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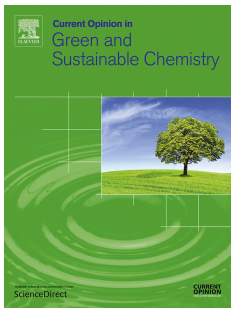

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Anthropogenic-driven perturbations on nitrogen cycles and interactions with climate changes

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Abstract

Anthropogenic activities have substantially perturbed the global nitrogen (N) cycle directly through enhancing reactive N (Nr) inputs and indirectly through climate and land-use change. However, the climatic impacts of the N cycle and its feedbacks on climate change remain very uncertain. In this review, we provide an overview of the dominant pathways by which anthropogenic Nr affects the climate system and summarize the available scientific assessments. We also review the latest progress on the responses of N cycle to changing climate to understand the potential for feedbacks between the N cycle and climate. With the urgent need to reduce Nr in the future to alleviate its negative environmental impacts, e.g. air pollution and eutrophication, we highlight the importance for bridging disciplines of atmospheric chemistry, ecology and climatology to improve the scientific understanding and develop co-benefits for both environmental protection and climate change mitigation.

Keywords: Anthropogenic nitrogen, Biogeochemistry-Climate interactions; Climate effects of anthropogenic nitrogen; Terrestrial carbon-nitrogen interactions; Atmospheric nitrogen chemistry; Ammonium and nitrate aerosols; Nitrogen cycles under climate changes

1. Introduction

Nitrogen (N) constitutes nearly 78% of the atmosphere, however nearly 99% of atmospheric N is gas-phase molecular N (N_2) (Galloway et al., 2003). Two processes in the natural environment, i.e. biological nitrogen fixation (BNF) and lightning, can break the triple bond of N_2 and thereby create reactive nitrogen (Nr). As one of the most important nutrients for living organisms supporting biosynthesis, growth, maintenance and propagation, Nr can be subjected to a vast number of chemical and biochemical reactions and functions through its importance in enzyme synthesis and biomolecules (Duce et al., 2008; Zaehle and Dalmonech, 2011). However, Nr entering marine and terrestrial ecosystems may also be exported out of the biosphere and emitted to the atmosphere, where it interferes with the radiative transfer in the atmosphere through tropospheric chemical reactions of greenhouse gases and aerosols. (Derwent et al., 2008; Shindell et al., 2009). As a result, anthropogenic Nr plays important roles in the global biogeochemical cycles (of carbon, nitrogen, phosphorus, etc.), further influencing environmental health (de Vries, 2021; Nieder and Benbi, 2022), ecosystem biodiversity (Bobbink et al., 2010), and climate changes (Erisman et al., 2011).

Fossil fuel combustion and N fixation technology (e.g. the Haber-Bosch reaction) have introduced large quantities of anthropogenic Nr to the Earth system since the beginning of the industrial revolution (around 1750). The scale of this perturbation has grown exponentially since the beginning of the industrial revolution and in current decades is estimated to be on par with or even exceed natural Nr generation through BNF and lightning (Fowler et al., 2013). Excessive Nr, on the one hand, substantially affects climate. For

instance, increased nitrous oxide (N_2O) concentrations and ammonium (NH_4^+) / nitrate (NO_3^-) aerosol loadings in the atmosphere could warm and cool the atmosphere through the greenhouse effect and solar-radiation diffusion, respectively (Thornhill et al., 2021b). The enhanced Nr inputs into ecosystems through N deposition, fertilizer and manure application may alleviate global warming by increasing ecosystem carbon sequestration (Lessmann et al., 2022; Schulte-Uebbing et al., 2022). Furthermore, short-lived nitrogen oxides (NO_x) play vital roles in atmospheric chemistry and non-linearly alter atmospheric greenhouse gases of ozone (O_3) (Lu et al., 2021a) and methane (CH_4) (Peng et al., 2022). On the other hand, climate change induced by anthropogenic greenhouse gases also substantially affects almost all of the natural N processes (Fowler et al., 2015; Greaver et al., 2016), with the possibility of causing feedbacks to climate. The net climate effects of anthropogenic Nr as well as the N climate feedbacks, although understood in principle, are challenging to quantify and therefore remain purely constrained.

The importance of interactions between N dynamics and climate has gained recognition inpast decades (Altieri et al., 2021; Erisman et al., 2011; Fowler et al., 2015). Substantial efforts have been dedicated in the past years to improve the scientific understanding through field experiments, meta-data analysis, machine learning techniques and model simulations. In this review study, we aim to give an overview on previous studies, most of which have predominantly focused on specific N compounds or processes within the global N cycles, and integrate the latest key findings with respect to interactions of N cycles and climate change. As illustrated in Fig. 1, we will firstly overview the pathways that N cycles influence climate and identify the contributions led by direct anthropogenic Nr inputs (Sect. 2), then we will briefly demonstrate the recent discoveries of key N-cycle processes responses to changing climate as well as the anthropogenic perturbations (Sect. 3). Finally, we will conclude and outline future perspectives in Sect. 4.

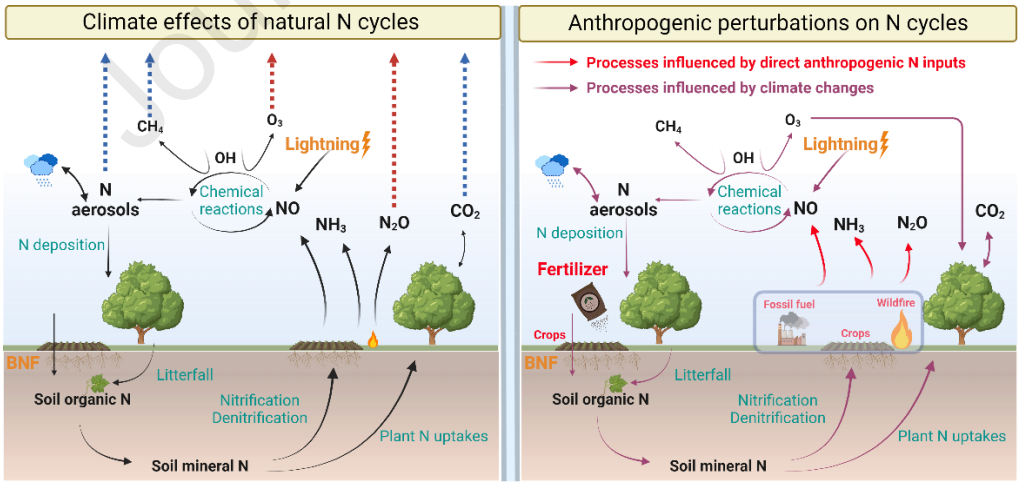

Figure 1. The climate effects of Nr compounds (left) also with anthropogenic-driven perturbations on N cycles (right). For each panel, the left part indicates the Nr inputs to the terrestrial ecosystem, while the right part indicates the Nr fluxes to the atmosphere. The blue or red dashed arrows on the top of the left panel indicate the cooling or warming effects of each component on climate, respectively.

