

LETTER • OPEN ACCESS

The importance of climate change and nitrogen use efficiency for future nitrous oxide emissions from agriculture

To cite this article: David R Kanter *et al* 2016 *Environ. Res. Lett.* **11** 094003

View the [article online](#) for updates and enhancements.

You may also like

- [Major point and nonpoint sources of nutrient pollution to surface water have declined throughout the Chesapeake Bay watershed](#)
Robert D Sabo, Breck Sullivan, Cuiyin Wu et al.
- [Cost of reactive nitrogen release from human activities to the environment in the United States](#)
Daniel J Sobota, Jana E Compton, Michelle L McCrackin et al.
- [Mowing alters nitrogen effects on the community-level plant stoichiometry through shifting plant functional groups in a semi-arid grassland](#)
Shijie Li, Fuwei Wang, Mengfei Chen et al.

Environmental Research Letters



LETTER

OPEN ACCESS

RECEIVED

25 December 2015

REVISED

30 May 2016

ACCEPTED FOR PUBLICATION

3 August 2016

PUBLISHED

30 August 2016

Original content from this work may be used under the terms of the [Creative Commons Attribution 3.0 licence](#).

Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.



The importance of climate change and nitrogen use efficiency for future nitrous oxide emissions from agriculture

David R Kanter^{1,7}, Xin Zhang^{2,8}, Denise L Mauzerall^{3,4}, Sergey Malyshev⁵ and Elena Shevliakova⁶

¹ Department of Environmental Studies, New York University, 285 Mercer Street, 9th floor, New York, NY, 10003, USA

² University of Maryland Center for Environmental Science, Appalachian Laboratory, 301 Braddock Road, Frostburg, MD 21532, USA

³ Woodrow Wilson School of Public and International Affairs, 445 Robertson Hall, Princeton University, Princeton, NJ, 08544, USA

⁴ Department of Civil and Environmental Engineering, E412 E-Quad, Princeton University, Princeton, NJ 08544, USA

⁵ Department of Ecology and Evolutionary Biology, 106A Guyot Hall, Princeton University, Princeton, NJ 08544, USA

⁶ National Oceanic and Atmospheric Administration Geophysical Fluid Dynamics Lab, Climate and Ecosystems Group, 201 Forrestal Road, Princeton, NJ, 08540, USA

⁷ The major portion of the research presented in this paper was done as part of David R Kanter's PhD at the Woodrow Wilson School of Public and International Affairs at Princeton University, under the supervision of his PhD advisor, Denise L Mauzerall.

⁸ The major portion of the research presented in this paper was done while Xin Zhang was a postdoctoral research associate at the Woodrow Wilson School of Public and International Affairs at Princeton University, under the supervision of Denise L Mauzerall.

E-mail: david.kanter@nyu.edu and mauzeral@princeton.edu

Keywords: nitrous oxide, agriculture, CO₂, fertilization, nitrogen use efficiency

Supplementary material for this article is available [online](#)

Abstract

Nitrous oxide (N₂O) is an important greenhouse gas and ozone depleting substance. Previous projections of agricultural N₂O (the dominant anthropogenic source) show emissions changing in tandem, or at a faster rate than changes in nitrogen (N) consumption. However, recent studies suggest that the carbon dioxide (CO₂) fertilization effect may increase plant N uptake, which could decrease soil N losses and dampen increases in N₂O. To evaluate this hypothesis at a global scale, we use a process-based land model with a coupled carbon-nitrogen cycle to examine how changes in climatic factors, land-use, and N application rates could affect agricultural N₂O emissions by 2050. Assuming little improvement in N use efficiency (NUE), the model projects a 24%–31% increase in global agricultural N₂O emissions by 2040–2050 depending on the climate scenario—a relatively moderate increase compared to the projected increases in N inputs (42%–44%) and previously published emissions projections (38%–75%). This occurs largely because the CO₂ fertilization effect enhances plant N uptake in several regions, which subsequently dampens N₂O emissions. And yet, improvements in NUE could still deliver important environmental benefits by 2050: equivalent to 10 Pg CO₂ equivalent and 0.6 Tg ozone depletion potential.

Introduction

A growing body of scientists and policy experts argue that N₂O, the third most important greenhouse gas (GHG) and the most abundantly emitted ozone depleting substance, requires more focused attention from the international policy community [1–3]. Humanity's ability to produce synthetic nitrogen (N) fertilizer via the Haber-Bosch process has dramatically increased N concentrations in agricultural soils, bolstering the major biogeochemical processes that produce N₂O: nitrification (the conversion of ammonium (NH₄⁺) to nitrate (NO₃⁻)), and denitrification (the conversion of NO₃⁻ to

atmospheric dinitrogen (N₂)). Supplemented by non-agricultural emission sources such as industry, energy production and transport, atmospheric concentrations of N₂O have increased from mid-19th century levels of approximately 275 ppb to 328 ppb in 2015 [4]. Agriculture is the dominant source, responsible for two thirds of gross anthropogenic emissions, and the focus of this study [5].

However, N₂O is not only an important GHG that exacerbates climate change; its emissions are also affected by climate change. Rising temperatures, shifting precipitation patterns, and increasing atmospheric CO₂ concentrations all impact N₂O emissions in a

variety ways that are still being studied [6]. Consequently, this study uses a process-based land model (Princeton-GFDL LM3 N.1, which captures vegetation, hydrological, carbon (C) and N dynamics [7, 8]) to examine both the potential climate and ozone benefits of reducing agricultural N₂O emissions at a global scale, and the direct and indirect effects of future climate change scenarios on N₂O emission rates.

