Agronomic phosphorus imbalances across the world's croplands

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Increased phosphorus (P) fertilizer use and livestock production has fundamentally altered the global P cycle. We calculated spatially explicit P balances for cropland soils at 0.5° resolution based on the principal agronomic P inputs and outputs associated with production of 123 crops globally for the year 2000. Although agronomic inputs of P fertilizer (14.2 Tg of P·y^{-1}) and manure (9.6 Tg of P·y^{-1}) collectively exceeded P removal by harvested crops (12.3 Tg of P·y^{-1}) at the global scale, P deficits covered almost 30% of the global cropland area. There was massive variation in the magnitudes of these P imbalances across most regions, particularly Europe and South America. High P fertilizer application relative to crop P use resulted in a greater proportion of the intense P surpluses (>13 kg of P·ha^{-1}·y^{-1}) globally than manure P application. High P fertilizer application was also typically associated with areas of relatively low P-use efficiency. Although manure was an important driver of P surpluses in some locations with high livestock densities, P deficits were common in areas producing forage crops used as livestock feed. Resolving agronomic P imbalances may be possible with more efficient use of P fertilizers and more effective recycling of manure P. Such reforms are needed to increase global agricultural productivity while maintaining or improving freshwater quality.

agriculture | eutrophication | nutrient balances | phosphorus depletion

Disparities between the nutrients applied to agricultural soils via fertilizer or manure and the nutrients removed by harvested crops result in nutrient imbalances that can influence environmental quality and productivity of agricultural systems (1). Growing consumption of inorganic phosphorus (P) fertilizers derived from mining of nonrenewable phosphate rock (2) has contributed to major increases in crop yields since the 1950s (3). Concurrent growth in fertilizer use and livestock production has more than tripled global P flows to the biosphere over preindustrial levels (4), resulting in P accumulation in some agricultural soils that acts as a driver of eutrophication in freshwater and coastal systems (5–7). At the same time, limited availability of P fertilizers in other regions has contributed to prolonged P deficits that can deplete soil P and limit crop yields (8–10). Although agricultural P surpluses and deficits have been documented for several regions (e.g., refs. 11 and 12), there is still limited understanding of the spatial patterns of P imbalances at the global scale.

Patterns of nutrient imbalances across agricultural systems may reflect contrasting agricultural practices, economic development, and broader agricultural policies (1, 13). Understanding agricultural P use is key to managing global phosphate rock reserves (14) and mitigating the risk for potentially irreversible eutrophication of lakes (15). Despite considerable advances in the development of spatially explicit global nitrogen balances (e.g., ref. 16), most previous global P balance studies have relied on globally or regionally aggregated data (4, 5, 17, 18), limiting our ability to infer spatial patterns of surpluses and deficits. The only spatially explicit global P balance study that we are aware of used estimates of inputs and outputs based primarily on regional or national agricultural statistics distributed over four aggregated cropping systems by using the IMAGE model (19). Here, we use empirical data to calculate P balances for croplands circa the year 2000 at 0.5° resolution in latitude and longitude (~50 × 50 km) to examine patterns of agronomic P imbalances globally. These P balances were calculated by using spatial estimates of the principal agronomic P inputs (P fertilizer and manure applications) and outputs (P in harvested crops) for cropland soils based on spatially explicit global maps of >100 crops.

Results

Spatial Patterns of Agronomic P Imbalances. We classified P surpluses and deficits by quartiles to compare P imbalances across all regions globally (Fig. 1). In total, 29% of the global cropland area had overall P deficits and 71% of the cropland area had overall P surpluses. A sizeable fraction of the global cropland area (~31%) had only small negative or positive imbalances (within ±2 kg of P·ha^{-1}·y^{-1} from zero), corresponding to the lowest two quartiles for deficits and the lowest quartile for surpluses (Fig. 2). These minor imbalances occurred in every region but were most prevalent in Africa and Oceania.

Moderate P imbalances [lower-middle and upper-middle quartiles for surpluses (3–13 kg of P·ha^{-1}·y^{-1}) and upper-middle quartile for deficits (−2 to −3 kg of P·ha^{-1}·y^{-1})] were characteristic of croplands in every region except Africa, occurring in 47% of croplands globally. The largest share of moderate surpluses occurred in South Asia (India, Pakistan, and Thailand) and North and Central America (United States, Canada, and Mexico). Moderate deficits occurred in only 8% of the global cropland area, largely in Eastern Europe (Russia and Ukraine) and West Africa, as well as smaller tracts of other regions, such as southeastern Australia.

