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Direct and Indirect Impacts on Agriculture of Methane, Black Carbon, and Other Pollutants, and Benefits of Intervention

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Tropospheric Ozone: Dependence on Emissions of NOx, CH_4, CO and VOCs

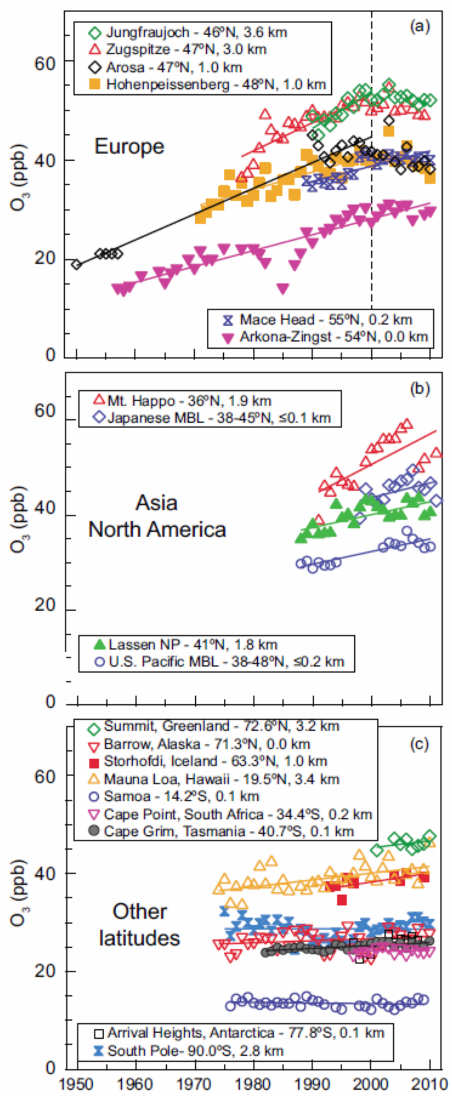
Tropospheric ozone estimates(AR5, chap 2):

- European surface O_3 more than doubled by the end of the 20th century ("medium confidence").
- Surface O_3 has increased at most (non-urban) sites in the NH (1 to 5 ppb per decade) ("medium confidence"), and 2 ppb per decade in the SH ("low confidence")
- Since 1990 surface O_3 has likely increased in East Asia, while in the eastern USA and Western Europe it has levelled off or is decreasing.

- **Approximately half of the increase of tropospheric ozone from pre-industrial times to the present day is due to changes in the chemistry of the atmosphere induced by the increase in NOx,**
- **The other half is due to the combined increase of CH_4, CO and VOC emissions:**
    - **~25% for CH_4,**
    - **~25% for CO and VOCs together**

(Wang and Jacob, 1998, cited in AQEG report, 2009).

- Reducing global anthropogenic methane emissions by 20% beginning in 2010 would decrease the average daily maximum 8-h surface ozone by ≈1 part per billion by volume globally (West et al 2006).

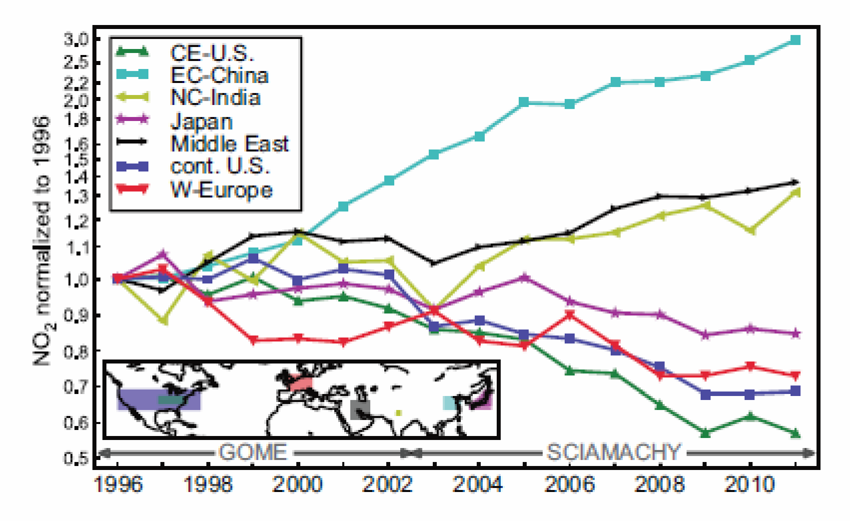


NO, NO_2, NOx

- NOx has natural and anthropogenic sources:

- Natural:
  - NO emitted from soils,
  - NO_2 formed in lightning discharges

- Anthropogenic:
  - Fossil fuel burning
  - Biomass burning
  - Oxidation of atmospheric ammonia



The figure shows the changes relative to 1996 in satellite-derived tropospheric NO_2 columns, with a strong upward trend over central eastern China and an overall downward trend in Japan, Europe and the USA.

