FIXED ON NITROGEN

CASA Science Symposium on Nitrogen
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Fairmont Chateau Lake Louise
Lake Louise, Alberta

Abstract

Nitrogen and Climate Change
Dr. Chris Evans

Since the 19th century, CO_2 from fossil fuel burning has been accumulating in the atmosphere, and is the major driver of anthropogenic climate change. Over a similar period, the production of man-made 'reactive nitrogen' has also increased hugely, potentially also influencing global climate. However the transportation, cycling and accumulation of reactive N in the atmosphere, terrestrial and aquatic ecosystems (the 'nitrogen cascade') is complex, and as a result N may impact on climate in a number of ways, some negative and some positive. In soils, particularly oxygen-poor areas such as wetlands, a proportion of N deposited from the atmosphere may be re-released as nitrous oxide, a greenhouse gas 296 times more powerful than CO_2. On the other hand, because nitrogen is the limiting nutrient for growth in most terrestrial ecosystems, adding moderate amounts of man-made N to these systems can lead to an increase in productivity, potentially sequestering CO_2 from the atmosphere into plant and soil organic matter. In addition, higher CO_2 in the atmosphere may itself lead to increased plant growth, but this can only occur where sufficient nitrogen is present. Finally, nitrogen oxides are a key precursor for ozone formation, and due to the detrimental effects of ozone on plant growth, this could act to reduce or even negate any beneficial effects of elevated N and CO_2. Overall, therefore, the complexity of the nitrogen cycle is such that it is difficult to categorise the influence of nitrogen on climate as either 'good' or 'bad'. In reality nitrogen may well be 'good' (in terms of climate change) for some ecosystems, but 'bad' for others, and much work is required to quantify its overall role.

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~~Nitrogen as a Contributor to Climate Change~~

Nitrogen and Climate Change

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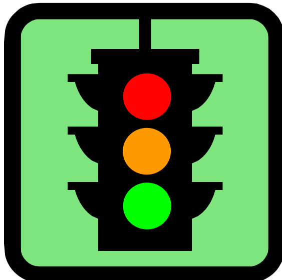
Ute Skiba, Wim de Vries and Sally Power

Nitrogen and climate change

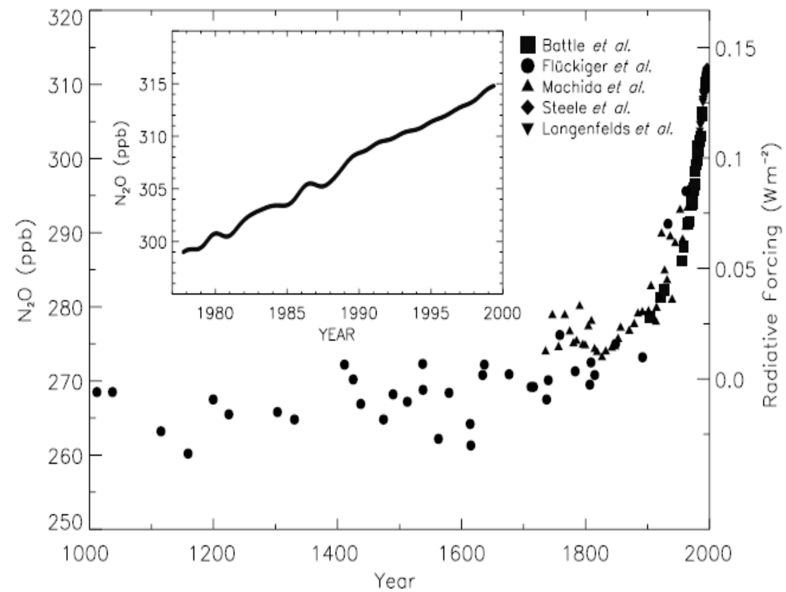
- Reactive N gets everywhere (the ‘N cascade’)
- As a result, the impact of N emissions on climate change are complex and involve:
  - One greenhouse gas that contains nitrogen (N_2O)
  - Three greenhouse gases that don’t contain nitrogen (CO_2, CH_4 and O_3)
  - Three gases that contain nitrogen but aren’t greenhouse gases (NO, NO_2 and NH_3)
- Some bits of this I know more about than others, so…



Nitrous Oxide

- N_2O is (with CO_2 and CH_4) one of the three main Greenhouse gases (GHGs)
- It has a long lifetime (~120 years) and a high global warming potential (296x CO_2 over 100 yrs)
- Fairly high background emissions (10.7 Tg N/yr)
- Anthropogenic source around 5.7 Tg N/yr)

1000 ice-core record and 20-year observed atmospheric N_2O



IPCC (2001)

Nitrous Oxide

- Direct anthropogenic emissions (e.g. nitric acid production, nylon production, fossil fuel burning) are relatively small
- Indirect anthropogenic emissions are larger, and occur due to N-enrichment of agricultural and natural ecosystems
- IPCC 2001: "*enhanced N_2O emissions from agricultural and natural ecosystems are believed to be caused by increasing soil N availability driven by increased fertilizer use, agricultural nitrogen (N_2) fixation, and N deposition*"

Nitrous Oxide

- N_2O produced by nitrification (in oxygen-limited conditions) and denitrificiation (in anaerobic conditions)
- Production rates controlled by supply of mineral N, labile C (for denitrification), temperature and moisture
- Mineral N supplied by:
  - Fertilisation (agricultural systems)
  - N deposition (semi-natural systems)
  - Disturbances (e.g. felling, burning)
  - Climatic fluctuations (e.g. freeze/thaw, dry/wet)

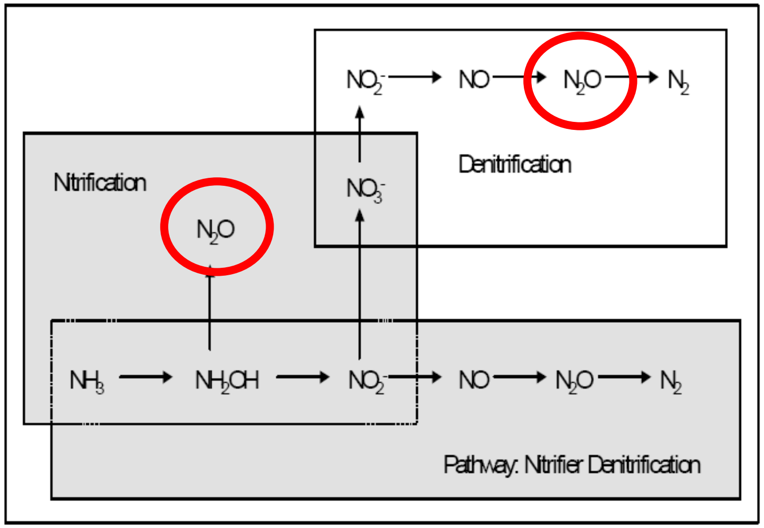
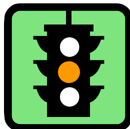


Figure 2 N_2O production by nitrifiers and denitrifiers (Wrage et al., 2001).



