~~Nitrogen as a Contributor to Climate Change~~

Nitrogen and Climate Change

Chris Evans

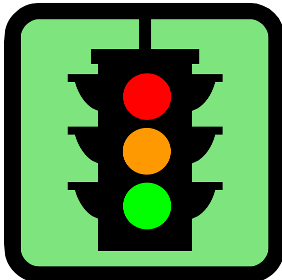
Centre for Ecology and Hydrology, Bangor, UK

With contributions gratefully received from:

Bridget Emmett, Gina Mills, Harry Harmens,
Ute Skiba, Wim de Vries and Sally Power

Nitrogen and climate change

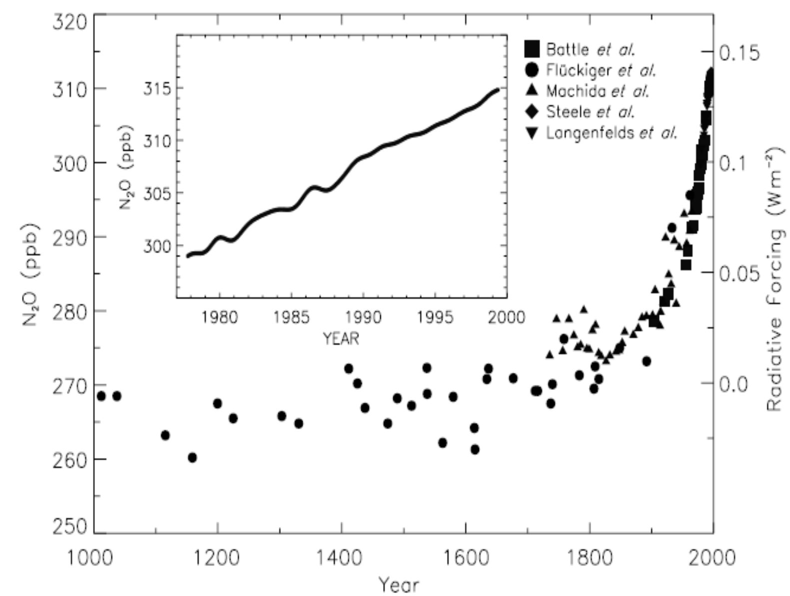
- Reactive N gets everywhere (the ‘N cascade’)
- As a result, the impact of N emissions on climate change are complex and involve:
  – One greenhouse gas that contains nitrogen (N_2O)
  – Three greenhouse gases that don’t contain nitrogen (CO_2, CH_4 and O_3)
  – Three gases that contain nitrogen but 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)

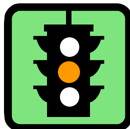
1000 ice-core record and 20-year observed atmospheric N_2O



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)

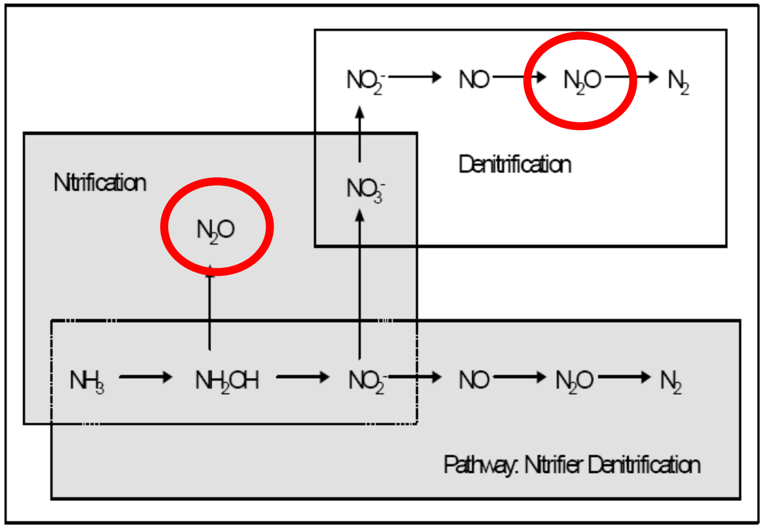
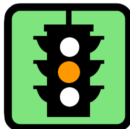


Figure 2 N_2O production by nitrifiers and denitrifiers (Wrage et al., 2001).

Nitrous Oxide

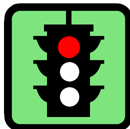
How much N_2O is emitted due to N inputs?

- 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)



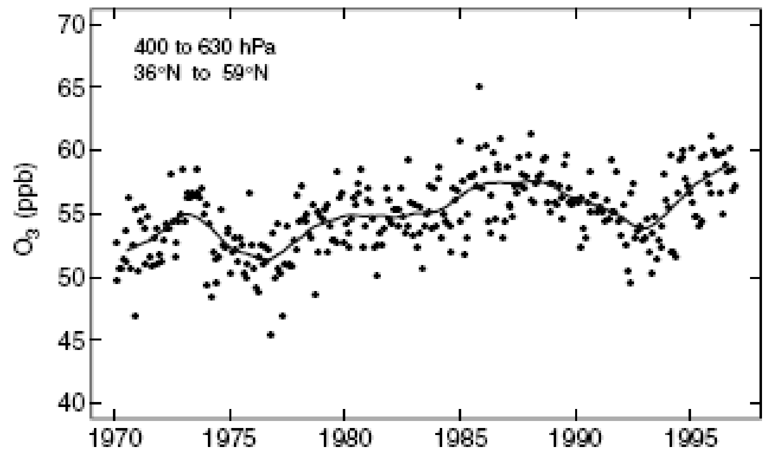
Nitrogen oxides and tropospheric ozone

It's complicated….

