



Spatial and temporal patterns of nutrients and their environmental impacts from the agriculture sector in India

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Abstract

Since the launch of the Green Revolution (GR) in Indian agriculture in the 1960s, Indian food production has successfully become self-sufficient but this has also led to increasing soil nitrogen (N) surpluses and various negative environmental impacts, such as NH₃ emissions. Using the IMAGE Global Nutrient Model, this study explores the development of food production, soil N surpluses and associated NH₃ emissions in India during the GR; the use of subnational data for compiling spatially explicit maps of N inputs (N fertilizers, manure N, biological N fixation, atmospheric deposition) and outputs (crop harvest, grazing) was compared with results using country-scale data. The results show that in the period 1960–2010 food production growth was dramatic (374%), particularly in the region of the GR states (Punjab, Haryana and western Uttar Pradesh). This production increase was primarily based on spectacular increases in crop yields and N inputs. However, due to slowly changing nutrient use efficiency, N surpluses and associated NH₃ emissions increased rapidly, with hotspots especially in the GR states. Maps using data at subnational scale yield a better representation of spatial heterogeneities of the soil N surpluses, emissions and environmental impacts than maps based on country data. This is beneficial for effect calculations, as the location of negative environmental side effects strongly depends on the location of soil N and P surpluses.

Keywords Soil nitrogen budget · Ammonia · Indian agriculture

Introduction

To feed India's growing population, the Green Revolution was launched in the 1960s. The aim of this major agricultural program was to improve agricultural productivity through the introduction of new, high-yielding varieties of wheat and rice. In 1970 Norman Borlaug, the father of the Green Revolution, was awarded the Nobel Peace Prize for his work to feed a hungry world (Stone 2019; Vergauwen and De Smet 2017). In 1974, India was declared self-sufficient in food production (Sumberg et al. 2012). Indian production of cereals shows a constant increase from 87 Mton/year in the early 1960s to 330 Mton/year in 2020 (FAOSTAT 2019), while the net sown-area of 141 Mha remained nearly constant over the past 50 years (Abrol et al. 2017). The net sown-area represents the total area sown with crops and orchards; area sown more than once in the same year is counted only once.

In India, the focus of the introduction of the Green Revolution technologies has been on the northwestern region of Punjab, Haryana and western Uttar Pradesh, which form an agriculturally productive and largely irrigated region of the

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Indo-Gangetic Plain. The new high-yielding varieties introduced in these states required increased use of fertilizer and the application of new, intensive irrigation techniques (Abrol et al. 2017; Baranski 2015). Unfortunately, the benefits of India's Green Revolution have been accompanied by various negative consequences such as serious environmental impacts in terms of pesticide and nutrient use, stagnant yields and declining soil quality (Abrol et al. 2017; Agoramoorthy 2008; Baranski 2015; Pingali 2012; Sumberg et al. 2012).

On a global scale, agriculture plays a dominant role in the acceleration of global nitrogen (N) and phosphorus (P) cycles, has led to increasing emissions to air (e.g. ammonia, nitrous oxide and nitric oxide), soil and water (e.g. nitrate, particulate nitrogen compounds) and resulted in several negative environmental side effects, such as eutrophication of terrestrial and aquatic ecosystems worldwide (Steffen et al. 2015). These impacts are not evenly distributed over the world and within countries. For example, using infrared spectra obtained by the IASI/MetOp satellite, Clarisse et al. (2009) identified 28 hotspots for ammonia (NH_3) emissions around the world with particularly high amounts of NH_3 over the intensively cultivated regions of Northern India.

Modelling tools help to better understand and analyze the spatial distributions of environmental consequences of human activities. The Integrated Assessment Model IMAGE (Stehfest et al. 2014) is used to study the impact of multiple environmental changes over time, capturing the mutual feedbacks between humanity and the Earth system. To assess eutrophication as a consequence of increasing population, and economic and technological development, IMAGE includes the Global Nutrient Model (IMAGE-GNM), which computes spatially explicit agricultural soil N and P budgets and related NH_3 emissions. Soil nutrient budgets in agriculture are generally regarded as useful indicators of the losses of these nutrients to the environment (Bouwman et al. 2009; Chang et al. 2021; Gu et al. 2023; Smaling and Fresco 1993; Zhang et al. 2021).