Nitrous Oxide

How much N_2O is emitted due to N inputs?

- IPCC:
  - 1.25% of N fertiliser
  - 1% of N deposition
- PnET-DNDC model, M. Kesik et al. (2005)
  - 1.8% of N deposition
- Field measurements, de Vries et al. (in press)
  - 1.4% of N deposition onto coniferous forests
  - 5.4% of N deposition onto deciduous forests
- Overall, de Vries et al. estimate that N_2O emissions from European forests have risen by 12-33% since 1960 due to N deposition

Nitrogen oxides

- NO and NO_2 (aka NO_x) are not GHGs
- However, the impact of NOx on atmospheric chemistry is complex, and it has important secondary impacts
- NO_x emissions (from fossil fuel burning, etc) are either stable (Europe, N America) or rising (Asia)

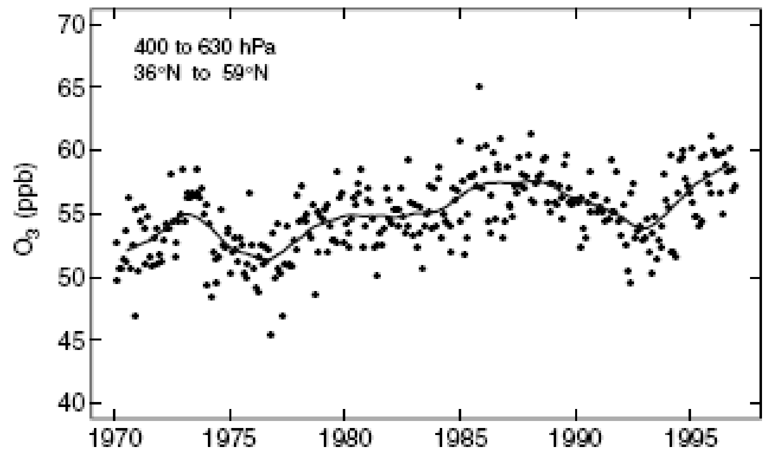
Nitrogen oxides and tropospheric ozone

It's complicated….

Nitrogen oxides (NO and NO_2) catalyse the formation of tropospheric ozone:

$$
\begin{array}{llll}
 & OH + CO + O_2 & \rightarrow & CO_2 + HO_2 \\
 & HO_2 + NO & \rightarrow & NO_2 + OH \\
 & NO_2 + h\nu & \rightarrow & NO + O(^3P) \\
 & O(^3P) + O_2 + M & \rightarrow & O_3 + M \\
 & & & \\
\text{net:} & CO + 2O_2 + h\nu & \rightarrow & CO_2 + O_3
\end{array}
$$

It's increasing….



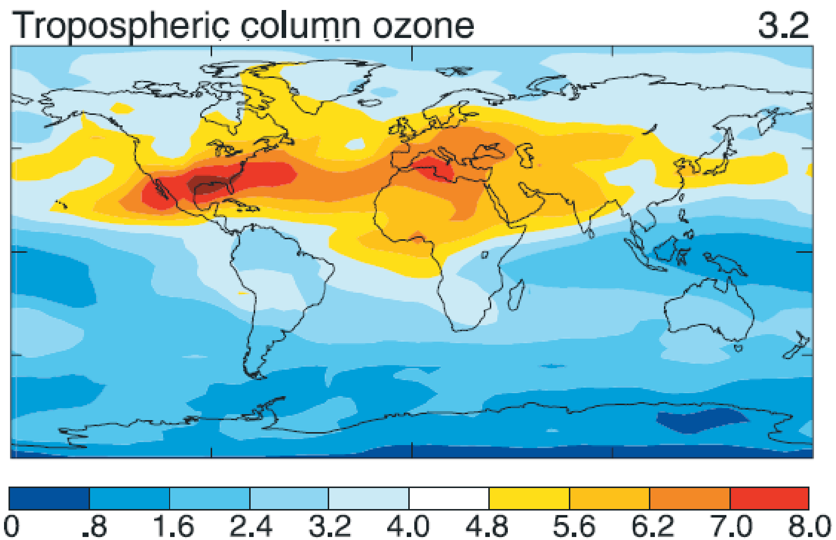
IPCC (2001)

…and the IPCC predicts a further 20-25% increase by 2050

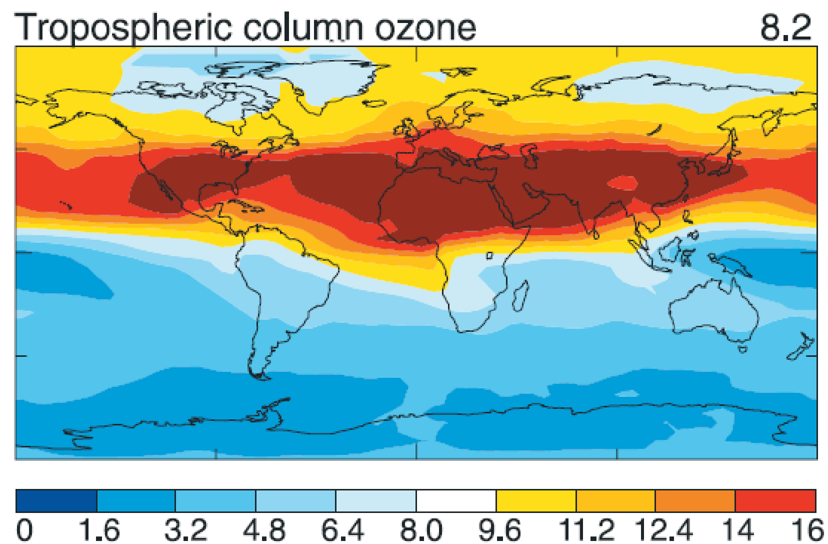
Tropospheric ozone as a GHG

- Short-lived but powerful: IPCC 1750-2000 mean global radiative forcing by tropospheric O_3 = 0.35 W/m^2
  (CO_2 = 1.46 W/m^2, CH_4 = 0.48 W/m^2, N_2O = 0.18 W/m^2)
- Most of precursors emitted over land in the N Hemisphere, but transported hemispherically