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

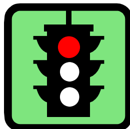
$$\begin{array}{llll} & OH + CO + O_2 & \rightarrow & CO_2 + HO_2 \\ & HO_2 + NO & \rightarrow & NO_2 + OH \\ & NO_2 + h\nu & \rightarrow & NO + O(^3P) \\ & O(^3P) + O_2 + M & \rightarrow & O_3 + M \\ \text{net:} & CO + 2O_2 + h\nu & \rightarrow & CO_2 + O_3 \end{array}$$

It's increasing….



IPCC (2001)

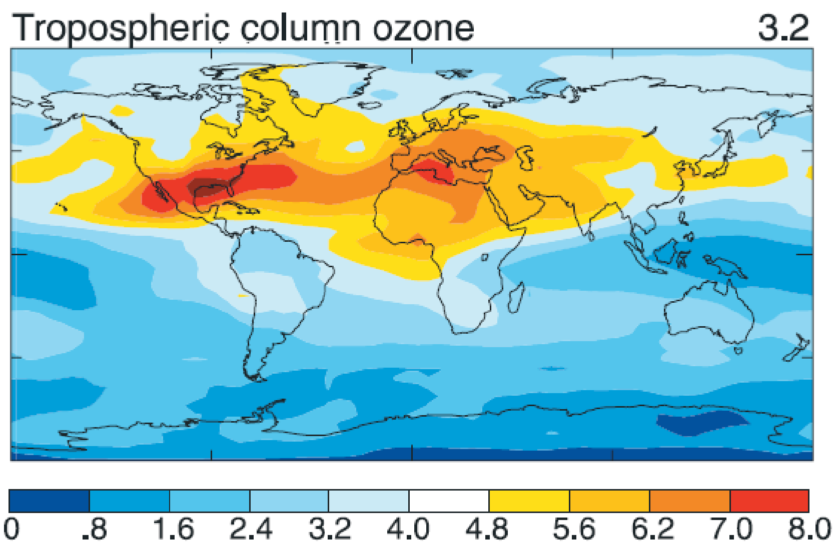
…and the IPCC predicts a further 20-25% increase by 2050