In IMAGE, the spatial heterogeneity within a country is not taken into account (e.g. in livestock production systems, crop production systems and fertilizer use), any behaviour is average behaviour at country level and major differences between regions within a country are masked. To demonstrate local variabilities that are not captured at the scale of national soil nutrient budget inventories, data at the subnational level have already been used for the US and China as input for the soil nutrient budget model for the US and China (Beusen et al. 2008; Bouwman et al. 2009; Bouwman et al. 2017; Bouwman et al. 2013).

Until now, this effort has not been made for India (e.g. the Indian Nitrogen Assessment (Abrol et al. 2017)). There are, however, several reasons why India is an interesting country for studying spatial heterogeneities in agricultural soil N and P budgets in more detail. First of all, India plays a major

role in global agricultural production. India ranks second worldwide in farm output (Bhattacharyya et al. 2015) and has emerged as the second largest producer and consumer of N fertilizers in the world (Abrol et al. 2017). Secondly, India's soil N surpluses are in the highest category in the world (Bouwman et al. 2013). Negative environmental side effects are already becoming visible, impacting NH_3 emissions, groundwater quality, surface waters and large parts of coastal areas along the Indian coastline, and are expected to intensify (Abrol et al. 2017).

This study explores the development of food production, soil N surpluses and related NH_3 emissions in relation to India's Green Revolution by using subnational data from the Indiatat (2018) database. Subsequently, spatially explicit soil N and P budgets and related NH_3 emissions are calculated with the soil nutrient budget model for the year 2007 to (a) analyze spatial patterns in soil N budgets and NH_3 emissions and identify hotspots, and (b) to compare the outcomes based on subnational versus national level data.

Materials and methods

The soil N budget (N_{budget}) (Beusen et al. 2008; Bouwman et al. 2013) applied in the soil nutrient budget model, which is part of IMAGE-GNM is calculated as the sum of N inputs minus the sum of N outputs and can be expressed as follows:

$$N_{budget} = N_{fix} + N_{dep} + N_{fert} + N_{man} - N_{withdr} \quad (1)$$

N inputs include biological N fixation (N_{fix}), atmospheric N deposition (N_{dep}) and application of synthetic N fertilizer (N_{fert}) and animal manure (N_{man}). In this equation, the N input of animal manure (N_{man}) excludes manure that is not recycled in the agricultural system and NH_3 emission from animal houses and storage systems. Outputs in the soil N budget include N withdrawal from the field through crop harvesting, hay and grass cutting, and grass consumed by grazing animals (N_{withdr}). The same approach is used for P, with P inputs being animal manure and fertilizer.

The N and P use efficiency calculated in this study is adopted from Bouwman et al. (2017). The N use efficiency (NUE) is defined as the ratio of output of N (in kg N per year) in harvested crop parts: input of N (in kg N per year). N inputs include fertilizer, manure, atmospheric deposition and biological N fixation. The same approach is used for the P use efficiency (PUE), with P inputs including fertilizer and manure.

The soil nutrient budget model ignores nutrient accumulation in soil organic matter buildup in case of a positive budget (surplus) and soil organic matter loss in years with a negative soil N budget. A nutrient surplus therefore represents a potential loss to the environment (for N, this includes NH_3

volatilization, denitrification, surface runoff and leaching; for P, this is runoff). Negative budgets indicate soil N or P depletion, and losses are confined to losses of organic materials, manure and fertilizers from the surface as runoff. The difference between N and P management, budgets and emissions in rainfed and irrigated crops is not accounted for in the model calculations. In the soil nutrient budget model, all N and P inputs, outputs and budgets are expressed in kg N and kg P₂O₅, respectively for all grid cells with agricultural land.

