MASTER'S THESIS

Exploring spatial heterogeneity in Indian agriculture

A comparison of Indian soil N and P budgets and related NH3 emissions based on subnational and national level data

Bode, L.

Award date:
2021

Exploring spatial heterogeneity in Indian agriculture

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September, 2021

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Colophon

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Reference to this report:

Bode, L. (2021). Exploring spatial heterogeneity in Indian agriculture. A comparison of Indian soil N and P budgets and related NH_3 emissions based on subnational and national level data. Master’s Thesis, Open Universiteit, Heerlen, NL.

Summary

The increasing food production, land-use change, production and application of fertilizer, discharge of human and animal waste, and combustion of fossil fuels have caused an increasing mobilization of essential nutrients such as nitrogen (N) and phosphorus (P) (Beusen, Bouwman, Van Beek, Mogollón, & Middelburg, 2016). This acceleration of global nutrient cycles caused by human activities has led to increasing nutrient 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). Agriculture plays a dominant role in the acceleration of global nutrient cycles and the related negative environmental side effects. According to Clarisse et al. (2009), the intensification of agriculture and the widespread use of fertilizers are responsible for more than doubling global NH_3 emissions since pre-industrial times. Modelling tools help to better understand and analyze the environmental consequences of human activities. The soil nutrient budget model, which is part of the Integrated Assessment Model IMAGE (Stehfest et al., 2014), calculates spatially explicit soil N and P budgets and related NH_3 emissions. This report sets out to explore spatial heterogeneity in soil N and P budgets and related NH_3 emissions for total agriculture in India by using subnational data as input for the soil nutrient budget model and comparing the results with calculations based on data at national level. To this end, historical subnational data from the Indiastat database are retrieved, processed and analyzed for all available years. Subsequently, soil N and P budgets and related NH_3 emissions are calculated with the soil nutrient budget model for the year 2007. These calculations, along with historical trends in N and P inputs and outputs for four regions of India, provide the basis for subsequent analysis and comparison of subnational and national results. The results show that, at subnational level, spatial heterogeneities of the model inputs, and therefore also of the calculated soil N and P surpluses and related NH_3 emissions, are much better represented than at national level. 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 as illustrated by the hot spot location of soil N surpluses and related NH_3 emissions in the Green Revolution States of India. Secondly, N and P fertilizer use and crop N uptake in India are rising and are likely to continue to increase in the future. For developing policy strategies aimed at better nutrient management, it is therefore recommended to use subnational rather than national level data when using simple indicators like soil N and P budgets. This will improve the efficiency and effectiveness of nutrient use and help to reduce negative environmental side effects of agriculture in India now and in the future.

Samenvatting

De toenemende voedselproductie, verandering in landgebruik, productie en toepassing van kunstmest, lozing van menselijk en dierlijk afval en verbranding van fossiele brandstoffen hebben geleid tot een toenemende mobilisatie van essentiële nutriënten zoals stikstof (N) en fosfor (P) (Beusen et al., 2016). Deze versnelling van de mondiale biogeochemische nutriënten kringlopen, veroorzaakt door menselijke activiteiten, heeft geleid tot een toenemende uitstoot van nutriënten naar lucht (bijv. ammoniak, lachgas en stikstofmonoxide), bodem en water (bijv. nitraat, fijnstofdeeltjes) en verschillende negatieve milieueffecten, zoals eutrofiëring van terrestrische en aquatische ecosystemen (Steffen et al., 2015). Landbouw speelt een belangrijke rol in deze versnelling en de daarmee samenhangende negatieve milieueffecten. Volgens Clarisse et al. (2009) zijn de intensivering van de landbouw en het wijdverbreide gebruik van meststoffen verantwoordelijk voor het meer dan verdubbelen van de wereldwijde NH_3 emissies sinds het pre-industriële tijdperk. Rekenmodellen kunnen helpen om de milieugevolgen van menselijke activiteiten beter te begrijpen en te analyseren. Het bodem nutriënten budget model, dat deel uitmaakt van het Integrated Assessment Model IMAGE (Stehfest et al., 2014), berekent ruimtelijk bepaalde bodem N en P budgetten en de daarmee samenhangende NH_3 emissies. In dit rapport wordt de ruimtelijke heterogeniteit in bodem N en P budgetten en NH_3 emissies, voor de totale landbouw in India, onderzocht door subnationale gegevens te gebruiken als input voor het bodem nutriënten budget model en de resultaten te vergelijken met modelberekeningen op basis van nationale gegevens. Hiertoe zijn historische subnationale gegevens uit de Indiastat database verzameld, verwerkt en geanalyseerd. Vervolgens zijn de bodem N en P budgetten en NH_3 emissies berekend voor het jaar 2007. Deze berekeningen, samen met historische trends in N en P inputs en outputs, vormen de basis voor de analyse en vergelijking van subnationale en nationale resultaten. De resultaten laten zien dat op subnationaal niveau ruimtelijke heterogeniteiten van de model inputs, en dus ook van de berekende bodem N en P budgetten en NH_3 emissies, veel beter tot hun recht komen dan op nationaal niveau. Dit is gunstig voor effectberekeningen, aangezien de locatie van negatieve milieueffecten sterk afhangt van de locatie van de bodem N en P overschotten, zoals blijkt uit de hotspotlocatie van bodem N overschotten en de gerelateerde NH_3 emissies in de Groene Revolutie Staten van India. Ten tweede nemen het N en P meststoffengebruik en de N gewasopname in India toe en zullen deze in de toekomst waarschijnlijk blijven toenemen. Voor het ontwikkelen van beleidsstrategieën gericht op een beter nutriëntenbeheer, is het daarom aan te raden om gegevens op subnationaal niveau te gebruiken bij het toepassen van eenvoudige indicatoren zoals bodem N en P budgetten. Dit zal de efficiëntie en effectiviteit van het nutriëntengebruik verbeteren en helpen om de negatieve milieueffecten van de landbouw in India nu en in de toekomst te verminderen.

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1 Introduction

1.1 Problem definition

The increasing food production, land-use change, production and application of fertilizer, discharge of human and animal waste, and combustion of fossil fuels have caused the additional mobilization of essential nutrients such as nitrogen (N) and phosphorus (P) (Beusen et al., 2016). This acceleration of global nutrient cycles caused by human activities has led to increasing nutrient 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.

One of these negative environmental side effects is eutrophication of terrestrial and aquatic ecosystems worldwide (Steffen et al., 2015). In water, eutrophication leads to enhanced carbon (C) production, as a result of N and P loading of surface waters. This process leads to turbid waters with decreased oxygen levels (hypoxia), toxin production by algae and bacteria, and death of fish. In terrestrial ecosystems, nitrogen loading due to re-deposition of nitrogen leads to loss of biodiversity and acidification. One of the major causes of increasing deposition is the emission of ammonia (NH_3), which is an important atmospheric pollutant. According to Clarisse et al. (2009), the intensification of agriculture and the widespread use of fertilizers are responsible for more than doubling global NH_3 emissions since pre-industrial times. Ammonia plays a significant role in the formation of atmospheric particulate matter, visibility degradation, atmospheric deposition of nitrogen to sensitive ecosystems and soil acidification (Behera, Sharma, Aneja, & Balasubramanian, 2013; van Breemen et al., 1982).

Agriculture plays a dominant role in the acceleration of global nutrient cycles and the related negative environmental side effects. According to Bouwman et al. (2013) crop and livestock production systems are the largest cause of human alteration of the global N and P cycles. In addition, NH_3 emissions are dominated by agriculture, which is responsible for about 80% of total global anthropogenic emissions in 2007 (Behera et al., 2013). Soil nutrient budgets in agriculture are generally regarded as useful indicators of the losses of these nutrients from agriculture to coastal water bodies via rivers and lakes, as well as present and future productivity of agricultural land (Bouwman, Beusen, & Billen, 2009; Smaling & Fresco, 1993) and are therefore used in several studies. These studies, of which a non-exhaustive list can be found in Table S1.1, mainly used data at a national level as input for the soil nutrient budget model.

Modelling tools play a central role in better understanding and analyzing the 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). One of the modules of IMAGE-GNM is the spatially explicit soil nutrient budget model, which considers all N and P inputs and outputs for IMAGE grid cells. The model outputs are maps of soil N and P budgets and NH_3 emissions from applied fertilizer and manure.

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 behavior is average behavior 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 subnational level have already been used for the US and China as input for the soil nutrient budget model (Beusen, Bouwman, Heuberger, Van Drecht, & Van Der Hoek, 2008; Bouwman et al., 2009; Bouwman et al., 2017; Bouwman et al., 2013). Until now, this effort has not been made for India. The most likely explanation is that complete and coherent datasets are not easily accessible and that, to achieve compatibility with the soil nutrient budget model, significant preprocessing would be required.

There are, however, several reasons why India is an interesting country for studying spatial heterogeneities in soil N and P budgets of agricultural systems in more detail.

(i) First of all, India plays a major role in global agricultural production. Although India has only 2.4% of the world's land area, it ranks second worldwide in farm output (Bhattacharyya et al., 2015).

(ii) Secondly, the Indian Nitrogen Assessment (Abrol et al., 2017) states that India has emerged as the second largest producer and consumer of N fertilizers in the world. Considering that India needs to double its food production by 2050, the growth trend of N fertilizer use is likely to continue (Abrol et al., 2017).

(iii) Thirdly, negative environmental side effects are already becoming visible, impacting ammonia and nitrous oxide emissions, groundwater quality, surface waters and large parts of coastal areas along the Indian coastline, and are expected to intensify (Abrol et al., 2017). Clarisse et al. (2009) visualized one of these negative environmental side effects by mapping global NH_3 concentrations from space over the course of 2008 using infrared spectra obtained by the IASI/MetOp satellite. Figure 1 shows their results, identifying 28 hotspots for NH_3 emissions around the world with particularly high amounts of NH_3 over the intensively cultivated region of Northern India and Pakistan known as the Indo-Gangetic Plain (Figure S2.1).

(iv) The fourth reason is that agricultural activity and its negative environmental side effects are spatially heterogeneously distributed across India. For example, spatial heterogeneity in fertilizer N consumption was demonstrated by Swaney et al. (2015) for the year 2000 by mapping district-level data for India for the year 2000 (Figure S2.2). Additionally, the mapping of NH_3 concentrations from space for the year 2008 (Clarisse et al., 2009), on May 13 2008 (Walker, Dudhia, & Carboni, 2011), a 5 year period of 2007-2012 (Van Damme et al., 2014; Walker et al., 2011) and the time period of 2004–2011 (Tanvir et al., 2019) all demonstrate the spatial heterogeneity of this negative environmental side effect of intensive agriculture in India with particularly high amounts of NH_3 emissions over the Indo-Gangetic Plain.

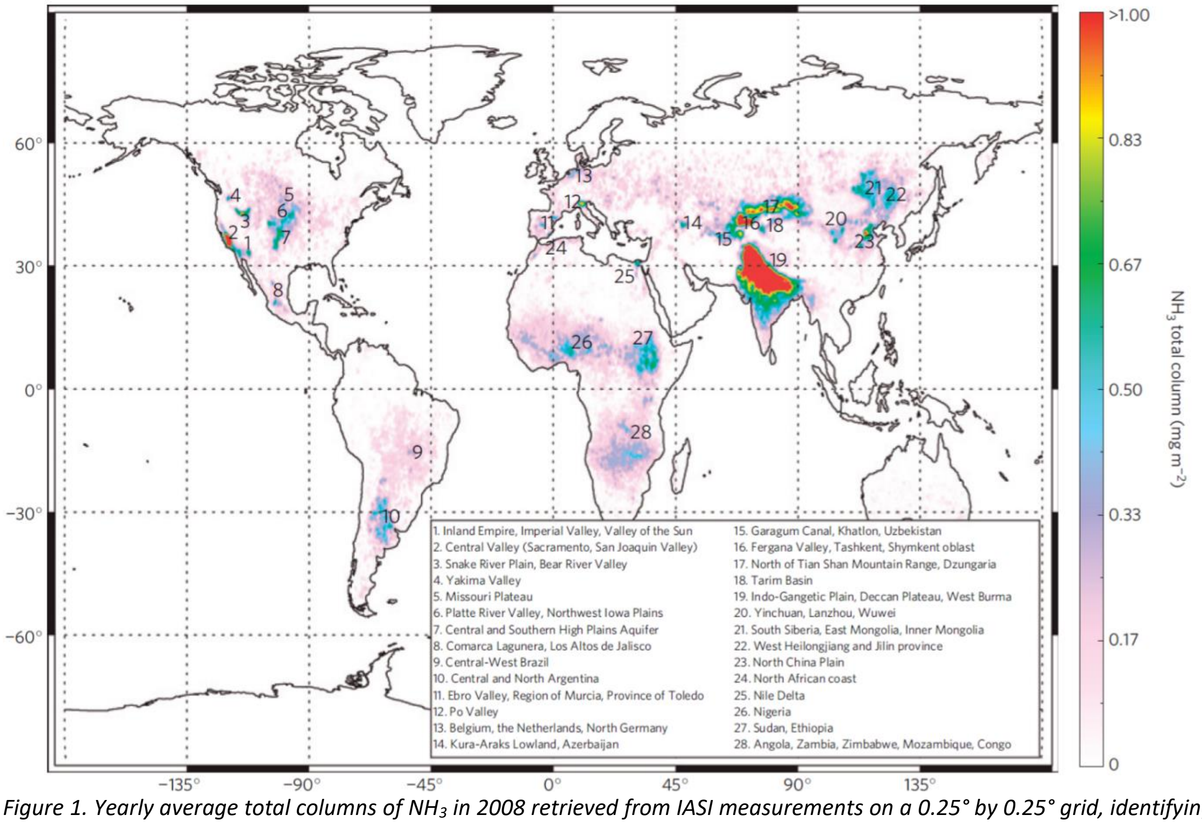

Figure 1. Yearly average total columns of NH_3 in 2008 retrieved from IASI measurements on a 0.25° by 0.25° grid, identifying a hotspot over the intensively cultivated region of Northern India and Pakistan known as the Indo-Gangetic Plain (Clarisse, Clerbaux, Dentener, Hurtmans, & Coheur, 2009)

To address this issue of scaling, the PBL Netherlands Environmental Assessment Agency acquired a comprehensive dataset from Indiastat with subnational agricultural data of India. In this study, historical subnational data from the Indiastat database for crop and livestock production systems of India are retrieved, processed and analyzed.

Policy interventions in modifying individual terms of the soil nutrient budget, with the aim of reducing nutrient surpluses in agriculture, can be effective in mitigating the related negative environmental side effects. The results of this study can assist policy and decision makers in the development of effective nutrient management strategies. Also, the model results of this study can be used as input for IMAGE-GNM's nutrient environmental fate module, calculating spatially explicit N and P discharge to surface water. As an additional benefit, this research will provide insight in the added value of calculating soil N and P budgets at subnational versus national level.

1.2 Research objective

From the general introduction to the problem, the focus areas of this study and the comparison of relevant published studies, the following research objective is derived:

The aim of this study is to determine whether there is an advantage in determining historical soil N and P budgets based on subnational level data versus national level data by comparing soil N and P budgets and the related negative environmental side effect of NH_3 *emissions for total agriculture in India (including crop and livestock production systems), calculated using the soil nutrient budget model and identifying, characterizing and explaining differences on a temporal and spatial scale.*

1.3 Research questions

The research objective of this study leads to the following central research question:

What are the differences in soil N and P budgets and related NH_3 *emissions for total agriculture in India when calculated at subnational or national level?*

The sub-questions answer parts of the central research question. Together, the answers to the sub-questions provide a sufficient answer to the central research question from which they are derived. The main function of the sub-questions is steering and structuring of the research process.

The sub-questions are:

1. *What are the historical soil N and P budgets calculated at national and subnational level?*

2. *What trends can be identified on a temporal and spatial scale in the historical soil N and P budgets calculated at subnational level?*

3. *What are the historical NH_3 emissions calculated at national and subnational level?*

4. *What factors can explain the differences between historical soil N and P budgets and NH_3 emissions calculated at national versus subnational level?*

2 Data and methods

2.1 Soil nutrient budget model

In this study soil N and P budgets in crop and livestock production systems in India are calculated for the year 2007 by using the distributed and spatially explicit soil nutrient budget model. A schematic representation of the model is presented in Figure 2. Beusen et al. (2008) describe the applied procedure for calculating yearly soil N and P budgets with the soil nutrient budget model. Bouwman et al. (2013) supply supporting information with the executable of the soil nutrient budget model, documentation and manual, and input files for running the software. The database used in IMAGE-GNM (Beusen et al., 2016; Beusen, Van Beek, Bouwman, Mogollón, & Middelburg, 2015), which is part of IMAGE (Stehfest et al., 2014), is also used in this study.

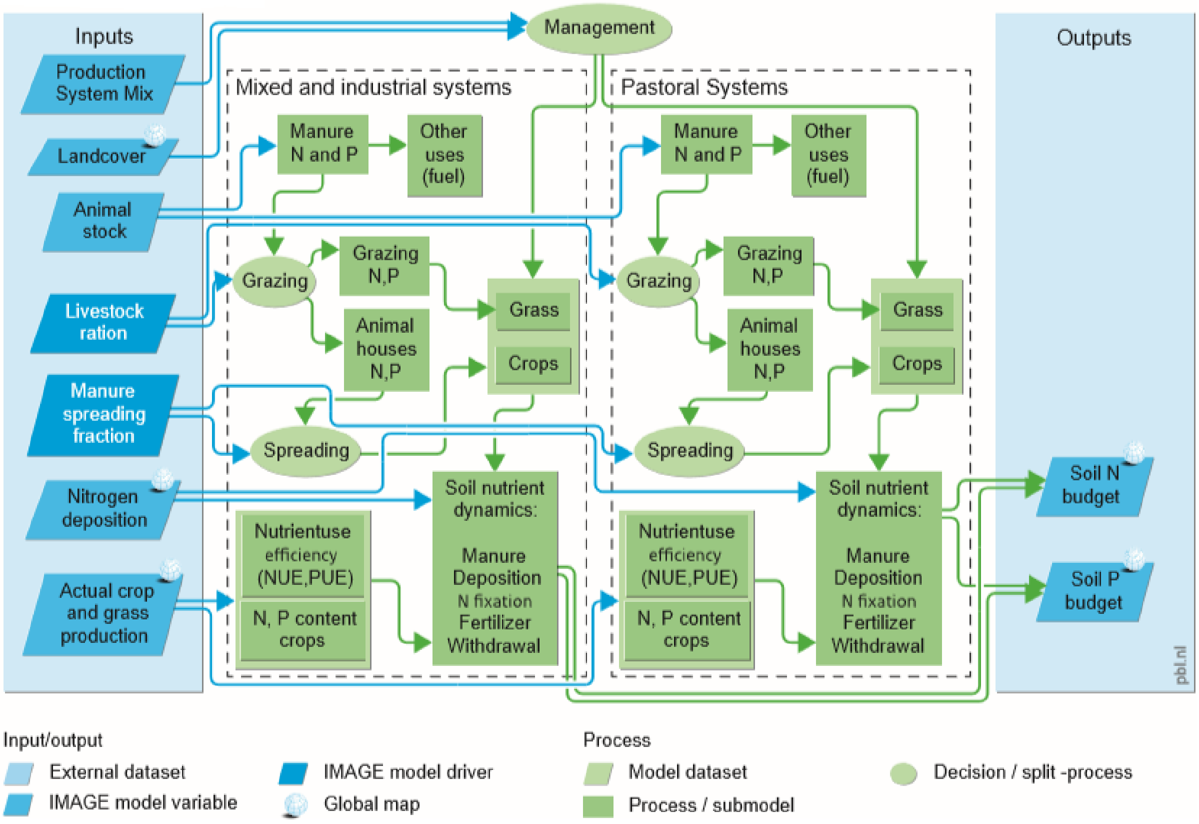

Figure 2. Schematic overview of the soil nutrient budget model adapted from Stehfest et al. (2014) . Source: Beusen (2014).

The definition of soil N and P budgets as supplied by Bouwman et al. (2013) is used. The soil N budget (N_{budget}) is defined as the sum of N inputs minus the sum of N outputs and can be expressed as follows:

$$N_{budget} = N_{fix} + N_{dep} + N_{fert} + N_{man} - N_{withdr} \qquad [1]$$

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 soil nutrient budget model ignores nutrient accumulation in soil organic matter buildup in case of a positive budget (surplus) and soil organic matter decomposition and mineralization. With no accumulation, a surplus 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. In the soil nutrient budget model, all N and P inputs, outputs and budgets are expressed in kg N and kg P_2O_5, respectively.

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 Equation 1) on a 30 by 30 minutes resolution (Beusen et al., 2016; Bouwman et al., 2017). 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 addition to the soil N and P budget, the soil nutrient budget model calculates NH_3 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 (Bouwman et al., 2013). Ammonia volatilization for grazing systems is based on emission factors for ten animal categories (Bouwman et al., 2013). The calculation of NH_3 volatilization from spreading of animal manure and N fertilizers is based on 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 (Bouwman, Boumans, & Batjes, 2002).

2.2 Collecting and preprocessing data at subnational level

As described in chapter 2.1, 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 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 calculated at subnational level. Data on crop and livestock production systems on a subnational level are not available for India in the FAOSTAT database. The following chapters describe the collection and preprocessing of the required data at subnational level.

2.2.1 Collecting crop and livestock production system raw data

In this study, all years are expressed as the fiscal year of India, which runs from April to March instead of January to December. Therefore, the year 2007 represents the period April 1st 2007 to 31st March 2008.

Subnational statistical data on crop production, livestock, and fertilizer use for India was retrieved from the Indiastat database. Collecting a complete and meaningful dataset proved to be a challenge. The Indiastat dataset for the year 2007 was the most complete and recent dataset available and was therefore selected as input for the soil nutrient budget model.

The classification and naming of states and union territories of India has been, and still is, subject of change. According to the National Informatics Centre, the federal union of India comprises 27 states (ruled by state government) and 7 union territories (ruled by central government), for a total of 34 entities in 2007. However, some union territories are too small for the chosen grid scale (30 minutes x 30 minutes) of this study. Instead of losing this information, the available data of these union territories are aggregated with the data of a neighboring state. The definition of states and union territories used in this study is presented in Table S1.2.

Animal stocks for the ten animal categories were collected per state and union territory from the Indiastat database for the years 1992, 1997, 2003, 2007 and 2012. The following categories needed some adjustments:

- Dairy cattle; this category equals the Indiastat sum of indigenous, exotic and cross-bred female cattle that are “In Milk” or “Dry”.
- Beef cattle; this category equals the Indiastat cattle (total) minus dairy cattle.
- Buffaloes; this category equals the Indiastat sum of yaks, mithuns and buffaloes.

The total use of N and P fertilizers and the type of fertilizer product was collected per state and union territory from the Indiastat database for the years 2000 to 2010.

Crop production and area data are available in the Indiastat database for various periods of years between 1950 and 2012 for all of the 34 crop groups distinguished by FAO (Alexandratos & Bruinsma, 2012), except for the following crop groups: potatoes, sweet potatoes, cassave, vegetables & melons, bananas, citrus fruit, fruit excluding melons, oilseeds not elsewhere specified (nes) and coconuts. Table 1 shows the data sources that were selected in consultation with the Indian Agricultural Research Institute (IARI)[1] for each of the missing crop groups for the year 2007.

Source	**Supplying crop data for FAO crop group:**
Indian Horticulture Database 2009, report published by the National Horticulture Board (NHB, 2010), Ministry of Agriculture, Government of India.	Potatoes, sweet potatoes, cassava (as tapioca), vegetables & melons, bananas, citrus fruit and fruit excluding melons
Status paper on oilseed crops (Singh, 2014), Directorate of Oilseeds Development, Ministry Of Agriculture, Government of India.	Oilseeds not elsewhere specified (nes): castor, niger, linseed and safflower
All India final estimates of Area and Production of Coconut (CDB), Coconut Development Board, Ministry of Agriculture and Farmers Welfare, Government of India.	Coconuts (production in “million nuts”)

Table 1. Selected sources for data on agricultural production volume and area for the missing nine crop groups.

For five crop groups, production and area data for the year 2007 where not specified or incomplete. Table 2 describes the missing data and the applied method for generating a complete and meaningful dataset for each crop group.

FAO crop group	**Description of missing data and applied method**
Maize	Where this leads to unrealistic crop yields, for these states, from 1999 onwards, the same growth in agricultural area has been applied as registered for the other states.
Pearlmillet	From 2001 onwards, only three states have registered agricultural area and production. In the states where production and area were not equal to zero in 2000, the same growth was applied as for the three aforementioned states.
Tea	From 2003 onwards, only five states have registered agricultural area and production. In the states where production and area were not equal to zero in 2002, the same growth was applied as for the five aforementioned states.

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[1] Dr. Arti Bhatia (Principal Scientist at the Centre for Environment Science and Climate Resilient Agriculture of the Indian Agricultural Research Institute)

Tobacco	Data on agricultural area and production are missing for the years 2002-2007. For the year 2007, the same year growth in area and production towards 2008 is assumed as from the year 2009 to 2010.
Rubber	Until 2010, production data per state is only registered for three states. In the states where production was not equal to zero in 2010, the same growth from 2007 to 2010 was applied as for the three aforementioned states.

Table 2. Applied method for generating a complete and meaningful dataset per applicable crop group.

2.2.2 Preprocessing crop and livestock production system raw data

Before the collected raw data can be used as input for the soil nutrient budget model, the data need to be preprocessed as described by Bouwman et al. (2017). This chapter describes the applied preprocessing steps that were specifically required for this study with data at subnational level for India for the year 2007.

Scaling to FAOSTAT totals

An important step is scaling the crop and livestock production system raw Indiastat data to FAOSTAT national totals, equal to the method used by Bouwman et al. (2017). In their study, subnational data for the USA and China are scaled so that the national totals match the FAOSTAT data. This method allows for comparison of model results between countries and, in this study, subnational versus national.

Distribution of animal manure over the livestock production systems per state and union territory

Two livestock production systems are distinguished, i.e., pastoral systems, and mixed and landless systems. The animal populations of the ten animal categories, along with the produced manure, need to be distributed between these two systems using the “fraction intensive”. For each animal population, the fraction intensive defines the part belonging to the mixed and landless systems. The fraction of the animal population in pastoral systems is the complement (1-this fraction). The fraction intensive for the ten animal categories is determined as follows:

- Cattle: work animals are assumed to belong to mixed and landless systems; the rest of cattle to pastoral. Animal stocks for work animals were collected per state and union territory from the Indiastat database.
- Dairy: 95% of all dairy is assumed to belong to mixed and landless systems.
- Buffaloes: 95% of all buffaloes is assumed to belong to mixed and landless systems, except for yaks; they belong to pastoral systems.
- Pigs and poultry: all pigs and poultry are assumed to belong to mixed and landless systems.

- Sheep & goats: all sheep and goats are assumed to belong to pastoral systems, except for milk goats over 1 year; they belong to mixed systems. Animal stocks for milk goats over 1 year were collected per state and union territory from the Indiastat database.
- Horses, asses, mules and camels: 60% of all horses, asses, mules and camels is assumed to belong to mixed and landless systems.

Subsequently, the animal manure production is calculated by multiplying animal stocks and excretion rates (Table S1.3). Further details on the method of calculating the manure available for application on crop- and grassland is supplied by Bouwman et al. (2017).

Distribution of N and P fertilizer over crop production systems per state and union territory

The distribution of N and P fertilizers over the crop production systems upland crops, legumes and wetland rice needs to be specified for each state and union territory. The applied procedure is:

1. The national total use of N and P fertilizer per crop group is obtained from the FAOSTAT database.
2. The use of N and P fertilizer per state and union territory for the crop group rice is calculated by dividing the national total fertilizer use for the crop group rice (as calculated in step 1) according to the ratio of rice production per state or union territory (as specified in paragraph 2.2.1) divided by the total rice production.
3. The use of N and P fertilizer per state and union territory for the crop group legumes is calculated by dividing the national total fertilizer use for the crop group legumes (as calculated in step 1) according to the ratio of soybean production per state or union territory (as specified in paragraph 2.2.1) divided by the total soybean production.
4. The use of N and P fertilizer per state and union territory for the crop group upland crops is calculated by dividing the national total fertilizer use for the crop group upland crops according to the ratio of wheat, sugarcane and cotton production per state or union territory, divided by the total wheat, sugarcane and cotton production. In this calculation, the wheat, sugarcane and cotton production is defined as its production area multiplied by a standard N/P fertilizer consumption for each crop group: 100/30.0, 125/44.0 and 90/22.6 kg N/P_2O_5 per ha for respectively N/P fertilizer consumption for wheat, sugarcane and cotton (FAO, 2005).

Fractions of different N fertilizers per state and union territory

The fraction of total N fertilizer use needs to be indicated for 11 N fertilizer types as distinguished by the International Fertilizer Industry Association (IFA) as input for the soil nutrient budget model. The fractions of the 11 N fertilizer types consumed for the year 2007 per state and union territory are calculated from the source data extracted from the Indiastat database. The nitrogen content of the different types of N fertilizers are based on the fertilizer specifications supplied by FAO's Plant Production and Protection Division (AGP).

Crop uptake per state and union territory

As input for the soil nutrient budget model, the N and P crop uptake per state and union territory needs to be calculated for the crop production systems upland crops, legumes and wetland rice. First, the crop uptake needs to be calculated for the 34 crop groups distinguished by FAO (Alexandratos & Bruinsma, 2012). The following equation is used to calculate the crop N uptake ($N\ uptake_{crop}$ in kg N per year), for each of the 34 crop groups:

$$N\ uptake_{crop} = prod_{crop}\ x\ dm_{crop}\ x\ N\ content_{crop} \qquad [2]$$

In this equation, $prod_{crop}$ represents the crop production of the crop group (kg of harvested product per year), dm_{crop} the dry matter fraction of the harvested product (-) and $N\ content_{crop}$ the N fraction on dry matter basis of the harvested product (-). For calculating the crop P uptake ($P\ uptake_{crop}$ in kg P_2O_5 per year) the same equation is applicable, using $P_2O_5\ content_{crop}$ instead of $N\ content_{crop}$. The values used for calculating the N and P crop uptake are equal to the values used for the national model run and are presented in Table S1.4. All FAO crop groups belong the crop production system upland crops, except for:

- The crop group rice, which belongs to the crop production system wetland rice.
- The crop groups pulses, soybeans and groundnut, which belong to the crop production system legumes.

Combining this information leads to the N and P crop uptake per state and union territory calculated for the crop production systems upland crops, legumes and wetland rice.

Biological nitrogen fixation per state and union territory

The major crop groups that have the capacity to fix atmospheric nitrogen are the leguminous crops, including the group of pulses, soybeans, groundnuts. The biological nitrogen fixation for leguminous crops is calculated according to a simplified version of the approach of Salvagiotti et al. (2008), in line with the model run based on national level data. Using this approach, the nitrogen fixation for a specific crop group ($Nitrogen\ fixation_{crop}$ in kg N per year) is calculated as follows (Bouwman et al., 2017):

$$Nitrogen\ fixation_{crop} = 0.6\ x\ Total\ plant\ N_{crop} \qquad [3]$$

The total plant nitrogen for a specific crop group ($Total\ plant\ N_{crop}$ in kg N per year) can be calculated using the following equation:

$$Total\ plant\ N_{crop} = prod_{crop}\ x\ N_{seed} + \frac{(1-Hi)}{Hi}\ x\ prod_{crop}\ x\ N_{straw} + \frac{1}{Hi}\ x\ prod_{crop}\ x\ Rr\ x\ N_{root} \qquad [4]$$

In this equation, $prod_{crop}$ represents the crop production (in kg of harvested product per year) of the crop group soybean, groundnut or pulses. N_{seed} equals the nitrogen content of the seeds (-), N_{straw} the nitrogen content of the straw (-) and N_{root} the nitrogen content of the root (-). The harvest index Hi (-) equals the ratio seed grains:aboveground biomass, the root ratio Rr (-) equals the ratio roots:aboveground biomass. The values of these parameters for the crop groups soybean, groundnuts and pulses are presented in Table S1.5 and are equal to the values used for the national model run. The total biological nitrogen fixation per state and union territory is obtained by summing the nitrogen fixation of the crop groups legumes, soy and groundnuts per state and union territory.

Crop uptake by fodder crops per state and union territory

Crop uptake of N and P by fodder crops is also included as input for the model. Since data on fodder crop production are not available for the states and union territories of India, the distribution of fodder crop production is mimicked by using the distribution of beef cattle, dairy cattle and pigs (Bouwman et al., 2017).

Four regions of India

For the purpose of this study, four regions of India have been defined by combining the definitions of the 6 Zonal Councils of India (States Reorganisation Commission, 1956) and the original Green Revolution States (Haryana, Punjab and western Uttar Pradesh). Figure 3 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), see also Figure S2.1. Additional information on the four regions of India can be found in Table S1.6 and Table S1.7.

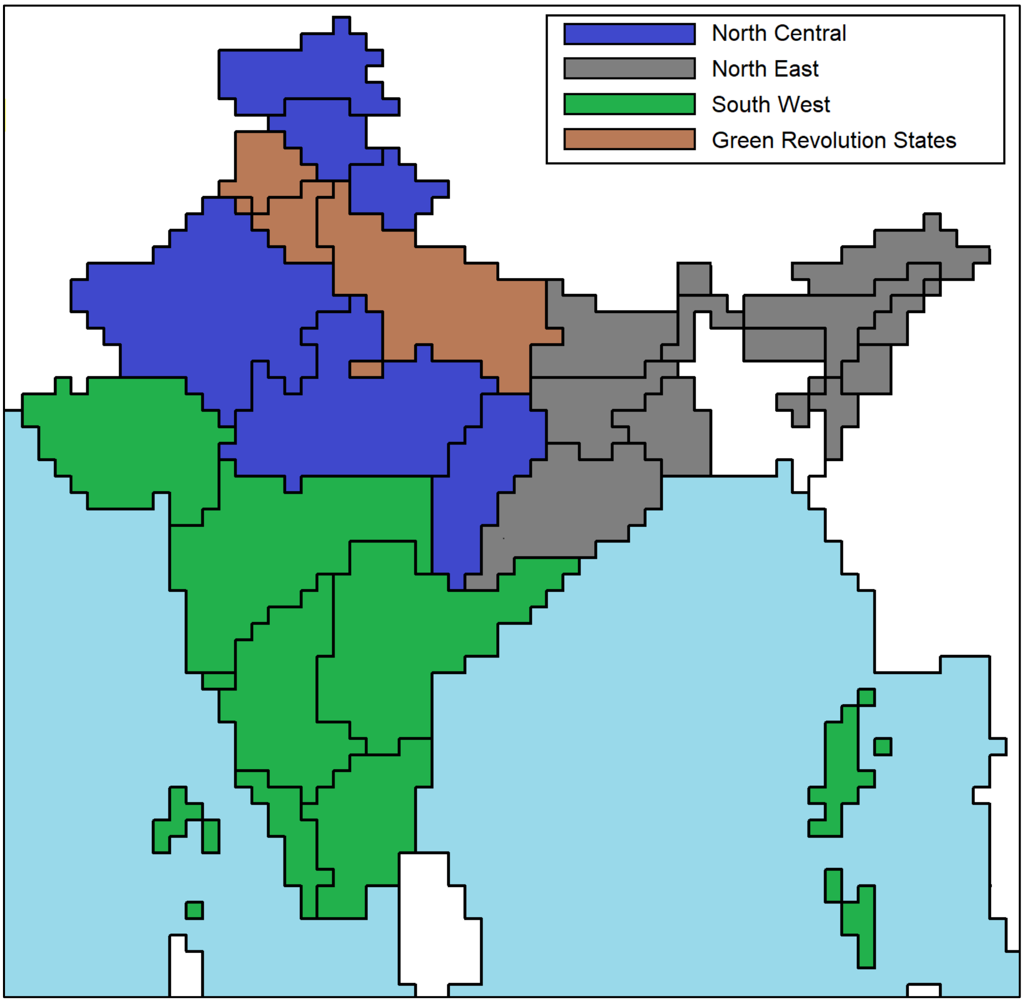

Figure 3. Four regions of India with the North Central region in dark blue, North East in grey, South West in green and the Green Revolution States in brown. Neighboring countries are presented in white, water in light blue.

Nitrogen Use Efficiency (NUE) and Phosphorus Use efficiency (PUE)

The N and P use efficiency calculated in this study is adopted from Bouwman et al. (2017) and defined as the ratio of output of N (in kg N per year) or P (in kg P_2O_5 per year) in harvested crop parts: input of N (in kg N per year) or P (in kg P_2O_5 per year) respectively. N inputs include fertilizer, manure, atmospheric deposition and biological N fixation, P inputs include fertilizer and manure.

Crop N uptake per state and union territory for five major crop groups for all available years

As input for the analysis of temporal and spatial patterns in N and P, the crop N uptake for all available years needs to be calculated. Since a complete dataset for all years and all 34 crop groups is not available in the Indiastat database, five crop groups have been selected as follows. First, the total crop N uptake for the 34 crop groups for India, based on the FAOSTAT database, was calculated for the years 1960 to 2010 according to Equation 2, with values for dry matter and N content as given in Table S1.8. Subsequently, the availability of a complete dataset for the period 1960-2010 was checked in the Indiastat database for the crop groups representing more than 5% of the total crop N uptake of India according to the FAOSTAT database. The crop groups wheat, rice, soybean, groundnut and cotton met these criteria and were selected for the analysis of temporal and spatial patterns of N crop uptake for the years 1960 to 2010. The crop N uptake for each of the five crop groups per state and union territory was calculated according to Equation 2, with dry matter and N content values as given in Table S1.8.

Mean, range and standard deviation values for all grid cells

To provide additional insight into the distribution of subnational and national N and P budgets and NH_3 emissions over grid cells, the mean, range and standard deviation for all grid cell values of India and for each of the four regions of India are calculated.

2.3 Uncertainties in soil nutrient budgets

There are many uncertainties involved in soil nutrient budget calculations with the soil nutrient budget model, 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.

3 Results

3.1 Subnational and national spatial patterns in soil N and P budgets

In this chapter, the results from the soil nutrient budget model are presented as spatial patterns on maps of India for the year 2007. The soil N and P budgets for total agriculture in India show a surplus for the year 2007 (Figure 4). In contrast to the national level (Figure 4B), hotspot areas with a high N surplus can be distinguished at subnational level (Figure 4A), especially in the original Green Revolution States (Figure 3). A similar, but less pronounced, difference in distribution of the available P surplus can be distinguished (Figure 4C and D).

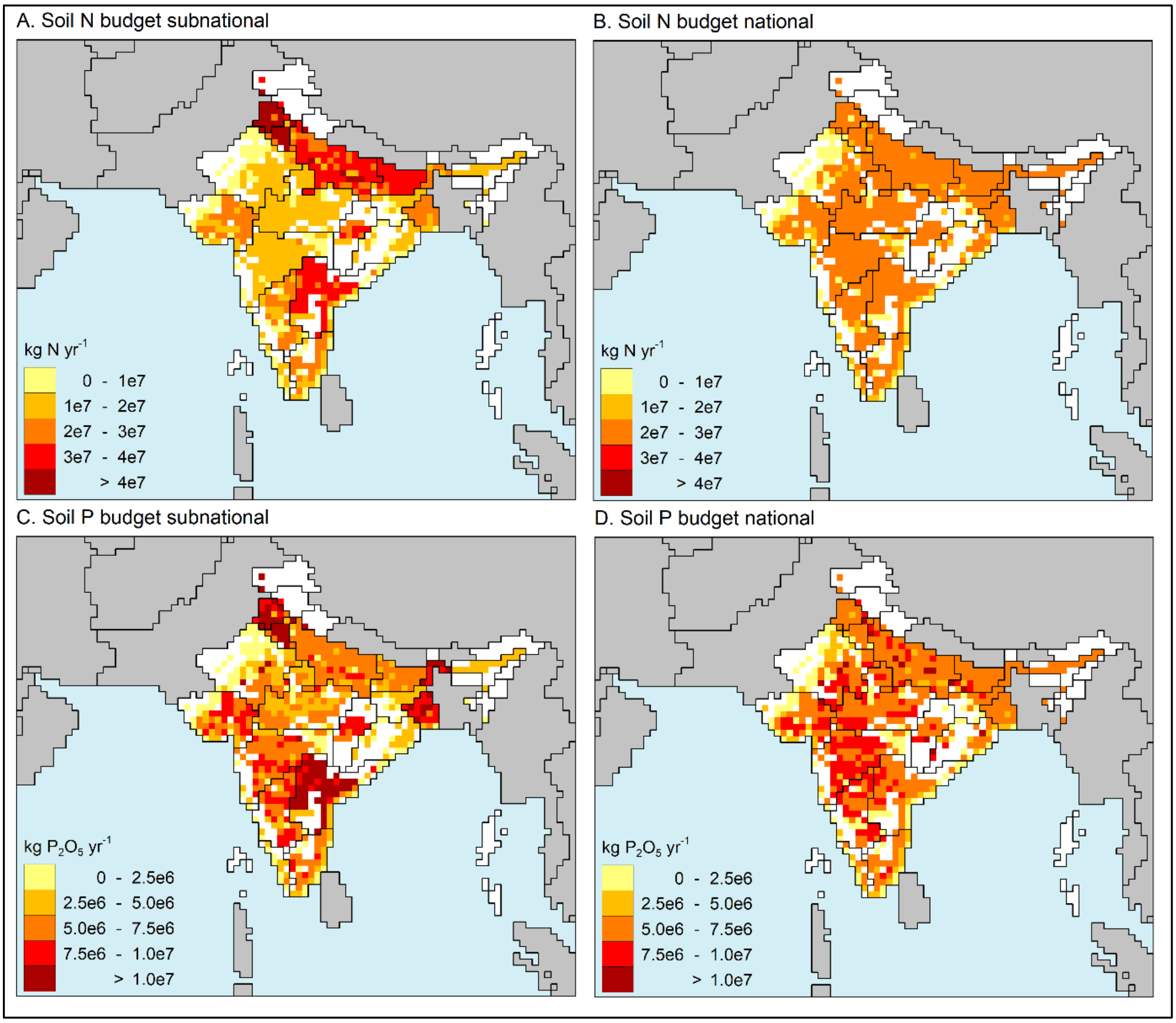

Figure 4. Spatially explicit soil N and P budgets for the year 2007 based on data on subnational (Figures A and C) and national level (Figures B and D) as input for the soil nutrient budget model. Neighboring countries are presented in grey, water in blue, non-agricultural land in white, grid size is 30 x 30 minutes.

These patterns are reflected in the mean and standard deviation values of all grid cells (Table S1.9). For example, the values of the standard deviation (mean value between brackets) of all grid cells for the soil N and P budget of India at subnational and national level are 14.3 (13.8) and 11.7 (13.8) Gg N and 3.8 (3.8) and 3.4 (3.8) Gg P_2O_5 respectively, indicating a higher dispersion in grid cell values at subnational level. Also, in the Green Revolution States, the mean values for all grid cells for the soil N and P budget are higher at subnational than at national level (37.2 versus 24.4 Gg N and 7.3 versus 6.4 Gg P_2O_5 respectively). Non-agricultural land, which represents 39% of India's total land area (Table S1.6), is not part of the scope of this study and is shown as white area in Figure 4 and Figure 5.

Figure 5 shows that N inputs (A, B, C and D) at subnational level are dominated by N fertilizer, again with hotspot areas in the Green Revolution States (Figure 5A). Crop N uptake (Figure 5E) is also highest in these states. N manure (Figure 5B) gives some higher values in single grid cell agricultural areas in the North Central region of India. Compared to the spatial distribution of N fertilizer and crop N uptake (Figure 5A and E, respectively), N manure is relatively homogeneously distributed across India and hotspot areas in the Green Revolution States are absent (Figure 5B). N deposition (Figure 5C) and N fixation (Figure 5D) are constant and low. Soil P budget terms at subnational level are presented in Figure S2.3.

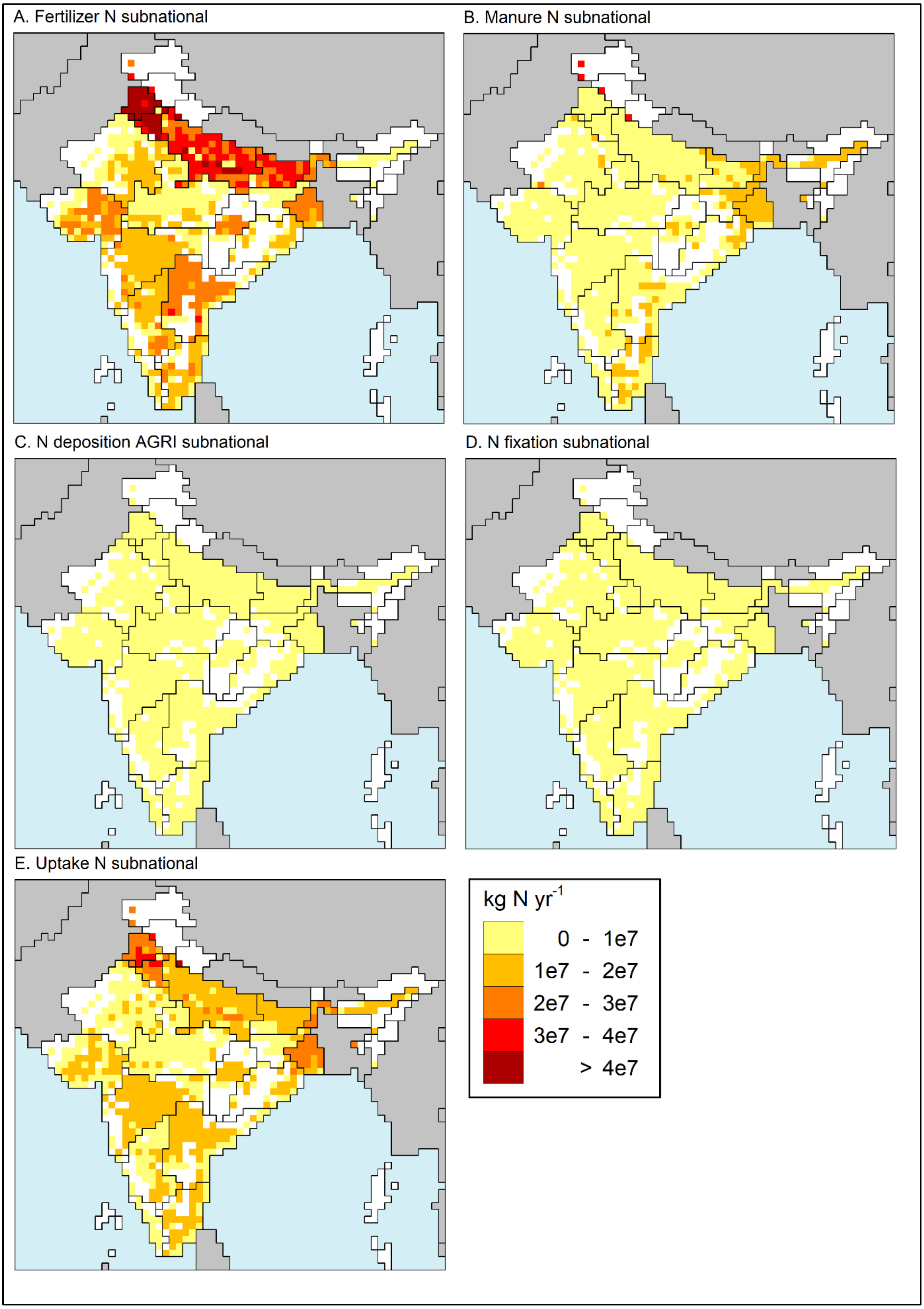

Figure 5. Spatially explicit N inputs (figures A-D) and output (figure E) for the year 2007 based on data on subnational level as input for the soil nutrient budget model. Neighboring countries are presented in grey, water in blue, non-agricultural land in white, grid size is 30 x 30 minutes.

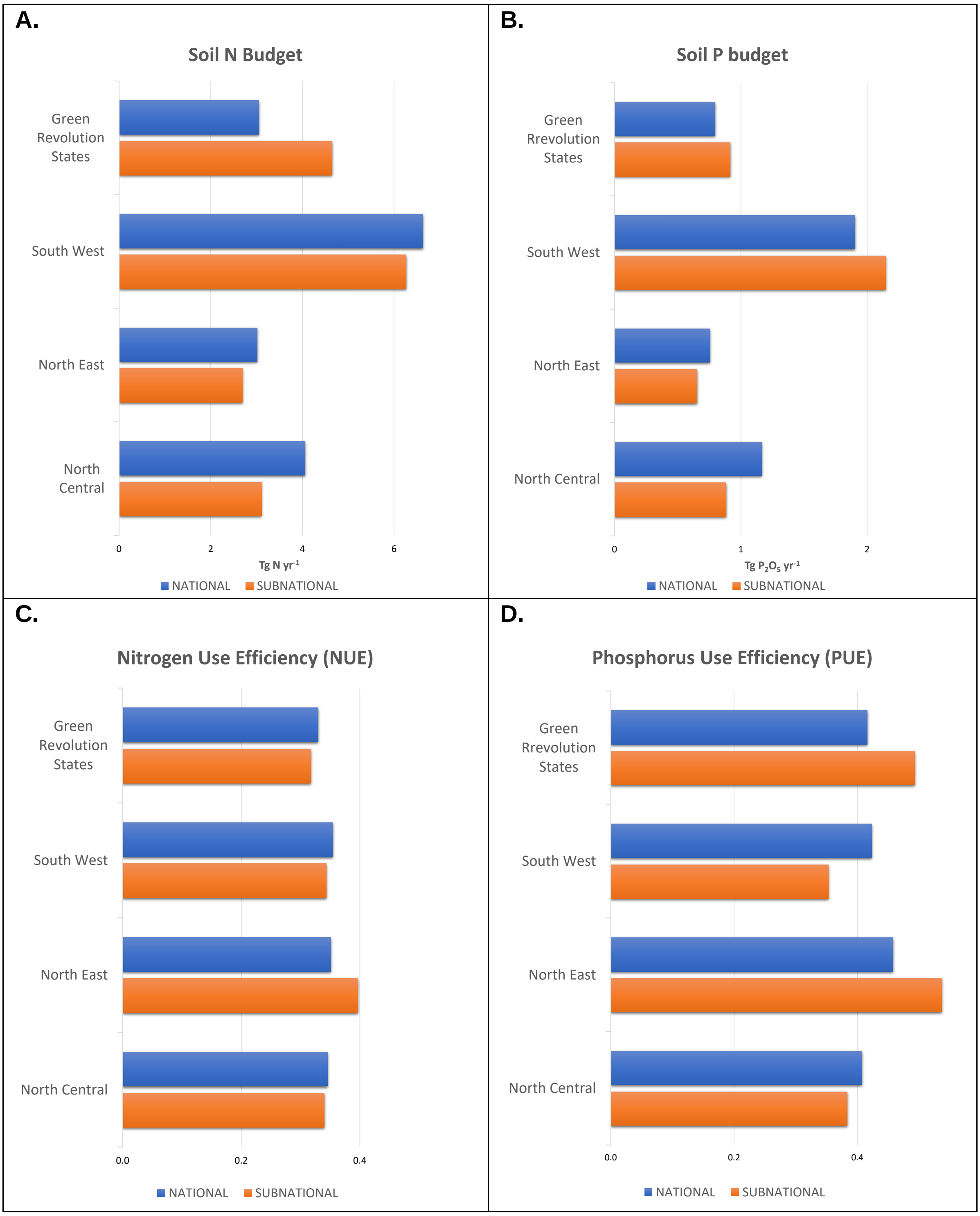

Figure 6. Soil N and P budget (figures A and B), NUE and PUE (figures C and D) for 2007 for the four regions of India, based on subnational (orange bars) and national (blue bars) level data as input for the soil nutrient budget model.

Figure 6 shows the model results for four regions of India. The soil N surplus for the Green Revolution States calculated at subnational level is 1.6 Tg N higher than at national level (Figure 6A). The NUE is higher for the North East region when calculated at subnational level and lower for the other regions compared to the calculation at national level (Figure 6C). The soil P surplus (Figure 6B) in the Green Revolution States is also higher at subnational than at national level (0.91 versus 0.80 Tg P_2O_5), but for P, this is also true for the South West region

(2.1 versus 1.9 Tg. P_2O_5). The PUE is higher for the Green Revolution States and North East region when calculated at subnational level and lower for the other regions compared to the calculation at national level (Figure 6D). The N and P inputs and outputs for the four regions of India are presented in respectively Figure S2.4 and Figure S2.5. The standard deviation and mean values of all grid cells for the soil N and P budget for each of the four regions of India at subnational and national level can be found in Table S1.9.

3.2 Temporal and spatial patterns of N and P inputs and outputs

In this chapter, the results from the collection of N and P input and output data (livestock, fertilizer use and crop production) from the Indiastat database are presented for all available years. In Figure 7 the patterns of N and P inputs and outputs are shown as trends for yearly N and P fertilizer use (2000-2010), manure production (1992-2012) and crop N uptake by the five major crop groups wheat, rice, soybean, groundnut and cotton (1960-2010), for each of the four regions of India. The aggregated totals of all states and union territories of India from the Indiastat database can be found in Figure S2.6, together with the national totals from the FAOSTAT database. The historical (years 1960-2014) and projected (years 2015-2030) use of N fertilizer for total India as published in the Indian Nitrogen Assessment (Abrol et al., 2017) is presented in Figure S2.7.

Figure 7. Historical yearly N and P fertilizer use (years 2000-2010), N manure production (years 1992-2012) and crop N uptake by the five major crop groups wheat, rice, soybean, groundnut and cotton (years 1960-2010) for the four regions of India, based on data from the Indiastat database.

In general, N (Figure 7A and Figure S2.7) and P (Figure 7B) fertilizer use and crop N uptake (Figure 7D) are rising. As an example, the use of N fertilizer in the Green Revolution States and the South West region increased from respectively 4.0 and 4.2 Tg N in 2000 to 5.3 and 6.7 Tg N in 2010. The crop N uptake in these regions increased from respectively 0.17 and 0.39 Tg N in 1960 to 1.3 and 1.2 Tg N in 2010.

The South West region has the highest N and P fertilizer use of India, respectively 40% and 46% of India's total use in 2010, and second highest crop N uptake for the five major crop groups. The five major crop groups are all grown in the South West region (Figure S2.8) 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.

The Green Revolution States account for the highest crop N uptake for the five major crop groups 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. 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, Figure S2.8A) and 0.30 Tg N (22% of India's total crop uptake by rice, Figure S2.8B) 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, Figure S2.8B) 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, Figure S2.8C) in 2010.

Compared to N fertilizer and crop N uptake (Figure 7A and D, respectively), N manure production (Figure 7C) does not show a rising trend and has remained relatively stable over the past 20 years. The South West region has the highest animal population, accounting for 31% of N manure production and 63% of the poultry population in India in 2012 (Figure S2.9).

3.3 Subnational and national spatial patterns in ammonia emissions

In this chapter, spatial patterns in NH_3 volatilization from animal manure excreted by grazing animals and from spreading of animal manure and N fertilizers calculated by the soil nutrient budget model are presented for the year 2007. Ammonia volatilization from animal houses and storage systems, representing 20% and 21% respectively of India's total NH_3 volatilization at subnational and national level (Table S1.10), is not a spatially explicit model result and is therefore not included in Figure 8.

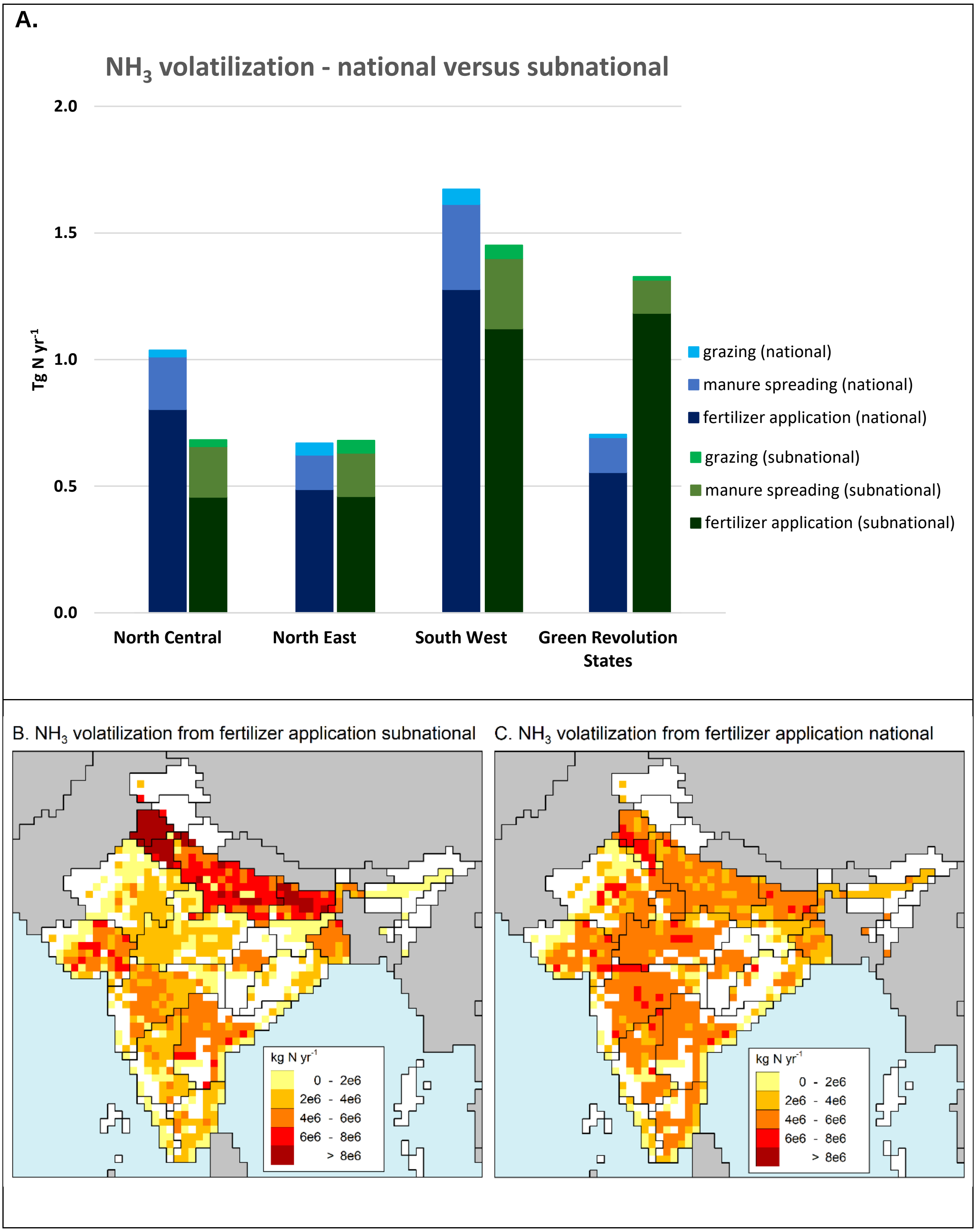

Figure 8. NH_3 volatilization from spreading of N fertilizers, animal manure and grazing for 2007 for four regions of India at subnational (green) and national (blue) level (A) and spatially explicit NH_3 volatilization from spreading of N fertilizers based on data on subnational (B) and national (C) level for 2007 as input for the soil nutrient budget model. Neighboring countries are presented in grey, water in blue, non-agricultural land in white, grid size is 30 x 30 minutes.

Figure 8A shows the volatilization of NH_3 due to application of N fertilizers, spreading of animal manure and grazing for the four regions of India at national and subnational level. In the calculations based on national data, the South West region is the highest contributor to NH_3

volatilization (1.7 Tg N, 41% of total for India), while the Green Revolution States contribute 0.70 Tg N (17% of total for India). Using the subnational data, the South West region still has the highest contribution (1.5 Tg N, 35% of total for India), however the contribution of the Green Revolutions States increased to 1.3 Tg N (32% of total for India).

Figure 8B and C show spatial patterns in NH_3 emissions from N fertilizer application on the map of India at subnational and national level, respectively. Non-agricultural land, which represents 39% of India's total land area (Table S1.6), is not part of the scope of this study and is shown as white area in Figure 8B and C. At subnational level (Figure 8B), hotspot areas with high NH_3 volatilization can be distinguished in the Green Revolution States. At national level (Figure 8C), NH_3 volatilization is more homogeneously distributed across India than at the subnational level. These patterns are reflected in the mean and standard deviation values of all grid cells (Table S1.9). For example, the values of the standard deviation (mean value between brackets) of all grid cells of India for NH_3 volatilization from N fertilizer application at subnational and national level are 3.8 (2.7) and 2.3 (2.6) Gg N respectively, indicating a higher dispersion in grid cell values at the subnational level than at the national level. Also, in the Green Revolution States, the mean value for all grid cells is higher at subnational than at national level (9.5 versus 4.4 Gg N).

4 Discussion

This chapter discusses the results and links them to the research objective and literature and starts with general findings followed by a reflection on the data and methods used. Finally, the factors explaining differences between historical soil N and P budgets and NH_3 emissions calculated at national versus subnational level are discussed.

4.1 General findings

Firstly, the results from the soil nutrient budget model show that there are clear differences between subnational and national spatial patterns in soil N and P budgets (Figure 4) and NH_3 emissions (Figure 8) for the year 2007. Secondly, in contrast to the national level results, the subnational level results show a hotspot in soil N budgets (Figure 4A) and related NH_3 emissions (Figure 8B) in the Green Revolution States. Thirdly, spatial heterogeneities in subnational soil N budgets (Figure 4A) and related NH_3 emissions (Figure 8B) are caused primarily by spatial heterogeneities in N fertilizer use and crop production (Figure 5A and E), and less by spatial heterogeneity in livestock production (Figure 5B) for the year 2007. Finally, N and P fertilizer use and crop production are increasing for all regions of India, while N manure production shows a relatively stable trend (Figure 7).

4.2 Reflecting on used data and methods

As discussed in chapter 2.3, there are many uncertainties involved in soil nutrient budget calculations with the soil nutrient budget model. 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, data on N and P fertilizer use, manure production and crop N uptake for five major crops collected from the Indiastat database were checked with FAOSTAT data on national totals for all available years. Data on N and P fertilizer use (Figure S2.6 A and B) from the Indiastat database were found to be in close agreement with data from the FAOSTAT database. In addition, the spatial pattern of N fertilizer application as published by Swaney et al. (2015) on district level for the year 2000 (Figure S2.2) shows a remarkable resemblance with the spatial pattern of N fertilizer application based on subnational data from the Indiastat database (Figure 5A). Data for manure production from the Indiastat database were found to be in close agreement with data from the FAOSTAT database (Figure S2.6 C), with the exception of a relatively high manure production in the year 1992 according to the Indiastat database. This high value is caused by a relatively high number of buffaloes (Figure S2.9C) compared to the following years in the state of Rajasthan, which is part of the North East region. Although the agreement of yearly trends for crop N uptake of the five major crop groups wheat, rice, soybean, groundnut and cotton (Figure S2.6D) from the

Indiastat database and the FAOSTAT database was poorer than for the other data, they followed the same pattern.

Despite the uncertainties, involved in soil nutrient budget estimates at subnational level for India, the similarity between the hotspot areas of high NH_3 emissions identified by satellite measurements (Figure 1) and calculated by the soil nutrient budget model at subnational level (Figure 8B) is striking.

The land-cover distribution used in this study includes agricultural areas for cropland and grassland that are consistent with statistical information from the FAOSTAT database on the country scale. This land-cover distribution does not fully match the agricultural data per state and union territory from the Indiastat database. As a result, 0.1% of total N fertilizer and 1.8% of total N manure (Table S1.11) could not be allocated to grid cells due to unavailability of agricultural area.

4.3 Factors explaining differences between subnational and national patterns

The spatial patterns of the calculated soil N and P budgets and 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 obvious difference in the spatial distribution between the subnational and national calculations is the hotspot area of soil N surpluses and NH_3 emissions in the Green Revolution States in the subnational calculations and the lack thereof in the national calculations. This spatial heterogeneity is caused primarily by spatial heterogeneities in N fertilizer use and crop production and less by spatial heterogeneity in livestock production, and can be explained by the impact of the Green Revolution in these states that initiated in the 1960s (Abrol et al., 2017). 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, Figure S2.8B) and 0.97 Tg N (67% of India's total crop uptake by wheat, Figure S2.8A) 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 7A 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 (Figure 8A), while having 17% of India's agricultural land area (Table S1.6).

5 Conclusions

This chapter presents the limitations of this research and recommendations for further research, followed by a discussion on the way in which the research questions as stated in the introduction of this report were addressed. Finally, recommendations for policy makers are presented.

5.1 Limitations of this research report and recommendations for further research

Before answering the research questions, it is important to note that the initial plan was to calculate and study historical soil N and P budgets for multiple years using the soil nutrient budget model and combine the results to answer the research questions. Unfortunately, the Indiastat database only provided complete datasets for N and P fertilizer use and animal numbers for the years 2003 and 2007 (see Figure S2.6A, B and C). In addition, obtaining a complete and meaningful crop production dataset required considerable effort and time, resulting in the selection of only the most recently available year as input for the soil nutrient budget model. The reader should thus keep in mind that the soil nutrient budget model results are based solely on the year 2007.

As an alternative to the trends in historical soil N and P budgets, trends in different inputs (N and P fertilizers and N manure) and outputs (crop N uptake by five major crop groups) of the soil nutrient budget were studied for four regions of India based on data from the Indiastat database and the Indian Nitrogen Assessment (Abrol et al., 2017). It should be noted that the most recent year available for crop N uptake and P fertilizer use was 2010, for N manure 2012 and for N fertilizer 2014.

Further research on Indian soil nutrient budgets at subnational level could benefit from additional datasets containing crop and livestock production systems data at subnational level for more (recent) years, IMAGE (Stehfest et al., 2014) smaller grid size (5 x 5 minutes) maps and land cover distribution more consistent with subnational level data from the Indiastat database.

In addition, it will be interesting to use the soil nutrient budget model results at subnational level as input for IMAGE-GNM’s nutrient environmental fate module, which can be used to calculate the spatially explicit N and P discharge to Indian surface waters for the year 2007.

5.2 Addressing the research questions

1. *What are the historical soil N and P budgets calculated at national and subnational level?*

In chapter 3.1, the historical soil N and P budgets calculated at national and subnational level for the year 2007 were studied. Although the soil N and P budgets show a surplus for the calculations at both national and subnational level, the subnational calculations better reflect the spatial heterogeneity of soil N and P surpluses within India than the national calculations.

2. *What trends can be identified on a temporal and spatial scale in the historical soil N and P budgets calculated at subnational level?*

In chapter 3.2, trends in inputs (N and P fertilizer and N manure) and outputs (crop N uptake by five major crop groups) for four regions of India were studied. Overall, N and P fertilizer use and crop N uptake by five major crop groups increase over the period studied, with clear differences between the four regions of India. Considering that India needs to double its food production by 2050 (Abrol et al., 2017), these growth trends are likely to continue.

3. *What are the historical NH_3 emissions calculated at national and subnational level?*

In chapter 3.3, historical NH_3 volatilization from animal manure excreted by grazing animals and from spreading of animal manure and N fertilizers calculated at national and subnational level was studied for the year 2007. National and subnational calculations both showed high NH_3 emissions. However, the subnational calculations better reflect the spatial heterogeneity of NH_3 emissions in India than the national calculations.

4. *What factors can explain the differences between historical soil N and P budgets and NH_3 emissions calculated at national versus subnational level?*

Chapter 4.3 discusses factors that explain differences in spatial patterns of soil N and P budgets and NH_3 emissions. The most notable difference is the hotspot area with high soil N surpluses and related NH_3 emissions in the Green Revolution states in the subnational calculations and the lack thereof in the national calculations. This spatial heterogeneity is caused primarily by spatial heterogeneities in N fertilizer use and crop production and less by spatial heterogeneity in livestock production and can be explained by the impact of the Green Revolution in these states that started in the 1960s. The primary objective of the Green Revolution in India was achieving self-sufficiency in the production of wheat and rice, through the application of high-yielding hybrid varieties, an increased use of mineral fertilizer and the development of irrigation.

5. *Central research question: What are the differences in soil N and P budgets and related NH_3 emissions for total agriculture in India when calculated at subnational or national level?*

There are major differences between the results of the calculations at subnational and national level. At subnational level, spatial heterogeneities of the model inputs, and therefore also of the calculated soil N and P surpluses and related NH_3 emissions, are much better represented than at national level. This is beneficial for effect calculations (runoff and leaching, eutrophication and NH_3 emission-deposition), as the location of these negative environmental side effects strongly depends on the location of the soil N and P surpluses.

5.3 Recommendations

The soil nutrient budget model calculations show N and P surpluses in all agricultural areas of India for the year 2007, with the subnational calculations better reflecting spatial heterogeneity in the model results than the national calculations and showing a clear hotspot area in the Green Revolution States. 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, impacting ammonia and nitrous oxide emissions, groundwater quality, surface waters and large parts of coastal areas along the Indian coastline, and are expected to intensify (Abrol et al., 2017). Policy interventions aimed at modifying individual terms of the soil N and budgets, for the purpose of reducing nutrient surpluses in agriculture, can be effective in mitigating the related negative environmental side effects. When using simple indicators like soil N and P budgets in nutrient management strategies, it is recommended that policy and decision makers in India use subnational rather than national level data. This will improve the efficiency and effectiveness of their nutrient management strategies and interventions and help reduce negative environmental side effects of agriculture in India now and in the future.

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Supporting information

S1. Supplementary tables

Authors (year of publication)	Aim of study
Bouwman et al. (2017)	Analysis and discussion of the evolution of soil N and P cycles in crop production during the past decades (1970–2010) in different world regions, based on the soil nutrient budget model. Subnational data were used for the U.S.A., China and Europe.
Bouwman et al. (2013)	Analysis of the historical (1900-2000) and possible future (2050) changes in N and P cycles in global crop-livestock production systems, based on the soil nutrient budget model. Subnational data were used for the U.S.A. and China.
Bouwman et al. (2009)	Development of trends in spatially explicit global N and P soil balances over the period 1970-2050, based on the soil nutrient budget model. Subnational data were used for the U.S.A. and China.
Beusen et al. (2008)	Development of uncertainty estimates of global NH_3 emissions from global agricultural production systems based on the soil nutrient budget model. Subnational data were used for the U.S.A. and China.
Lesschen, Stoorvogel, Smaling, Heuvelink, and Veldkamp (2007)	Development of a spatially explicit methodology to quantify soil N, P and potassium (K) balances and their uncertainties at the national level based on NUTBAL, applied to Burkina Faso.
Smaling and Fresco (1993)	Development of a decision-support model (NUTMON) for monitoring soil N, P and K balances under agricultural land use, based on NUTBAL.
Smaling, Stoorvogel, and Windmeijer (1993)	Calculating soil N, P and K balances for the arable soils of the Kisii District in Southwestern Kenya at district level.
Stoorvogel, Smaling, and Janssen (1993)	Calculating soil N, P and K balances for the arable soils (NUTBAL) of 38 sub-Saharan African countries for the period 1982-1984 and for 2000 at supra-national level.
Stoorvogel and Smaling (1990)	Development of a soil N, P and K balance method (NUTBAL), in order to assess the state of soil nutrient depletion under agriculture in sub-Saharan Africa for 1983 and the year 2000, on request of FAO.

Table S1.1. Non-exhaustive list of scientific articles in which a soil nutrient budget model is used.

ISO	Name of state/union territory
356001	Andaman & Nicobar Islands
356002	Andhra Pradesh
356003	Arunachal Pradesh
356004	Assam
356005	Bihar
356007	Chhattisgarh
356010	Delhi
356011	Goa
356012	Gujarat, Dadra, Nagara Haveli, Daman & Diu
356013	Haryana
356014	Himachal Pradesh
356015	Jammu & Kashmir
356016	Jharkhand
356017	Karnataka
356018	Kerala & Lakshadweep
356020	Madhya Pradesh
356021	Maharashtra
356022	Manipur
356023	Meghalaya
356024	Mizoram
356025	Nagaland
356026	Orissa
356028	Punjab & Chandigarh
356029	Rajasthan
356030	Sikkim
356031	Tamil Nadu & Pondicherry
356032	Tripura
356033	Uttar Pradesh
356034	Uttaranchal
356035	West Bengal

Table S1.2. Definition of states and union territories of India and corresponding ISO code used in this study.

Animal category	Excretion in kg N or P_2O_5 head^{-1} year^{-1}	
	N	P_2O_5
1. Beef cattle	40	7.0
2. Dairy cattle	60	10.5
3. Buffaloes	45	7.9
4. Pigs	11	1.8
5. Poultry	0.5	0.1
6. Sheep and goats	10	1.5
7. Horses	45	6.5
8. Asses	30	4.4
9. Mules	30	4.4
10. Camels	55	8.0

Table S1.3. Excretion rates for the different animal categories (Bouwman et al., 2017).

11 IMAGE crop groups	FAO crop groups	N content$_{crop}$ (-)	P_2O_5 content$_{crop}$ (-)	dm$_{crop}$ (-)
1	Wheat, barley, other cereals (Temperate cereals)	0.021109	0.008918	0.879718334
2	Rice	0.014773	0.006507	0.88
3	Maize	0.015909	0.007548	0.88
4	Millet, sorghum, (Tropical cereals)	0.017647	0.008083	0.85
5	Pulses	0.041176	0.006736	0.85
6	Potatoes, sweet potatoes, cassava, other roots, (root & tuber crops)	0.009994	0.003737	0.261909188
7	Oilseeds nes	0.032608696	0.012447405	0.92
7	Rapeseed	0.038351648	0.014094293	0.91
7	Oil palm fruit	0.015851064	0.007553191	0.94
7	Soybeans	0.072941176	0.013472486	0.85
7	Groundnuts in shell	0.060509554	0.010211629	0.942
7	Sunflower seed	0.037173913	0.011202665	0.92
7	Sesame seed	0.035531915	0.013644475	0.94
7	Coconuts	0.002366071	0.00100994	0.896
8	Plantains, sugar beets, sugar cane, vegetables & melons, bananas, citrus fruit, fruit excl. melons, cocoa beans, coffee, tea, tobacco, seed cotton, fibre crops primary, rubber (other crops)	0.015078	0.005901	0.201054033

Table S1.4. Values used for calculating the crop N and P_2O_5 uptake per state and union territory for the year 2007.

FAO crop group	Harvest index Hi (-)	N_{seed} (-)	N_{straw} (-)	N_{root} (-)	Root ratio Rr (-)
Soybean	0.5	0.062	0.015	0.015	0.19
Groundnut	0.5	0.035	0.008	0.008	0.19
Pulses	0.5	0.035	0.008	0.008	0.19

Table S1.5. Values used for calculating the biological nitrogen fixation per state and union territory for the year 2007 (Bouwman et al., 2017).

Region	Land area (10^5 km^2)	Agricultural land area (10^5 km^2)	Natural land area (10^5 km^2)
North Central	9.9	4.6	5.3
North East	6.8	3.3	3.5
South West	11.3	7.8	3.5
Green Revolution States	3.4	3.2	0.1
Total India	31.4	19.0	12.4

Table S1.6. Total land area, agricultural land area and natural land area for each of the four regions of India and for total India, as used by the soil nutrient budget model for the national and subnational calculations for the year 2007.

North Central		North East		South West		Green Revolution States	
356007	Chhattisgarh	356003	Arunachal Pradesh	356001	Andaman and Nicobar Islands	356013	Haryana
356010	Delhi	356004	Assam	356002	Andhra Pradesh (& Telangana)	356028	Punjab & Chandigarh
356014	Himachal Pradesh	356005	Bihar	356011	Goa	356033	Uttar Pradesh
356015	Jammu and Kashmir (& Ladakh)	356016	Jharkhand	356012	Gujarat, Dadra & Nagar Haveli, Daman & Diu		
356020	Madhya Pradesh	356022	Manipur	356017	Karnataka		
356029	Rajasthan	356023	Meghalaya	356018	Kerala & Lakshadweep		
356034	Uttarakhand	356024	Mizoram	356021	Maharashtra		
		356025	Nagaland	356031	Tamil Nadu & Puducherry		
		356026	Odisha				
		356030	Sikkim				
		356032	Tripura				
		356035	West Bengal				

Table S1.7. Definition of the four regions of India and corresponding ISO codes, states and union territories per region, as used in this study.

Crops	Name	N content (-)	Dry matter (-)
1	Wheat	0.019	0.880
2	Rice, Paddy	0.013	0.880
3	Maize	0.014	0.880
4	Barley	0.017	0.880
5	Millet	0.015	0.850
6	Sorghum	0.015	0.850
7	Other cereals	0.016	0.870
8	Potatoes	0.003	0.212
9	Sweet Potatoes	0.003	0.272
10	Cassava	0.002	0.326
11	Other roots	0.003	0.270
12	Plantains	0.002	0.653
13	Sugar Beets	0.002	0.260
14	Sugar Cane	0.002	0.232
15	Pulses, Total	0.035	0.850
16	Vegetables & Melons, Total	0.002	0.070
17	Bananas	0.002	0.257
18	Citrus Fruit, Total	0.001	0.103
19	Fruit excl Melons, Total	0.001	0.131
20	Oilseeds nes	0.030	0.920
21	Rapeseed	0.035	0.910
22	Oil Palm Fruit	0.015	0.940
23	Soybeans	0.062	0.850
24	Groundnuts in Shell	0.057	0.942
25	Sunflower Seed	0.034	0.920
26	Sesame Seed	0.033	0.940
27	Coconuts	0.002	0.896
28	Cocoa Beans	0.014	1
29	Coffee, Green	0.024	1
30	Tea	0.078	0.525
31	Tobacco Leaves	0.003	0.210
32	Seed Cotton	0.029	0.920
33	Fibre Crops Primary	0.081	1
34	Rubber	0.000	1

Table S1.8. List of the 34 crops (FAOSTAT), their N content on dry matter basis, and dry matter content of the harvested product (Bouwman et al., 2017).

	Subnational			National		
	Mean	Range	Standard deviation	Mean	Range	Standard deviation
A. Soil N budget agriculture (in Gg N)						
India	13.76	94.49	14.34	13.83	28.58	11.74
North Central	8.58	94.49	10.21	11.23	28.58	11.71
North East	10.68	38.63	12.43	12.00	28.07	12.11
South West	13.17	39.97	11.47	13.99	27.59	11.35
Green Revolution States	37.17	88.00	15.34	24.37	28.05	4.24
B. Soil P budget agriculture (in Gg P_2O_5)						
India	3.80	18.14	3.81	3.82	12.69	3.38
North Central	2.45	15.35	2.95	3.23	12.52	3.51
North East	2.60	11.19	3.18	3.01	12.69	3.17
South West	4.53	18.14	4.11	4.02	10.27	3.35
Green Revolution States	7.32	17.88	2.87	6.37	12.21	1.78
C. NH_3 volatilization from application of N fertilizer (in Gg N)						
India	2.66	33.58	3.82	2.58	7.67	2.30
North Central	1.27	33.58	2.19	2.22	7.67	2.39
North East	1.83	9.26	2.55	1.94	6.22	2.04
South West	2.37	7.58	2.12	2.69	6.71	2.32
Green Revolution States	9.47	29.81	6.64	4.44	6.86	1.19

Table S1.9. Mean, range and standard deviation for all grid cell values of India and for all grid cell values in one of the four regions of India, for national and subnational level soil N budgets (A), soil P budgets (B) and NH_3 volatilization from spreading of N fertilizers (C).

Source of NH_3 volatilization	Subnational		National	
	Tg N yr^{-1}	% of total	Tg N yr^{-1}	% of total
N fertilizer application	3.2	62%	3.1	61%
Manure spreading	0.8	15%	0.8	16%
Grazing	0.1	3%	0.1	3%
Storage and housing	1.0	20%	1.1	21%

Table S1.10. NH_3 volatilization from spreading of N fertilizers, animal manure, grazing and storage and housing for 2007 for India at subnational and national level.

	Total	Not allocated:	
	(Tg N)	(Tg N)	(% of total)
N fertilizer	14.4	0.018	0.13
N manure	16.1	0.283	1.75

Table S1.11. Total and not allocated manure from the soil nutrient budget model for the subnational level.

S2. Supplementary figures

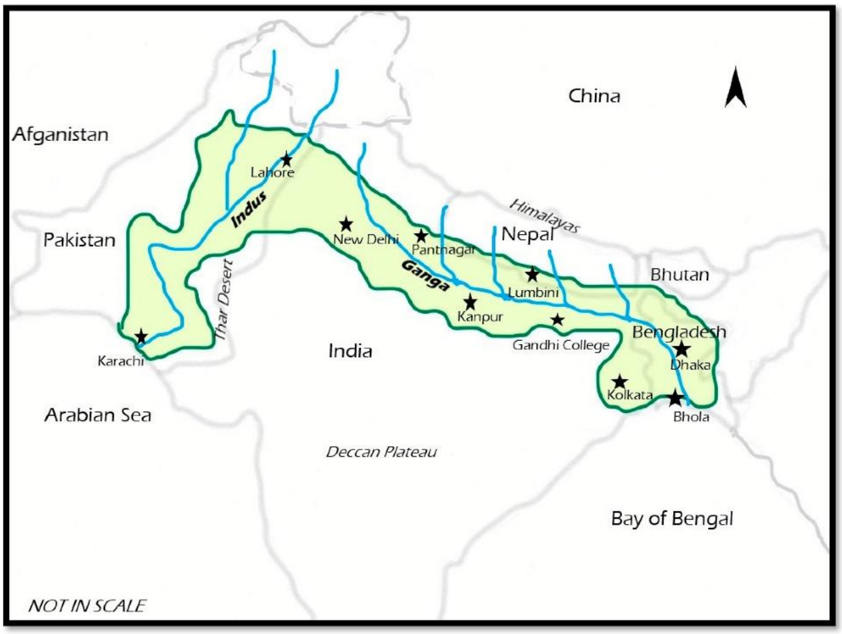

Figure S2.1. Indo-Gangetic Plain highlighted in light green (Shrestha, Peel, & Moore, 2018)

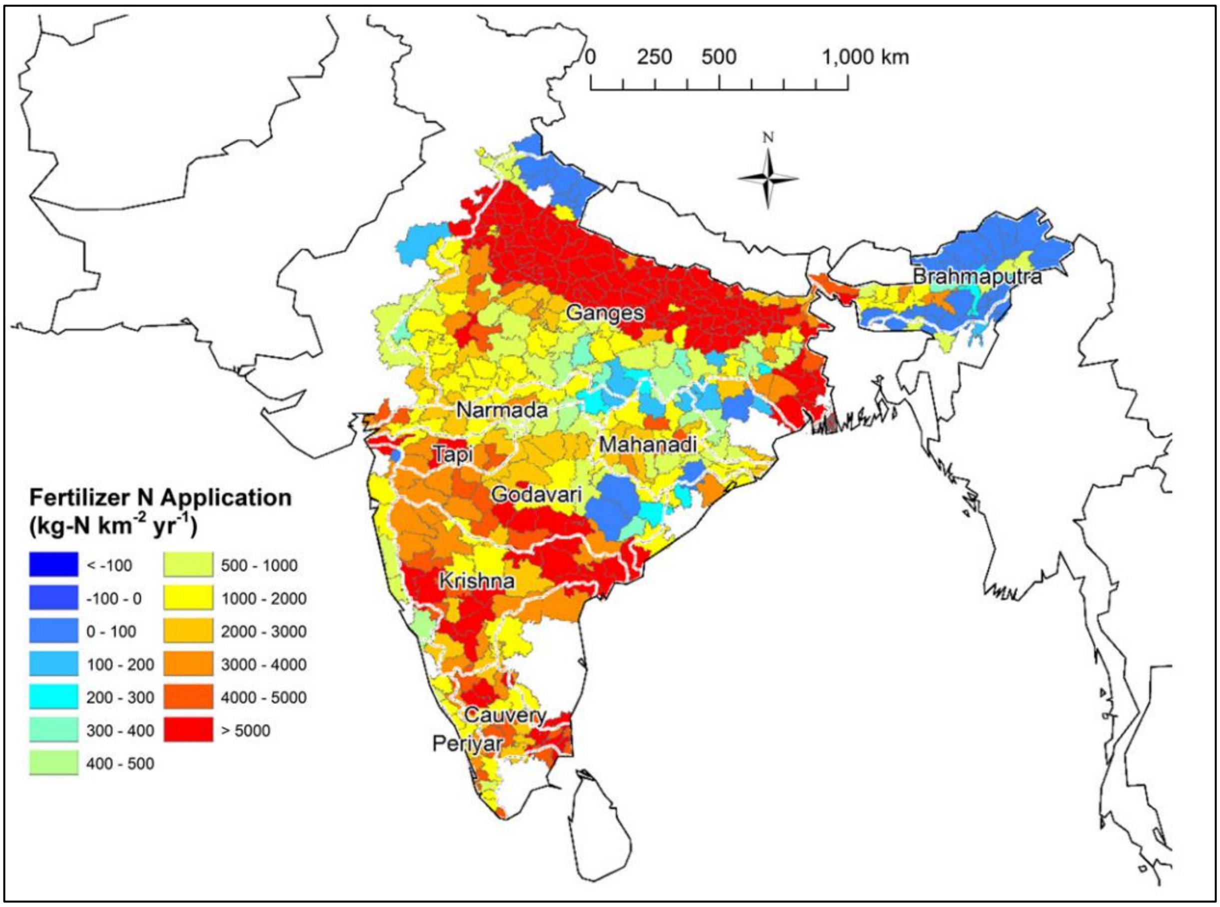

Figure S2.2. District-level N fertilizer consumption from Fertilizer Association of India for the year 2000 (Swaney et al., 2015).

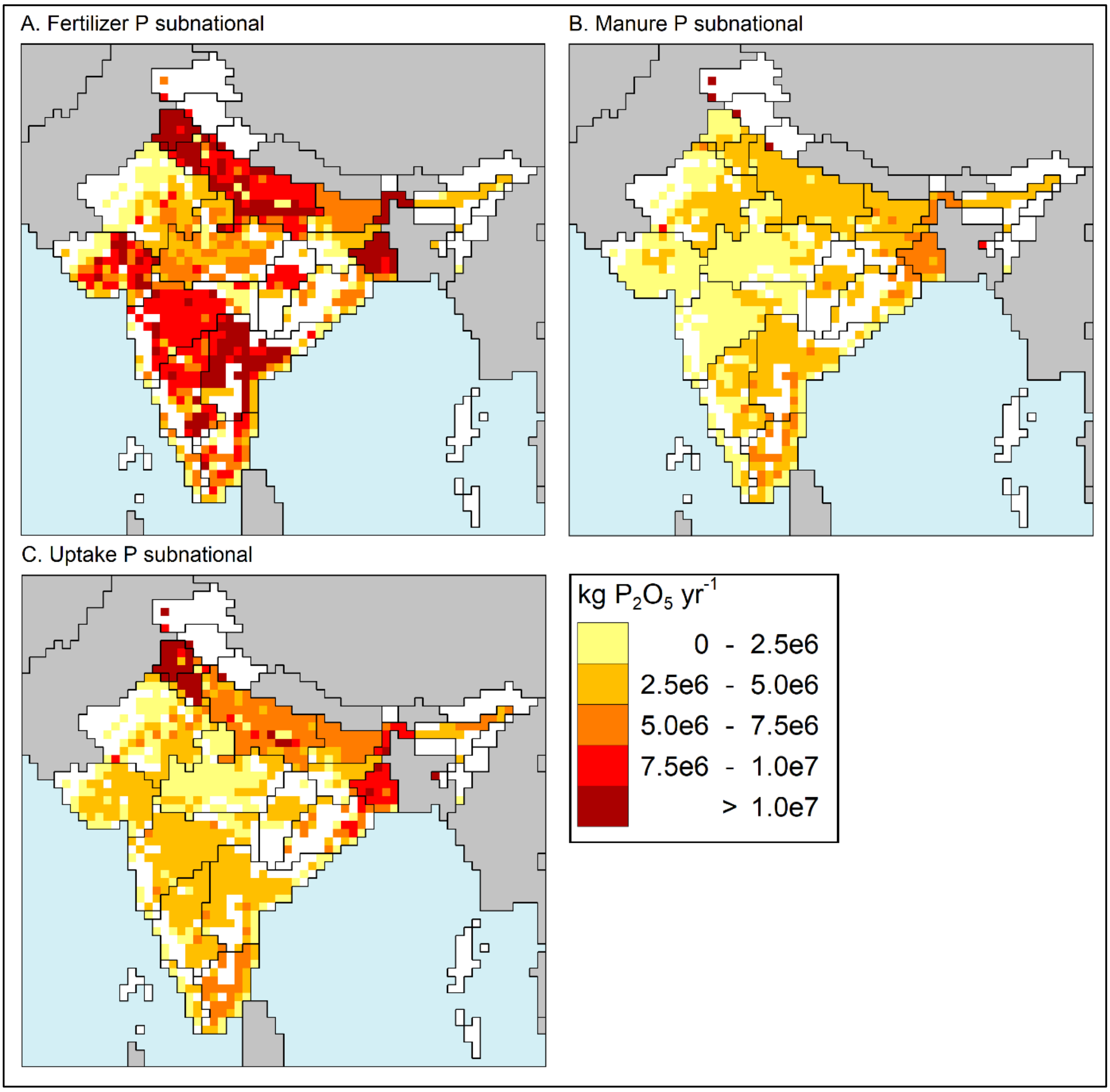

Figure S2.3. Spatially explicit P inputs (figures A and B) and output (figure C) in India for 2007, as calculated by the soil nutrient budget model at subnational level. Neighboring countries are presented in grey, water in blue, non-agricultural land in white, grid size is 30 x 30 minutes.

Figure S2.4. Soil N budget, N inputs and outputs for the year 2007 for four regions of India at subnational (green) and national (blue) level.

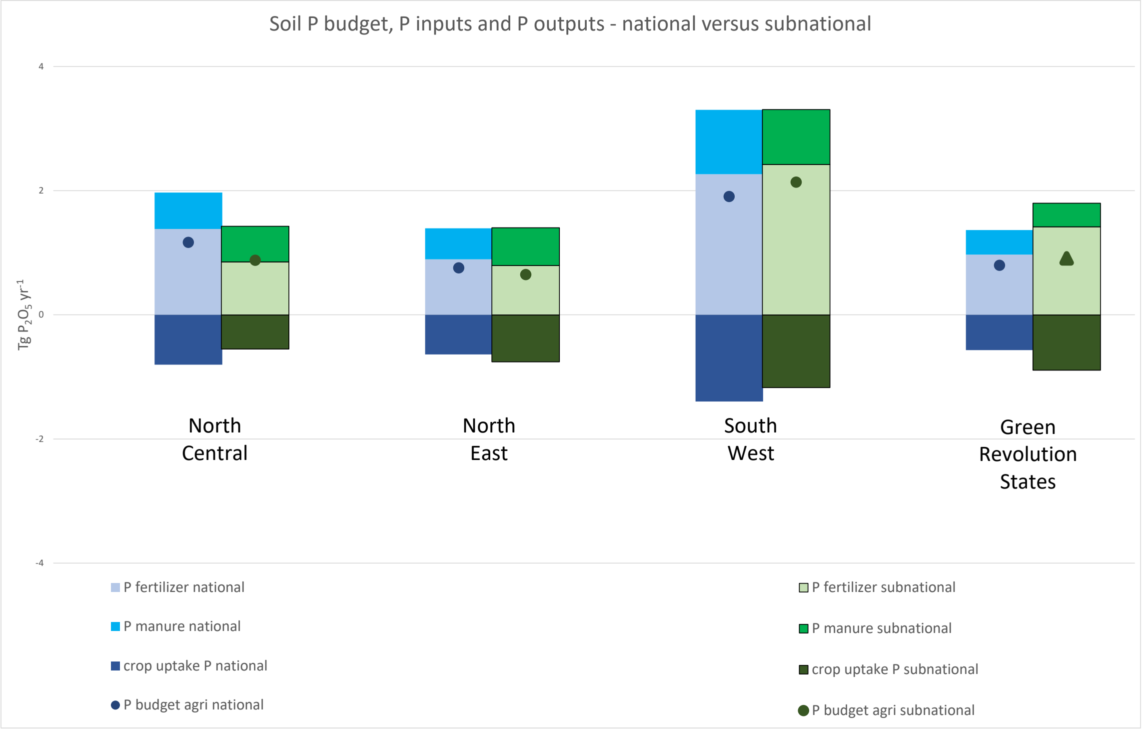

Figure S2.5. Soil P budget, P inputs and outputs for the year 2007 for four regions of India at subnational (green) and national (blue) level.

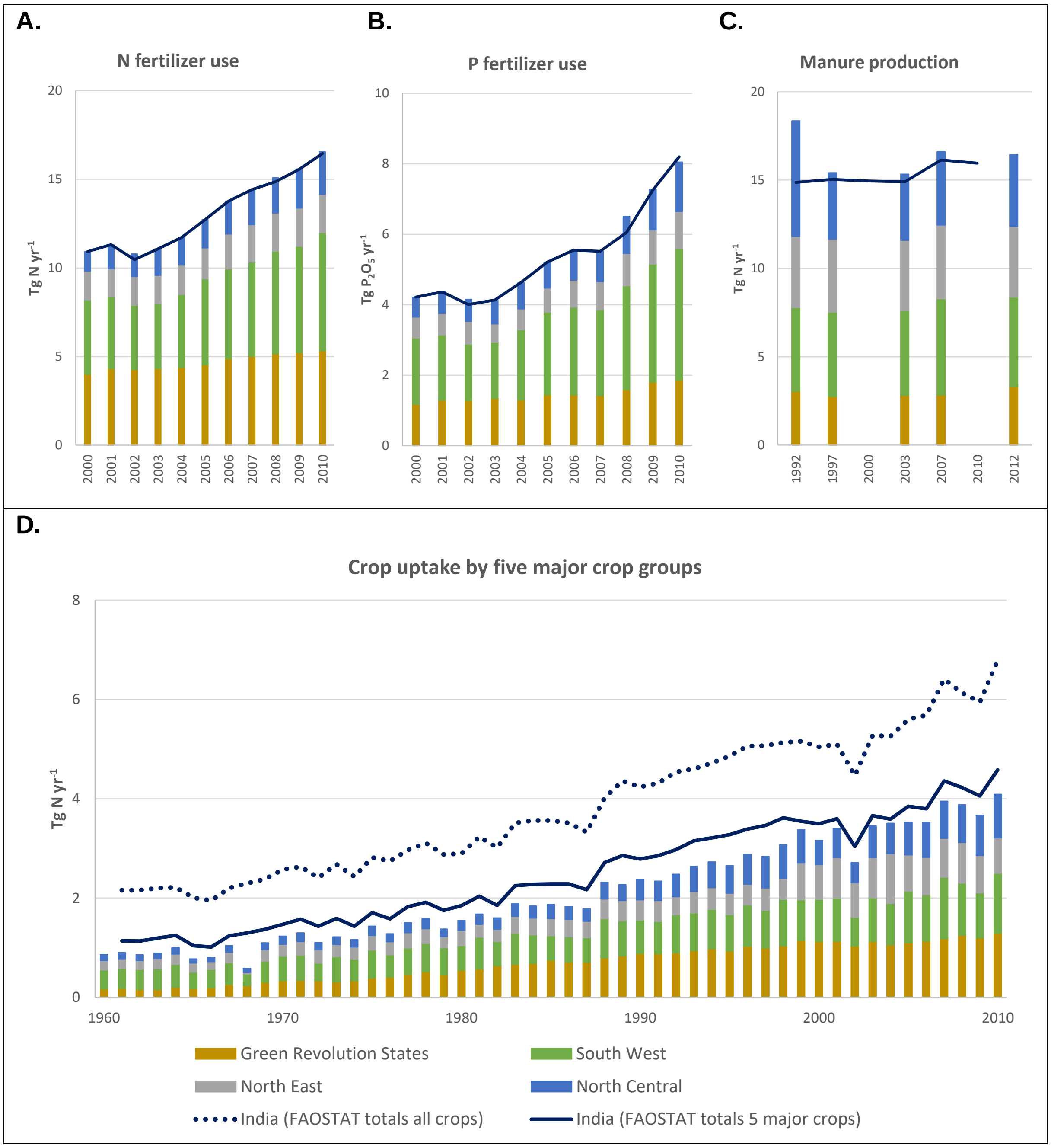

Figure S2.6. Historical yearly N and P fertilizer use (years 2000-2010), N manure production (years 1992-2012) and crop N uptake by five major crop groups wheat, rice, soybean, groundnut and cotton (years 1960-2010) for the four regions of India represented as stacked columns, based on data from the Indiastat database. The dark blue lines represent the national total values according to the FAOSTAT database for all available years (figures A-D), the dotted dark blue line represents the value national total values for all 34 crop groups according to the FAOSTAT database for all available years (figure D).

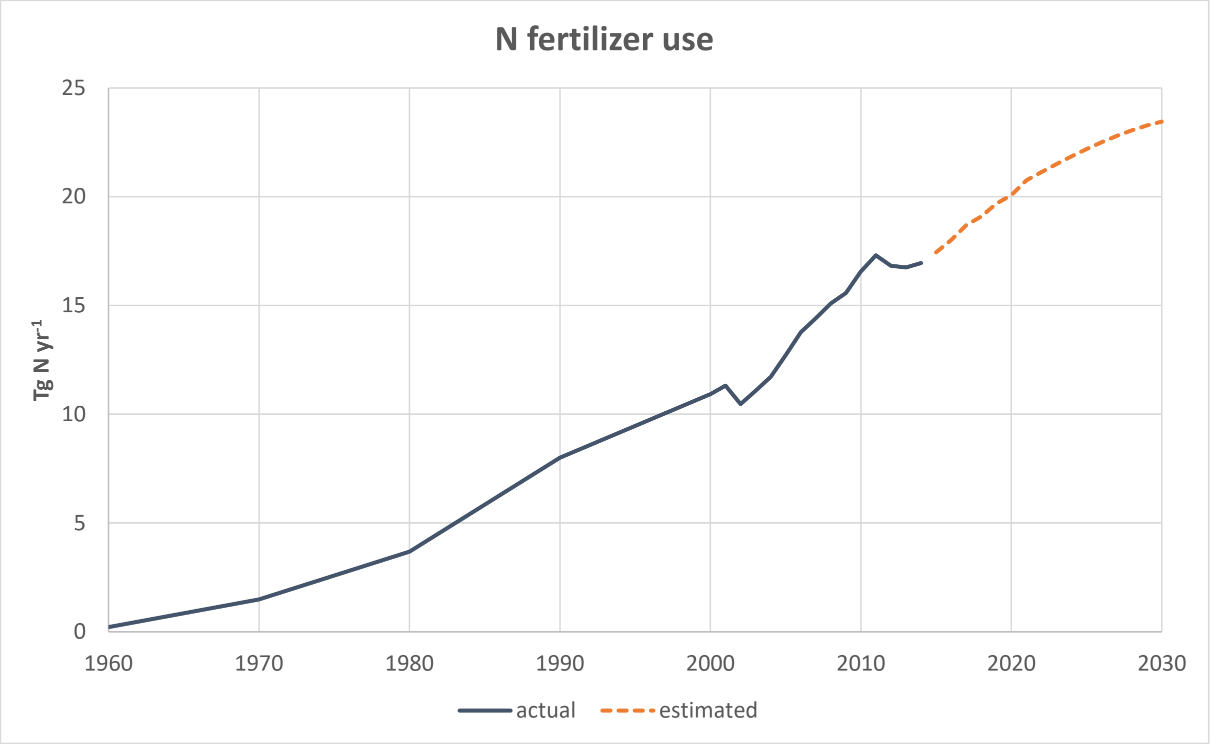

Figure S2.7. Historical yearly N fertilizer use (years 1960-2014) and projected yearly N fertilizer use (years 2015-2030) for total India, based on data from the Indian Nitrogen Assessment (Abrol et al., 2017). The dark blue line represents the actual yearly N fertilizer use, the dotted orange line represents the projected N fertilizer use.

Figure S2.8. Historical yearly crop uptake of five major crops wheat, rice, soybean, groundnut and cotton, for the four regions of India for the years 1960-2010, based on data from the Indiastat database.

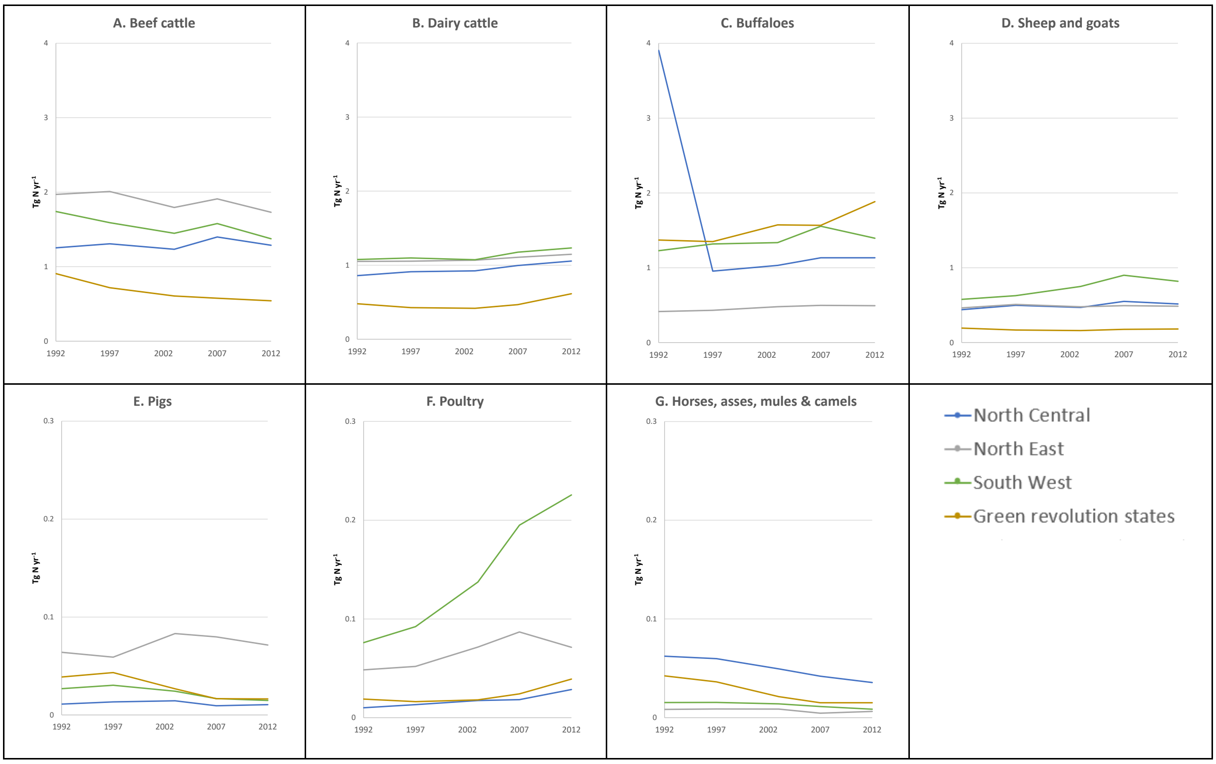

Figure S2.9. Historical yearly N manure production (years 1992-2012) per animal category for the four regions of India, based on data from the Indiastat database. Maximum value of vertical axis in Figures A-D is 4 Tg N, in figures E-G 0.3 Tg N.