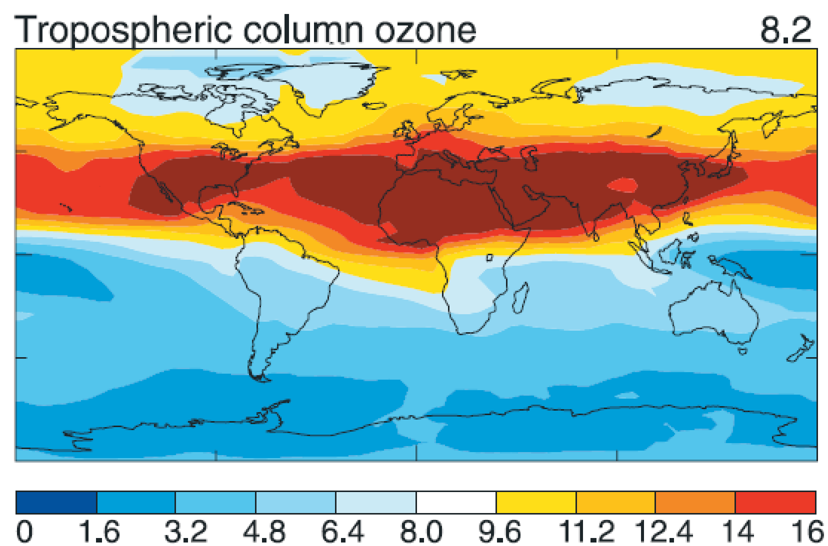
Tropospheric ozone as a GHG

- 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

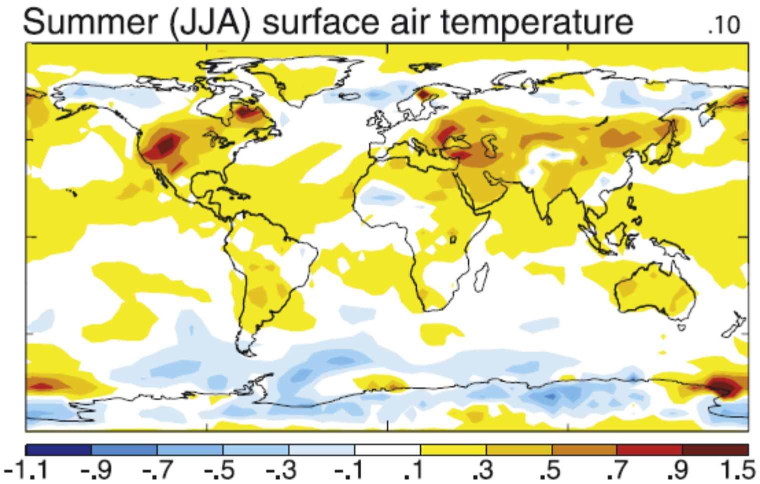


D. Shindell et al., J Geophysical Res. (2006)

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

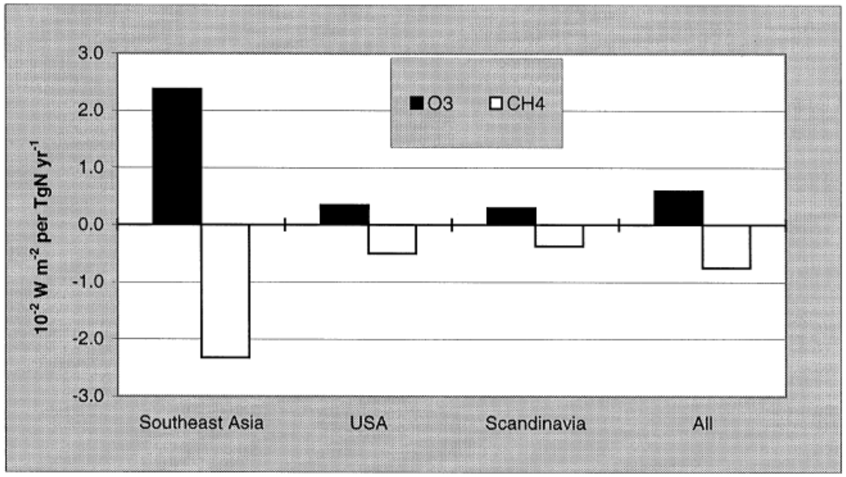


D. Shindell et al., J Geophysical Res. (2006)

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



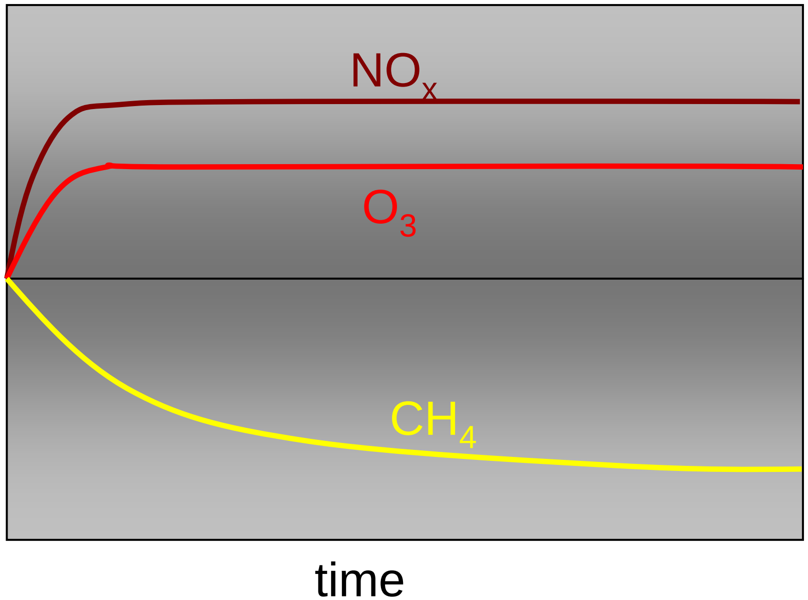
J.S. Fuglestvedt et al, Atmos Env (1999)

Nitrogen oxides, O_3 and CH_4

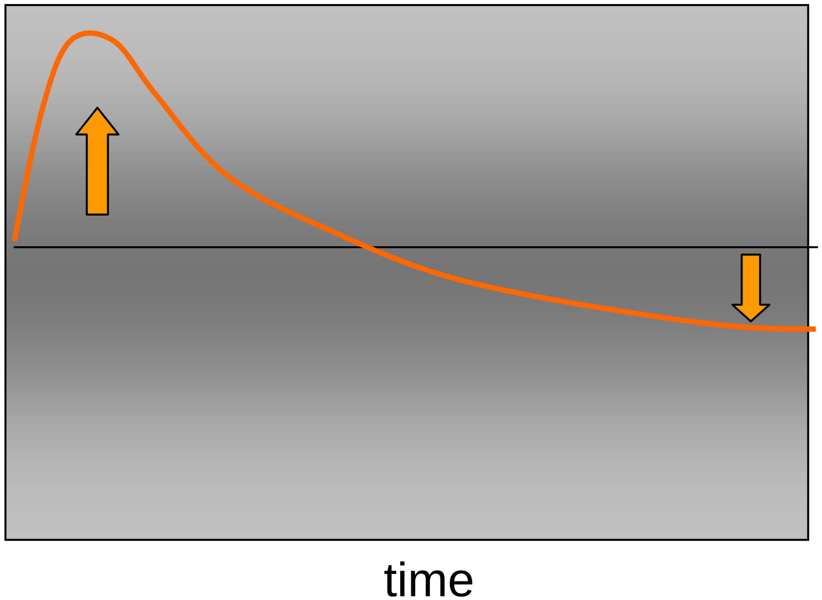
What's the overall climate impact?

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

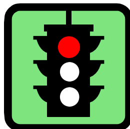
Change in O_3 and CH_4 resulting from a sustained NO_x increase



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…

Ammonia and methane

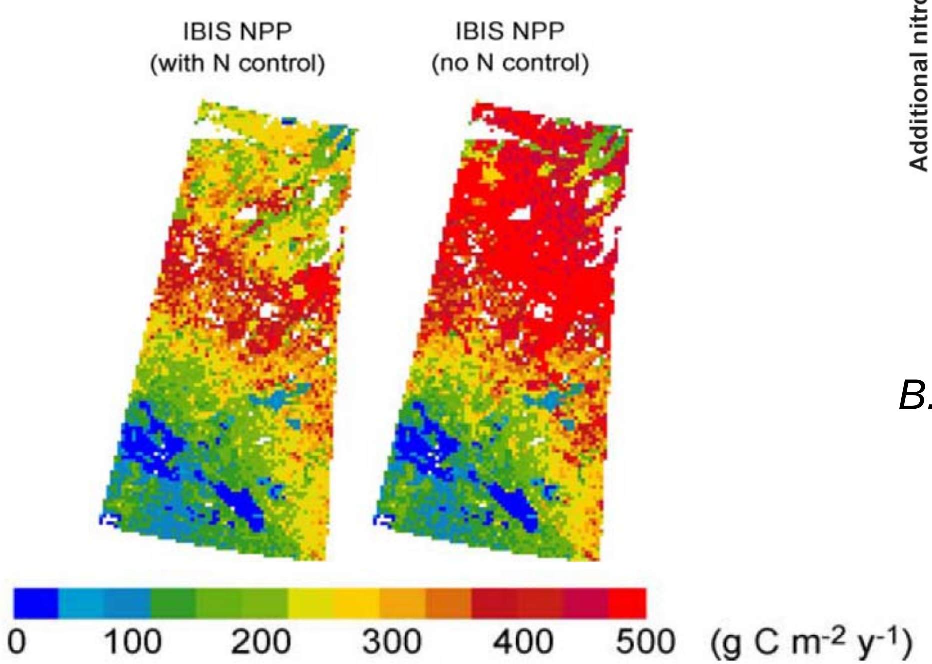
- Wetlands are the major source of CH_4 from soils
- Dryer forest soils are generally CH_4 sinks
- Fertilised soils consume around 40% less CH_4 than undisturbed forest soils, possibly/partly due to inhibition of methanotrophic activity by NH_4
- However the effect appears small: de Vries et al. (in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

