driving emission abatement through carbon pricing is important, but only part of the risk management portfolio. There will be hard decisions in the future. Policymakers will need rigorous tools that account for all available options for the risk management of climate change to inform these decisions.

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COMMENTARY:

Representation of nitrogen in climate change forecasts

Benjamin Z. Houlton, Alison R. Marklein and Edith Bai

The models used by the IPCC are yet to provide realistic predictions for nitrogen emissions from the land to the air and water. Natural isotopic benchmarks offer a simple solution to this emerging global imperative.

We must make progress in our ability to represent nitrogen (N) in global models if we are to reduce uncertainty in climate change projections and develop more insightful impact scenarios for decision-makers. Nitrogen can both warm and cool the climate system, depending on its form, phase and flux, and interaction with the biosphere's natural CO_2 sinks[1], with non-trivial effects on Earth's heat balance[2,3]. For instance, gaseous N emissions from the soil limit the availability of this nutrient for plant CO_2 capture — an indirect warming effect — yet can simultaneously cool global temperatures via the N-based aerosols that alter the planet's reflectance[4]. Once in the atmosphere, gaseous N species can directly increase the Earth's greenhouse effect, particularly when incomplete soil denitrification releases nitrous oxide (N_2O), the third most important greenhouse gas in modern climate change[2]. Moreover, downstream and downwind transport of N accelerates eutrophication, decreases aquatic biodiversity, impairs water- and air-quality for human health, and contributes to N_2O emissions in coastal ecosystems[1,5,6]. A recent assessment[7] in the European Union (EU27) showed that the externality damages associated with excess N spillovers are roughly equivalent to the gross profits attributable to enhanced food production via N-based fertilizers, at around €100 billion annually.

Terrestrial N fates are therefore vital to many aspects of the environment, society and climate system; but the models used by the IPCC have been criticized for their lack of constraint on terrestrial N balances and loss pathways[8]. We suggest that including the ratios of natural N isotopes ($^{15}N/^{14}N$ or $\delta^{15}N = [(^{15}N/^{14}N_{\mathrm{sample}})/(^{15}N/^{14}N_{\mathrm{standard}})] - 1$ where the standard is atmospheric N_2) can improve the efficacy of Earth system models generally, and N-based projections of modern climate change in particular. As a case study, we demonstrate here how natural N isotope composition can be used to validate and advance N cycle predictions in the Community Land Model with Coupled Carbon Nitrogen (CLM-CN, hereafter just CLM)[9]. We focused on this model because of its historical importance in setting climate science and policy: CLM was the only model to consider the effect of N in CO_2 and climate change simulations in the Fifth Assessment Report from the IPCC (ref. 2).

Towards a benchmarking scheme

We conducted our investigation in two sequential steps. First, we used empirical relationships to project patterns of soil $\delta^{15}N$ throughout the land surface and thereby develop an observation against which the efficacy of global models can be quantitatively appraised. The $\delta^{15}N$ of plant and soil pools varies systematically as a function of mean annual temperature and precipitation ($r^2 = 0.39$)[10]; hence climate correlations have been widely used to estimate soil $\delta^{15}N$ globally, capturing biome-scale patterns to within ~1‰ of empirical observations and latitudinal differences in soil $\delta^{15}N$ equal to ~10‰ (ref. 11). Such patterns in soil $\delta^{15}N$ reflect N losses to fractionating (denitrification) relative to non-fractionating (leaching) pathways[11], with the highest proportions of denitrification (relative to total N losses) observed for desert ecosystems, and lowest denitrification proportions in high-latitude boreal regions where N leaching losses are generally high (Fig. 1a,b).

