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Estimating global terrestrial denitrification from measured N_2O:(N_2O + N_2) product ratios☆

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The use of nitrogen (N) fertilizers has grown exponentially over the last century, with severe environmental consequences. Most of the anthropogenic reactive nitrogen will ultimately be returned by denitrification to the atmosphere as inert N_2, but the magnitude of denitrification and the ratio of N_2O to (N_2O+N_2) emitted (R_{N_2O}) is unknown for the vast majority of terrestrial ecosystems. This paper provides estimates of terrestrial denitrification and R_{N_2O} by reviewing existing literature and compiling a N budget for the global land surface. We estimate that terrestrial denitrification has doubled from 80 Tg-N year^{-1} in pre-industrial times to 160 Tg-N year^{-1} in 2005 and that at the global scale N_2O comprises approximately 8% (6–11%) of the terrestrial denitrification flux. We conclude that upscaling of R_{N_2O} can provide spatial estimates of terrestrial denitrification when data from acetylene inhibition methods are excluded. Recent advances in methodologies to measure N_2 emissions and R_{N_2O} under field conditions could open the way for more effective management of terrestrial N flows.

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Introduction

The Green (Agricultural) Revolution has primarily been fuelled by nitrogen (N), with the required reactive N (N_r) provided mainly by increased fertilizer use but also by increased cultivation of N-fixing crops; both of which have increased the amount of N_r in the biosphere [1•]. As a result, the global N cycle is more severely altered by human activity than the global carbon (C) cycle [2]. While humans have doubled levels of N_r in circulation, the global C cycle has only been altered by 5–7% due to human activity. The increased accumulation of N_r in the biosphere is causing serious environmental impacts, including eutrophication, biodiversity loss, human health problems and perturbations of the climate system [3,4•,5].

Two microbial processes (nitrification and denitrification) play key roles in the removal of N_r from soils. Nitrification first oxidizes ammonia/ammonium (NH_3/NH_4^+) to nitrate (NO_3^-), which can then be reduced via denitrification to nitrite (NO_2^-), nitric oxide (NO), nitrous oxide (N_2O) and finally dinitrogen (N_2). Denitrification is the primary sink for N_r by the conversion to inert N_2 and its release back to the atmosphere, although other processes like anaerobic ammonium oxidation (anammox) may play an important role in the removal of N_r in aquatic ecosystems [6]. Unfortunately, N_2 fluxes are very difficult to quantify because of the high atmospheric N_2 concentration, substantially hampering our ability to estimate terrestrial N budgets. There are several main N loss pathways from fertilised agro-ecosystems, including NH_3 volatilisation, NO_3^- leaching, and NO, N_2O and N_2 emissions. These N losses often represent a substantial loss of applied fertiliser; possibly resulting in less plant N uptake and reducing crop N use efficiency (NUE). Furthermore, these losses create environmental concerns; particularly for N_2O, which is not only a potent greenhouse gas with a global warming potential 298 times greater than CO_2, but is also currently the primary contributor to stratospheric ozone depletion [7•,8].

Rates of both denitrification and N_2O emissions have increased with the augmented use of N fertiliser and animal manure and it has been clearly shown that N_2O

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emissions increase exponentially once plant N requirements have been met [9]. Consequently, further intensification of global cropping systems to feed a growing population that includes higher inputs of N fertiliser will result in even higher N_2O emissions per unit of N fertilizer used, which if abatement action is not taken, could lead to a doubling of N_2O emissions by 2050 [7•,10]. Therefore, a better understanding of terrestrial denitrification (i.e. the dominant process for N_r removal and N_2O emissions) is essential for the development of management strategies that improve crop yields while also mitigating N_r losses. In spite of its importance, terrestrial denitrification is still one of the least well understood processes in the global N cycle [11••], with the magnitude of total denitrification losses ($N_2 + N_2O$) virtually unknown for the vast majority of terrestrial ecosystems [12••].

This paper provides estimates of terrestrial denitrification and the product ratio of N_2O to ($N_2O + N_2$) emitted (R_{N_2O}), by reviewing existing literature and compiling a N mass balance for the global land surface, where we balanced rates of N_r creation for the global land surface with outputs to the ocean and atmosphere. Finally, we calculated terrestrial denitrification based on measured R_{N_2O} and assessed how well such an estimate compares with other methods.