Nitrogen and carbon dioxide

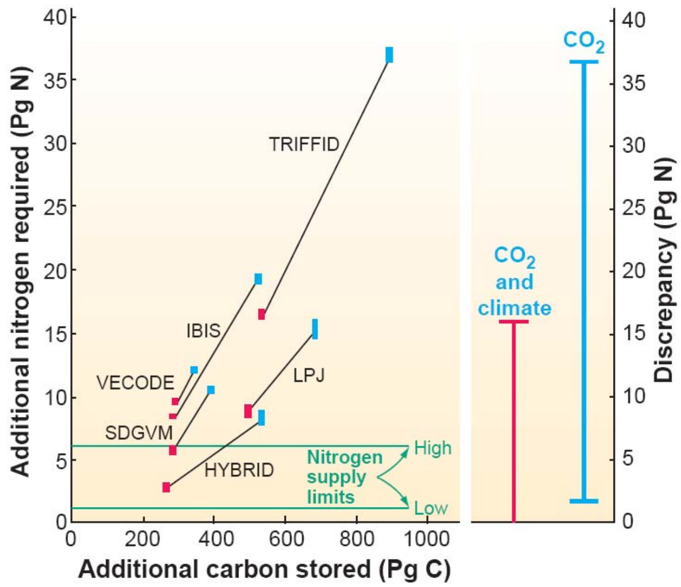
- The productivity of many temperate ecosystems is nitrogen limited
- Adding N via deposition has the potential to increase growth, and therefore to sequester CO_2 from the atmosphere.
- The long-term amount of CO_2 removal depends on the net effect of N on growth and decomposition

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)

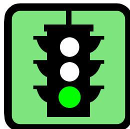
N and CO_2 sequestration
Why C/N ratios matter

