Negative global phosphorus budgets challenge sustainable intensification of grasslands

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Grasslands provide grass and fodder to sustain the growing need for ruminant meat and milk. Soil nutrients in grasslands are removed through withdrawal in these livestock products and through animal manure that originates from grasslands and is spread in croplands. This leads to loss of soil fertility, because globally most grasslands receive no mineral fertilizer. Here we show that phosphorus (P) inputs (mineral and organic) in global grasslands will have to increase more than fourfold in 2050 relative to 2005 to achieve an anticipated 80% increase in grass production (for milk and meat), while maintaining the soil P status. Combined with requirements for cropland, we estimate that mineral P fertilizer use must double by 2050 to sustain future crop and grassland production. Our findings point to the need to better understand the role of grasslands and their soil P status and their importance for global food security.
Global food demand will rise rapidly in the coming decades\textsuperscript{1–3}. In particular, meat and milk consumption are projected to increase markedly due to rising incomes and decreasing prices\textsuperscript{4–7}, especially in developing countries\textsuperscript{8}. The global area of permanent grassland (3.3 billion hectares)\textsuperscript{9} covers 26% of the Earth’s ice-free land, and provides an important contribution to global food security by supplying proteins and energy to ruminants. Between 1970 and 2005 the world’s grasslands expanded by about 4%. Grassland degradation is likely to accelerate given the expected growth of livestock production\textsuperscript{10}, overgrazing and consequent soil erosion, nutrient deficiency, weed encroachment and desertification.

Sustainably meeting global food demand is one of humanity’s grand challenges\textsuperscript{11,12}, and P is increasingly considered to be a new global sustainability issue because of its finite reserves\textsuperscript{12}. Like nitrogen, P is a major limiting nutrient in agriculture\textsuperscript{13,14} and is removed from arable and grassland soils by crop and grass withdrawals and erosion. Soil P removed in the harvest needs to be replaced by weathering and inputs through organic (mostly mineral) and mineral fertilizers to sustain crop and grass production\textsuperscript{15,16}.

Most global studies on the agricultural P cycle focus on arable land\textsuperscript{17–20}. However, we are not aware of any global study addressing the P cycle in grasslands and its connection with croplands. In this paper we assess grassland P budgets between 1970 and 2005, as well as P requirements to sustain projected future grass production. We consider soil P budgets to assess changes in soil fertility, and the budget for the grassland system to assess the P exchange between grasslands and croplands (Fig. 1). The classification of livestock production systems (intensive and pastoral) and grassland systems is shown in Supplementary Fig. 1.

This study focuses on P, but it is evident that nutrient management will have to consider all nutrient requirements in grazing systems, including nitrogen, potassium and many other (micro-) nutrients.

Our general conceptual framework for P budgeting in grasslands focuses on grazing systems including the key P inflows and outflows of four compartments within the grassland system boundary: grassland-based livestock population, grassland-based livestock manure, soil (including weathering) and grass (Fig. 1). Our calculations include all countries of the world. We distinguished two categories of grasslands, that is, those occurring in mixed (and landless) livestock production systems (denoted as intensive systems) and those in pastoral systems. The difference between intensive and pastoral systems is in the P exchange between grassland and croplands through feed and manure. Most pastoral systems are in developing countries, and typically there is little exchange of nutrients between these pastoral systems and croplands (little feed import or manure export). However, there is P withdrawal in the various products (milk, meat, wool, skin and so on). The intensive ruminant systems are mixed, that is, they rely on grass, often supplemented with feed produced in croplands, and part of the manure produced in these systems is collected (in ‘kraal’ or animal houses) and spread in the backyard farms or croplands. Where P in manure exported from grassland thus exceeds the P in feed, there is net P transfer from grassland to cropland. The pastoral systems are extensive everywhere and generally located in dry or cold climates in remote regions away from human populations and croplands. In contrast, the intensive (mixed) systems generally feature in more favourable climates, but their productivity varies from country to country; in industrialized countries they are generally intensive with high productivity of grasslands and animals and large feed requirements, and they are less intensive in developing countries (with limited feed use, often low-quality feed such as crop residues, and relatively low grass and animal productivity).

Using the Dynamic Phosphorus Pool Simulator (DPPS)\textsuperscript{15} model we simulated historical P uptake in grasslands and then calculated the amount of P needed for meeting the global grass requirement in intensive and pastoral systems until 2050.

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**Figure 1** | **Phosphorus budget model for the grassland system.** Phosphorus flows within grassland and between the grassland and cropland systems. The grassland system comprises four compartments (grassland-based livestock population, grassland-based livestock manure, soil including weathering supplying P from soil minerals and grass) and six compartments outside the grassland boundaries (products, other uses of manure, erosion and atmospheric deposition, fertilizer (only in the intensive system) and non-grassland-based livestock manure). Next to the grassland system budget, we also consider the agronomic soil P budget, with the soil surface as boundary; grass P uptake (that is, the P withdrawal by grass harvest or grazing) is considered as output, and mineral fertilizer and manure (internal and external manure inputs) as inputs. We assume that grass P uptake equals livestock P intake. Thus, this approach ignores any P losses during mowing, transporting or stall-feeding of grass. P transfers between grasslands and croplands are represented by the flows (thick arrows): ‘Livestock feed’ (imported P from cropland to grassland as livestock feed) and ‘Spreading in cropland’ (exported P, the manure P that is deposited in grasslands, but is transferred to croplands for spreading). The bold, dashed arrow represents the P flow leaving the grassland systems via animal products, mainly meat and milk.
according to the Rio + 20 scenario, avoiding soil P deficits and surpluses. This research is the first study that estimates soil P budgets in grasslands at the global scale and hence allows the assessment of total future P requirements of agriculture. The P budget of the grassland system was found to be negative between 1970 and 2005 in most of the world regions. Thus, to meet anticipated growth of ruminant production and associated grass requirement, the nutrient status of grassland soils needs to be improved to increase productivity of existing grasslands and to avoid expansion of grassland areas. We estimate that P inputs (mineral and organic) will have to increase more than fourfold in 2050 (relative to 2005) to meet the projected demand for ruminant products as targeted in the Rio + 20 (ref. 21) scenario for 2050.

**Results**

**Agronomic soil P budget.** Historical data show that soil P uptake by grass in intensive and pastoral grazing systems exceeded P application (input) through fertilizer and manure in most parts of the world (Fig. 2). Both uptake and applications were relatively
The total P budget of the grassland system was negative in 1970 and 2005 in most of the regions; only Eastern Europe and North America had (small) P surpluses (Table 1). Globally, grassland system P outputs exceeded P inputs, particularly in Asia (65, 72 and 82 Tg P, respectively) over the same period (calculations are based on Supplementary Figs 2 and 3, respectively).

Manure was the most important input of P for grassland soils worldwide and mineral fertilizer P application was systematically much smaller than P in manure in all world regions (Table 1). During the 1970–2005 period only 23 Tg of mineral fertilizer P was applied to global grassland soils, which is similar to the global use of mineral P fertilizers in croplands of 18.5 Tg P in just the single year of 2010 (ref. 22). Europe alone accounted for almost 80% of the global cumulative mineral P fertilizer use in grassland.

