Reassessing optimal climate-change mitigation strategies through more explicit consideration of the role of time in impact assessments.

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Forest ⟶ pasture ⟶ forest

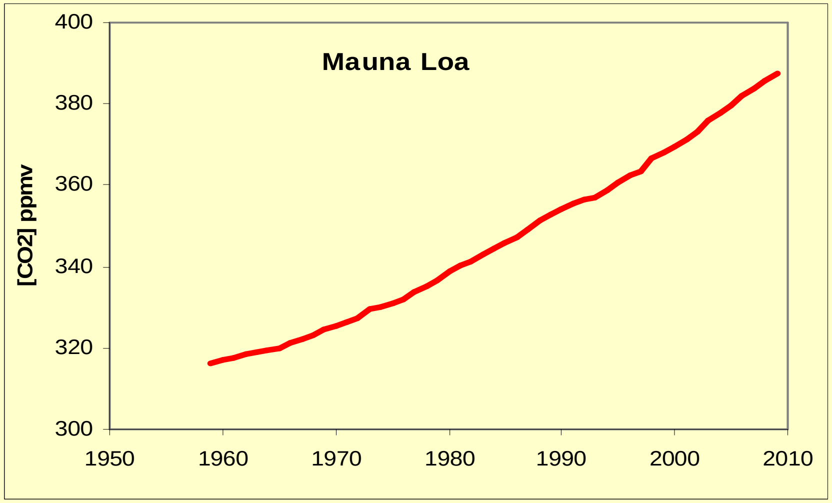
CO_2 with full carbon cycle

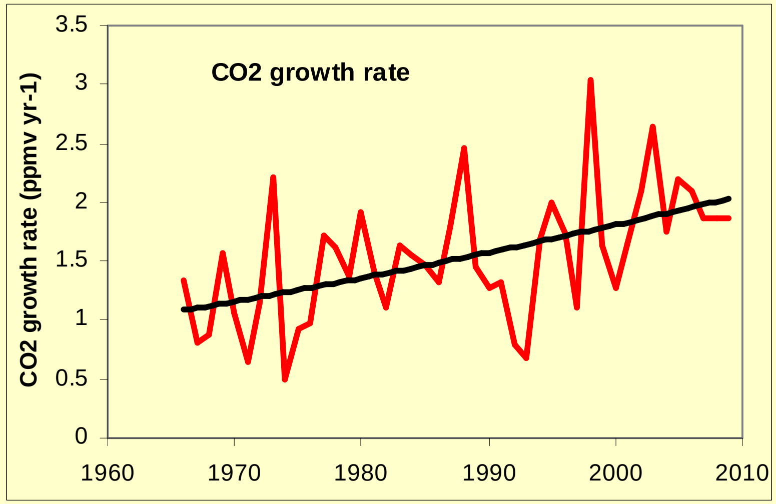
Nitrous oxide (long-lived gas)

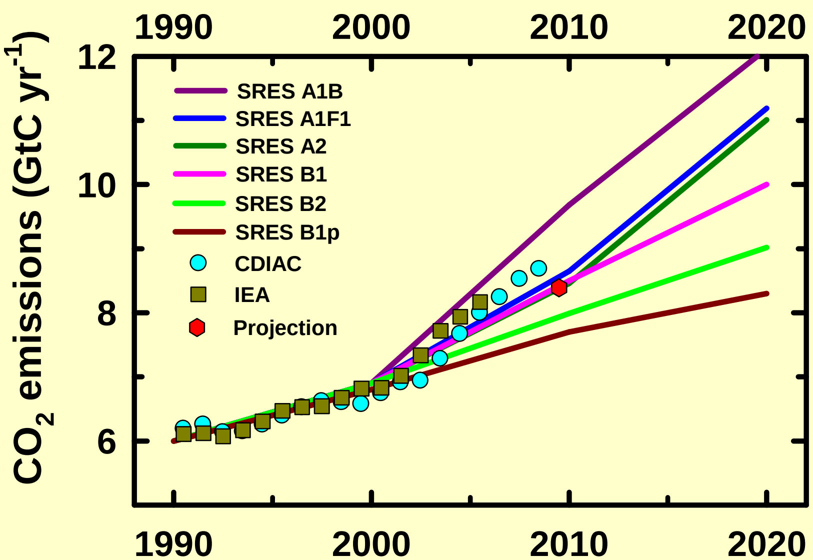
Methane (short-lived gas)

Albedo (surface reflectance)