The LM3 N.1 model allows us to simulate both the processes that directly control agricultural N₂O emissions (such as temperature and soil water content), and the indirect effects such as crop N uptake that change under different climate, N consumption, and atmospheric CO₂ concentration scenarios. Climate change is expected to impact all of these effects. Rising soil temperatures induced by climate change will likely increase the rate of soil organic matter decomposition, releasing more mineral N into the soil, and thereby make more N available for nitrification and denitrification—the major biogeochemical processes that produce N₂O [9]. Meanwhile, nitrification and denitrification are a function of oxygen levels in the soil, which are inversely proportional to soil water content. Soil water content is a function of soil topography, texture, and the balance between precipitation and evapotranspiration [10]. Therefore, the effect of shifting precipitation patterns and rising temperatures could impact nitrification and denitrification rates across the globe.

In addition to these direct effects, there is evidence to suggest that increasing atmospheric CO₂ concentrations have an indirect effect on N₂O emissions [6]. The CO₂ fertilization effect has been shown to decrease N₂O emissions by increasing plant N and C uptake, which can reduce N losses, including N₂O [11]. The magnitude and persistence of the CO₂ fertilization effect depends on the availability of mineral N and the ability of plants to acquire it. Hence, previous modeling and empirical studies have focused on the effects of N limitation on CO₂ fertilization in natural ecosystems and pasturelands. These land systems are often characterized by limited N inputs, and thus N limitation is believed to be the main limiting factor on their C storage capacity [9, 12–15]. N limitation is an important issue, particularly for natural ecosystems, where the main sources of N inputs (biological N fixation and N deposition) may not be able to sustain increased plant demand for N stimulated by CO₂ fertilization [6]. However, in intensive agricultural systems (the dominant source of anthropogenic N₂O emissions), N limitation is usually not a concern; there is, in fact, an excess supply of N, largely from synthetic fertilizers and manure [16]. Therefore, without N limitation cropping systems in certain regions could be more able to take advantage of the CO₂ fertilization effect and potentially increase their yields by up to 20% [17], improving N use efficiency (NUE) and water use efficiency [18] albeit with a possible deterioration in key micronutrient levels [19]. If certain

cropping systems can increase yields as a result of the CO₂ fertilization effect, this could then reduce excess N in soils, thereby potentially reducing agricultural N losses and N₂O emissions. This paper evaluates this hypothesis for the first time at a global scale under different climate scenarios. It builds on previous studies that have analyzed future N₂O emissions using other process-based land models [20] by explicitly disaggregating the impacts of climate, CO₂ concentrations and N inputs on agricultural biomass growth and agricultural N₂O emissions.

The other focus of this study is to better understand the mitigation potential of agricultural N₂O emissions via improvements in global NUE. Previously published scenarios of global NUE improvements and their impacts on agricultural N₂O emissions in the 21st century have relied primarily on modified N₂O emission factors and projections of global N fertilizer demand based on assumptions that are often opaque [3, 16, 20–22]. While these projections are useful in generating order of magnitude estimates of future N₂O emissions, they do not simulate the effects of farmer N management practices that ultimately determine NUE. In the only other study to have evaluated future NUE scenarios using a process-based global land model [20], the assumptions underpinning the ambitious NUE improvement scenario are not clear. By contrast, this study builds on previous work by representing the effects of farmer N management practices that underpin NUE improvements using the LM3-N.1 model. While this is by no means the first process-based land model with a coupled C–N cycle to simulate the effects of farmer N management practices on N cycle dynamics [23], we believe it is the first to do so with the goal of projecting future agricultural N₂O emissions under different climate and NUE scenarios. This could lead to a more complete assessment of how improvements in global NUE will affect N₂O emissions, and thus the climate and stratospheric ozone benefits that could follow.

Princeton GFDL-LM3 N.1 model

To conduct our analysis we introduce a new N₂O flux function based on Xu-Ri and Prentice into the LM3-N.1 model [24]. This model captures vegetation, C, N and water dynamics and was developed by Princeton University and the National Oceanic and Atmospheric Administration's (NOAA) GFDL [7]. The N sub-model couples each C pool in vegetation and the soil with a N compartment [8]. The model allows for N limitation on plant growth and CO₂ assimilation, includes processes such as N fixation, leaching (both mineral and organic), N volatilization from fire, N plant uptake, mineralization, nitrification, denitrification and hydrological and gaseous N export. Global to site-scale evaluations of this model have been presented in previous work [7, 8]. The general

denitrification function is adapted from Heinen [25] and was first introduced into LM3-N.1 and evaluated in Lee *et al* [26]:

$$D = k_d \times W_d \times T_d \times C_{\text{NO}_3^-},$$

k_d = denitrification rate coefficient (yr^{-1})

W_d = soil water content function (dimensionless)

T_d = soil temperature function (dimensionless)

$C_{\text{NO}_3^-}$ = soil NO_3^- concentration ($\text{kg NO}_3^- \text{N m}^{-2}$).

The focus on soil temperature, water content and NO_3^- concentrations emulates the approach of several other global denitrification models [27, 28]. The effect of labile C availability is reflected in the denitrification rate coefficient [29–31]. Meanwhile, the N_2O flux function is adapted from Xu-Ri and Prentice [24]:

$$\text{N}_2\text{O} = (F_{\text{denit}} \times T_{\text{N}_2\text{O}} \times D) + (F_{\text{nit}} \times \text{Nit}),$$

F_{denit} = Proportion of denitrification flux which is converted to N_2O (0.02) independent of the temperature modifier ($T_{\text{N}_2\text{O}}$)

D = Denitrification rate ($\text{kg N m}^{-2} \text{yr}^{-1}$)

$T_{\text{N}_2\text{O}} = e^{\left[308.56 \times \left(\frac{1}{68.02} - \frac{1}{T+46.02}\right)\right]}$ (T is in degrees Celsius)

F_{nit} = Proportion of nitrification flux which is converted to N_2O (fixed at 0.001)

Nit = Nitrification rate ($\text{kg N m}^{-2} \text{yr}^{-1}$).