1890-1950



1950-1990

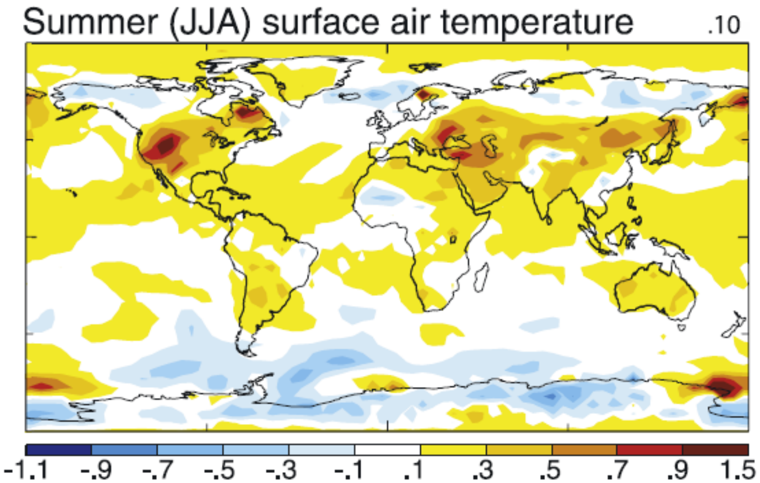


D. Shindell et al., J Geophysical Res. (2006)

Tropospheric ozone as a GHG

- Radiative forcing varies temporally and spatially:
  - Summer: high concentrations but short lifetime, so greatest impacts occur close to precursor sources (USA, Europe)
  - Winter: lower concentrations but longer lifetime, greater transport into and impact on the Arctic

Average 1900–2000 surface temperature trends (°C per century) in response to tropospheric ozone changes

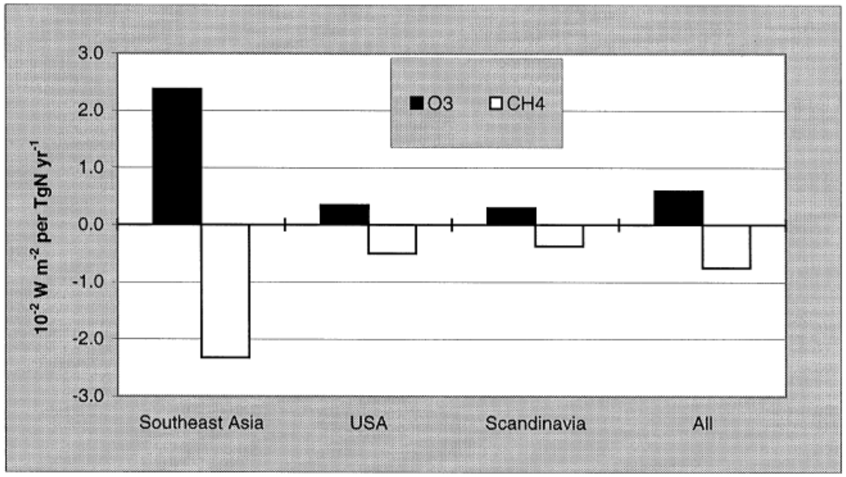


D. Shindell et al., J Geophysical Res. (2006)

Nitrogen oxides and methane

- Nitrogen oxides generate OH radicals, which remove CH_4, CO_2 and other GHGs from the atmosphere
- This substantially offsets the negative climate impact of NOx on tropospheric O_3 formation

Modelled change in global annual radiative forcing from O_3 and CH_4 per unit change in NO_x emissions



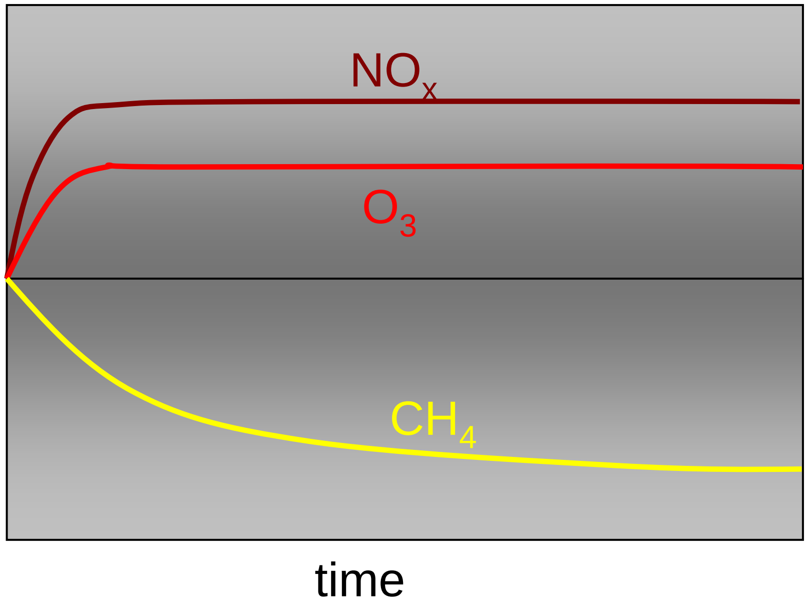
J.S. Fuglestvedt et al, Atmos Env (1999)

Nitrogen oxides, O_3 and CH_4

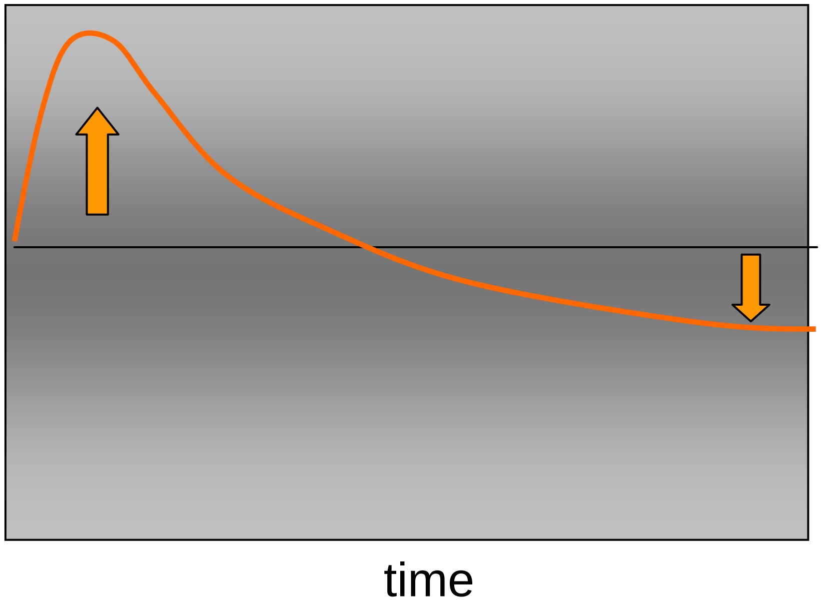
What's the overall climate impact?