Global estimates of terrestrial N_2O emissions

Existing information about spatial and temporal patterns of N_2O exchange between terrestrial ecosystems and the atmosphere at a regional or global scale is uncertain, despite its important role in the Earth's climate system. Currently there are two main approaches for estimating N_2O emissions from terrestrial ecosystems: bottom-up and top-down approaches. Bottom-up approaches extrapolate site specific emission estimates based on field measurements or modelling results to estimate regional and global N_2O budgets, while top-down approaches infer N_2O emissions based on changes in atmospheric N_2O mixing ratios and an inversion model [7•,13].

The most common bottom-up method used to quantify terrestrial N_2O emissions is based on emission factors (EFs) that estimate N_2O emissions as a percentage of soil N inputs. Current inventories of N_2O emissions from agriculture are mainly based on standard Tier 1 IPCC methodologies, which uses a default emission factor (1% of N inputs in upland systems on mineral soils) and agricultural census data on cropping area and fertilizer use [14]. However, the assumption of a default EF has been questioned from its inception since it does not reflect underlying processes and the impact of management or environmental conditions. A particular concern is that a static EF assumes a linear relationship between N application rates and N_2O emissions, whereas for many fertilized cropping systems the relationship is non-linear [7•,9]. Another important bottom-up approach is the use of process-based models and over the last decade, several studies have used different simulation models to estimate N_2O emissions from terrestrial soils at the global scale [15–19]. Top-down approaches provide an integrated picture of the regional and long-term emissions and a check on the total budget [20]. With improved data precision and modeling capabilities over the recent years, these top-down approaches have been used to determine the spatial and temporal distribution of N_2O emissions [20–24].

Other recent studies have used a combination of 'top-down' constraints with a bottom-up global inventory approach. This approach compares the observed changes in atmospheric N_2O mixing ratios over time with the amount of newly fixed N (via Haber–Bosch and biological N fixation in soils) to derive the fraction of newly fixed N that is converted to N_2O. They estimate that 3–5% of newly fixed N is converted to N_2O when direct and indirect effects (i.e. cascading effects of fixed N via leaching, runoff, atmospheric deposition, and disposal of human sewage) are considered [7•,26,30].

Both bottom-up and top-down estimates of terrestrial N_2O emissions on global scale are subject to large uncertainties, but it has been shown that estimates of both methods converge at large scales [13]. Estimates of terrestrial N_2O emissions derived from previous bottom-up ($n = 4$) and top-down ($n = 6$) studies ranged from 11.1 to 15.2 Tg N year^{-1} with mean global terrestrial N_2O emissions estimated to be 12.9 ± 0.4 Tg N year^{-1}. Soils under natural vegetation account for the largest part of terrestrial N_2O emissions (4.9–9,3 Tg N year^{-1}), while agricultural activities contribute 5.0–6.8 Tg N year^{-1} to the terrestrial N_2O budget (Table 1).

Global estimates of terrestrial denitrification

The main reasons for the uncertainty around terrestrial denitrification rates are that there is not only high spatial and temporal variability, but it is also extremely difficult to measure N_2 emissions against the huge atmospheric N_2 background [31]. As a consequence, only few estimates of denitrification on site, landscape (100 000 m^2), regional (>100 km^2) and global scales exist and these come with large uncertainties. Recent research suggests that denitrification may be the dominant N loss pathway from agricultural soils and natural ecosystems alike [32–34], while the importance of anammox as a N_2 producing process remains still largely unquantified for terrestrial systems [6]. Estimates of total global denitrification (i.e. from marine and terrestrial systems combined) vary from 220 to 570 Tg-N year^{-1} [35–37,38••], although global denitrification rates in excess of 450 Tg-N year^{-1} are difficult to reconcile with current estimates of total global N fixation (fertilizer, biological N fixation, energy processes, lightning), which range from 390 to 440 Tg-N year^{-1} [28•,35,36]. This discrepancy may be partially

Table 1

Estimates of nitrous oxide emissions from terrestrial ecosystems (Tg N_2O–N $year^{-1}$)