See supplementary information section 1 for more detail on each individual parameter.

To evaluate these functions, we simulate agricultural N_2O emissions from 1990 to 2000 and find that our emission estimates are largely consistent with other model simulations and bottom-up inventories (see supplementary information section 1 for a model evaluation and sensitivity analysis). The denitrification function was also previously evaluated at the watershed scale, comparing model output with data from 16 monitoring stations in the Susquehanna River Basin. It was shown to capture fluxes well at multiple locations within the basin with different climate regimes and land-use types [26].

We define agricultural N_2O emissions as direct and indirect N_2O emissions (the latter from N leached into waterways and N deposition) from cropland and pasture, excluding manure management. Manure management is not currently simulated as emissions from this sector occur during the collection, handling, storage, and treatment of manure, practices that are not yet explicitly integrated into the model. The explicit simulation of indirect N_2O emissions is currently in development for LM3-N.1 and partially implemented in this study. While indirect N_2O emissions from N deposition are currently simulated (as the N deposited on land becomes part of the soil NH_4^+ and NO_3^- pools which impact nitrification and denitrification fluxes), indirect emissions from N leaching are not. Consequently, for this study we follow a similar approach to other recent process-based land model simulations [20] and apply the IPCC emission factor for indirect

N_2O emissions from N leaching (0.75% of leached mineral N is emitted as N_2O [32]). The dynamics of fertilizer and manure N application to cropland and pasture used in this study are described in supplementary information section 2.

Climate and NUE scenarios

For model simulations from 1990–2000 to 2040–2050 we use a global fertilizer and manure dataset from Bouwman *et al* (described in detail in supplementary information section 2) under two climate and land-use change scenarios [33]. These scenarios are Representation Concentration Pathway (RCP) 2.6, representing a highly ambitious climate mitigation scenario that maintains the possibility of reaching the 2°C target, and RCP 8.5, a high emission/business-as-usual (BAU) scenario [34, 35]. The latter approximates the path the world is currently following.

In addition to simulating BAU agricultural N_2O emissions, a central goal of this study is to better understand the potential environmental benefits of improving global NUE. Here we evaluate the impacts of a moderate (20%) and an ambitious (50%) increase in NUE by country by 2050 under both climate scenarios. These targets are based on results from previous studies of NUE improvements in cereal production, using a combination of plant breeding, proper technology and incentives [36–39]. NUE is measured in this study using partial factor productivity (kg C kg N^{-1}), one of the most widely used and easily measured NUE metrics, which measures the ratio of crop yield per unit of applied N [40]. All agricultural biomass in the model is represented as either a C3 or C4 grass type (determined as a function of climate, with C3 grasses more prevalent in temperate zones and C4 grasses more prevalent in tropical zones [7]), which precludes crop-specific analysis, a drawback shared by several similar models [6, 20] and an active area of model development. Net primary productivity on agricultural land is currently considered proportional to crop yields in the model, and is calculated as a function of gross primary productivity, growth and maintenance respiration, and N limitation [8]. All aboveground C and N in leaves and labile stores on cropland is annually harvested and released back to the atmosphere the following year. In pasture, 25% of leaf C and N is annually removed to represent livestock grazing and partitioned between a livestock respiration fraction (0.9) and a grazing residue fraction (0.1) that is returned to the soil pools. Given this relatively simplistic representation of agricultural activities currently in LM3 N.1, it is not possible to explicitly simulate specific agricultural management practices such as improving crop cultivars or using enhanced efficiency fertilizers. Instead, we evaluate three more basic approaches for achieving global NUE improvements of 20% and 50%, which represent the effects of a suite

of improved N management strategies that better synchronize soil N supply with crop N demand:

- (1) Reduced N inputs: fertilizer and manure application rates are reduced to achieve a 20% and 50% increase in NUE on a country-by-country basis by 2050.
- (2) Increased N uptake: plant N uptake is increased by 20% and 50% by 2050.
- (3) Combined: a combination of the reduced N input and increased N uptake strategies.

See supplementary information section 4 for more detail on these approaches, including a description of the most commonly used NUE-improving best management practices and technologies. It should also be noted that we are focusing on NUE at the field-level (an approach taken by similar studies [20, 33]). However, in reality N can continue to cascade through the environment, from field to feedlot and ultimately to the consumer's plate, with N losses throughout. New metrics are emerging to estimate NUE across the entire supply chain in which N use occurs, notably 'full chain NUE' [16]. While these efforts are important, the focus of this study is on in-field NUE given the capacity of our model.

Experimental set-up

The model was spun up for 1000 years with preindustrial climate forcing (using atmospheric CO₂ concentrations of 280 ppm) starting from bare ground without C–N coupling (i.e. a plant's capacity to photosynthesize was not limited by N concentrations in the soil) in order to accelerate vegetation growth. C–N coupling was then initiated and the spin-up continued for an additional 400 years to reach steady state. The model runs analyzed in this paper were begun in 1860 using historical CO₂ concentrations [41], high frequency forcings obtained from GFDL-ESM2 model output (temperature, wind, short- and long-wave downward radiation, specific humidity, and precipitation [42]) and the Bouwman *et al* fertilizer and manure data beginning in 1900. Depending on the run, forcings from RCP 2.6 or RCP 8.5 using the GFDL-ESM2 simulations were used from 2006 onwards, and modified Bouwman *et al* fertilizer and manure data were used to represent the various NUE scenarios (see supplementary materials section 1–3). Land use was prescribed from Hurtt *et al* [43].