The largest imbalances of agronomic P, corresponding to the top quartiles of both deficits and surpluses (−3 to −39 kg of P·ha^{-1}·y^{-1} and 13–840 kg of P·ha^{-1}·y^{-1}, respectively), were spatially concentrated in certain areas. Just 10% of the global cropland area with the largest P deficits contributed 65% of the cumulative global P deficit (Fig. 3). The most widespread large deficits were in South America (particularly Argentina and Paraguay), the northern United States, and Eastern Europe. Similarly, 10% of the cropland area with the largest surpluses contributed 45% of the cumulative global P surplus. These large surpluses (which had a median value of 26 kg of P·ha^{-1}·y^{-1}) covered most of East Asia, as well as sizeable tracts of Western and Southern Europe, the coastal United States, and southern Brazil, but <2% of the cropland in Africa (Fig. 2). A more detailed breakdown of the P balance quartile ranges and variations

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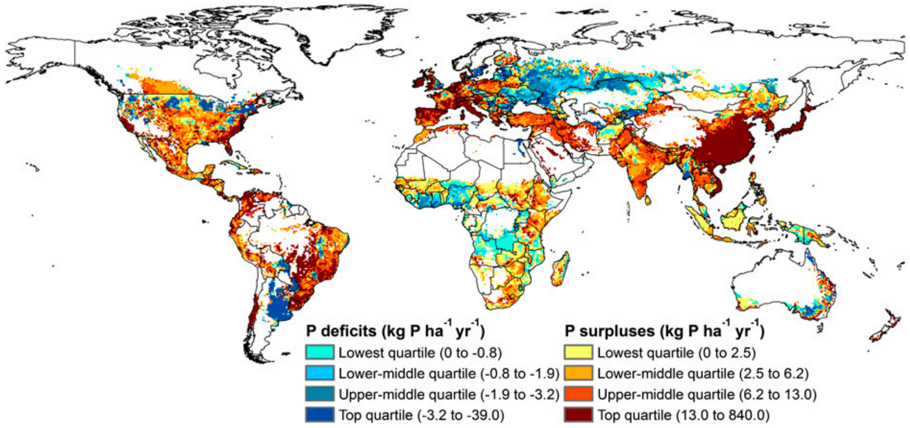

Fig. 1. Global map of agronomic P imbalances for the year 2000 expressed per unit of cropland area in each 0.5° grid cell. The P surpluses and deficits are each classified according to quartiles globally (0–25th, 25–50th, 50–75th, and 75–100th percentiles).

by continent highlights the particularly large intraregional variation in agronomic P imbalances in Europe and South America (Fig. S1).

Global Agronomic P Flows. Fertilizer application to croplands in the year 2000 totalled 14.2 Tg of P·y^{-1}, of which more than half was applied to cereal crops. The largest P fertilizer application rates occurred predominantly in East Asia, Western Europe, the midwestern United States, and southern Brazil [Fig. S2 and Potter et al. (20)]. Approximately 9.6 Tg of P·y^{-1}, or 40% of total manure P excreted by livestock in 2000 (20), was used for cropland application based on estimates of recoverable manure for 12 regions (21) and for US states (22). Recoverable manure P shows much greater spatial variation than P fertilizer applications (Fig. S2), with clusters of more intense manure P applications occurring in many countries (such as the United States and Brazil) and more widespread high manure P applications in East Asia and Western Europe.

The production of 123 crops in the year 2000 (23) removed 12.3 Tg of P·y^{-1} from cropland soils. The greatest crop P removal occurred in the northern United States, Western Europe, East Asia, South America (particularly southern Brazil and Argentina), and Australia, largely reflecting crop yields. Cereal crops accounted for approximately half and by far the largest share of P removal, most of which was attributable to harvest of wheat, maize, and rice.