Atmospheric CO:

Major sources are:

- In situ production by oxidation of hydrocarbons (mostly CH_4 and isoprene);
- Direct emission resulting from incomplete combustion of biomass and fossil fuels

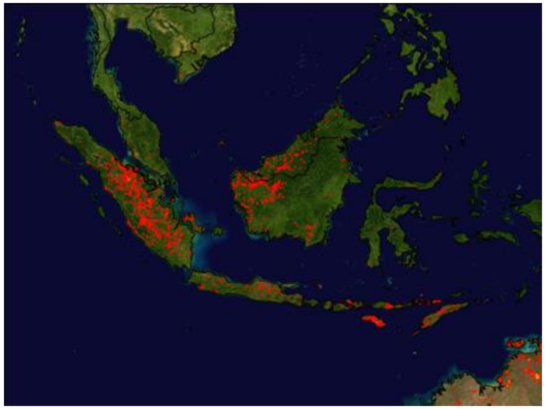
Trends:

- Satellite data suggests a clear and consistent decline of CO columns for 2002–2010 over a number of polluted regions in Europe, North America and Asia, with a global trend of about –1% /yr.

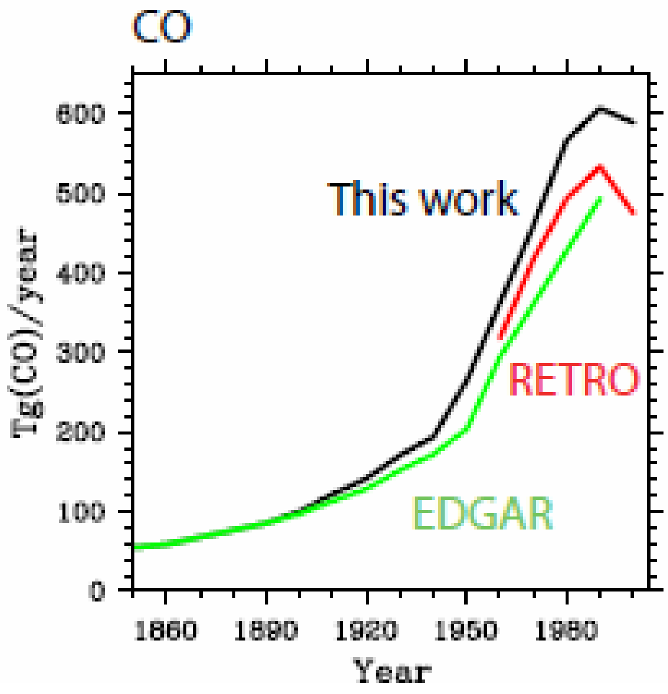
Biomass burning:

- Source of CO, NMVOCs and BC

NMVOCs include aliphatic, aromatic and oxygenated compounds (e.g., aldehydes, alcohols and organic acids), and have atmospheric lifetimes ranging from hours to months.

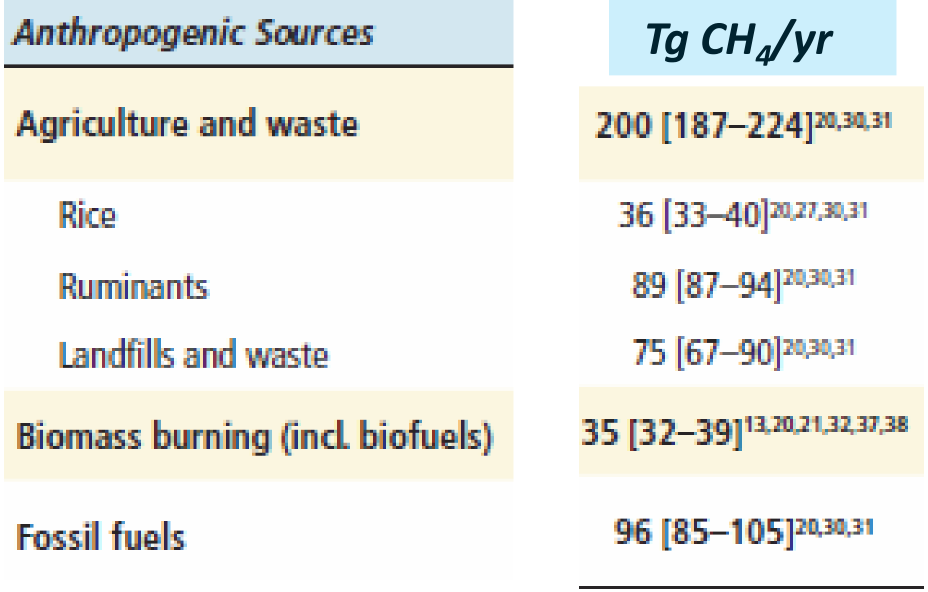


Fires in Indonesia, 2008



(Lamarque et al, Atmos Chem Phys 2010)

Methane: Global budget for 2000-2009 (Ciais et al, AR5, 2013):



Anthropogenic Sources	*Tg CH_4/yr*
Agriculture and waste	200 [187–224][20,30,31]
Rice	36 [33–40][20,27,30,31]
Ruminants	89 [87–94][20,30,31]
Landfills and waste	75 [67–90][20,30,31]
Biomass burning (incl. biofuels)	35 [32–39][13,20,21,32,37,38]
Fossil fuels	96 [85–105][20,30,31]

Total: 331 (304-368)

