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Global Opportunities to Increase Agricultural Independence Through Phosphorus Recycling

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Key Points:

- Many nations import mineral phosphorus (P) fertilizers to support agriculture but possess alternative, local, recyclable sources of P in manure and biosolids
- A global, subnationally resolved analysis revealed where manure-rich and populous cultivated areas occur and, in turn, where P recycling potential may be high
- Abundant P recycling opportunities exist in nations that have relied on fertilizer imports or had rising fertilizer demand, and these could be important to future agricultural independence

Supporting Information:

- Supporting Information S1
- Figure S1
- Figure S2
- Figure S3
- Figure S4
- Figure S5
- Table S1
- Table S2
- Table S3

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Abstract Food production hinges largely upon access to phosphorus (P) fertilizer. Most fertilizer P used in the global agricultural system comes from mining of nonrenewable phosphate rock deposits located within few countries. However, P contained in livestock manure or urban wastes represents a recyclable source of P. To inform development of P recycling technologies and policies, we examined subnational, national, and global spatial patterns for two intersections of land use affording high P recycling potential: (a) manure-rich cultivated areas and (b) populous cultivated areas. In turn, we examined overlap between P recycling potential and nation-level P fertilizer import dependency. Populous cultivated areas were less abundant globally than manure-rich cultivated areas, reflecting greater segregation between crops and people compared to crops and livestock, especially in the Americas. Based on a global hexagonal grid (290-km^2 grid cell area), disproportionately large shares of subnational "hot spots" for P recycling potential occurred in India, China, Southeast Asia, Europe, and parts of Africa. Outside of China, most of the remaining manure-rich or populous cultivated areas occurred within nations that had relatively high imports of P fertilizer (net P import:consumption ratios ≥0.4) or substantial increases in fertilizer demand between the 2000s (2002–2006) and 2010s (2010–2014). Manure-rich cultivated grid cells (those above the 75th percentiles for both manure and cropland extent) represented 12% of the global grid after excluding cropless cells. Annually, the global sum of animal manure P was at least 5 times that contained in human excreta, and among cultivated cells the ratio was frequently higher (median = 8.9). The abundance of potential P recycling hot spots within nations that have depended on fertilizer imports or experienced rising fertilizer demand could prove useful for developing local P sources and maintaining agricultural independence.

1. Introduction

Phosphorus (P) is an essential element in food security. The bulk of commercial P fertilizer currently used in global food production originates from nonrenewable phosphate rock mines (Chen & Graedel, 2016; Obersteiner et al., 2013) located in a handful of countries that control these reserves. Consequently, most countries are dependent on P fertilizer imports (Cooper et al., 2011; Obersteiner et al., 2013). Accessing recyclable sources of P fertilizer could be critical for optimizing the future global P system and maintaining some degree of agricultural independence at subnational, national, or regional levels. But in the current system, much P used in food production is ultimately lost to landfills (Chowdhury et al., 2014; Chowdhury & Chakraborty, 2016), coastal waters (Seitzinger et al., 2010), or inland waters (Beusen et al., 2016; Carpenter & Bennett, 2011) where it degrades water resources (Bennett et al., 2001; Powers et al., 2016; Smith & Schindler, 2009) and associated ecosystem services such as commercial fishing and recreation (MacDonald et al., 2016). Development of more efficient P recycling pathways (Childers et al., 2011; Metson et al., 2018) can help minimize P losses and provide a local recyclable P source (Cordell & White, 2013; Ulrich & Schnug, 2013; Withers, Elser, et al., 2015). Decisions about where and how to implement P recycling technologies and policies could be aided by enhanced understanding about the global distribution of potential P recycling hot spots, and their overlaps with P import dependency at the national level.

Nations differ widely in terms of recent P consumption trends and fertilizer trade dependencies (Cordell & White, 2014; Nesme et al., 2018; Webeck et al., 2015). These differences reflect dynamic and globally uneven P fertilizer production, consumption, export, and import, each of which could be linked to long-term motivations for recycling P. For example, many nations in Europe lack native phosphate rock deposits, which has led to import of P fertilizer for agriculture, although less additional fertilizer may be needed in soils that have already achieved high levels of P fertility (Bouwman et al., 2017; Withers, Sylvester-Bradley, et al., 2014). One indicator of P dependency is the ratio of net fertilizer P import (imports – exports) to total fertilizer P consumption (hereon, *fertilizer import ratio*). P fertilizer import ratios near 1.0 indicate countries where net P fertilizer import is equivalent to P consumption, negative values indicate net export of P fertilizer, and values near 0 indicate that import and export are nearly balanced. P import ratios are not currently viewed as drivers of management or policy but could foretell future vulnerabilities to rising fertilizer prices (Elser et al., 2014) or shifts in fertilizer access, which threaten agricultural independence. Under such scenarios, nations or regions with high P import ratios could have added motivations to recycle domestic P (Schipanski & Bennett, 2012). The P used by trade partners for food or animal feed (Lassaletta et al., 2014; MacDonald et al., 2015; Nesme et al., 2016) could also become a concern if partners acquire P from unknown or objectionable sources of phosphate rock.

Some of the most intense locations of P throughput occur where crop production is colocated with livestock (Bouwman et al., 2013) or people (Garnier et al., 2015; Morée et al., 2013; van Puijenbrook et al., 2018), and these areas have high P recycling potential. Where crop production occurs adjacent to livestock operations, application of P-rich manure provides a more circular P source to partially offset mineral fertilizer needs. While some degree of manure P recycling to croplands is common worldwide, it has not been fully optimized (Hanserud et al., 2017; Metson et al., 2016; Withers, Elser, et al., 2015) largely because many cereal or forage croplands are spatially segregated from livestock operations (MacDonald et al., 2011; Nesme et al., 2015). Consequently, transportation distance is frequently cited as a major economic and logistical barrier to recycling (Buckwell & Nadeu, 2016; Freeze & Sommerfeldt, 1985). Alternatively, for populated places colocated near crop production, P-rich agricultural amendments such as composted food waste, sewage-derived biosolids, or struvite precipitated from wastewater can be recovered from waste streams for localized reuse (Chowdhury et al., 2017; Mayer et al., 2016). Enhanced recovery of P from secondary sources such as manure and urban waste could enable nations to sustain their agricultural production with less reliance on imported fertilizers (Cordell et al., 2011; Koppelaar & Weikard, 2013; Mihelcic et al., 2011) while also lengthening the lifespan of existing mineral P reserves nationally and globally. Moreover, P recovery helps to address not only challenges of food security but water resource conservation as well, if pollution associated with fertilizer production is avoided and P discharges from agricultural and urban systems are reduced (Trimmer et al., 2017).