Our global estimate of total P inputs to cropland soils exceeds P removed by harvested crops, resulting in a global agronomic surplus of 11.5 Tg of P·y^{-1}. We also calculated P balances based on contrasting crop residue management scenarios by using plausible high and low residue recycling and removal estimates from Smil (24) that reflect broad differences in residue management between developed and developing countries (detailed in *SI Methods*). The high residue removal scenario resulted in a slight decrease in our global P balance estimate (to 11.2 Tg of P·y^{-1}), whereas the low residue removal scenario resulted in a considerable increase (to 12.5 Tg of P·y^{-1}) due to the influence of residue P recycling inputs. These crop residue scenarios had minimal influence on the spatial patterns of P surpluses and deficits (Fig. S3).

Agronomic Drivers of Cropland P Imbalances. We found considerable spatial variation in the main drivers of P surpluses based on the magnitudes of fertilizer and manure inputs relative to crop P use (using crop P removal as a proxy for crop use) (Fig. 4*A*). Fertilizer alone exclusive of manure inputs exceeded crop P use in the largest fraction of P-surplus cropland in all continents except Africa (Fig. 4*B*), and particularly in intensive agricultural regions of Asia and North America (40% of the cropland area in each continent). The combination of fertilizer and manure was the primary driver of P surpluses in ~30% of the global cropland area with P surpluses; manure and fertilizer each individually exceeded crop use in half of this area, particularly in southern China and eastern Brazil, whereas the sum of fertilizer plus manure exceeded crop use in the remaining half. Manure P alone exclusive of fertilizer P exceeded crop use in only 11% of croplands globally, particularly in areas with high livestock densities but relatively

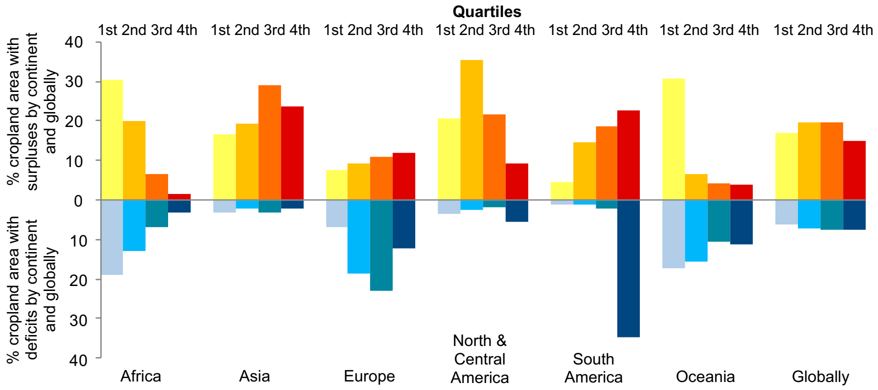

Fig. 2. Distributions of P surpluses and deficits by quartiles shown as percent of total cropland area in each continent and as percent of global cropland area.

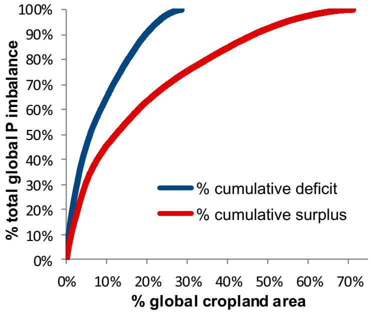

Fig. 3. Cumulative distributions of global cropland P imbalances (surpluses or deficits, sorted from largest to smallest) in relation to cumulative global cropland area.

limited cropland areas (e.g., parts of the United States) or in regions with relatively low P fertilizer application and low P surpluses (e.g., across central Africa).

Half of the cropland area with the largest P surpluses (>13 kg of P·ha^{-1}·y^{-1}) globally corresponded to locations where P fertilizer and manure applications each individually exceeded crop P use, but P fertilizer application alone was particularly influential in some regions. When summed across both categories (Fig. 4*B*), P fertilizer applications exceeding crop P use coincided with a greater proportion (87%) of the global cropland area that had large P surpluses compared with manure P applications in excess of crop P use (62%). In particular, a much greater proportion of the large P surpluses in Asia and South America corresponded to locations where P fertilizer application alone exceeded crop P use compared with areas where manure P alone exceeded crop P use. Roughly the same proportion of cropland areas with large P surpluses in Europe and North America corresponded to locations where either fertilizer or manure P, or both, exceeded crop P use.