### Table 1 | Grassland system P budget in 1970 and 2005.

| Region     | Area (10^3 ha) | Grass P uptake (kg P per ha) | Internal manure (kg P per ha) | External manure (kg P per ha) | Fertilizer P (kg P per ha) | Imported feed (kg P per ha) | Exported manure to cropland (kg P per ha) | Livestock products (kg P per ha) | Other use of manure (kg P per ha) | Erosion (kg P per ha) | Grassland P budget (kg P per ha) |
|------------|----------------|-----------------------------|-------------------------------|-------------------------------|----------------------------|----------------------------|----------------------------------------|-------------------------------|----------------------------------|------------------|---------------------------------|
| 1970       | 2005           | 1970                        | 2005                          | 1970                         | 2005                       | 1970                      | 2005                                    | 1970                         | 2005                             | 1970              | 2005                             |
| Africa     | 582            | 904                         | 19                            | 3.1                          | 1.6                        | 2.6                       | 0.0                      | 0.0                          | 0.1                            | 0.1              | 0.2                             |
| Asia       | 874            | 971                         | 5.1                            | 6.4                          | 1.8                        | 2.1                       | 0.1                      | 0.1                          | 0.1                            | 0.1              | 0.1                             |
| East Europe| 107            | 115                         | 10.2                           | 4.0                          | 8.0                        | 3.4                       | 0.0                      | 0.0                          | 0.1                            | 0.1              | 0.1                             |
| Latin America| 487          | 546                         | 4.0                            | 6.0                          | 3.6                        | 4.9                       | 0.0                      | 0.0                          | 0.1                            | 0.1              | 0.1                             |
| North America| 263         | 256                         | 5.1                            | 4.1                          | 4.5                        | 3.4                       | 0.4                      | 0.5                          | 0.0                            | 0.1              | 0.1                             |
| Oceania    | 462            | 407                         | 1.3                            | 1.4                          | 1.2                        | 1.2                       | 0.0                      | 0.0                          | 0.1                            | 0.1              | 0.1                             |
| West Europe| 79             | 67                          | 18.5                           | 15.7                         | 13.3                       | 13.2                      | 1.6                      | 2.5                          | 3.2                            | 1.7              | 2.1                             |
| World      | 3,150          | 3,270                       | 4.0                            | 4.6                          | 2.6                        | 2.9                       | 0.1                      | 0.2                          | 0.1                            | 0.1              | 0.1                             |
| Intensive  | 560            | 537                         | 13.2                           | 16.1                         | 7.6                        | 8.8                       | 0.6                      | 1.1                          | 0.6                            | 0.4              | 0.2                             |
| Pastoral   | 2,590          | 2,730                       | 2.0                            | 2.4                          | 1.5                        | 1.7                       | 0.1                      | 0.2                          | 0.0                            | 0.1              | 0.1                             |

Table 1 notes:
- *Imported feed* represents the feed produced in croplands that is taken in by ruminants in the grassland system. Exported manure to cropland is the manure P produced by ruminants (intensive and pastoral) that is transferred to croplands.
- The grassland system P budget is computed as follows: external manure (applied manure from non-ruminants), fertilizer P, imported feed and atmospheric deposition (0.2 kg P per ha) are grassland P inputs; and export manure to cropland, livestock products P, the other use of manure P and erosion are grassland P outputs. Weathering is an internal flow.

Grassland system P budget. Manure P excretion is an input in the soil P budget (Fig. 1), but in the grassland system it is in fact partly an internal cycling of P, as it partly originates from grass P uptake from the soil. Manure P application from non-ruminants (external manure), fertilizer P, atmospheric P deposition and P in imported feed are considered grassland system P inputs and manure P exported from grassland to cropland, P that leaves grasslands via livestock products, P in the other use of manure (for non-agricultural purposes) and erosion are included as grassland system P outputs.

The total P budget of the grassland system was negative in 1970 and 2005 in most of the regions; only Eastern Europe and Oceania had (small) P surpluses (Table 1). Globally, grassland systems received an estimated 125 Tg of P (from external manure, mineral P, atmospheric deposition and feed) between 1970 and 2005. Over the same period, estimated global cumulative P inputs to croplands. Low during the period 1970–2005 in most regions of the world (≈5 kg ha⁻¹ per year or less) in contrast to the more intensive grazing systems of Western and Eastern Europe (Fig. 2). Specifics for the intensive and pastoral systems are shown in Supplementary Figs 2 and 3, respectively.

Between 1970 and 2005 cumulative inputs of P in Eastern Europe (38 Tg P; Tg = teragram = 10¹² g) and Western Europe (56 Tg P) were slightly larger than the cumulative grass uptake of 34 and 49 Tg P, respectively; North America and Oceania had a balanced P budget. By contrast, cumulative soil P uptake by grass in Africa (76 Tg P), Asia (191 Tg P) and Latin America (96 Tg P) exceeded P inputs, particularly in Asia (65, 72 and 82 Tg P, respectively) over the same period (calculations are based on Fig. 2 and grassland area shown in Table 1).

Manure was the most important input of P for grassland soils worldwide and mineral fertilizer P application was systematically much smaller than P in manure in all world regions (Table 1). During the 1970–2005 period only 23 Tg of mineral fertilizer P was applied to global grassland soils, which is similar to the global use of mineral P fertilizers in croplands of 18.5 Tg P in just the
outputs (P in manure exported to cropland, livestock products, the other use of manure and erosion) were 264 Tg P, which caused a negative P budget of $-139$ Tg for grassland systems between 1970 and 2005.

**Phosphorus transfers between grasslands and croplands.** Two flows are involved in the P transfers between grassland and cropland systems, that is, 'Livestock feed (from croplands)' and 'Spreading (of manure) in croplands' (Figs 1 and 3). On the one hand, grassland-based ruminants consume feed produced in croplands, which effectively imports P into the grassland systems. On the other hand, P is effectively transferred from grasslands to croplands when manure from ruminants is used as organic fertilizer in the latter systems.

Feed use varied between different world regions (Fig. 4). Africa and Oceania had a maximum rate of feed use of only 0.1 kg P per year, while Asia had a maximum rate of 0.8 kg P per year. North America and Western Europe had the highest rates of feed use, with peak rates of 4.0 kg P per year for North America and 4.5 kg P per year for Western Europe. Eastern Europe had a moderate rate of 2.0 kg P per year, and Latin America had a rate of 1.5 kg P per year.

Figure 4 | Phosphorus transfers between grasslands and croplands. Historical trends of annual P import to and export from grasslands (intensive and pastoral) as livestock feed and manure spread in croplands, respectively, for the period 1970-2005 in (a) Globe, (b) Africa, (c) Asia, (d) Eastern Europe, (e) Latin America, (f) North America, (g) Oceania and (h) Western Europe. Dashed and solid lines represent imported P (feed) and exported P (manure), respectively. Imported P stands for the feed produced in croplands that is consumed by livestock on grasslands, and exported P stands for the manure P that originates from grasslands (intensive and pastoral), but is transferred to croplands.
ha per year in 2005 (Table 1), while Western Europe’s feed use (4 kg P per ha per year) was around seven times the global rate (0.6 kg P per ha per year) in 2005 (Table 1 and Fig. 4a). The feed P import to the grassland systems in Asia and Latin America remained minimal at 0.7 and 0.2 kg P per ha per year, respectively, in 2005. North America’s feed input rate was 1.9 kg P per ha per year in 2005 (Table 1 and Fig. 4).

North America (with 14.5 Tg), Asia (13.3 Tg), Eastern Europe (11.7 Tg) and Western Europe (8.2 Tg) were responsible for about 90% of cumulative global feed use (33.4 Tg) in 1970–2005. In contrast, the imported P from croplands to grassland (as livestock feed) in Latin America (3.4 Tg), Africa (2.1 Tg) and Oceania (0.4 Tg) accounted for only 10% of the global total (1970–2005).