- May be positive, negative or zero, depending on a) location, b) time-frame

Change in O_3 and CH_4 resulting from a sustained NO_x increase



Net climate forcing resulting from NO_x increase



After K.P. Shine et al., PNAS (2005)

Ammonia

- NH_3 is not a GHG either
- No significant climate impacts in terms of atmospheric chemistry
- But it may affect the rate of methane removal in forest soils…

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Ammonia and methane

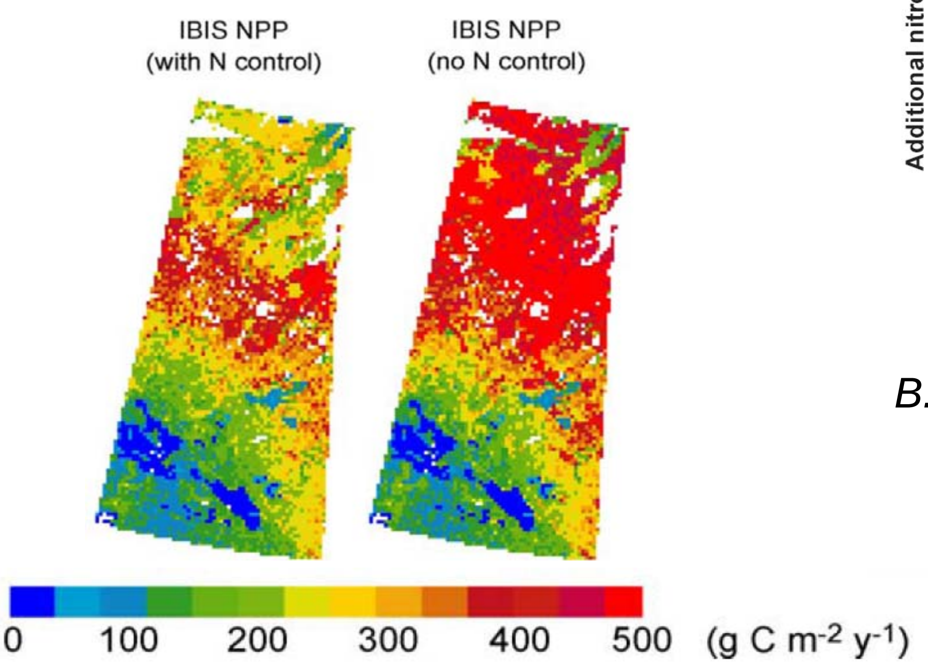
- Wetlands are the major source of CH_4 from soils
- Dryer forest soils are generally CH_4 sinks
- Fertilised soils consume around 40% less CH_4 than undisturbed forest soils, possibly/partly due to inhibition of methanotrophic activity by NH_4
- However the effect appears small: de Vries et al. (in press) estimate that elevated NH_4 has reduced European forest CH_4 uptake by only 1.6% since 1960

Nitrogen and carbon dioxide

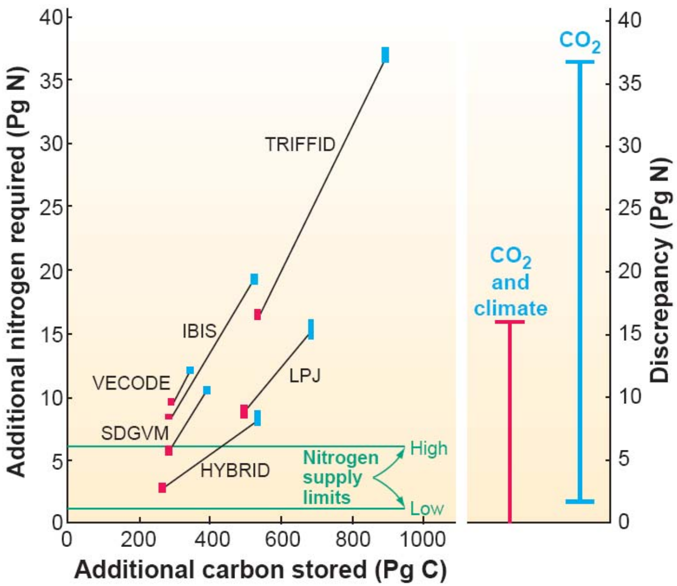
- The productivity of many temperate ecosystems is nitrogen limited
- Adding N via deposition has the potential to increase growth, and therefore to sequester CO_2 from the atmosphere.
- The long-term amount of CO_2 removal depends on the net effect of N on growth and decomposition

N and CO_2 sequestration

- Modelling studies which don't incorporate N-limitation may overestimate growth, e.g. due to CO_2 stimulation



J. Liu et al., Ecological Modelling (2005)



B.A. Hungate et al., Science (2003)

N and CO_2 sequestration

Why C/N ratios matter

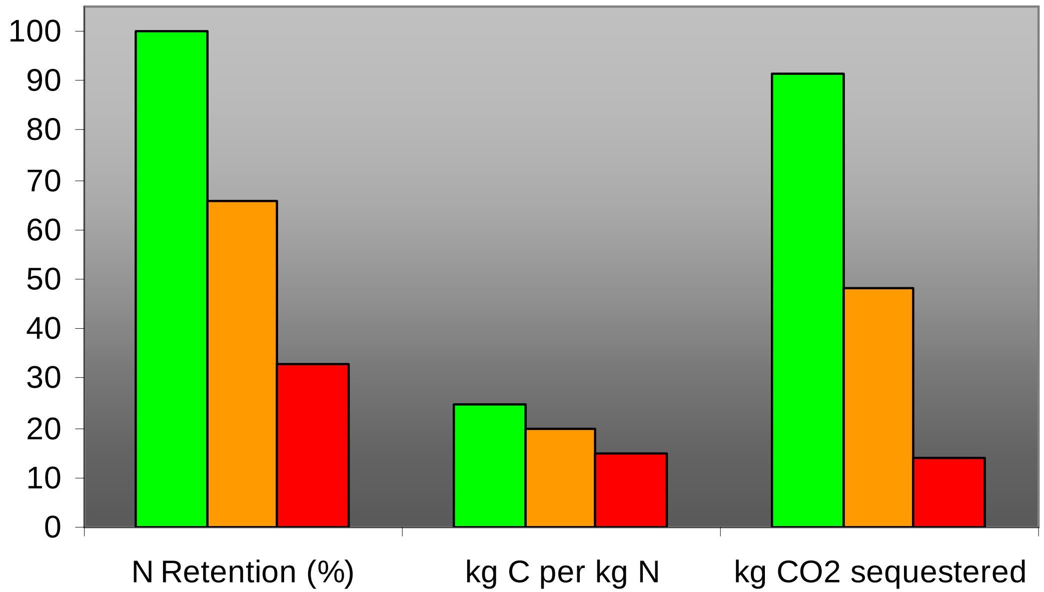
- Some studies have suggested very large (up to 2.0 Pg/yr) CO_2 sequestration due to N deposition
- These studies assumed that most (~80%) of the deposited N would be stored in woody biomass (C/N 250-500)
- Nadelhoffer et al. (1999) showed that most (~70%) of deposited N is actually stored in soils (C/N 10-30)
- Because of the different C/N ratios, a lot more N is required to lock up C in soils than in woody biomass
- As a result, Nadelhoffer et al. suggested that true level of CO_2 sequestration due to N deposition may only be around 0.25 Pg/yr

