Corrections

SUSTAINABILITY SCIENCE

Correction for "Exploring global changes in nitrogen and phosphorus cycles in agriculture induced by livestock production over the 1900–2050 period," by Lex Bouwman, Kees Klein Goldewijk, Klaas W. Van Der Hoek, Arthur H. W. Beusen, Detlef P. Van Vuuren, Jaap Willems, Mariana C. Rufino, and Elke Stehfest, which appeared in issue 52, December 24, 2013, of *Proc Natl Acad Sci USA* (110:20882–20887; first published May 16, 2011; 10.1073/pnas.1012878108).

The authors note that Table 1 appeared incorrectly. The corrected table appears below. Additionally, the authors note that on page 20886, left column, first paragraph, lines 2–4, "In 2000, about 50% of the N surplus (138 Tg) was lost through denitrification (67 Tg) (Table 1)" should instead appear as "In 2000, about 50% of the N surplus (138 Tg) was lost through denitrification (67 Tg including N_2O and NO emissions) (Table 1)." Both the online article and the print article have been corrected.

Table 1. Global input terms (fertilizer, manure excluding NH_3 emission from animal houses and storage systems, biological N_2 fixation, and atmospheric N deposition), soil budget (total, arable land, and grassland) and the various loss terms for N [NH_3 volatilization, denitrification (excluding N_2O and NO), and N_2O and NO emission], nitrate leaching and runoff, and P runoff for 1900, 1950, 2000, and 2050 for the baseline and five variants

	Year scenario or variant*								
Input/output balance term	1900	1950	2000	2050 base	2050 EX	2050 FE	2050 ST	2050 IM	2050 DI
N, $Tg \cdot y^{-1}$									
N fertilizer	1	4	83	104	103	109	104	82	104
N manure[†,‡]	33	48	92	139	143	130	142	153	133
N_2 fixation	14	23	39	54	55	56	54	55	53
N deposition	6	13	35	49	51	49	49	49	48
Total N inputs	54	89	248	347	352	344	350	340	337
N withdrawal	34	52	110	176	183	180	178	184	172
N budget	20	36	138	170	169	165	172	156	165
Arable land	6	12	93	119	117	114	121	104	116
Grassland	14	24	45	52	52	51	51	51	49
NH_3 volatilization	4	7	24	36	34	34	37	33	33
Denitrification (N_2)	6	12	48	55	55	54	56	51	55
N_2O emission[§]	3	4	7	9	9	9	9	9	9
NO emission	1	1	2	3	3	3	3	3	3
N leaching + runoff	6	12	57	68	67	66	68	60	66
NH_3 emission from animal houses and storage systems[‡]	2	4	10	15	15	14	11	18	15
P, $Tg \cdot y^{-1}$									
P fertilizer	0	3	14	23	23	24	23	18	23
P manure[†]	6	9	17	26	27	25	26	29	25
Total P inputs	6	11	31	49	50	49	49	47	48
P withdrawal	6	9	19	31	32	31	31	31	30
P budget	0	2	12	18	18	17	18	16	18
Arable land	0	2	11	16	16	15	16	14	16
Grassland	1	1	1	2	2	2	2	2	2
P runoff	1	1	4	6	6	6	6	6	6

*IAASTD projection serves as the base; EX, 10% of the production in mixed systems is moved to pastoral systems; FE, 10% lower excretion rates in mixed and industrial systems; ST, 20% reduced emissions from animal houses and ST systems; IM, recycling of animal manure that is used as fuel or building material or is unused manure in the baseline and with better integration of animal manure in mixed systems in countries where manure contributes less than 25% total N or P inputs in crop production; DI, as in IAASTD projection but with 10% of ruminant meat production replaced by poultry meat.

[†] Excluding manure that is not recycled in the agricultural system, such as manure stored in lagoons or manure used as fuel.

[‡] Excluding NH_3 emission from animal houses and storage systems, which is presented separately.

[§] N_2O emissions include direct emissions and indirect emissions from leached N and atmospheric N deposition.

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ENVIRONMENTAL SCIENCES

Correction for "Enduring legacy of a toxic fan via episodic redistribution of California gold mining debris," by Michael Bliss Singer, Rolf Aalto, L. Allan James, Nina E. Kilham, John L. Higson, and Subhajit Ghoshal, which appeared in issue 46, November 12, 2013, of *Proc Natl Acad Sci USA* (110:18436–18441; first published October 28, 2013; 10.1073/pnas.1302295110).

