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Global assessment of nitrogen losses and trade-offs with yields from major crop cultivations

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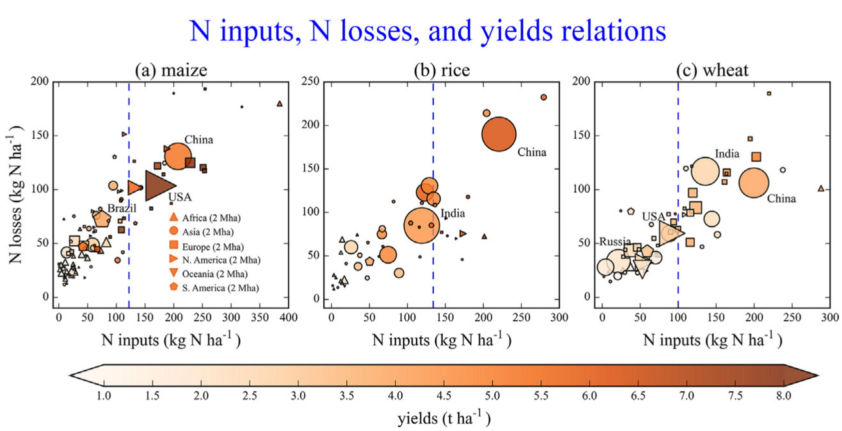
HIGHLIGHTS

- We simulate N losses of major cereal crops by using a global crop model.
- N losses are focused on several main producers, where more attentions should be paid.
- NLI is a useful indicator for assessing trade-offs between N losses and yields.
- Mitigation scenarios show that N losses can be reduced without compromising yields.

GRAPHICAL ABSTRACT



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ABSTRACT

Agricultural application of reactive nitrogen (N) for fertilization is a cause of massive negative environmental problems on a global scale. However, spatially explicit and crop-specific information on global N losses into the environment and knowledge of trade-offs between N losses and crop yields are largely lacking. We use a crop growth model, Python-based Environmental Policy Integrated Climate (PEPIC), to determine global N losses from three major food crops: maize, rice, and wheat. Simulated total N losses into the environment (including water and atmosphere) are 44 Tg N yr^{-1}. Two thirds of these, or 29 Tg N yr^{-1}, are losses to water alone. Rice accounts for the highest N losses, followed by wheat and maize. The N loss intensity (NLI), defined as N losses per unit of yield, is used to address trade-offs between N losses and crop yields. The NLI presents high variation among different countries, indicating diverse N losses to produce the same amount of yields. Simulations of mitigation scenarios indicate that redistributing global N inputs and improving N management could significantly abate N losses and at the same time even increase yields without any additional total N inputs.

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Major crops
PEPIC

1. Introduction

Anthropogenic activities are the major driver of changes in the global nitrogen (N) cycle (Fowler et al., 2013). Terrestrial N flows resulting from anthropogenic activities have increased to >3.3-fold of those resulting from natural processes by 2010 (Fowler et al., 2013; Galloway et al., 2014). As a consequence, the global N cycle is now 3.5 times above what is considered as a safe threshold (Rockstrom et al., 2009). Agriculture is the largest consumer (63%) of annual terrestrial reactive N (Sutton et al., 2013). Global industrial N fertilizer application increased 9-fold from 1960 to 2010 (Ladha et al., 2016; Sutton et al., 2013), with N fertilizer inputs to croplands reaching 120 Tg N yr^{-1} (Tg = 10^{12} g) at the end of that period (Fowler et al., 2013). This unprecedented increase in N flows was made possible by the development of industrial fixation of atmospheric N (Haber-Bosch process) and the associated mineral N fertilizer use (Galloway et al., 2008). The drivers of this development are the need to supply food for an increasing global population, dietary shift towards more meat and dairy products consumption, and growing biofuel demand (Foley et al., 2011). On the downside, this development is associated with increasing agricultural N losses into the environment, causing stratospheric ozone depletion, eutrophication and acidification of water and soil, as well as losses in the diversity of ecosystems (Babbin and Ward, 2013; Clark and Tilman, 2008; Conley et al., 2009; Davidson, 2009; Diaz and Rosenberg, 2008; Erisman et al., 2013; Foley et al., 2005; Foley et al., 2011; Guo et al., 2010; Liu et al., 2013b; Sutton et al., 2013). Many studies have found that N use efficiency (NUE, defined as the ratio of crop harvested N to total N inputs) is low in major food producing regions. On global average, it is only about 0.42 in 2010 (Zhang et al., 2015). Without emission reductions, global N losses are expected to further increase and reach levels higher than 150% of the 2010 values by 2050 (Bodirsky et al., 2014).