To understand the global distribution of P recycling potential, here we focus on (1) manure-rich cultivated areas and (2) populous cultivated areas. In these areas, multiple land uses occur in proximity and the P in manure or urban waste may provide local, recyclable alternatives to traditional mineral fertilizers. We ask (A) How are manure-rich and populous cultivated areas (i.e., where P recycling opportunity is high) distributed globally? and (B) How do these hot spots for recycling potential intersect with national P fertilizer import dependence, where vulnerability to fertilizer trade dynamics may be highest? To address the questions, we used subnational data on cropland extent, livestock density, and population density along with nation-level data for P fertilizer flows and P excretion factors by animals. For urban systems globally, considerable uncertainty exists for per capita P flows as human excreta and household and industrial wastes, so we used population density as an indicator of the potentially recoverable flows and then in discussion we explore possible conversions to P mass units. We expected that P recycling potential would be imbalanced both within and across nations, especially within larger nations where land availability permits spatial segregation of croplands, people, and livestock. We also hypothesized that the global distribution of manure-rich cultivated areas would be distinct from that of populous cultivated areas, partly due to disproportionate human settlement near coasts (Kummu et al., 2016). These geographic patterns may foretell distinct P futures as societies address spatially uneven options for P use and agricultural independence.

Table 1
Data Sets Used in the Analysis

Data category	Description (units)	Data source	Reporting year(s)	Spatial resolution
Global hexagonal grid[a]	Contiguous, nonoverlapping hexagonal grid cells (unitless)	Derived in *R* using package *dggrid* (Barnes, 2016)	—	290 km^2, mean internode spacing =18.3 km, side length = 10.5 km
National phosphorus	Fertilizer import ratio, calculated as ratio of *net P import*: *P consumed* (mass per mass) where *net import* = *import–export*	FAOSTAT (Food & Agricultural Association of the U.N. 2016)	2010–2014	National
	Trend in fertilizer P consumption, calculated as ratio of consumed P mass *2010–2014*: *2002–2006*	FAOSTAT (Food & Agricultural Association of the U.N. 2016)	2010–2014, 2002–2006	National
Subnational land use	Cropland extent (% of landscape as cropland or crop mosaic)	Globcover 2009 (Arino et al., 2012)	2009	10 arc second (~300 m at equator)
Subnational livestock	Density of animals (number per square kilometer) by animal type including cattle, pigs, chickens, sheep, and goats	Gridded livestock of the world (Robinson et al., 2014)	2006	3 arc min (~5 km at equator)
Subnational population	Human population density (people per square kilometer)	Gridded population of the world (GPW v4, Center for International Earth Science Information Network 2016)	2010	30 arc sec (~1 km at equator)
Subnational Phosphorus	P in manure production ($\text{kg P}\cdot\text{km}^{-2}\cdot\text{year}^{-1}$)	Calculation based on livestock densities and P excretion factors from Bouwman et al., 2017	2006	290 km^2 (same as global grid)

Note. For all subnational variables, we used the mean value within each hexagonal grid cell.
[a] Supporting computations for a larger grid cell size (23,000 km^2) were also explored (see the supporting information).

2. Materials and Methods

We analyzed subnational, national, and global patterns of P recycling potential, with emphasis on manure-rich and populous cultivated areas. Gridded global data sets for cropland extent, livestock density, and human population density were integrated with Food and Agriculture Organization (FAOSTAT) nation-level data (Table 1) on P fertilizer import, export, consumption, and production, along with animal P excretion factors. Shares of P recycling "hot spots" (where livestock and/or human populations are near croplands) within each nation were tabulated and analyzed to understand global distributions and intersections with P fertilizer import and consumption.

2.1. Subnational Data

To integrate multiple subnational data sets derived at different spatial resolutions, we generated global hexagonal grids with consistent grid cell areas across latitudes using the *dggrid* package (Barnes, 2016; Sahr, 2011) in the platform *R* (R Core Team, 2016). Two different hexagonal grid cell sizes were considered. This work focuses on the finer resolution grid, whose grid cells had a mean side length of 10.5 km, which loosely corresponds to an "in-town" transport distance for recyclable P (Paudel et al., 2009). Each hexagonal grid cell had a mean area of 290 km^2 and a mean internode spacing of 18.3 km. The second coarser grid had a mean side length of 95 km (mean hexagon area of 23,300 km^2 and mean internode spacing of 165 km), which was large enough to encompass megacities such as London and Paris along with peri-urban areas but small enough to maintain subnational resolution in relatively small nations. In general, calculations performed on the coarser grid produced similar results to those of the finer grid, and we report relevant similarities and differences. For a minority of hexagonal grid cells, slight deviations in the dimensions were mathematically necessary to avoid overlapping cells and gaps over the world's surface (Barnes, 2016).

Independent globally gridded data sets on cropland extent, livestock density, and human population density were used to summarize P-associated features of each cell in the global hexagonal grid (Figures S1 and S2 in the supporting information). For cropland calculations, we used the GlobCover cropland data classes (base year 2009) determined from MERIS fine resolution (300 m) remotely sensed data (Arino et al., 2012). We included any lands classified as irrigated cropland, rainfed cropland, mosaic cropland (classes 11, 14, and 20) or mosaic vegetation (class 30, which includes 20–50% cropland). For livestock density calculations, we used the Gridded Livestock of the World data set, which is based on statistical modeling of agricultural censuses and gridded land use and land cover (Robinson et al., 2014; base year 2006). Number of head per grid cell was calculated for each animal type including cattle, chickens, sheep, and goats. Total manure P production in each grid cell was calculated by summing the contributions from each animal type, using animal-specific and nation-specific P excretion factors from Bouwman et al. (2017). For cattle we used 16.6 kg P per head year^{-1} in Canada, United States, and Japan, 13.1 kg P per head year^{-1} in the other OECD (Organization for Economic Cooperation and Development) countries, and 8.75 kg P per head year^{-1} in the remaining countries (Bouwman et al., 2017). For other animals we used 1.8 kg P per head year^{-1} for pigs, 0.1 kg P per head year^{-1} for chickens, and 1.5 kg P per head year^{-1} for sheep and goats for all countries (Bouwman et al., 2017). Livestock head and annual P excretion varied widely across the global grid (Table S1). These values are thought to represent approximate upper bounds for the fluxes of manure P available for P recycling, as not all of that manure can be readily collected. For human population, we used the Gridded Population of the World data set (year 2010) which is based on population censuses and spatial administrative boundaries (Gridded Population of the World version 4, Center for International Earth Science Information Network, 2016). Changes in cropland, livestock, human population density, and their associations were assumed to be small over the available data years (2006, 2009, and 2010). Mean values for every variable were calculated for each grid cell using *QGIS*.