In 1970, the application of manure to cropland soils varied from 0.1 kg P per ha per year in Oceania to 4.5 kg P per ha per year in Western Europe (Table 1 and Fig. 4g,h). The maximum manure P export to croplands occurred in 1980 in Western Europe (4.9 kg P per ha per year) followed by Eastern Europe (3.7 kg P per ha per year). The other world regions reached rates of only 1.8 kg P per ha per year (Asia) and 1.7 kg P per ha per year (North America) or less in 2005. Cumulative global use of manure as fertilizer in croplands for the 1970–2005 period was 113 Tg of P. Asia alone was responsible for 44% of the global number, with a total of 50 Tg P. Africa (11.7 Tg P), Eastern (11.3) and Western Europe (11.5) had an almost equal share in the global P export from grassland to cropland (≈10% each). Cumulative transfer of P to cropland (1970–2005) was only 1.7 Tg in Oceania, 14.3 Tg in Latin America and 12.6 Tg in North America.

Historical trends of annual P feed imports to grasslands and manure exports from grasslands to croplands for the intensive grassland system for the period 1970–2005 are shown in Supplementary Fig. 4.

**Future demand of P in grassland.** We used the DPPS model to estimate P application rates (mineral fertilizer and manure) needed to achieve projected future grass production under the Rio + 20 scenario. Rio + 20 projects a substantial increase in required global grass production and P uptake between 2005 and 2050 from 4.6 to 8.3 kg per P per ha due to the rapid increase in global ruminant meat and milk consumption and production (Fig. 5). This increase in grass production can come from either expansion of grasslands or enhanced productivity. Here we assume no expansion of the grassland area, so raising grass production will only be possible if the P status of soils under grassland is improved. With this assumption, the DPPS model estimates that to achieve the 2050 target grass production, 375 kg P per ha is required between 2006 and 2050, resulting in a cumulative global P requirement of 1,220 Tg (Fig. 5). According to the Rio + 20 scenario, 650 Tg of this cumulative P input can be supplied through manure. To achieve the target grass production and P uptake until 2050 and assuming no expansion of grasslands, the rest of the required cumulative P input (570 Tg) needs to come from mineral P fertilizer. The 2.5–97.5 percentiles of the required P uptake in global grasslands under the Rio + 20 scenario are, respectively, 810 and 1,500 Tg, for the period 2006–2050.

### Table 2 | Global manure P allocation in intensive and pastoral grassland systems in 1970 and 2005.

| Manure P allocation per source (Tg P per year) | World intensive 1970 | World intensive 2005 | World pastoral 1970 | World pastoral 2005 | World total 1970 | World total 2005 | Reference |
|-----------------------------------------------|----------------------|----------------------|---------------------|---------------------|------------------|------------------|-----------|
| Total manure (grassland-based)                | 7.9                  | 9.7                  | 5.0                 | 6.1                 | 12.9             | 15.8             | Equation (3) |
| Other use of manure outside the agricultural domain (manure use as fuel, building material and so on) | 1.4 (17%) | 1.8 (19%) | 0.6 (13%) | 0.7 (12%) | 2.0 (16%) | 2.6 (16%) | Equation (4) |
| Internal recycling of manure                  | 4.3 (54%)            | 4.7 (49%)            | 4.0 (80%)           | 4.9 (80%)           | 8.3 (64%)        | 9.6 (61%)        | Equations (5) and (6) |
| Export of manure (grassland-based manure application to croplands) | 2.2 (29%) | 3.1 (32%) | 0.4 (7%) | 0.5 (8%) | 2.6 (20%) | 3.5 (23%) | Equation (7) |
| Manure application from non-ruminants         | 0.3                  | 0.6                  | 0.1                 | 0.0                 | 0.3              | 0.6              | External manure |
| Manure input to grassland soils (manure application and grazing in grasslands) | 4.6                  | 5.3                  | 4.1                 | 4.9                 | 8.6              | 10.2             | Sum of internal and external manure |
compared with P in the manure, reflecting the low P conversion difference. Our estimations for the transfer from cropland to grasslands, that is, 1.9 and 0.4 Tg P, for pastoral grassland systems (Table 2). The estimated P flows generally show a fair agreement with values calculated from Fig. 4. Although the contribution of grass to total dry matter intake by all animals is projected to decrease from 50 to 45% between 2005 and 2050 (Rio + 20 data), the total amount of excretion for each animal category kg N per head per year for pastoral grassland systems covering more than 80% of the global grassland area. Although the contribution of grass to total dry matter intake by all animals is projected to decrease from 50 to 45% between 2005 and 2050, grasslands were hardly fertilized. North America and Eastern Asia alone being responsible for 44%. For instance in China, the share and absolute amounts of P in manure transferred from grassland to croplands are much larger for intensive than for pastoral grassland systems (Table 2). The estimated cumulative global use of manure originating from grassland to fertilize croplands during the 1970–2005 period was 113 Tg of P, Asia alone being responsible for 44%. For instance in China, the grazing system was confronted with a severe P deficit problem due to the massive transfers of P in the form of manure, while grasslands were hardly fertilized. North America and Eastern Europe were the only regions that showed a cumulative net P deficit, while South America might have had an equivalent net P surplus. More ruminant production in intensive systems based on crop feed concentrates, or less manure transfer from grasslands to croplands, will both require more P use in the world’s croplands. Our estimate of the global P input required in grasslands of 1.220 Tg P for the 2005–2050 period includes P from both mineral fertilizer and animal manure. In 2050, globally 24 Tg per year in 2050 (ref. 15). This indicates significant opportunities to increase crop production, with less than proportional increases of P use and associated environmental impacts. By contrast, we estimate here that to realize an anticipated 80% increase in grassland production (for milk and meat), the P input from

### Table 3 | Abbreviations used in the soil P budget model, description and units.

| Symbol | Description | Units |
|--------|-------------|-------|
| y      | Year        | Year  |
| c      | Country     |       |
| s      | Production systems |       |
| a      | Animal category |       |
| i      | Fraction of meat and by-products |       |
| R      | Regional data |       |
| PlMe   | Phosphorus in meat and livestock by-products | kg P |
| LPD    | Livestock production data | kg carcass |
| DP     | Dressing percentage | kg carcass per kg live weight |
| LWFP   | Live weight partitioning fraction | kg fraction (muscle, adipose tissue and so on) per kg live weight |
| FPC    | Phosphorus content | kg per kg products or by-products |
| PLMi   | Phosphorus in milk | kg P |
| MPD    | Milk production data | kg milk |
| MPC    | Milk phosphorus content | kg P per kg milk |
| Manure | Total P in manure excreted by livestock | kg P |
| LPN    | Livestock population numbers | heads |
| Excretion | Annual P excretion for each animal category | kg N per head per year |
| FrMeat | Fraction of meat and by-products | kg P |
| FrOthers | Fraction of total manure allocated to other uses | kg P |
| Grazing | Amount of P in the manure allocated to grazing | kg P |
| FrGrazing | Fraction of total manure allocated to grazing | kg P |
| Grasslands | Amount of P in the manure that is applied in grasslands as fertilizer | kg P |
| FrGrass | Fraction of stored manure that is applied in grasslands as fertilizer | kg P |
| Croplands | Amount of P in the manure that is used in croplands as fertilizer | kg P |
| PlF  | Total amount of phosphorus in livestock feed | kg P |
| LPF  | Livestock productivity. It is calculated as the total amount of products associated with the animal category (carcass weight or milk) over the total number of animals | kg carcass per head (non-dairy cattle and sheep & goats) kg milk per head (dairy cattle) |
| LPN  | Livestock population numbers | No. of heads |
| FEED | Total amount of feed item used in a certain region | kg feed item |
| PFI  | Phosphorus content for a given feed item | kg P per kg feed item |
| PGU  | Total grass phosphorus uptake | kg P |