The scope of this study covers crop and livestock production systems of the agricultural system of India. In crop production systems, the broad crop groups “upland crops”, “legumes”, “wetland rice” and “grassland” are distinguished, allowing for the spatial distribution of N and P inputs, outputs and budgets (as defined by Eq. (1)) on a 30 by 30-min resolution (Beusen et al. 2015; Beusen et al. 2016; Bouwman et al. 2017). This grid size corresponds to approximately 55 × 55 km at the equator. Additionally, ten animal categories (beef cattle, dairy cattle, buffalo, pigs, poultry, sheep and goats, along with the category of small ruminants, asses, mules, horses and camels) and two livestock production systems (“pastoral systems” and “mixed and landless/industrial systems”) are distinguished by Beusen et al. (2008). Together, these form the basis for distributing the animal manure over the crop production systems. In the crop production systems, all major cropping seasons are included (e.g. Kharif, Rabi, Zaid). For each crop, the harvested area is taken as well as the inputs and withdrawal. In the case of multiple cropping, this leads to a ratio of the sum of harvested areas:arable area > 1. The multiple cropping index for the regions are 1.3 for NC and SW, 1.5 for NE and 1.6 for GRS according to the Indiastat (2018) database.

In addition to the soil N and P budget, the soil nutrient budget model calculates NH₃ volatilization from animal manure in animal housing and storage systems, from animal manure excreted by grazing animals and from spreading of animal manure and N fertilizers. Ammonia volatilization from animal housing and storage systems is 20% of the N in the manure in animal housing and storage systems (Beusen et al. 2008; Bouwman et al. 2013). Ammonia volatilization for grazing systems is based on emission factors for ten animal categories (Beusen et al. 2008). The calculation of NH₃ volatilization from spreading of animal manure and N fertilizers is based on a regression model that relates NH₃ losses to various factors related to agricultural management (crop type, fertilizer type and manure or fertilizer application technique) and factors related to environmental conditions such as soil properties and climate conditions (Beusen et al. 2008; Bouwman et al. 2002).

Part of the model input data is supplied by IMAGE (Stehfest et al. 2014), such as land cover, environmental data and soil properties. In case of calculations based on national data, statistical data on crop production, livestock

and fertilizer use are country-specific and typically retrieved from the FAOSTAT (2019) database, generated by the Statistics Division of the Food and Agricultural Organization of the United Nations. In this study, soil N and P budgets for India are also calculated at the subnational level retrieved from the Indiastat (2018) database. Data handling, approaches to deal with missing data and preparing input datasets for IMAGE-GNM are described in the Supporting Information (SI). Due to missing data in the Indiastat (2018) database, it was not possible to collect a complete and meaningful dataset suitable for analyzing temporal patterns in soil nutrient budgets. The available data did allow for the analysis of spatial patterns of the soil nutrient budgets and related NH₃ emissions for the year 2007 and the analysis of spatial and temporal patterns in food production.

For the purpose of this study, four regions of India have been defined by combining the definitions of the 6 Zonal Councils of India and the original Green Revolution States (Haryana, Punjab and western Uttar Pradesh) (Abrol et al. 2017). Fig. S1 shows the location of these four regions of India. The original Green Revolution States are part of the Indo-Gangetic Plain (Abrol et al. 2017). Additional information on the four regions of India can be found in Table S1 and Table S2.

Results

Temporal and spatial patterns in food production

The results from the collection of N and P input and output data (livestock, fertilizer use and crop production) from the Indiastat (2018) database are presented as historical trends for all available years. Figure 1 shows the crop N uptake by five major crop groups wheat, rice, soybean, groundnut and cotton (1960–2010), for each of the four regions of India.

For the period 1960–2010, the crop N uptake for the five major crop groups increased 3.7 times from 0.86 to 4.1 Tg N for India (Fig. 1). Although all regions of India show increased crop N uptake, there are major differences between regions. The South West region represents the lowest growth region, with crop N uptake for the five major crop groups increasing 2.1-fold from 0.39 to 1.2 Tg N. The Green Revolution States witnessed the largest growth. In this region, crop N uptake for the five major crop groups increased 6.8 times from 0.17 to 1.3 Tg N.