2.2. National Fertilizer Data

We used nation-level P fertilizer data from FAOSTAT including import, export, agricultural use, and production for the most recent available years (2002–2014). FAOSTAT data were downloaded on *26 February 2018*. Fertilizer data are reported annually, and we took the nation-specific means for each budgetary term over two different five year intervals (2010–2014 and 2002–2006); these years deliberately exclude the global food crisis of 2007/2008 when the global phosphate rock price spiked by 400% (Chowdhury et al., 2017) and nation-level consumption often deviated from the medium-term trend. A small number of countries had data gap years, requiring that the mean be calculated over fewer years.

Import ratios, an indicator of fertilizer P import dependency, were calculated as *net import*: *consumption*, where *net import* = *import* – *export*. Recent fertilizer P consumption trends were summarized by calculating a consumption ratio of the 2010s to 2000s (2010–2014:2002–2006). Calculations involving P import ratios and consumption trends were conducted directly on Food and Agriculture Organization data, prior to disaggregation within the global grid. In cases where grid cells overlapped multiple countries, the nation representing the largest share of the grid cell was assigned to the whole cell using administrative data from *Natural Earth*. A minority of nations lacked P import or P consumption data (Figure S3)—mostly small island nations, followed by Africa and Middle East—and these were excluded from P import ratio calculations. Nations that lacked P export data were assumed to have zero gross P export in these calculations. All nations had nonzero import ratios.

2.3. Grid Cell Classifications

Grid cells were classified based on percentile breaks in the subnational data sets. Global percentiles for each variable (i.e., cropland extent, manure P production, and population density) were calculated after excluding cells with zero cropland extent, which removed areas of desert, high latitude, and rugged terrain. For the breaks, we used the 90th (highest value), 75th, 50th, and 25th percentiles. Grid cells were more specifically classified as follows:

1. *Cultivated areas* were those grid cells falling above the 75th percentile for cropland extent, or 60% of the grid cell area as crops (Table 2).
2. *Manure-rich areas* were those grid cells falling above the 75th percentile for P manure production, or 280 kg P/km^2.
3. *Populous areas* were those grid cells falling above the 75th percentile for population density, or 58 people per square kilometer.
4. *Manure-rich cultivated areas* were those grid cells falling above the 75th percentile for both cropland extent and P manure production.
5. *Populous cultivated areas* were those grid cells falling above the 75th percentiles for both cropland extent and human population density.

Table 2
Summaries for Subnational Variables

Variable	Data year	Median	90th percentile	75th percentile	25th percentile	Max	Min
Cropland Occurrence (%)	2009	21	90	60	3.1	100	0
Annual manure P production (kg P/km^2)	2006	95, *86*	610, *570*	280, *260*	21, *19*	130,000	0
Human population density (people/km^2)	2010	13	200	58	2.1	41,000	0

Note. Percentiles (90th, 75th, 25th, 10th) were calculated across all cells in the global grid. Alternative estimates of manure P (italics) were calculated using a uniform P excretion factor for cattle worldwide (8.75 kg P per head year^{-1}).

In addition, very cultivated areas, manure-rich cultivated areas, and populous cultivated areas were identified using the 90th percentile values, which were as follows: cropland 90%, human population density 200 people per square kilometer, and manure P production 610 kg P/km^2. Global medians: cropland 21%, manure P production 95 kg P/km^2, and human population density 13 people per square kilometer.

Using the above grid cell classifications, we then explored the abundances of manure-rich cultivated areas and populous cultivated areas within the whole global grid, within individual nations, and within nation groups. The nation groups of interest to us were (1) nations that had higher/lower/intermediate fertilizer P import ratios and (2) nations that had increasing/decreasing/no-change trends in recent P consumption (i.e., ratio of consumption, 2010s:2000s). For P import ratios, there was a natural break (inflection in the frequency distribution) in the data around 0.4, so we explored the fraction of grid cells falling in nations with P import ratios <0.4 (lower import dependency) and ≥0.4 (higher import dependency). Less than 3% of cultivated grid cells occur within nations where the import ratio could not be calculated, due to a lack of national P consumption or import data. For recent fertilizer consumption trends, we explored the fraction of grid cells falling in nations with the following trends: <10% change in either direction, ≥10% decline, 10–49% increase, or ≥50% increase).

3. Results and Discussion

3.1. Manure-Rich and Populous Cultivated Grid Cells as Hot Spots for P Recycling

Our results indicate that both broad types of potential P recycling hot spots, manure-rich cultivated grid cells (75th percentiles; >60% cropland and >280 kg P/km^2 annually within hexagons of side length of 10.5 km) and populous cultivated grid cells (>60% cropland, >58 people per square kilometer) occurred on every continent besides Antarctica. The two types of hot spots were similarly distributed in Eurasia but had distinct distributions over much of the rest of the world. Thus, while a considerable amount of the world's food production occurs in relatively remote croplands and rangelands (Ellis & Ramankutty, 2008), many grid cells had combinations of high cropland extent, manure P production, and population density, making them potential hot spots for local P recycling via reuse of manure, biosolids, or other recovered substances that contain P, such as food waste or compost.