- 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

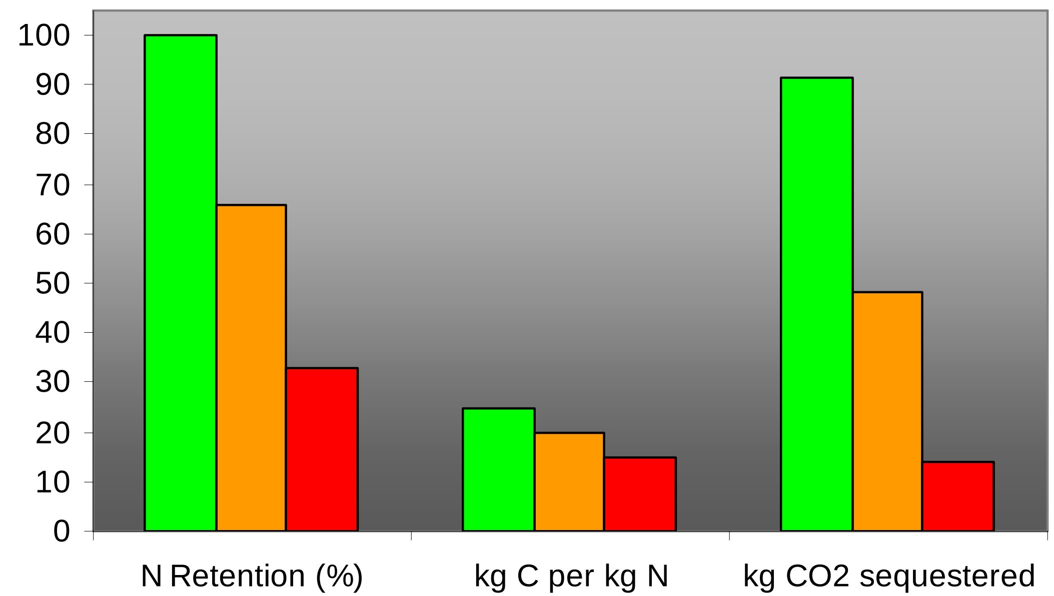
Why N saturation matters

- 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

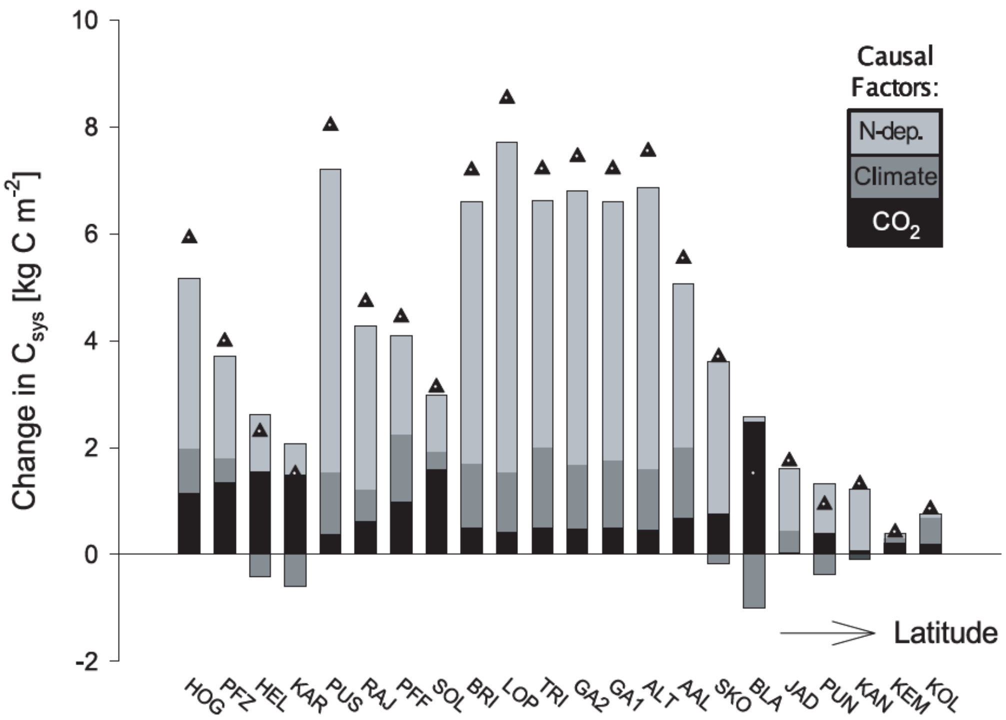
Why N saturation matters



If all N is leached, no CO_2 will be sequestered

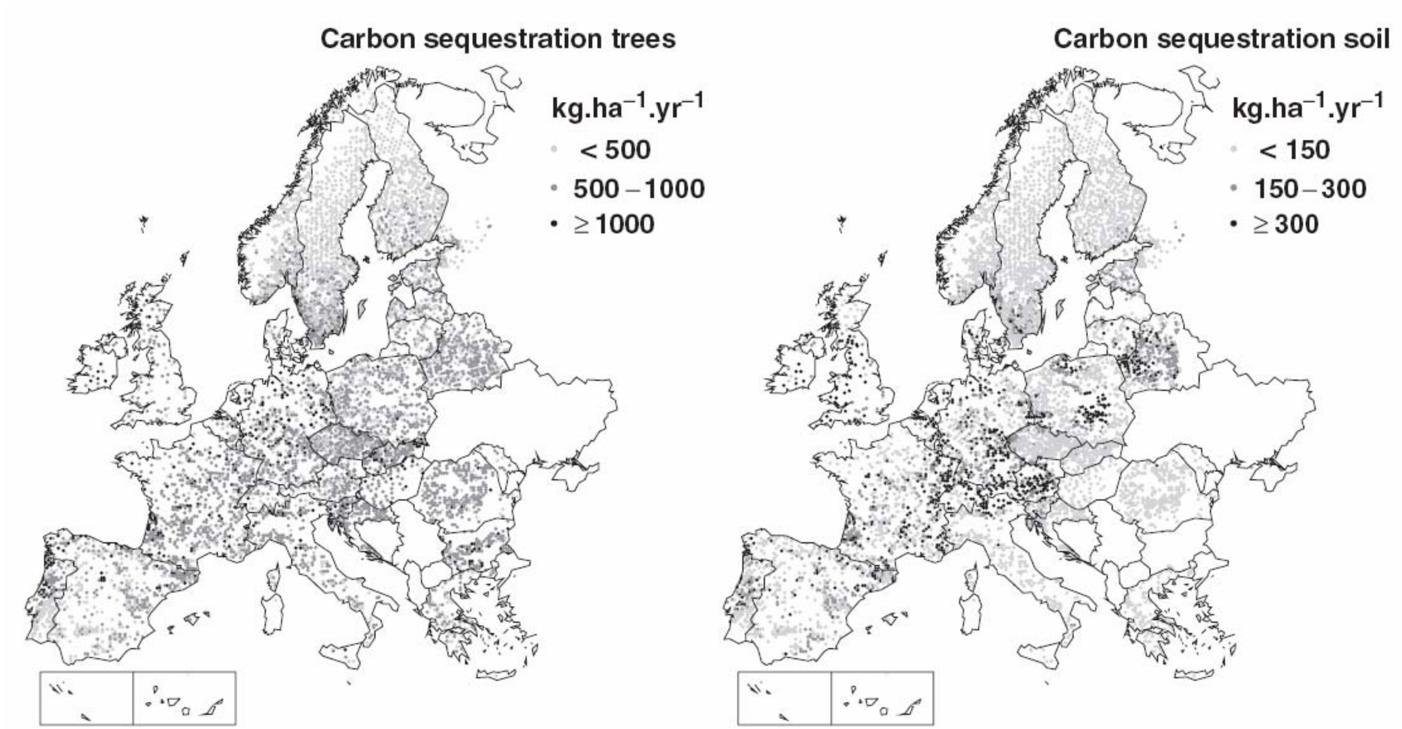
N and CO_2 sequestration
Model assessments

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)

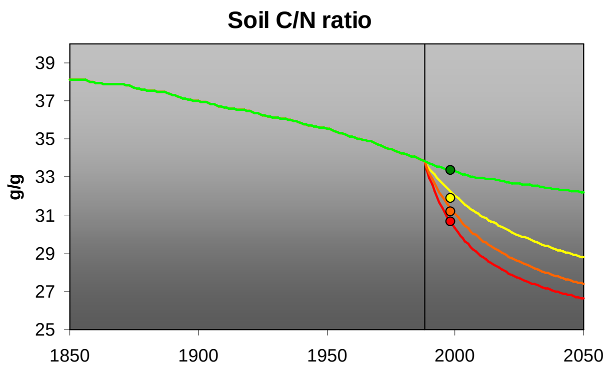
N and CO_2 sequestration
Site-based assessments