CO_2 emissions are rising fast



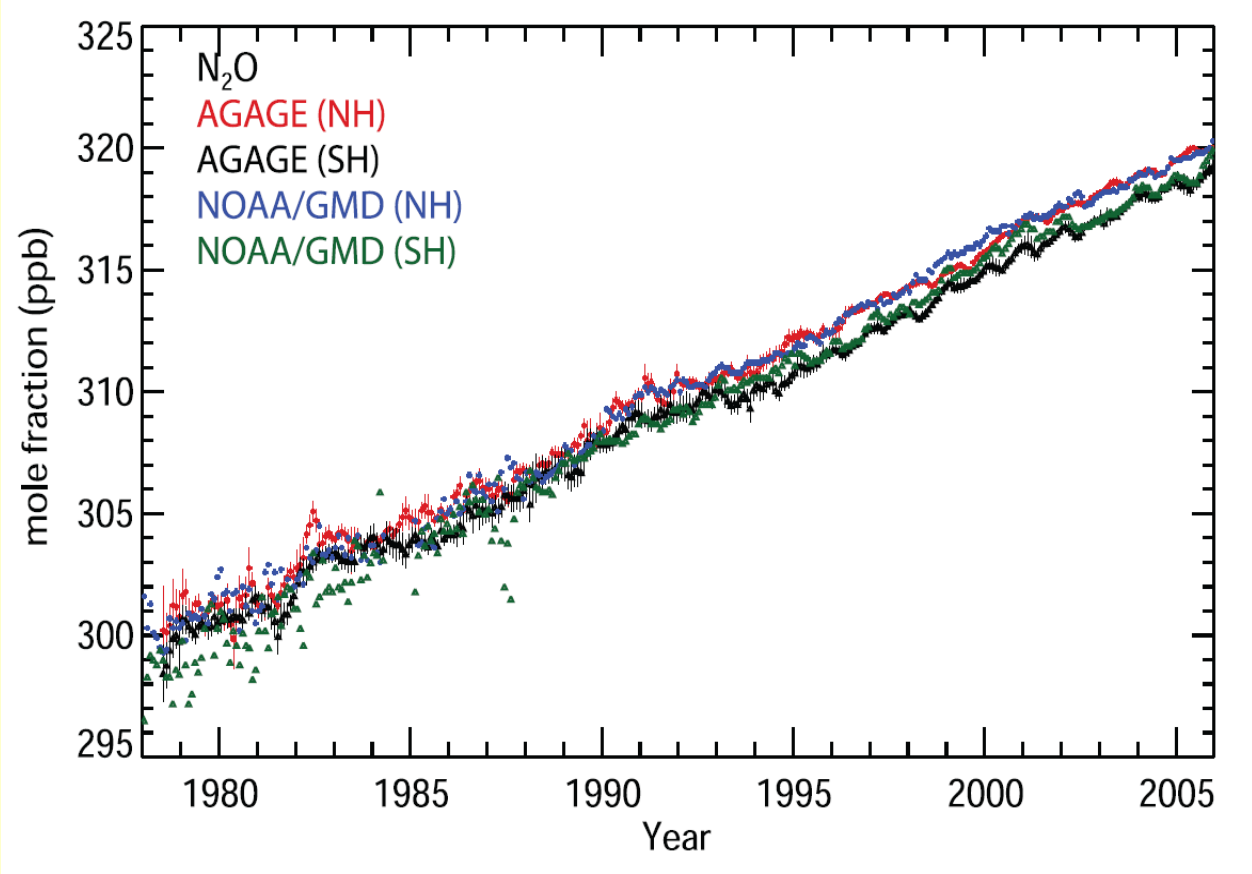




Key points:
CO_2 concentrations are rising rapidly, with annual growth rate now being about 2 ppmv yr^{-1}. The atmospheric increase is driven primarily by the large emissions from the burning of fossil fuels. Observed emissions are at the upper range of IPCC scenarios.

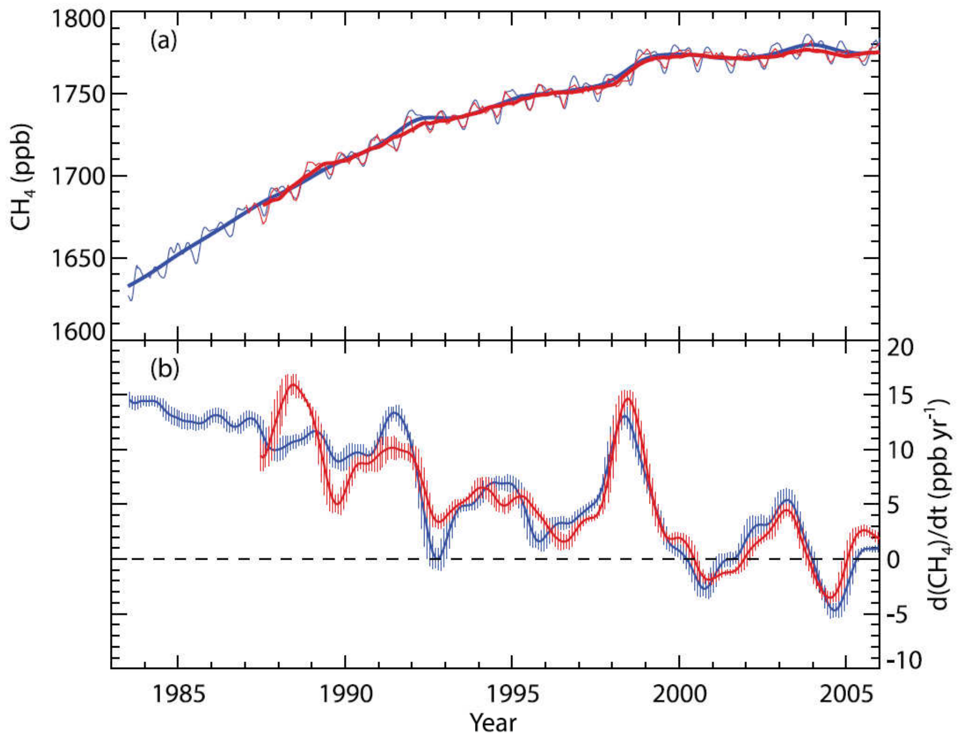
Raupach et al. (2007); Steffen (2009); NOAA (2009); IMF (2009)

Nitrous oxide



Key points:
N_2O concentrations have been going up steadily for at least the past 25 years. While concentrations are low, they are nonetheless important because N_2O has powerful radiative absorptive properties.

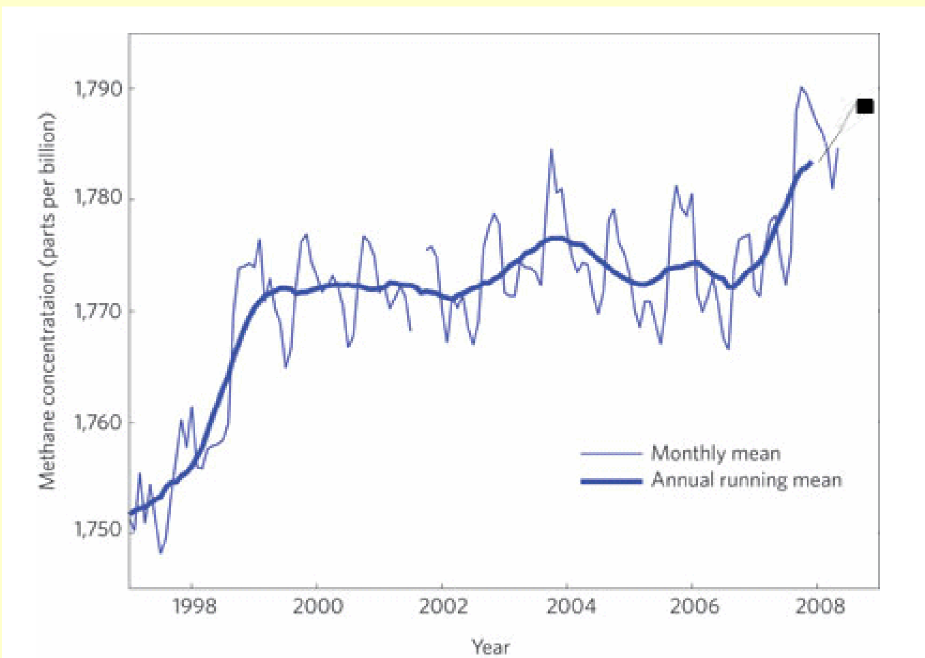
IPCC (2007)



Methane

IPCC (2007)