2. Main climate-affecting N compounds

2.1 N_2O

N_2O is a long-lived greenhouse gas with a global warming potential that is about 273 times greater larger than that of CO_2 per unit mass over a period of 100 years. IPCC AR6 reported with high confidence that atmospheric N_2O mole fractions have risen from 270 ppb in 1750 to 331 ppb in 2019 and contributed to +0.21 ± 0.03 W m^{-2} effective radiative forcing relative to the pre-industrial period (Canadell et al., 2021). Increases in agricultural fertilizer/manure application, N deposition and fossil fuel combustions were identified as primary drivers behind this increase of N_2O (Tian et al., 2019), but the exact attribution of anthropogenic contributions to the N_2O increases is still challenging. Anthropogenic sources during 2007-2016 were estimated to be 7.3 [4.2-11.4] Tg N yr^{-1} among the global total 17.0 Tg N yr^{-1} emissions (Tian et al., 2020). Limited but also challenging flux measurements (Barton et al., 2015; Liao et al., 2023; Wang et al., 2020), uncertain and dynamic spatiotemporal distributions of N fertilizer application and agricultural land uses (Lu and Tian, 2017), as well as imperfections in model representations (Feng et al., 2023) together are the main cause for this large range.

2.2 N-species aerosols

Aerosols remain in the troposphere for a timescale of days to weeks. Most compounds result in a cooling effect on climate as they scatter solar radiation and interact with cloud formation and lifetime. Ammonium (NH_4^+) and nitrate (NO_3^-) are the two dominant N-species aerosols. It is well-known that the major source of ammonia (NH_3), which is the primary precursor to generate NH_4^+, is from agricultural activities (Hoesly et al., 2018), but significant gaps remain in quantifying global NH_3 emissions. Recent bottom-up estimates assessed global agricultural NH_3 emissions at about 58 Tg N yr^{-1} in 2010 (Liu et al., 2022a), while the top-down inversion accounting for natural and other anthropogenic NH_3 sources suggested global emissions from 90 to 191 Tg N yr^{-1} (Evangeliou et al., 2021; Luo et al., 2022). Some studies also showed current emission inventories tended to underestimate NH_3 emissions particularly in hotspot regions, such as Western Europe (Cao et al., 2022) and Eastern China (Kong et al., 2019). With uncertainties in NH_3 emissions, the effective radiative forcing (ERF) of NH_4^+ in 2014 was estimated to be about -0.07 W m^{-2} based on ensemble means of earth system models (Thornhill et al., 2021b).

Emissions of nitrogen oxide (NO_x), which is the main precursor of NO_3^-, are dominated by fossil fuel sources (Hoesly et al., 2018). Both bottom-up and top-down estimates showed consistently similar magnitudes and decadal trends in anthropogenic NO_x emissions (Ding et al., 2017; Jena et al., 2015; McDuffie et al., 2020). NO_x engages in numerous chemical reactions and significantly perturbates atmospheric hydroxyl radical (OH) concentrations (see below Sect 2.3). The non-linearity of atmospheric chemistry introduces uncertainties in the global burden, spatial distribution as well as the particle sizes of NO_3^-, all of which are essential to quantify the NO_3^- climate effects. Therefore, estimates of the cooling effects of NO_3^- through solar diffusion varied from very small (~-0.025 W m^{-2}) to more substantial effects (-0.14 W m^{-2}) (An et al., 2019; Bian et al., 2017; Hauglustaine et al., 2014; Thornhill et al., 2021b; Zaveri et al., 2021). The interactions between NO_3^- aerosols and cloud remained quite uncertain, with radiative forcing assessed by a limited number of studies ranging from -0.05 to -0.22 W m^{-2} (Bellouin et al., 2011; Lu et al., 2021c; Xu and Penner, 2012).

2.3 NO_x indirect effects through atmospheric chemical reactions

As the highly reactive gas, NO_x is involved in various chemical reactions with other greenhouse gases, in particular O_3 and CH_4. It thereby affects climate indirectly by changing the

lifetime and thus atmospheric burden of these gases. In general, increased atmospheric NO_x concentrations will lead to higher OH concentrations, further increasing O_3 concentrations (Lu et al., 2021a), while at the same time shortening CH_4 lifetime and thereby reducing CH_4 concentrations (Peng et al., 2022). A recent assessment based on an ensemble of Earth System models showed that NO_x-induced O_3 enhancement warmed the climate by $+0.2\pm0.07$ W m^{-2}, while the reduced CH_4 lifetime led by NO_x contributed a cooling effect of about -0.2 W m^{-2} to -0.37 W m^{-2} until 2014 since pre-industrial (Thornhill et al., 2021b). The complexity of OH chemical dynamics and non-linear interactions among NO_x, volatile organic compounds and O_3 is the primary cause for the uncertainty in this quantification.

2.4 C-N interactions in terrestrial ecosystems

The majority of the N element in the terrestrial ecosystem constitutes plants and microbes in organic forms and plays crucial roles in enzyme-mediated processes. However, the available N for plants is normally in the forms of dissolved inorganic N, such as ammonium or nitrate ions, which is mineralized from soil organic N by microbial activities (Li et al., 2019). Meanwhile, soil microbes also regulate BNF levels, thereby influencing the overall N availability for plants (Aasfar et al., 2021). A portion of the mineralized inorganic N will be lost from the terrestrial ecosystem as gases phase though nitrification and denitrification (Feng et al., 2023), or as dissolved forms through leaching (Wang and Li, 2019).

Next to phosphorus, N in terrestrial ecosystems is one of the most important nutrients for plants and microbial organisms. It is essential for C assimilation, growth and maintenance and thereby tightly connected to the C cycle. The N limitation of biomass production is generally believed to be strong in natural temperate and boreal forests (Du et al., 2020), attenuating the expected increases in carbon storage due to CO_2 fertilization of plant photosynthesis under future climate change (Terrer et al., 2019). Anthropogenic-driven increases in N fertilizer application and atmospheric Nr deposition can increase productivity by lifting N limitation. Synthesis of available data from ecosystem manipulation experiments by meta-analysis or machine learning have revealed responses of terrestrial C sinks to N addition, ranging from 1 kg C (kg N)$^{-1}$ to 25 kg C (kg N)$^{-1}$ depending on different land cover types, amounts and types of N addition (Liu and Greaver, 2009; Liu et al., 2022b; Poulton et al., 2018; Schulte-Uebbing et al., 2022).

Terrestrial biosphere models (TBMs) integrate process understanding of biogeochemical cycles at large scales and is another useful tool to quantify the climate effects of N-induced increases in C sequestration (Zaehle and Dalmonech, 2011). For instance, Zaehle et al. (2011 attributed a cumulative cooling effect of about -0.1 W m^{-2} to Nr induced carbon storage in the terrestrial biosphere since pre-industrial times by applying a TBM to reproduce global observed trends of atmospheric CO_2. In recent years, dynamic C-N coupling has been induced in an increasing number of TBMs (Davies-Barnard et al., 2020; Kou-Giesbrecht et al., 2023; Wieder et al., 2015; Zaehle et al., 2014). These models generally agree with earlier findings, but evaluation against independent benchmark highlights remaining uncertainty and a formidable challenge to further constrain model uncertainties to better quantify the N effects on terrestrial carbon sinks and the resulting climate impacts (Kou-Giesbrecht et al., 2023) (Fig. 2).