The types of crops grown contributed substantially to the locations of deficits. Forage crops, and particularly grasses, were associated with large P deficits in several regions. These crops received ∼5% of the total global P fertilizer application in countries with crop-specific fertilizer data in 2000 (which collectively represent 95% of global P fertilizer inputs), yet they accounted for >20% of global crop P removal. Approximately 13% of crop P removal globally was attributable to mixed leguminous grasses and alfalfa, which may receive manure applications but are only fertilized in a few countries (25). Nonforage croplands in several areas had small or moderate P surpluses (e.g., throughout the United States and Australia) (Fig. S4), confirming that some P deficits (Fig. 1) were linked to harvest of forage crops. Forage crops were less influential for P deficits in other locations (e.g., Argentina and Nigeria) (Fig. S4; see *SI Methods* for further explanation). For example, the concentration of top quartile deficits in South America was primarily related to soybean harvest in Argentina and, to a lesser extent, harvest of grasses and wheat. Soybean received on average 2.5 kg of P·ha^{-1}·y^{-1} of P fertilizer in Argentina circa 2000 (10% of the reported P fertilizer rate for soybean in neighboring Brazil; ref. 25), which was a small fraction of the P removal rate for soybean (15 kg of P·ha^{-1}·y^{-1}).

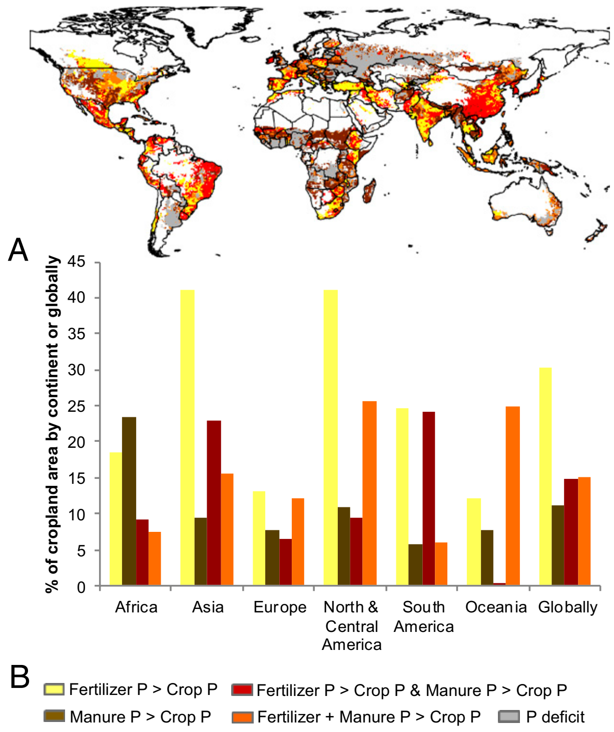

Fig. 4. Agronomic drivers of P surpluses based on the magnitude of fertilizer or manure P applied relative to crop P use in different locations (*A*) and summarized according to percent of cropland area by continent and globally (*B*). Each category is mutually exclusive based on locations where either fertilizer alone or manure alone exceeded crop P use, where fertilizer and manure each individually exceeded crop P use, or where only the sum of fertilizer and manure exceeded crop P use.

Phosphorus-Use Efficiency (PUE). To assess the relationship between P imbalances and overall crop productivity, we calculated a map of agronomic PUE, defined here as total crop dry-matter production per unit of P applied (kg of crop·kg of P input^{-1}; Fig. 5) (26). This method incorporates the contribution of both agronomic P inputs and existing soil nutrients to crop production (27). High PUE values can therefore indicate large crop production returns per unit of P applied (e.g., where high PUE coincides with P surpluses) or reliance on soil P depletion for crop production (e.g., where high PUE coincides with P deficits). Variation in PUE also reflects the types of crops grown and differences in productivity across regions (Fig. S5*A*).