Natural Sources:
347 (238-484) Tg CH_4/yr

- **Largest contributors are Fossil Fuels, Ruminants, Landfills & Waste**
- **Major potential for reductions in emissions from fossil fuels and landfills by technical fixes and/or a switch to renewable energy.**
- ***However, reduction in agricultural emissions more difficult: will involve changes in traditional practices and lifestyles.***
- **Agriculture & biomass burning total = 160 Tg CH_4/yr**
  = 48% of all anthropogenic emissions = 24% of all emissions

Modelled changes in Ozone as a result of changing CH_4 emissions

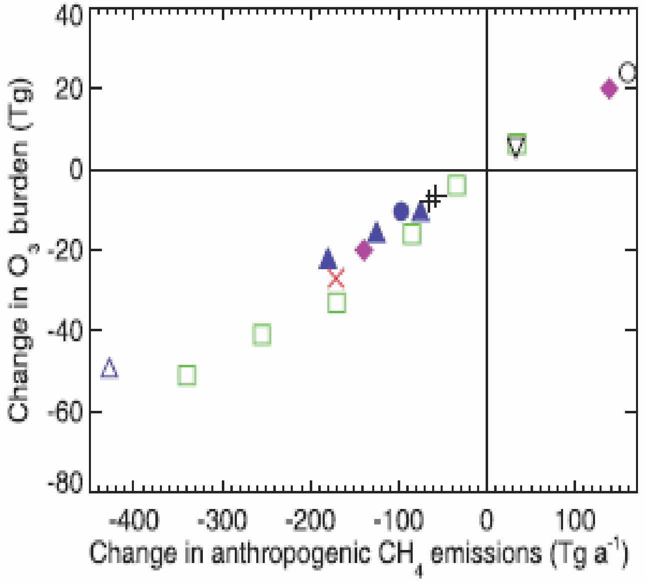


Figure 1. The change in tropospheric O_3 burden (Tg) as a function of the change in anthropogenic CH_4 emissions (Tg a^{-1}), compiled from modeling studies in the literature encompassing a range of modeling approaches:

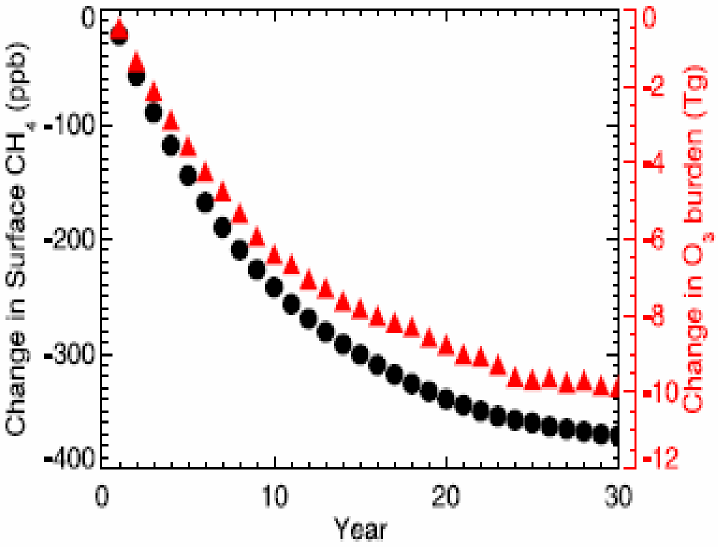
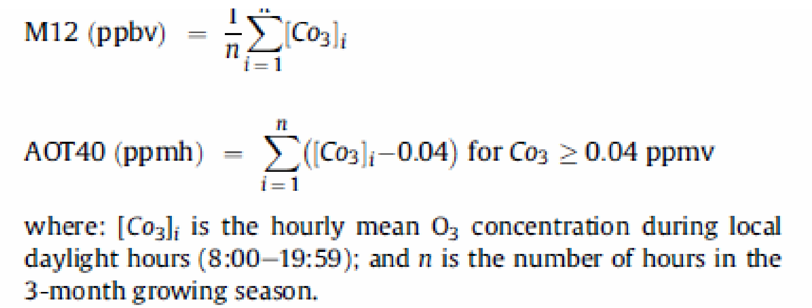


Figure 5. Annual mean change in surface CH_4 abundances (black circles; left axis) and in the tropospheric O_3 burden (red triangles; right axis), resulting from a 97 Tg a^{-1} decrease in global anthropogenic CH_4 emissions

(Fiore et al, JGR, 113, D08307, 2008)

Impacts of Tropospheric Ozone on Crops

- Global estimates of yield losses due to increased O_3 in soybean, wheat, and maize in 2000 range from 8.5 to 14%, 3.9 to 15%, and 2.2 to 5.5% respectively, amounting to economic losses of US$11 to 18 billion (Avnery et al., 2011a).
    - They used two exposure-based metrics, M12
    - and AOT40:



$$\text{M12 (ppbv)} = \frac{1}{n}\sum_{i=1}^{n}[Co_3]_i$$

$$\text{AOT40 (ppmh)} = \sum_{i=1}^{n}([Co_3]_i - 0.04) \text{ for } Co_3 \geq 0.04 \text{ ppmv}$$

where: $[Co_3]_i$ is the hourly mean O_3 concentration during local daylight hours (8:00–19:59); and n is the number of hours in the 3-month growing season.