N and CO_2 sequestration
Why N saturation matters

- Terrestrial ecosystems will only respond to elevated N inputs if they are N limited
- In P-limited (e.g. tropical) ecosystems N additions more likely to lead to N_2O production than CO_2 sequestration
- With increasing N-enrichment, soil and vegetation C/N will decline, and less C will be sequestered per unit N depostion
- If NO_3 is being leached to surface waters, this N is not contributing to CO_2 sequestration at all
- So, paradoxically, N deposition may be most effective at sequestering C in regions of low N deposition

N and CO_2 sequestration

Why N saturation matters

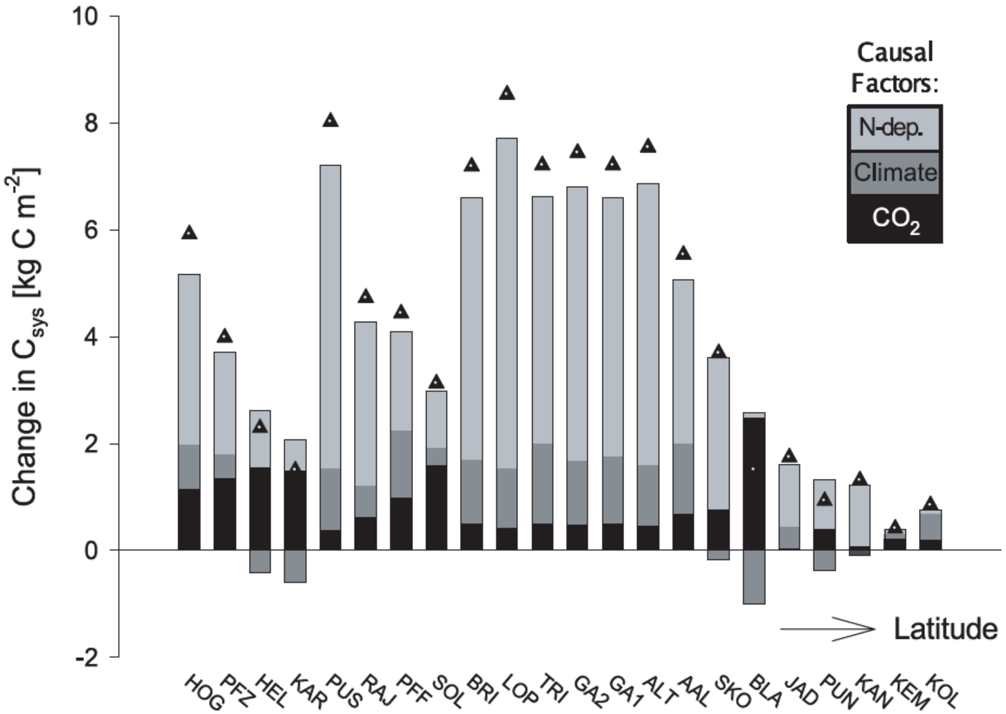


If all N is leached, no CO_2 will be sequestered

N and CO_2 sequestration

Model assessments

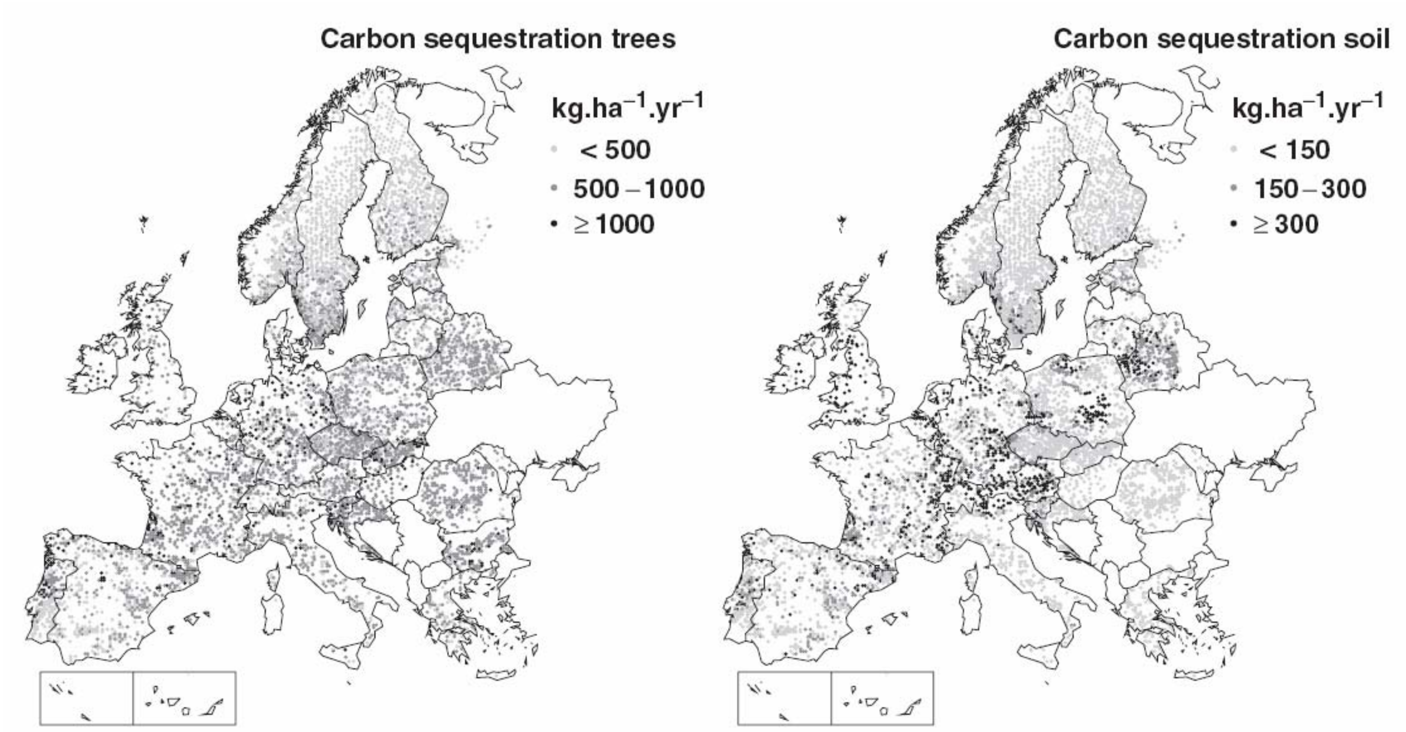
Modelled contribution of N deposition, climate and elevated CO_2 from 1920 to 2000, at 22 European forest sites



