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Global temperature change potential of nitrogen use in agriculture: A 50-year assessment

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Nitrogen (N) use in agriculture substantially alters global N cycle with the short- and long-term effects on global warming and climate change. It increases emission of nitrous oxide, which contributes 6.2%, while carbon dioxide and methane contribute 76% and 16%, respectively of the global warming. However, N causes cooling due to emission of NO_x , which alters concentrations of tropospheric ozone and methane. NO_x and NH_3 also form aerosols with considerable cooling effects. We studied global temperature change potential (GTP) of N use in agriculture. The GTP due to N_2O was 396.67 and 1168.32 Tg CO_2e on a 20-year (GTP_{20}) and 439.94 and 1295.78 Tg CO_2e on 100-year scale (GTP_{100}) during years 1961 and 2010, respectively. Cooling effects due to N use were 92.14 and 271.39 Tg CO_2e (GTP_{20}) and 15.21 and 44.80 Tg CO_2e (GTP_{100}) during 1961 and 2010, respectively. Net GTP_{20} was 369.44 and 1088.15 Tg CO_2e and net GTP_{100} was 429.17 and 1264.06 Tg CO_2e during 1961 and 2010, respectively. Thus net GTP_{20} is lower by 6.9% and GTP_{100} by 2.4% compared to the GTP considering N_2O emission alone. The study shows that both warming and cooling effects should be considered to estimate the GTP of N use.

Nitrogen is the most limiting nutrient controlling the primary production of agricultural systems. Intensively cultivated systems require external application of N to increase and sustain global food production. Consumption of fertilizer N has increased globally from ~12 Tg in 1960 to ~113 Tg in 2010¹. If current N consumption trends continues, considerably higher amount of fertilizer N will be used in agriculture to provide food for an additional 2 billion people by 2050². The N cycle involves five steps i.e., N fixation ($\text{N}_2 \rightarrow \text{NH}_3/\text{NH}_4^+$), nitrification ($\text{NH}_3/\text{NH}_4^+ \rightarrow \text{NO}_3^-$), assimilation (uptake of NH_4^+ and NO_3^- into plant tissues), ammonification (organic N $\rightarrow \text{NH}_3$) and denitrification ($\text{NO}_3^- \rightarrow \text{N}_2$)³. During the N cycle several reduced (NH_3) and oxidised N compounds (NO_x , NO, N_2O , NO_3^-) are emitted to the atmosphere affecting the climate system⁴.

Climate change due to emission of greenhouse gases (GHGs) viz. carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) contributing 76.0%, 16.0% and 6.2%, respectively is likely to affect agricultural productivity and food security adversely⁵. Addition of N in agricultural soil alters the fluxes of GHGs^{6–8}. The reactive N (Nr) has direct as well as indirect effects on N_2O emission from agricultural soil^{9–12}. Emission of N_2O is a major concern because of its long atmospheric lifetime (about 116 years), higher global warming potential (GWP) i.e., 310 times that of CO_2 ⁵ and high global temperature change potential (GTP) of 290 on 100-year basis¹³.

The GWP is the global mean radiative forcing of 1 kg pulse emissions of a greenhouse gas relative to 1 kg of reference gas i.e., CO_2 ¹⁴. The GWP is an index of time-integrated radiative forcing. However, it does not give a quantitative information on effect of GHG emission on global temperature^{13,15,16}. The GTP is the global average temperature change at time t due to emission of a GHG relative to CO_2 emission^{13,17}. The GTP is directly related to surface temperature changes as a result of GHG emission. Thus GTP has an advantage in quantifying temperature change compared to GWP.

In addition to N_2O emission, N use in agriculture results in increased emission of NH_3 and NO_x contributing to climate change indirectly¹⁸. The NO_x impacts global warming by (i) formation of ozone (O_3), which contributes to warming¹⁹ and (ii) removal of CH_4 by hydroxyl radical, thus contributing to cooling²⁰. Moreover, CH_4 enhances ozone formation in the upper atmosphere over longer time-scales. Thus NO_x can also reduce production of O_3 and contribute to cooling²¹. Both NO_x and NH_3 enhance formation of light-scattering sulphate and organic aerosols. NO_x can be oxidised to form nitric acid (HNO_3), which forms aerosols of ammonium nitrate