Manure-rich cultivated grid cells were most abundant in India, China, Southeast Asia, Europe, and Brazil (Figure 1, green shades). Smaller patches occurred in central and east Africa, central United States, and Central America. Very manure-rich cultivated grid cells (>90th percentiles; >90% cropland and >610 kg P/km^2) accounted for 3.2% of the global grid and were particularly abundant in India and China (Figures 1 and S4). These areas offer opportunities for efficient use of recoverable manure (Kellogg et al., 2014; Sheldrick et al., 2002) to partially offset P fertilizer requirements. Grid cells with high manure production (75th percentile) and low to intermediate cropland extent (<75th percentile; blue shades in Figure 1) likely have manure P surpluses, and these occupied 13% of the global grid—particularly Southeast Asia, Japan, northern Europe, and United States. However, many regions of manure P surplus were segregated from crop P demand, presenting a significant management challenge for P recycling. Places with lower manure production (<75th percentile) and higher cropland extent (75th percentile; red shades in Figure 1) were located mainly in western Russia, the interior of China, Indonesia, western Africa, and Brazil. In many regions, rising densities of animals over the past 20–40 years has greatly increased the potential supply of P from recoverable manure and may continue in association with rising meat and poultry consumption (Metson et al., 2012; Metson et al., 2014; Metson et al., 2016). Challenges remain for understanding the fraction of manure P currently recycled into crop production, as well as the fate of residual soil P (Bouwman

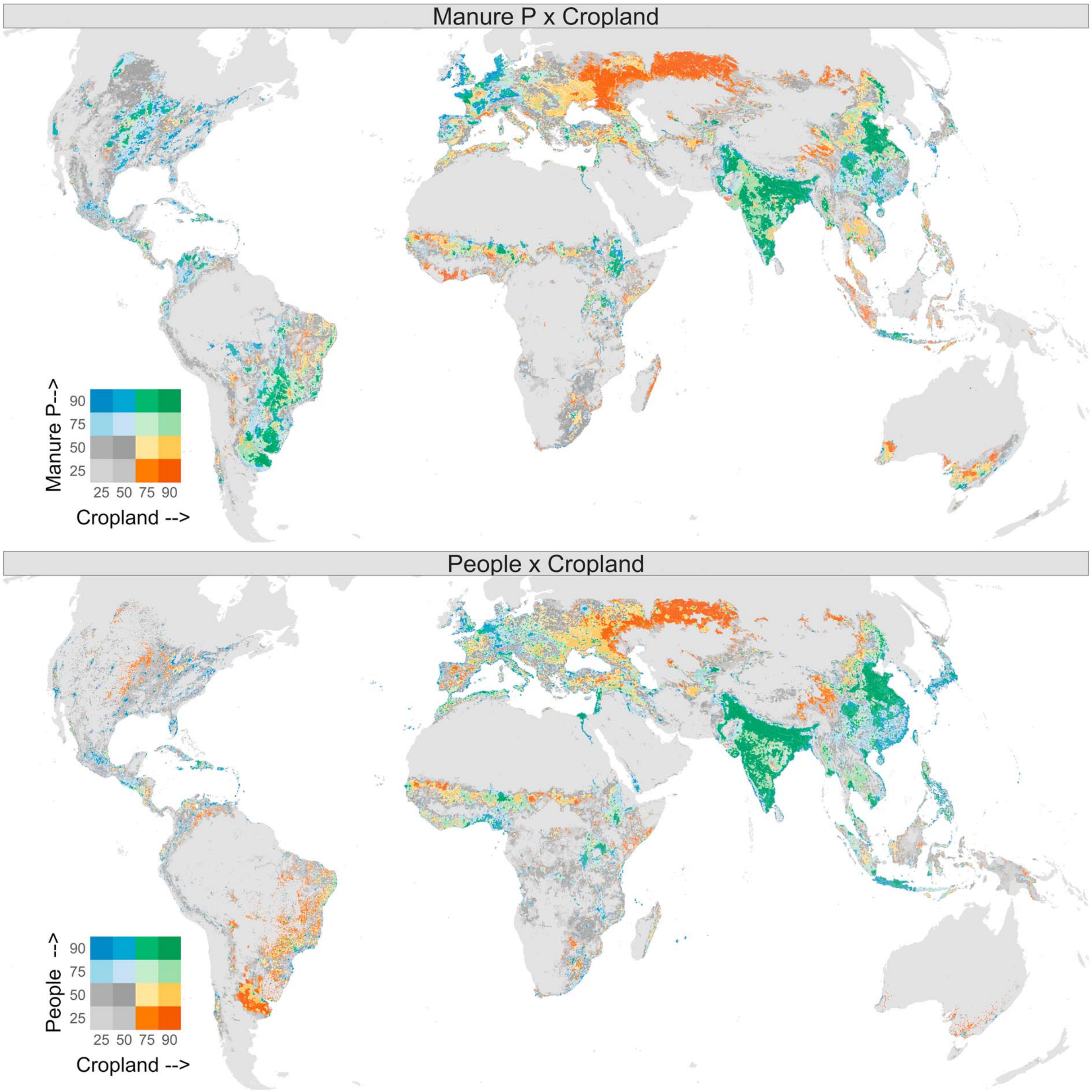

Figure 1. Global distribution of manure-rich cultivated areas and populous cultivated areas. (top) Green shades exceed the global 75th percentiles for manure as kilograms of phosphorus per square kilometer and cropland extent as % grid cell area. (bottom) Green shades exceed the global 75th percentiles for human population density as number per square kilometer and cropland extent as % grid cell area.

et al., 2017; Sattari et al., 2012); Bouwman et al. (2017) calculated that circa 2013, 8 TG/year of P was potentially applied to croplands via manure compared to 17 TG/year applied via mineral P fertilizer. Questions about finer-scale heterogeneity of animal densitites (i.e., within a grid cell) and associated manure P production also remain difficult to answer with available public data. But technology and policy solutions are being pursued to harness more value from recoverable manure (Kellogg et al., 2014) and maximize corecovery of nutrients and energy through processes such as anaerobic digestion (Bloem et al., 2017; Liu et al., 2017; Withers, Elser, et al., 2015; Withers, van Dijk, et al., 2015).