### Discussion

This paper presents the first estimates of global and regional soil P budgets in grasslands. In terms of production, mixed and landless systems are dominant for all ruminants (73% of beef, 92% of milk, 65% of mutton and goat meat and nearly all monogastrics production); however, in terms of area usage, the pastoral systems are covering more than 80% of the global grassland area. Although the contribution of grass to total dry matter intake by all animals is projected to decrease from 50 to 45% between 2005 and 2050, grasslands were hardly fertilized. North America and Eastern Asia alone being responsible for 44%. For instance in China, the share and absolute amounts of P in manure transferred from grassland to croplands are much larger for intensive than for pastoral grassland systems (Table 2). The estimated cumulative global use of manure originating from grassland to fertilize croplands during the 1970–2005 period was 113 Tg of P, Asia alone being responsible for 44%. For instance in China, the grazing system was confronted with a severe P deficit problem due to the massive transfers of P in the form of manure, while grasslands were hardly fertilized. North America and Eastern Europe were the only regions that showed a cumulative net P deficit, while South America might have had an equivalent net P surplus. More ruminant production in intensive systems based on crop feed concentrates, or less manure transfer from grasslands to croplands, will both require more P use in the world’s croplands. Our estimate of the global P input required in grasslands of 1.220 Tg P for the 2005–2050 period includes P from both mineral fertilizer and animal manure. In 2050, globally 24 Tg per year in 2050 (ref. 15). This indicates significant opportunities to increase crop production, with less than proportional increases of P use and associated environmental impacts. By contrast, we estimate here that to realize an anticipated 80% increase in grassland production (for milk and meat), the P input from

efficiency in ruminant systems. Although soil stocks of P in grasslands are substantial, there is a systematic loss of soil fertility through export in manure to cropland that may aggravate current rates of soil degradation across most of the global grasslands. More grass production can be achieved, while avoiding grassland expansion and deforestation, through mineral P fertilization (and maintaining a balance between nitrogen, P and potassium), adequate management of livestock and manure, and soil conservation to control P loss through erosion. More ruminant production in intensive systems based on crop feed concentrates, or less manure transfer from grasslands to croplands, will both require more P use in the world’s croplands. Our estimate of the global P input required in grasslands of 1.220 Tg P for the 2005–2050 period includes P from both mineral fertilizer and animal manure. In 2050, globally 24 Tg per year in 2050 (ref. 15). This indicates significant opportunities to increase crop production, with less than proportional increases of P use and associated environmental impacts. By contrast, we estimate here that to realize an anticipated 80% increase in grassland production (for milk and meat), the P input from

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fertilizer (mineral and organic) will have to increase fourfold. Thus, the amount of mineral fertilizer $P$ needed in cropland and grassland systems in total is estimated to be 45 Tg per year in 2050, corresponding to 350 Tg phosphate rock. For the entire agricultural system (crop and grass production), we estimate that relative to 2005 mineral $P$ fertilization needs to more than double by 2050. In the next four decades, a global cumulative amount relative to 2005 mineral $P$ fertilization needs to more than double by 2050. This implies that up to 2050, 10,700 Tg of phosphate rock will need to be mined across the globe to produce the $P$ fertilizer for the agricultural and food production sectors.

Livestock grazing systems are far more complex than crop production systems, and the available data on grass production are scarce (see Methods section). For example, Food and Agricultural Organization provides livestock production, animal stocks, numbers of slaughtered animals and milking cows, carcass weights and milk yield per animal$^{22}$, but lacks data on the age distributions of animals and more importantly, data on grass production and management and grass withdrawal by grazing and mowing. Similarly, most national statistics lack such data$^{29,30}$. Our sensitivity analysis revealed that the global model results for the total grazing system are strongly sensitive to animal stocks, excretion rates and the initial labile and stable soil $P$ pools, which are known to be uncertain$^{31}$ (Supplementary Table 8). Yet, our modelling results and data analysis suggest that negative $P$ budgets in the world’s grassland soils can be an obstacle when intensifying grassland production. This comprehensive analysis underlines the necessity to adopt nutrient management strategies, balancing $P$, nitrogen and other nutrients for croplands and grasslands. It also shows the urgent need for empirical data on grass production, fertilization and nutrient withdrawal.

### Methods

#### Overview

We coupled two models in our study, that is, the soil $P$ budget model (Fig. 1) and the DPPS model, to reproduce the soil $P$ budget for the 1970–2005 period and to estimate future $P$ requirements in grasslands. The soil $P$ budget model considers two system boundaries: the grassland system boundary and the grassland soil boundary. Phosphorus is leaving the grassland systems’ boundary via animal products (mainly meat and milk), livestock manure and runoff or erosion. On the other hand there is $P$ import from cropland into grassland through animal feed.

Within the grassland soil boundary, we distinguish different sources of soil $P$ inputs, including manure generated inside the grasslands and spread in the grasslands (grassland-based, internal, livestock manure; Fig. 1), manure produced by pigs and poultry outside the grassland boundaries (non-grassland-based, external, livestock manure; Fig. 1), mineral $P$ fertilizer (only in intensive livestock production systems, see section below) and $P$ from weathering and atmospheric deposition. Grass $P$ uptake, runoff and erosion are regarded as $P$ outflows from the system.

#### Livestock production systems and animal groups.

In their global classification, Sere and Steinfeld$^{32}$ distinguished livestock production systems (LPSs) and mixed farming production systems (MPS). LPS includes systems in which more than 90% of dry matter fed to animals comes from rangelands, pastures, annual forages and purchased feed. MPS systems are in systems in which more than 10% of the dry matter fed to...
animals comes from crop by-products or stubble, or more than 10% of the total value of production comes from non-livestock farming activities. They further distinguished four subgroups: landless LPS; grassland LPS; rainfed MPS and irrigated MPS (Supplementary Fig. 1a). They collected data on buffaloes, cattle, goats, pigs, poultry and sheep population numbers and meat and milk production in each system. Later, Bouwman et al. modified the classification from Sere and Steinfeld et al. for their global analysis of ruminant production systems. Landless LPS and MPS were merged into mixed-landless systems (or intensive systems) while grassland LPS was renamed into pastoral systems (Supplementary Fig. 1b,c).

Following Bouwman et al., in the present study also two production systems were distinguished, that is, grasslands in mixed and landless (referred to as intensive hereafter) and extensive pastoral LPSs. Within each system, two groups of animals were considered: ‘grassland-based livestock’ including asses, buffaloes, camels, dairy cattle, horses, mules, non-dairy cattle, sheep and goats, and ‘non-grassland-based livestock’ including pigs and poultry (Fig. 3). Owing to lack of data, it was not possible to include all animal categories for all the calculations (Table 4). Furthermore, non-grassland-based livestock categories were not included in products’ P flow calculations since in our definition they are not located within the grassland system boundaries (Fig. 1).

Data used. The P flows considered for different animal categories and their data sources are listed in Table 4. Phosphorus inflows to the grasslands comprise feed, P fertilizer, external manure P and atmospheric deposition; P outflows from grasslands boundaries include P in livestock products, exported manure to other regions as feeding and management. For each country, animal stocks and P inflows and outflows were estimated from literature reviews and IMAGE data. The sections below provide more details on the methods and data used for the various model components.

Livestock products. Livestock production data include milk, meat and livestock by-products. Livestock by-products include adipose tissue, skeleton, viscera, blood, skin, hair and digestive content. Country-scale meat production data for non-dairy cattle and sheep and goats, as well as milk production were obtained from FAOSTAT data. Meat and milk production for buffaloes, horses, asses, mules and camels was not included due to lack of data. The total amount of P in livestock products is the sum over P in milk, meat and livestock by-products.