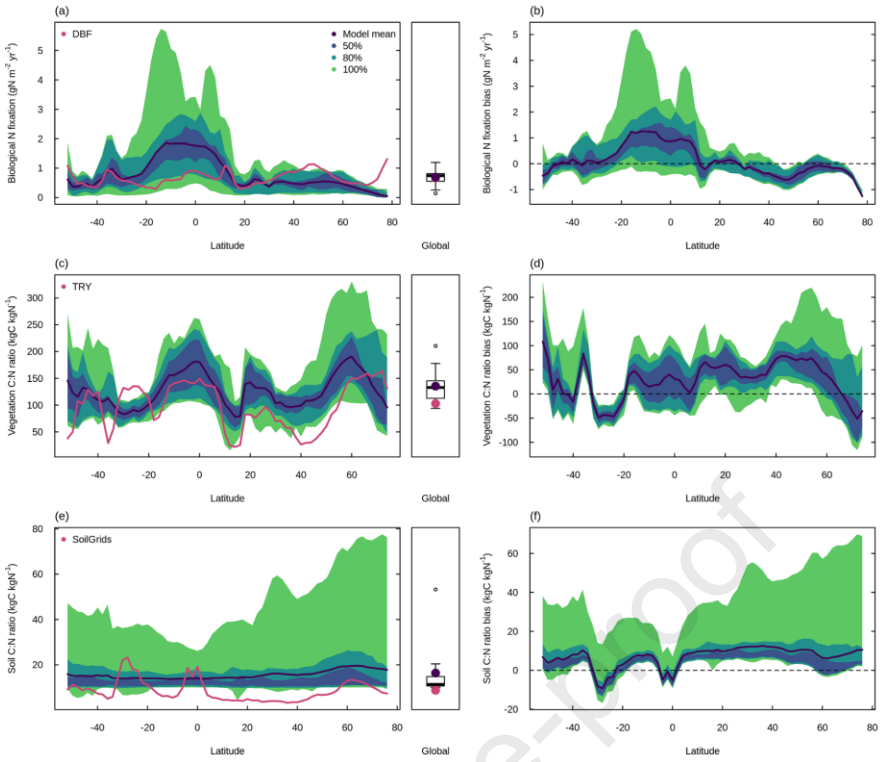

Figure 2. Latitudinal distributions and global means of BNF, vegetation C : N ratio, and soil C : N ratio simulated by the TRENDY-N ensemble (averaged across models over 1980–2021) in comparison to observations. Panels (a, c, e) show the latitudinal distribution of the mean and boxplots show the global mean. Panels (b, d, f) show the latitudinal distribution of the bias. Latitudinal distributions show the mean (black line) and the 50 %, 80 %, and 100% percentiles across models. Boxplots show the median, interquartile range (box), and 80% percentiles (whiskers) across models. Observation-based datasets are from Davies-Barnard and Friedlingstein (2020) for biological N fixation, the TRY plant trait database for vegetation C:N ratio, and SoilGrids for soil C:N ratio. This figure is from Kou-Giesbrecht et al. (2023).

2.5 Other Nr-related climate effects

There are additional, less well-quantified pathways of Nr known to affect climate, which are summarized here: (1) Nr-induced increases in aerosols and O_3 could influence terrestrial carbon sinks by reducing ratios of direct to diffuse photosynthetically active radiation (Mercado et al., 2009; Zhou et al., 2022) and by damaging leaf photosynthesis (Franz et al., 2018; Gong et al., 2021; Sitch et al., 2007), respectively. (2) Nr inputs into terrestrial ecosystems may reduce soil CH_4 uptake (Li et al., 2021b; Liu and Greaver, 2009) and thus increase atmospheric CH_4. However, soil CH_4 uptake plays only a small role in the global CH_4 cycle and the magnitude of the Nr effects ranges from -60% to +10% (Xia et al., 2020). (3) Riverine and marine N_2O emissions and the C-N interactions might also be influential on climate. Yao et al. (2020) suggested that increased N inputs enhanced riverine emissions of N_2O from 70.4±15.4 Gg N yr^{-1} in 1900 to 291.3±58.6 Gg N yr^{-1} in 2016, while marine N deposition is estimated to contribute to present-day marine N_2O emissions by about 0.01-0.32 Tg N yr^{-1} (Canadell et al., 2021) and marine primary productivity by 0.3 Pg C yr^{-1} increases (Duce et al., 2008), respectively, but with neglectable changes in the resultant air-sea CO_2 fluxes (Yamamoto et al., 2022).

198 2.6 The net climate effects of anthropogenic Nr

199 Quantifying the net climate effects of anthropogenic Nr requires crossing different time-scales
200 and disciplines among atmospheric chemistry, climate dynamics and ecological science. To
201 date, this gap among different scientific communities and quantifications is typically bridge in
202 a 'puzzle-style' framework, wherein climate effects (e.g. radiative forcing) or key parameters
203 (e.g. terrestrial C responses to N addition; N_2O emission factors) from previous independent
204 studies are combined to generate a 'best estimate' of anthropogenic Nr climate effects. Table 1
205 summarized the four most recent and comprehensive estimates to our knowledge, covering the
206 U.S., Europe, China and globe, respectively. To improve our understanding of the Nr imprint
207 of anthropogenic Nr on climate, it is important to (1) address remaining uncertainties in the
208 underlying regional to global emission data-bases for all Nr species and improve consistency
209 between emission categories; (2) integrate process-understanding to derive non-linear response
210 functions of ecosystems to reduce the dependency of the assessments on linear approximations,
211 (3) and appropriately deal with the evaluation of climate impact by accounting for regional and
212 global short- as well as long-lived climate forcers.

213

214 **Table 1. Summary of present-day climate effects of anthropogenic Nr.** The uncertainty
215 ranges of each estimate were indicated by standard deviation (±) or square brackets depending
216 on each individual study.
217

	Erisman et al. (2011	Pinder et al. (2012	Butterbach-Bahl et al. (2011)	Shi et al. (2015
Region	Global	U.S.	Europe	China
Metrics	Radiative forcing	GWP20 / GWP100	Radiative forcing*	GWP20 / GWP100
Units	W m^{-2}	Tg eCO_2	W m^{-2}	Tg eCO_2
N_2O	+0.16	+314 [+202, +428] / +291 [+180, +395]	0.017	345±19 / 311±17
Nr-related aerosols	-0.38	-36.67 [-8.18, -103.5] / 0	-0.0165	-156±45 / -0.12±0.13
NOx effects on CH_4 lifetime		-271 [-177.4, -385] / -7.19 [0, -15.64]	-0.0046	-349.8±155.6 / -13.2±7.6
NOx effects on O_3	+0.13		0.0029	
N-induced terrestrial carbon sinks	-0.2	-206.8 [-134.65, -292.4] / -155.02 [-98.96, -236.76]	-0.019 (excluding agricultural fertilization)	-49.9±54.7 / -86.2±39.7
Other effects	+0.05	[+66 +140]	0.0453	111±100 / 111±100
Net climate effects	-0.24 [-0.5 +0.2]	-200.47 [-299.6, +17.6] / +128.79 [+112.2, +317.1]	-0.0173	-100±414 / 322±163

218 *The values indicated the global radiative forcing induced by emissions in Europe.