To control N emissions, it is important to quantify and identify the main pathways and major contribution regions of N emissions. Previous studies of N losses performed at a global scale were mainly based on mass balance methods. On this basis, Liu et al. (2010) found that about half of global total N inputs into croplands were lost to the environment. Bouwman et al. (2013) estimated that around 93 Tg N yr^{-1} was lost from arable lands and 45 Tg N yr^{-1} from grasslands. Lassaletta et al. (2014) investigated the relationship between crop yields and N inputs based on FAO (Food and Agriculture Organization of the United Nations) data from 124 countries and concluded that about 53% of N added to croplands was lost to the environment. Zhang et al. (2015) built a global N budget database and the total N losses to the environment were estimated at about 100 Tg N yr^{-1} in 2010. However, all of these studies require crop yields as data inputs to quantify harvested N. Consequently, interactions between N dynamics and crop growth cannot be represented, which are essential to explore the trade-offs of N losses and yield benefits for future N management. Mass balance method applies the same empirical equations to calculate N fluxes over a large scale without explicitly considering the spatial variability (e.g. site-, climate- and management-specific differences). Besides, most of these global N balance assessment studies focus on total N fluxes aggregated from different crops (and grasses) with much less attention on crop-specific disparity, which is important to guide N fertilization management, especially from the major cereal crop cultivations. Therefore, it is critical to explicitly investigate crop-specific N losses and the related trade-offs with yields in order to provide suggestions for controlling N emissions.

While biophysical crop growth models nowadays have the ability to account for site- and crop-specific interactions between plant growth and N turnover, only few studies so far have made use of this ability in assessing agricultural N losses on a large scale. Examples are the studies of van der Velde et al. (2009) who used the Environmental Policy Integrated Climate (EPIC) model (Williams, 1995; Williams et al., 1984) to estimate N losses through leaching for rapeseed cultivation in Europe; and the study of Del Grosso et al. (2009) who used the DAYCENT model to study global N losses from maize, soybean, and wheat cultures. In addition, the spatial resolution in the simulations by Del Grosso et al. (2009) is quite coarse (1.9 arcdeg), and no crop-specific information on N fertilizer use and N leaching is given. Another example is the study of Qiu et al. (2011) who applied the GIS-based DNDC (Denitrification-Decomposition) model to simulate N leaching from croplands at the county level in China, but did not give site- and crop-specific information on N losses. None of these studies include rice. Three major cereal crops, i.e. maize, rice, and wheat, together consume about 60% of global N fertilizer application (Ladha et al., 2005) and provide about 57% of the dietary calories produced by agriculture (Tilman et al., 2011). In order to identify the hotspots of N losses from crop cultivations, it is important to conduct a high spatial resolution assessment of N losses by focusing on these three major crops.

The concept of NUE is generally used in N management. Achieving high NUE is one of the major targets for modern agriculture (Conant et al., 2013; Cui et al., 2014; Lassaletta et al., 2014; Zhang et al., 2015). However, this concept cannot be directly used for N loss assessment due to soil N imbalance, either N accumulation or N depletion (Liu et al., 2010). For example, Liu et al. (2010) estimated NUE based on the

Table 1
Description of different nitrogen fertilization schedules and scenarios.

	Application time			Application rates
	1st	2nd	3rd	
Schedules				
FixN1	3 days before planting			Applying N inputs once
FixN2	3 days before planting	35 days after planting		One-second of N inputs for each time
FixN3	3 days before planting	35 days after planting	65 days after planting	One-third of N inputs for each time
Scenarios				
FixN3E	3 days before planting	35 days after planting	65 days after planting	One-third of 122, 134, 100 kg N ha^{-1} for maize, rice, and wheat for each time[a]
AutoN	Dynamic			Applying N when crop needs with a cap set at the current level of N inputs
AutoNE	Dynamic			Applying N when crop needs with a maximum amount of 122, 134, 100 kg N ha^{-1} for maize, rice, and wheat[a]

[a] Global average nitrogen inputs for maize, rice, and wheat are 122, 134, and 100 kg N ha^{-1}, respectively.