R. Milne and M. van Oijen, Annals Forest Sci. (2005)

N and CO_2 sequestration

Empirical assessment



- C sequestration calculated from N immobilisation and soil C/N ratio
- Sequestration lowest in boreal forest (low N dep), higher in central/E Europe (high N dep)

W. De Vries et al., Global Change Biol. (2006)

N and CO_2 sequestration

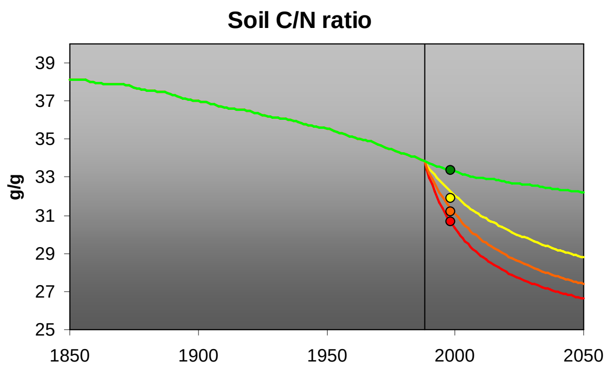
Site-based assessments

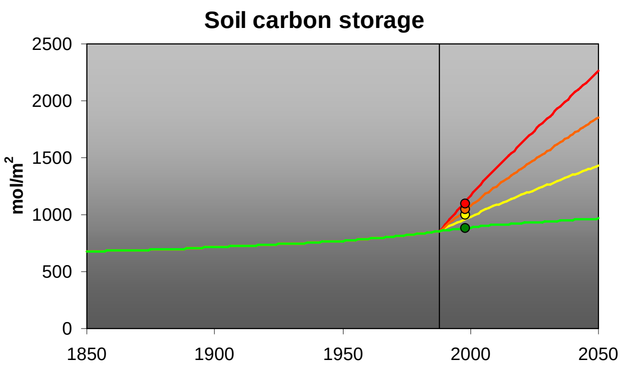
- Three long-term (>10 yr) UK heathland N-addition studies have been assessed in terms of C and N stock changes
- Consistent evidence that N addition led to:
  - Enhanced plant growth
  - Accumulation of C in litter/surface soils
  - Decreased C/N ratio in soils and vegetation
  - Increase/initiation of N leaching under largest N doses
- Experimental responses simulated using the MAGIC biogeochemical model

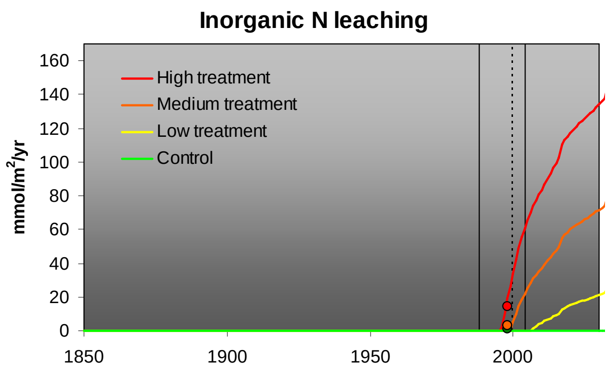
N and CO_2 sequestration

Site-based assessments

Simulated and observed C and N changes at the Ruabon N addition site, UK







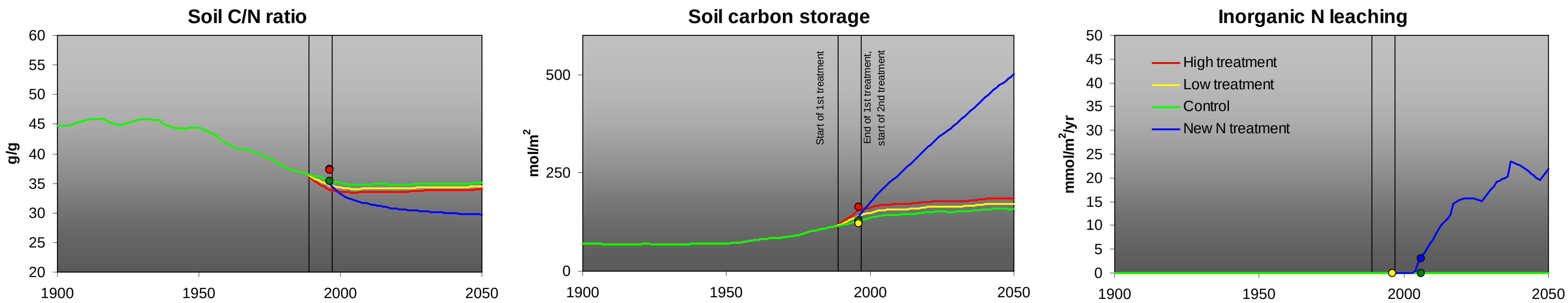
Evans et al., Environmental Pollution (2006)

Site run by Manchester Metropolitan University (Simon Caporn)

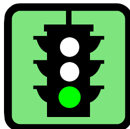
N and CO_2 sequestration

Site-based assessments

Simulated and observed C and N changes at the Thursley Common N addition site, UK



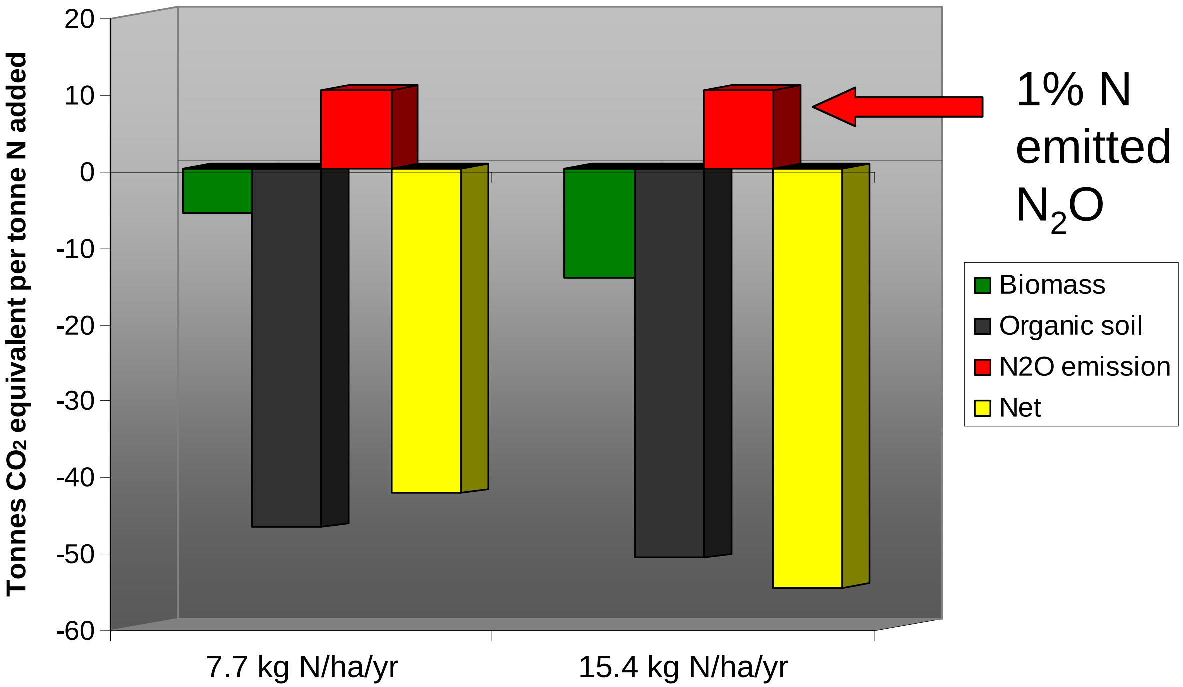
C.D. Evans unpublished results, based on data provided by Sally Power, Imperial College