219

220

221 3. Climate feedbacks due to perturbated N cycle

Besides direct anthropogenic Nr inputs, anthropogenic-driven climate change substantially alters the global N cycle, which in turn results in feedback effects on climate. Here, we provide a brief overview of key findings in the past years covering changes in ecosystem N cycles and atmospheric Nr-related chemistry and extrapolate the potential climate feedbacks.

3.1 Responses of ecosystem N cycling to climate changes

A number of processes in the terrestrial N cycle are substantially influenced by climate changes through the responses of enzyme activities, microbial species and strategy (Mattoo and Suman, 2023). Firstly, the biological nitrogen fixation, the major natural source of Nr, is responding to temperature with new emerging evidence to better quantify the optimal temperature for BNF and its thermal acclimation to growth temperature (Houlton et al., 2008; Bytnerowicz et al., 2022). Secondly, increased temperature accelerates the decay of organic material, which enhances inorganic N cycling in the soil and thereby enhance terrestrial carbon storage (Kou-Giesbrecht and Arora, 2023; Melillo et al., 2011). The intensification of inorganic N cycles can not only lead to a positive N_2O-warming feedback (Stocker et al., 2013), but also intensify the soil emissions of NH_3 (Shen et al., 2020) and NO_x (Romer et al., 2018). These processes may be particularly relevant in permafrost regions and peatlands, which are even more sensitive to global warming due to arctic amplification. Recent studies have demonstrated that the increases in mineralized N with permafrost thawing failed to enhance the N availability of plants due to increased N demands and higher N-gas loss (Kou et al., 2020; Lacroix et al., 2022; Ramm et al., 2022). Thirdly, the simultaneous changes in multiple environmental factors, e.g. elevated CO_2 concentrations, warming and changes in soil moisture, may enhance the strength of N limitation on terrestrial C uptake (Mason et al., 2022; Tu et al., 2022). Last but not least, land use changes and increased ecosystem disturbance (e.g. wildfire) may also deeply alter the whole ecosystem N cycle (Dove et al., 2020; Li et al., 2021a; Perez-Quezada et al., 2022). For example, the expansion of agricultural land may lead to higher N fertilizer application (Tian et al., 2022), while strategically intercropping of N-fixing crops (e.g. grain legumes) and cereals may alleviate such issue by improving N use efficiency (Jensen et al., 2020). Meanwhile, more frequent wildfire under the changing climate accelerates the turnover rates of terrestrial N into the atmosphere, generating varied Nr-related gases and particles and substantially feeding back to the climate (Fu et al., 2018; Ward et al., 2012). Overall, although specific components of the Nr related feedbacks have been studied, a comprehensive and quantitative overview of the likely effects on future climate-biogeochemical feedbacks, such as N availability for the carbon cycle, is still lacking (Canadell et al., 2021).

3.2 Responses of atmospheric Nr-related chemistry to climate changes

Higher temperatures in general accelerate reaction rates in atmospheric chemistry, but can also exert significant non-linear influences on individual reactions. Clear evidence supports the hypothesis that higher temperature could accelerate evaporation of ammonium nitrate and thereby reduce Nr-related aerosol loadings (Megaritis et al., 2013). Current earth system models in general reported positive sensitivities of lightning NO_x emissions to the warmer climate (Thornhill et al., 2021a), while insignificant or even negative sensitivities in other studies (Finney et al., 2018; Finney et al., 2016). The NO_x effects on CH_4 and O_3 with warming is strongly dependent on changes in global OH concentrations and distributions and therefore subject to significant uncertainties (Murray et al., 2021; Zhao et al., 2023).

4. Concluding remarks

In this review, we firstly summarized the known pathways that Nr impacts climate. Recent findings underscored the vital roles of the N cycles in affecting global climate, however, each

pathway was still associated with uncertainty. In particular, two major challenges of (1) improving estimates in global soil emissions of Nr gases (N_2O, NH_3 and NO_x), and (2) reducing uncertainties in atmospheric OH chemistry and associated NO_x effects on aerosols, O_3 and CH_4 substantially impede a more comprehensive understanding of the climatic effects of anthropogenic Nr. To fill this knowledge gap, on the one hand, long-term continuous observations of soil Nr-gas fluxes, especially for short-lived NH_3 and NO_x, and improved understandings in microbial dynamics with soil ammonification, nitrification and denitrification (e.g. Li et al., 2020) are both essential. On the other hand, new chemical mechanisms revealed from smog chambers (e.g. Chen et al., 2022), field campaigns (e.g. Cho et al., 2023) and the constrains by satellite retrievals (e.g. Pimlott et al., 2022; Zhang et al., 2018) could promote a better description in global OH chemistry. Last but not least, comprehensive Earth system models, which represent process-based terrestrial and marine N biogeochemical cycles, atmospheric chemical reactions, radiative transfer and climate dynamics, would be crucial to comprehensively reveal climate effects of anthropogenic Nr as well as the potential climate feedbacks through N cycles.

We further overviewed the latest progresses on the effects of anthropogenic perturbations on global N cycles. While the direct anthropogenic Nr addition into soil (e.g. via fertilizer application and N deposition) or atmosphere (e.g. via fossil fuel combustion) has been widely studied, the effects of indirect pathways, such as N processes influenced by changing climate, elevated CO_2, land use changes, intensified wildfire and diverse agricultural management strategies, remained inadequately understood. In-depth manipulating experiments in crucial zones, including tropical rainforest (Lu et al., 2021b), permafrost (Voigt et al., 2020) and agricultural lands (Patil et al., 2010), with as many N-cycle variables are urgently required. On the other hand, some national or regional practices have indicated that improved human management on both forests and croplands holds promise in mitigating ecosystem disturbances (e.g. wildfire) (Tymstra et al., 2020) and increasing N use efficiency (You et al., 2023). Those practices could increase Nr sequestration in the terrestrial plants and soil, thereby alleviating the environmental pollution led by anthropogenic Nr. For instance, the extensively practiced crop rotation, in particular over South Asian, with more N-fixing crops is effective in reducing Nr loss and increasing crop yields with less fertilizer application (Kumar et al., 2020; Venkatesh et al., 2017). Nevertheless, it is still unknown how climate will respond to the efforts of reducing anthropogenic Nr. It is urgently required to bridge knowledge gaps among communities of agricultural nutrition, global biogeochemical science, atmospheric chemistry, and climate dynamics to achieve win-win in both environmental protection and climate change mitigation.

Conflict of interest

The authors declare no conflict of interest.