In 2010, the South West region has the second highest crop N uptake for the five major crop groups (30% of India's total crop N uptake for the five major crop groups). The five major crop groups are all grown in the southwest region (Fig. S2) with a crop N uptake for wheat, rice, soybean, groundnut and cotton of respectively 0.11, 0.35, 0.25, 0.37 and 0.11 Tg N in 2010.

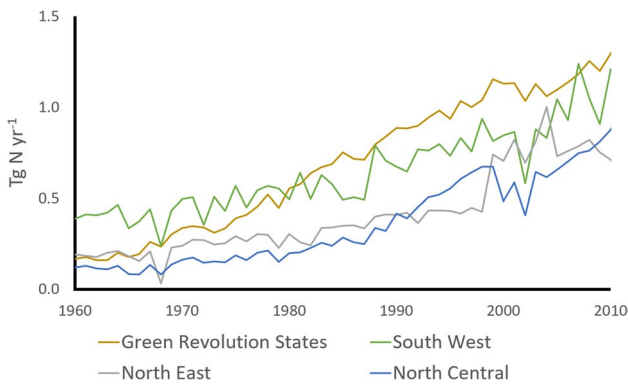


Fig. 1 Historical yearly crop N uptake by the five major crop groups wheat, rice, soybean, groundnut and cotton for the period 1960–2010 for the four regions of India (North Central, NC, North East, NE, South West, SW and Green Revolution States, GRS; see Fig. S1), based on data from the Indiastat (2018) database

The Green Revolution States account for the highest crop N uptake for the five major crop groups (32% of India’s total) and second highest N and P fertilizer use of India, respectively 32% and 23% of India’s total N and P fertilizer use in 2010 (Fig. S3). Wheat and rice are the main cropping systems in the Green Revolution States, with a crop N uptake of 0.97 (67% of India’s total crop uptake by wheat, Fig. S2a) and 0.30 Tg N (22% of India’s total crop uptake by rice, Fig. S2b) respectively in 2010.

Rice production is highest in the North East region with a crop N uptake of 0.61 Tg N (44% of India’s total crop uptake by rice, Fig. S2b) in 2010. The North Central region has the highest soybean production with a crop N uptake of 0.42 Tg N (62% of India’s total crop uptake by soybean, Fig. S2c) in 2010.

Spatial patterns in soil nitrogen budgets

The results from the soil nutrient budget model calculations are presented as spatial patterns on the map of India for the year 2007. The soil N budgets for total agriculture show a surplus for the year 2007 in the entire India (Fig. 2). In contrast to the national level (Fig. S4b), hotspot areas with a high N surplus can be distinguished at the subnational level (Fig. 2 and Fig. S4a), especially in the original Green Revolution States (Fig. S1).

Figure 3 shows spatial patterns in the different inputs and outputs of the soil N budget for the four regions of India, expressed in kilogrammes of N (kg N) per hectare of agricultural land for the year 2007. The stacked blue columns represent the contributions of the different N inputs (application of fertilizer, spreading of animal manure, atmospheric nitrogen deposition and biological nitrogen fixation). The green columns represent the removal of nitrogen by crop N uptake. The Green Revolution states stand out with the highest