Results and discussion

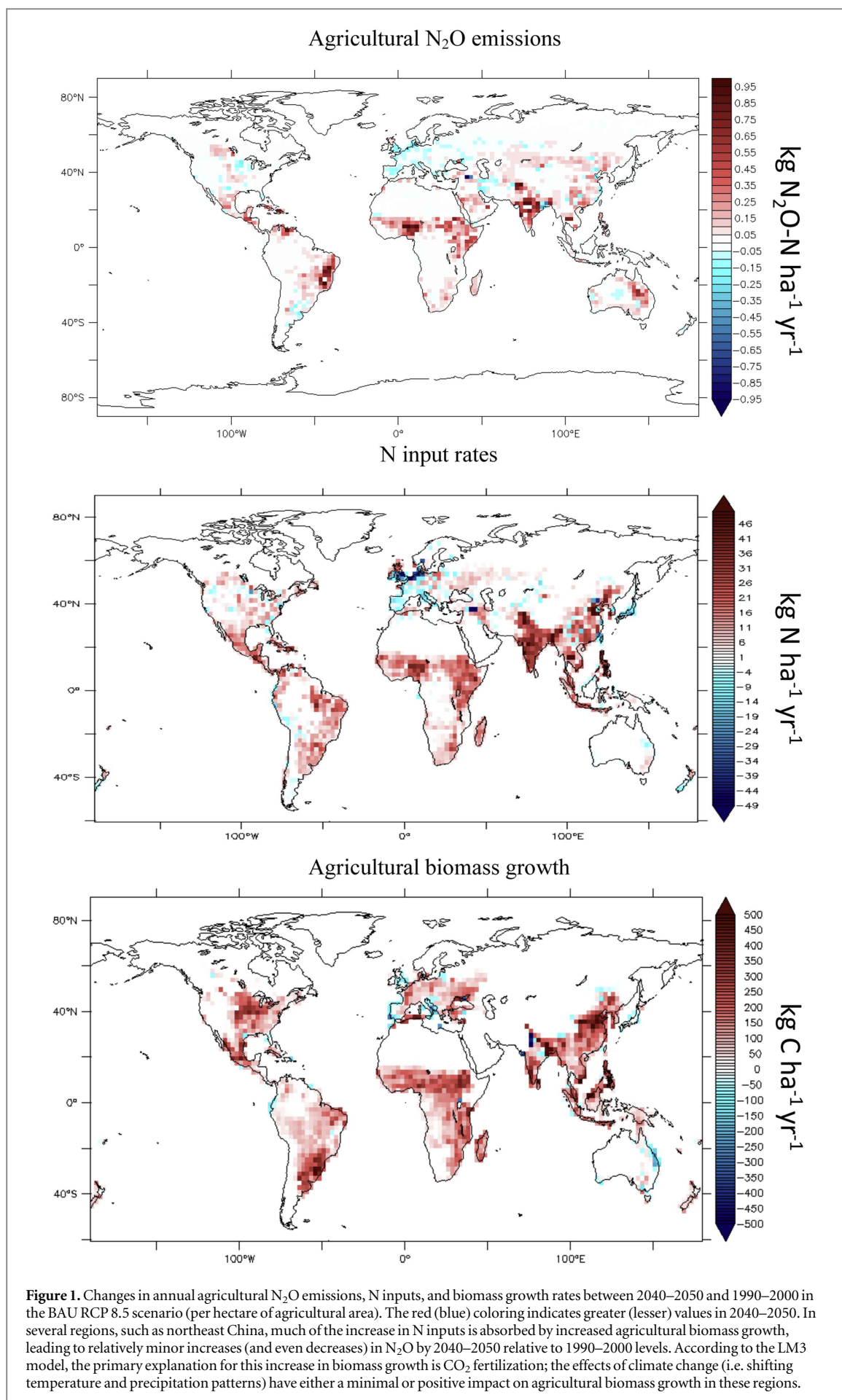
Agricultural N₂O emissions in 2040–2050 assuming little improvement in NUE

Under the baseline fertilizer and manure consumption scenario [33], which assumes little improvement in

global NUE by 2050 (see supplementary information section 2), our model projects a 24%–31% increase in agricultural N₂O emissions: from 2.9 Tg N₂O-N yr⁻¹ in 1990–2000 to 3.6 and 3.8 Tg N₂O-N yr⁻¹ by 2040–2050 for the RCP 2.6 and RCP 8.5 scenarios, respectively. Figure 1 globally maps the increases in emissions from 1990–2000 to 2040–2050 for the RCP 8.5 scenario (equivalent maps for RCP 2.6 are included in supplementary information section 5). The most significant increases in N₂O emissions are concentrated in regions with rapidly increasing N input rates, driven by sustained population growth and food production (e.g. India, sub-Saharan Africa) over the first half of the 21st century.

Nevertheless, changes in N input rates only partly explain future emission trends. There are several regions in figure 1 where N inputs are projected to increase considerably, but N₂O emissions are not. A likely explanation is that the CO₂ fertilization effect enhances agricultural biomass growth in regions where N is not limiting, which subsequently absorbs a significant portion of the increased N inputs, leaving less excess N to be lost as N₂O. In northeast China, for example, N input rates are projected to increase by up to 50 kg N ha⁻¹ yr⁻¹ by 2040–2050 (a 30% increase relative to 1990–2000 levels) and yet N₂O emissions are projected to rise less than 0.3 kg N₂O-N ha⁻¹ yr⁻¹ (a 10% increase). Meanwhile, agricultural biomass is projected to increase by over 0.2 kg C m⁻² yr⁻¹ (a 50% increase relative to 1990–2000 levels), indicating that much of the projected increase in N input is absorbed by an increase in crop yields. A similar dampening effect of agricultural biomass growth on agricultural N₂O emissions can be seen in other important agricultural regions such as northeastern and southern India, and southeastern South America.