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Reference

Aasfar A, Bargaz A, Yaakoubi K, Hilali A, Bennis I, Zeroual Y, et al. Nitrogen Fixing Azotobacter Species as Potential Soil Biological Enhancers for Crop Nutrition and Yield Stability. Frontiers in Microbiology 2021; 12.

Altieri KE, Fawcett SE, Hastings MG. Reactive Nitrogen Cycling in the Atmosphere and Ocean. In: Jeanloz R, Freeman KH, editors. Annual Review of Earth and Planetary Sciences, Vol 49, 2021. 49, 2021, pp. 523-550.

An Q, Zhang H, Wang ZL, Liu Y, Xie B, Liu QX, et al. The Development of an Atmospheric Aerosol/Chemistry-Climate Model, BCC_AGCM_CUACE2.0, and Simulated Effective Radiative Forcing of Nitrate Aerosols. Journal of Advances in Modeling Earth Systems 2019; 11: 3816-3835.

Barton L, Wolf B, Rowlings D, Scheer C, Kiese R, Grace P, et al. Sampling frequency affects estimates of annual nitrous oxide fluxes. Scientific Reports 2015; 5.

Bellouin N, Rae J, Jones A, Johnson C, Haywood J, Boucher O. Aerosol forcing in the Climate Model Intercomparison Project (CMIP5) simulations by HadGEM2-ES and the role of ammonium nitrate. Journal of Geophysical Research-Atmospheres 2011; 116.

Bian HS, Chin M, Hauglustaine DA, Schulz M, Myhre G, Bauer SE, et al. Investigation of global particulate nitrate from the AeroCom phase III experiment. Atmospheric Chemistry and Physics 2017; 17: 12911-12940.

Bobbink R, Hicks K, Galloway J, Spranger T, Alkemade R, Ashmore M, et al. Global assessment of nitrogen deposition effects on terrestrial plant diversity: a synthesis. Ecological Applications 2010; 20: 30-59.

Butterbach-Bahl K, Nemitz E, Zaehle S, Billen G, Boeckx P, Erisman JW, et al. Nitrogen as a threat to the European greenhouse balance. In: Bleeker A, Grizzetti B, Howard CM, Billen G, van Grinsven H, Erisman JW, et al., editors. The European Nitrogen Assessment: Sources, Effects and Policy Perspectives. Cambridge University Press, Cambridge, 2011, pp. 434-462.

*Bytnerowicz TA, Akana PR, Griffin KL, Menge DNL. Temperature sensitivity of woody nitrogen fixation across species and growing temperatures. Nature Plants 2022; 8: 209-+.

** This study challenged the traditionall empirical relationships of BNF responses to increased temperature.*

Canadell.J.G, Monteiro PMS, Costa MH, Cunha LCd, Cox PM, Eliseev AV, et al. Global Carbon and other Biogeochemical Cycles and Feedbacks. In Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, 2021, pp. 673–816.

Cao HS, Henze DK, Zhu LY, Shephard MW, Cady-Pereira K, Dammers E, et al. 4D-Var Inversion of European NH_3 Emissions Using CrIS NH_3 Measurements and GEOS-Chem Adjoint With Bi-Directional and Uni-Directional Flux Schemes. Journal of Geophysical Research-Atmospheres 2022; 127.

Chen TZ, Zhang P, Ma QX, Chu BW, Liu J, Ge YL, et al. Smog Chamber Study on the Role of NOx in SOA and O3 Formation from Aromatic Hydrocarbons. Environmental Science & Technology 2022.

Cho C, Fuchs H, Hofzumahaus A, Holland F, Bloss WJ, Bohn B, et al. Experimental chemical budgets of OH, HO2, and RO2 radicals in rural air in western Germany during the JULIAC campaign 2019. Atmos. Chem. Phys. 2023; 23: 2003-2033.

Davies-Barnard T, Friedlingstein P. The Global Distribution of Biological Nitrogen Fixation in Terrestrial Natural Ecosystems. Global Biogeochemical Cycles 2020; 34.

Davies-Barnard T, Meyerholt J, Zaehle S, Friedlingstein P, Brovkin V, Fan YC, et al. Nitrogen cycling in CMIP6 land surface models: progress and limitations. Biogeosciences 2020; 17: 5129-5148.

de Vries W. Impacts of nitrogen emissions on ecosystems and human health: A mini review. Current Opinion in Environmental Science & Health 2021; 21.

Derwent RG, Stevenson DS, Doherty RM, Collins WJ, Sanderson MG, Johnson CE. Radiative forcing from surface NOx emissions: spatial and seasonal variations. Climatic Change 2008; 88: 385-401.

Ding J, Miyazaki K, van der A RJ, Mijling B, Kurokawa JI, Cho S, et al. Intercomparison of NOx emission inventories over East Asia. Atmos. Chem. Phys. 2017; 17: 10125-10141.

Dove NC, Safford HD, Bohlman GN, Estes BL, Hart SC. High-severity wildfire leads to multi-decadal impacts on soil biogeochemistry in mixed-conifer forests. Ecological Applications 2020; 30.

Du EZ, Terrer C, Pellegrini AFA, Ahlstrom A, van Lissa CJ, Zhao X, et al. Global patterns of terrestrial nitrogen and phosphorus limitation. Nature Geoscience 2020; 13: 221-+.

Duce RA, LaRoche J, Altieri K, Arrigo KR, Baker AR, Capone DG, et al. Impacts of atmospheric anthropogenic nitrogen on the open ocean. Science 2008; 320: 893-897.

*Erisman JW, Galloway J, Seitzinger S, Bleeker A, Butterbach-Bahl K. Reactive nitrogen in the environment and its effect on climate change. Current Opinion in Environmental Sustainability 2011; 3: 281-290.

The only estimates to our knowledge that assessed the global climate effects of anthropogenic reactive nitrogen.

Evangeliou N, Balkanski Y, Eckhardt S, Cozic A, Van Damme M, Coheur PF, et al. 10-year satellite-constrained fluxes of ammonia improve performance of chemistry transport models. Atmos. Chem. Phys. 2021; 21: 4431-4451.

Feng MY, Peng SS, Wang YL, Ciais P, Goll DS, Chang JF, et al. Overestimated nitrogen loss from denitrification for natural terrestrial ecosystems in CMIP6 Earth System Models. Nature Communications 2023; 14.

Finney DL, Doherty RM, Wild O, Stevenson DS, MacKenzie IA, Blyth AM. A projected decrease in lightning under climate change. Nature Climate Change 2018; 8: 210-+.

Finney DL, Doherty RM, Wild O, Young PJ, Butler A. Response of lightning NO_x emissions and ozone production to climate change: Insights from the Atmospheric Chemistry and Climate Model Intercomparison Project. Geophysical Research Letters 2016; 43: 5492-5500.

*Fowler D, Coyle M, Skiba U, Sutton MA, Cape JN, Reis S, et al. The global nitrogen cycle in the twenty-first century. Philosophical Transactions of the Royal Society B-Biological Sciences 2013; 368.