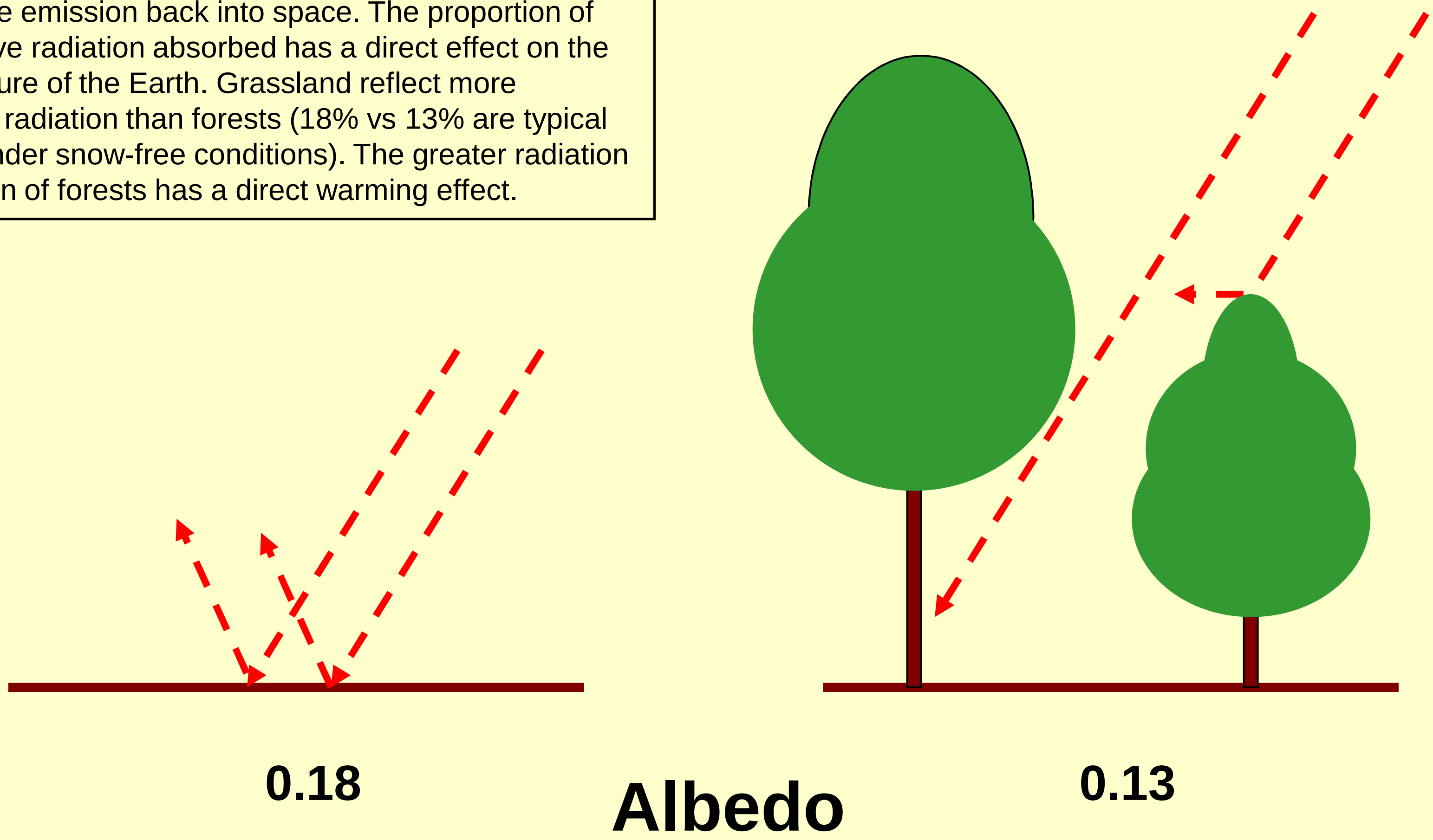
Key points:
Methane concentrations have more than doubled since pre-industrial times, then appeared to have stabilised by about 2000. The most recent measurements suggest, however, that its atmospheric concentration has started to increase again.



NOAA (2009)

Forests absorb more radiation than pastures

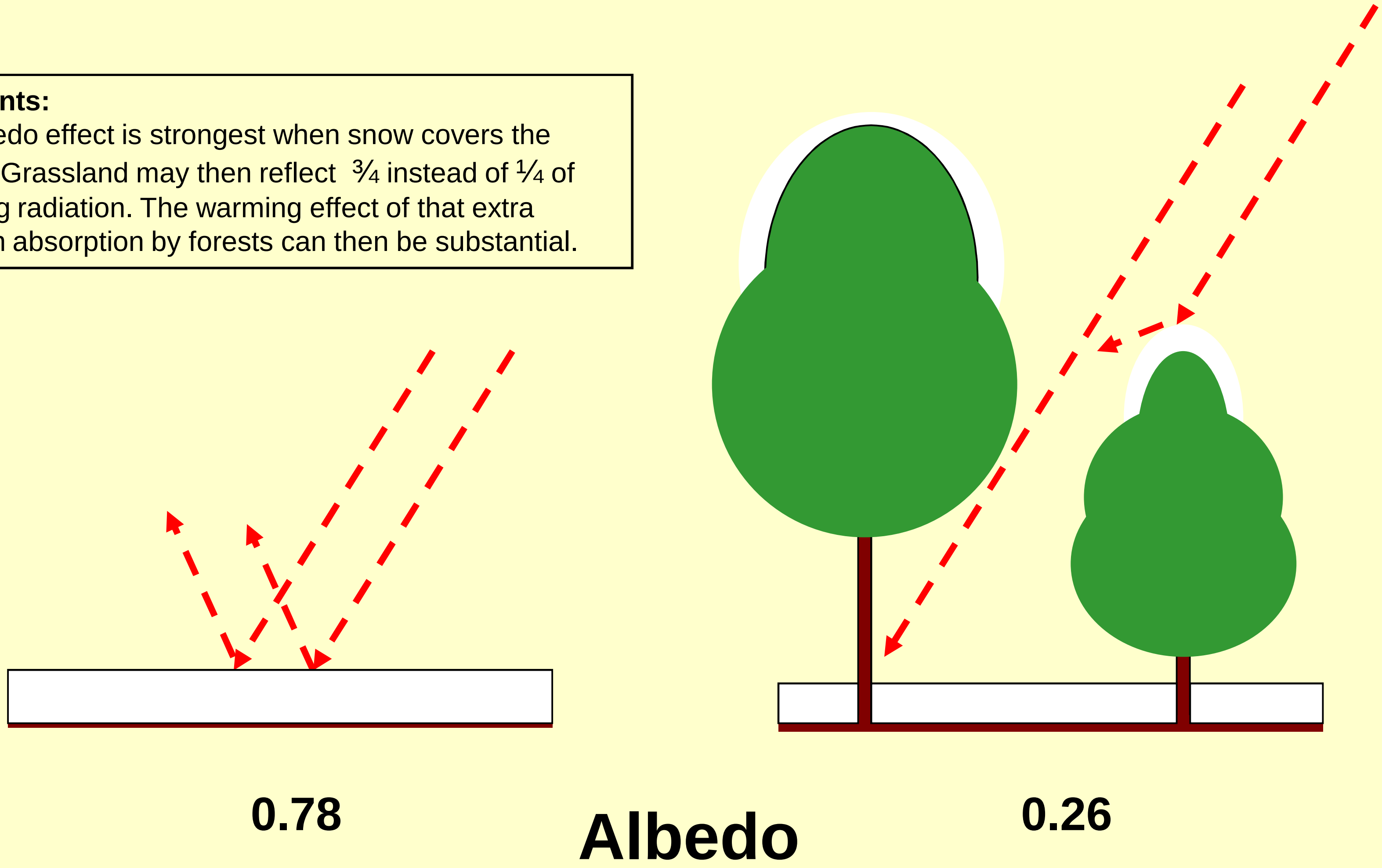
Key points:
The Earth receives basically all of its energy as short-wave radiation from the sun which must be balanced by long-wave emission back into space. The proportion of short-wave radiation absorbed has a direct effect on the temperature of the Earth. Grassland reflect more incoming radiation than forests (18% vs 13% are typical values under snow-free conditions). The greater radiation absorption of forests has a direct warming effect.