	Total terrestrial[a]	Soils under natural vegetation	Total agricultural[b]	Other sources[c]	Method
Bottom up					
Mosier *et al.* [25]	–	–	6.8	1.3	Emission factors (*IPCC* [1998] methodology)
DelGrosso *et al.* [13]	–	–	5.8	–	Combined DAYCENT model simulations and *IPCC* [2006] methodology
Davidson [26]	–	–	5.5	0.8	Emission factors for manure and fertiliser-N
Syakila and Kroeze [27]	13.7	6.5	6.0	1.2	Revised emissions factors
Xu-Ri *et al.* [19]	–	9.3	–	–	Global vegetation model (DyN-LPJ)
Bouwman *et al.* [11••]	13.5	4.9	6.7	1.9	Integrated Model to Assess the Global Environment (IMAGE)
Ciais *et al.* [28•]	13.3	6.6	5.4	0.9	Upscaling of local flux measurements, emission factors
Tian *et al.* [29]	15.2	8.4	5.5	0.3	Meta analysis of bottom up estimates
Tian *et al.* [18]	–	6.5	–	–	Ensemble of terrestrial biosphere models
Mean bottom-up	13.9 ($n = 4$)	7.0 ($n = 6$)	6.0 ($n = 7$)	1.1 ($n = 6$)	
Top down					
Hirsch *et al.* [21]	11.4	–	–	–	Atmospheric inversion modelling
DelGrosso *et al.* [13]	–	–	5.6	–	Changes in atmospheric N_2O concentration and N_2O removal rates. Emission factor for newly fixed N_r
Crutzen *et al.* [30]	12.8	6.7	5.1	1.0	Changes in atmospheric N_2O concentration and N_2O removal rates. Emission factor for newly fixed N_r
Huang *et al.* [22]	–	6.7	–	–	Atmospheric inversion modelling
Saikawa *et al.* [24]	12.5	7.7	–	0.8	Atmospheric inversion modelling
Thompson *et al.* [23]	12.9	–	–	–	Atmospheric inversion modelling
Thompson *et al.* [20]	11.1	–	–	–	Atmospheric inversion modelling
Tian *et al.* [29]	12.6	7.5	5.0	–	Meta analysis of atmospheric inversion modelling studies
Mean top-down	12.2 ($n = 6$)	7.1 ($n = 4$)	5.2 ($n = 3$)	1.0 ($n = 2$)	
Total mean	12.9 ± 0.4	7.1 ± 0.4	5.7 ± 0.2	1.1 ± 0.2	

[a] Total emissions from terrestrial ecosystems including fossil fuel combustion and industrial processes.
[b] Direct and indirect soil emissions including manure management and biomass burning.
[c] Fossil fuel combustion, industrial processes and human sewage.

explained by the high uncertainty in estimates of terrestrial (77–387 Tg-N $year^{-1}$) and marine (75–200 Tg-N $year^{-1}$) biological N fixation (BNF) [6,39], and marine denitrification (100–330 Tg-N $year^{-1}$) [35].

We found 10 studies that estimated denitrification rates for terrestrial ecosystems at the global scale (Table 2). In this paper the term terrestrial denitrification is used for NO_3^- reduction to N_2, N_2O and NO occurring on the global land surface including upland soils, wetlands, riparian zones, and freshwater aquatic ecosystems. Typically, denitrification requires an anoxic environment with a ready supply of NO_3^- and organic carbon, so terrestrial ecosystems characterized by high water contents (e.g. wetlands, riparian zones and heavily irrigated cropping systems) are considered hot-spots for denitrification [36,40]. However, it has also been shown that anaerobic microsites within soil aggregates can produce hot-spots and hot moments of denitrification activity, resulting in significant contributions to denitrification at the landscape scale from apparently well-drained soils [41,42].

Global estimates of terrestrial denitrification range from 100 to 250 Tg-N $year^{-1}$ (Mean 157 ± 27 Tg-N $year^{-1}$), equivalent to about 50% of newly fixed terrestrial N [35]. Soils account for the largest proportion of terrestrial denitrification (67–130 Tg-N $year^{-1}$) with about half (22–87 Tg-N $year^{-1}$) occurring in fertilized agricultural soils, while 24–44 Tg-N $year^{-1}$ is denitrified in the groundwater and 37–66 Tg-N $year^{-1}$ in lakes, rivers and reservoirs (Table 2). However, there is still a high uncertainty in estimates of denitrification in wetlands and freshwater systems, since only few estimates exist and denitrification in aquatic systems is often confounded with other microbial pathways that potentially remove nitrate, such as reduction of nitrate to ammonium (DNRA), and anammox [6]. In addition, it is hard to distinguish between aquatic and soil denitrification because denitrification often occurs at the interface of aquatic and soil ecosystems (e.g. wetlands, riparian zones) which are key zones in controlling the flow of terrestrial N_r to rivers and the oceans [11••].