- Estimates of soybean and maize yield losses are generally larger, but those of wheat are smaller, when the M12 rather than the AOT40 metric is used.

Choice of metric: Improved prediction of plant injury may be achieved using stomatal uptake of O_3 (flux; F) or its cumulative value, dose (D) as a metric. (Grantz 2014).

- Meta-analysis of published data show yield losses for other crops such as bean and rice range up to 20% at a mean O_3 concentration of 41-42 ppb, as shown in the figure (Feng and Kobayashi 2009)

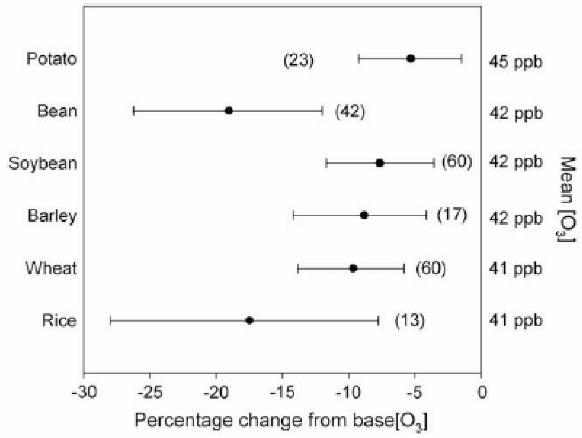


Fig. 1. Response of crop yields to current $[O_3]$ (31–50 ppb) for six crops. Symbols represent the mean percent change at current ambient $[O_3]$ relative to base $[O_3]$ ($\leq$26 ppb) and the bars show the 95% confidence intervals (CIs). Degree of freedom (d.f.) for each species is given in parenthesis. Mean $[O_3]$ is expressed on y-axis.

Impacts of Tropospheric Ozone on Pastures

- Ozone can induce shifts in species composition
  - e.g. the enhancement of grass species at the expense of legumes
- Decrease in grassland forage quality and hence livestock productivity.
  - Projected 4% decrease in UK lamb production (Hayes et al 2016)
- Differences between plant types:
  - Light-loving species tend to be more sensitive than shade-tolerant;
  - Plants of dry sites tend to be more sensitive than those found in more moist soils;
  - Plants tolerant of moderately saline conditions are more sensitive than those of nonsaline habitats Fuhrer et al (2016).

Impacts on forests: metrics

- Annual living biomass C stock in N Europe reduced by 10% compared to that under pre-industrial O_3 (Karlssson 2012, cited by Huttenen).
- Flux-based risk assessment of O_3 effects on forests is gradually superseding the exposure-based alternative (Tuovinen et al).

Impacts on non-food crops

- Ozone causes 5% loss of cotton yield in India (Ramanathan et al)

Outcome of future scenario modelling

Avnery et al 2011b modelled the impact in 2030 using the A2 and B1 storylines of the IPCC Special Report on Emissions Scenarios (IPCC SRES).

These represent upper- and lower-boundary projections, respectively, of most O_3 precursor emissions in 2030. (Next slide shows effect of scenario on predicted changes in precursor emissions)

The A2 world has less international cooperation than the A1 or B1 worlds. …….Global environmental concerns are relatively weak, although attempts are made to bring regional and local pollution under control and to maintain environmental amenities.

The central elements of the B1 future are a high level of environmental and social consciousness combined with a globally coherent approach to a more sustainable development.

Results:

- Yield losses, A2 scenario:
  - Wheat 5.4-26% (a further 1.5-10% from year 2000 values),
  - Soybean 15-9% (a further 0.9-11%),
  - Maize 4.4-8.7% (a further 2.1-3.2%),

  depending on the metric used, with total global agricultural losses worth $17-35 billion (an increase of $6-17 billion in losses from 2000).
- Yield losses, B1 scenario, less severe
  - Wheat 4.0-17%, Soybean 9.5-15%, maize 2.5-6.0% , worth $12-21 billion annually (an increase of $1-3 billion in losses from 2000).