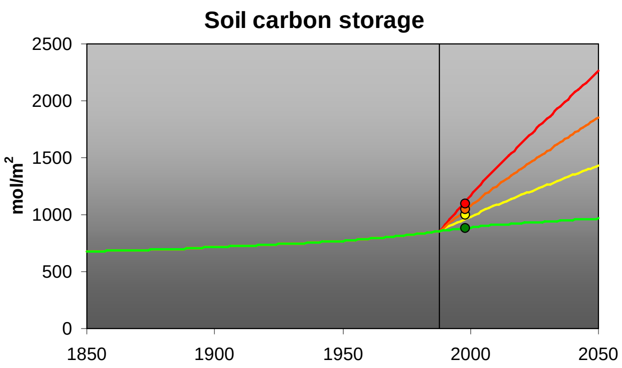
- Three long-term (>10 yr) UK heathland N-addition studies have been assessed in terms of C and N stock changes
- Consistent evidence that N addition led to:
  - Enhanced plant growth
  - Accumulation of C in litter/surface soils
  - Decreased C/N ratio in soils and vegetation
  - Increase/initiation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

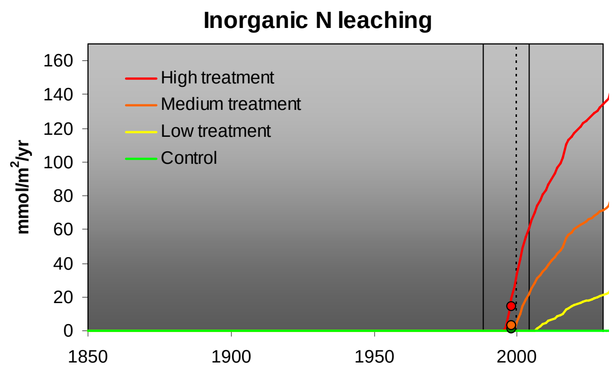
N and CO_2 sequestration

Site-based assessments

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







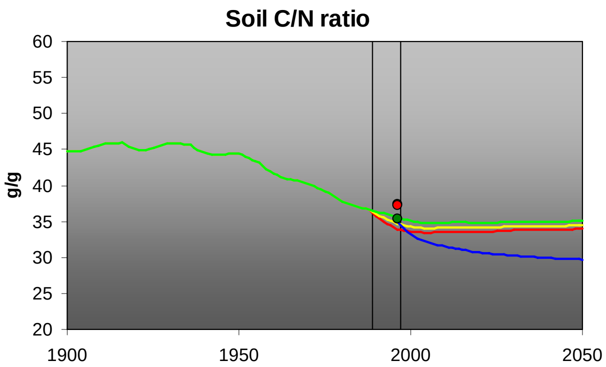
Evans et al., Environmental Pollution (2006)

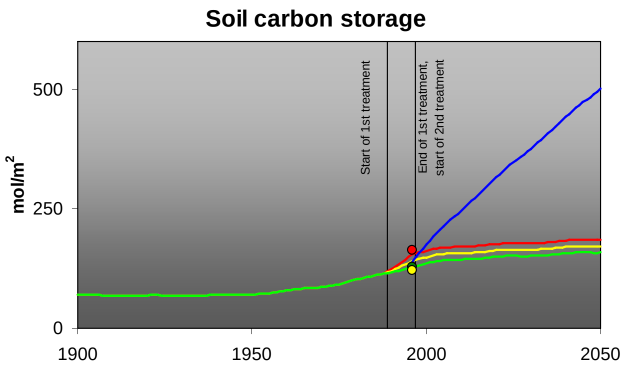
Site run by Manchester Metropolitan University (Simon Caporn)

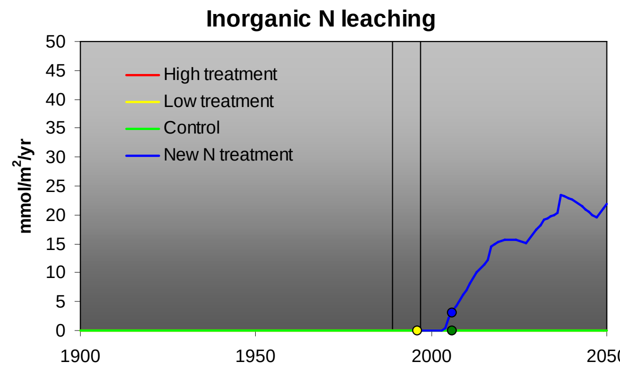
N and CO_2 sequestration

Site-based assessments

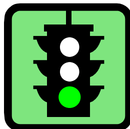
Simulated and observed C and N changes at the Thursley Common N addition site, UK