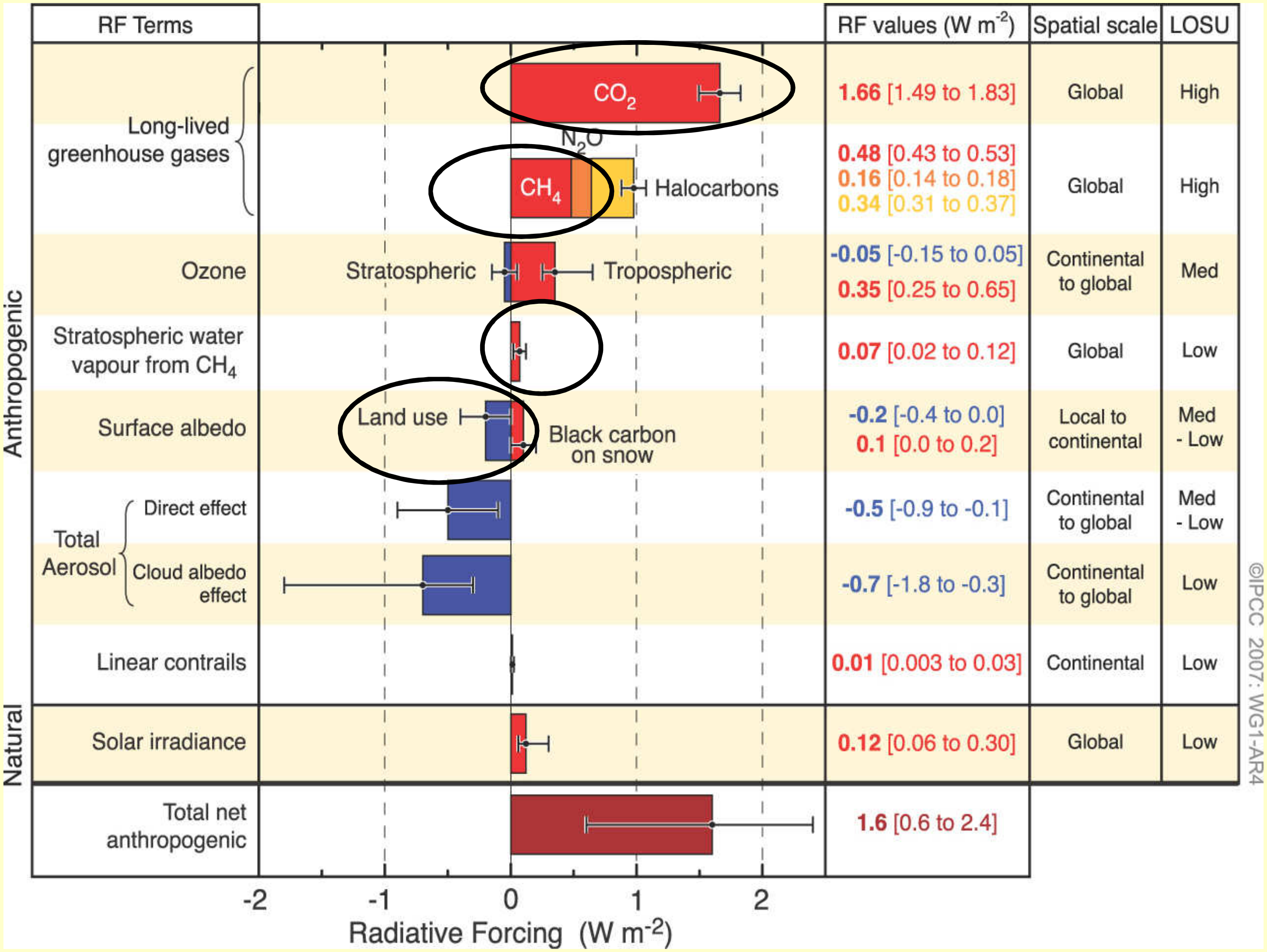
Betts (2000)

Forests absorb more radiation than pastures, especially with a snow cover

Key points:
The albedo effect is strongest when snow covers the ground. Grassland may then reflect ¾ instead of ¼ of incoming radiation. The warming effect of that extra radiation absorption by forests can then be substantial.



Betts (2000)

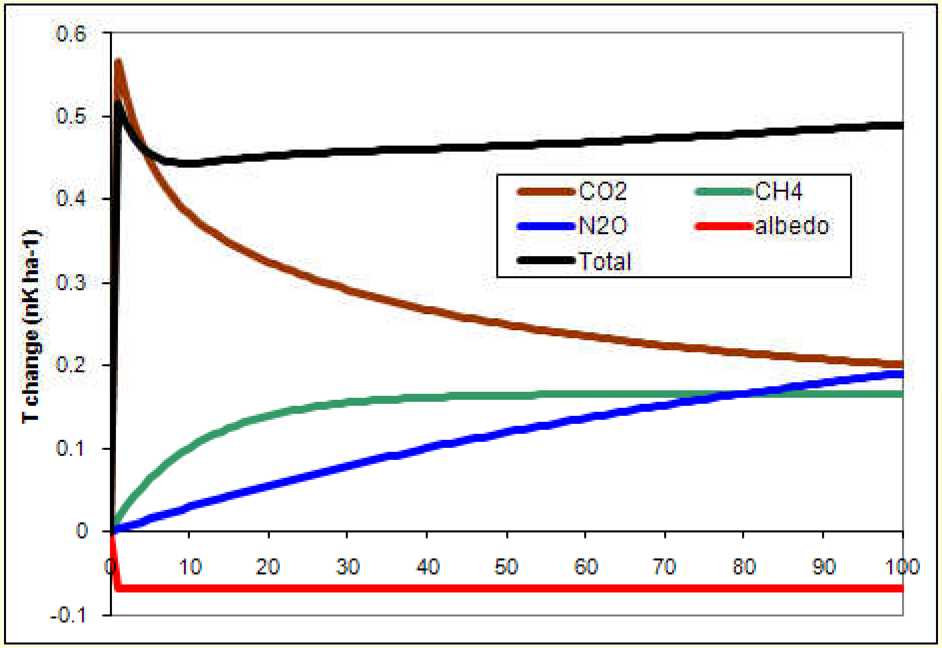


Key points:
This graph shows the contribution to observed radiative forcing changes by all radiative forcing agents. The radiative forcing agents affected by land-use change are circled.

IPCC (2007)

Deforestation

Dairying



Methane: 240 kgCH_4 ha^{-1} yr^{-1}
Nitrous oxide: 10 kgN_2O (N) ha^{-1} yr^{-1}
Forest: 200 tC ha-1
Albedo: 0.13 and 0.18 (forest, pasture)

CH_4 and N_2O emission factors from Saggar (pers. comm.)