The carcass weight is the most common way of expressing livestock meat production. Carcass weight is defined as the weight left after slaughter and removal of head, skin, genitourinary organs and offals. The ratio between the carcass weight and the live weight is called the dressing percentage (DP). Live weight consists of the following fractions: muscles; adipose tissue; skeleton; viscera; blood; skin; hair; and digestive content. Live weight partitioning allows for a more accurate P accounting due to large differences in P concentration in different fractions such as bones and blood.

To allocate the total national production to mixed-landless and pastoral systems, national, annual values of the fraction allocated to mixed-landless systems (Fraction intensive) were obtained from IMAGE. A list of countries and regions as used in the present study based on IMAGE has been shown in Supplementary Table 1.

In addition, data on DP’s were obtained from Kemper et al., who reported 53 and 50% DP for, respectively, non-dairy cattle and for sheep and goats. Live weight partitioning fraction (LWF) data and P content of those fractions were obtained from different sources (Supplementary Table 2).

Equation (1) was used to calculate P in meat and livestock by-products:

\[
P_{\text{LPM}} = \sum \left[ \left( \text{LPD} \times \text{FrGrazing} \right) + \left( \text{LPF} \times \text{FrGrass} \right) \right]
\]

where \( y \) denotes year, \( c \) country, \( s \) production system, \( a \) animal category and \( i \), fraction of meat and by-products.

Phosphorus in milk and livestock by-products is denoted by PLM (kg P). LPD and DP refer to the livestock production data (kg carcass weight) and DP (kg carcass weight per kg live weight), respectively. LWF (kg meat or livestock by-products per kg live weight) represents live weight partitioning and FPC refers to P content (kg P per kg meat or livestock by-products).

The total amount of P in milk was calculated by multiplying the total amount of milk production with the P content of milk, as shown in equation (2). The P content was considered to be 8.4 \( \times 10^{-4} \) kg P per kg milk:

\[
P_{\text{Milk}} = \left( \text{LPM} \times \text{FrOthers} \right)
\]

where \( y \) denotes year, \( c \) country, \( s \) production system and \( a \) animal category.

Manure refers to the total P in manure excreted by livestock (kg P); LPN is livestock P production (number of heads); Excretion rate is the annual amount of P excreted for each animal category (kg P per head per year). The sum of manure for grassland-based animal categories (cattle, buffaloes, sheep, goats, camels, horses and asses) corresponds to the ‘Livestock excretion flow’ depicted in Fig. 1.

The amount of P (kg) in manure used for non-agricultural purposes (other uses) was calculated according to equation (4).

\[
\text{Other uses}_{y,c} = \left( \text{Manure}_{y,c} - \text{FrManure}_{y,c} \right)
\]

For ‘Grasslands’ and ‘Croplands’ as shown in equations (6) and (7), respectively.

Grassland-based grazing animals. In the case of non-grassland-based species, it represents their deposition as they scavenge in grasslands.

The rest of the manure P was considered to be excreted in animal houses and stored, and available for use as organic fertilizer either in grasslands or in croplands and stored manure. Two fractions were calculated, ‘Grasslands’ and ‘Croplands’ as shown in equations (6) and (7), respectively.

Grassland-based systems. The sum of ‘Grazing’ and ‘Grasslands’ for grassland-based and non-grassland-based species corresponds to the internal and external manure input flows, respectively, as depicted in Fig. 1.

The values for the manure allocation fractions (other uses, grazing and application to grasslands) are listed in Supplementary Table 4.

Livestock feed. The IMAGE model used FAOSTAT data on crops for feed and energy requirements of animals to estimate the amount of feed for each country, year and animal category. Only the animal categories of non-dairy cattle, dairy cattle and sheep and goats were considered for estimating feed crop use. Thus, a 100% grass ration was assumed for the rest of grassland-based animal categories (buffaloes, horses, mules and camels).
road-side grazing, food waste and so on). FAOSTAT provides data on the amount of feed crop use per country, but does not specify feed use by animal species. In IMAGE the specification of feed crop use for individual animal categories is based on feed rations that are calibrated to match FAOSTAT data on total feed use at the scale of world regions. Therefore, disaggregation of world-region feed crop use by animal category to the country scale was needed. To do so, it was assumed for each animal category that the fraction of feed crop use is in proportion to regional livestock productivity. The total amount of feed crops available for a specific animal category within a world region was thus calculated on the basis of the productivity of the animal category considered in a specific country relative to the regional productivity. Country and regional productivity were calculated for each animal category using the respective regional amount of product divided by the country and regional animal numbers, respectively. Since this calculation was done for each animal category, the productivity numbers were expressed in terms of kg of carcass weight per head (or non-dairy and sheep and goats) or kg milk per head (for dairy cattle). Then, for each country the ratio between its productivity over the regional productivity of the animal category considered in a specific country relative to the regional productivity that the fraction of feed crops in the ration is proportional to feed rations that are calibrated to match FAOSTAT data on total feed use at the regional level, but does not specify feed use by animal category. In this study, we needed scenarios that focus on nutrients and included future food demand, production and the nutrient uptake and future production and consequently P uptake and excretion as a target for selecting the appropriate scenarios. A few recent examples of scenarios that included projections of nutrient uptake are the MEA28 and more recently the Rio +20 scenarios. The P content of the feed item. By adding up all the feed items and animal productivity was computed, which yielded a weighing factor (first term of equation (8)). With the information on the regional feed amount and the animal weight per head (for non-dairy and sheep and goats) or kg milk per head (for dairy cattle). Then, for each country the ratio between its productivity over the regional productivity that the fraction of feed crops in the ration is proportional to the regional animal category that the fraction of feed crops in the ration is proportional to feed rations that are calibrated to match FAOSTAT data on total feed use at the regional level, but does not specify feed use by animal category. In this study, we needed scenarios that focus on nutrients and included future food demand, production and the nutrient uptake and future production and consequently P uptake and excretion as a target for selecting the appropriate scenarios. A few recent examples of scenarios that included projections of nutrient uptake are the MEA28 and more recently the Rio +20 scenarios. The P content of the feed item. By adding up all the feed items and animal productivity was computed, which yielded a weighing factor (first term of equation (8)). With the information on the regional feed amount and the animal numbers, the regional average feed intake was calculated for each feed item and animal category. The total amount of P for each feed item for a specific animal category within a certain country was thus the product of the weighting factor times the country’s animal numbers times the regional average feed intake times the P content of the feed item. By adding up all the feed items and animal categories, the country total P amount in livestock feed crops was calculated.

Livestock grass intake and grass P uptake. The estimation of grass uptake (and grass intake by animals) is based on a mass balance approach. At the animal level, P inputs (feed plus grass intake) equal the P outputs (manure plus products). Phosphorus in the livestock grass intake was assumed to be equal to grass P uptake from the soil. Thus, this approach ignores any P losses during mowing, transporting or stall-feeding of grass. The grass P uptake was calculated according to equation (9). The amount of feed (PFE) and products (PLMe and PLMi) were assumed to be zero for buffaloes, horses, asses, mules and camels. For these animal categories the amount of P in grass intake equals the excretion of P. (PFE,kg) is the total amount of P in livestock feed. LPR refers to the livestock productivity (kg P per head). It is calculated as the total amount of products associated with the animal category (carcass weight or milk) over the total number of animals. LPN refers to the animal numbers and the total amount of feed item used in a certain region as presented by FEED (kg). PFI (kg P per kg feed item) is the P content for a given feed item. It is clear that part of the P in feed used in grassland-based systems is imported from other countries. Owing to lack of data we ignore feed trade, but in regions such as Western Europe, P in feed produced in croplands in other world regions may be a significant part of total feed use. However, this does not affect the global budget of the grassland-based systems, but may lead to overestimation of the net transfer from cropland to grassland within feed importing countries.