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Gaseous emission process altered by reactive N	Climate forcing element	Process of warming/cooling	Overall impacts
1. N ₂ O	N ₂ O	Emitted from agricultural soils	Warming
2. NO _x → ozone and CH ₄	Ozone, CH ₄	NO _x perturbs the chemical production and destruction of the greenhouse gases ozone and CH ₄ .	Cooling
3. NO _x → aerosol	Nitrate, ammonium aerosol	NO _x can enhance the formation of light-scattering aerosols.	Cooling
4. NH ₃ → aerosol	Nitrate, ammonium aerosol	NH ₃ enhances the formation of light-scattering aerosols.	Cooling
5. N fertilizer → CO ₂ flux	CO ₂	On croplands, nitrogen from fertilizer and manure may enhance the storage of CO ₂ .	Cooling
6. N fertilizer → CH ₄ flux	CH ₄	On croplands, N from fertilizer and manure may perturb uptake and emission of CH ₄ .	Warming

Table 1. Gaseous emission process altered by reactive nitrogen, climate forcing elements, process of warming/cooling and their overall impacts. Source: Modified from Pinder *et al.*¹⁸.

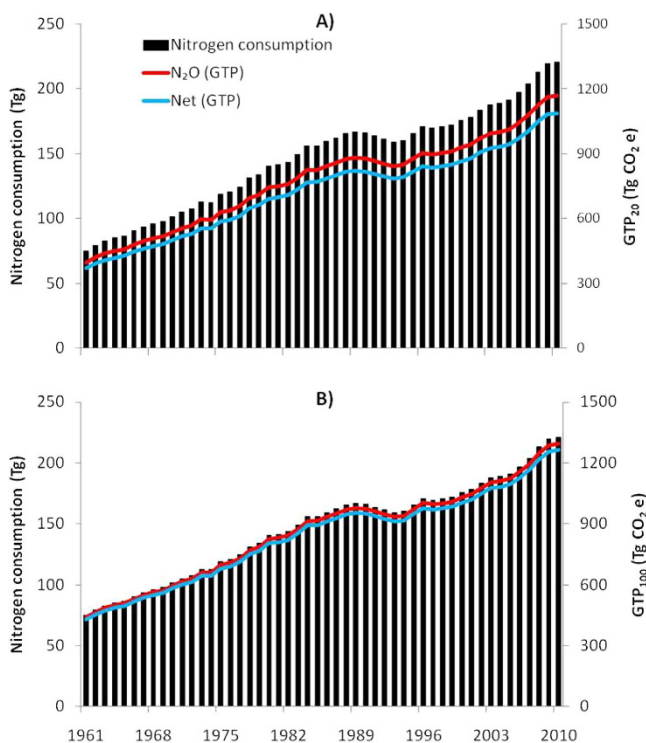


Figure 1. Total nitrogen consumption, global temperature change potential (GTP) due to N₂O emission alone and net GTP of N use in global agriculture (A) 20-year and (B) 100-year time-scales.

(NH₄NO₃) in presence of NH₃²². Moreover, use of N usually increases net primary productivity with more CO₂ fixation in terrestrial systems^{23–26} and enhances carbon sequestration in soil due to more litter production²⁷. The direct and indirect impacts of reactive N (Nr) on global warming and cooling are summarized in Table 1.

The previous reports have evaluated the emission of N₂O only due to N use in agriculture for a short period. However, besides global warming due to N₂O emission, N use in agriculture has other direct and indirect effects causing warming and cooling. To assess the impacts of N use on climate change, therefore, the warming as well as cooling effects should be considered¹⁸. Moreover, such warming and cooling effects need to be assessed for a sufficiently long period as the N use in global agriculture has undergone substantial changes in the last decades. The present study quantified the global warming and cooling potentials of N use in global agriculture during last 50 years (1961–2010).

Results and Discussion

Total N input in global agriculture. Total N input in global agriculture increased by 2.95 times during 1961 to 2010 (Fig. 1 and Table 2). In 1961, total N input from different sources was 74.93 Tg N. Animal manure accounted the highest amount (32.30%), followed by biological N fixation (BNF, 29.33%), crop residues (18.75%), fertilizer N (15.47%) and atmospheric deposition (4.16%) (Table 2). In 2010, total N input was 270.70 Tg N (Fig. 1 and Table 2) and fertilizer N was the largest source (51.38%) followed by animal manure (15.41%), crop residue (14.40%), BNF (12.31%) and atmospheric deposition (6.49%) (Table 2).