The LM3 model attributes approximately 80% of the globally projected agricultural biomass growth by 2040–2050 to the CO₂ fertilization effect and 24% to increases in N inputs, while changes in soil temperature and precipitation patterns alone lead to a 4% decrease in global agricultural biomass growth (see supplementary information section 8). The dominance of the CO₂ fertilization response over the warming response concurs with empirical experiments that have evaluated these effects [44]. The CO₂ fertilization effect increases agricultural biomass levels by about 20% in RCP 8.5 and 10% in RCP 2.6 by 2040–2050 compared to model runs where atmospheric CO₂ concentrations are kept at 1990–2000 levels, which is within the range of previous estimates [17, 45, 46]. This increase in agricultural biomass growth takes up N that could otherwise be lost as N₂O. Indeed, without the CO₂ fertilization effect, we project that global agricultural N₂O emissions would be 0.5 Tg N₂O-N yr⁻¹ higher in 2040–2050, consistent with previously reported values [6]. A similar phenomenon is seen for RCP 2.6 (supplementary information section 5; see also section 6 for an analysis of the differences in



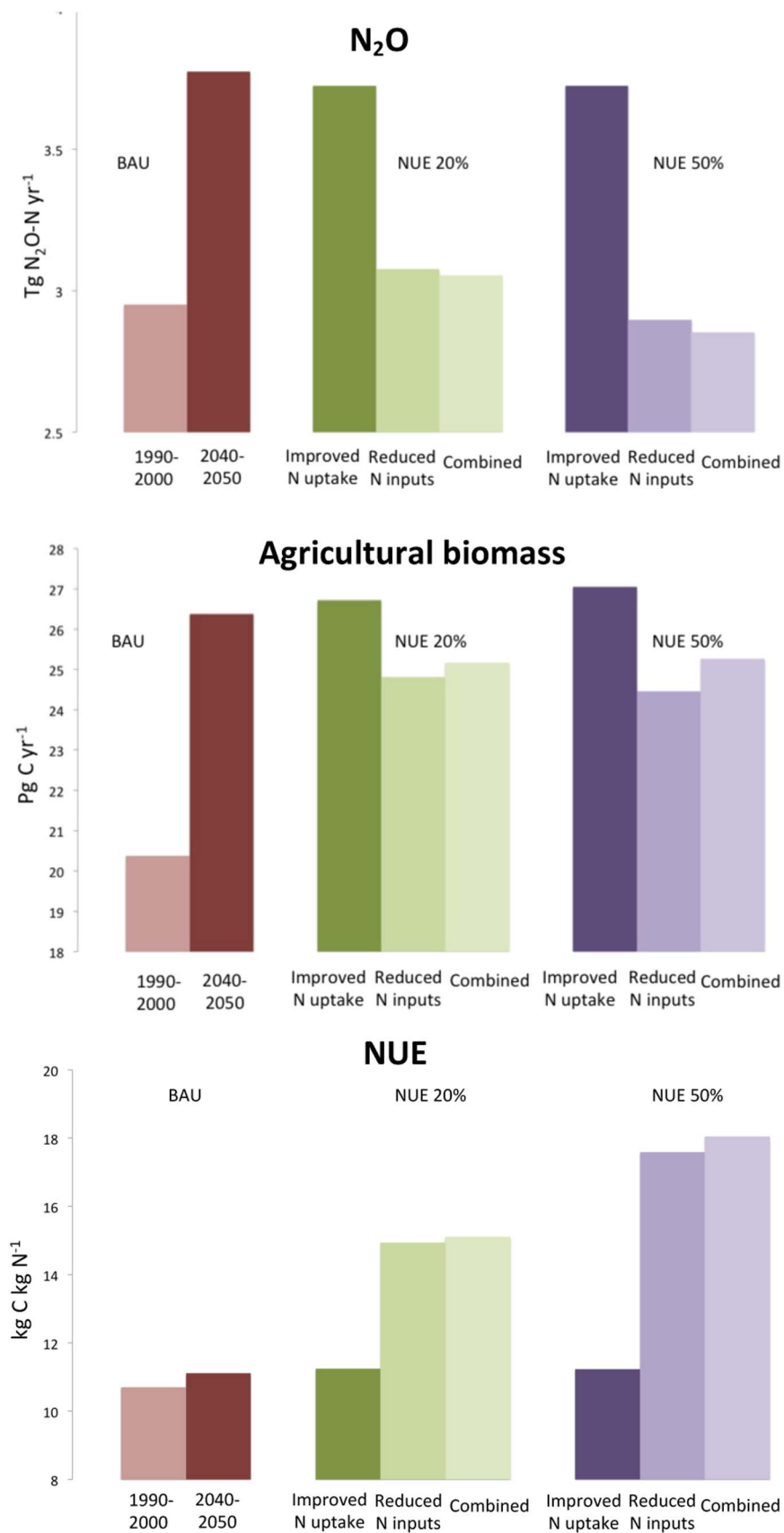


Figure 2. Changes in agricultural N₂O emissions, biomass growth and NUE across the different NUE scenarios and the three implementation approaches for RCP 8.5 in 2040–2050. While the combined reduced N input/improved N uptake scenarios are most effective in terms of reducing N₂O and increasing NUE, the improved N uptake scenarios are most effective in terms of increasing agricultural biomass growth. Nevertheless, the effectiveness of the improved N uptake scenario is limited by how N uptake is represented in the model (supplementary information section 8).