There was considerable variation in the drivers of medium-high and high PUE, which comprised ∼45% of the global cropland area in 2000. Locations with P deficits were overwhelmingly associated with higher PUE (61% of areas with medium-high or high PUE had P deficits), indicating that overall crop production in these areas was more reliant on soil P drawdown than on agronomic P inputs to meet crop requirements. This situation was particularly extensive in Eastern Europe, southern South America, as well as West and Central Africa. The remaining fraction (39%) of the global cropland area with medium-high or high PUE

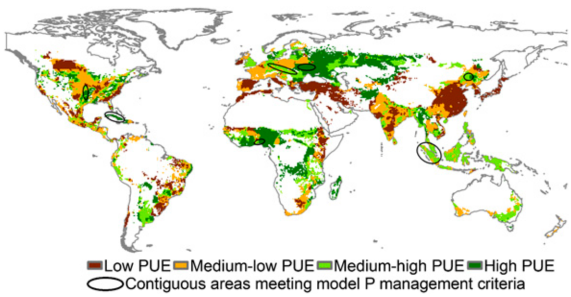

Fig. 5. Map of total agronomic PUE (kg of crop·kg of P·input^{-1}) for 123 crops in 2000 classified from low to high based on quartiles globally. Ovals indicate examples of contiguous areas with model P management (relatively balanced P situations, with PUE and crop production each above the global median; based on Fig. S5*B*).

was associated with P surpluses, indicating high crop production returns per unit of P input without dependence on soil P drawdown. Large tracts of South and Southeast Asia as well as parts of the central United States and Western Europe showed these higher PUE values in areas with P surpluses and relatively high overall crop production (Fig. S5*A*). Widespread parts of Africa and isolated areas in other regions with low overall crop production also had relatively high PUE, typically with small surpluses related to low P inputs. Approximately 13% of cropland with higher PUE also had high (top quartile) manure applications (e.g., in parts of the United States), whereas <6% had high P fertilizer applications (e.g., parts of Germany) (Fig. S2).

Medium-low and low PUE (55% of the global cropland area) were associated most with locations of high fertilizer use and larger P surpluses, where excess P fertilizer use likely provided little additional benefits for improving crop productivity. Approximately 46% of the cropland area with lower PUE worldwide corresponded to areas with high fertilizer P applications, which is almost double the proportion of cropland area with lower PUE that had high manure P applications (25%) (Fig. S2). This pattern is particularly evident in China, the midwestern United States, and Southern Europe. Other areas with lower PUE often had relatively low P fertilizer applications and relatively low overall crop production (Fig. 5 and Fig. S5*A*), such as East Africa and northern Brazil, indicating potential constraints on crop productivity other than agronomic P inputs, including fixation of applied fertilizer P to less plant-available forms in soils, deficiencies of other soil properties (28), or the lack of adequate irrigation. Relatively low agronomic P inputs may have contributed minimally to augmenting crop production in these areas compared with other areas that have low crop production.

Discussion

Implications for Regional Phosphorus Management. Our study provides a consistent global account of the spatial pattern of agronomic P surpluses and deficits, highlighting areas of potential soil P accumulation that can increase P loading to aquatic ecosystems (29, 30), as well as areas of P deficits that could impose constraints on crop productivity and food security (8, 31, 32). Large disparities between agronomic P inputs and outputs pose major challenges for long-term management of water quality and agricultural productivity at all scales. However, regional agronomic P imbalances are difficult to address because they represent the aggregate effects of many complex factors, including nutrient management decisions by individual farmers, socioeconomic conditions, government policies, and environmental setting (4, 12, 33).

Global P-fertilizer use efficiency must be improved to make agricultural P use more sustainable. Consumption of P fertilizers globally increased by ∼20% between 2000 and 2008 (based on an average of 2007–2008 consumption) (34). Farmers may apply P fertilizer in excess of crop requirements to build soil P concentrations, which may be important in P-deficient soils, yet there are typically diminishing returns of additional P fertilizer application for crop yields above a critical level at which plant-available P is maximized (7, 30). On average, developing countries had P deficits during the mid-20th century (5), but our results suggest that current P fertilizer use may be contributing to soil P accumulation and relatively low PUE in some rapidly developing areas. Although there is considerable uncertainty in the rate of current economic phosphate rock reserve depletion, increases in the cost of P fertilizer in the coming decades is likely (2, 14). Potential constraints on future access to P fertilizers could be better reflected in current P fertilizer use, particularly in regions with low PUE.