Second, we used the N loss proportions from CLM (versions 4.0 and 4.5) under the present climate to inversely model soil $\delta^{15}N$ and compared these results to the empirically projected patterns as described

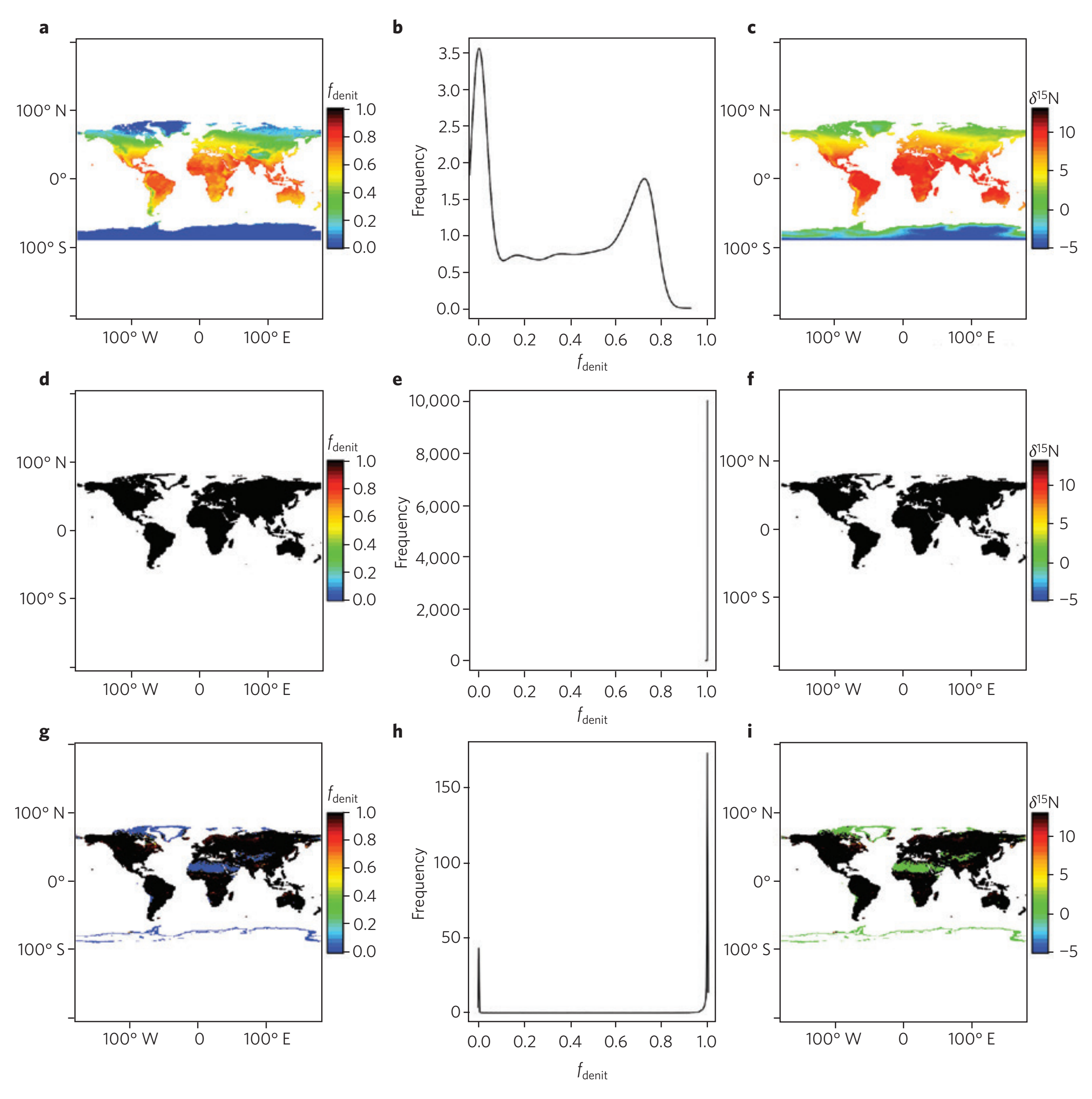

Figure 1 | CLM-CN projections used by the IPCC versus natural isotopic benchmarks. **a**,**d**,**g**, Proportion of soil nitrogen emissions to denitrification (f_{denit}) versus total nitrogen emissions (that is, denitrification plus nitrogen leaching) from isotopic modelling (**a**), CLM 4.0 (**d**) and CLM 4.5 (**g**). **b**,**e**,**h**, Frequency distribution of f_{denit} for the land surface for isotopic modelling (**b**; $N = 20{,}975$), CLM 4.0 (**e**; $N = 14{,}505$) and CLM 4.5 (**h**; $N = 15{,}337$) . **c**,**f**,**i**, Soil δ^{15}N as based on globally projected observations corrected for ammonia volatilization (**c**; see text), CLM 4.0 (**f**) and CLM 4.5 (**i**). Global and spatial inconsistencies between nitrogen isotopic modelling (**a**–**c**) and CLM 4.0 (**d**–**f**) reveal a high level of discordance in the nitrogen-based forecasts used in aspects of the Fifth Assessment Report of the IPCC. Marginal improvement is seen for CLM 4.5 (**g**–**i**). The explicit inclusion of natural isotopic benchmarks into global nitrogen models will allow for more accurate projections of nitrogen-based effects on climate change in future IPCC assessments.

above. Specifically, following the method of Bai *et al.*[12], we applied the following mass- and isotope-balance equations to CLM at a resolution of 1° latitude and longitude:

$$f_{denit} + f_{NH3} + f_L = 1 \quad (1)$$

$$\delta^{15}N_{soil} = \delta^{15}N_{input} + \varepsilon_{denit} f_{denit} + \varepsilon_{NH3} f_{NH3} + \varepsilon_L f_L \quad (2)$$

where f equals the fraction of N lost to denitrification (f_{denit}), ammonia (NH_3) volatilization (f_{NH3}) and leaching (f_L), and ε is the isotope effect of a given process ($\varepsilon = (^{14}k/^{15}k - 1) \times 1{,}000$, where k is the rate constant of the heavy and light N isotopes). We parameterized this set of equations with mid-range estimates of ε (that is, 13‰ for denitrification, 29‰ for NH_3 volatilization, 0‰ for N fixation, −1.3‰ for N deposition and 0.8‰ for leaching)[7] to constrain N loss pathways.