* A comprehensive review study that went through each process in N cycles and provided the estimates of global N budget.*

**Fowler D, Steadman CE, Stevenson D, Coyle M, Rees RM, Skiba UM, et al. Effects of global change during the 21st century on the nitrogen cycle. Atmospheric Chemistry and Physics 2015; 15: 13849-13893.

** A comprehensive review study that summarized all known influences of climate changes on global N cycles.*

Franz M, Alonso R, Arneth A, Büker P, Elvira S, Gerosa G, et al. Evaluation of simulated ozone effects in forest ecosystems against biomass damage estimates from fumigation experiments. Biogeosciences 2018; 15: 6941-6957.

Fu YY, Li R, Huang JG, Bergeron Y, Fu YF, Wang Y, et al. Satellite-Observed Impacts of Wildfires on Regional Atmosphere Composition and the Shortwave Radiative Forcing: A Multiple Case Study. Journal of Geophysical Research-Atmospheres 2018; 123: 8326-8343.

Galloway JN, Aber JD, Erisman JW, Seitzinger SP, Howarth RW, Cowling EB, et al. The nitrogen cascade. Bioscience 2003; 53: 341-356.

Gong C, Yue X, Liao H, Ma YM. A humidity-based exposure index representing ozone damage effects on vegetation. Environmental Research Letters 2021; 16.

Greaver TL, Clark CM, Compton JE, Vallano D, Talhelm AF, Weaver CP, et al. Key ecological responses to nitrogen are altered by climate change. Nature Climate Change 2016; 6: 836-843.

412 Hauglustaine DA, Balkanski Y, Schulz M. A global model simulation of present and future nitrate
413 aerosols and their direct radiative forcing of climate. Atmospheric Chemistry and Physics
414 2014; 14: 11031-11063.
415 Hoesly RM, Smith SJ, Feng LY, Klimont Z, Janssens-Maenhout G, Pitkanen T, et al. Historical (1750-
416 2014) anthropogenic emissions of reactive gases and aerosols from the Community
417 Emissions Data System (CEDS). Geoscientific Model Development 2018; 11: 369-408.
418 Houlton BZ, Wang YP, Vitousek PM, Field CB. A unifying framework for dinitrogen fixation in the
419 terrestrial biosphere. Nature 2008; 454: 327-U34.
420 Jena C, Ghude SD, Beig G, Chate DM, Kumar R, Pfister GG, et al. Inter-comparison of different NOX
421 emission inventories and associated variation in simulated surface ozone in Indian region.
422 Atmospheric Environment 2015; 117: 61-73.
423 Jensen ES, Carlsson G, Hauggaard-Nielsen H. Intercropping of grain legumes and cereals improves
424 the use of soil N resources and reduces the requirement for synthetic fertilizer N: A global-
425 scale analysis. Agronomy for Sustainable Development 2020; 40.
426 Kong L, Tang X, Zhu J, Wang ZF, Pan YP, Wu HJ, et al. Improved Inversion of Monthly Ammonia
427 Emissions in China Based on the Chinese Ammonia Monitoring Network and Ensemble
428 Kalman Filter. Environmental Science & Technology 2019; 53: 12529-12538.
429 Kou D, Yang GB, Li F, Feng XH, Zhang DY, Mao C, et al. Progressive nitrogen limitation across the
430 Tibetan alpine permafrost region. Nature Communications 2020; 11.
431 Kou-Giesbrecht S, Arora VK. Compensatory Effects Between CO_2, Nitrogen Deposition, and Nitrogen
432 Fertilization in Terrestrial Biosphere Models Without Nitrogen Compromise Projections of
433 the Future Terrestrial Carbon Sink. Geophysical Research Letters 2023; 50.
434 **Kou-Giesbrecht S, Arora VK, Seiler C, Arneth A, Falk S, Jain AK, et al. Evaluating nitrogen cycling in
435 terrestrial biosphere models: a disconnect between the carbon and nitrogen cycles. Earth
436 Syst. Dynam. 2023; 14: 767-795.
437 *** The latest study that comprehensively assessed the performance of current terrestrial biosphere*
438 *models in simulating global N cycles.*
439 Kumar R, Mishra JS, Rao KK, Mondal S, Hazra KK, Choudhary JS, et al. Crop rotation and tillage
440 management options for sustainable intensification of rice-fallow agro-ecosystem in eastern
441 India. Scientific Reports 2020; 10.
442 Lacroix F, Zaehle S, Caldararu S, Schaller J, Stimmler P, Holl D, et al. Mismatch of N release from the
443 permafrost and vegetative uptake opens pathways of increasing nitrous oxide emissions in
444 the high Arctic. Global Change Biology 2022; 28: 5973-5990.
445 Lessmann M, Ros GH, Young MD, de Vries W. Global variation in soil carbon sequestration potential
446 through improved cropland management. Global Change Biology 2022; 28: 1162-1177.
447 Li JQ, Pei JM, Liu JJ, Wu JH, Li B, Fang CM, et al. Spatiotemporal variability of fire effects on soil
448 carbon and nitrogen: A global meta-analysis. Global Change Biology 2021a; 27: 4196-4206.
449 Li Q, Peng CH, Zhang JB, Li YF, Song XZ. Nitrogen addition decreases methane uptake caused by
450 methanotroph and methanogen imbalances in a Moso bamboo forest. Scientific Reports
451 2021b; 11.
452 Li ZL, Tian DS, Wang BX, Wang JS, Wang S, Chen HYH, et al. Microbes drive global soil nitrogen
453 mineralization and availability. Global Change Biology 2019; 25: 1078-1088.
454 Li ZL, Zeng ZQ, Tian DS, Wang JS, Fu Z, Zhang FY, et al. Global patterns and controlling factors of soil
455 nitrification rate. Global Change Biology 2020; 26: 4147-4157.
456 Liao JQ, Huang YY, Li ZL, Niu SL. Data-driven modeling on the global annual soil nitrous oxide
457 emissions: Spatial pattern and attributes. Science of the Total Environment 2023; 903.
458 *Liu L, Xu W, Lu XK, Zhong BQ, Guo YX, Lu X, et al. Exploring global changes in agricultural ammonia
459 emissions and their contribution to nitrogen deposition since 1980. Proceedings of the
460 National Academy of Sciences of the United States of America 2022a; 119.
461 ** This study give a robust bottom-up estimates of global agricultural NH_3 emissions*