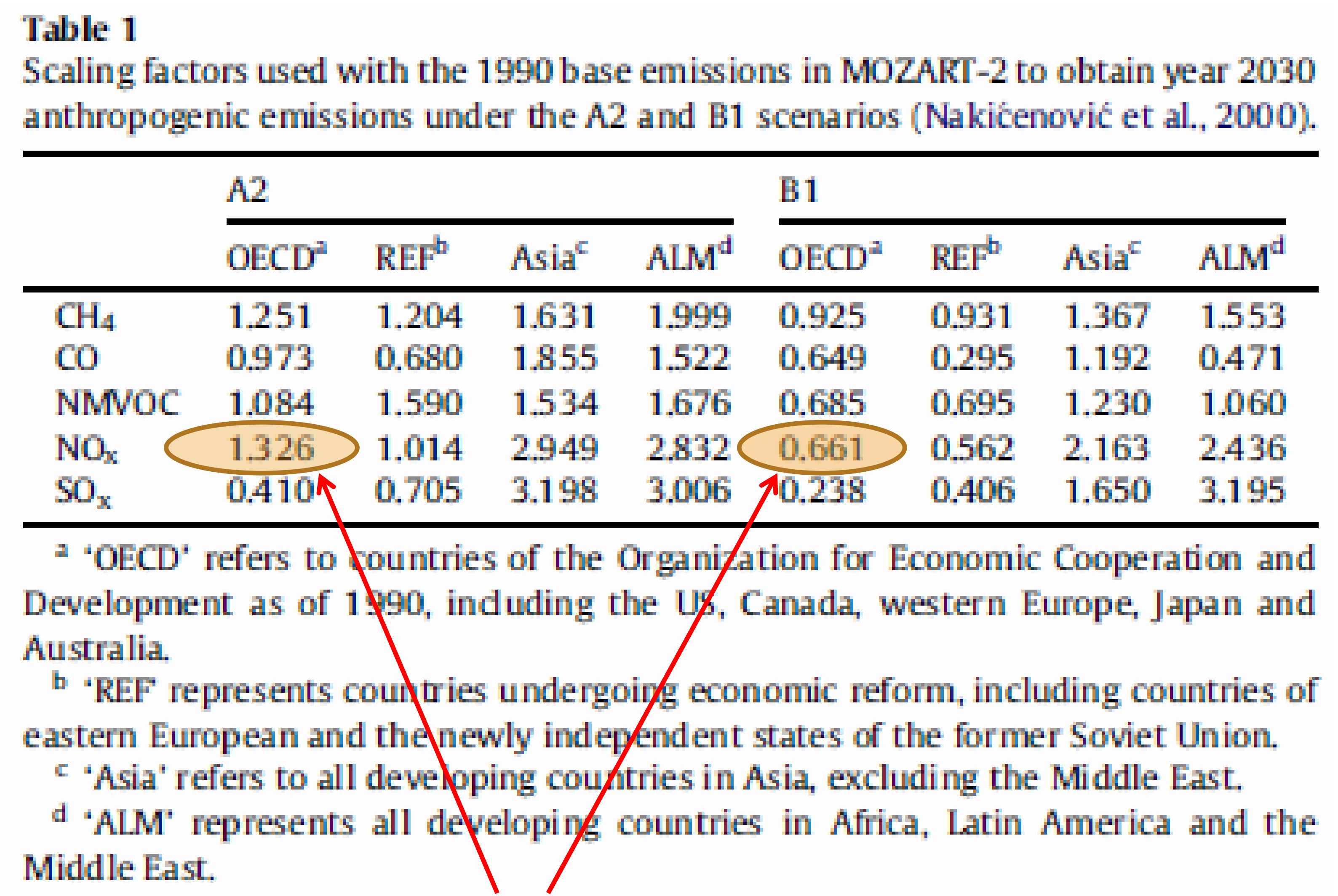


Table 1

Scaling factors used with the 1990 base emissions in MOZART-2 to obtain year 2030 anthropogenic emissions under the A2 and B1 scenarios (Nakićenović et al., 2000).

	A2				B1			
	OECD[a]	REF[b]	Asia[c]	ALM[d]	OECD[a]	REF[b]	Asia[c]	ALM[d]
CH_4	1.251	1.204	1.631	1.999	0.925	0.931	1.367	1.553
CO	0.973	0.680	1.855	1.522	0.649	0.295	1.192	0.471
NMVOC	1.084	1.590	1.534	1.676	0.685	0.695	1.230	1.060
NO_x	1.326	1.014	2.949	2.832	0.661	0.562	2.163	2.436
SO_x	0.410	0.705	3.198	3.006	0.238	0.406	1.650	3.195

[a] 'OECD' refers to countries of the Organization for Economic Cooperation and Development as of 1990, including the US, Canada, western Europe, Japan and Australia.

[b] 'REF' represents countries undergoing economic reform, including countries of eastern European and the newly independent states of the former Soviet Union.

[c] 'Asia' refers to all developing countries in Asia, excluding the Middle East.

[d] 'ALM' represents all developing countries in Africa, Latin America and the Middle East.

NOx up by a third, or down by a third, creating a two-fold difference

Shindell et al 2012 identified 14 measures targeting methane and BC emissions that would reduce projected global mean warming ~0.5°C by 2050.

Seven measures target CH_4 emissions from:

- coal mining,
- oil and gas production,
- long-distance gas transmission,
- municipal waste and landfills,
- wastewater,
- livestock manure,
- rice paddies.

The others ("BC measures") target emissions from incomplete combustion in:

- diesel vehicles,
- biomass stoves,
- brick kilns,
- coke ovens,

as well as regulatory measures including

- banning agricultural waste burning,
- eliminating high-emitting vehicles,
- providing modern cooking and heating.

They calculate that the measures would also

- avoid 0.7 to 4.7 million annual premature deaths from outdoor air pollution,
- increase annual crop yields by 30 to 135 million metric tons due to ozone reductions in 2030 and beyond.

Similar measures proposed by Maione et al 2015

Shindell, 2016 : Impact of climate-forcing agents

- Human induced emissions to date have led to an overall 9.5±3.0% decrease in agricultural yields worldwide, with about 93% of these losses caused by non-CO_2 emissions, in particular methane (-5.2±1.7%)
- In past, **yield increases** from CO_2 fertilization, and from cooling effects of NH_3, OC and SO_2 creating aerosols (Fig 5 below)
- **Projected losses 25±11% under high-emission scenario**
- Over the remainder of the 21st century, methane abatement appears to offer the greatest potential to limit agricultural yield losses.