Redistribution of P fertilizers from certain areas with more intense P surpluses to P-deficit croplands could be particularly effective at resolving global P imbalances. We estimate that a 21% reduction in P fertilizer use in all locations with top quartile surpluses (>13 kg of $\text{P}\cdot\text{ha}^{-1}\cdot\text{y}^{-1}$) associated with P fertilizer inputs (Fig. 4*A*) in 2000 could have been achieved without causing any of these areas to transition to P deficits. This hypothetical reduction in P fertilizer use would provide a net fertilizer savings of 1.2 Tg of $\text{P}\cdot\text{y}^{-1}$ globally, resulting in a 13% decrease in the average P surplus and a 14% increase in average PUE across these locations. If this fertilizer P were instead redistributed across all P-deficit cropland, it would effectively meet the total crop P requirements in these locations, eliminating all P deficits globally. These findings highlight the inherent interconnectedness of solutions to both P surpluses and deficits at the global scale.

Opportunities to more effectively capture and recycle manure in mixed livestock-cropping systems could also help move some subregional P deficits closer to net zero P balances, particularly in forage croplands with extensive P deficits (35). Our results show that manure P was typically associated with P surpluses in areas with high livestock densities but insufficient cropland to effectively assimilate the manure P produced by these animals (22, 36). In some regions with low manure recoverability (e.g., South Asia and Africa) (21), there may be a large magnitude of potentially underused manure P currently lost from agricultural systems that could serve as a useful organic fertilizer source to reduce reliance on inorganic P fertilizers. Achieving more effective manure P recycling at the global scale may require broader management or structural changes in livestock farming, such as improved access to manure collection and treatment technologies, changes in livestock diets, or even reductions in livestock densities (35).

Areas with relatively balanced P situations (first quartile surplus or deficit), and coincident medium-high or high PUE and crop production represent a model for P management that could provide insight on how to resolve P imbalances in other areas. Locations meeting these criteria were scattered throughout every region, across a wide range of development statuses and types of agricultural systems (Fig. S5*B*). Examples of larger contiguous areas that meet these criteria were in Southeast Asia, Central and Eastern Europe, the central United States, and the Caribbean (Fig. 5). One pattern common to most of these locations (85%) is that neither fertilizer nor manure P applications alone exceeded crop P use (Fig. 4*A*); also, <10% of these areas had top quartile P fertilizer applications, and <20% had top quartile manure P applications (Fig. S2). This finding indicates that practices such as integrated nutrient management, which more effectively recycle manure nutrients from livestock and reduce fertilizer use accordingly (37, 38), are important for mitigating P surpluses in areas with high livestock densities and high fertilizer application rates.

Evaluation of Results and Limitations. Our global agronomic P balance estimates for 2000 are broadly comparable to those calculated by other studies using a similar agronomic balance approach (Table S1). Our estimate of global P fertilizer application compares particularly well to reported values from other studies for this time period. Smil's (4) estimate of manure P applied to croplands for the mid-1990s (6-8 Tg of $\text{P}\cdot\text{y}^{-1}$) is lower than our recoverable manure P estimate of 9.6 Tg of $\text{P}\cdot\text{y}^{-1}$ because of the higher total manure P production used as a baseline in our study (20). We also estimated greater crop P removal (12.3 Tg of $\text{P}\cdot\text{y}^{-1}$) than Smil (4) (8–9 Tg of $\text{P}\cdot\text{y}^{-1}$), which may be attributable to our more detailed calculation of P removal for individual crops (23). Bouwman et al. (19) estimated P balances separately for grasslands and all other croplands in 2000; however, they grouped some cultivated grasses, such as hay crops, with their estimate for noncultivated pasture lands, making comparison somewhat challenging because our study addresses only cultivated lands. They estimated a total agronomic P surplus of 15 Tg of $\text{P}\cdot\text{y}^{-1}$ for agricultural soils globally (11 and 4 Tg of $\text{P}\cdot\text{y}^{-1}$ in cropland and grassland soils, respectively) when omitting losses to hydrological systems of 2 Tg of $\text{P}\cdot\text{y}^{-1}$ (19). This value is within the range of our estimate of 11.5 Tg of $\text{P}\cdot\text{y}^{-1}$ given that we included inputs and outputs associated with cultivated grasses and several additional crops, but not with pastures, therefore our crop P removal estimates are higher and our manure P estimates are lower. Our overall agronomic P balance results are close to Smil's (4) lower estimate of 12 Tg of P·y^{-1}, whereas we estimate a higher agronomic P balance than Sheldrick et al. (18) because of their lower manure and fertilizer estimates (Table S1).