N and CO_2 sequestration

Site-based assessments

Net greenhouse gas budget (in CO_2 equivalents) per unit N added, for two levels of N addition, Thursley Common

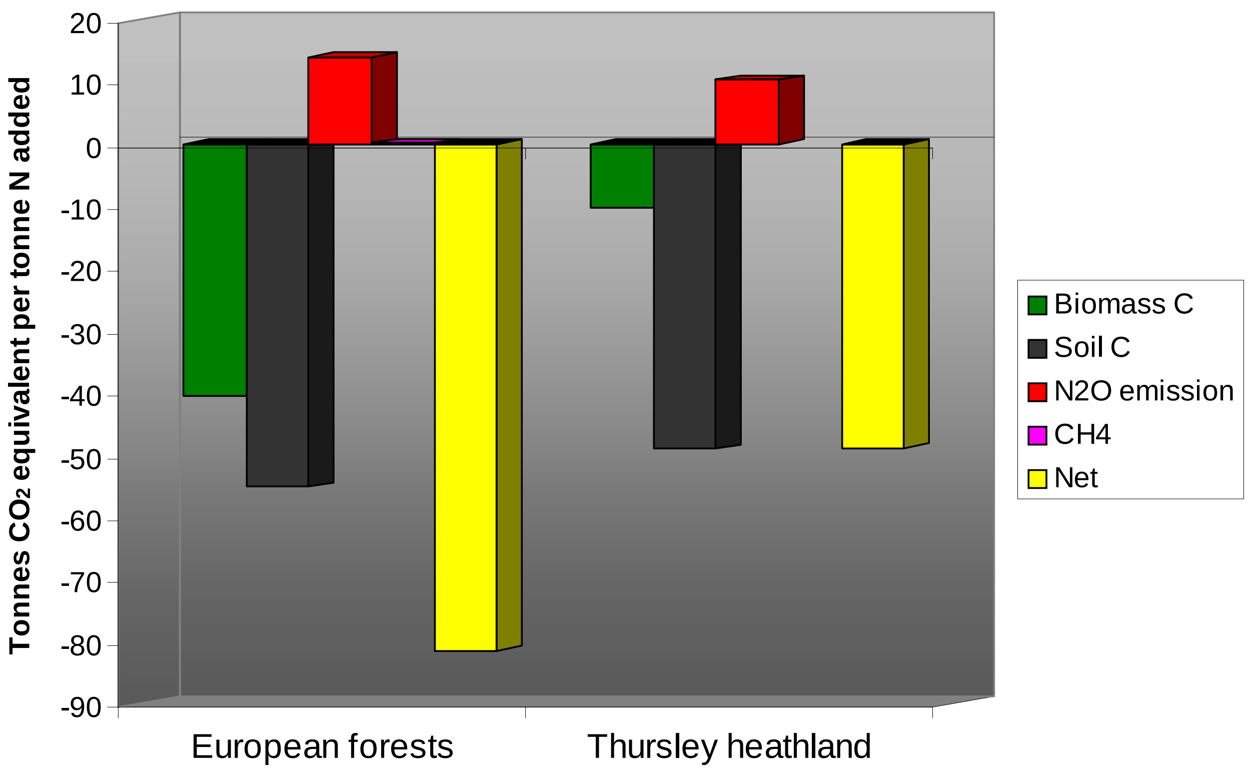


Overall, N addition has led to a large net greenhouse gas sink

N and CO_2 sequestration

Empirical assessment

Comparison of net greenhouse gas budget (in CO_2 equivalents) per unit N added, European forests and Thursley Common



N and CO_2 sequestration
How much C is sequestered per kg N added?

- Rehfuess et al. (1999)
  - Modelled **15-25** kgC/kgN
- De Vries et al (2006)
  - Estimated **25** kgC/kgN for European forests
- Ruabon (N-retaining site)
  - Simulated **28** kgC/kgN
  - Observed low N addition **33** kgC/kgN
  - Observed high N addition **21** kgC/kgN
- Thursley (N-retaining site)
  - Simulated **32** kgC/kgN
- Budworth (N-leaching site)
  - Simulated **21** kg/kg

N and CO_2 sequestration

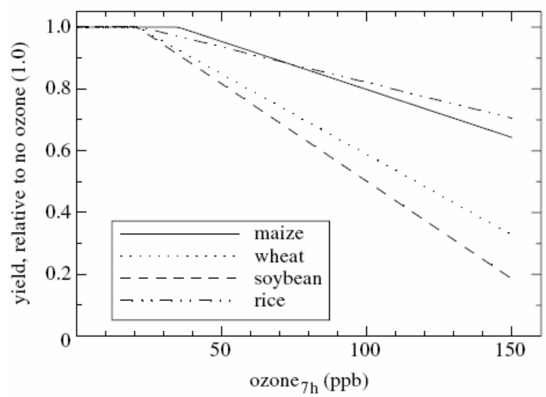
What happens to the C in the long-term?