462 Liu LL, Greaver TL. A review of nitrogen enrichment effects on three biogenic GHGs: the CO2 sink
463 may be largely offset by stimulated N2O and CH4 emission. Ecology Letters 2009; 12: 1103-
464 1117.
465 Liu YW, Piao SL, Makowski D, Ciais P, Gasser T, Song J, et al. Data-driven quantification of nitrogen
466 enrichment impact on Northern Hemisphere plant biomass. Environmental Research Letters
467 2022b; 17.
468 Lu CQ, Tian HQ. Global nitrogen and phosphorus fertilizer use for agriculture production in the past
469 half century: shifted hot spots and nutrient imbalance. Earth System Science Data 2017; 9:
470 181-192.
471 Lu X, Ye XP, Zhou M, Zhao YH, Weng HJ, Kong H, et al. The underappreciated role of agricultural soil
472 nitrogen oxide emissions in ozone pollution regulation in North China. Nature
473 Communications 2021a; 12.
474 Lu XK, Vitousek PM, Mao QG, Gilliam FS, Luo YQ, Turner BL, et al. Nitrogen deposition accelerates
475 soil carbon sequestration in tropical forests. Proceedings of the National Academy of
476 Sciences of the United States of America 2021b; 118.
477 Lu Z, Liu X, Zaveri RA, Easter RC, Tilmes S, Emmons LK, et al. Radiative Forcing of Nitrate Aerosols
478 From 1975 to 2010 as Simulated by MOSAIC Module in CESM2-MAM4. Journal of
479 Geophysical Research-Atmospheres 2021c; 126.
480 Luo Z, Zhang Y, Chen W, Van Damme M, Coheur PF, Clarisse L. Estimating global ammonia (NH3)
481 emissions based on IASI observations from 2008 to 2018. Atmos. Chem. Phys. 2022; 22:
482 10375-10388.
483 Mason RE, Craine JM, Lany NK, Jonard M, Ollinger SV, Groffman PM, et al. Evidence, causes, and
484 consequences of declining nitrogen availability in terrestrial ecosystems. Science 2022; 376:
485 261-+.
486 Mattoo R, Suman BM. Microbial roles in the terrestrial and aquatic nitrogen cycle-implications in
487 climate change. Fems Microbiology Letters 2023; 370.
488 McDuffie EE, Smith SJ, O'Rourke P, Tibrewal K, Venkataraman C, Marais EA, et al. A global
489 anthropogenic emission inventory of atmospheric pollutants from sector- and fuel-specific
490 sources (1970-2017): an application of the Community Emissions Data System (CEDS). Earth
491 System Science Data 2020; 12: 3413-3442.
492 Megaritis AG, Fountoukis C, Charalampidis PE, Pilinis C, Pandis SN. Response of fine particulate
493 matter concentrations to changes of emissions and temperature in Europe. Atmospheric
494 Chemistry and Physics 2013; 13: 3423-3443.
495 Melillo JM, Butler S, Johnson J, Mohan J, Steudler P, Lux H, et al. Soil warming, carbon-nitrogen
496 interactions, and forest carbon budgets. Proceedings of the National Academy of Sciences of
497 the United States of America 2011; 108: 9508-9512.
498 Mercado LM, Bellouin N, Sitch S, Boucher O, Huntingford C, Wild M, et al. Impact of changes in
499 diffuse radiation on the global land carbon sink. Nature 2009; 458: 1014-U87.
500 Murray LT, Fiore AM, Shindell DT, Naik V, Horowitz LW. Large uncertainties in global hydroxyl
501 projections tied to fate of reactive nitrogen and carbon. Proceedings of the National
502 Academy of Sciences of the United States of America 2021; 118.
503 Nieder R, Benbi DK. Reactive nitrogen compounds and their influence on human health: an
504 overview. Reviews on Environmental Health 2022; 37: 229-246.
505 Patil RH, Laegdsmand M, Olesen JE, Porter JR. Effect of soil warming and rainfall patterns on soil N
506 cycling in Northern Europe. Agriculture Ecosystems & Environment 2010; 139: 195-205.
507 Peng SS, Lin X, Thompson RL, Xi Y, Liu G, Hauglustaine D, et al. Wetland emission and atmospheric
508 sink changes explain methane growth in 2020. Nature 2022; 612: 477-+.
509 Perez-Quezada JF, Cano S, Ibaceta P, Aguilera-Riquelme D, Salazar O, Fuentes JP, et al. How do land
510 cover changes affect carbon-nitrogen-phosphorus stocks and the greenhouse gas budget of
511 ecosystems in southern Chile? Agriculture Ecosystems & Environment 2022; 340.

512 Pimlott MA, Pope RJ, Kerridge BJ, Latter BG, Knappett DS, Heard DE, et al. Investigating the global
513 OH radical distribution using steady-state approximations and satellite data. Atmospheric
514 Chemistry and Physics 2022; 22: 10467-10488Pinder RW, Davidson EA, Goodale CL, Greaver
515 TL, Herrick JD, Liu LL. Climate change impacts of US reactive nitrogen. Proceedings of the
516 National Academy of Sciences of the United States of America 2012; 109: 7671-7675.
517 Poulton P, Johnston J, Macdonald A, White R, Powlson D. Major limitations to achieving "4 per 1000"
518 increases in soil organic carbon stock in temperate regions: Evidence from long-term
519 experiments at Rothamsted Research, United Kingdom. Global Change Biology 2018; 24:
520 2563-2584.
521 Ramm E, Liu CY, Ambus P, Butterbach-Bahl K, Hu B, Martikainen PJ, et al. A review of the importance
522 of mineral nitrogen cycling in the plant-soil-microbe system of permafrost-affected soils-
523 changing the paradigm. Environmental Research Letters 2022; 17.
524 Romer PS, Duffey KC, Wooldridge PJ, Edgerton E, Baumann K, Feiner PA, et al. Effects of
525 temperature-dependent NO_x emissions on continental ozone production. Atmospheric
526 Chemistry and Physics 2018; 18: 2601-2614.
527 Schulte-Uebbing LF, Ros GH, de Vries W. Experimental evidence shows minor contribution of
528 nitrogen deposition to global forest carbon sequestration. Global Change Biology 2022; 28:
529 899-917.
530 Shen HZ, Chen YL, Hu YT, Ran LM, Lam SK, Pavur GK, et al. Intense Warming Will Significantly
531 Increase Cropland Ammonia Volatilization Threatening Food Security and Ecosystem Health.
532 One Earth 2020; 3: 126-134.
533 Shi YL, Cui SH, Ju XT, Cai ZC, Zhu YG. Impacts of reactive nitrogen on climate change in China.
534 Scientific Reports 2015; 5.
535 Shindell DT, Faluvegi G, Koch DM, Schmidt GA, Unger N, Bauer SE. Improved Attribution of Climate
536 Forcing to Emissions. Science 2009; 326: 716-718.
537 Sitch S, Cox PM, Collins WJ, Huntingford C. Indirect radiative forcing of climate change through
538 ozone effects on the land-carbon sink. Nature 2007; 448: 791-U4.
539 Stocker TF, Qin D, Plattner G, Tignor M, Allen S, Boschung J, et al. Contribution of working group I to
540 the fifth assessment report of the intergovernmental panel on climate change. Climate
541 change 2013; 5: 1-1552.
542 Terrer C, Jackson RB, Prentice IC, Keenan TF, Kaiser C, Vicca S, et al. Nitrogen and phosphorus
543 constrain the CO2 fertilization of global plant biomass. Nature Climate Change 2019; 9: 684-
544 +.
545 Thornhill G, Collins W, Olivi D, Skeie RB, Archibald A, Bauer S, et al. Climate-driven chemistry and
546 aerosol feedbacks in CMIP6 Earth system models. Atmospheric Chemistry and Physics
547 2021a; 21: 1105-1126.
548 **Thornhill GD, Collins WJ, Kramer RJ, Olivi D, Skeie RB, O'Connor FM, et al. Effective radiative
549 forcing from emissions of reactive gases and aerosols - a multi-model comparison.
550 Atmospheric Chemistry and Physics 2021b; 21: 853-874.
551 *** This study summarized the current understanding gained from ensembles of earth system models*
552 *for the radiative forcing of atmospheric components (including Nr-related gases and aerosols)*
553 Tian HQ, Bian ZH, Shi H, Qin XY, Pan NQ, Lu CQ, et al. History of anthropogenic Nitrogen inputs
554 (HaNi) to the terrestrial biosphere: a 5 arcmin resolution annual dataset from 1860 to 2019.
555 Earth System Science Data 2022; 14: 4551-4568.
556 **Tian HQ, Xu RT, Canadell JG, Thompson RL, Winiwarter W, Suntharalingam P, et al. A
557 comprehensive quantification of global nitrous oxide sources and sinks. Nature 2020; 586:
558 248-+.
559 ***The most comprehensive study that estimated the global N_2O budget.*
560 Tian HQ, Yang J, Xu RT, Lu CQ, Canadell JG, Davidson EA, et al. Global soil nitrous oxide emissions
561 since the preindustrial era estimated by an ensemble of terrestrial biosphere models:
562 Magnitude, attribution, and uncertainty. Global Change Biology 2019; 25: 640-659.