The spatial patterns in our P balance results are also generally consistent with spatially explicit P balances for Asia and Europe by Gerber et al. (11, 39), for China by Shen et al. (40), and for India by Pathak et al. (41). Gerber et al. (11) found similar large P surpluses driven by fertilizer use in eastern China and northern India, as well as P deficits or small P surpluses in Burma, parts of Malaysia, Indonesia, and northern China. However, they found P deficits throughout southern India and in pockets of southern China and Vietnam, where we found mostly larger P surpluses, which is likely attributable to our use of a more simplified method to calculate manure P applications to ensure global consistency. Our P balance results also generally agree with Gerber et al. (39) for subnational jurisdictions in Western Europe, showing larger P surpluses driven primarily by manure P inputs in the Netherlands, Belgium, northern Italy, western Germany, Ireland, and Finland, although we found slightly higher P surpluses for parts of France and Italy. Pathak et al. (41) found P surpluses ranging from small to large across different states in southern and northern India that are more consistent with our results for that region, except that they found P deficits in the northeastern state of Assam and the central state of Madhya Pradesh. Shen et al. (40) calculated P surpluses >10 kg of P·ha^{-1}·y^{-1} throughout most provinces in China that correspond to our top quartile P surpluses calculated for that region (>13 kg of P·ha^{-1}·y^{-1}), particularly in eastern China; however, they generally found lower P surpluses in southern China. We also compared our global results to those of Bouwman et al. (19) based on slight modifications of their P balance calculations to provide greater comparability with our study (see *SI Methods* for a detailed description; Fig. S6). Our P balance results show greater spatial variation than Bouwman et al. (19) because of our use of data derived from additional subnational sources for inputs and outputs (23, 42). Other differences are most likely related to our more detailed calculation of P removal for 123 individual crops and their inclusion of manure P produced by pasture-grazed animals not included in our calculations for croplands.

Our study is based on a soil-surface balance approach (13, 18) that considers direct agronomic P inputs and outputs but not potential losses from cropland soils. Estimates of total P losses due to agricultural soil erosion range from 12.5 to more than 22.5 Tg of P·y^{-1}, with particularly large P erosion losses in Africa and Southeast Asia (4, 43). Bouwman et al. (19) used a more conservative estimate of agricultural P loss via runoff and leaching based on 10% of total P inputs (roughly 2.4 Tg of P·y^{-1} using our estimates). Accounting for P losses from soils to water in areas with small P surpluses, such as sub-Saharan Africa, would possibly lead to results of small deficits in many locations, reflecting the small P deficits typically found in studies that considered P losses in that region (10, 12, 33). Occlusion of P in soils to less plant-available forms may also limit the effectiveness of surplus agronomic P to supplement crop growth, especially in highly weathered and P-limited tropical soils, such as those in parts of Brazil and East Africa (28), which may partially explain lower PUE in these areas.

Moving Forward. Although P deficits and P surpluses may appear to be geographically separate and essentially opposite problems, our analysis indicates that global solutions to both types of P imbalances should be approached in tandem. Closing the gaps between areas with the most intense P surpluses and deficits may be achievable with more efficient P fertilizer use, which would help redistribute P fertilizers to P-deficit cropland, and more effective recycling of manure P that would promote tighter P cycling in agricultural landscapes and ease reliance on inorganic P sources.

Global food production may need to increase by up to 70% over year 2000 levels to meet demands from population growth by 2050 (44). Much of this increase will likely need to come from increasing crop yields in developing countries (44). Agricultural P management is central to maximizing agricultural productivity while simultaneously reducing threats to water quality due to P loading from agricultural lands, as well as accounting for uncertainties in future access to inorganic P fertilizers. Although improvements in PUE with more integrated management of fertilizer and manure will be helpful, long-term solutions to regional P surpluses and deficits may require transformations in underlying agricultural policies and management practices (1, 35), as well as better recycling of P from human and agricultural waste streams (2, 14). The challenge of supplying sufficient P to meet agricultural demands worldwide without degrading freshwater resources will be a key issue for agriculture in the 21st century.