Key points:
The graph shows the contribution to global warming for 1 ha converted from forest to dairying. It converts radiative forcing directly into temperature changes and the lag between radiative forcing and temperature changes is ignored in these calculations.
Albedo changes at the time of land-use change and makes an on-going cooling contribution.
N_2O is added year after year to cumulatively add to its warming contribution.
CH_4 adds to warming for some years, but then an equilibrium is reached, with new added CH_4 balancing the loss of methane emitted in earlier years.
CO_2 makes a one-off large contribution when the original forest is cut. Some of that atmospheric CO_2 is taken up by the oceans to lower the warming effect of the originally emitted CO_2 over later years.

Deforestation

Dairying

Integrals over 100 years

CO_2	27.5 (51%)
CH_4	14.9 (28%)
N_2O	11.2 (21%)
Albedo	-6.8 (-13%)
Total	46.7

Methane: 240 kgCH_4 ha^{-1} yr^{-1}
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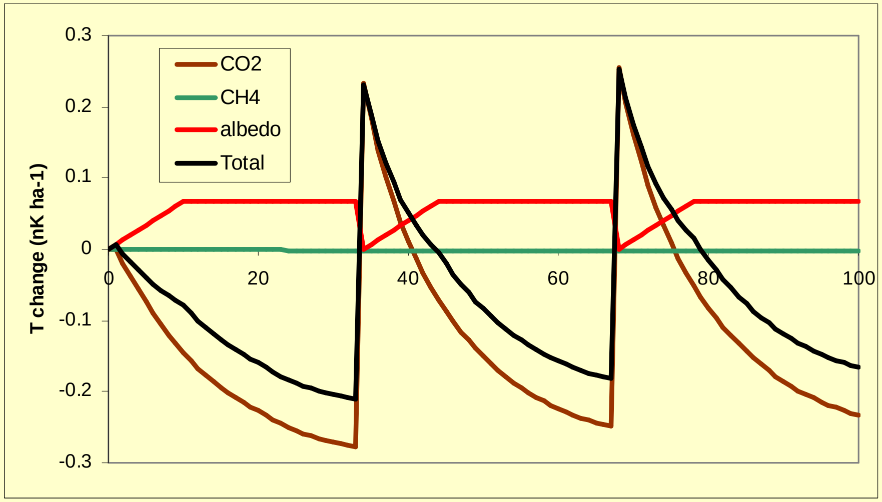
CH_4 and N_2O emission factors from Saggar (pers. comm.)

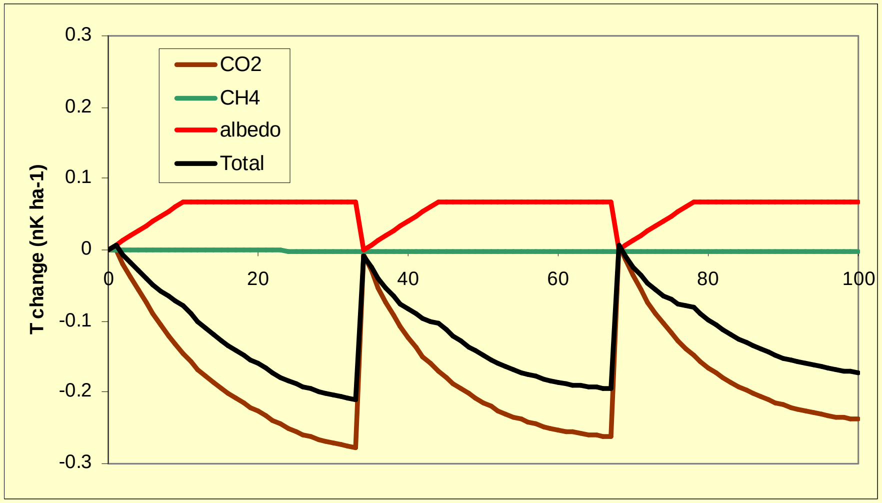
Key points:
This shows the integrated effect of warming effect in individual years integrated over 100 years. CO_2 contributes about half of total warming and CH_4 and N_2O about a quarter each. Albedo changes offset the warming effect by about 10-20%. These relativities are strongly affected by the magnitude of respective emissions of the different greenhouse gases. The numbers here are based on New Zealand numbers for dairying, which have high emissions of methane and nitrous oxide. It is also based on large numbers for carbon loss which are based on the emission when a mature *Pinus radiata* stand is felled.

Reforestation

Wood for paper use



With wood products



Model assumptions:
33-year rotations, albedo increase over 10 years, no methane or nitrous oxide emissions from forests.
Paper use – immediate loss
Wood products: 50% of biomass, exponential decay with 25-yr time constant

Key points:
When pastures are reforested, the C storage in trees has a cooling effect. That is partly negated as albedo decreases, with a warming effect. When trees are harvested, C storage gains are reversed. Atmospheric CO_2 is even higher (with a net-warming effect) than it would have been without temporary carbon storage in trees because ocean uptake is reduced over the time when atmospheric CO_2 is lowered by C storage in trees.
This pattern is much less pronounced when longer-lived wood products are produced and extended the period of time over which C is held out of the atmosphere.

Reforestation

Wood for paper use

	Actual	With credit
CO_2	-12.8	-12.8 (-38%)
CH_4	-0.1	-11.5 (-34%)
N_2O	0	-9.8 (-29%)
Albedo	5.8	5.8 (17%)
Total	-7.1	-28.4

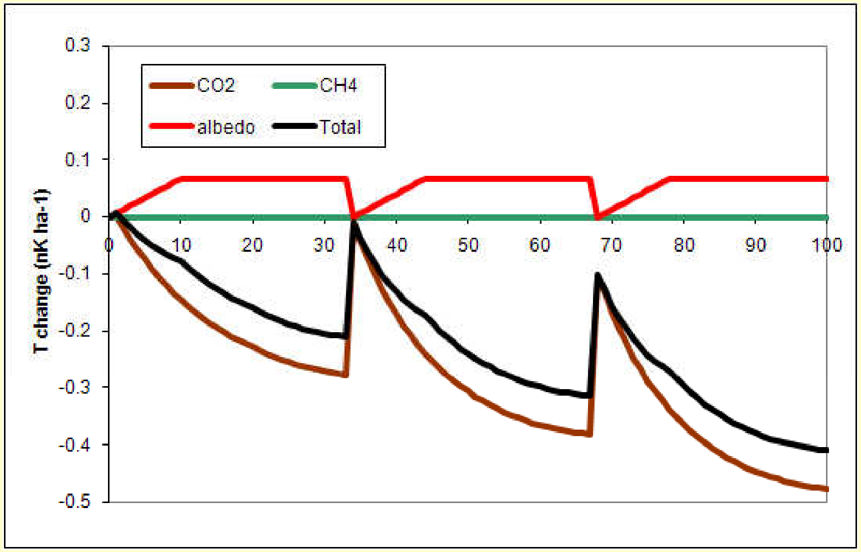
With wood products

	Actual	With credit
CO_2	-18.1	-18.1 (-46%)
CH_4	-0.1	-11.5 (-29%)
N_2O	0	-9.8 (-25%)
Albedo	5.8	5.8 (15%)
Total	-12.5	-33.7