Mineral phosphorus fertilization. The IMAGE data include the total use of mineral phosphorus fertilizers in grasslands for 1950, 1970, 1980, 1990, 1995, 2000 and 2005 at country level. The values are based on FAOSTAT22 and the International Fertilizer Industry Association45,46 for the period 1970–2000, and extrapolations for earlier and later years4,21. Those numbers were exclusively used to calculate long-term trends in grassland-based systems, but may lead to overestimation of the net transfer from cropland to grassland within feed importing countries. For more details of the model see Sattari et al.15 and Wolf et al.56

The initial P stock in the top 30 cm was taken from Yang et al.50 for the year 1900, and residual soil P was calculated from the soil P budget up till the year 2005 (ref. 42). All inputs and outputs of the soil balance were assumed to occur in the top 30 cm; the soil budget model replaces P enriched or depleted soil material lost at the surface by erosion with fresh soil material (with the initial soil P content) at the bottom. Simulated cumulative P loss amounted to 33 Tg P over the 1970–2005 period, which corresponds to an average loss of about 1 Tg P per year over the entire region. For a mean P content of soils of 0.5 kg per tonne of soil51,52 this means a soil loss of 60 ton km⁻², which exceeds the European estimates by 50% due to larger erosivity of grasslands in especially tropical and (semi-)arid climates. Estimates of erosion rates are uncertain. Erosion rates in overgrazed grasslands have been estimated to amount to 1 500 t of soil per km² per year52,53. Such rates may locally be possible, but as a global average they seem unrealistic as they exceed the European average erosion rates of 40 t of soil per km² per year48 by a factor of 40.

Weathering and atmospheric deposition. On the basis of the ratio of cropland area to world total land areas, Liu et al.27 calculated the amount of weathering and atmospheric deposition on croplands. Employing the same approach, we have estimated about 4.0 Tg P per year as weathering and atmospheric deposition in grasslands.

Scenario for the period 2006–2050. There are different global scenarios, such as from the Organization for Economic Cooperation and Development54, MEA28, IPCC-SRES55 and Rio + 20 (ref. 21). For this study, we needed scenarios that focus on nutrients and included future food demand, production and the nutrient uptake and future production and consequently P uptake and excretion as a target for selecting the appropriate scenarios. A few recent examples of scenarios that included projections of nutrient uptake are the MEA28 and more recently the Rio + 20 (ref. 21) scenarios. Future demand of P fertilizer in global croplands was calculated based on the target crop yields, given by four different MEA scenarios for 2050 (ref. 15). Recently, van Vuuren et al.21 developed new pathways (Rio +20) to achieve global sustainability goals for food, land and biodiversity, as well as for energy and climate by 2050. The Rio + 20 study describes four scenarios, that is, the Trend scenario and three challenge pathways. The Trend scenario describes possible trends in the absence of climate and sustainability policies. The three challenge pathways were designed to assess the potential to achieve sustainability goals. We used the Rio + 20 (ref. 21) Trend scenario for simulating future P requirement in grasslands. Baseline scenarios represent a continuation of current trends, with no marked changes or shifts in production and management systems, attitude towards environmental problems and so on. The Rio + 20 Trend scenario is a baseline or business-as-usual scenario, and comparable with the baseline scenario of the Environmental Outlook of the Organization for Economic Cooperation and Development54, the Global Orchestration scenario of the MEA28 and the A1 scenario of IPCC-SRES55.

DPPS model description. DPPS is a simple two-pool P model29 including labile soil P pools and long-term P input and output. The DPPS model reproduces historical grass uptake as a function of P inputs (fertilizer and manure). P inputs are allocated to two dynamic P pools, namely the stable (Pst 20%) and the labile P pools (Plt 80%). The model simulates the P transfers between the pools, the uptake of P by the grass and the size of both pools. To calculate the dynamics of P in these two pools, two differential equations are used:

\[ \frac{dP_{st}}{dt} = f_{P} + \mu_{Pst} P_{st} - \mu_{st} P_{st} - ap_{P} - a_{e} \] (10)

\[ \frac{dP_{lt}}{dt} = (1 - f_{P}) + \mu_{Pst} P_{st} - \mu_{lt} P_{lt} + \delta \] (11)

The rates of P transfer from Pst to Plt and vice versa are denoted by \( \mu_{st} \) and \( \mu_{lt} \) respectively (per year). The coefficient \( f_{P} \) refers to the total P input (mineral fertilizer and manure). The coefficients \( f \) and \( 1 - f \) refer to the fraction of \( f_{P} \) that transfers to Pst and Plt, respectively. Coefficient \( \delta \) represents the grass P uptake fraction from Pst. Parameters \( \omega \) and \( \delta \) are weathering and deposition inputs to Pst and Plt, respectively. The parameter \( \omega \) stands for soil P erosion-runoff outflow from Pst. A large \( \mu_{lt} \) makes \( P_{lt} \) less available for plant uptake and a large \( \mu_{st} \) indicates that the stable pool acts as a buffer that replenishes the labile pool.

This model considers the essential P fluxes between grass and soil with a yearly time step. It can calculate P transfer between the labile and stable soil pools, the P uptake by grass and the pool sizes. The model can also be formulated in a target-oriented approach57, in which the (future) P uptake is a model input and the required P application a result assuming no change in grassland area. The DPPS model successfully simulated the historical patterns of crop P uptake as a response to the application rates in all continents and the entire globe as shown by Sattari et al.15. In the present paper, the model was used to calculate future P fertilizer and manure application rates in grasslands based on target grass productions in 2050 derived from the Rio + 20 Trend (baseline) scenarios21. For more details of the model see Sattari et al.15 and Wolf et al.56

Comparing the results with other studies. The estimates of global P budgets of grassland soils and P transfers between grasslands and croplands are compared in
Supplementary Table 5, with those reported by other authors. Although it is not easy to compare all results obtained in this study with those in other studies, due to differences in approaches, system boundaries and the scope, a result of selected flows calculated here at country level with other studies is possible (Supplementary Table 5). Frequently, in literature larger values than the ones reported here are found, primarily due to inclusion of pigs and poultry, while in our study only ruminants are considered.

**Sensitivity analysis.** The sensitivity of the results to 26-model parameters was investigated for 6 output variables for the soil P budget model, and the sensitivity of two output variables of the DPPS model to variation of 13 model parameters was investigated. These output parameters represent global results for P uptake by grass (Supplementary Table 6). To limit computational load in the sensitivity analysis, the Latin Hypercube Sampling (LHS) technique was used. LHS offers a stratified sampling method for the separate input parameters based on subdividing the range of each of the k parameters into disjoint equiprobable intervals based on a uniform distribution. The intervals were selected on the basis of earlier analysis of the livestock system. By sampling one value in each of the N intervals according to the associated distribution in this interval, we obtained N sampled values for each parameter. The number of samples for the soil budget model is 100 and for the DPPS model.

The sampled values for the first model parameter are randomly paired to the samples of the second parameter, and these pairs are subsequently randomly combined with the samples of the third source and so on. This results in an LHS consisting of N combinations of k parameters. The parameter space is thus represented by N × k intervals with a limited number of samples. LHS can be used in combination with linear regression to quantify the uncertainty contributions of the input parameters to the model outputs.