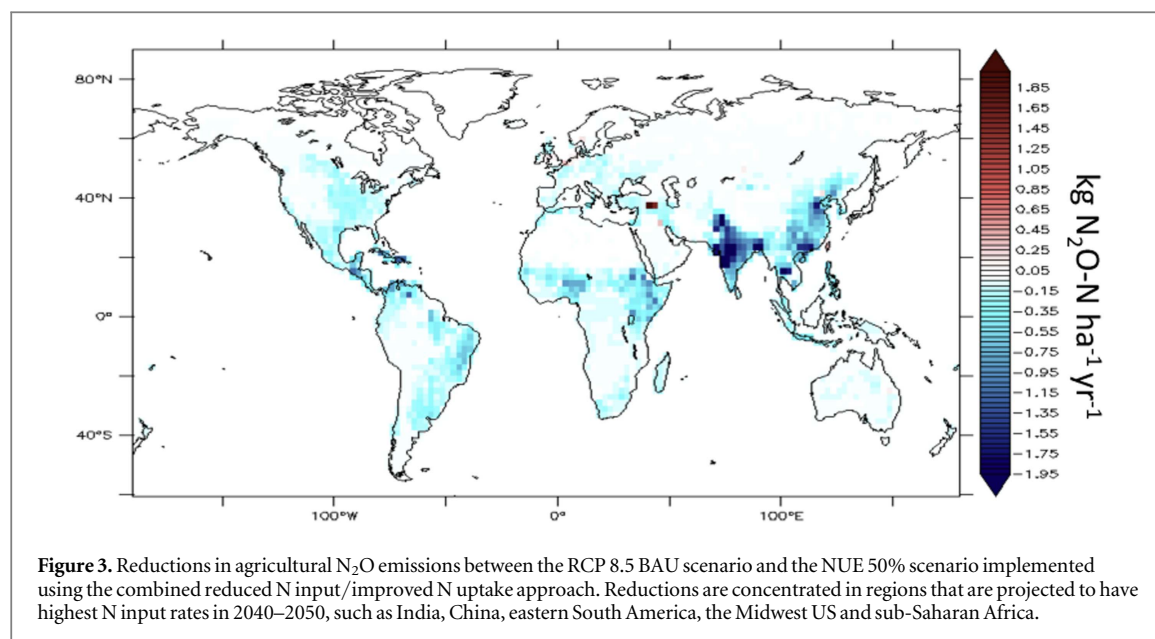


Table 1. The cumulative environmental benefits generated from achieving the 20% and 50% improvements in global NUE (integrated over the period 2015–2050) using the ‘improved N uptake’, ‘reduced N input’ and ‘combined’ implementation approaches. These benefits are reported in terms of reductions in N_2O emissions ($\text{Tg N}_2\text{O-N}$), climate forcing ($\text{Pg CO}_2 \text{ eq.}$) and stratospheric ozone depletion (Tg ODP). The lower bound of the uncertainty range marks the benefits from achieving the NUE 20% scenario and the upper bound marks the benefits from achieving the NUE 50% scenario. The results represent the range of benefits achievable across both NUE scenarios and the RCP scenarios.

NUE approach	Nitrous oxide ($\text{Tg N}_2\text{O-N}$)	Climate ($\text{Pg CO}_2 \text{ eq.}$)	Ozone (Tg ODP)
Improved N uptake	0.4–2.6	0.2–1.2	0.01–0.07
Reduced N inputs	13.7–17.5	6.4–8.2	0.4–0.5
Combined	14.0–21.2	6.6–9.9	0.4–0.6

N_2O emissions between RCP 2.6 and RCP 8.5). A common feature of the regions where CO_2 fertilization is most pronounced (e.g. northeast China)—and thus where N_2O emissions are most dampened—is that the effects of climate change (i.e. shifting temperature and precipitation patterns) have either a minimal or positive impact on agricultural biomass growth (figure S10). Nevertheless, it should be noted that CO_2 fertilization only dampens N_2O emissions during the growing season; a significant proportion of annual N_2O emissions have been shown to occur during periods when agricultural land is bare (i.e. directly following fertilizer application or off-season during freeze-thaws events and post-harvest [47]), periods that are represented in the LM3 model. However, intra-annual variability is less important for the purposes of this study given our focus on decadal time-scales.

The dampening effect that agricultural biomass growth has on agricultural N_2O emissions in certain regions suggests that simply applying N_2O emission factors to projected N input rates might overestimate future emissions. For example, applying the Davidson emission factors (approximately 2% for manure and 2.5% for fertilizer) to the Bouwman *et al.* N input projections suggests a 42%–44% increase in agricultural N_2O emissions across the RCPs by 2040–2050 relative to 1990–2000, which is substantially larger

than the 24%–31% increase projected in this study [33, 48]. Our results also contrast with the results published in Stocker *et al.* using the LPX-Bern Earth System Model of intermediate complexity, which projects the relative increase in agricultural N_2O emissions by 2040–2050 (38%–75%) to be greater than the relative increase in N inputs (20%–60%) which is counter to our findings [20]. While they do not offer an explanation for this dynamic, we believe the differences stem from the fact that the balance in their model between climatic factors that enhance N_2O emissions (e.g. rising surface temperatures that can increase soil N mineralization and ultimately denitrification rates) and those that dampen emissions (i.e. the CO_2 fertilization effect) skew towards the former, while the balance in LM3-N.1 skews towards the latter. More research in this area is necessary to better understand which of the climatic drivers of N_2O emissions can be expected to dominate in the future.

Impact of global NUE increases on future agricultural N_2O emissions

Despite the impact of the CO_2 fertilization effect, improving NUE could still lead to significant reductions in agricultural N_2O emissions, depending on the target set and the implementation strategy used. Figure 2 shows the impact of each NUE improvement

and implementation strategy on global N_2O emissions, agricultural biomass growth, and NUE for the RCP 8.5 scenario. RCP 2.6 has similar results (supplementary information sections 5 and 8). The largest N_2O reductions are achieved with the scenario that combines N input reductions and N uptake increases (reducing emissions to $2.8 \text{ Tg N}_2\text{O-N yr}^{-1}$ in 2040–2050, a 28% reduction in emissions compared to the baseline scenario). In this scenario, agricultural biomass growth is slightly reduced relative to the baseline scenario ($25.3 \text{ Pg C yr}^{-1}$ versus $26.4 \text{ Pg C yr}^{-1}$). However this is still a 24% increase in agricultural biomass growth from 1990–2000 levels, with 24% less N inputs (see figure 3 for spatial distribution of N_2O reductions). Reductions are concentrated in regions that are projected to have the highest N input rates in 2040–2050.