- A short-term increase in ecosystem carbon stock may not translate into stable long-term storage
- The effects of N deposition on soil organic matter turnover is less clear than effects on production, but in general it may:
  - Increase decomposition rates in reactive soils/soil pools)
  - Decrease decomposition rates in unreactive soils/soil pools
- As a result, the greatest increases in C stock are likely in C-rich, N-poor systems
- But possibly not if N deposition triggers species change (e.g. replacement of sphagnum by higher plants, *Berendse et al. Global Change Biol., 2001*)

Ozone and carbon dioxide

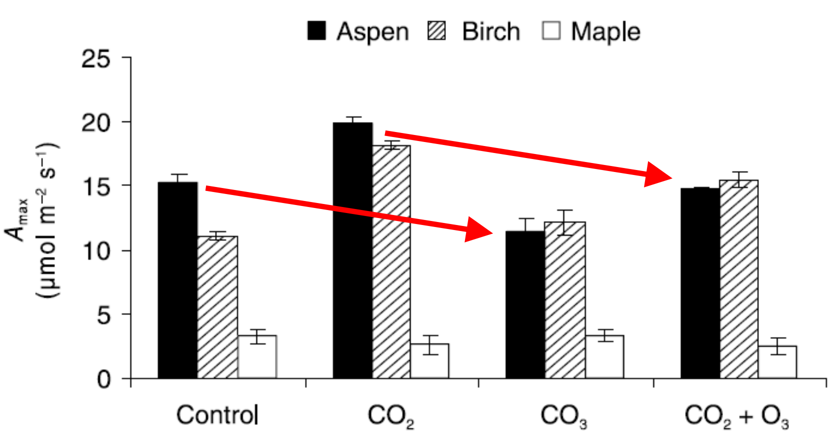
- Tropospheric O_3 damages plants
- Predictions for food crops show significant yield reductions under elevated O_3
- Similar productivity reductions observed in natural ecosystems under elevated O_3, e.g.:
  - 7-40% decrease in grassland biomass (ICP-Vegetation, 4 European experiments)
  - Decrease in aspen photosynthesis under elevated O_3, and reduction in CO_2 growth stimulation (*Karnosky et al.*)

Crop yield changes, elevated O_3



Long et al., Phil. Trans. R. Soc. B (2005)

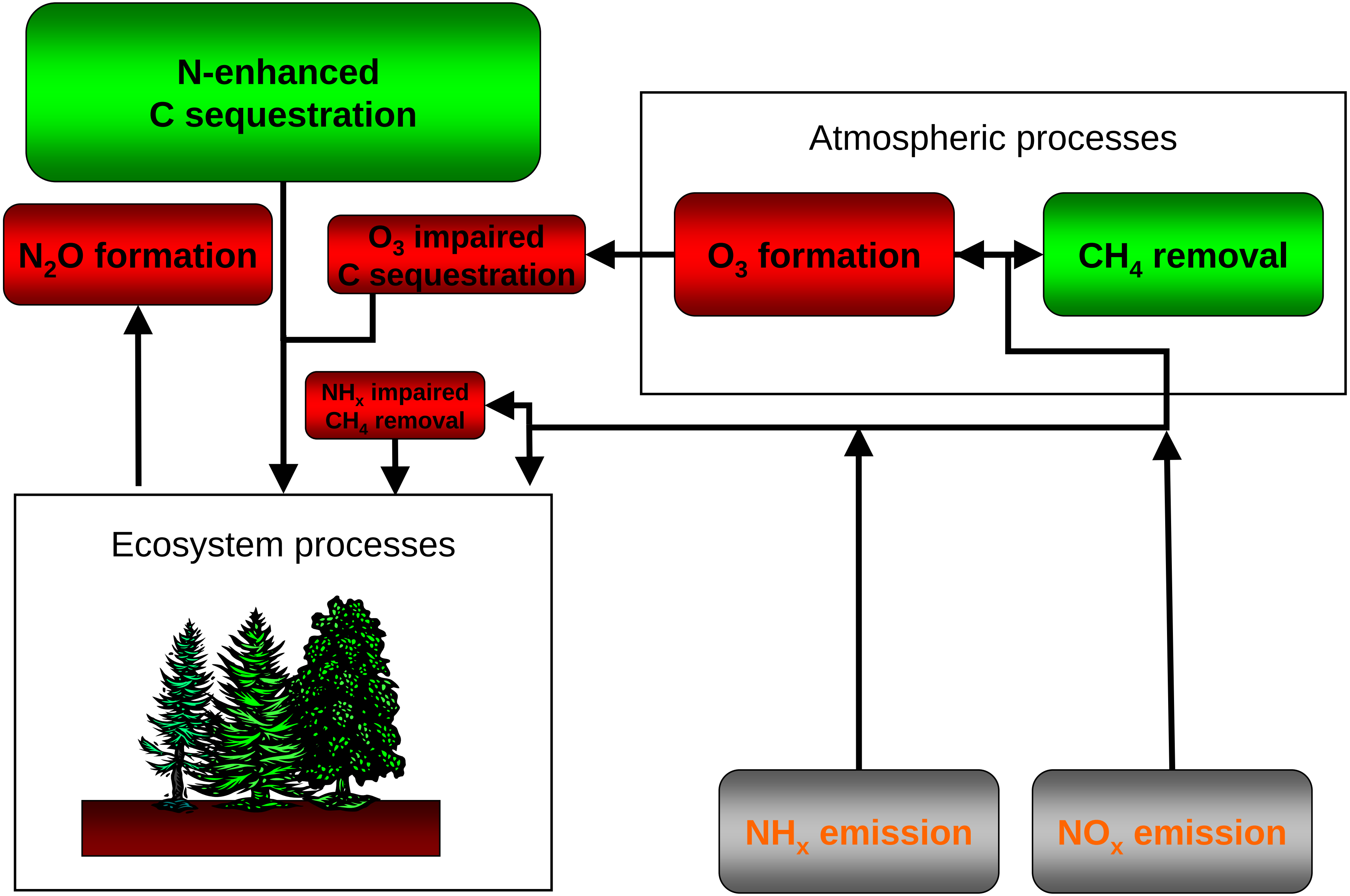
Photosynthesis changes, elevated O_3 / CO_2



Karnosky et al., Functional Ecol. (2003)

Summary

- The effects of emitted N on climate change are many and varied
- The direct effects of NO_x on atmospheric O_3 and CH_4 may cancel out on average, but could be important at certain times/locations (e.g. O_3 in the Arctic in winter)
- N_2O emissions are enhanced by N deposition
- N-induced changes in CH_4 are probably minor
- Enhancement of CO_2 sequestration by N deposition appears (in N-limited systems) to be the dominant climate-related impact of N emissions
- Consequently, N emissions in temperate regions probably (to some extent, and with large uncertainties) act to ameliorate climate change


N-enhanced C sequestration
N_2O formation
O_3 impaired C sequestration
Atmospheric processes
O_3 formation
CH_4 removal
NH_x impaired CH_4 removal
Ecosystem processes
NH_x emission
NO_x emission

Can/should N be managed for climate change amelioration?

- Given the complex and uncertain net impacts, probably not.
- But it may be possible to maximise C sequestration and minimise N_2O emission, e.g. through:
  - Permitting some N deposition (but below the critical load)
  - Periodic biomass removal
  - Reduced disturbance, e.g. during felling
- Finally, climate impacts of N must not be considered in isolation – the mechanism through which N enhances CO_2 sequestration (increased growth) is the same one that leads to species change and biodiversity loss