The output Y considered (see columns in Supplementary Tables 7 and 8) is approximated by a linear function of the parameters X_i expressed by

\[ Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \cdots + \beta_n X_n + \epsilon \]

where \( \beta_i \) is the so-called ordinal regression coefficient and \( \epsilon \) is the error of the approximation. The quality of the regression model is expressed by the coefficient of determination (R^2), representing the amount of variation Y explained by \( Y - \epsilon \). Since \( \beta_i \) depends on the scale and dimension of \( X_i \), we used the standardized regression coefficient (SRC), which is a relative sensitivity measure obtained by rescaling the regression equation on the basis of the standard deviation of all the parameters considered (both with respect to their s.d.). Hence, SRC is independent of the units, scale and size of the parameters. A positive SRC value indicates that increasing a parameter value will cause an increase in the calculated model output, while a negative value indicates a decrease in the output considered caused by a parameter increase.

The sum of squares of SRC values of all parameters equals the coefficient of determination (R^2), which for a perfect fit equals 1. Hence, SRC^2/R^2 yields the contribution of parameter X_i to Y. For example, a parameter X_i with SRC = 0.1 adds 0.01% to Y in case R^2 equals 1.

Here we discuss the SRC for 26 parameters in the soil P budget model (Supplementary Table 7) and 13 parameters in the DPPS model (Supplementary Table 8). We focus on significant SRC values exceeding 0.2, which we consider to be an important influence on the model sensitivity or an important parameter (that is, \( SRC \geq 0.2 \)). The fraction of the livestock production in mixed and industrial systems (FrProdint) is very important for both P uptake in 2005 and cumulative uptake but has a smaller influence on the instantaneous uptake in 2005.

**Dynamic Phosphorus Pool Simulator.** Median simulated P uptake of global grasslands in 2015 is 13 Tg, with a variation of 11.0–17.6 Tg (2.5 and 97.5 percentiles as a result of variation of all the parameters in Supplementary Table 8). The cumulative P uptake (1970–2005) is 374–598 Tg around the median of 510 Tg. U_t (initial P uptake from unfertilized soil) and U_0 (initial P uptake from fertilized soil) are the most important parameters for the sensitivity of all 13 parameters tested. U_t (SRC = 0.46, indicating sensitivity of 20%) and U_0 (SRC = 0.64, indicating sensitivity of 41%) have a strong influence on the cumulative curve of the total livestock system, and a smaller influence on the sensitivity of the uptake in 2005. The coefficient C_r the maximum fraction of crop P uptake from the labile pool is an important factor for the sensitivity of the cumulative uptake but has a smaller influence on the instantaneous uptake in 2005.

P input (\( \rho \)) manure plus mineral) has a stronger influence on the sensitivity of the instantaneous uptake in 2005 than on that of the cumulative uptake. This is due to depletion of the P in the two pools, which results in a strong and growing instantaneous effect of fertilizer, which is mostly flowing into the labile pool from where uptake occurs.

The time constant of P transfer from labile to stable pool, \( \mu_L \), is more important for the uptake in 2005 and cumulative uptake than \( \mu_s \), because the transfer from the labile to the stable pool is much faster, so variation of \( \mu_L \) has a much larger impact on uptake in 2005 and cumulative uptake than \( \mu_s \). Sensitivity to erosion (c) is not significant.

This is related to the initialization of the model when the initial uptake is determined by tuning the size of the slow and labile soil P pools to achieve an equilibrium and initial uptake, after this initialization erosion is no longer important because its value is small and it is almost constant. Sensitivity to the weathering rate is significant, but with a small influence.

**References**

1. Tilman, D., Cassman, K. G., Matson, P. A., Naylor, R. & Polasky, S. Agricultural sustainability and intensive production practices. *Nature* 418, 671–677 (2002).
2. Mueller, N. D. et al. Closing yield gaps through nutrition and water management. *Nature* 490, 254–257 (2012).
3. Tilman, D., Balzer, C., Hill, J. & Befort, B. L. Global food demand and the sustainable intensification of agriculture. *Proc. Natl Acad. Sci. USA* 108, 20160–20164 (2011).
4. Bouwman, A. F. et al. Exploring global changes in nitrogen and phosphorus cycles in agriculture induced by livestock production over the 1900–2050 period. *Proc. Natl Acad. Sci. USA* 110, 20882–20887 (2013).
5. Godfray, H. C. J. et al. Food security: the challenge of feeding 9 billion people. *Science* 327, 812 (2010).
6. Kasnier, T., Rivas, M. J. I., Koch, W. & Nonhebel, S. Global changes in diets and the consequences for land requirements for food. *Proc. Natl Acad. Sci. USA* 109, 6868–6872 (2012).
7. Koning, N. J. et al. Long-term global availability of food: continued abundance or new scarcity? *Neth. J. Agric. Sci.* 55, 229–292 (2008).
8. Steinfeld, H. et al. Livestock’s Long Shadow—Environmental Issues and Options (FAO, 2006).
9. Foley, J. A. et al. Solutions for a cultivated planet. *Nature* 478, 337–342 (2011).
10. Suttie, J. M., Reynolds, S. G. & Ratelö, C. Grasslands of the World (Food and Agriculture Organization, 2005).
11. West, P. C. et al. Leverage points for improving global food security and the environment. *Science* 345, 325–328 (2014).
12. Cordell, D. & Neset, T. S. Phosphorus vulnerability: a qualitative framework for assessing the vulnerability of national and regional food systems to the multi-dimensional stressors of phosphorus scarcity. *Global Environ. Change* 24, 108–122 (2014).
13. Sattari, S. Z., van Ittersum, M. K., Bouwman, A. F., Smit, A. L. & Janssen, B. H. Crop yield response to soil fertility and N, P, K inputs in different environments: testing and improving the QUEFTS model. *Field Crops Res.* 157, 35–46 (2014).
14. Syers, J. K., Johnston, A. E. & Curtin, D. Efficiency of Soil and Fertilizer Phosphorus Use: Reconciling Changing Concepts of Soil Phosphorus Behaviour with Agronomic Information 1–110 (Food and Agriculture Organization of the United Nations, 2008).
15. Sattari, S. Z., Bouwman, A. F., Giller, K. E. & Van Ittersum, M. K. Residual soil phosphorus as the missing piece in the global phosphorus crisis puzzle. *Proc. Natl Acad. Sci. USA* 109, 6348–6353 (2012).
16. Vitousek, P. M. et al. Nutrient imbalances in agricultural development. *Science* 324, 1519–1520 (2009).
17. Cordell, D., Jackson, M. & White, S. Phosphorus flows through the Australian food system: identifying intervention points as a roadmap to phosphorus security. *Environ. Sci. Policy* 29, 87–102 (2013).
18. Cooper, J. & Cariliev-Marquet, C. A substance flow analysis of phosphorus in the UK food production and consumption system. *Resour. Conserv. Recycl.* 74, 82–100 (2013).
19. Antikainen, R. et al. Stocks and flows of nitrogen and phosphorus in the Finnish food production and consumption system. *Agric. Ecosyst. Environ.* 107, 287–305 (2005).
20. MacDonald, G. K., Bennett, E. M. & Carpenter, S. R. Embodied phosphorus and the global connections of United States agriculture. *Environ. Res. Lett.* 7, 044024 (2012).

21. van Vuuren, D., Bouwman, A. F. & Lyon, S. *Roads from Rio* + 20: Pathways to Achieve Global Sustainability Goals by 2050—Summary and Main Findings to the Full Report (PBL, Netherlands Environmental Assessment Agency, 2012).

22. FAO. *Production/Crops and Resource/Fertilizer. FAOSTAT database Collections* (Food and Agriculture Organization of the United Nations, 2014) http://faostat.fao.org.

23. Bouwman, A., Van der Hoek, K., Eickhout, B. & Soenarto, I. Exploring changes in world ruminant production systems. *Agric. Syst.* 84, 121–153 (2008).