Figure 2 demonstrates the global distributions of manure-rich cultivated versus populous cultivated lands are indeed distinct, but there were overlaps in portions of Europe and Asia. Most of the world's populous cultivated areas occurred in India, China, Southeast Asia, Europe, central and East Africa, and Central America, consistent with previous studies that were not P focused (e.g., Ellis & Ramankutty, 2008; Thebo et al., 2014). In China, India, and Southwest Asia, populous cultivated areas co-occurred with manure-

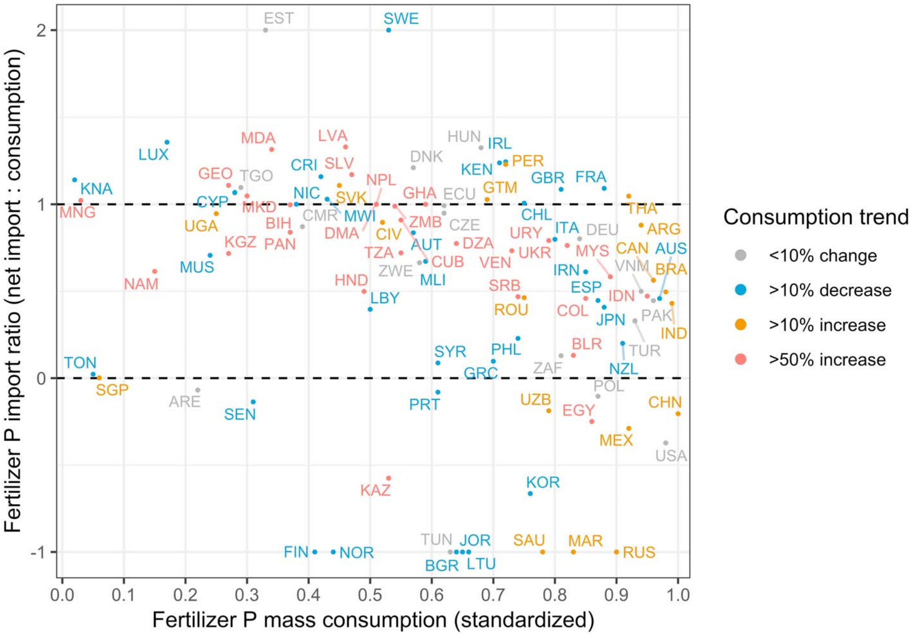

Figure 2. National fertilizer P import ratios (2010–2014) ordered by national consumption. The import ratio, an indicator of fertilizer P import dependency, is defined as net P fertilizer import: consumption, where net import = gross import − gross export. P mass consumption (x-axis) was rescaled in terms of percentiles. Color key indicates recent P consumption trend (2010s: 2000s, with 2007–2009 deliberately excluded). Nation abbreviations are listed in Table S2. Outlier nations with import ratios above 2 or below −1 are plotted as 2 or −1 to aid visualization. Nations with no reported P export were excluded from this plot.

rich cultivated areas, whereas segregation of manure-rich and populous cultivated areas was apparent in the Americas (both North and South), which had a disproportionately small share of populous cells (>58 people per square kilometer; Figure 1 and Table 2). Some of these locations nonetheless offer opportunities for using recovered byproducts from sewage or food waste to offset mineral P fertilizer requirements.

Globally, 12% of the hexagonal grid cells were occupied by manure-rich cultivated areas, corresponding to 49% of cultivated areas worldwide. A slightly smaller portion (11%) of the global grid was occupied by populous cultivated areas, corresponding to 45% of cultivated areas worldwide. Similarly, very populous cultivated areas (>90th percentiles; >90% cropland and >200 people per square kilometer) accounted for an equal fraction of the global grid (3.2%) as very manure-rich cultivated cells. Urban P demand, and thus quantities of potentially recyclable urban P, vary considerably worldwide with differences in diet, food waste generation, P detergent use, industrial P use, and other factors. Integrating these multiple urban P flows into a complete global grid, in P units, is a task for future research, but human excreta provides a starting point. Global analyses by Mihelcic et al. (2011) and Chen and Graedel (2016) report 0.49 and 0.46 kg P per person as excreta, similar to the dietary intake required to achieve "healthy function," 0.44 kg P per year (Cordell et al., 2009). Assuming that each person excretes 0.5 kg P per person annually, our thresholds for human population density of 13, 58, and 200 people per square kilometer (median, 75th, and 90th percentiles) translate to excreta values of 6.5, 29, and 100 kg P/km^2. The corresponding manure P percentiles were 5 to 10 times higher, and 74% of the cultivated grid cells had a manure:human P ratio of 25 or higher (median = 8.9), though 6.4% of the cells had a manure:human P ratio <1.0. These results indicate that across most grid cells, recycled manure represents a larger potential P supply than recycled human excreta. However, the role of urban P recycling could be locally important (Trimmer & Guest, 2018). This still leaves questions of feasibility for distinct P sources, as human excreta or centralized manure from dairy or animal feeding operations can be easier to collect than manure from openly grazed animals, while the presence of pathogens, plastics, and pharmaceuticals can create additional management complexities.

Areas with higher population density (75th percentile) and low to intermediate cropland extent (<75th percentiles; blue shades in Figure 1) may have abundant urban wastes but relative shortages of agricultural P demand and were scattered across Southeast China, Southeast Asia, coastal areas of Europe, and parts of Central America, East Africa, and the Middle East. P demand for urban agriculture, greenhouses, and landscaping in such areas could be considerable in the future, but these remain largely unquantified regionally and globally. P recycling in areas with intermediate population density (50–74th percentiles) and higher cropland extent (75th percentiles; red shades in Figure 1) were located mainly in Western Russia, Southern Europe, Argentina, and West Africa and could become more important sites of urban P recycling with human population growth. While much recent human population growth has occurred in coastal cities that are relatively distant from croplands, inland population growth is projected to continue as well. As populations grow or relocate (Kummu et al., 2016), reuse of urban P from sludge byproducts or food waste could become more attractive (van Puijenbrook et al., 2018), enabling societies to use the P imported in commodities other than fertilizer. In rural croplands, high transportation costs remain an obstacle for recycling of urban P; however, processing of recovered urban P into commercialized and/or dry forms (e.g., struvite) could allow transport over larger distances.