CLM does not consider NH_3 emissions from the soil. Although NH_3 emissions from the soil under natural vegetation are relatively small globally (~5 TgN yr^{-1})[13], this N loss pathway imparts a large isotope effect on ecosystem pools and has been shown to elevate δ^{15}N in high pH soils of arid ecosystems[14]. We thus corrected for the flux-weighted isotope effect of ammonia volatilization on soil $\delta^{15}N$ by subtracting $\varepsilon_{NH3}f_{NH3}$ from $\delta^{15}N_{soil}$ (results shown in Fig. 1c). We used this NH_3-corrected map (that is, Fig. 1c) to examine CLM's ability to simulate the isotope and mass-balance effects of N lost to denitrification versus leaching pathways across terrestrial ecosystems.

Fleshing out the nitrogen challenge

We observe a high level of discordance between CLM's N cycle and empirically projected patterns of soil $\delta^{15}N$, both globally and spatially within the terrestrial biosphere (compare Fig. 1c with 1f,i). The globally integrated $\delta^{15}N$ of soil predicted by CLM 4.0 is ~13‰, for example, and the newest version of the model, CLM 4.5, provides a slightly lower estimate for soil $\delta^{15}N$ (~11‰). Both of these results greatly exceed empirical estimates of the global mean $\delta^{15}N$ of soil equal to 5.5‰ (ref. 11), thus revealing unrealistically high isotope-fractionating N losses from the land in CLM models. Although ε_{denit} affects the magnitude of this comparison, we note that the 13‰ isotope effect for denitrification used in our analysis falls at the lower end of laboratory observations[11], and so the global disagreement between CLM and empirically projected $\delta^{15}N$ should be taken as a conservative assessment of the model's performance. Using a higher isotope effect for denitrification would only increase the disagreement between CLM-estimated $\delta^{15}N$ and the globally integrated value.