Table 2

Global estimates of terrestrial denitrification (Tg N year^{-1})

	Soils	Agricultural soils	Ground-water	Riparian zone	Lakes and rivers	Total terrestrial	Ocean	Global
Galloway *et al.* [36] (1990s)	67				48	125	278	403
Hofstra and Bouwman [43]		22–87						
Seitzinger *et al.* [38••]	124	66	44		66	242	331	565
Gruber and Galloway [37]	127				37	164	244	408
Schlesinger [44••]		17				109		
Canfield *et al.* [45]						100	238	338
Bouwman *et al.* [11••] (year 2000)	79	51	24	6		109		
Fowler *et al.* [35]	113						108–285	218–399
Zaehle [46]	115	47						
Battye *et al.* [1•]	130				120[a]	250	150	400
Mean (± SE)	108 ± 9	48 ± 10	34 ± 5	6	50 ± 7	157 ± 24	233 ± 30	390 ± 51

[a] Estimate for freshwater and groundwater combined, not counted for the mean.

Estimating total terrestrial denitrification from N balance

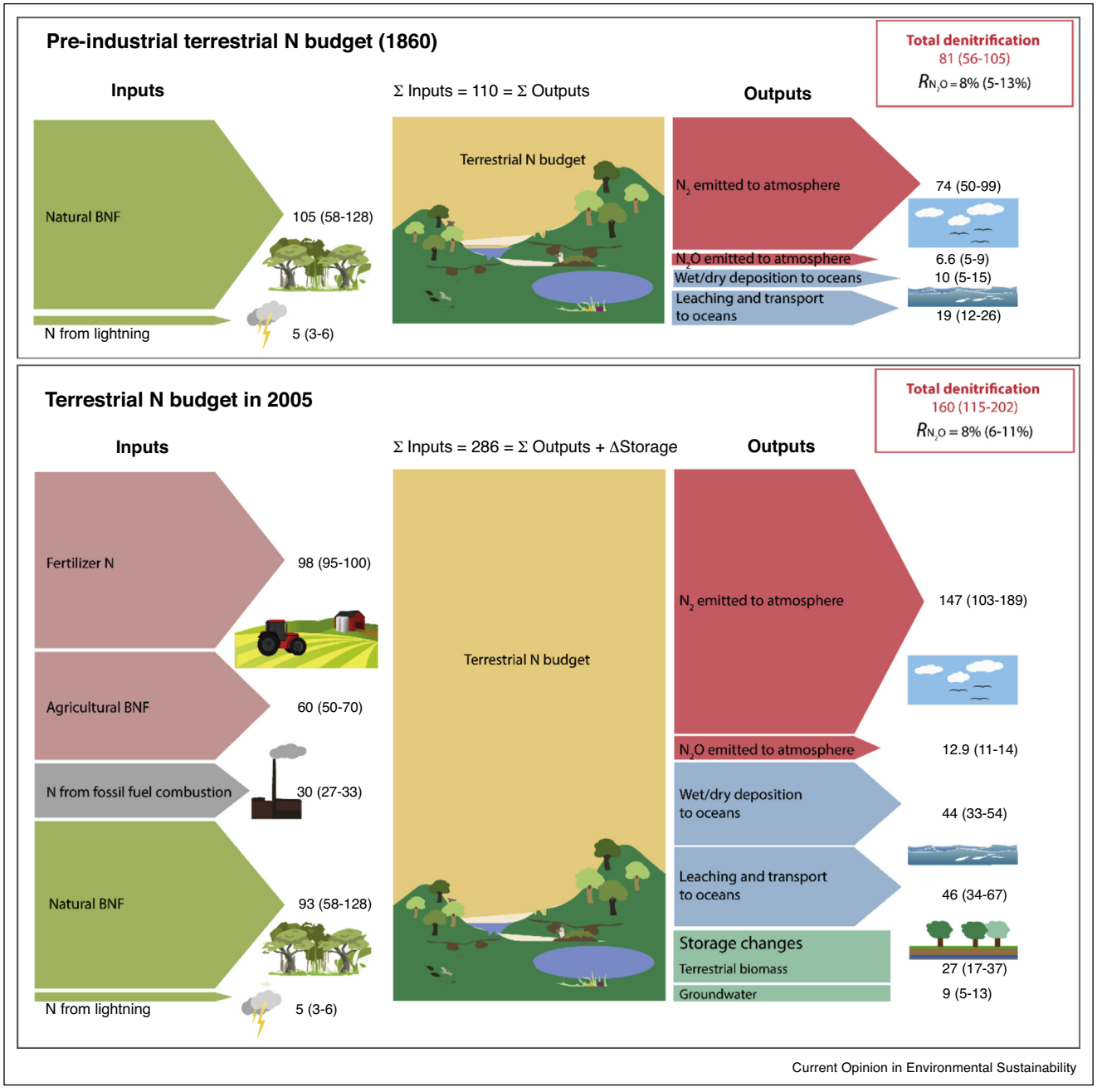
Terrestrial denitrification rates were also calculated for the global land surface using a mass balance approach where we juxtapose rates of N_r creation for the global land surface with outputs to the ocean and atmosphere (Figure 1). For a balanced budget the difference between the input and the output will be either stored in terrestrial 'sinks' (e.g. in surface and groundwater, the biosphere or terrestrial soils) or denitrified and released as inert N_2 back to the atmosphere. We estimate that in 2005, N_r input rates for the global land surface were 286 Tg N year^{-1} (98 Tg N year^{-1} as fertilizer via the Haber–Bosch process [28•,47,48]; 93 Tg N year^{-1} via Biological Nitrogen Fixation (BNF) in natural ecosystems [39,47,49]; 60 Tg N year^{-1} via BNF in agricultural systems [50]; 30 Tg N year^{-1} via fossil fuel combustion [35,51]; and 5 Tg N year^{-1} via lighting [35]. Of this 90 Tg N year^{-1} were transported to the ocean via river flow or atmospheric deposition [52–54], 36 Tg N year^{-1} stored in terrestrial or inland aquatic ecosystems [11••,46], and 12.9 Tg N year^{-1} emitted as N_2O to the atmosphere (Table 1). This provides an estimate of 147 Tg N year^{-1} emitted as N_2 from terrestrial ecosystems to the atmosphere. If we assume that the 12.9 Tg N_2O-N year^{-1} emissions mentioned above (Table 1) are produced entirely through denitrification, then 160 Tg N year^{-1} are denitrified from the terrestrial land surface with a mean R_{N_2O} of approximately 0.08. Using the same approach, we estimate that in pre-industrial times terrestrial N_r creation was 110 Tg N year^{-1}, and 80 Tg-N year^{-1} denitrified and released to the atmosphere (Figure 1).