24. Chen, M., Shen, J. & Sun, F. Agricultural phosphorus flow and its environmental impacts in China. *Sci. Total Environ.* 405, 140–152 (2008).

25. Sattari, S. Z., van Ittersum, M. K., Giller, K. E., Zhang, F. & Bouwman, A. F. Key role of China and India in global sustainable phosphorus management. *Environ. Res. Lett.* 9, 054003 (2014).

26. Smil, V. Phosphorus in the environment: natural flows and human interferences. *Annu. Rev. Energy Environ.* 25, 25–53 (2000).

27. Janssen, B. H. Efficient use of nutrients: an art of balancing. *Image-3.0*, 2014).

28. Yang, X., Post, W. M., Thornton, P. E. & Jain, A. The distribution of soil phosphorus for global biogeochemical modeling. *Biogeoosci. Discuss.* 9, 16347–16380 (2012).

29. Eurostat. European Commission. *Your key to European Statistics, http://ec.europa.eu/eurostat.* Accessed on March 2015.

30. USDA, National Agricultural Statistical Service. Quick Stats ftp://ftp.nass.usda.gov/quickstats/ (retrieved on 21 March 2015).

31. York, X., Post, W. M., Thornton, P. E. & Jain, A. The distribution of soil phosphorus for global biogeochemical modeling. *Biogeoosci.* 9, 16347–16380 (2012).

32. Seré, C. & Steinfeld, H. *World Livestock Production Systems. Current Status, Issues and Trends* (Food and Agriculture Organization of the United Nations, 1996).

33. Stehfest, E., van Ittersum, M. K., Giller, K. E., Zhang, F. & Bouwman, A. F. Integrated Assessment of Global Environmental Change with IMAGE 3.0. Model description and policy applications. 366 p. (PBL Netherlands Environmental Assessment Agency, also available as pdf from http://www.pbl.nl/en/publications/integrated-assessment-of-global-environmental-change-with-IMAGE-3.0, 2014).

34. FAO/IFA/IFDC. *Fertilizer use by crop* 4th edn (Food and Agriculture Organization of the United Nations/International Fertilizer Industry Association/International Fertilizer Development Center, 1999).

35. IFA/FAO. *Fertilizer Use by Crop* 5th edn (Food and Agriculture Organization of the United Nations, 2003).

36. Kempster, T., Cuthbertson, A. & Harrington, G. *Carcase Evaluation in Livestock Breeding, Production and Marketing* (Granada, 1982).

37. Midwest Plan Service. *Livestock Waste Facilities Handbook* 2nd edn (Iowa State University, 1983).

38. Shellick, W., Syers, J. K. & Lingard, J. Contribution of livestock excrement to nutrient balances. *Nutr. Cycling Agroecosyst.* 66, 119–131 (2003).

39. Smith, L. W. in *Handbook of Animal Science* (ed Putnam, P. A.) 280–291 (Academic, 1991).

40. Van Horn, H. H., Newton, G. L. & Kunkle, W. E. Ruminant nutrition from an environmental perspective: factors affecting whole-farm nutrient balance. *J. Anim. Sci.* 74, 3082–3102 (1996).

41. Wilkerson, V. A., Mertens, D. R. & Casper, D. P. Prediction of excretion of manure and nitrogen by Holstein dairy cattle. *J. Dairy Sci.* 80, 3193–3204 (1997).

42. Beusen, A. H. W., Van Beek, L. P. H., Bouwman, A. F., Mogollón, J. M. & Middelburg, J. Coupling global models for hydrology and nutrient loading to simulate nitrogen and phosphorus retention in surface water. Description of IMAGE-GNM and analysis of performance. *Geoscientific Model Development* 8, 4045–4067 doi:10.5194/gmd-4048-4045-2015 (http://www.geosci-model-dev.net/4048/4045/2015/ (2015).

43. Hart, M. R., Quin, B. F. & Nguyen, M. L. Phosphorus runoff from agricultural land and direct fertilizer effects: A review. *J. Environ. Qual.* 33, 1954–1972 (2004).

44. McDowell, R. W. & Sharpney, A. N. Approximating phosphorus release from soils to surface runoff and subsurface drainage. *J. Environ. Qual.* 30, 508–520 (2001).

45. Tarkalson, D. D. & Mikkelsen, R. L. Runoff phosphorus losses as related to soil test phosphorus and degree of phosphorus saturation on Piedmont soils under conventional and no-tillage. *Commun. Soil Sci. Plant Anal.* 35, 2987–3007 (2004).

46. Cerdan, O. et al. Rates and spatial variations of soil erosion in Europe: a study based on erosion plot data. *Geomorphology* 122, 167–177 (2010).

47. Bogena, H., Kunkel, R., Schobal, T., Schrey, H. P. & Wendland, F. Distributed modeling of groundwater recharge at the macroscale. *Ecol. Model.* 187, 15–26 (2005).

48. Velthof, G. L. et al. Integrated assessment of nitrogen losses from agriculture in EU-27 using MITERRA-EUROPE. *J. Environ. Qual.* 38, 402–417 (2009).

49. Velthof, G. L., Oudendag, D. A. & Oenema, O. Development and Application of the Integrated Nitrogen Model MITERRA-EUROPE 102 (Alterra, Wageningen UR, The Netherlands; EuroCARE, University of Bonn, Germany; ASC, Wageningen UR, The Netherlands, Wageningen, 2007).

50. Yang, Z., Post, W. M., Thornton, P. E. & Jain, A. The distribution of soil phosphorus for global biogeochemical modeling. *Biogesciences* 10, 2525–2537 (2015).

51. Liu, Y. *The Human Intensified Global Phosphorus Flows and Environmental Impacts*. Report No. IR-06-081, 25 (International Institute for Applied Systems Analysis, Laxenburg, Austria, 2006).

52. Liu, Y., Villalba, G., Ayres, R. U. & Schroder, H. Global phosphorus flows and environmental impacts from a consumption perspective. *J. Ind. Ecol.* 12, 229–247 (2008).

53. Liu, M., Yu, Z., Liu, Y. & Konijn, N. T. Fertilizer requirements for wheat and maize in China: the QUEFTS approach. *Nutr. Cycling Agroecosyst.* 74, 245–258 (2006).

54. OECD. *OECD Environmental Outlook to 2050: The Consequences of Inaction* 350 (Organization for Economic Cooperation and Development, 2012).

55. Nakicenovic, N. et al. *Special Report on Emissions Scenarios* (Cambridge Univ. Press, 2000).

56. Wolf, J., De Wit, C. T., Janssen, B. H. & Lathwell, D. J. Modeling long-term crop response to fertilizer phosphorus. I. The model. *Agron. J.* 79, 445–451 (1987).

57. Van Ittersum, M. & Rabbinge, R. Concepts in production ecology for analysis and quantification of agricultural input-output combinations. *Field Crops Res.* 52, 197–208 (1997).

58. Saltelli, A., Chan, K. & Scott, E. M. *Sensitivity Analysis* (Wiley, 2000).

59. Saltelli, A., Tarantola, S., Campolongo, F. & Ratto, M. *Sensitivity Analysis in Practice. A Guide to Assessing Scientific Models* (Wiley, 2004).

60. IPCC. *IPCC Guidelines for National Greenhouse Gas Inventories (IPCC NGGIP Programme, IPCC-TSU/IGES)*. Institute for Global Environmental Strategies (IGES), Hayama, Japan on behalf of the IPCC, Hayama, Japan, 2006.

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S.Z.S., A.F.B. and M.K.v.I. designed research; S.Z.S. and R.M.R. performed research; S.Z.S., A.F.B. and M.K.v.I. analyzed data; S.Z.S., A.F.B. and M.K.v.I. wrote the paper.

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