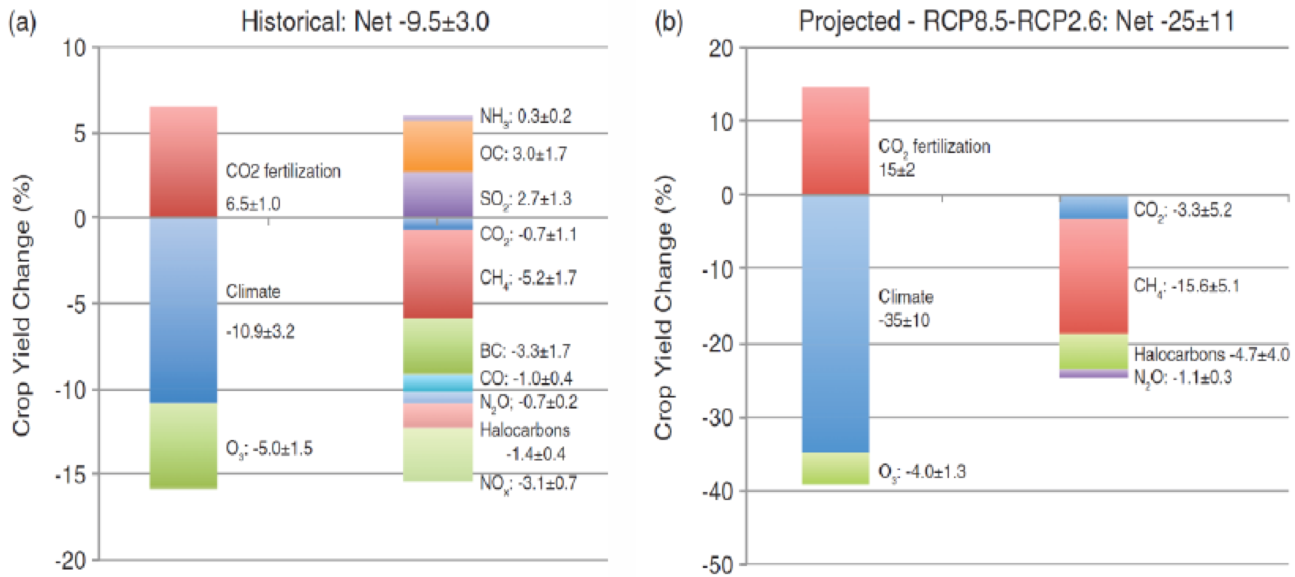


Figure 5: Historical and projected impacts of climate forcing agents on crop yield. Source: Shindell D.T.[23]

CH_4 emissions from manures

- The most promising way of reducing methane emissions from animal production seems to be the fermentation of slurry on an industrialised scale, and using the methane as an energy source
  - The trend towards larger animal enterprises that already exists, with associated mechanical handling of wastes and waste disposal, should help the development of digesters/fermenters.
  - In some regions, e.g. Western Europe and North America, technology is available which is capable of generating all the electricity requirements of the animal enterprise by using waste-derived methane, and even providing surplus electricity for sale.

CH_4 from rice

Downward trend in estimates of global methane emission from rice, as more data have become available

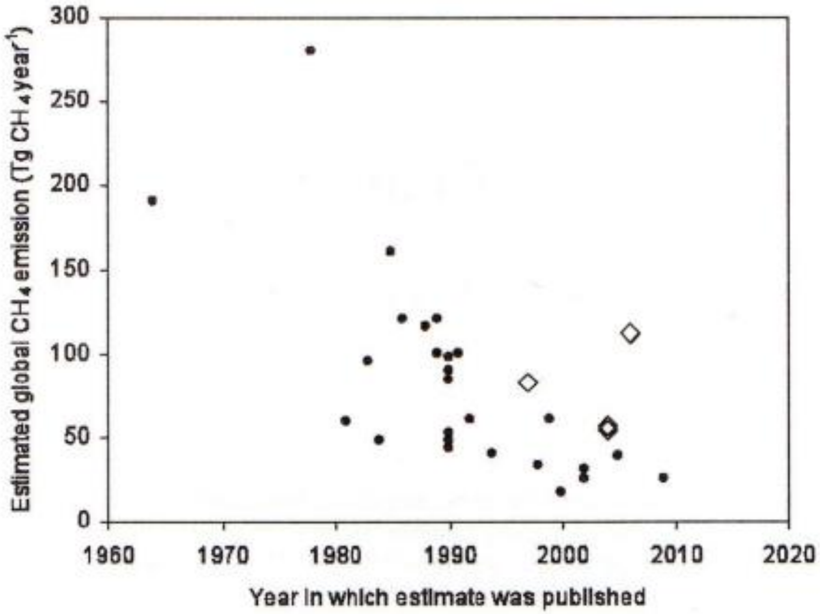
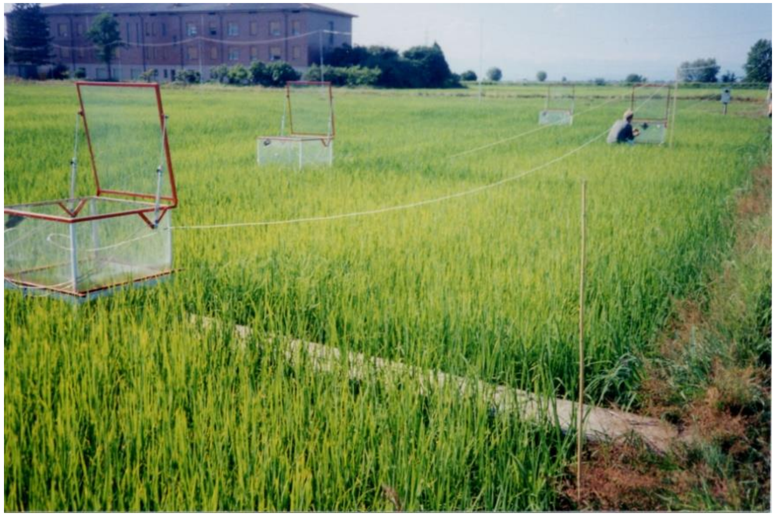