Sources of N	Nitrogen (Tg)	
	1961	2010
Fertilizer	11.59 (15.47) ^a	113.40 (51.38)
Animal manure	24.20 (32.30)	34.02 (15.41)
Crop residue	14.05 (18.75)	31.79 (14.40)
Atmospheric deposition	3.12 (4.16)	14.33 (6.49)
Biological N fixation	21.98 (29.33)	27.16 (12.31)
Total	74.93 (100)	220.70 (100)

Table 2. Sources of nitrogen and their contribution in global agriculture. Source: FAOSTAT¹ ^aFigures in the parenthesis are percent of total N.

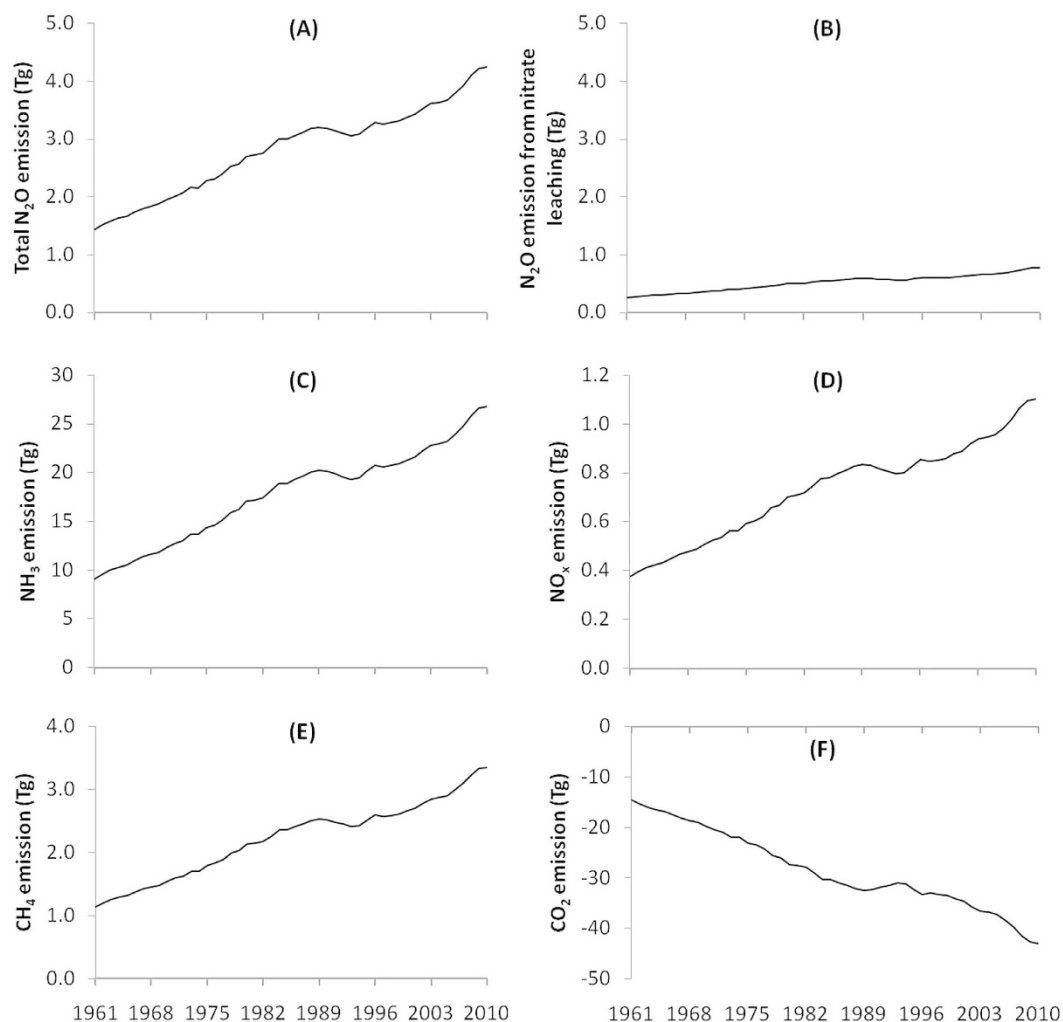


Figure 2. Emissions of total (direct + indirect) N₂O (A), N₂O from nitrate leaching (B), NH₃ (C), NO_x (D), CH₄ (E) and CO₂ (F) from global N use in agriculture during 1961–2010.