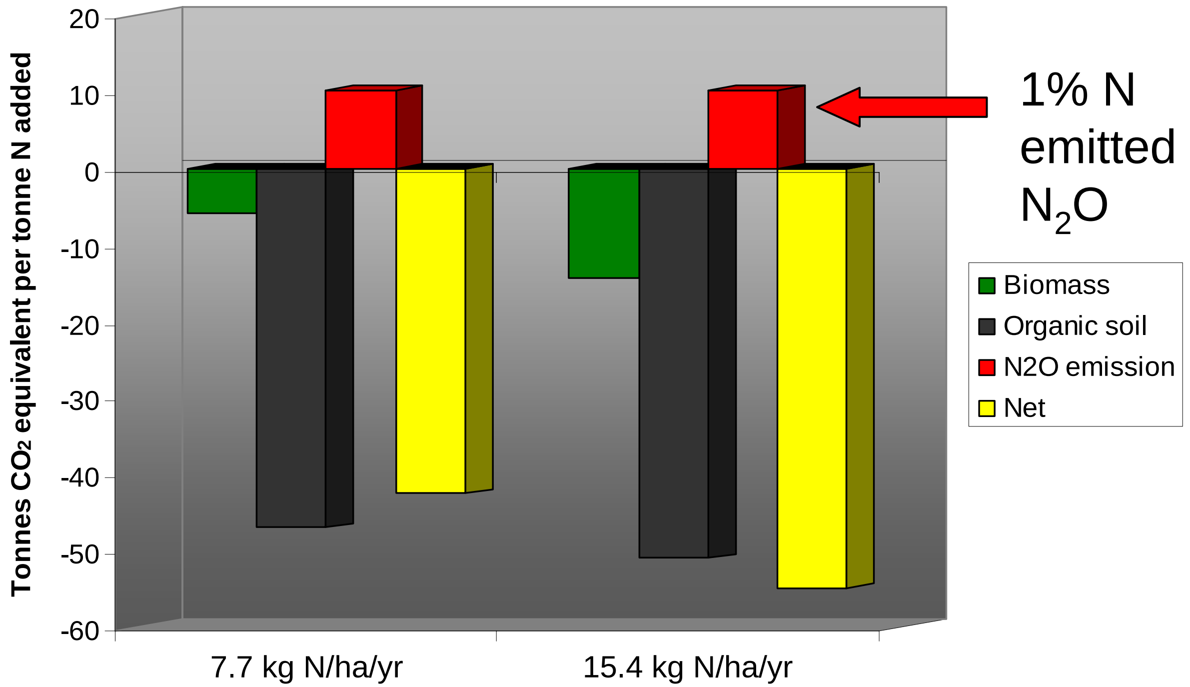


C.D. Evans unpublished results, based on data provided by Sally Power, Imperial College



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

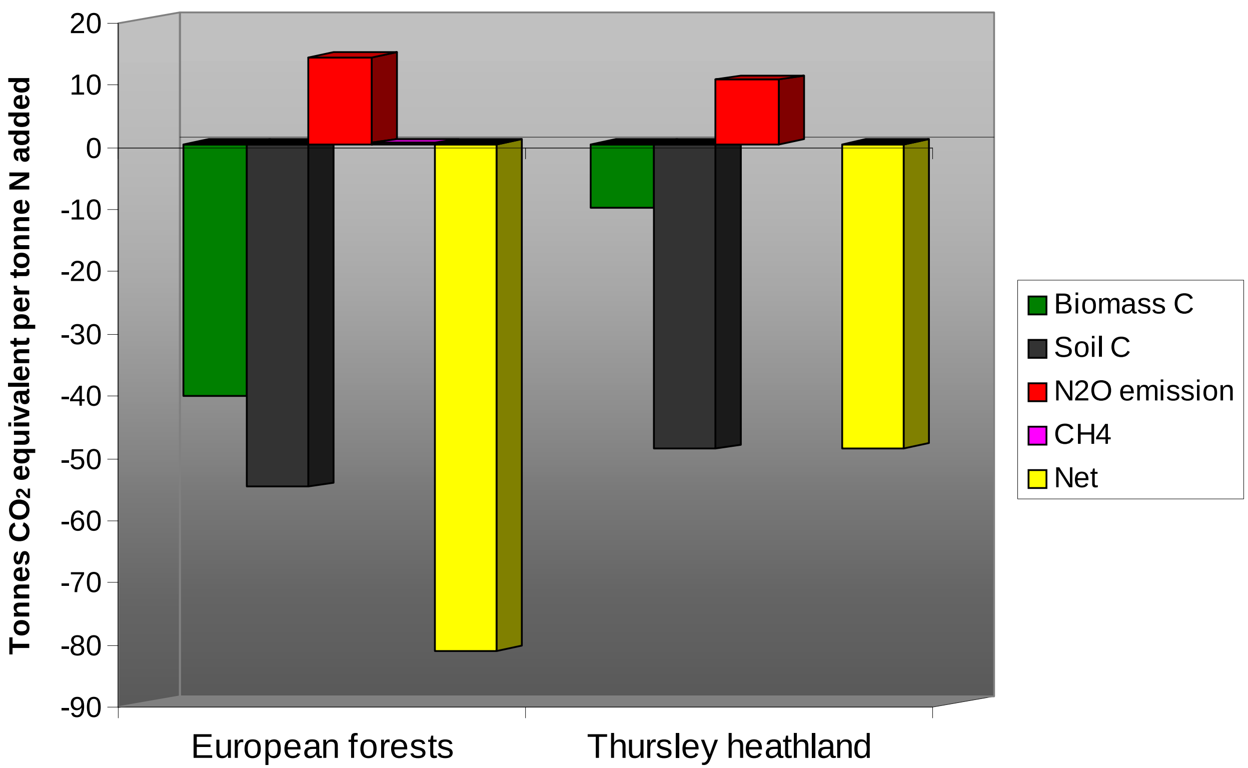


Overall, N addition has led to a large net greenhouse gas sink

N and CO_2 sequestration

Empirical assessment

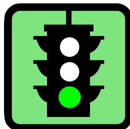
Comparison of net greenhouse gas budget (in CO_2 equivalents) per unit N added, European forests and Thursley Common



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

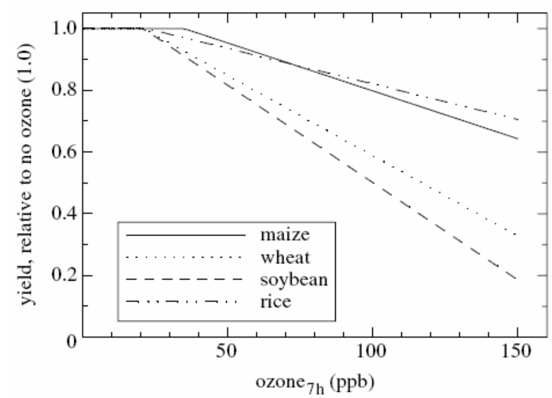
What happens to the C in the long-term?