3.2. National Fertilizer Import Dependency and Rising Agricultural P Demand as Motivations to Recycle P

Turning to the national scale, we confirmed that most nations were net importers for fertilizer P. The median import ratio during 2010–2014 was 0.66, and 67% of nations had import ratios ≥ 0.4 (Figure 2), indicative of a relatively high fertilizer P import dependency. For 2010–2014, four nations with high P fertilizer use (China, India, Brazil, and United States) accounted for 66% of world P fertilizer use (as P_2O_5) as well as 72% of world P fertilizer production. P fertilizer consumption in Brazil and India was considerably larger than domestic P production (Table S2, Keil et al., 2017). Similarly, many other agriculturally developed nations and much of Europe depend almost entirely on imports to supply P fertilizer (Nesme et al., 2016; Schoumans et al., 2015). Among the top 50 P consumer nations (agricultural P use $>6.5 \times 10^6$ kg per year), nations with the highest P import ratios (≥ 0.9) included (in order of decreasing national consumption) Thailand, France, Great Britain, Chile, Peru, Ireland, Kenya, Guatemala, Hungary, Ecuador, Ghana, Denmark, and Sweden. Other major P consuming nations with intermediate-to-high import ratios (≥ 0.4) included India, Brazil, Australia, Canada, Pakistan, Indonesia, Argentina, Vietnam, Malaysia, Japan, Spain, and Germany. On the opposite end of the spectrum, the lowest P import ratios occurred in Morocco and Russia (Table S2) due to domestic P mining, production, and export. These inequalities in fertilizer import, production, and consumption define the modern global P system, its vulnerabilities, and possibly, motivations to recycle in a more P-limited future.

Recent increases in P fertilizer consumption occurred largely in economically developing nations that had P import ratios ≥ 0.4. Rapid rises in fertilizer P consumption (defined as $>50\%$ increase between the 2000s and 2010s) occurred in 36% of nations, including Indonesia, much of Africa, Venezuela, and Colombia. A rise of 10–49% occurred in 16% of nations, including China, Brazil, India, Argentina, Canada, and Russia. Increases in fertilizer use represent a step toward closing yield gaps in certain locations (Mueller et al., 2012; Simons et al., 2014) but as yield gaps close and soils approach P saturation, the risk of P losses and associated water quality degradation can rise, necessitating adaptive nutrient management. Another 35% of nations had a decline of $\geq 10\%$, including much of Europe, Australia, Japan, and Chile, where food production has been maintained through higher P use efficiencies or incorporation of residual soil P into crop production (Macintosh et al., 2018; Withers, van Dijk, et al., 2015). The remainder experienced $<10\%$ change, including United States. These nation-level estimates of P use and trade are based partly on self-reporting and should be interpreted with caution, along with P import ratios. Several nations had P import ratios >1, which was somewhat surprising as it implies stockpiling of unused P if the import, export, and consumption values are unbiased. A comprehensive assessment of uncertainty, reporting errors, and differences in P tracking methods among nations would likely be valuable but is beyond the scope of this analysis. We interpret these P import ratios as approximate indicators of P import dependency. Overall, recent P consumption dynamics vary considerably among nations, reflecting diverse combinations of mineralogy, agricultural history, wealth, and P management.

3.3. Counts of Manure-Rich and Populous Cultivated Grid Cells, by Nation

China is a major producer and consumer of fertilizer P (Sattari et al., 2014) and had the largest shares of both manure-rich and populous cultivated areas, accounting for $>17\%$ and 20% of the world totals, respectively (Figure 3). Recent estimates of China's economically exploitable phosphate rock reserves, like United

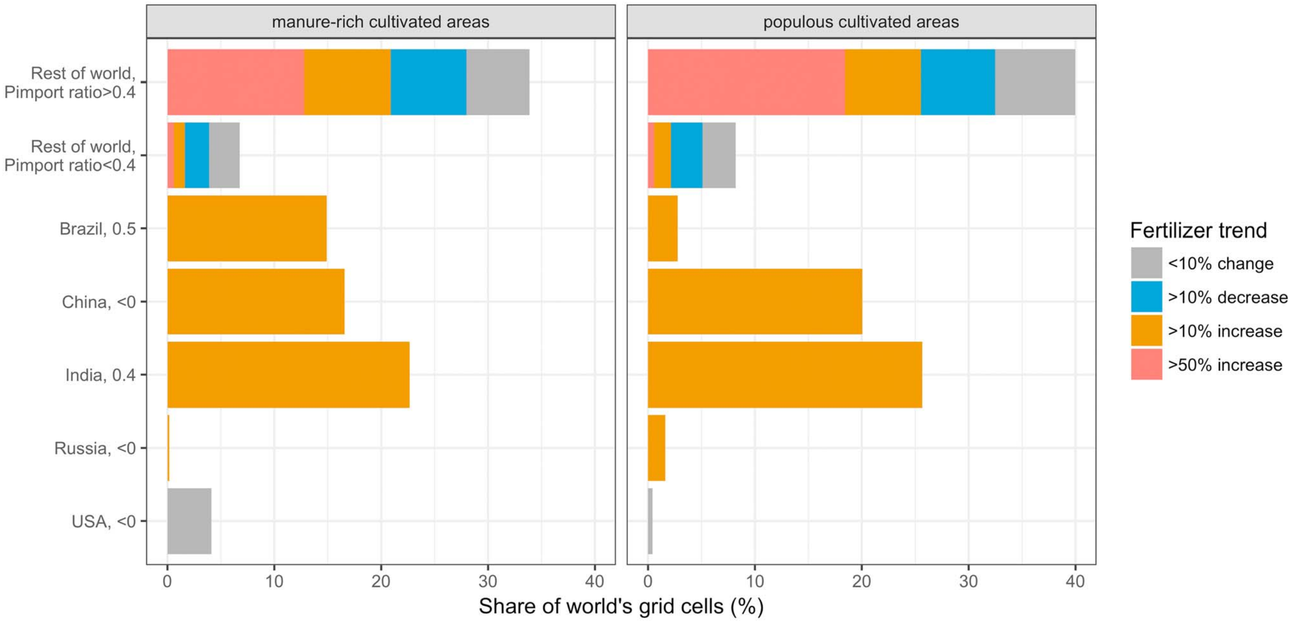

Figure 3. Shares of manure-rich cultivated areas and populous cultivated areas (grid cells that were above the 75th percentiles) located within five large nations (Brazil, China, India, Russia, and United States) and rest of world (decomposed in Figure 4). Fertilizer P import ratios indicative of fertilizer P import dependency are labeled at left. Colors indicate P fertilizer consumption trends between the 2000s and 2010s.