GTP of N₂O emission. Total N₂O emission from agriculture increased from 1.44 Tg to 4.25 Tg during 1961 to 2010 (Fig. 2A). The GTP of total N₂O emission, thus increased from 396.67 to 1168.32 TgCO₂e in a 20-year time-scale (GTP₂₀) (Fig. 3A) and from 439.94 to 1295.78 Tg CO₂e in 100-year time-scale (GTP₁₀₀) (Fig. 3B) during 1961 to 2010.

GTP of NH₃ and NO_x emissions. Emission of NH₃ from global agriculture was 9.10 and 26.80 Tg during 1961 and 2010, respectively (Fig. 2C). Emission of NO_x was 0.37 and 1.10 Tg during 1961 and 2010, respectively (Fig. 2D). Cooling impacts due to these emissions of NO_x and NH₃ were 77.58 and 228.50 Tg CO₂e in GTP₂₀ and 0.65 and 1.91 Tg CO₂e in GTP₁₀₀ during 1961 and 2010, respectively (Fig. 4). Aerosol formation from NH₃ contributed 69% of the cooling effect, followed by ozone and CH₄ alternation due to NO_x (22%) and aerosol formation from NO_x (9%)

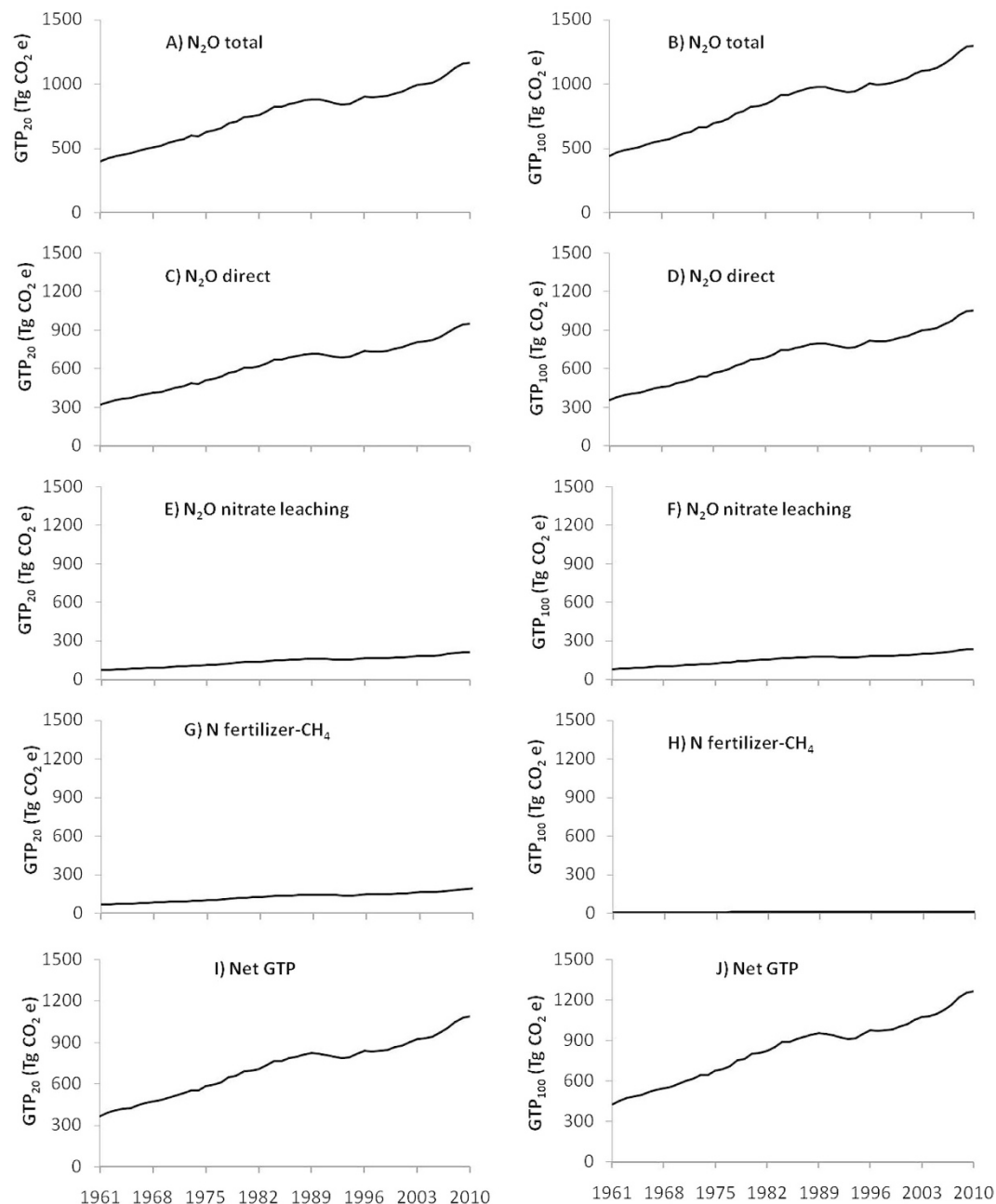


Figure 3. Warming or global temperature change potential (GTP) due to total (direct + indirect) N_2O emission (A,B), direct N_2O emission including atmospheric deposition (C,D), N_2O emission from nitrate leaching (E,F), N fertilizer- CH_4 flux (G,H) and net GTP (I,J) of global N use in agriculture on 20-year (left) and 100-year (right) times-scales.

