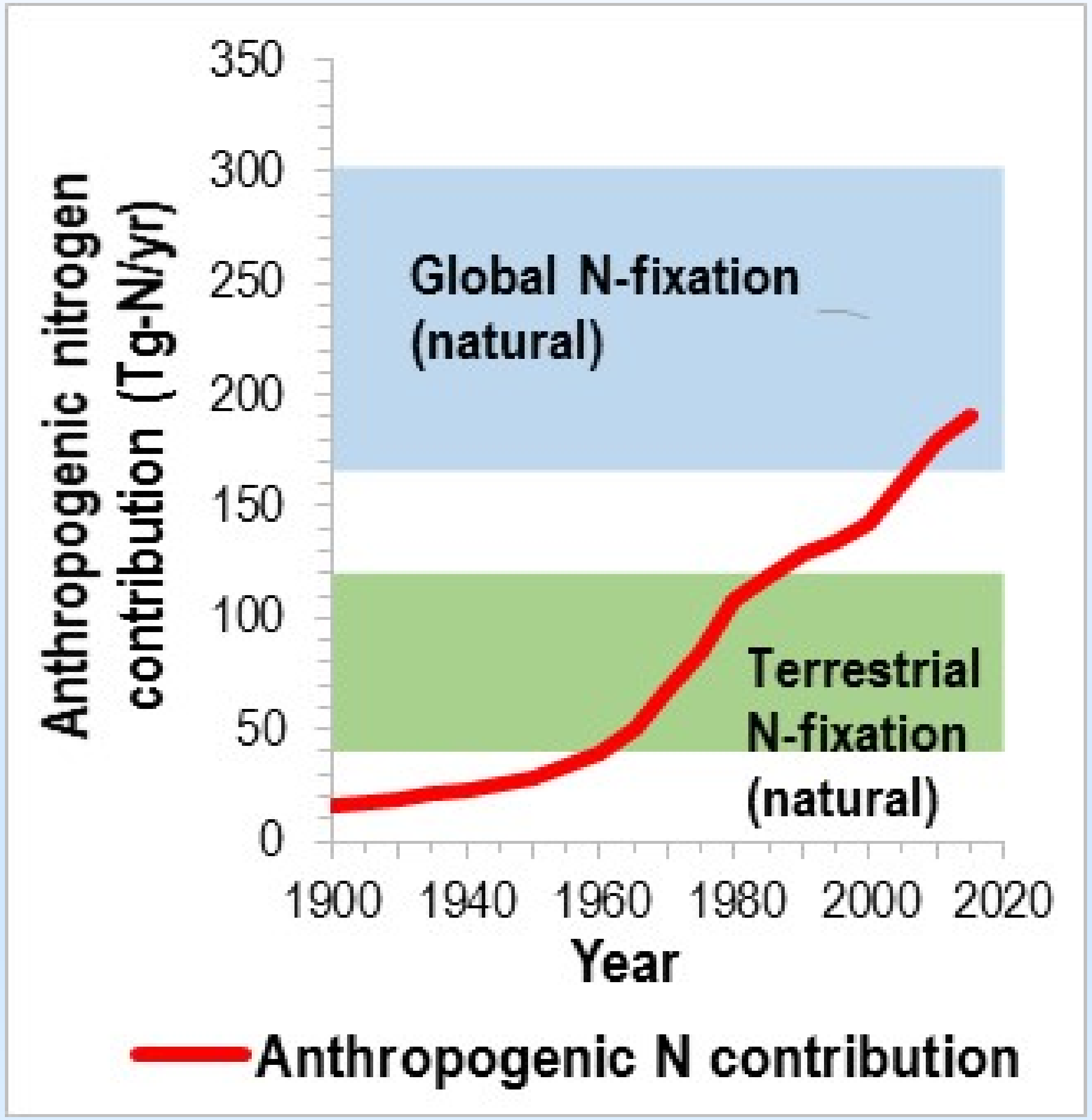
Climate change–induced precipitation changes alone will substantially increase (19 ± 14%) riverine total nitrogen loading within the continental United States by the end of the century for the "business-as-usual" scenario.

Source: Sinha et al., Science 357, 405-408 (2017)

Natural Nitrogen Fixation

- Terrestrial
  - Bottom up sum of ecosystem fluxes: ~120 Tg/y (Galloway et al, 2004)
  - Based on isotope abundances: 40-100 Tg/y (Vitousek et al, 2013)
- Oceans
  - 121-177 Tg/y (Galloway et al, 2004; Groβkopf et al, 2013)
- Total global
  - Best estimate: ~210 Tg/y (Battye, Aneja, and Schlesinger, 2017)
  - Range: 166-300 Tg/y

Anthropogenic trend in relation to natural N fixation



- **Uncertainties**
  - All figures are subject to considerable uncertainty
  - …except the anthropogenic trend, which is based on detailed sales records
- **Impacts**
  - Anthropogenic Nr fixation has well-surpassed the highest estimates for pre-industrial terrestrial ecosystems
  - Anthropogenic reactive-N is on a par with the best estimate of global natural N-fixation i.e. ~210 Tg/y.