Estimating terrestrial denitrification from N_2O emissions and R_{N_2O}

Another approach to estimate total denitrification rates from terrestrial ecosystems is to use the ratio of N_2O to the total N_2+N_2O emitted from denitrification (R_{N_2O}) as measured in more controlled, local studies and then scaling these up to regional or global estimates [44••]. But high uncertainties in N_2 flux estimates exist, caused by the high atmospheric N_2 background. Moreover, many studies on soil denitrification have been conducted in laboratory incubations, with high levels of NO_3^- and glucose added to stimulate denitrification. Such studies do most likely not reflect denitrification rates under field conditions. These methodological constraints are further aggravated by the fact that the historically most widely applied method to quantify total denitrification in the field (i.e. the Acetylene Inhibition Technique [AIT]) has been shown to create a systematic but variable, and therefore irreproducible underestimation of denitrification [55–58], and results in a substantial overestimation of R_{N_2O} [12••]. Therefore, to determine R_{N_2O} we summarized available datasets where N_2 emissions were measured by ^{15}N-labelling, the natural N and oxygen isotope approach or with the gas-flow helium incubation method and provide estimates for N_2 as well as N_2O emissions under field conditions (see supplementary material). Mean R_{N_2O} for agricultural soils and soils under natural vegetation were 0.11 (n = 34) and 0.12 (n = 33), respectively, while the ratio for wetland soils was significantly lower (0.02, n = 10) (Table 3). These ratios are significantly lower than other studies that estimated R_{N_2O} using the AIT. For example, Schlesinger [44••] estimated that the mean R_{N_2O} of denitrification from cropped soils was approximately 0.37, whereas Wang *et al.* [59] came up with a ratio of 0.33. The mean ratios from our summary, however, are in good agreement with the overall R_{N_2O} for total terrestrial denitrification obtained by our mass balance approach (Figure 1). This corroborates the results of a previous study from Butterbach-Bahl *et al.* [12••] who showed that R_{N_2O} for soils from different ecosystems are significantly lower if measurements that used AIT are ignored.