States, are equivalent to about 25–35 years of the domestic agricultural P use at current rates (Vaccari et al., 2018). Other P-producing nations excluding Morocco may face similar planning horizons, and the considerable uncertainties for phosphate rock reserve quantities, exploitability, and future price provide added reasons to pursue P recycling options.

A central result of our analysis was that most manure-rich cultivated areas were located within nations that had relatively high P import dependency (P import ratios ≥0.4), amounting to 72% of world total. 23% of these manure-rich cultivated cells were located in India and 15% in Brazil, which had P import ratios of 0.4 and 0.5, respectively. Likewise, 68% of populous cultivated areas were located within nations with higher P import ratios (>0.4), of which India accounted for 25%, and Brazil 3%. The prevalence of potential P recycling hot spots within nations that currently depend heavily on imported P fertilizer suggests that domestic P alternatives (e.g., manure) could have an important role in agricultural independence. Knowledge of crop P demands and soil P surpluses would aid future investigations that delineate where P recycling has already occurred and where unharnessed P recycling potential remains.

Many nations with high P import ratios (≥0.4) have simultaneously experienced rapid increases in P fertilizer consumption (≥50% increase between the 2000s and 2010s) and a disproportionately large share of populous cultivated areas, about 18% of the world total, fell within these nations. These rapidly transitioning P importer nations included Nigeria, Indonesia, Ethiopia, and Congo (Figure 4; see Table S2 for nation codes). Another 7% of populous cultivated areas fell within smaller nations that experienced moderate rises in fertilizer consumption (10–49% increase), including Thailand, Uganda, and Ivory Coast. Likewise, a considerable fraction of the manure-rich cultivated areas also fell in P importer nations with rising fertilizer P demand, such as Argentina, Ukraine, and once again Indonesia, Nigeria, and Thailand.

Relative to the overall number of cultivated cells in each nation, abundances of populous and manure-rich cultivated areas varied (Figure 4), a further indication that manure-based and urban-based P recycling opportunities are often imbalanced within a given nation. Disproportionately low shares of populous cultivated area occurred in Argentina, Ukraine, Turkey, and Mali. Multiple P import-dependent nations lacked increases in fertilizer P consumption, such as Turkey, which contained 1.6% of the world's manure-rich cultivated areas also notable shares of both manure-rich and populous cultivated areas (>1%) were found in Nigeria, Pakistan, Ethiopia, France, Myanmar, and Poland. In such areas, recovering P from secondary

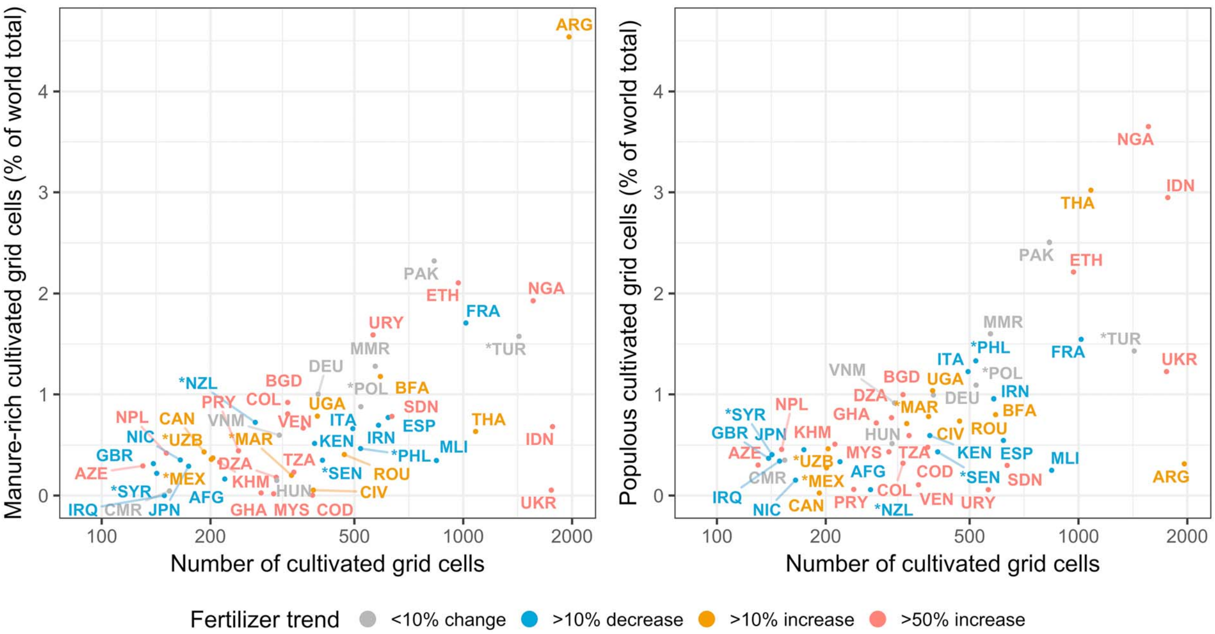

Figure 4. Rest of world (excludes Brazil, China, India, Russia, and United States; see Figure 3) variation in the abundance of manure-rich and populous cultivated areas relative to the number of cultivated cells in each nation. Color key indicates recent P fertilizer consumption trend (2010s: 2000s): red = ≥50% increase, maize = 10–50% increase, blue = ≥10% decrease, and gray = <10% change. Nation abbreviations are listed in Table S2. The few nations with P fertilizer import ratios <0.4 are indicated with asterisk. Plots are restricted to nations that had at least five cultivated grid cells.

sources such as manure and urban waste could enable nations to increase their agricultural independence under growing P demand, without increasing fertilizer imports or depleting mineral P reserves (Van Vuuren et al., 2010). These factors could be important for sustaining or expanding food production, particularly in locations where access to affordable, high-quality P fertilizer has been historically limited or where manure P represents a considerable fraction of the agricultural P budget. Construction of complete P budgets at subnational and national levels remains a challenge. In a recent nation-level analysis by Nesme et al. (2018), the highest gross exporters of P in agricultural products (Mg P per year, as of 2011) were United States, Brazil, Argentina, India, Australia, Canada, France, and Germany; except for United States, these countries all had relatively high P fertilizer import dependency.