Source: Battye, Aneja, and Schlesinger, *Earth's Future*, 2017

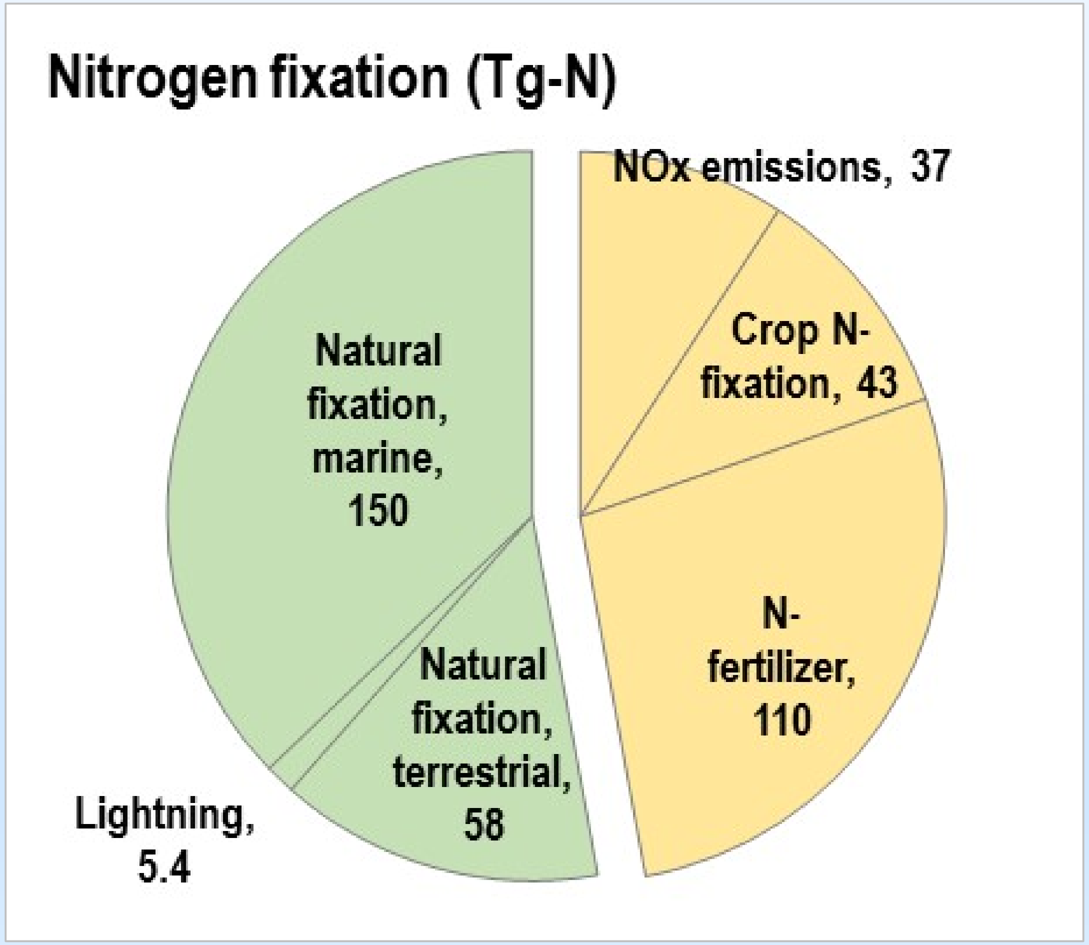
Fate of anthropogenic reactive-N

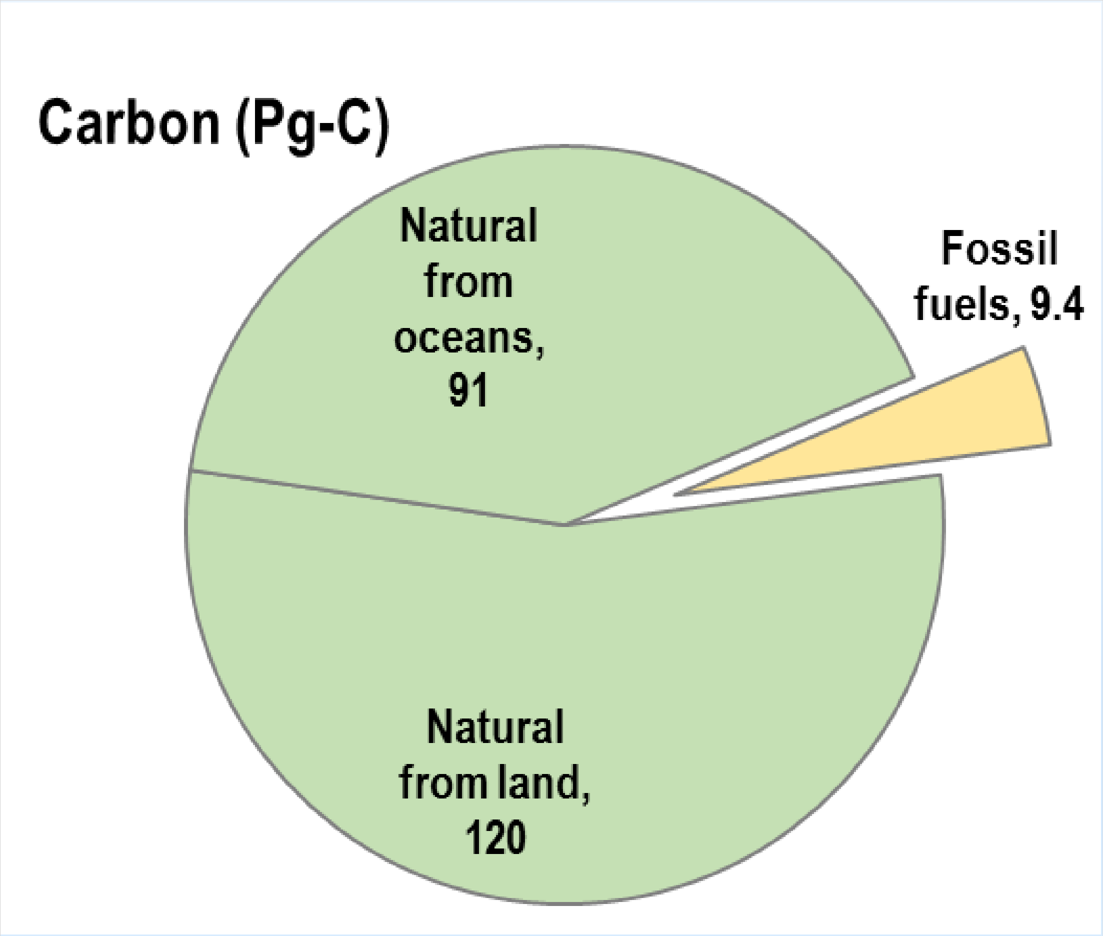
- **In the natural N-cycle, Global N-fixation is balanced by N-denitrification *(Best estimate = 240 Tg-N/yr (Range 166-310))***