Stratospheric ozone and climate benefits

The different NUE approaches produce a range of environmental benefits over 2015–2050 (table 1). The highest mitigation potential comes from a combination of the reduced N inputs/improved N uptake approach and switching from a RCP 8.5 to a RCP 2.6 forcing scenario. In this case, emissions in 2040–2050 are $2.7 \text{ Tg N}_2\text{O-N yr}^{-1}$ (instead of $3.9 \text{ Tg N}_2\text{O-N yr}^{-1}$, a 31% reduction), with cumulative savings of $21.2 \text{ Tg N}_2\text{O-N}$ over 2015–2050, equivalent to $9.9 \text{ Pg CO}_2 \text{ eq.}$ and 0.6 Tg ODP . These estimates do not take into account the other indirect environmental and health benefits that could result from reducing N pollution, namely improved water quality from less N leaching and a reduction in air pollution due to decreases in NH_3 and NO_x volatilization. A more holistic assessment of the entire N cascade is an area of active model development. In addition, a better representation of agricultural crops and practices is also being developed for the LM3-N.1 model. This will allow for a more nuanced and realistic evaluation of NUE scenarios, with an ability to analyze the effect of different fertilizer best management practices and technologies in different climates and growing cultures.

With growing calls for an effective international framework to manage N pollution, policy-makers require scientific information on a range of issues to better evaluate policy options. This study has attempted to contribute to this need for policy-relevant science by demonstrating the importance of climatic feedbacks in determining future agricultural N_2O emissions, and that increasing NUE can deliver important global environmental benefits. This is an important step if humanity hopes to return within a safe planetary boundary for nitrogen.

Author contributions

DRK, XZ, DLM, SM and ES designed the study, analyzed the data, and wrote the paper. DRK, SM and ES designed the model experiments. DRK and XZ

designed and performed the model evaluation and sensitivity analysis. DRK wrote the new code and ran the model.

Competing interests

We have no competing interests.

References

- [1] Ravishankara A R, Daniel J S and Portmann R W 2009 Nitrous oxide (N_2O): the dominant ozone-depleting substance emitted in the 21st century *Science* **326** 123–5
- [2] Kanter D *et al* 2013 A post-kyoto partner: considering the stratospheric ozone regime as a tool to manage nitrous oxide *Proc. Natl Acad. Sci. USA* **110** 4451–7
- [3] Bouwman L *et al* 2013 *Drawing Down N_2O to Protect Climate and the Ozone Layer. A UNEP Synthesis Report* (Nairobi, Kenya: United Nations Environment Programme)
- [4] Butler J H M and Montzka S A 2015 *The NOAA Annual Greenhouse Gas Index (AGGI)* (Boulder, CO: Laboratory NESR)
- [5] Davidson E A and Kanter D 2014 Inventories and scenarios of nitrous oxide emissions *Environ. Res. Lett.* **9** 105012
- [6] Zaehle S 2013 Terrestrial nitrogen–carbon cycle interactions at the global scale *Phil. Trans. R. Soc. B* **368** 20130125
- [7] Shevliakova E *et al* 2009 Carbon cycling under 300 years of land use change: Importance of the secondary vegetation sink *Glob. Biogeochem. Cycles* **23** GB2022
- [8] Gerber S, Hedin L O, Oppenheimer M, Pacala S W and Shevliakova E 2010 Nitrogen cycling and feedbacks in a global dynamic land model *Glob. Biogeochem. Cycles* **24** GB1001
- [9] Fowler D S *et al* 2015 Effects of global change during the 21st century on the nitrogen cycle *Atmos. Chem. Phys. Discuss.* **15** 1747–868
- [10] Robertson G P G and Vitousek P M 2007 Nitrogen transformations *Soil Microbiology, Biochemistry, and Ecology* ed E A Paul (Berlin: Springer) p 341–64
- [11] Xu-Ri, Prentice I C, Spahni R and Niu H S 2012 Modelling terrestrial nitrous oxide emissions and implications for climate feedback *New Phytol.* **196** 472–88
- [12] Zaehle S, Friedlingstein P and Friend A D 2010 Terrestrial nitrogen feedbacks may accelerate future climate change *Geophys. Res. Lett.* **37** L01401
- [13] Zaehle S, Jones C D, Houlton B, Lamarque J F and Robertson E 2015 Nitrogen availability reduces CMIP5 projections of twenty-first-century land carbon uptake *J. Clim.* **28** 2494–511
- [14] Zaehle S *et al* 2014 Evaluation of 11 terrestrial carbon-nitrogen cycle models against observations from two temperate free-air CO_2 enrichment studies *New Phytol.* **202** 803–22
- [15] Newton P C D *et al* 2010 The rate of progression and stability of progressive nitrogen limitation at elevated atmospheric CO_2 in a grazed grassland over 11 years of free air CO_2 enrichment *Plant Soil.* **336** 433–41
- [16] Sutton M A B *et al* 2013 *Our Nutrient World: The Challenge to Produce More Food and Energy with Less Pollution* Centre for Ecology and Hydrology (Edinburgh) on Behalf of the Global Partnership on Nutrient Management and the International Nitrogen Initiative
- [17] McGrath J M and Lobell D B 2013 Regional disparities in the CO_2 fertilization effect and implications for crop yields *Environ. Res. Lett.* **8** 014054
- [18] Leakey A D B, Ainsworth E A, Bernacchi C J, Rogers A, Long S P and Ort D R 2009 Elevated CO_2 effects on plant carbon, nitrogen, and water relations: six important lessons from FACE *J. Exp. Bot.* **60** 2859–76
- [19] Myers S S *et al* 2014 Increasing CO_2 threatens human nutrition *Nature* **510** 139
- [20] Stocker B D *et al* 2013 Multiple greenhouse-gas feedbacks from the land biosphere under future climate change scenarios *Nat. Clim. Change* **3** 666–72