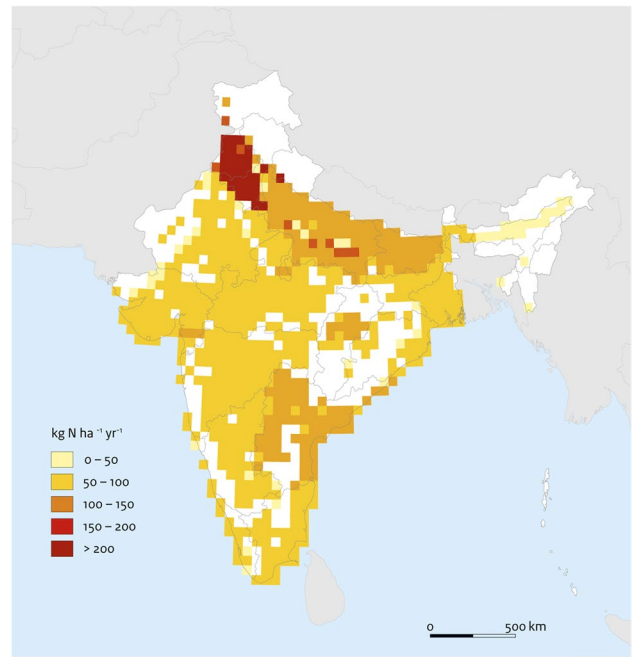


Fig. 2 Spatially explicit soil N budgets for the year 2007, expressed in kg N per hectare of agricultural area, based on data on subnational level as input for the soil nutrient budget model. Neighbouring countries are presented in grey, water in blue, non-agricultural land in white, grid size is 30 × 30 min

nitrogen inputs and crop N uptake per hectare of agricultural land. Moreover, Fig. 3 clearly shows that in the Green Revolution States, fertilizer application is the largest source of nitrogen in agriculture (155 kg N ha⁻¹ yr⁻¹). Despite the highest crop uptake in India per hectare of agricultural land (67 kg N ha⁻¹ yr⁻¹), the Green Revolution States have the highest soil nitrogen surplus (144 kg N ha⁻¹ yr⁻¹) compared

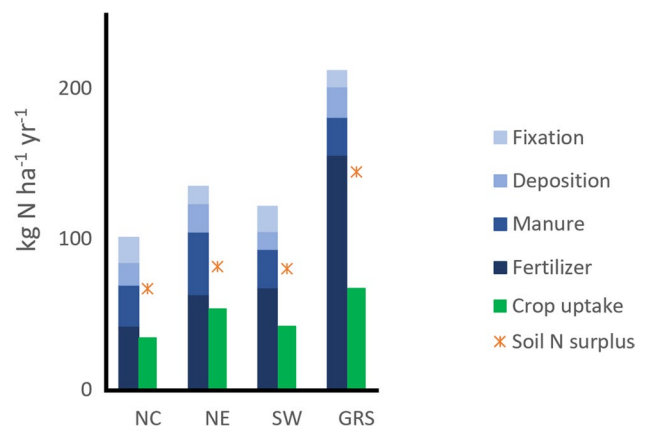


Fig. 3 Inputs (fixation, deposition, manure and fertilizer) and outputs (crop uptake) of the soil N budget and soil N surplus for the year 2007 for the four regions of India (North Central, NC, North East, NE, South West, SW and Green Revolution States, GRS; see Fig. S1), expressed in kg N per hectare of agricultural area, based on data at the subnational level

to the other regions of India (respectively 67, 80 and 82 kg N ha⁻¹ yr⁻¹ for the regions North Central, South West and North East).

Figure 4 shows the nitrogen use efficiency (NUE) and phosphorus use efficiency (PUE) for four regions of India and total India for the year 2007. The Green Revolution States represent the region with the lowest NUE (0.32), while the PUE is relatively high (0.49). The PUE is lowest in the South West region (0.35). The North East region has a relatively high NUE (0.40) and PUE (0.54). The relatively small differences in nutrient use efficiencies between the regions are related to both the crop mix and management. For example, efficiencies in rice cultivation are inherently lower than for other cereals due to the inundated conditions that are prone to leaching and ammonia volatilization (Bouwman et al. 2002).

Spatial patterns in ammonia emissions

Figure 5 shows the volatilization of NH₃ from animal manure excreted by grazing animals, animal housing and storage systems, spreading of animal manure and application of N fertilizers calculated by the soil nutrient budget model for the year 2007 for the four regions of India. Figure 6 shows spatial patterns in NH₃ emissions from N fertilizer application on the map of India. The Green Revolution States account for 32% (1.5 Tg N) of India's total NH₃ volatilization (Table S10). In the Green Revolution States, the NH₃ volatilization per hectare of agricultural area (47 kg N ha⁻¹ yr⁻¹) is more than two times higher than the NH₃ volatilization from the other states (see Fig. 5). The hotspot area of high NH₃ volatilization in the Green Revolution States is mainly caused by the high application of N fertilizer (see Figs. 5 and 6). At national level (Fig. S5c), NH₃ volatilization is more homogeneously distributed across India than at the subnational level (Fig. 6 and Fig S5b).

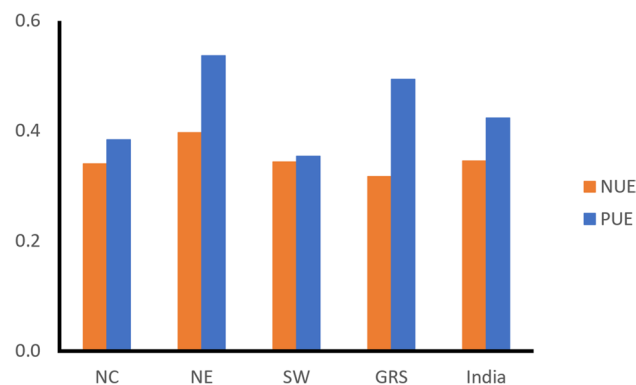


Fig. 4 Nitrogen use efficiency (NUE) and phosphorus use efficiency (PUE) for 2007 for the four regions of India (North Central, NC, North East, NE, South West, SW and Green Revolution States, GRS; see Fig. S1), and total India, based on subnational level data as input for the soil nutrient budget model

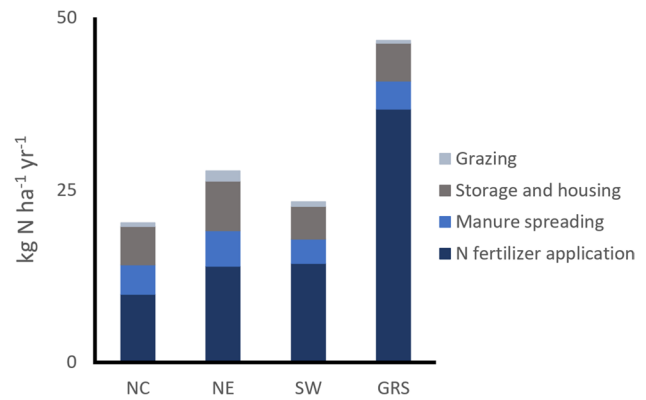


Fig. 5 NH₃ volatilization from grazing, storage and housing, spreading of animal manure and application of N fertilizers for four regions of India (North Central, NC, North East, NE, South West, SW and Green Revolution States, GRS; see Fig. S1), expressed in kg N per hectare of agricultural area, based on data on subnational level for 2007 as input for the soil nutrient budget model

Discussion

We found that the soil nutrient budget model demonstrates a good balance between detail and simplification and has proven to be successful in identifying hotspot locations of high soil N surpluses and related NH₃ emissions in the intensively cultivated region of Northern India (Figs. 4 and 6 respectively). Those hotspots are found at similar

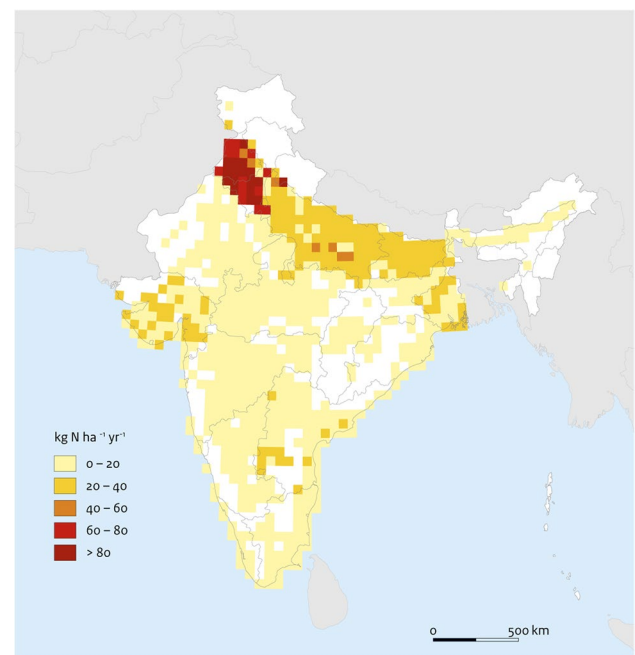


Fig. 6 Spatially explicit NH₃ volatilization from application of N fertilizers, expressed in kg N per hectare of agricultural area, based on data on subnational level for 2007 as input for the soil nutrient budget model. Neighbouring countries are presented in grey, water in blue, non-agricultural land in white, grid size is 30 × 30 min

place as compared to studies with satellite measurements of global NH_3 concentrations (Clarisse et al. 2009).

There are many uncertainties involved in soil nutrient budget calculations, as described by, amongst others, Stehfest et al. (2014) and Bouwman et al. (2017). In this study, a new uncertainty arises regarding the validity of the distribution of data on crop and livestock production systems across the states and union territories of India. For this purpose, gathering a complete and consistent dataset at subnational level was done as accurate as possible. Subnational datasets from the Indiastat (2018) database were compared with FAOSTAT (2019) data on national totals for all available years, proving close agreement between the datasets (Fig. S6). In addition, the spatial pattern of N fertilizer application as published by Swaney et al. (2015) on district level for the year 2000 shows a remarkable resemblance with the spatial pattern of N fertilizer application based on subnational data from the Indiastat (2018) database.

A general finding from this study is that, for entire India, the spatial patterns of the calculated soil N and P budgets and related NH_3 emissions differ between the national and subnational level calculations due to differences in the spatial distribution of the N and P inputs in the soil nutrient budget model. The most notable outcome of this study is the hotspot location with high soil N surpluses and related NH_3 emissions in the Green Revolution states at the subnational level and the lack thereof at the national level. This hotspot location is caused primarily by N fertilizer use and crop production and less by livestock production, and can be explained by the impact of the Green Revolution in these states that began in the 1960s. The primary objective of the Green Revolution in India was to achieve self-sufficiency in the production of wheat and rice, through the application of high-yielding hybrid varieties, increased use of mineral fertilizer and the development of irrigation. Due to the Green Revolution, rice-wheat emerged as the major cropping system in the Green Revolution States with a crop N uptake of respectively 0.30 Tg N (22% of India's total crop uptake by rice, Fig. S2b) and 0.97 Tg N (67% of India's total crop uptake by wheat, Fig. S2a) and total N and P fertilizer use of respectively 5.3 Tg N and 1.9 Tg P_2O_5 (32% and 23% of India's total N and P fertilizer use, Figure S3a and b) in 2010. As a result, the Green Revolution States account for 32% of India's total NH_3 volatilization due to application of N fertilizers, spreading of animal manure and grazing in 2007 (Table S10), while representing 17% of India's agricultural land area (Table S1).

Nitrogen input from irrigation is usually not accounted for in agricultural N balances in N use efficiency (NUE) studies, neither at global nor at the European scale. By not including this N input, environmental and agricultural policies are underestimating the real extent of N pollution hotspots in European irrigated systems (Serra et al. 2023). Abrol et al. (2017) state that information on N contribution via irrigation in various

agro-ecosystems of India is very limited, but irrigation water also contributes a significant amount of N to agricultural soils in India. In Indian agriculture, 650 km³ of irrigation water is used in 2007 (AQUASTAT 2023). The source of the irrigation water is 60% from groundwater, 27% from canals, 3% from ponds and 10% from other sources (Indiastat 2018). The concentration of groundwater is estimated at 3 mg N/L based on an average on 966 locations of the maximal nitrate concentrations for the year 2021 reported in the Indiastat (2018) database. The estimation of nitrate in canal water is 2.5 mg N/L based on the average of the maximal nitrate concentrations of 48 locations for the year 2021. Let us assume that the ponds and other sources have the same concentration as groundwater, this would lead to an average concentration of 2.6 mg N/L in all irrigation water. Together with the amount of irrigation water, this would add up to a total of 1.7 Tg N/yr or 7% of the inputs from fertilizers, animal manure, biological N fixation and atmospheric deposition. In this study, N input from irrigation is not accounted for in the model calculations. Therefore, the magnitude of N pollution hotspots in Indian irrigated systems are likely to be underestimated.

According to Zhang et al. (2015), improvements in NUE in crop production are critical for addressing the triple challenges of food security, environmental degradation and climate change. The NUE for total India in the year 2007 calculated in this study (0.34) is slightly higher than calculated by Zhang et al. (2015), but similar to the NUE calculated by Lassaletta et al. (2014). This study provides a unique insight in the spatial heterogeneity of the NUE across different regions of India, with NUE values for the year 2007 ranging from 0.32 in the Green Revolution States to 0.40 in the North East region of India.

In a global perspective, India plays a pivotal role in FAO's long-term projections due to its size and expected future increase of food demand, given current low levels of consumption, high undernourishment and the prospect of continuation of sustained income growth (Alexandratos and Bruinsma 2012). Developments in India will have a major impact on the global magnitudes of food and agriculture in the future. According to Lassaletta et al. (2016), Indian agricultural soil N surpluses increased considerably in the period 1960–2010, while the growth of agricultural soil N surpluses in developed countries such as North America has slowed down. In line with the projected growth of Indian agricultural production, Indian soil N surpluses, which are already in the highest category worldwide, are expected to increase even further until 2050 (Bouwman et al. 2013).

Ammonia emissions in the Northern region of India, obtained by satellite measurements, are in the highest category worldwide (Clarisse et al. 2009; Van Damme et al. 2014). Considering the expected growth trends in agricultural production and soil N surpluses, NH_3 emissions and other negative environmental side effects of Indian agriculture are expected

to intensify (Abrol et al. 2017). National level NUE (– 35%) and PUE (– 52%) have been strongly declining in the period 1970–2007 (Bouwman et al. 2017); however, comparison with other countries shows that considerable improvement can be achieved in practice (Zhang et al. 2015). It is not clear how the balance between future changes in production on the one hand and policies oriented towards increasing efficiencies and decreasing environmental losses on the other hand will affect overall surpluses, NH₃ emissions and other environmental losses (Prasad et al. 2003).

Conclusions

Our study shows that the Green Revolution in India has resulted in substantially higher crop N uptake and N fertilizer application rates in the Green Revolution states than in other regions of India, leading to substantially higher soil N surpluses and related NH₃ emissions. The related environmental impacts such as eutrophication of terrestrial and aquatic ecosystems are expected to be more severe in this region than in the other regions of India.

This study also shows major differences between the results of the calculations at subnational and national level. At the subnational level, spatial heterogeneities of the model inputs, the calculated soil N and P surpluses and related NH₃ emissions, more realistically reflect regional differences in food production systems than the same calculation based on the national level data. This improves environmental effect calculations (such as NH₃ emissions), as the location of these negative environmental side effects strongly depends on the location of the soil N and P surpluses. Of this, the hot spot location of high soil N surpluses and related NH₃ emissions in the Green Revolution States of India is a good example.

The soil nutrient budget model calculations show N and P surpluses in all agricultural areas of India for the year 2007. Since 2007, N and P fertilizer use and crop N uptake have been increasing in India. Considering that India needs to double its food production by 2050, these growth trends are likely to continue. Negative environmental side effects are already becoming visible, and are expected to intensify. Policy interventions aimed at modifying individual terms of the soil N and budgets, for the purpose of reducing N surpluses in agriculture, can be effective in mitigating the related negative environmental impacts. At the same time, this will contribute to improving resource efficiency, which according to FAO (2014) is crucial to sustainable agriculture. Using simple indicators like soil N and P budgets based on local, regional and subnational data will be helpful to support the development of targeted agricultural and environmental policy strategies aimed at reducing nutrient losses from food production systems.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s10113-023-02137-9>.

Data Availability Data will be made available upon reasonable request. **Open Access** This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

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