- **It appears that the anthropogenic N-fixation is also being balanced by N-denitrification (Battye, Aneja, and Schlesinger, 2017) *(Best estimate = 190 Tg-N/yr (Range 160-210))***

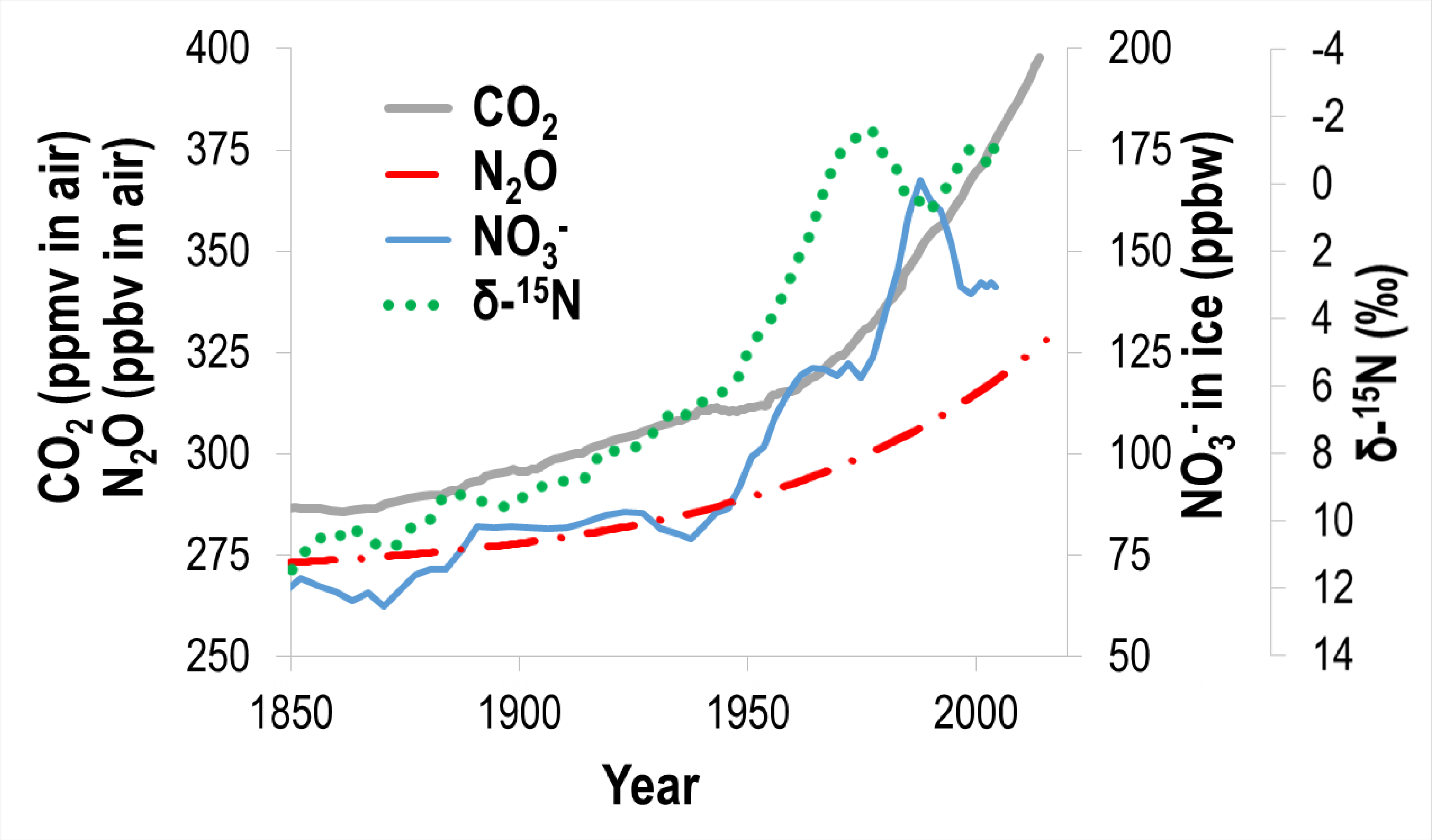
- **It is unlikely that this balance can continue indefinitely with our current trends; with enhanced negative impacts and/or with impacts we have not yet envisioned.**