(Fig. 4A,C,E). However, on GTP_{100} (Fig. 4B,D,F) these cooling impacts of NH_3 and NO_x were smaller compared to GTP_{20} indicating that as the time horizon becomes longer, short-lived compounds have less effects on GTP^{18} .

GTP due to altered CH_4 and CO_2 fluxes. The CH_4 is produced in soil during microbial decomposition of organic matter under anaerobic conditions. Soils submerged under water, rice fields for example, are the potential sources of CH_4 . Addition of N increases CH_4 emission by inhibiting CH_4 oxidation and reducing CH_4 uptake in aerobic soils due to increased concentration of ammonium (NH_4^+)²⁸ and nitrate (NO_3^-)^{29,30} in soil. This increase in CH_4 flux due to N use in agriculture ranged from 1.14 Tg in 1961 to 3.35 Tg in 2010 (Fig. 2E) contributing to 42.14 and 124.12 Tg CO_2e in GTP_{20} (Fig. 3G) and 4.44 and 13.80 Tg CO_2e in GTP_{100} (Fig. 3H) in 1961 and 2010, respectively. Fluxes of CO_2 decreased by 14.56 Tg to 42.89 Tg during the same period (Fig. 2F) due to increased uptake of CO_2 as a result of N application (Fig. 4G,H).