3.4. Implications and Future Challenges

Food imports have allowed societies to overcome local limits to growth (Porkka et al., 2017) but often with a loss of agricultural independence; the same can be said for imported P fertilizer. During the long period of relatively stable fertilizer markets between World War II and the mid-2000s, the marginal costs of P fertilizer in economically developed nations were relatively stable (Mew, 2016) and low compared to the value of agricultural produce. These conditions enabled the historic surge in global P fertilizer production and trade, and high P import dependency was not a major consideration in agricultural planning. However, concern about finite and globally uneven geological P reserves has grown, along with recognition of phosphate as a strategic mineral. In 2008, the global economic crisis was associated with price spikes for commodities and P fertilizer (Elser et al., 2014), leading to a pronounced decrease in P fertilizer consumption in many countries (Schoumans et al., 2015). Nations such as France, Italy, and Japan provide noteworthy examples where P fertilizer consumption did not immediately return to pre-2008 levels (Table S4) yet crop yields were sustained (Sattari et al., 2012), likely due to use of residual soil P, although use of other fertilizer reserves cannot be completely ruled out. This raises the possibility that socioeconomic disruptions may contribute to lasting agronomic, technological, institutional, or social reorganization that in turn alters P use from mineral or recovered sources, necessitating analyses of recoverable P worldwide.

In several regions, the spatial distributions of human population and animal agriculture have become more concentrated in recent decades. This trend could be a double-edged sword for P reuse, creating more recoverable P over smaller areas, but longer distribution distances to crop P users (Metson et al., 2016). Meanwhile, recent trajectories for subnational P use are understood for subsets of the globe, while research on the full global heterogeneity and dynamics remains a challenge, particularly for recycled P flows and social factors (e.g., cultural norms, regulations) that affect of P use. The fact remains that prior P research was dominated by biophysical studies of fluvial transport (e.g., Mayorga et al., 2010; Seitzinger et al., 2010) and soil pools (e.g., Ringeval et al., 2017; Sattari et al., 2012; Zhang et al., 2017), substance flow and mass balance studies at coarse national or continental resolution (Bai et al., 2016; Mihelcic et al., 2011; Morée et al., 2013; Seyhan, 2009; Van Dijk et al., 2016), and finer-scale budgets of catchments and regions that lack global completeness (e.g., Powers et al., 2016; Worrall et al., 2016). Future global and subnationally resolved analyses of P, recycling fluxes, and options and constraints linked to economics, policies, land management, and regulatory complexities (e.g., legality of transport across jurisdictions and transfer permits) could accelerate development of spatially prioritized plans for P use and food security.

In terms of P recycling, where can the most impact be made? Figures 1 and 3 provide new information about P recycling potential at subnational to global levels. Wealthier nations of Europe and North America possessed a relatively small share of the "hot spot" grid cells for P recycling potential worldwide, suggesting that implementations would be needed elsewhere to meaningfully impact the global P system. India provides one such case where landscape designs provide expansive opportunities for localized P recycling due to colocated manure, croplands, and people, some of which have already been widely implemented through traditions of waste reuse. This invokes the concept of a P recycling gap—the difference between current P recycling rates on the ground and some upper limit for P recycling potential—which remains a frontier. Several smaller clusters of P recycling potential were located in developing and transitioning nations, in particular Africa, where P systems (and likely P recycling potential) and socioenvironmental contexts are not identical (Metson et al., 2018) and continue to change. For grid cells that have low densities of livestock, people, or cropland, P recycling may still be facilitated through transport, especially if waste processing steps can concentrate or pelletize the P; however, Figure S5 indicates that the general locations of P recycling hot spots (green cells) did not change dramatically with a nearly 100-fold larger grid cell size (side length = 95 km and mean internode spacing = 23,300 km^2) was used, suggesting that even longer transport distances may be required to open up new areas of P recycling potential. Understanding of the trajectories for key agricultural and urban features at multiple spatial scales (e.g., agricultural land use, sewerage connectivity, and access to mineral fertilizer) could facilitate planning that accounts for the shifting abundances and types of P recycling opportunities present.

In this work, we focused on manure-rich and populous cultivated areas (Figures 1, 3, and S4) where P recycling potential is high, through recycling of P in wastewater (Mayer et al., 2016; Metson et al., 2016; Mihelcic et al., 2011), integrated livestock-cropping systems (Costa et al., 2014; Metson et al., 2012; Withers, van Dijk, et al., 2015), and recycling of P in food waste (Cooper & Carliell-Marquet, 2013; Koppelaar & Weikard, 2013; Metson et al., 2016). However, these are not the only options for alleviating P import dependency and satisfying agricultural P demand. Other options include the following: closer matching of fertilizer P application with crop needs (Withers, Jordan, et al., 2014); biotechnological reductions in P requirements of plants and animals (Gaxiola et al., 2011; Kebreab et al., 2012); reduction of P-containing wastes such as wastewater, food waste (Baker, 2011), and agricultural runoff (Schoumans et al., 2015); and facilitated crop uptake of legacy P stores already in soils (Bouwman et al., 2017; MacDonald & Bennett, 2009; Sattari et al., 2012). In some areas, spatial segregation of the sites of P surplus and P deficit remains a challenge for recycling P in large quantities. However, use of local recycled P sources can minimize the costs of distribution over long distances and help avoid regulatory entanglements associated with transporting commodities or wastes across geopolitical or management boundaries.

Where dense human populations, animal populations, and croplands occur adjacently, many large P flows converge within a relatively small locus. These areas disproportionately influence the modern global P system and thus are hot spots for not only P recycling potential but also global impact as we approach limits of food production and other critical functions of the biosphere (Cordell et al., 2009; Steffen et al., 2015). International coordination and recognition of local contexts could reveal shared P recycling solutions that can be scaled worldwide to optimize the global P cycle.

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