Figure 8.1 Decrease over time in estimates of global CH_4 emissions from rice fields.

Note: Large open symbols represent estimates from global inverse modelling (top-down method).
Source: Adapted from Sass (2002), with inclusion of the estimates by Fung et al (1991), Hein et al (1997), Olivier et al (1999, 2005), Scheehle et al (2002), Wang et al (2004), Mikaloff Fletcher et al (2004), Chen and Prinn (2006) and Yan et al (2009)

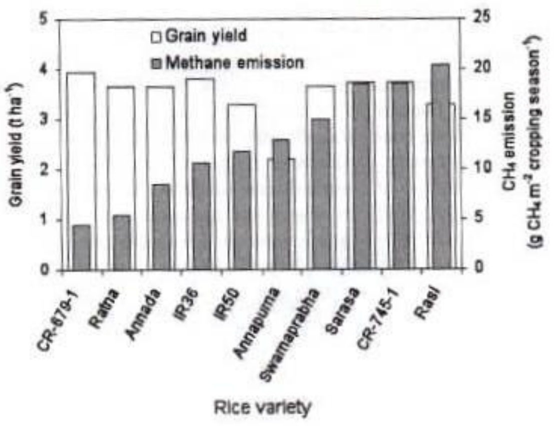


Options for mitigating methane emissions from rice fields include:

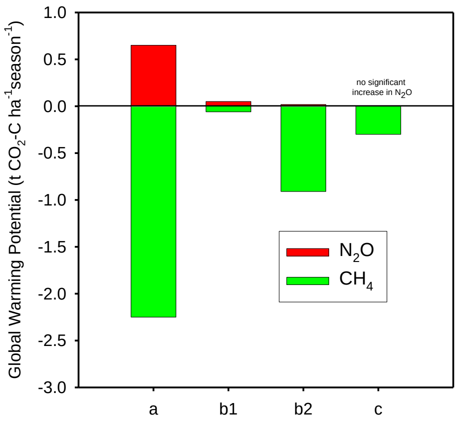
- the use of sulphur-containing inorganic fertilisers, e.g ammonium sulphate, to replace other currently used N fertiliser forms.
- more “upland rice” production (i.e. grown in a similar way to wheat, without any flooding)
- manipulation of the water regime of paddy rice, with delayed or interrupted flooding. Some increases in N_2O emissions ensue, but are generally much less in global warming terms than the CH_4 reductions.
- selection of varieties (and possibly use of GM techniques) to increase yield-to-emission ratios.

Rice varieties with different emissions

(Data of Satpathy et al, 1998)



Impact of flooding manipulation



(a) Delayed flooding, Italy (Leip et al., 2002);

(b1, b2) drainage at mid-tillering, Philippines (Bronson et al., 1997);

(c) intermittent draining, Japan (Yagi et al., 1996).

CH_4 Emissions from Ruminants

- There is substantial scope for improvement in the ratio of methane emitted by ruminant livestock to the amount of meat or milk produced,
  - Where normal agricultural development can improve feed quality;
  - and where there are no cultural and/or religious barriers to culling and replacing animals with improved breeds or genetic strains.

- "High-tech" solutions to the problem of ruminant methane emission seem unlikely to provide any major reduction in the near future.
  - Dietary additives can reduce enteric CH_4 formation, but no commercial adoption as yet.
  - Use of growth hormones such as bST give more meat or milk output, and thus less CH_4, per kg of product, but not acceptable in Europe. Animal welfare considerations push the balance in the opposite direction.

- Only a reduction in the ruminant herd seems likely to bring substantial reductions in emissions,
  - but growing demand for meat and milk is *increasing* global herd size (next slide).

Ruminants: steadily increasing number of animals, and increasing size.