- [21] van Vuuren D P *et al* 2011 The representative concentration pathways: an overview *Clim. Change* **109** 5–31
- [22] Davidson E A 2012 Representative concentration pathways and mitigation scenarios for nitrous oxide *Environ. Res. Lett.* **7** 024005
- [23] Del Grosso S J *et al* 2009 Global scale DAYCENT model analysis of greenhouse gas emissions and mitigation strategies for cropped soils *Glob. Planet Change* **67** 44–50
- [24] Xu-Ri and Prentice I C 2008 Terrestrial nitrogen cycle simulation with a dynamic global vegetation model *Glob. Change Biol.* **14** 1745–64
- [25] Heinen M 2006 Simplified denitrification models: overview and properties *Geoderma* **133** 444–63
- [26] Lee M M S, Shevliakova E, Milly P C D and Jaffé P R 2014 Capturing interactions between nitrogen and hydrological cycles under historical climate and land use: susquehanna watershed analysis with the GFDL land model LM3-TAN *Biogeosciences* **11** 5809–26
- [27] Lin B L, Sakoda A, Shibasaki R, Goto N and Suzuki M 2000 Modelling a global biogeochemical nitrogen cycle in terrestrial ecosystems *Ecol. Model.* **135** 89–110
- [28] Tian H Q L, Liu M, Zhang C, Ren W, Chen G S, Xu X F and Lu C Q 2005 DLEM—The Dynamic Land Ecosystem Model User Manual (Auburn, AL: The Ecosystem Dynamics and Global Ecology (EDGE), Auburn University)
- [29] Hansen S, Jensen H E, Nielsen N E and Svendsen H 1990 DAISY—soil plant atmosphere system model, Danish simulation model for transformation and transport of energy and matter in the soil plant atmosphere system *Contract No.: NPO Report A10* The National Agency for Environmental Protection, Copenhagen, Denmark
- [30] Ramos C and Carbonell E A 1991 Nitrate leaching and soil-moisture prediction with the leachm model *Fert. Res.* **27** 171–80
- [31] Breve M A, Skaggs R W, Parsons J E and Gilliam J W 1997 DRAINMOD-N, a nitrogen model for artificially drained soils *Trans. ASAE* **40** 1067–75
- [32] Eggleston S B, L, Miwa K, Ngara T and Tanabe K 2006 *IPCC Guidelines for National Greenhouse Gas Inventories* (Kanagawa, Japan: Intergovernmental Panel on Climate Change)
- [33] Bouwman L *et al* 2013 Exploring global changes in nitrogen and phosphorus cycles in agriculture induced by livestock production over the 1900–2050 period *Proc. Natl Acad. Sci. USA* **110** 20882–7
- [34] Riahi K *et al* 2011 RCP 8.5-A scenario of comparatively high greenhouse gas emissions *Clim. Change* **109** 33–57
- [35] van Vuuren D P *et al* 2011 RCP2.6: exploring the possibility to keep global mean temperature increase below 2 degrees C *Clim. Change* **109** 95–116
- [36] Cassman K G, Dobermann A and Walters D T 2002 Agroecosystems, nitrogen-use efficiency, and nitrogen management *Ambio* **31** 132–40
- [37] Cassman K G, Dobermann A, Walters D T and Yang H 2003 Meeting cereal demand while protecting natural resources and improving environmental quality *Annu. Rev. Environ. Resour.* **28** 315–58
- [38] Chen X P *et al* 2011 Integrated soil-crop system management for food security *Proc. Natl Acad. Sci. USA* **108** 6399–404
- [39] Dobermann A and Cassman K G 2005 Cereal area and nitrogen use efficiency are drivers of future nitrogen fertilizer consumption *Sci. China Ser. C* **48** 745–58
- [40] Dobermann A 2007 Nutrient use efficiency—measurement and management *Fertilizer Best Management Practices* (Paris, France: Association IFI)
- [41] Meinshausen M *et al* 2011 The RCP greenhouse gas concentrations and their extensions from 1765 to 2300 *Clim. Change* **109** 213–41
- [42] Dunne J P *et al* 2012 GFDL's ESM2 global coupled climate-carbon earth system models: I. Physical formulation and baseline simulation characteristics *J. Clim.* **25** 6646–65
- [43] Hurtt G C *et al* 2011 Harmonization of land-use scenarios for the period 1500–2100: 600 years of global gridded annual land-use transitions, wood harvest, and resulting secondary lands *Clim. Change* **109** 117–61
- [44] Dieleman W I J *et al* 2012 Simple additive effects are rare: a quantitative review of plant biomass and soil process responses to combined manipulations of CO₂ and temperature *Global Change Biol.* **18** 2681–93
- [45] Müller C, Bondeau A, Wahav K and Fader M 2010 *Climate Change Impacts on Agricultural Yields: Background Note to the World Development Report 2010* Potsdam Institute for Climate Impact Research (PIK)
- [46] Rosenzweig C *et al* 2014 Assessing agricultural risks of climate change in the 21st century in a global gridded crop model intercomparison *Proc. Natl Acad. Sci. USA* **111** 3268–73
- [47] Groffman P M *et al* 2009 Challenges to incorporating spatially and temporally explicit phenomena (hotspots and hot moments) in denitrification models *Biogeochemistry* **93** 49–77
- [48] Davidson E A 2009 The contribution of manure and fertilizer nitrogen to atmospheric nitrous oxide since 1860 *Nat. Geosci.* **2** 659–62