Anthropogenic share of the N-cycle compared with the anthropogenic share of the C-cycle 2015



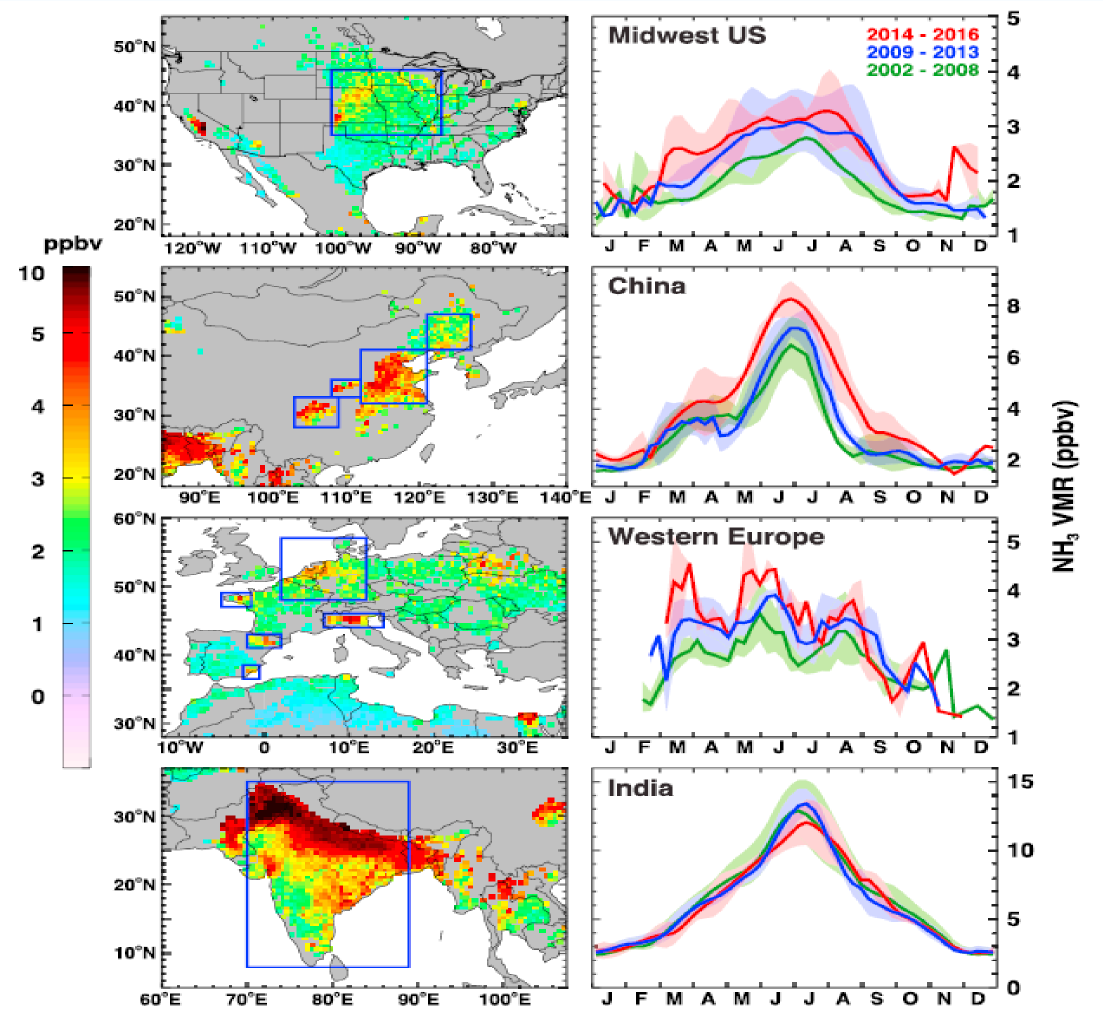


Trends – trends in ice cores



Source: Battye, Aneja, and Schlesinger, *Earth's Future*, 2017

Atmospheric Ammonia Trends Over the World's Major Agricultural Areas Detected From Space