563 Tu XS, Wang J, Liu XY, Elrys AS, Cheng Y, Zhang JB, et al. Inhibition of Elevated Atmospheric Carbon
564 Dioxide to Soil Gross Nitrogen Mineralization Aggravated by Warming in an Agroecosystem.
565 Environmental Science & Technology 2022; 56: 12745-12754.
566 Tymstra C, Stocks BJ, Cai XL, Flannigan MD. Wildfire management in Canada: Review, challenges and
567 opportunities. Progress in Disaster Science 2020; 5.
568 Venkatesh MS, Hazra KK, Ghosh PK, Khuswah BL, Ganeshamurthy AN, Ali M, et al. Long-term effect
569 of crop rotation and nutrient management on soil-plant nutrient cycling and nutrient
570 budgeting in Indo-Gangetic plains of India. Archives of Agronomy and Soil Science 2017; 63:
571 2007-2022.
572 Voigt C, Marushchak ME, Abbott BW, Biasi C, Elberling B, Siciliano SD, et al. Nitrous oxide emissions
573 from permafrost-affected soils. Nature Reviews Earth & Environment 2020; 1: 420-434.
574 Walker AP, De Kauwe MG, Bastos A, Belmecheri S, Georgiou K, Keeling RF, et al. Integrating the
575 evidence for a terrestrial carbon sink caused by increasing atmospheric CO₂.
576 New Phytologist 2021; 229: 2413-2445.
577 Wang QH, Zhou F, Shang ZY, Ciais P, Winiwarter W, Jackson RB, et al. Data-driven estimates of global
578 nitrous oxide emissions from croplands. National Science Review 2020; 7: 441-452.
579 Wang ZH, Li SX. Nitrate N loss by leaching and surface runoff in agricultural land: A global issue (a
580 review). In: Sparks DL, editor. Advances in Agronomy, Vol 156. 156, 2019, pp. 159-217.
581 Ward DS, Kloster S, Mahowald NM, Rogers BM, Randerson JT, Hess PG. The changing radiative
582 forcing of fires: global model estimates for past, present and future. Atmospheric Chemistry
583 and Physics 2012; 12: 10857-10886.
584 Wieder WR, Cleveland CC, Smith WK, Todd-Brown K. Future productivity and carbon storage limited
585 by terrestrial nutrient availability. Nature Geoscience 2015; 8: 441-444.
586 Xia N, Du EZ, Wu XH, Tang Y, Wang Y, de Vries W. Effects of nitrogen addition on soil methane
587 uptake in global forest biomes. Environmental Pollution 2020; 264.
588 Xu L, Penner JE. Global simulations of nitrate and ammonium aerosols and their radiative effects.
589 Atmospheric Chemistry and Physics 2012; 12: 9479-9504.
590 *Yamamoto A, Hajima T, Yamazaki D, Aita MN, Ito A, Kawamiya M. Competing and accelerating
591 effects of anthropogenic nutrient inputs on climate-driven changes in ocean carbon and
592 oxygen cycles. Science Advances 2022; 8.
593 *This study investigated the Nr effects on ocean productivity as well as the air-ocean C fluxes.*
594 Yao YZ, Tian HQ, Shi H, Pan SF, Xu RT, Pan NQ, et al. Increased global nitrous oxide emissions from
595 streams and rivers in the Anthropocene. Nature Climate Change 2020; 10: 138-+.
596 You LC, Ros GH, Chen YL, Shao Q, Young MD, Zhang FS, et al. Global mean nitrogen recovery
597 efficiency in croplands can be enhanced by optimal nutrient, crop and soil management
598 practices. Nature Communications 2023; 14.
599 Zaehle S, Ciais P, Friend AD, Prieur V. Carbon benefits of anthropogenic reactive nitrogen offset by
600 nitrous oxide emissions. Nature Geoscience 2011; 4: 601-605.
601 Zaehle S, Dalmonech D. Carbon-nitrogen interactions on land at global scales: current understanding
602 in modelling climate biosphere feedbacks. Current Opinion in Environmental Sustainability
603 2011; 3: 311-320.
604 *Zaehle S, Medlyn BE, De Kauwe MG, Walker AP, Dietze MC, Hickler T, et al. Evaluation of 11
605 terrestrial carbon-nitrogen cycle models against observations from two temperate Free-Air
606 CO2 Enrichment studies. New Phytologist 2014; 202: 803-822.
607 *This study overviewed the C-N coupling in the terrestrial biosphere models.*
608 Zaveri RA, Easter RC, Singh B, Wang HL, Lu Z, Tilmes S, et al. Development and Evaluation of
609 Chemistry-Aerosol-Climate Model CAM5-Chem-MAM7-MOSAIC: Global Atmospheric
610 Distribution and Radiative Effects of Nitrate Aerosol. Journal of Advances in Modeling Earth
611 Systems 2021; 13.
612 Zhang YZ, Jacob DJ, Maasakkers JD, Sulprizio MP, Sheng JX, Gautam R, et al. Monitoring global
613 tropospheric OH concentrations using satellite observations of atmospheric methane.

614 Atmospheric Chemistry and Physics 2018; 18: 15959-15973.Zhao Y, Saunois M, Bousquet P,
615 Lin X, Hegglin MI, Canadell JG, et al. Reconciling the bottom-up and top-down estimates of
616 the methane chemical sink using multiple observations. Atmos. Chem. Phys. 2023; 23: 789-
617 807.

618 Zhou H, Yue X, Lei YD, Tian CG, Zhu J, Ma YM, et al. Distinguishing the impacts of natural and
619 anthropogenic aerosols on global gross primary productivity through diffuse fertilization
620 effect. Atmospheric Chemistry and Physics 2022; 22: 693-709.

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Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: