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Characterizing the Spatial Patterns of Global Fertilizer Application and Manure Production

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ABSTRACT: Agriculture has had a tremendous impact on soil nutrients around the world. In some regions, soil nutrients are depleted because of low initial soil fertility or excessive nutrient removals through intense land use relative to nutrient additions. In other regions, application of chemical fertilizers and manure has led to an accumulation of nutrients and subsequent water quality problems. Understanding the current level and spatial patterns of fertilizer and manure inputs would greatly improve the ability to identify areas that might be sensitive to aquatic eutrophication or to nutrient depletion. The authors calculated spatially explicit fertilizer inputs of nitrogen (N) and phosphorus (P) by fusing national-level

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statistics on fertilizer use with global maps of harvested area for 175 crops. They also calculated spatially explicit manure inputs of N and P by fusing global maps of animal density and international data on manure production and nutrient content. Significantly higher application rates were found for both fertilizers and manures in the Northern Hemisphere, with maxima centered on areas with intensive cropland and high densities of livestock. Furthermore, nutrient use is confined to a few major hot spots, with approximately 10% of the treated land receiving over 50% of the use of both fertilizers and manures. The authors' new spatial disaggregation of the rich International Fertilizer Industry Association (IFA) fertilizer-use dataset will provide new and interesting avenues to explore the impact of anthropogenic activity on ecosystems at the global scale and may also have implications for policies designed to improve soil quality or reduce nutrient runoff.

KEYWORDS: Fertilizer Application; Manure Production; Global Dataset

1. Introduction

Since the dawn of agriculture, humans have managed the land for food production. Nearly a third of our planet's land surface is used for agriculture today [Cassman and Wood 2005; the Food and Agriculture Organization of the United Nations (FAO) Statistical Database (FAOSTAT) data (see <http://faostat.fao.org/>); Klein Goldewijk et al. 2007; Ramankutty et al. 2008]. Societies have developed many methods for improving food production, including conversion of land from forests and other ecosystems to agriculture and various agricultural intensification practices, including tilling and fertilizing the soil, using improved seed varieties, and crop rotations (Matson et al. 1997). Perhaps the most dramatic example of improved food production is the "green revolution," which resulted in manyfold increases in crop yields through the use of new technologies including new varieties of crops, irrigation, and fertilizer application (Borlaug 2007; Tilman 1998).

Chemical fertilizers are a major facet of the green revolution's package of yield-increasing advances and techniques (Mann 1999). While manures are a traditional source of soil nutrients on farms, chemical fertilizers became widely available only in the mid-twentieth century (Frink et al. 1999). The development of Haber–Bosch ammonia synthesis and the worldwide extraction of phosphate from rock greatly increased the supply of these agricultural inputs, which have been harnessed around the world to increase crop productivity (Tilman et al. 2001; Vitousek et al. 1997). Since the 1960s, global chemical fertilizer use has more than tripled, reaching over 130 million metric tons by the mid-1990s, and irrigated areas doubled, but cropland areas increased by only 12% (Tilman et al. 2001). The intensification of existing agricultural activity, with commensurate increases in fertilizer application, rather than cropland expansion, has been a primary driver of the monumental growth in global agricultural production over the past half century (FAO 2002; Foley et al. 2005).

Large-scale land-use changes for agriculture have unleashed a litany of global environmental problems (Foley et al. 2005; Tilman et al. 2001). While several studies have characterized the changes in global land cover and evaluated the global environmental consequences of land-cover conversions (Bonan 1999; Green et al. 2005; Houghton 1995; Klein Goldewijk 2001; Ramankutty and Foley 1999), few have examined the global consequences of agricultural intensification [but see Caraco (Caraco 1993), Diaz and Rosenberg (Diaz and Rosenberg 2008), Bennett et al. (Bennett et al. 2001), and Vitousek et al. (Vitousek et al. 2009) for exceptions].

Intensification has proven to be a double-edged sword. While the benefits of intensification has brought obvious benefits to crop yields and food production, it has also resulted in widespread degradation of soil fertility and water quality (Bennett et al. 2001; Galloway et al. 2008; Oldeman et al. 1991; Richter 2007; Vitousek et al. 2009). Nutrients applied to croplands can leach into aquatic systems and alter ecosystem function (Carpenter et al. 1998; Smil 2000; Smil 2002). For example, excess nutrients can stimulate the growth of algae and other aquatic plants; the decomposition of this additional organic matter consumes dissolved oxygen and can therefore create hypoxic or anoxic conditions. The development of a “dead zone” on the continental shelf of the northern Gulf of Mexico each summer is attributed in large part to nitrogen fertilizer use across the Mississippi River basin (Boesch et al. 2009; Burkart and James 1999; Turner and Rabalais 1994). Hypoxic zones like that in the northern Gulf of Mexico have been reported in coastal areas around the world (Diaz and Rosenberg 2008). While some regions of the world are adversely impacted by excess nutrients, many other regions are still adversely impacted by declines in soil fertility, especially where farmers do not have the means or expertise to replace the nutrients removed through crop harvest or removal of residues (Vitousek et al. 2009). Sub-Saharan Africa, for example, suffers from low crop yields as a legacy of nutrient exhaustion over the past several decades (Sheldrick and Lingard 2004; Smaling and Dixon 2006; Stoorvogel and Smaling 1990; Vitousek et al. 2009). For these reasons, it is important to understand the geographic distribution and rates of application of chemical fertilizers and manure.

While data on fertilizer use are available at the country level for various crops around the world, the geographic distribution within nations is not well known. Matthews (Matthews 1994) developed a global database of nitrogen fertilizer application rates at 1° resolution in latitude by longitude by redistributing national statistics on fertilizer consumption into her global spatial database on land use. The dataset is representative of the 1980s and has not been updated since; moreover, finer spatial resolution and better quality maps of global land use have become available through remote sensing. Matthews (Matthews 1994) also did not consider manure application, which is widely used as a fertilizer in many parts of the world. Van Dreht et al. (Van Dreht et al. 2005) compared four different global datasets (Bouwman et al. 2005; Boyer et al. 2004; Green et al. 2004; Siebert 2005) that were used to calculate global nitrogen balances for driving models of river N export. These studies modeled global-scale nitrogen balances considering nitrogen inputs from both synthetic fertilizers and livestock, using similar approaches to estimate these inputs. For synthetic fertilizer inputs, they either evenly distributed national-level fertilizer consumption data from FAO over a global dataset of croplands (Boyer et al. 2004; Green et al. 2004) or distributed crop-specific fertilization rates from the FAO “Fertilizer Use by Crop” publication series over the distribution of crops or crop groups taken from the Integrated Model to Assess the Global Environment (IMAGE) (Bouwman et al. 2005; Siebert 2005). For manure production, these studies used either national data on animal populations (Bouwman et al. 2005) or animal distribution maps (Green et al. 2004; Siebert 2005) and combined them with country-level or regional-level animal excretion rates. We now have new global databases of the distribution of 175 major crops (Monfreda et al. 2008) and of livestock distributions (Wint and

Robinson 2007) that allow us to improve upon these earlier studies. Moreover, none of these previous studies consider phosphorus, an important nutrient for plants and also a major cause of eutrophication (Bennett et al. 2001; Schindler et al. 2008). However, a forthcoming study by Bouwman et al. (Bouwman et al. 2009) does consider phosphorus, and we compare our results to this study in the discussion section.

Many studies address fertilizer and manure inputs in the context of a soil nutrient balance or budget, where inflows to and outputs from an agricultural system are considered at scales ranging from individual fields to entire continents (FAO 2004; Van der Hoek and Bouwman 1999). One of the first comprehensive approaches to calculating soil nutrient balances at a national to continental scale was by Stoorvogel and Smaling (Stoorvogel and Smaling 1990), where national-level balances were calculated for sub-Saharan Africa using the “land-use system” (a well-defined tract of land with specific management characteristics) as the spatial unit of analysis. This early effort was followed by a wealth of publications in the peer-reviewed literature (Grizetti et al. 2007; Janssen 1999; Oenema and Heinen 1999; Schlecht and Hiernaux 2004; Scoones and Toulmin 1998; Sheldrick et al. 2002; Van Drecht et al. 2005) and in government/research institutes (Gerber et al. 2002; Mutert 1996; PARCOM 1995; Smaling and Dixon 2006; Syers et al. 2002). A recent paper in the journal *Science* stressed the policy relevance of nutrient balance calculations and identified the need for comprehensive nutrient budgets that quantify pathways of nutrient input and loss over time and under different management practices around the world (Vitousek et al. 2009). At the continental scale of analysis, Lesschen et al. (Lesschen et al. 2007) created a spatially explicit version of the Stoorvogel and Smaling (Stoorvogel and Smaling 1990) model by improving transfer functions, taking advantage of more detailed and updated data sources. Despite these advances, existing large-scale fertilizer application datasets are limited by a lack of spatially explicit crop distribution data, meaning that national values had to be spread evenly over a country for each crop (Lesschen et al. 2007). Such limitations prevent the accurate calculation of soil nutrient budgets at the continental to global scale.

It is predicted that agricultural production must double over the next 50 years to meet the demands of a growing and changing human population (Tilman et al. 2001). While some of this advance may be met through expansion of cultivated area, much of it will need to be met by increased intensification of crop production on lands currently under agricultural use (Tilman et al. 2001). Different, but equally important, consequences are associated with both the overfertilization and underfertilization of agricultural systems. The former leads to eutrophication, while the latter leads to diminished soil fertility, and both have implications for the long-term sustainability of food production systems (Vitousek et al. 2009). To begin to address this challenge, we have developed spatially explicit databases of fertilizer inputs and manure inputs of nitrogen (N) and phosphorus (P) to agricultural areas around the world. These datasets will be useful for evaluating the environmental consequences of global fertilizer use. They may also be useful inputs to global models addressing food production, soil nutrient dynamics, eutrophication, and nitrous oxide emissions. Finally, these datasets also allow us to identify the target areas where fertilizer reductions are needed to manage water quality as well as the areas undergoing nutrient depletion and require additional inputs.

Table 1. IFA database of national-level fertilizer application rates for Albania and Guatemala.

Albania									
Commodity (IFDC)	Area	N	P ₂ O ₅	K ₂ O	N	P ₂ O ₅	K ₂ O	Total	
Year 1999	(000 Ha)	Average (Kg Ha ⁻¹)			Consumption (000 Mt)				
Alfalfa	10.5	20.0	10.0		0.2	0.1	0.0	0.3	
Barley	1.6	20.0	10.0		0.0	0.0	0.0	0.0	
Citrus fruits	0.5	10.0	10.0		0.0	0.0	0.0	0.0	
Total	183.1				7.2	4.8	0.1	12.1	
1999 Overall consumption estimate (IFDC)					6.0	5.0	0.1	11.1	
1999 Overall consumption estimate (FAO)					6.0	5.0	0.1	11.1	

Guatemala									
Commodity (IFDC)	Area	% area	N	P ₂ O ₅	K ₂ O	N	P ₂ O ₅	K ₂ O	Total
Year 1997	(000 Ha)	fertilized	Rate (Kg Ha ⁻¹)			Consumption (000 Mt)			
Banana	21.0	80.0	120.0	60.0	150.0	2.0	1.0	3.2	6.2
Citrus fruits	8.2	60.0	80.0	30.0	60.0	0.4	0.2	0.4	1.0
Coffee	263.5	80.0	120.0	40.0	60.0	25.3	6.3	7.9	39.5
Total	1351.6					118.3	65.3	42.6	226.2
1997 Overall consumption estimate (IFDC)						118.4	48.9	42.0	209.3
1997 Overall consumption estimate (FAO)						118.6	76.0	42.0	236.6

2. Methods

2.1. Data sources

2.1.1. National-level fertilizer data

We obtained national-level fertilizer application rates of two major fertilizers (N and P) for crops found in 88 countries from the International Fertilizer Industry Association (IFA) (data are from “Fertilizer Use by Crop 2002,” a fertilizer statistics database available by request from FAO). This dataset (referred to as IFA database) represents the consensus of experts from the IFA, International Fertilizer Development Center (IFDC), International Potash Institute (IPI), Phosphate and Potash Institute (PPI), and FAO regarding global application rates and use of fertilizer by crop and is based on data from questionnaires sent to government officials, agronomists, and consultations with other industry experts (Fertilizer Use by Crop 2002). The fertilizer use in these 88 countries account for over 90% of global fertilizer consumption (data are from “Means of Production: Fertilizers,” part of the FAOSTAT 2000 data archives; see <http://faostat.fao.org/>). The number of crop-specific fertilizer application rates reported for each country ranged from 2 crops (Guinea) to over 50 crops (United States), and the years for which the data are reported range from 1994 to 2001.

Countries report their fertilizer application rates to the FAO in one of two formats. For 46 of the 88 countries in the IFA database, average application per crop (kg ha⁻¹ yr⁻¹) is reported alongside the hectares of that crop that are grown in that country. In Table 1, Albania is presented as an example of how data were reported by IFA/FAO/IFDC for these countries. In these cases, application rates represent averages for the entire crop area, including both fertilized and unfertilized crop area. For example, the database indicates that the 10 500 ha of alfalfa grown in Albania are fertilized at 20 kg N ha⁻¹ yr⁻¹ on average.

For the remaining 42 countries (see Table 1, Guatemala entry, for an example), the rate of application per crop ($\text{kg ha}^{-1} \text{ yr}^{-1}$) is presented alongside the total hectares grown for that crop and the percentage of this area that was fertilized. For these countries, the actual crop area fertilized was known, and fertilizer application rates were averages only over the fertilized areas and thus reflected the fact that not all of the area planted in that crop was fertilized. We converted these values to an average application rate applied to the total area of the particular crop in that country since there is no information on the spatial distribution of fertilizer use on the particular crop within the country. For example, the database indicates that 80% of the 21 000 ha of bananas grown in Guatemala (i.e., 16 800 ha) are fertilized at 120 kg N ha^{-1} . For our purposes, we converted this to indicate that 100% of the bananas grown there (all 21 000 ha) are fertilized at $96 \text{ kg N ha}^{-1} \text{ yr}^{-1}$.

The IFA database presents different estimates of national total fertilizer consumption for each country. We also calculated a total from the IFA database by multiplying the average fertilizer application for each crop by the crop area cultivated; the others are based on independent national estimates of consumption. For example, Table 1 shows the total Guatemalan fertilizer consumption based on calculations from the IFA database (226 200 Mt) as well as external estimates of total fertilizer consumption from the FAO (236 600 Mt) and IFDC (209 300 Mt). Comparing calculated consumption from the IFA database and other independent estimates indicates significant differences. When we compare the total consumption for all countries that have both IFA crop-specific data as well as FAO consumption data, consumption as calculated by the IFA database is 62 Tg, while total FAO consumption is 72 Tg. As we will see later in the discussion, this difference has repercussions for intercomparison of different fertilizer products.

The source of fertilizer data for each of the 161 countries considered in the analysis is shown in Figure 1. In countries for which the crop-specific IFA fertilizer data were unavailable, FAO total fertilizer consumption estimates for the year 2000 were utilized (data are from “Means of Production: Fertilizers,” part of the FAOSTAT 2000 data archives; see <http://faostat.fao.org/>). For three countries in which neither IFA crop-specific fertilizer data nor FAO total consumption data were available (Andorra, Hong Kong, and Western Sahara), fertilizer use was assumed to be negligible, and indeed total harvested area in these countries from Monfreda et al. (Monfreda et al. 2008) was zero.

2.1.2. Global maps of 175 crops

Monfreda et al. (Monfreda et al. 2008) recently developed global maps of the harvested area and yields of 175 different crops of the world (known as the “M3-crop” database). These data were developed by synthesizing a rich subnational database of crop inventory statistics from around the world with a global map of cropland area for the year 2000 known as “M3-cropland” [the latter was derived by merging satellite-based land-cover data with global subnational cropland inventory data by Ramankutty et al. (Ramankutty et al. 2008)]. The data are representative of the year 2000 and available at 0.5° spatial resolution in latitude by longitude.

2.1.3. Global data on livestock distribution and nutrient content of manure

Standardized global, spatially explicit maps of livestock distribution were obtained from FAO Gridded Livestock of the World (GLW) project (Wint and Robinson

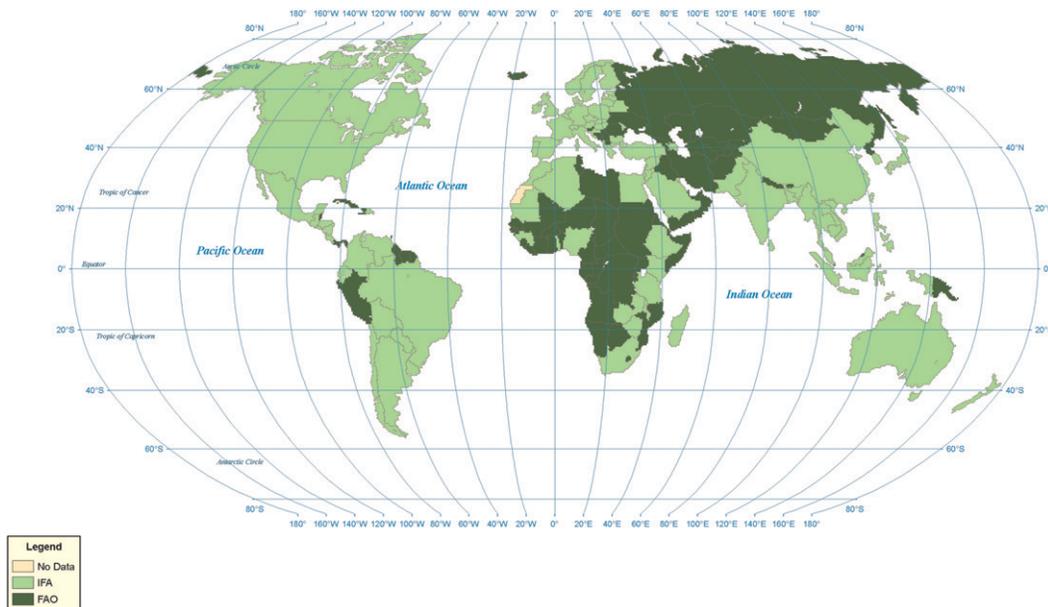


Figure 1. Source of fertilizer data for each of the 161 countries considered. Countries labeled IFA (88 of them) had crop-specific national-level fertilizer data available from the IFA database. Countries labeled FAO only had national-level total fertilizer consumption estimates.

2007). These data were developed by establishing statistical relationships between observed livestock inventory data (cattle, buffalo, goats, sheep, pigs, and poultry) and various environmental variables (e.g., rainfall and human population density) and using these relationships to predict livestock distributions across the entire globe (Wint and Robinson 2007). These data are presented as livestock densities at a 3-arc-min spatial resolution (approximately 5 km at the equator). We multiplied the densities (head km^{-2}) by the area of each cell (km^2) to arrive at the number of head per cell and spatially aggregated the data to match the spatial resolution (0.5°) of our other datasets. We also gathered data on national average nutrient excretion rates ($\text{kg N head}^{-1} \text{ yr}^{-1}$ and $\text{P head}^{-1} \text{ yr}^{-1}$) for cattle, pigs, poultry, sheep, goats, and buffalo for each Organisation for Economic Co-operation and Development (OECD) country (OECD 2008).

2.2. Developing geographically explicit global data on fertilizer application and manure production

The global maps of N and P input through fertilizer were developed by merging the harvested area from the M3-crops database with our national-level fertilizer-use data for the same crops. The total harvested area calculated from M3-crops was not always fully consistent with the harvested areas reported in IFA because of the various assumptions involved in developing M3-crops (see Monfreda et al. 2008) and inconsistencies in the exact years that the data represent (M3-crops represents

an average for 1997–2003, while IFA reports individual years). Therefore, we only used the spatial pattern in M3-crops to disaggregate the national harvested areas reported by the IFA. This ensured that total fertilizer consumption estimates in the IFA database and the new geographically explicit maps were consistent. To achieve this, we scaled the fertilizer application rates based on the ratio between the national harvested area as reported in the IFA database and the harvested area as calculated from the M3-crops data. Our spatial disaggregation approach can be represented by the following equation:

$$F(i, j) = \sum_c F_{\text{IFA}}(k, c) A_{\text{M3-crops}}(i, j, c) \frac{A_{\text{IFA}}(k, c)}{A_{\text{M3-crops}}(k, c)} \text{kg ha}^{-1}, \quad i, j \in k,$$

where $F(i, j)$ are the spatially explicit fertilizer maps of N and P (units = kg of N or P ha⁻¹ of gridcell area), with a spatial resolution of 0.5° in latitude by longitude; i and j are the longitude and latitude indices, c is an index indicating different crops, and k is the country index (and we use a 0.5° resolution spatial map relating countries to latitude–longitude indices); $F_{\text{IFA}}(k, c)$ are the crop-specific IFA national fertilizer statistics (units = kg ha⁻¹ of crop area); $A_{\text{M3-crops}}(i, j, c)$ is the spatially explicit crop harvested area data from Monfreda et al. (Monfreda et al. 2008) (units = ha of crop area ha⁻¹ of gridcell area); $A_{\text{IFA}}(k, c)$ is the national total harvested area reported in the IFA statistics (units = ha of crop area); and $A_{\text{M3-crops}}(k, c)$ is the national total harvested area calculated from the M3-crops database (units = ha of crop area).

Where IFA crop listings did not exactly match the names used in the global harvested area maps, an appropriate match was selected or calculated. For example, “citrus fruit” fertilizer rates were available from the IFA fertilizer statistics, but citrus fruits were mapped separately in the M3-crops database. We summed the harvested area maps of all citrus crops found in the M3-crops database to match the available IFA statistics. In cases where no appropriate crop maps could be found (“set-aside industrial crops,” for example), the M3-cropland map of Ramankutty et al. (Ramankutty et al. 2008) was used to distribute the fertilizer rates. Again in this approach, we used the national harvested areas reported by IFA, and only the spatial patterns in the croplands map were used for disaggregation, as represented by the following equation:

$$F(i, j) = \sum_c F_{\text{IFA}}(k, c) A_{\text{M3-Cropland}}(i, j) \frac{A_{\text{IFA}}(k, c)}{A_{\text{M3-Cropland}}(k)} \text{kg ha}^{-1}, \quad i, j \in k,$$

where $A_{\text{M3-cropland}}(i, j)$ is the spatially explicit cropland area data from Ramankutty et al. (Ramankutty et al. 2008) (units = ha of cropland area ha⁻¹ of gridcell area), and $A_{\text{M3-cropland}}(k)$ is the national total harvested area calculated from the M3-cropland map (units = ha of crop area). Similarly, for “grassland” in the IFA database, we used the global M3-pasture map of Ramankutty et al. (Ramankutty et al. 2008).

For those countries where no crop-specific fertilizer application data were available from the IFA database (see Figure 1), FAO total fertilizer consumption estimates for the year 2000 were distributed using the spatial patterns of the cropland map of Ramankutty et al. (Ramankutty et al. 2008) as represented by the following equation:

$$F(i, j) = F_{\text{FAO}}(k) \frac{A_{\text{M3-Cropland}}(i, j)}{A_{\text{M3-Cropland}}(k)} \text{ kg ha}^{-1}, \quad i, j \in k,$$

where $F_{\text{FAO}}(K)$ is the total consumption of N or P in the country k (units = kg of N or P).

To estimate manure application, we first standardized global livestock density maps developed by the FAO (Wint and Robinson 2007) by converting head of livestock (cattle, pigs, poultry, sheep, goats, and buffalo) into “equivalent OECD livestock,” using “livestock unit” values. Standardized livestock unit estimates take into account feed requirements of animals in different regions; these are used to account for differences in species and production systems across geographical regions (FAO 2003). We used the livestock unit estimates for 11 world regions and 10 livestock categories provided in FAO (2003) to convert the global data on livestock numbers into equivalent OECD livestock. For example, a sub-Saharan head of cattle would correspond to one-half of one head of cattle in the OECD, based on differences in feed requirements. We chose OECD equivalents in order to utilize the most recent and accurate estimates of nutrient excretion available (OECD 2008). Once all global livestock numbers were expressed in terms of equivalent OECD animals, average OECD nutrient excretion data could be applied uniformly around the world to calculate the mass of N and P produced as manure and introduced into the landscape. Our approach can be represented by the following equation:

$$M(i, j) = \sum_{\text{lc}} D_{\text{FAO}}(i, j, \text{lc}) \frac{\text{LU}(\text{lc}, r)}{\text{LU}(\text{lc}, \text{OECD})} E_{\text{OECD}}(\text{lc}) \text{ kg ha}^{-1},$$

where $M(i, j)$ are the nutrients (N and P) produced in manure (units = kg of N or P ha^{-1} of gridcell area), with a spatial resolution of 0.5° in latitude by longitude; i and j are the longitude and latitude indices; lc is an index indicating different livestock categories; D_{FAO} is the density of that livestock category at that location (units = head ha^{-1} of gridcell area); LU is the livestock unit estimate for livestock category in the region (r) in which the grid cell is located and in OECD countries (OECD) (units = unitless); and E_{OECD} is the nutrient excretion rate of N and P for each livestock category, averaged across all countries in the OECD (units = kg of N or P excreted $\text{head}^{-1} \text{ yr}^{-1}$).

This method estimates the nutrient available from manure production, not the amount of manure nutrient actually spread on the field. It therefore produces an overestimate of the nutrients returning to the agricultural system in the particular grid cell. The management of manures is difficult to assess at the global scale because of considerable regional variations. For example, whether a farmer allows livestock to graze on agricultural fields or keeps them in a pen has a significant effect on the proportion of manure nutrients that return to the soil (Sheldrick et al. 2004). In the latter scenario, losses through storage, transportation, and eventual spreading have to be considered. These losses are usually addressed as the recoverable manure nutrient, a reported percentage of the amount of manure that is recovered and applied to cropland in a given region. A comprehensive survey of regional farming and manure management techniques would be required to ascertain the geographic variation in recoverable manure nutrients (see Sheldrick et al. 2004), and this is outside

the scope of our current global analysis. Moreover, because of the large scale of this study, we assume that all manure nutrients return to the landscape by some means (deposited directly or spread onto cropland). For this reason, in this study we distinguish our datasets as representing fertilizer nutrients *applied* to cropland and manure nutrients *produced* and present on the landscape.

3. Results

3.1. Patterns of fertilizer application

Figures 2a,b show the geographic distribution of N and P applied to all crops considered in this study. The values shown represent an average application rate for all crops over a 0.5° resolution grid cell. The highest rates of N fertilizer application are found in the midwestern United States, western Europe, northern India, eastern China, Vietnam, Indonesia, and Egypt's Nile Delta (where the highest average N application rate, 220 kg ha^{-1} , is found) (Figure 2a). The highest rates of P fertilizer application are found in the midwestern United States, eastern China, and southern New Zealand (where the highest average P application rate, 96 kg ha^{-1} , is found) (Figure 2b).

3.2. Patterns of manure nutrient production

Figures 3a,b show the geographic distribution of N and P produced from excreta of all livestock categories considered in this study. The highest rates of N in manures produced are found in the United States, parts of South America, western Europe, East Africa, northern India, eastern China, and New Zealand (where the highest average N production rate, 370 kg ha^{-1} , is found) (Figure 3a). The highest rates of P in manures produced are found in the midwestern United States, southern Brazil, western Europe, northeastern China, northern India, Bangladesh, and New Zealand (where the highest average P production rate, 64 kg ha^{-1} , is found) (Figure 3b). The manure N and P follow a similar spatial pattern because they are both based on the same spatial distribution of livestock but differ significantly in magnitude.

3.3. Latitudinal distribution of fertilizer application and manure production

The latitudinal distribution of average fertilizer application rates shows a marked difference north and south of the equator (Figure 4). Significantly higher application rates can be found in the Northern Hemisphere, with maxima centered on 30° and 35°N for N and P, respectively. These latitudes correspond to the extensive and intensive agricultural activity found in the United States, western Europe, and China. In the Southern Hemisphere, application rates are generally much lower, with the exception of 7° and 40°S , where high fertilizer use is found in Indonesia and New Zealand's agricultural areas, respectively. Rates of manure nutrient production follow a similar pattern, with the highest average production found between 20° and 60°N (corresponding to high livestock densities in the American Midwest, western Europe, China, and India/Bangladesh), 11°N (eastern Africa and

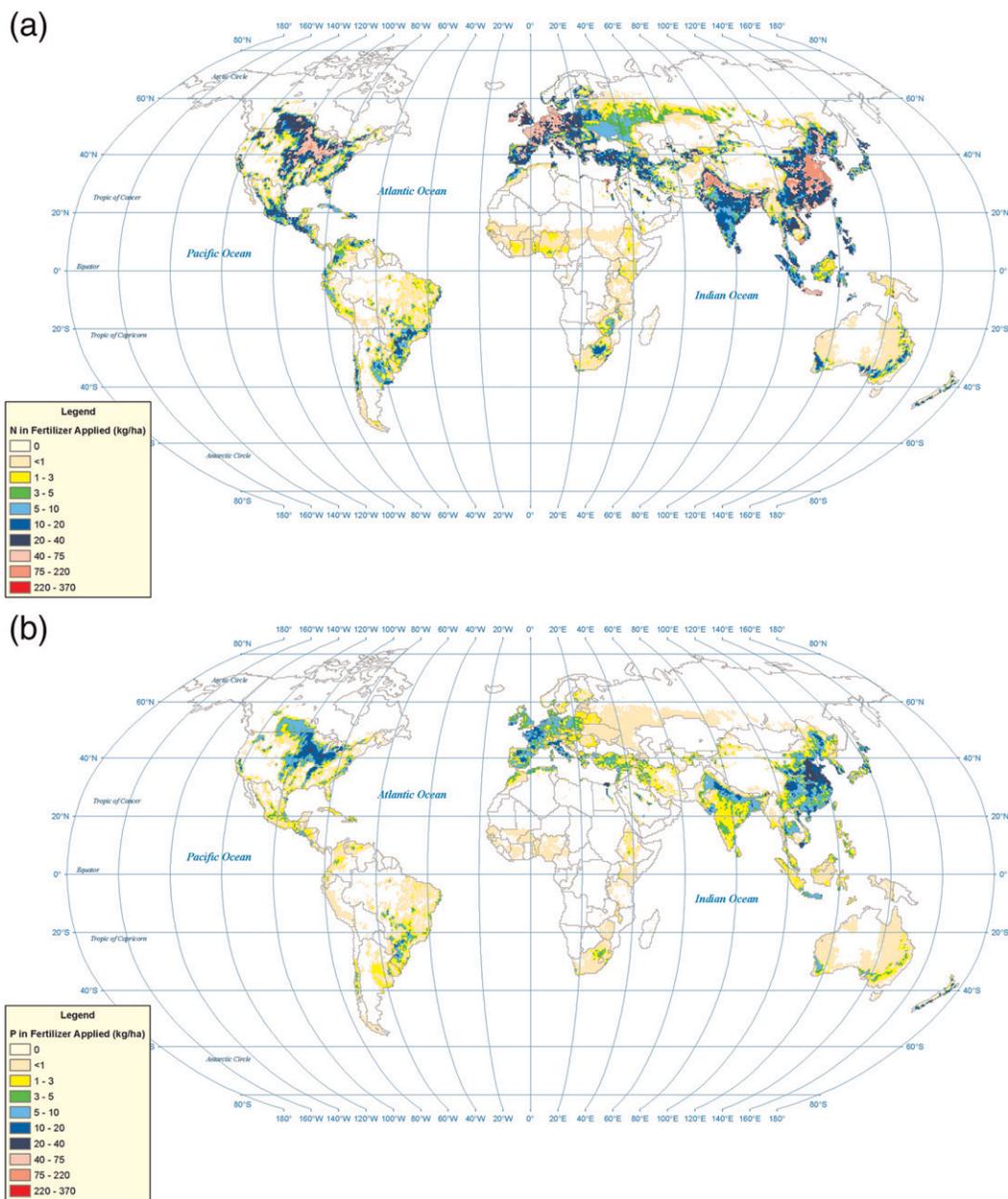


Figure 2. (a) Global map of N fertilizer application rates (kg ha^{-1} of gridcell area). Values represent average N applied over all crops across each 0.5° resolution in latitude \times longitude grid cell. (b) Global map of P fertilizer application rates (kg ha^{-1} of gridcell area). Values represent average over all crops across each 0.5° resolution in latitude \times longitude grid cell.

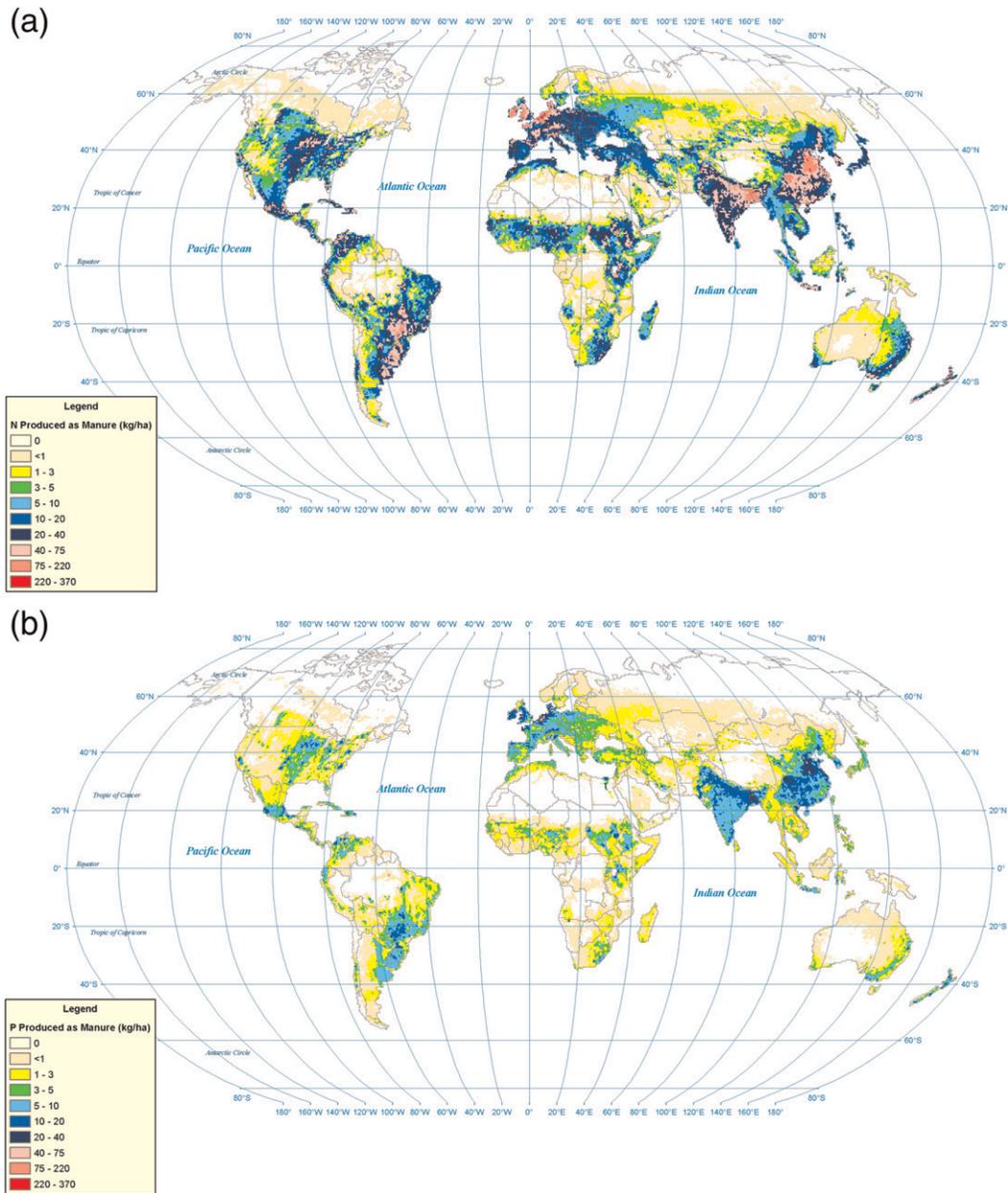


Figure 3. (a) Global map of N produced in manure (kg ha^{-1} of gridcell area). Values represent average over all animals across each 0.5° resolution in latitude \times longitude grid cell. (b) Global map of P produced in manure (kg ha^{-1} of gridcell area). Values represent average over all animals across each 0.5° resolution in latitude \times longitude grid cell.

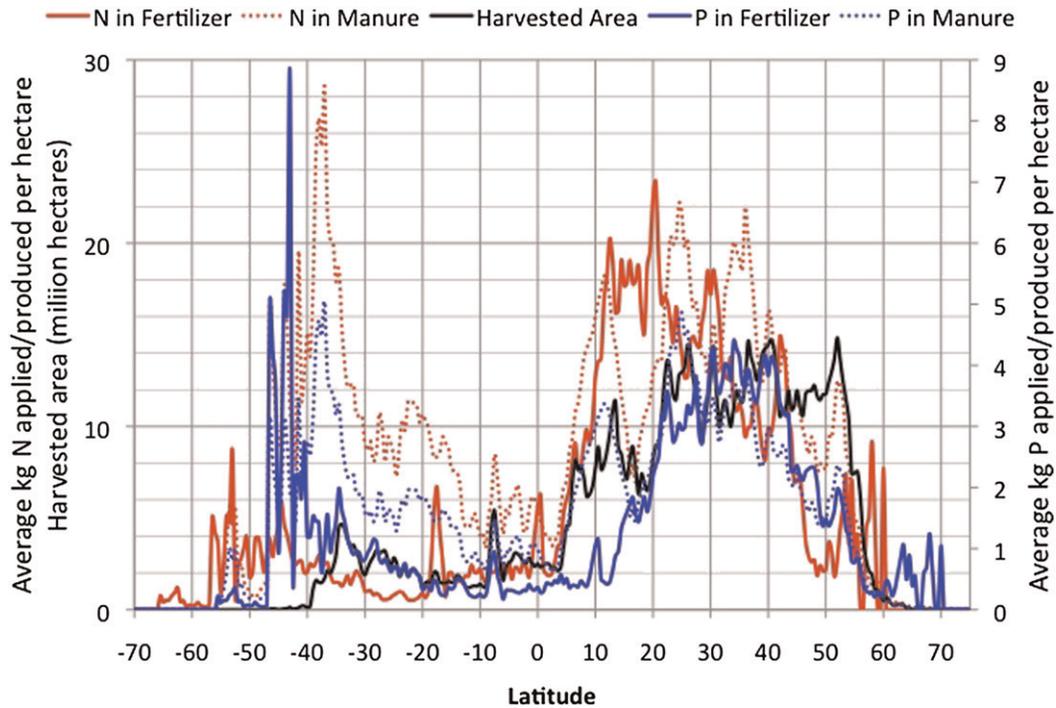


Figure 4. Latitudinal distribution of application/production of N and P in fertilizers and manure, as well as of total harvested area from Monfreda et al. (Monfreda et al. 2008). Values averaged across each 0.5° of latitude are shown.

northern South America), and 37°S (New Zealand). Average N production rates are consistently higher than average P production rates in both hemispheres.

3.4. Fertilizers or manure?

The geographically explicit datasets allow us to examine whether chemical fertilizer application or manure production dominates inputs in different regions of the world (Figures 5a,b). Generally, chemical fertilizers dominate in the developed north as well as parts of India and China, while manure appears to dominate in South America and Africa. Fertilizers dominate in the central United States, Canada, much of Europe and China, and parts of Southeast Asia. Manure nutrient availability exceeds fertilizer application in South America and Africa, as well as small portions of the eastern United States, eastern Europe, central Asia, Southeast Asia, and northeastern Australia. But an important caveat to this analysis is that the manure dataset represents total manure nutrients *produced*, rather than the recoverable fraction.

3.5. “Hot spot” nature of fertilizer application and manure production

Most fertilized grid cells have low application rates—for example, more than 50% of cropland area fertilized with N is fertilized at a rate of less than 2.5 kg ha⁻¹

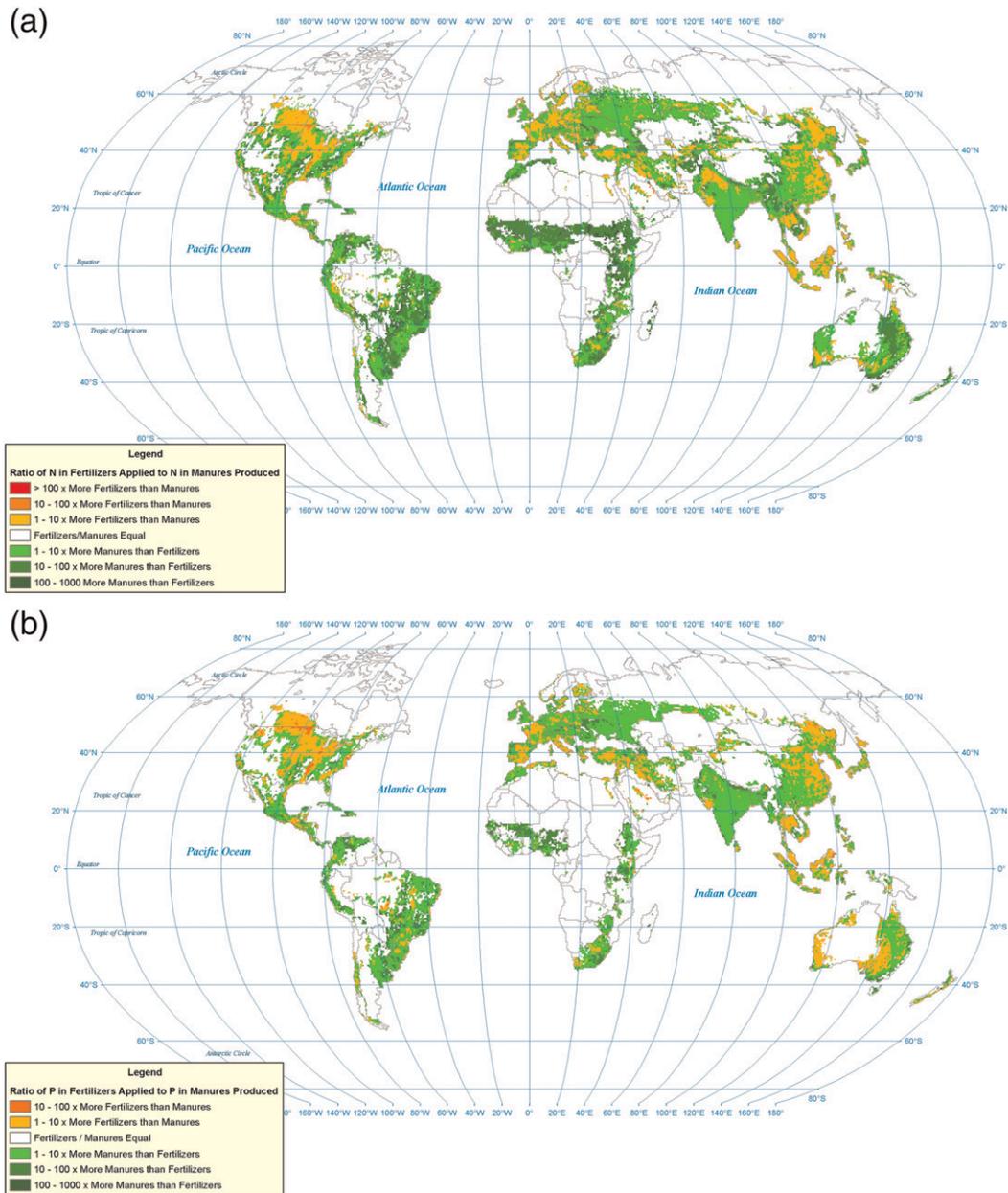


Figure 5. (a) Global map of the ratio of N in fertilizers applied to N in manures produced. This is the ratio of the data in Figures 2a and 3a. (b) Global map of the ratio of P in fertilizers applied to P in manures produced. This is the ratio of the data in Figures 2b and 3b.

(figure not shown). On the other hand, a small proportion of the fertilized land area receives a disproportionately large proportion of the total fertilizers applied (Figure 6). In fact, 8.5% and 10.2% of the grid cells fertilized with N and P, respectively, at rates greater than 36 and 7 kg ha⁻¹, respectively, account for more than 50% of the total N

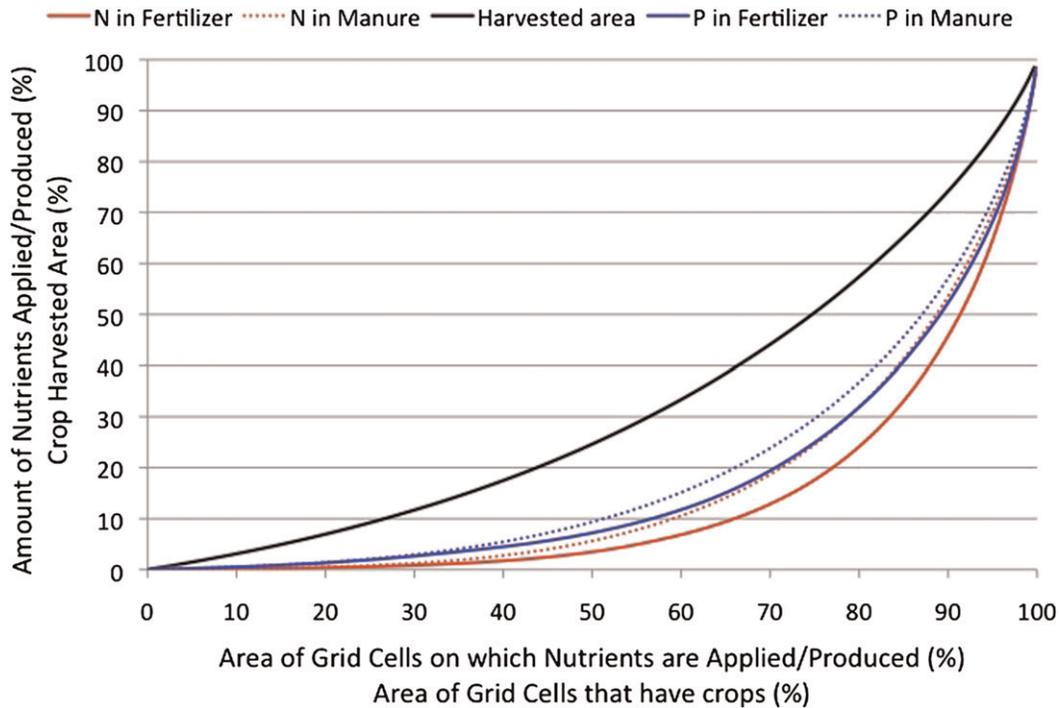


Figure 6. Cumulative histograms of application/production of N and P in fertilizers and manure compared to the distribution of total harvested area from Monfreda et al. (Monfreda et al. 2008). The x axis represents, for nutrients, the cumulative area of grid cells that are fertilized expressed as a percentage of the global total fertilized area, and in the case of harvested area, the cumulative harvested area as a percentage of total harvested area. The y axis represents, for nutrients, the cumulative amounts of nutrients applied/produced as a percentage of global total amounts, and for harvested area, the cumulative gridcell area for harvested grid cells as a percentage of total global gridcell area.

and P applied globally. Similarly, for manure, 11.2% and 12.8% of the grid cells fertilized with N and P, respectively, at rates greater than 32 and 6 kg ha⁻¹, respectively, account for more than 50% of the total N and P applied globally. These regions point to the global fertilizer and manure “hot spots” where high nutrient loading to waterways may be expected, depending on climate, drainage networks, and other factors. The fraction of land responsible for the majority of the world’s nutrient application is likely to be overestimated here because of the coarse spatial resolution of the datasets. Extensive subgrid heterogeneity in application rates is expected because of local variations in soil texture, drainage, and farm management.

4. Discussion

These new spatially explicit datasets provide a global picture of the distribution of fertilizer application and manure production rates across the globe. The datasets

Table 2. Comparison of selected results with other existing global estimates.

Source	Nutrients introduced through manures (Tg)		Nutrients introduced as fertilizers (Tg)		Year for which estimates are relevant	
	N	P	N	P	Manures	Fertilizers
Van der Hoek and Bouwman (Van der Hoek and Bouwman 1999)	102.4	—	73.6	—	1994	1994
Smil (Smil 2000)	—	>15	—	15	2000	2000
Sheldrick et al. (Sheldrick et al. 2002)	— ^a	— ^a	78.2	12.7	—	1996
Sheldrick et al. (Sheldrick et al. 2004)	93.6	21.1	—	—	1996	—
Boyer et al. (Boyer et al. 2004)	—	—	81.1	—	1995	1995
Green et al. (Green et al. 2004)	81.5	—	78.3	—	1995	1995
Siebert (Siebert 2005)	107.7	—	72.3	—	1995	1995
Bouwman et al. (Bouwman et al. 2005)	104.1 ^b	—	82.9	—	1995	1995
Bouwman et al. (Bouwman et al. 2009)	101.4	17.1	82.9	13.8	2000	2000
This study	128.3	24.3	70.2	14.3	2007	2000 ^c

^a Estimates shown in this paper represent the recoverable fraction. The reader is referred to Sheldrick et al. (Sheldrick et al. 2004) for manure nutrient estimates.

^b The value of 81.5 reported in Van Drecht et al. (Van Drecht et al. 2005) represents manure actually recycled in agriculture. The total amount of N in manure produced is 104.1 Tg (L. Bouwman 2009, personal communication).

^c While spatial patterns of harvested area represent an average from the period 1997–2003 (Monfreda et al. 2008), fertilizer data range from 1994 to 2001.

show that the highest fertilizer application and manure production is confined to a few major global hot spots relative to the distribution of cultivation (Figures 2a,b; 3a,b; and 6).

Comparison of our results with other existing global and regional estimates of nutrient application provides a partial evaluation of our product (Table 2). Van der Hoek and Bouwman (Van der Hoek and Bouwman 1999) developed nitrogen budgets at various spatial scales to evaluate the impacts of upscaling budgets from the farm to the global scale. Using livestock numbers from the FAO, excretion rates from published literature, and fertilizer consumption estimates from FAOSTAT, they estimated global manure N production to be 102.4 Tg yr⁻¹ and global fertilizer N application to be 73.6 Tg yr⁻¹ in 1994 (see their Table 3.5). Smil (Smil 2000) estimated P introduced as manures to be greater than 15 Tg yr⁻¹ globally and P introduced as fertilizers to be 15 Tg yr⁻¹ in 2000 (see his Table 4). Sheldrick et al. (Sheldrick et al. 2002) developed a methodology for conducting nutrient audits at national to global scales, using FAO fertilizer consumption data, and modeled excreta produced at the national level using FAOSTAT livestock numbers, assuming an average livestock profile with excretion rates proportional to slaughtered animals weights [the model was described in detail in a companion manuscript, Sheldrick et al. (Sheldrick et al. 2004)]. The main global nutrient audit paper (Sheldrick et al. 2002) estimated nutrients introduced as fertilizers to be 78.2 Tg N yr⁻¹ and 12.7 Tg P yr⁻¹ in 1996 (see their Table 2), while the companion paper (Sheldrick et al. 2004) estimated the recoverable fraction of nutrients introduced as manures to be

93.6 Tg N yr⁻¹ and 21.1 Tg P yr⁻¹ in 1996 (see their Table 3). We also obtained four different global estimates of N introduced as fertilizers and manure in 1995 from the publication by Van Drecht et al. (Van Drecht et al. 2005). Boyer et al. (Boyer et al. 2004) estimated global fertilizer N to be 81.1 Tg (manure was not presented explicitly in their study), while Green et al. (Green et al. 2004) estimated N introduced as manures to be 81.5 Tg yr⁻¹ globally and N fertilizers to be 78.3 Tg yr⁻¹. Siebert (Siebert 2005) estimated global production of N in manure to be 107.7 Tg yr⁻¹ and global fertilizer application of N to be 72.3 Tg yr⁻¹. Finally, Bouwman et al. (Bouwman et al. 2005) estimated N introduced as manures to be 81.5 Tg yr⁻¹ globally and N introduced as fertilizers to be 82.9 Tg yr⁻¹. Additionally, we present the results of a paper by Bouwman et al. (Bouwman et al. 2009), who estimated N introduced as manure and fertilizers as 101 and 83 Tg, respectively, and P introduced as manure and fertilizers as 17 and 14 Tg, respectively, all for the year 2000.

Our results, when aggregated to the global scale, compare quite reasonably with other existing global estimates (Table 2). Global estimates of N introduced as fertilizers range from 72.3 to 83 Tg yr⁻¹ in the other studies, which is higher than our estimate of 70.2 Tg yr⁻¹. Our lower estimate of N introduced as fertilizers is likely due to the fact that we used the IFA crop- and country-specific fertilizer rates instead of the broad FAO country-level consumption data utilized in the higher estimates of Van der Hoek and Bouwman (Van der Hoek and Bouwman 1999) (73.6 Tg), Sheldrick et al. (Sheldrick et al. 2002) (78.2 Tg), Boyer et al. (Boyer et al. 2004) (81.1 Tg), and Green et al. (Green et al. 2004) (78.3 Tg). Siebert (Siebert 2005) also utilized country- and crop-specific fertilizer rates, and his estimate of 72.3 Tg comes closest to our results. Indeed, for the 82 countries where both sources report data, total N applied according to IFA equals 62 Tg, while N consumption according to FAO is 72 Tg. This 10 Tg difference can explain the range of estimates in Table 2. Both Bouwman et al. results [82.9 (Bouwman et al. 2005) and 83 Tg (Bouwman et al. 2009)] are higher than our results, despite utilizing crop-specific fertilizer data from the IFA, similar to the methodology presented here. However, they used the IFA data only for determining the partitioning between crops and used FAO consumption data for the country totals (L. Bouwman 2009, personal communication). Published global estimates of P introduced as fertilizer range from 12.7 to 15 Tg yr⁻¹; our result of 14.3 Tg yr⁻¹ falls in between these estimates. Our estimates of nutrients introduced through manure are somewhat higher than the previously published estimates shown in Table 2—36% greater than the average of the published estimates for N and 37% greater than the average for P. Some of the increase in our estimates may simply be due to the approximately 31% increase in livestock between the mid-1990s dates for which the published estimates are relevant and our 2007 estimate. Note that all other estimates to which we compare our manure results are also of nutrients produced, and not the recoverable fraction, so that cannot explain why our results are higher.

Rates of N and P fertilizer application represented in our dataset may seem lower than those found in farm-level studies. For example, while our dataset shows a maximum global N application rate of 220 kg ha⁻¹ in Egypt's Nile Delta, Vitousek et al. (Vitousek et al. 2009) report an N application rate of over 500 kg ha⁻¹ of northern China. This apparent disparity is mainly an issue of scale and methodology; our data source, IFA reporting of *average* application rates at the national level, does

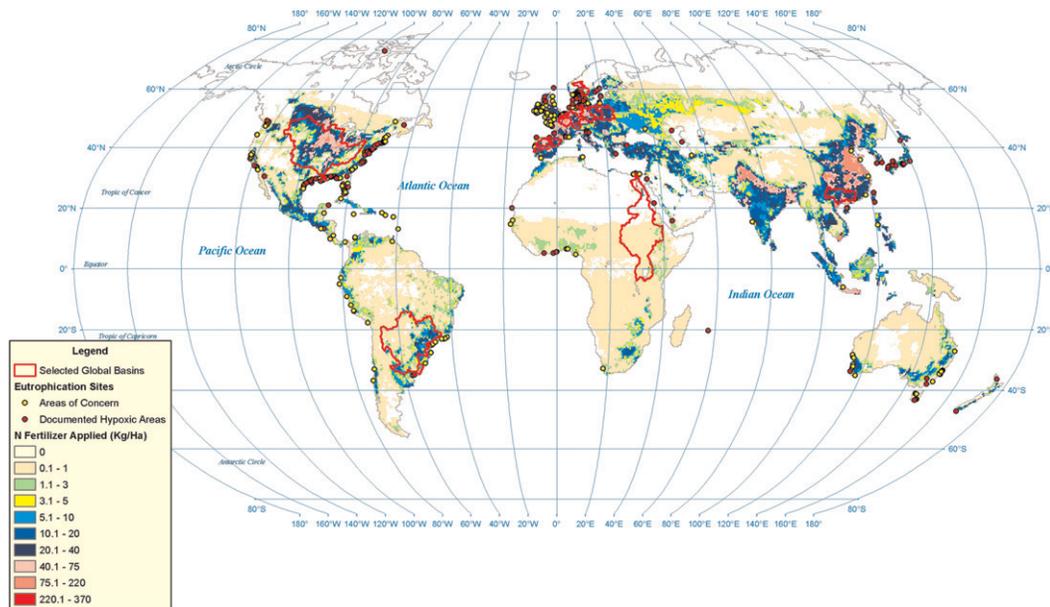


Figure 7. Global map of coastal hypoxic areas in relation to N application in fertilizers. Figure 2a is overlain with selected global basins that discharge into saline receiving waters (where nitrogen represents the dominant limiting nutrient) and location of documented hypoxic areas from Diaz and Rosenberg (Diaz and Rosenberg 2008).

not, by nature, capture extreme values. Also, our data represent averages over a 0.5° grid box, representing broad average patterns and inherently underestimating spatial variability. These data- and scale-related limitations are noted as an important caveat.

Global fertilizer application maps are presented in Figures 2a,b as a summation of all crops considered in this study. However, maps of crop-specific fertilizer application are only available for countries where crop-specific fertilizer application data were available (see IFA countries in Figure 1). For the remainder of the countries, national fertilizer consumption was distributed over a generic croplands map, as described in section 2. For this reason, global fertilizer use by crop is not presented at this time because of the gaps in reporting preclude creation of datasets with complete global coverage. We hope that identifying these data gaps, and how they limit the application of the IFA database, will bring attention to the need to improve national reporting of fertilizer statistics.

Our new spatial disaggregation of the rich IFA fertilizer-use dataset will provide new and interesting avenues to explore the impact of anthropogenic activity on ecosystems at the global scale. This dataset can be used to calculate nutrient budgets, model the impacts of nutrient management on crop growth and yield, and track the fate of nutrients from production/mining of mineral fertilizers through trade routes to their final uses. For example, examination of the location of documented hypoxic areas with respect to fertilizer use (Figure 7) indicates that these areas tend to be located downstream of basins with significant fertilizer application (Diaz and

Rosenberg 2008). North America's Mississippi River basin, Africa's Nile River basin, and several smaller European drainage areas stand out in this respect. Our datasets can also be used to enhance regional and global estimates of air quality and greenhouse gas emissions as well as serve as input to Earth systems models that include a complete nitrogen cycle.

Our spatially explicit estimation of nutrient application rates in fertilizer and production rates in manure also has implications for policies designed to improve soil quality or reduce nutrient runoff. We have provided evidence that a few hot spots are contributing to the majority of the water quality and runoff problems around the world. Identifying specific regions that have freshwater or estuarine eutrophication problems and linking those areas of high inputs via our spatially explicit nutrient budgets may allow policy makers to identify and target key areas in which to implement policies to decrease nutrient inputs or diminish runoff. Likewise, linking our estimates of nutrient inputs with maps of areas with naturally nutrient-poor soils can help decision makers direct nutrient enrichment policies toward areas where they are most needed and may be most beneficial. These new spatially explicit datasets, which provide a global picture of the distribution of fertilizer application and manure production rates across the globe, have a host of important implications for policy makers and scientists around the world.

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Datasets of fertilizer application and manure production for N and P are available for download at <http://www.geog.mcgill.ca/~nramankutty/Datasets/Datasets.html>.

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