Key points:
This shows the integrated cooling effect from reforestation in individual years integrated over 100 years. It is shown both for the actual emissions (assuming no methane or nitrous oxide emissions from forests), or with inclusion of credits for avoided emissions that would have occurred from on-going pastoral activity. Looking at the numbers with credit, and for wood products used for paper, CO_2 ,CH_4 and N_2O each contribute about the same to overall cooling, and albedo changes offset the benefit by about 15-20%.
When long-lived wood products are produced, the benefit of reforestation increases, but the effect is not huge, increasing the carbon benefit by about 50% (from 12.8 to 18.1), but for all radiative agents combined, it increases the benefit by only 15% (from 28.4 to 33.7)

Reforestation

Bioenergy



	Actual	With credit
CO_2	-27.5	-27.5 (-56%)
CH_4	-0.1	-11.5 (-24%)
N_2O	0	-9.8 (-20%)
Albedo	5.8	5.8 (12%)
Total	-7.1	-43.1

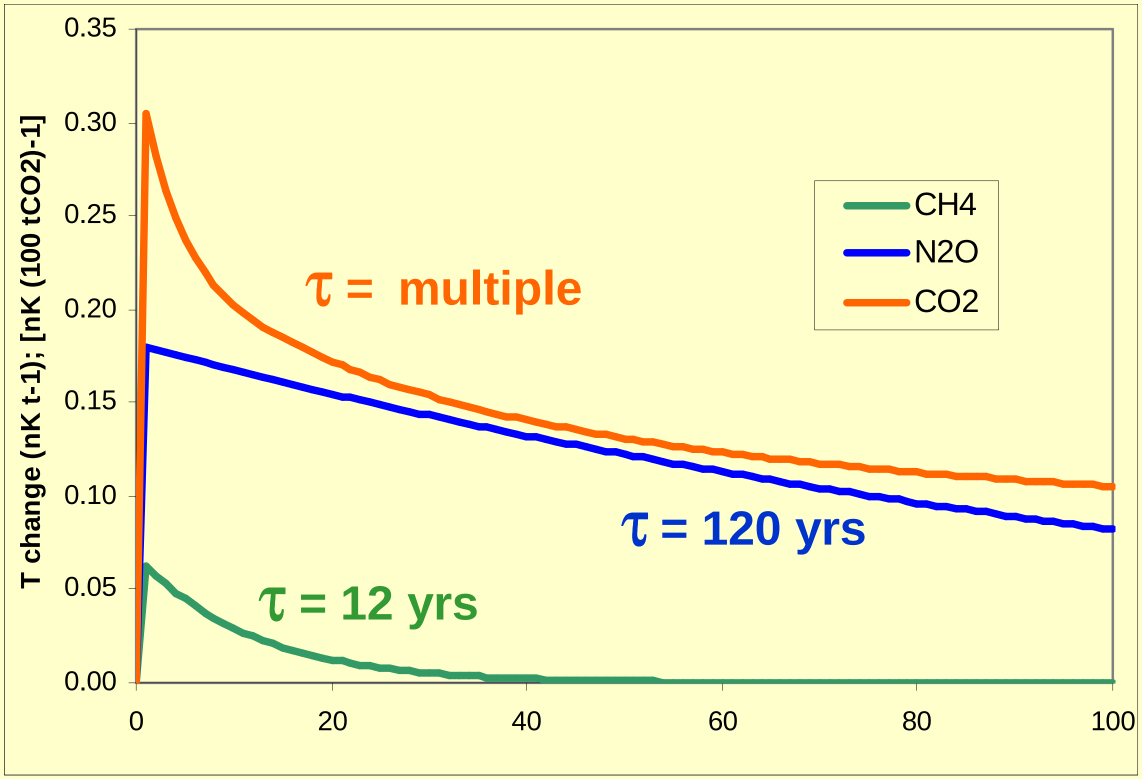
Key points:
When bioenergy can be generated from wood products (and thereby replace CO_2 release from burning fossil fuels), it has the same benefits as shown on previous slides, and additionally generates on-going and accumulating benefits through fossil-fuel substitution. If further increases the benefit of reforestation.
The increased benefit is also not large, but can accrue beyond the 100-year analysis horizon.

Reforestation (100-yr gains) [nK ha^{-1} (100 yr)$^{-1}$]

	CO_2	Total
No harvest	-23.6	-38.5
Short-rotation 15 years (paper use)	-5.0	-21.5
Short-rotation 33 years (paper use)	-12.8	-28.4
Short-rotation (construction wood)	-18.1	-33.7
Short rotation (bioenergy)	-27.5	-43.1

Key points:
This summarises the benefit of different reforestation options by considering only CO_2 effects or all effects, including those from avoided pastoral emissions and avoided fossil-fuel emissions.
Short rotations with wood used for paper has the lowest benefit. It increases with length of the rotation, or when wood is used for construction purposes. Wood used for bioenergy has the greatest benefit because of the on-going and accruing substitution of fossil fuels. Over 100 years, the benefit of a bioenergy plantation is comparable to that of a permanently re-established forest.
Differences between options are quite marked if one considers only CO_2 benefits, but options are more similar if one looks at the total effect from all radiative agents as their effect is similar for all forest-use options.

A closer look at time



Key points:
The different greenhouse gases have quite different atmospheric lifetimes. The atmospheric lifetimes of methane and nitrous oxide are usually described with first-order decay kinetics of 12 and 120 years, respectively, and CO_2 is described with multiple decay constants for different fractions of emitted CO_2. These different turn-over times affect their respective climatic impacts.

Which aspect of climate change impacts us most?

Instantaneous climatic conditions?

- Heat damage
- Severe weather
- Tropical diseases (e.g. malaria)
- Food production

Rate of climate change?