Perhaps more important, CLM predicts invariance in soil $\delta^{15}N$ across the land surface, implying a 'flat-Earth' characterization of N loss pathways from diverse terrestrial ecosystems and conditions (Fig. 1 d,f,g,i). Rather than demonstrating the strong latitudinal gradient in soil $\delta^{15}N$ equal to ~10‰ (refs 6,8; Fig. 1a,c), for example, CLM simulates little to no N isotopic differentiation among Earth's major biomes (Fig. 1f,i). Whereas CLM 4.0 shows no spatial variation at all, CLM 4.5 predicts the lowest $\delta^{15}N$ for desert ecosystems (compare Fig. 1i with Fig. 1c) and exceedingly enriched soil $\delta^{15}N$ for all other terrestrial biomes. This binary pattern and lack of spatial variation is in opposition to thousands of empirical observations of soil $\delta^{15}N$ within the terrestrial biosphere[10,15].

Underlying the lack of conformity to soil $\delta^{15}N$ benchmarks are the exceedingly high denitrification fluxes simulated by the CLM models. In CLM 4.0, for instance, gaseous N losses from the soil account for nearly 100% of terrestrial N outputs (Fig. 1d,e). CLM 4.5 scarcely improves upon this prediction, with dissolved pathways still only accounting for <2% of total N losses from the soil (that is, $f_{denit} = 98\%$; Fig. 1g,h). CLM thereby over-represents highly fractionating N losses (via denitrification) and in so doing predicts unrealistically high soil $\delta^{15}N$ for the great majority of terrestrial ecosystems. Moreover, CLM 4.5 simulates the highest N leaching loss proportions for desert ecosystems where aridity and negative soil water potentials would greatly preclude such high N leaching losses. In contrast, according to this model, N leaching losses are lowest where water budgets are positive and rivers and streams are perennial in many tropical/subtropical environments.

These results highlight a substantial disconnect between CLM's predictions and our understanding of N emissions from the terrestrial biosphere. The globally integrated isotope model suggests that ~2/3 of the terrestrial N balance can be explained by hydrological N leaching losses[11]. This agrees with an extensive and profoundly important literature which demonstrates that N leaching losses either dominate or contribute substantially to N balances in many terrestrial ecosystems. Such dissolved N losses are seen in the nitrate concentrations of natural streamwater in the tropics[16] and long-term studies at the Hubbard Brook Experimental Forest[17]; dissolved organic N compounds in pristine temperate forest watersheds in South America[18]; and spillover of N fertilizers in the hydrosphere, which lead to downstream eutrophication of estuaries and contaminate drinking water[6], to name but a few. That CLM does not allow for meaningful quantities of hydrological N transport greatly limits its capacity to simulate key processes in the N cycle and critical connections among Earth's land- and water-systems.

Implications of a unified standard

Problems with CLM's N-cycle has been raised before[19,20], although not in a spatial context or side-by-side comparison against natural N isotope benchmarks. The lack of an empirical ground-truth scheme has hitherto limited our ability to quantitatively appraise the model's spatial and global performance. A central motivation behind our emphasis on $\delta^{15}N$ is that this natural tracer provides quantitative constraints on gaseous and N leaching losses simultaneously. Natural N isotope composition of soil is simple to measure and it integrates over the time-frame of ecosystem N turnover; thus, models can use soil $\delta^{15}N$ patterns to ensure proper baseline conditions for simulation-forecasting. Building towards a truly predictive understanding of natural and human influences on N emissions from the soil, and their competing radiative forcing effects on the climate[4], will require many different N-cycle models. We envisage $\delta^{15}N$ as a common standard through which models of various degrees of complexity can communicate with one another.

Hence, we offer a solution to the challenge of improving N in global climate forecasts via natural isotopic benchmarking. As we have demonstrated with our offline simulations, the direct inclusion of natural N isotope benchmarks into Earth system models is relatively straightforward and provides both global and regional constraints that can be incorporated into online simulations of CLM as well (that is, equations (1), (2); see also ref. 12). Moreover, past work has shown that N loss predictions from the widely used DAYCENT model can be validated at smaller watershed-scales using our $\delta^{15}N$ benchmarking technique[21]. The $\delta^{15}N$ approach assumes negligible net N accumulation in plant and soil pools, an assumption that will not hold for every terrestrial ecosystem, particularly those exposed to new disturbance regimes. Further research and more data on soil $\delta^{15}N$ will help to reduce the uncertainty in the N isotope model itself, and an improved understanding of isotope effect expression of denitrification across scales and ecosystems will lead to more accurate estimates of terrestrial N balances via the isotopic benchmarking approach[11].