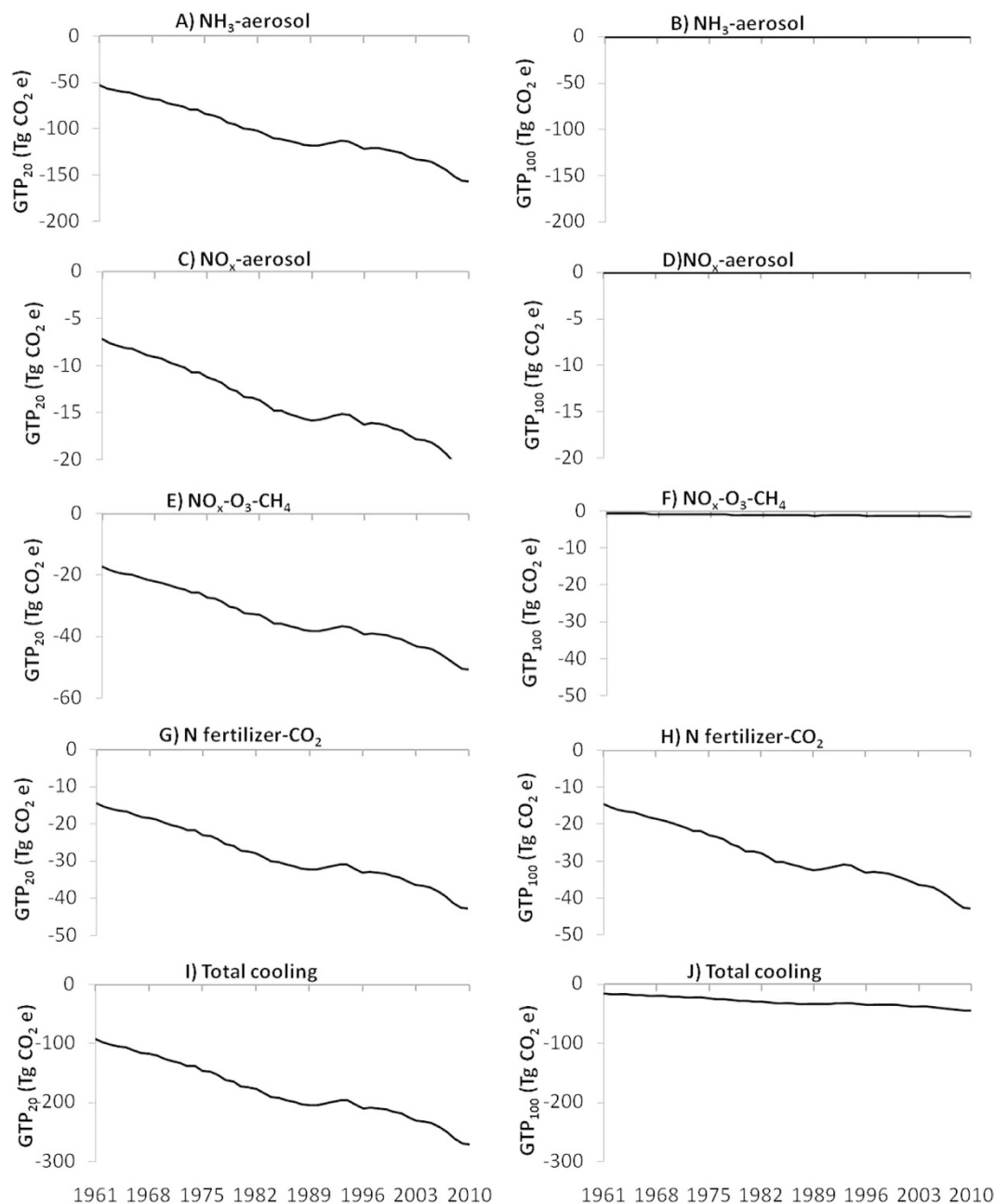


Figure 4. Cooling or Global temperature change potential (GTP) due to NH_3 aerosol (A,B), NO_x aerosol (C,D), NO_x - O_3 - CH_4 (E,F), CO_2 with N fertilizer (G,H) and total cooling (I,J) of global N use in agriculture on 20-year (left) and 100-year (right) times-scales.

Net impact of N use in agriculture on GTP. Net GTP of N use in agriculture was 369.44 and 1088.55 $\text{Tg CO}_2\text{e}$ on GTP_{20} (Fig. 1A) and 429.17 and 1264.06 $\text{Tg CO}_2\text{e}$ on GTP_{100} (Fig. 1B) in 1961 and 2010, respectively. The net GTP_{20} was lower by 6.9% and GTP_{100} by 2.4% compared to the respective GTPs when N_2O emission alone was considered.

Total GTP during 1961–2010. Total warming due to N use in global agriculture during 50 years was 45041.92 $\text{Tg CO}_2\text{e}$ in GTP_{20} and 43362.98 $\text{Tg CO}_2\text{e}$ in GTP_{100} (Fig. 5). Emission of N_2O due to N use in agriculture contributed 86% and 99% of this warming in GTP_{20} and GTP_{100} , whereas CH_4 contributed 14% and 1% in GTP_{20} and GTP_{100} , respectively. Total cooling was 8991.28 and 1484.19 $\text{Tg CO}_2\text{e}$ in GTP_{20} and GTP_{100} , respectively (Fig. 5). The major cooling was due to NH_3 aerosol formation (57.8%) followed by NO_x induced O_3 and CH_4 alteration (18.7%), N fertilizer-induced C sequestration (15.8%) and NO_x aerosol (7.7%). However, on GTP_{100} N fertilizer-induced C sequestration contributed the maximum (95.74%) and others were marginal.

The net GTP_{20} was 36050.64 $\text{Tg CO}_2\text{e}$ i.e., 6.84% lower and GTP_{100} was 41878.79 $\text{Tg CO}_2\text{e}$ i.e., 2.45% lower compared to the respective GTPs when warming due to N_2O emission alone was considered.

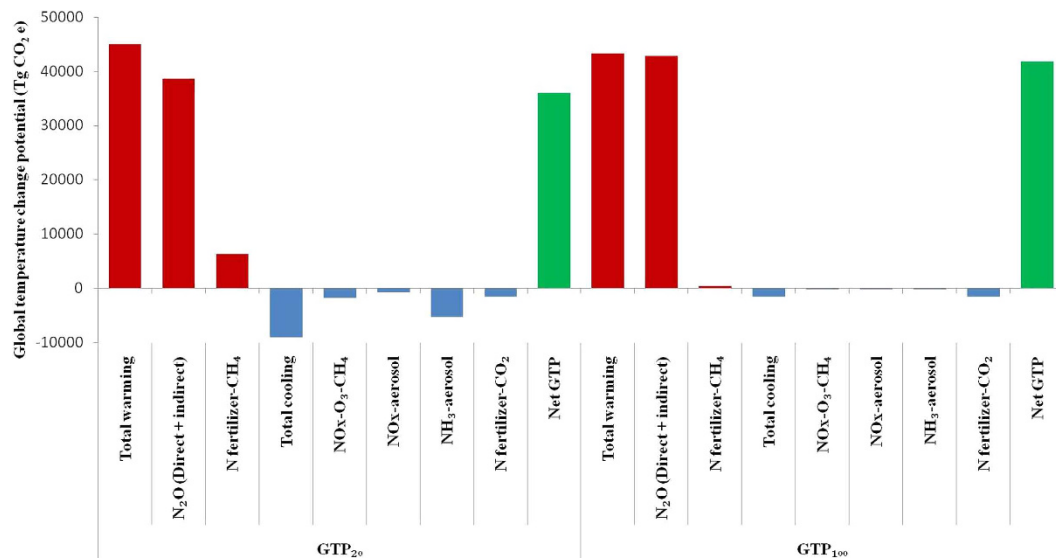


Figure 5. Total Global temperature change potentials of global N use in agriculture in 50 year on 20-year (left) and 100-year (right) times-scales.

Sl. No.	Parameters	Emission/uptake factor	Unit	Source
1	Direct N ₂ O-N	0.01	kg N ₂ O-N ha ⁻¹ yr ⁻¹ kg ⁻¹ N	33
2	N ₂ O-N from nitrate leaching	0.0075	kg N ₂ O-N ha ⁻¹ yr ⁻¹ kg ⁻¹ N	33
3	Nitrate leaching	0.3	kg NO ₃ ⁻ N ha ⁻¹ yr ⁻¹ kg ⁻¹ N	33
4	NH ₃ -N	0.1	kg NH ₃ -N ha ⁻¹ yr ⁻¹ kg ⁻¹ N	33
5	NOx-N	0.005	kg NOx-N ha ⁻¹ yr ⁻¹ kg ⁻¹ N	34
6	CH ₄ -C uptake (Upland soil)	-0.012	kg CH ₄ -C ha ⁻¹ yr ⁻¹ kg ⁻¹ N	24
7	CH ₄ -C emission (Lowland soil)	0.008	kg CH ₄ -C ha ⁻¹ yr ⁻¹ kg ⁻¹ N	24
8	CO ₂ -C uptake	-0.053	kg CO ₂ -C ha ⁻¹ yr ⁻¹ kg ⁻¹ N	24

Table 3. Emission and uptake factors of different parameters used in the present study.

Methods

Total N use in global agriculture. Total N input in global agriculture (N_T) was calculated using the equation (1).

$$N_T(\text{Tg}) = N_{\text{SN}} + N_{\text{AM}} + N_{\text{CR}} + N_{\text{AD}} + N_{\text{BNF}} \quad (1)$$

Where, N_{SN} , N_{AM} , N_{CR} , N_{AD} and N_{BNF} are amounts of N added (Tg) to soil annually through fertilizer, animal manure, crop residue, atmospheric deposition, and biological nitrogen fixation (BNF), respectively. Data on N_{SN} , N_{AM} , N_{CR} were obtained from FAOSTAT¹. The N_{AD} and N_{BNF} were calculated as per the equations (2) and (3) respectively.

$$N_{\text{AD}}(\text{Tg}) = \text{Agricultural area (Mha)} \times \text{Deposition factor (kg ha}^{-1}\text{)} \quad (2)$$

$$N_{\text{BNF}}(\text{Tg}) = \text{Global pulses area (Mha)} \times \text{BNF rate (kg ha}^{-1}\text{)} \quad (3)$$

Data on area under global agricultural and pulse crops were obtained from FAOSTAT¹ whereas data on deposition factor were calculated from Liu *et al.*³¹ and Liu *et al.*³² and BNF were calculated from Liu *et al.*³¹.

Emission/uptake factors. Emission and uptake factors (EF) used in the study are mentioned in Table 3. Factor for direct N₂O emission was taken as 0.01³³ and N₂O from NO₃⁻ leaching was 0.0075³³. Emission factor for NO₃⁻ leaching, NH₃ and NOx emissions were 0.3³³, 0.10³³ and 0.005³⁴ kg kg⁻¹ N applied, respectively. Emissions

Species	GTP ₂₀	GTP ₁₀₀	Source
N ₂ O	+260 to +290	+290 to +320	13
NO _x → ozone and CH ₄	-55 to -37	-2.9 to -0.024	35
NO _x → aerosol	-31 to -7	-0.0024 to 0	36
NH ₃ → aerosol	-9.5 to -2.2	-0.022 to 0	36
N fertilizer → CH ₄ flux	+37 to +77	+2.9 to +4.9	37
N fertilizer → CO ₂ flux	+1	+1	38

Table 4. Global temperature change potential (kg CO₂ kg⁻¹ N) of different species used in this study.

of CH₄ from anaerobic and aerobic fields were taken as 0.008 and -0.012 kg CH₄-C ha⁻¹ yr⁻¹ kg⁻¹ N applied²⁴. The factor for C sequestration was 0.053 kg CO₂-C ha⁻¹ yr⁻¹ kg⁻¹ N²⁴.

Emission/uptake fluxes. Total flux (F_T) of N₂O, NO₃⁻ leaching, NO_x, NH₃, CH₄ and CO₂ were calculated using the equation (4).

$$F_T(\text{Tg}) = N_T(\text{Tg}) \times \text{EFn} \quad (4)$$

Where N_T is total amount of N (Tg) added to agricultural land and EFn is the respective emission/uptake factor.

N₂O flux from NO₃⁻ leaching was calculated using the equation (5).

$$\text{N}_2\text{O emission from NO}_3^- \text{ leaching} = \text{NO}_3^- \text{ leaching flux} \times \text{EF} \quad (5)$$

GTP of N₂O, NO_x, NH₃, CH₄ and CO₂ fluxes. The GTP of N₂O, NO_x and NH₃ fluxes were calculated using the equation (6).

$$\text{GTP}_{\text{Nt}}(\text{Tg CO}_2\text{e}) = F_T(\text{Tg}) \times \text{GTP}_{\text{txi}} \quad (6)$$

Where GTP_{Nt} is GTP at 't' time-scale i.e., 20 or 100 years; F_T is flux of NO_x, NH₃ and N₂O emission (kg yr⁻¹), GTP_{txi} is GTP for 'i' kg of 'x' compound (N₂O, NO_x, NH₃) at time-scale 't'. GTP₂₀ and GTP₁₀₀ used in the study are mentioned in Table 4.

The following equation (7) was used to calculate GTP of CH₄ and CO₂ emission/uptake (GTP_{Ct}).

$$\text{GTP}_{\text{Ct}}(\text{Tg CO}_2\text{e}) = F_T \times \text{GTP}_{\text{txi}} \quad (7)$$

Where GTP_{txi} is GTP for 'i' kg of 'x' compound (CH₄ and CO₂) at time-scale 't'.

Finally, the net GTP (GTP_T) of N addition to global agriculture was calculated using the equation (8).

$$\text{GTP}_T(\text{Tg CO}_2\text{e}) = \text{GTP}_{\text{Nt}}(\text{Tg CO}_2\text{e}) + \text{GTP}_{\text{Ct}}(\text{Tg CO}_2\text{e}) \quad (8)$$

Summary

Globally, nitrogen is the most widely used nutrient in agriculture. Nitrogen fertilizer acts as a source of global warming as it contributes to N₂O emission. However, it also contributes to global cooling with emissions of NH₃ and NO_x. Therefore, while assessing global temperature change potential (GTP), both the warming and cooling effects of N use in agriculture should be considered. Our estimates showed that net GTP in 20-year time-scale is 6.9% lower and in 100-year time-scale 2.4% lower when warming as well as cooling effects of N use in agriculture were considered compared to considering warming due to N₂O emission alone.

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Author Contributions

H. Pathak designed and conceptualized the study. R. K. carried out the data analysis and prepared the first draft. All the authors provided critical inputs and contributed to the writing of the paper.

Additional Information

Competing Interests: The authors declare no competing financial interests.

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