To provide an estimate of terrestrial denitrification from soils under natural vegetation, agricultural soils

Figure 1



Global terrestrial N budget for 1860 and in 2005 (Tg N $year^{-1}$); values in brackets show the 95% confidence interval. Inputs for natural BNF from Refs. [39,47,49]; BNF in agricultural systems from Refs. [50]; Haber–Bosch fertilizer from Refs. [28•,47,48]; fossil fuel combustion from Refs. [35,51]; lighting from Ref. [35]. Outputs for N transported to the ocean via river flow or atmospheric deposition from Refs. [52–54]; N_2O emitted to the atmosphere (this study, Table 1); storage of N in terrestrial or inland aquatic ecosystems [11••,46].
*Note: The terrestrial N budget was assumed to be in equilibrium in pre-industrial times, with no net accumulation of N in terrestrial biomass, soils or groundwater. Consequently, there are no storage changes given for the in pre-industrial N budget.

and wetlands we used N_2O emissions estimates from Bouwman *et al.* [11••] for natural and agricultural soils, and wetlands and flooded soils and divided those by the mean R_{N_2O} (Table 3). The calculated denitrification for agricultural soils is 656 Tg-N $year^{-1}$ (38−(56-78)), for soils under natural vegetation 45 Tg-N $year^{-1}$ (42−37-57) and wetlands 56 Tg-N $year^{-1}$ (39−40-96). The resulting estimate of total terrestrial denitrification, 166 Tg-N $year^{-1}$ (131−133 - 231), is thus consistent with the estimate using the mass balance approach

Table 3

Mean R_{N_2O}, N_2O emissions and calculated rates of N_2 emissions and total denitrification for different terrestrial ecosystems

Ecosystem	R_{N_2O} $N_2O/(N_2+N_2O)$	N_2O emissions[a] (Tg N_2O–N yr^{-1})	N_2 emissions (Tg N yr^{-1})	Total denitrification (Tg N yr^{-1})
Agricultural soils	0.109 ± 0.020	6.4	59 (50–72)	65 (56–78)
Soils under natural vegetation	0.124 ± 0.031	4.9	40 (32–52)	45 (37–57)
Freshwater wetlands and flooded soils	0.020 ± 0.009	1.1[b]	55 (39–95)	56 (40–96)
Total terrestrial	0.08[c]	12.4[d]	153 (120–219)	166 (133–231)

[a] Estimates are taken from Bouwman *et al.* [11••].
[b] Riparian zones and groundwater in Bouwman *et al.* [11••].
[c] Calculated from the sum of estimated N_2 and N_2O emissions.
[d] Sum from Bouwman *et al.* [11••]. Differs slightly from the value used in Figure 1.

(160 Tg-N $year^{-1}$). However, there are still a number of caveats that should be addressed in future research to allow the presented approach to become more widely applicable:

1 Limited database on non-AIT estimates of R_{N_2O}

The magnitude of total denitrification losses ($N_2 + N_2O$) and $R_{N_2O}$is still unknown for the vast majority of terrestrial ecosystems. In total, we found 34 studies that reported estimates for N_2 as well as N_2O emissions under field conditions. 13 for soils under natural vegetation, 14 for fertilized agricultural soils and 8 for wetland or flooded soils. The majority of the studies comes from temperate climate zones, while only 4 studies were carried out in a tropical or subtropical environment. More research on denitrification and R_{N_2O} for a wide range of ecosystems is urgently required for more robust estimates of terrestrial denitrification.

2 High uncertainty in environmental controls of R_{N_2O}

Dynamic, short-term changes in R_{N_2O} values as driven by changes in soil environmental parameters have been reported in various studies and R_{N_2O} has been shown to be controlled by soil moisture and temperature [60–62], soil oxygen (O_2) availability [63,64], soil texture and pH [43,65,66], or soil nitrate (NO_3^-) and carbon (C) concentrations [67,68]. Thus, using a mean R_{N_2O} for estimating N_2 fluxes from terrestrial ecosystems results in major uncertainties and a recent study showed that parametrization of R_{N_2O} with environmental controls can improve estimates of denitrification from agricultural ecosystems [69].