Methods

Agronomic P Inputs and Outputs. We estimated P fertilizer applications to croplands in 2000 based on a slight modification of methods from Potter et al. (20). For 88 countries with crop-specific average national P fertilizer rates from the International Fertilizer Industry Association (IFA) (25), the spatial patterns of 104 individual crop maps and 30 grouped crop maps (23) were used to estimate the distribution of P fertilizer applications (20). For 73 countries without crop-specific data, we distributed total national P fertilizer consumption estimates for the year 2000 (or 2002 in some cases) from the Food and Agriculture Organization of the United Nations (FAO) based on the spatial patterns of a generic cropland map (45). We also added subnational P fertilizer estimates for four major P-fertilizer consuming countries each representing >5% of the total global P fertilizer consumption circa 2002 (China, United States, India, and Brazil; ref. 34), as well as adjustments for P fertilizer applications to cultivated grasslands, and national or crop-specific P fertilizer application updates for certain countries (described in *SI Methods*).

Total manure P excreted by animals in each grid cell was estimated by using the method of Potter et al. (20) based on global livestock distribution maps (42) for major livestock species (cows, pigs, poultry, sheep, goats, and buffalo). The number of animals in each grid cell was multiplied by species-specific manure P production coefficients, which were scaled based on regional livestock weights to account for interregional differences (20). The fraction of total manure P produced by animals that is available for cropland application may vary based on factors such as the degree of livestock confinement or pasture grazing, transportation costs, and agricultural technology (21). We estimated manure P used for cropland application in each grid cell based on regional estimates of manure recoverability from Sheldrick et al. (21) for 12 regions. For the United States, we used recoverable manure P fractions for cattle, pigs, and poultry from Kellogg et al. (22) for each state based on comprehensive surveys of livestock confinement and manure collection. The approximate fraction of manure used as fuel was also excluded from the total recoverable manure P based on regional estimates for cattle, buffalo, and chickens for West, South, and Southeast Asia (assuming that buffalo were representative of dairy cattle) (46).

Total P removed from cropland soils by harvested crops circa 2000 was estimated by using spatially explicit crop production maps for 123 individual crops (23) and P harvest removal fractions for each of these crops. The Monfreda et al. (23) crop maps are based largely on subnational crop production statistics (or national in some countries without subnational data), which is the most comprehensive spatial source showing inventories for individual crops globally that we are aware of. We calculated P removal based on this spatial crop production data for each cropland grid cell by multiplying the total production (in kilograms) for each individual crop by the dry matter (DM) content and P content of that crop [for all crops and all grid cells, Total P removal (kg) = Crop production (kg) × (%DM/100) × (%P/100)]. We used crop-specific P content and dry matter content of grains or harvested portions for 80 crops from the US Department of Agriculture-Natural Resources Conservation Service (47), and averages based on crop groups for 14 crops when crop-specific P contents were unavailable. For the remaining crops where P data were not available from this source, we used P contents from IFA (48) and Lesschen et al. (33) and dry matter contents from

Monfreda et al. (23). Our method for estimating crop residue production, as well as the contrasting high and low residue P recycling and removal scenarios based on Smil (24), are detailed in *SI Methods*.

P Balance and PUE Calculations. The P balance for each cropland grid cell was calculated as the difference between total inputs and outputs, divided by the total cropland area in that cell. The cropland map from Ramankutty et al. (45) was used as the basis for cropland areas; however, in addition to cultivated areas, this map includes substantial amounts of temporary pasture and fallow in some regions. To test the sensitivity of our results to the inclusion of these uncultivated areas, we also calculated P balances based on total harvested areas summed for all 123 individual crops from Monfreda et al. (23) (Fig. S4). This and other alternative P balance calculations related to known uncertainties in our analysis are described in *SI Methods*; differences in the spatial patterns of P surpluses and deficits based on these alternative calculations were typically minimal, but we found larger surpluses and deficits in most regions when using total harvested area for all crops as the denominator. PUE was calculated as total crop dry-matter production divided by total P fertilizer and manure application in each grid cell (19). The calculations of quartile ranges for the P input, output, P balance, and PUE maps excluded grid cells with <5% cropland area to avoid marginal agricultural areas that typically showed extreme values for each term.

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