Developing a more thoughtful and accurate forecasting scheme for terrestrial N cycling has implications for climate science and policy development. Nitrogen is a key limiting nutrient that controls CO_2 sequestration in the marine and terrestrial biospheres[22]. Past work has shown that N limitation of terrestrial CO_2 uptake could result in up to 2 °C of additional warming by 2100 (ref. 3). Uncertainty surrounding the effect of N limitation is large[8], however, and will ultimately come down to the balance of N in terrestrial ecosystems[8]. In addition, N_2O is the third most important greenhouse gas behind CO_2 and CH_4 (ref. 2). Isotope-based models have provided a baseline for natural N inputs via fixation, constraints on gaseous N emissions (including N_2O, NO, NH_3 and N_2) and hydrological N leaching to downstream ecosystems[12,23], and insights into 'unexplained' atmospheric NO_2 concentrations observed in space-borne satellites over the Sahel region of Africa[12]. We suggest that multi-model frameworks that consider human N inputs to agricultural soils can benefit from isotopic benchmarks too, allowing the fate of N to be traced from human sources into natural terrestrial ecosystems, the air we breathe and the water we drink.

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Author contributions

B.Z.H. designed the research and wrote the manuscript; A.R.M. and E.B. provided comments and edits. B.Z.H. and E.B. developed the nitrogen isotope model. A.R.M. prepared the figures and ran the CLM model against nitrogen isotopic benchmarks.

COMMENTARY:

Linking coasts and seas to address ocean deoxygenation

Lisa A. Levin and Denise L. Breitburg

Accelerated oxygen loss in both coastal and open oceans is generating complex biological responses; future understanding and management will require holistic integration of currently fragmented oxygen observation and research programmes.

Deoxygenation of the ocean is one of the major manifestations of global change. It accompanies ocean warming and ocean acidification as one of three primary ocean consequences of rising atmospheric CO_2. For the past half century, the study of oxygen stress (hypoxia) — its occurrence, causes and implications for life in the ocean — has been an active area of research. But there have been two separate schools of study, one that addresses eutrophication-induced hypoxia in coastal ecosystems and another that examines naturally occurring oceanic hypoxic zones (including oxygen minimum and limiting zones, and their shoaling into coastal habitats). Each has developed with somewhat different emphases and tools, and largely in isolation of the other. Even within oceanic or coastal realms, geographically based management and funding sources have led to more geographically segregated interactions than might be ideal to stimulate advances in understanding, management and adaptation.

Declines in oxygen have accelerated in recent decades in both realms, as highlighted by Fifth Assessment Report of the IPCC in 2013[1]. The number of eutrophication-induced hypoxic sites reported in the coastal zone has increased by an order of magnitude since the 1960s[2]. At the same time, open-ocean deoxygenation is resulting from a warming ocean, increased stratification and changing circulation[3]. Time-series data reveal an extensive oxygen decline in the northeast Pacific (for example, ref. 4), and a significant expansion of oxygen minimum zones in the tropical and subtropical ocean over the past half century[5].

Coastal and open-ocean hypoxia are largely treated as distinct — spatially and in causality. Adaptation and management discussions generally occur separately. But it is now clear that these phenomena are not distinct and in fact are highly interconnected. Carbon dioxide-induced climate change is increasing the extent and severity of both forms of hypoxia. And we are learning that nutrient enrichment, typically associated with coastal hypoxia, can also worsen oceanic hypoxia by increasing surface-layer production that ultimately fuels microbial respiration at depth. Intensified wind-driven upwelling, related to atmospheric warming and its effect on the depth of waters with low oxygen and low pH, is bathing continental shelves in hypoxic, carbonate-undersaturated waters along the US west coast and in other regions[6], while other areas such as the coasts of Mexico and countries bordering the Bay of Bengal are becoming increasingly vulnerable[7]. Added nutrients and reduced oxygen in upwelling source waters create seasonal dead zones on the inner Oregon Shelf[8]. Excess nutrients from land can stimulate further biogeochemical activity and tip even open-ocean systems into anoxia. At the same