Source: Warner et. al., *GRL* (2017)

(left column):
Regions with intense agricultural activities.
The averaged 14 year NH_3 Volume Mixing Ratios (VMRs) are shown for the
(left column, first panel) American Midwest
(left column, second panel) China
(left column, third panel) EU, and
(left column, fourth panel) South Asia.

The blue boxes outline areas used in the trend studies.

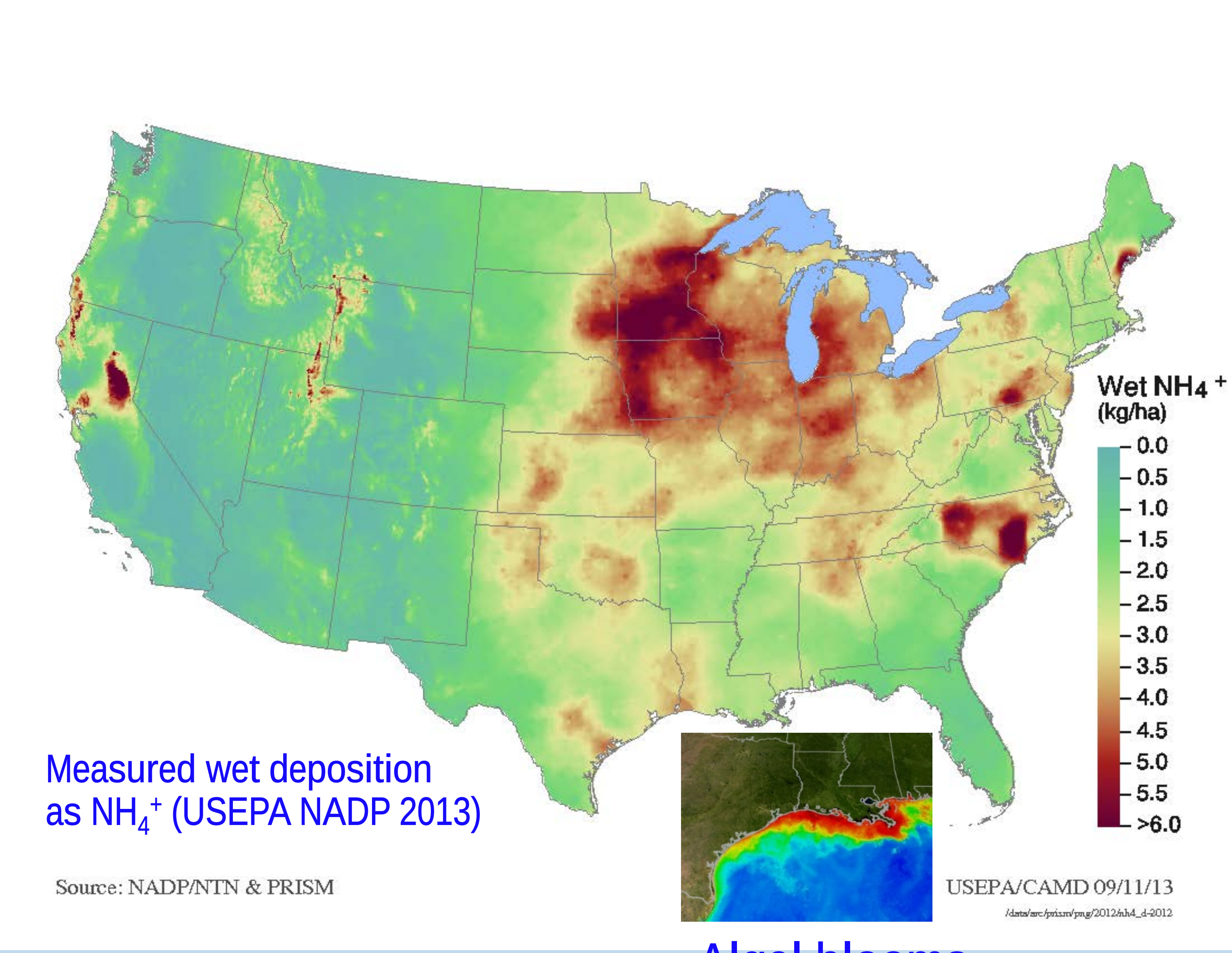
(right column):
The seasonal variability in
(right column, first panel) Midwest U.S.,
(right column, second panel) China,
(right column, third panel) EU, and
(right column, fourth panel) South Asia.

The 7 day means of NH_3 VMRs at 918 hPa are averaged in 2002–2008 (green color), 2009–2013 (blue color), and 2014–2016 (red color) temporal bands, where broad solid lines represent the averages and shaded areas are within 1 sigma standard deviations.

Impacts of anthropogenic N releases – overview

- **Local and regional**
  - Leachate contributes to elevated groundwater nitrate
  - NH_3 and NO_X emissions contribute to elevated levels of fine particulate ($PM_{2.5}$)
  - NO_X emissions contribute to elevated levels of urban ozone – smog (O_3)
  - Runoff and deposition contribute to elevated nutrient levels and soil pollution
  - Elevated nutrient levels contribute to eutrophication and affect species diversity
  - Terrestrial systems denitrify only about half of deposited N, suggesting the possibility of chronic N saturation
- **Global**
  - N_2O is accumulating in the atmosphere (a product of increased denitrification)

NH_3 Impacts – Nitrogen Deposition



Measured wet deposition as NH_4^+ (USEPA NADP 2013)

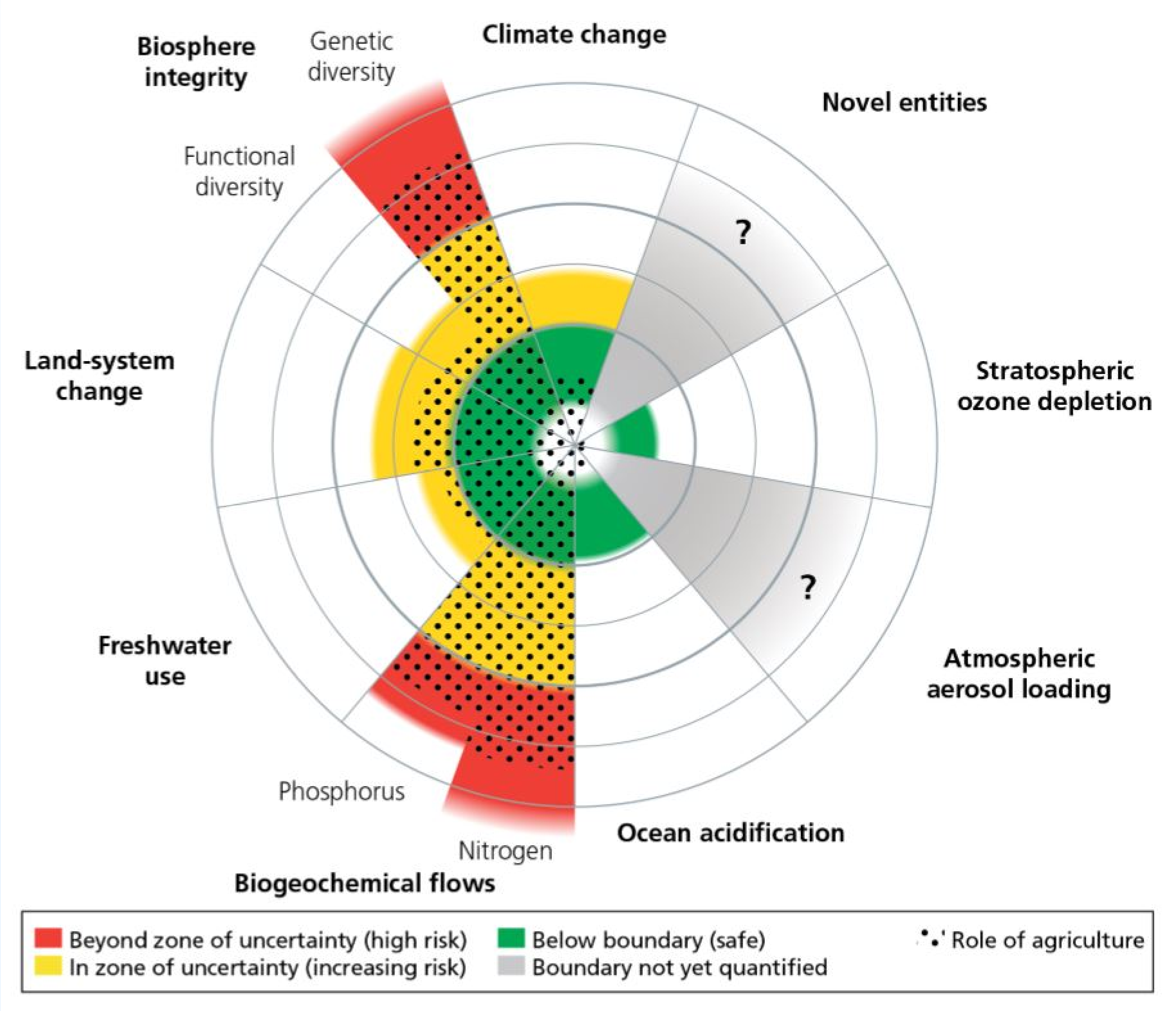
Algal blooms (NASA MODIS)

Planetary boundaries

- Concept to evaluate the limits of human impacts to allow sustainable maintenance and development (Rockstrom et al, 2009)
  - Take into account climate change, stratospheric ozone, atmospheric aerosols, ocean acidification, **N** and P **biogeochemical flows**, freshwater use, land-use change, and biosphere integrity
- Estimates of planetary boundaries for nitrogen (DeVries et al, 2013)
  - Anthropogenic nitrogen fixation: 62 – 82 Tg-N/y
    - (excluding NO_X emissions)
    - based on the risk of eutrophication of terrestrial and aquatic ecosystems (Steffen et al., 2015).
  - Note: though characterized as 'planetary', the boundaries for N pertain primarily to local and regional impacts

Within this construct, the planetary boundary for the anthropogenic contribution to total reactive nitrogen fixation is estimated at 62–82 Tg N y^{-1} (DeVries et al, 2013). This threshold was exceeded in the 1970s, and the current anthropogenic Nr fixation is approximately 153 Tg N y^{-1} (Battye et al., 2017).

Impact of agriculture on planetary boundaries



The impact of agriculture on the planetary boundary exceeds the nitrogen biogeochemical flow.

For the sustainable development of our planet, improvements of agriculture and the overall food system will be a significant step in optimal nitrogen management.

Source: Campbell, et al, Ecology and Society 22(4): 8, 2017

Potential mitigation measures

- **Agricultural sources**
  - Nitrogen-use efficiency has increased in the developed world
    - Nitrogen fertilizer usage has leveled off while agricultural production continues to increase
    - This suggests that increases in nitrogen-use efficiency may abate the worldwide increase
  - Best management practices and engineering solutions can reduce releases from both fertilizer and animal waste
- **Combustion sources**
  - NO_X emissions have been reduced without preventing economic growth
  - Renewable energy sources produce less NO_X (or no NO_X)
  - Natural gas produces less NO_X than coal
  - Energy conservation measures reduce NO_X emissions

Policy status

- **Generally**
  - Approaches are piecemeal and no integrated strategy to control Nr
  - Some regulatory and voluntary measures have been adopted
- **Agricultural sources**
  - NH_3 emissions are regulated in Europe
  - Surface water discharges are regulated in the U.S.
- **Combustion sources**
  - NO_X emissions are broadly regulated in developed nations
    - To control urban smog formation
    - To control acid precipitation
  - Measures to limit CO_2 generally have a co-benefit of reducing NO_X
- **No integrated regulatory approach for the control of reactive N**

Example – policy for ammonia (NH_3) in the U.S.

- NH_3 contributes to the formation of $PM_{2.5}$
- U.S. states can regulate NH_3 as part of their approaches to meeting $PM_{2.5}$ national ambient air quality standards (NAAQS)
- However, the U.S. has not adopted a national program for NH_3 emissions
- NH_3 is the largest volume air pollutant with **no** national or regional control programs
- No reporting requirements for fertilizer usage, animal waste handling, or control measures
- Wet deposition of NH_4^+ has increased by ~22% in the last 20 years (Li et al, 2016)

Returning to the question
(Is nitrogen the next carbon?)

- **There are obvious similarities**
  - Both C and reactive-N have produced tremendous societal benefits
  - Both have grown exponentially over the last century
  - We are dependent on both
  - In both cases, impacts become more difficult to rectify as time passes

More subtle similarities between N and C

- **Impacts of climate change are difficult to perceive at the human level**
  - Warming due to CO_2 was predicted in 1896 (Arrhenius)
  - But impacts occur on a long time scale superimposed on a background of short-term variability
  - Consequently, 30 year international program of measurement and modeling (IPCC) has been needed to evaluate the impacts of increasing CO_2
- **Reactive nitrogen**
  - Some impacts, notably species diversity impacts, are difficult to evaluate
  - Monitoring of these changes may not be adequate to fully appreciate the impacts

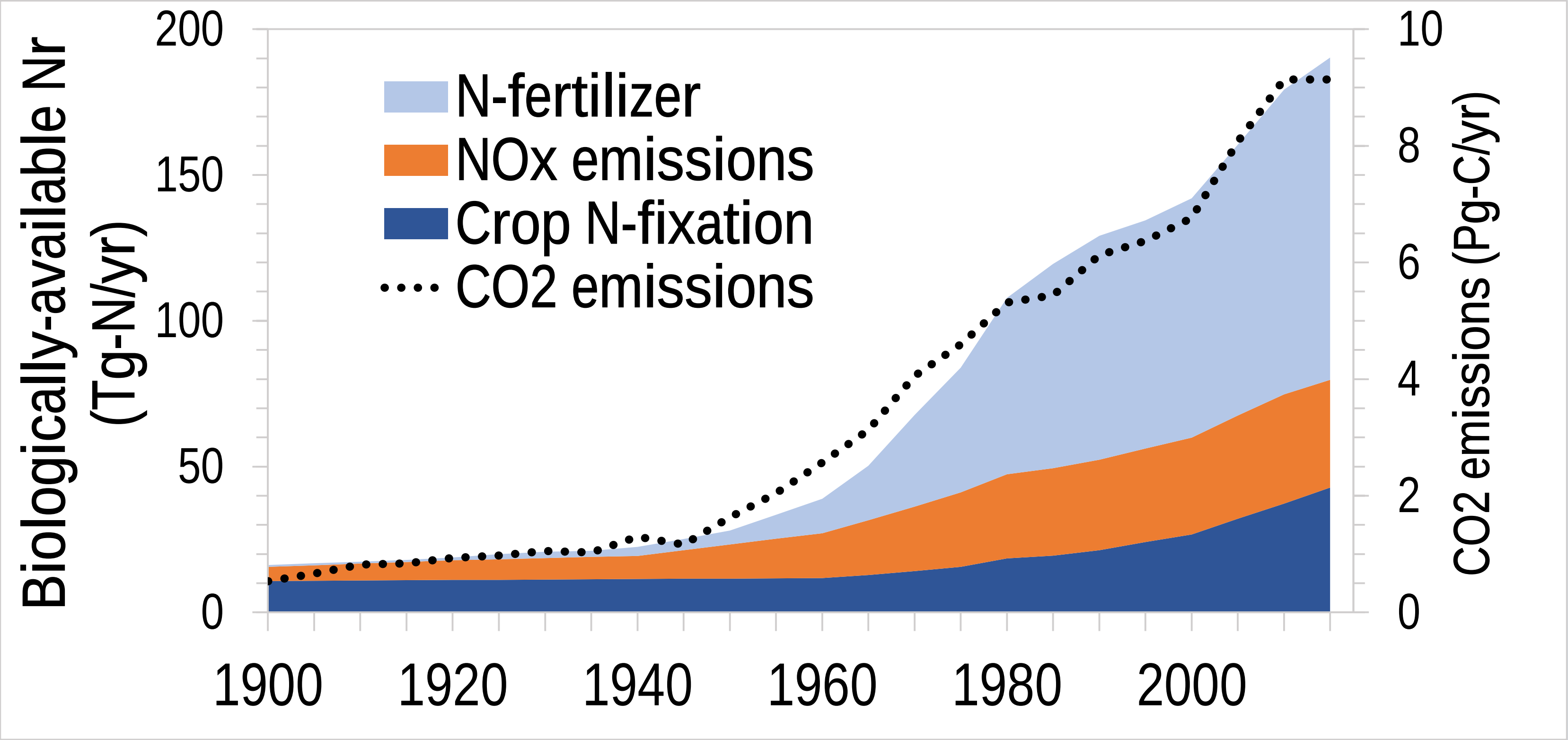
Is Nitrogen the Next Carbon?

- Nitrogen is necessary to sustain all life and is required to sustain agriculture and the global food supply.
- Like the industrial revolution, the modern agricultural revolution has produced great improvements in living standards
- Since 1960, the amount of nitrogen (N) used in agriculture has doubled on the planet, as has food production.
- Human Activities introduce five times more reactive nitrogen (Nr) into the U.S. environment than natural sources.
- The largest anthropogenic sources of Nr are: synthetic fertilizer, nitrogen fixing legumes, and fossil fuel combustion.
- Like CO2 and other combustion products, reactive-N species also produce environmental impacts at local, regional, and global scales
- The difficulties of altering our carbon-trajectory have become more and more apparent
- Similarly, it will be difficult to alter our nitrogen-trajectory
- This leads us to ask the question:

Is nitrogen the next carbon?

Is Nitrogen the Next Carbon?

Trend in Anthropogenic Reactive Nitrogen Compared with Carbon



Source: Battye, Aneja, and Schlesinger, 2017.

Is Nitrogen the Next Carbon?

Some Important Problems

- The nitrogen cascade amplifies reactive nitrogen (N_r) effects through both time and space,
- Reactive nitrogen is a significant driver of biodiversity loss,
- Excess nitrate in drinking water has negative effects on human health,
- Over the long term, reactive nitrogen will have a net global warming effect.

Potential Solutions

- Increasing nitrogen use efficiency in agriculture,
- Engineered solutions and BMPs are available to optimize reactive nitrogen (Nr) use and change the way we humans interact with the nitrogen cascade.
- Reducing waste in the food chain,
- Promoting diets with less animal protein in developed countries, and
- A shift from fossil fuels to renewable energy sources such as solar and wind energy.

Conclusions:
Is Nitrogen the next Carbon?

- **It depends….**
  - Can the growth in anthropogenic reactive N be abated?
  - Can denitrification continue to offset increased anthropogenic inputs?
  - How disruptive are the impacts of increased reactive N on species diversity?
  - Will increased denitrification result in an accelerated accumulation of N_2O, and thus impact climate change?
- **Is nitrogen the next carbon?** is a thought provoking question

Mitigating nitrogen is a grand challenge

Acknowledgements

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IS NITROGEN THE NEXT CARBON?