Cattle and sheep numbers by country

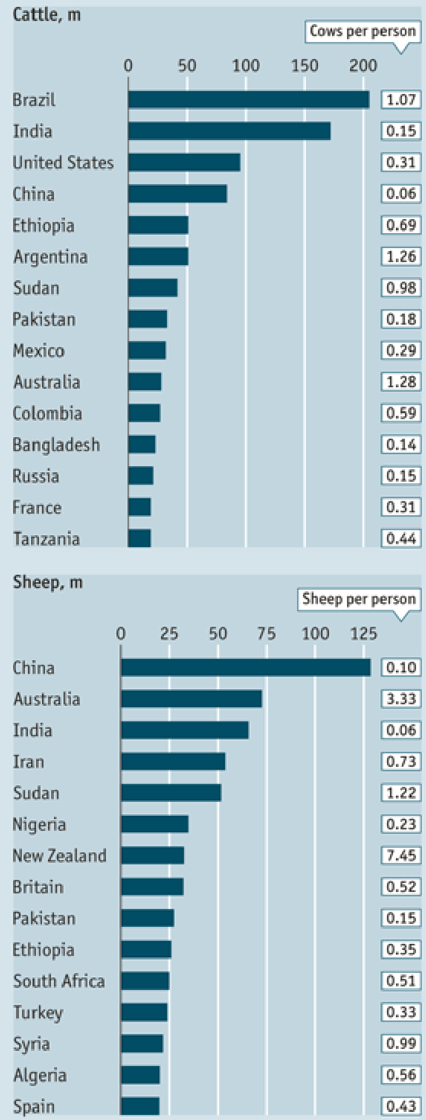
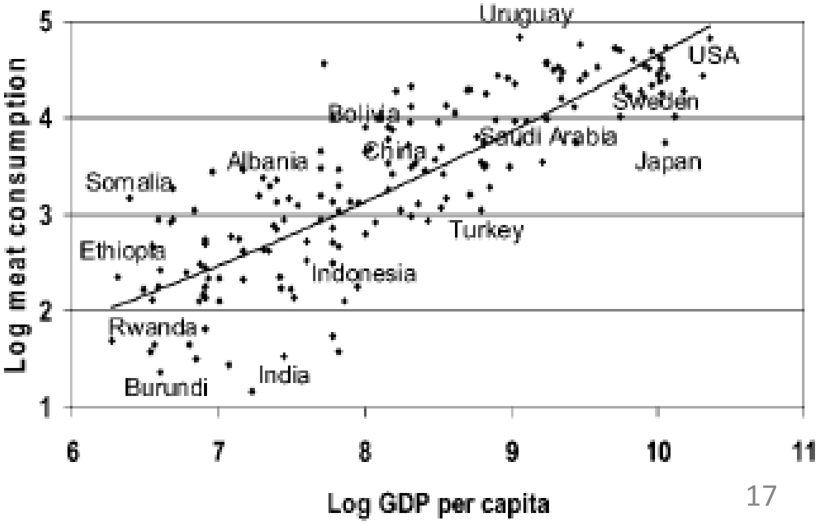


TABLE 5.3: Meat production: number of animals and carcass weight (FAO data)

	Number of animals (millions)				Number of animals (% p.a.)			Carcass weight (kg/animal)		
	1967/69	1987/89	1997/99	2030	1969 -1999	1989 -1999	1997/99 -2030	1967/69	1997/99	2030
World										
Cattle and buffaloes	1189	1418	1497	1858	0.8	0.5	0.7	174	198	211
Sheep and goats	1444	1708	1749	2 309	0.9	-0.1	0.9	14	14	17

Relationship between meat consumption and affluence as indicated by GDP per capita (Speedy, 2003)



Other pollutants: BC, SO_2 etc

Maione et al, 2015: BC-induced climate effects on agriculture:

- Impacts through the effect on temperatures, cloudiness, rainfall and river flow (via glacier melting);
- In regions affected by atmospheric brown clouds (ABCs) , surface warming due to GHGs and BC would decrease rice productivity, amplified by a decrease in monsoon rainfall;
- Of the total effect on agriculture of ABCs, 70% could be due to BC and OC
- Estimated losses from ABCs on rice harvest: 4 % (1966 to 1984) and 11 % (1985 to 1998) (Auffhammer et al., 2006)

Sulphur dioxide:

- From fossil fuel combustion, smelters
- Removal from atmosphere important from pollution control viewpoint,
  - but aerosol cooling has decreased yields (as shown above);
  - some crop yield decreases from reduction in S emission have occurred in N America and Europe, particularly in sandy soils. Readily remedied by adding S fertilisers.

Fluoride:

- From smelters, brickworks,
  - Localised effects, e.g. damage to fruit orchards, maize, mung beans in S Asia, damage to grapevines at 0.2-0.3 μg/m^3

Summary and conclusions

- Primary precursors of surface O_3 are NOx, NMHC, CO and CH_4
- O_3 increasing in E Asia, but has levelled off or is decreasing in W Europe, eastern US
- Biomass burning is major source of CO, NMVOCs and BC
- Main anthropogenic sources of CH_4 are fossil fuels, ruminants, landfills & waste
- Agriculture and biomass burning are responsible for almost half this CH_4
- Reduction in manure and rice emissions potentially easier than ruminant emissions
  - Global ruminant herd increasing steadily
- Significant yield losses in major crops due to O_3 have occurred, and modelling indicates these will get worse
  - But extent of impact very dependent on future emissions scenarios.
- 14 practical measures identified targeting methane and BC emissions, that would
  - reduce projected global mean warming ~0.5°C by 2050,
  - avoid millions of deaths from outdoor air pollution, and
  - substantially increase crop yields through O_3 reduction after 2030.