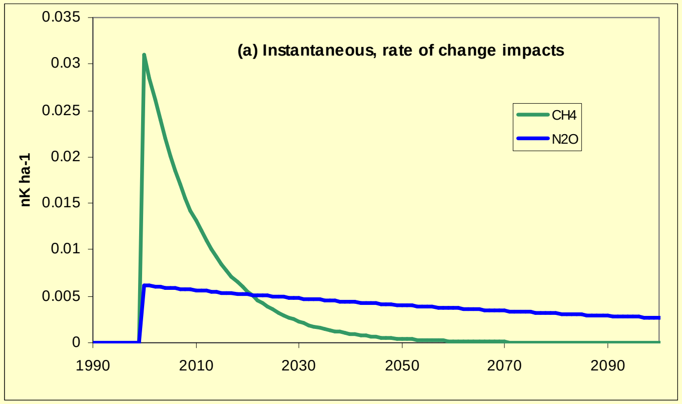
- Ecological mal-adaptation
- Socio-economic institutions

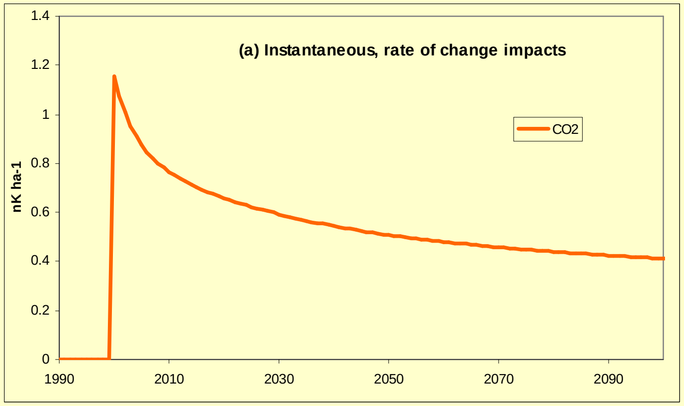
Cumulative climate change?

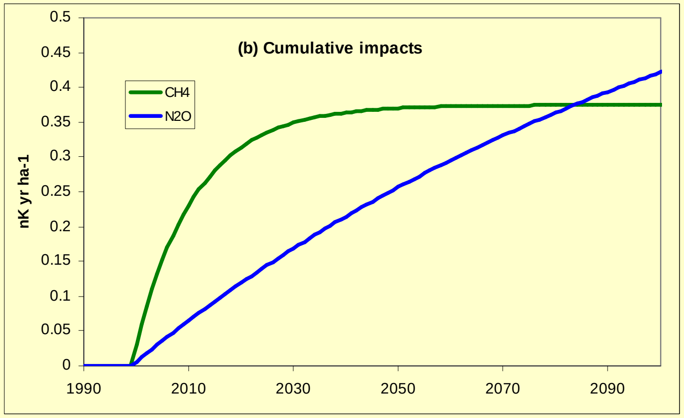
- Sea level rise

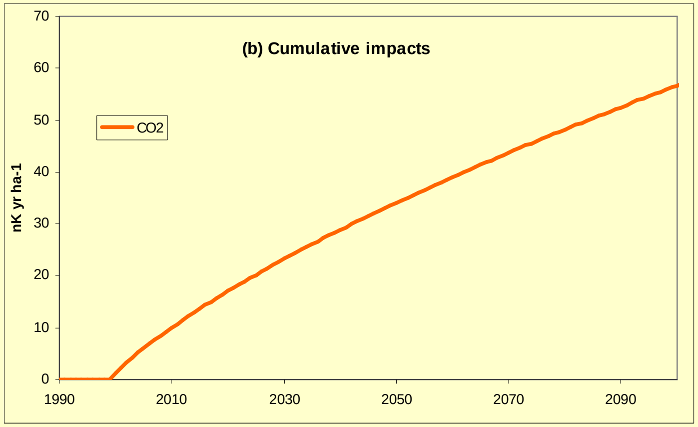
Key points:
These different climatic impacts require very different quantifications. Instantaneous climate impacts are quantified directly as a function of temperature itself. Rate of change impacts are quantified as a function of temperature divided by the time over which a temperature increase has occurred.
Cumulative temperature impacts are quantified through summing the temperature increases over the number of years over which they occur.

A detailed look at impacts (from 1 year's worth of emission)









Key points:
The top graphs give the instantaneous and rate of change impact due to a single one-off emission of a unit of greenhouse gas. It shows that N_2O and CO_2 emitted in 2000 still have a substantial warming impact in 2100 whereas all methane emitted in 2000 will have been oxidised well before 2100.

Key points:
The bottom graphs show that in terms of cumulative temperature impacts, a unit of gas emitted of all three gases will add to the cumulative impact experienced in 2100. In the case of CO_2 and N_2O, the cumulative impact will further continue to increase beyond 2100.
Traditional greenhouse warming potentials are calculated with an approach similar to that used to calculate cumulative temperature impacts.

Greenhouse Warming Potentials
or
Climate Change Impact Potentials (CCIP)
(relative to CO_2, 100 year horizon)

Current	CCIP
$CH_4 = 25$	$CH_4 \approx 9$
$N_2O = 298$	$N_2O \approx 298$

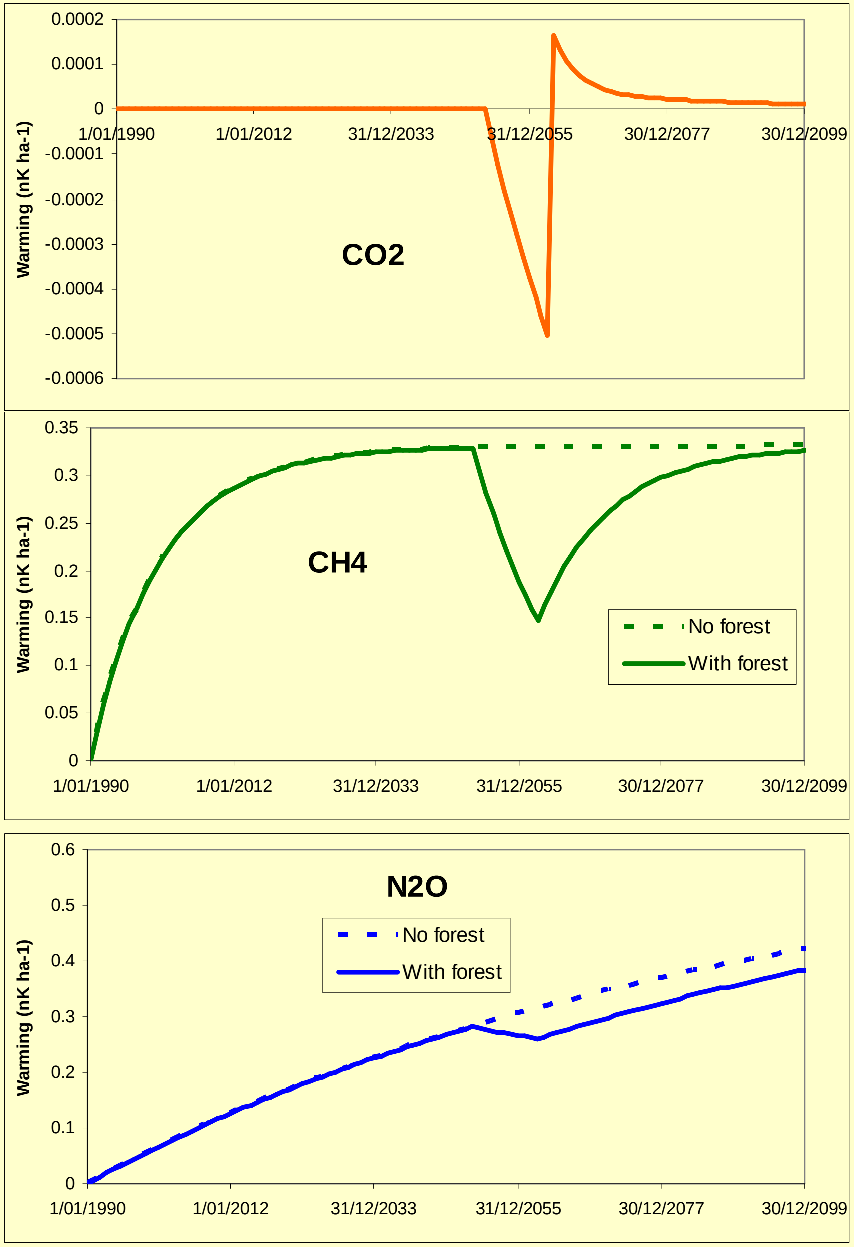
Key points:

If one

a) defines the mitigation goal to minimise the most severe climatic impacts expected to be experienced by the end of this century; and
b) gives each of the three kinds of the climatic impacts (defined above) equal weight, then
c) that would not make much difference for the quantification of N_2O relative to CO_2; but
d) it would greatly reduce the calculated (impact-weighted) warming potential of methane from 25 to about 9.

This would have significant implications for the relative importance attached to the emission of different greenhouse gases and the urgency in controlling their respective emissions. It would mean that short-term emission controls should focus primarily on the long-lived gases N_2O and CO_2, whereas emission control of methane can be given somewhat lower priority in the near term.

An example: The effect of short-term plantations



10-year plantations on pasture, cease CH_4 and N_2O emissions for 10 years; wood growth for 10 years, then harvested with immediate release of CO_2.

Key points:

This assesses the mitigation effect of planting a forest in 2050, cutting it after 10 years and thereafter immediately releasing the temporarily stored carbon.

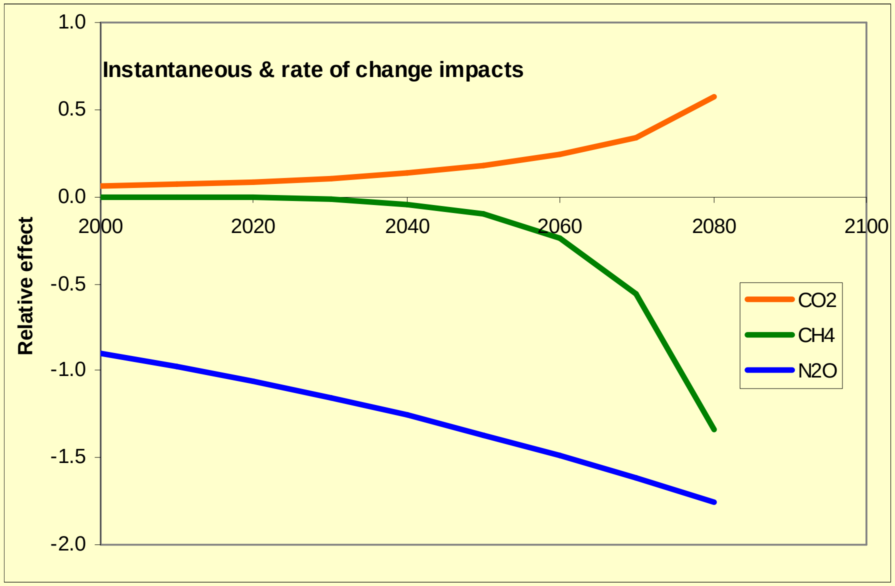
Atmospheric CO_2 is decreased while the forest is storing carbon, but after re-release of the carbon in the forest, atmospheric CO_2 is higher than it would have been without temporary storage. Hence, atmospheric CO_2 and temperature in 2100 will be higher than without the 10-year plantation.

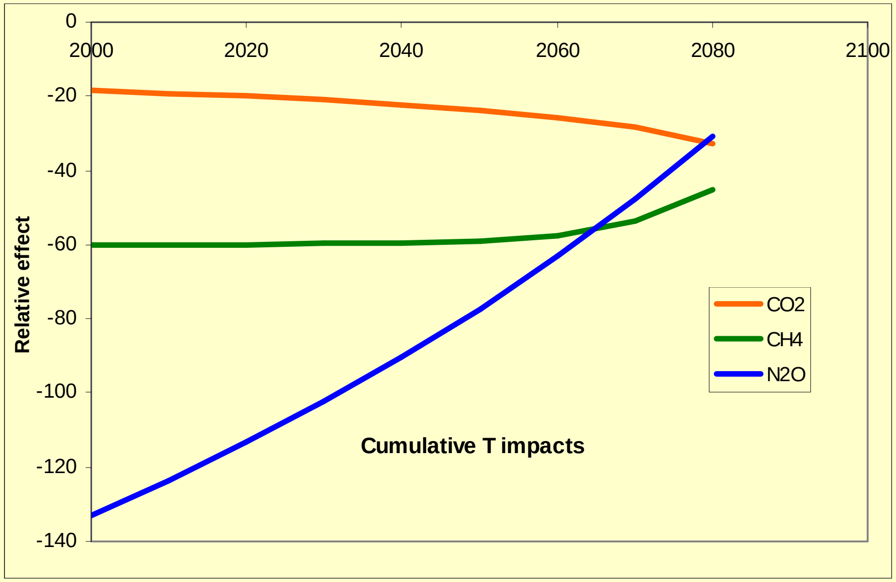
Methane radiative forcing decreases while the land is under forest, but the gains are lost over the following decades. By 2100, there is only a very small benefit remaining.

The N_2O concentration falls while land is under forest, and the gain is maintained to 2100 and beyond.

An example: The effect of short-term plantations

Analysed by effect on ameliorating most severe impacts to 2100.





Key points:

It shows that a short-term plantation would marginally **worsen** instantaneous and rate of change impacts related to CO_2, and more so for plantations established later in the century, but it ameliorates cumulative temperature impacts.

For methane, plantations established before about 2050, have almost no effect on instantaneous and rate of change impacts but improve cumulative temperature impacts. Only plantations established later can also improve instantaneous and rate of change impacts.

For nitrous oxide, plantations established at any time affect significant amelioration of all kinds of impacts, and for cumulative temperature impacts, the benefit diminishes almost linearly with any delay in establishing those plantations.

Climate change impacts (the key questions)

Instantaneous climatic conditions?

Rate of climate change?

Cumulative climate change?

Give equal weight? Or is one more important than others?

Minimise the most severe impacts? To 2100?

Impacts weighted (e.g. $I_{targ} = \Sigma I^s$, with $s > 1$)?

Apply discount factors? Is the future less important than the present?

Traditional GWPs assume the answers without asking the questions

Conclusions

- CO_2, CH_4, N_2O are of comparable significance under LUC
- Albedo changes are opposite in their effect to that of greenhouse gases by (≈10-20%) and more in snow-covered areas
- Impact assessment should quantify impacts in detail, esp. cumulative vs instantaneous
- The importance of methane is over-rated.

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