- 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

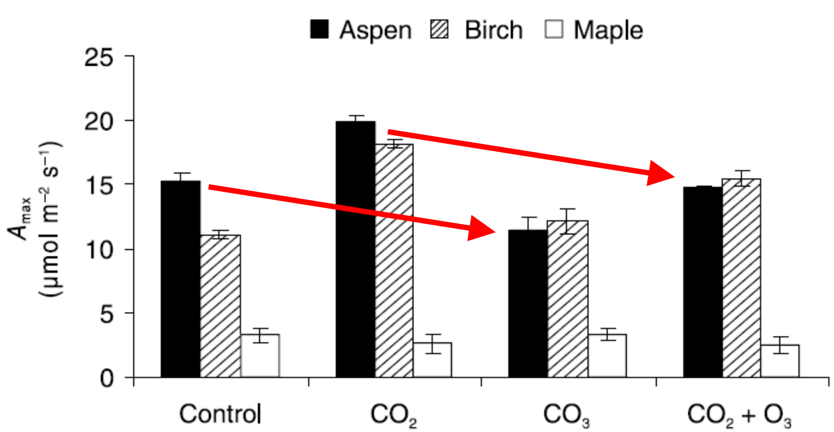
- Tropospheric O_3 damages plants
- Predictions for food crops show significant yield reductions under elevated O_3
- Similar productivity reductions observed in natural ecosystems under elevated O_3, e.g.:
  - 7-40% decrease in grassland biomass (ICP-Vegetation, 4 European experiments)
  - Decrease 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)

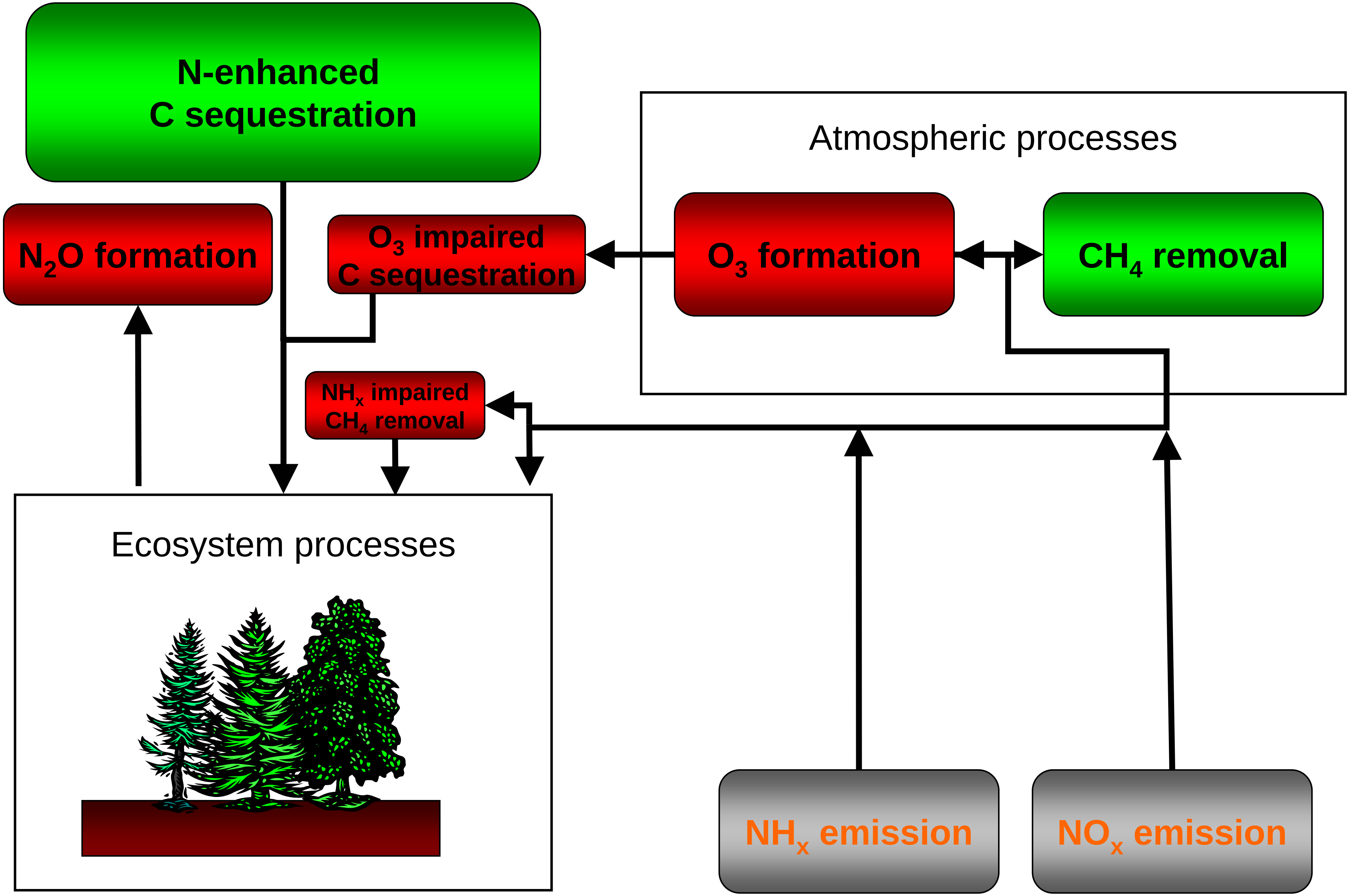
Photosynthesis changes, elevated O_3 / CO_2



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
Atmospheric processes
N_2O formation
O_3 impaired C sequestration
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