3 More accurate attribution of N_2O emissions to different microbial processes

We did our calculations based on the assumption that N_2O emissions are produced entirely through denitrification, while it is well-known that soil N_2O emissions are produced via a number of complex processes with several microbial sources involved, of which denitrification may or may not be the most significant [70,71]. Estimates of N_2O emissions (from field to global scale) are generally not denitrification specific, and therefore the current study is likely to overestimate denitrification derived N_2O emissions and the R_{N_2O}. To date it is mainly the ^{15}N-gas flux approach that can reliably be used for measuring denitrification derived N_2O since the He/O_2 gas-flow incubation method (without ^{15}N tracer used) cannot discriminate the source of N_2O [72]. Therefore, more field measurements of denitrification, in combination with a more accurate apportionment of N_2O sources are needed to derive accurate estimates of R_{N_2O} from denitrification.

Conclusion

The amount of N_r applied to land has increased by 160% over the last 200 years, causing severe environmental disturbances. We used two methods to derive global estimates of N_r removal by terrestrial denitrification: (i) a mass balance approach with recent estimates of terrestrial N inputs minus N exports via rivers and wet/dry N deposition to oceans (Figure 1), and (ii) a literature review on measured R_{N_2O} in combination with estimates of N_2O emissions from soils. Both approaches indicate that at the global scale N_2O comprises approximately 8% (6–11%) of the terrestrial denitrification flux, which is much lower than previous estimates that also considered studies of denitrification and N_2 formation using the C_2H_2 inhibition technique (AIT) and estimated R_{N_2O} in the range of 30–40% for terrestrial soils [44••,59]. This global mean R_{N_2O} of 8% is much more in line with recent estimates that 3–5% of newly fixed N is converted to N_2O and 50% removed by denitrification in terrestrial ecosystems [7•,26,30,73], while ratios above 30% are hard to reconcile with these estimates. Our analysis demonstrates that

using measured R_{N_2O} can provide estimates of terrestrial denitrification that are in good agreement with a global mass balance approach when data from AIT studies are excluded. An advantage of the R_{N_2O} approach is that it can be used to estimate denitrification rates from specific regions or ecosystems, both with and without fertilizer applications, given that specific data on N_2O emissions and the product ratio of denitrification is available. This will provide more reliable estimates of denitrification than other methods, and could provide the targeted data required for improving our understanding of this crucial N_r sink. However, the limited database on non-AIT estimates of R_{N_2O} still causes high uncertainty, which calls for more research on denitrification and R_{N_2O} for a wide range of ecosystems. Recent advances in isotopic approaches and analytical methods could pave the way for a significantly improved understanding of N cycling and denitrification in terrestrial agro-ecosystems [32,74–79].

We estimate that terrestrial denitrification has doubled since pre-industrial times and is now in the range of 115–202 Tg-N $year^{-1}$, removing 56% of the newly fixed terrestrial N each year, less than the removal rate of 72% in pre-industrial times. This implies that we are in a phase of accelerated accumulation of N_r in the biosphere with potentially serious environmental consequences [80]. However, much remains to be learned about how denitrification is affected by increasing levels of N_r in the environment. Such knowledge is required if we want to understand the fate of N_r and identify strategies for reducing N_r creation and its unwanted impact. Our analysis demonstrates that wetlands and flooded soils are important hotspots of denitrification. Despite an area of only 8% of the global land mass, our calculations indicate that approximately one third of the terrestrial denitrification (56 Tg-N $year^{-1}$) occurs in wetlands and flooded soils with a much lower R_{N_2O}. This highlights that the preservation and restoration of wetlands, or the introduction of constructed wetlands in landscapes, can be a key strategy for removing excess N_r. In addition to the carbon sequestration potential (0.2–0.8 Gt CO_2e $year^{-1}$) [81], the restoration of peatlands and wetlands would also help to remove N_r pollution from agricultural runoff. The needed intensification of crop production for feeding a growing and hungry planet will require a significantly improved N use efficiency in cropping systems and/or even higher inputs of N_r to terrestrial cropping systems and denitrification will play a key role in maximising the benefits of N_r while minimizing the environmental impact.

Conflict of interest statement

Nothing declared.

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