The authors note that on page 18440, left column, second full paragraph, line 8 "Hg mass (~200 kg)" should instead appear as "Hg mass (~200 t)."

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Exploring global changes in nitrogen and phosphorus cycles in agriculture induced by livestock production over the 1900–2050 period

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Crop-livestock production systems are the largest cause of human alteration of the global nitrogen (N) and phosphorus (P) cycles. Our comprehensive spatially explicit inventory of N and P budgets in livestock and crop production systems shows that in the beginning of the 20th century, nutrient budgets were either balanced or surpluses were small; between 1900 and 1950, global soil N surplus almost doubled to 36 trillion grams (Tg)·y^{-1} and P surplus increased by a factor of 8 to 2 Tg·y^{-1}. Between 1950 and 2000, the global surplus increased to 138 Tg·y^{-1} of N and 11 Tg·y^{-1} of P. Most surplus N is an environmental loss; surplus P is lost by runoff or accumulates as residual soil P. The International Assessment of Agricultural Knowledge, Science, and Technology for Development scenario portrays a world with a further increasing global crop (+82% for 2000–2050) and livestock production (+115%); despite rapidly increasing recovery in crop (+35% N recovery and +6% P recovery) and livestock (+35% N and P recovery) production, global nutrient surpluses continue to increase (+23% N and +54% P), and in this period, surpluses also increase in Africa (+49% N and +236% P) and Latin America (+75% N and +120% P). Alternative management of livestock production systems shows that combinations of intensification, better integration of animal manure in crop production, and matching N and P supply to livestock requirements can effectively reduce nutrient flows. A shift in human diets, with poultry or pork replacing beef, can reduce nutrient flows in countries with intensive ruminant production.

emissions | global nitrogen and phosphorus cycle | soil nutrient budget

Human-induced flows of nitrogen (N) and phosphorus (P) are a major component of the earth's biogeochemical cycles (1). The changes in global nutrient cycles have had both positive and negative effects. The increased use of N and P fertilizers has allowed for the production of food that is necessary to support a rapidly growing human population, and for increasing per-capita overall consumption of meat and milk in particular (2). However, significant fractions of the anthropogenically mobilized N are lost through emissions of ammonia (NH_3), nitrous oxide (N_2O), and nitric oxide (NO). NH_3 contributes to eutrophication and acidification when redeposited on the land. NO plays a role in tropospheric ozone chemistry, and N_2O is a potent greenhouse gas. Also, large fractions of the anthropogenically mobilized N and P in watersheds enter groundwater through leaching and surface runoff and are transported in freshwater toward coastal marine systems. This has resulted in numerous negative impacts on human health and the environment, such as groundwater pollution, loss of habitat and biodiversity, an increase in frequency and severity of harmful algal blooms, eutrophication, hypoxia, and fish kills (3–8).

Global crop production is often seen as the primary accelerator of N and P cycles (9). However, the demand for animal feed produced from different crops and byproducts of the food industry has rapidly increased in the past century. At present, about 30% of global arable land is used for producing animal feed, probably also involving a similar fraction of fertilizer use (10). In addition, total N and P in animal manure generated by livestock production exceed the global N and P fertilizer use (11). Therefore, it is, in fact, global livestock production that drives the nutrient cycling in the total agricultural system (12).

Livestock production has increased rapidly in the past century in response to increasing demand for livestock products. There has been a gradual intensification that has influenced the composition of livestock diets. In general, intensification is accompanied by decreasing dependence on open-range feeding in ruminant systems and increasing use of concentrate feeds, mainly feed grains, to supplement other fodder in both ruminant and monogastric systems. At the same time, improved feeding practices and improved breeds have enabled more of the feed to go to meat and milk production rather than to maintenance of the animals. This has led to increasing overall feed conversion efficiency (FE) (13). Intensification generally leads to higher efficiency of nutrient conversion at the scale of individual animals (14). However, at the scale of the livestock production system, including feed production, this is not always the case because of the nutrient losses in arable systems. To study environmental impacts of livestock production, it is therefore necessary to consider the total agricultural system and not to restrict the analysis to animal husbandry.

Projections indicate that the world population may increase from about 6.9 billion now to 7.9–10.5 billion people by 2050 (15). Food production will have to increase to meet the demand for this growing population; moreover, increasing prosperity and falling production costs will lead to shifts in human diets toward more meat and milk consumption, requiring additional feed production. The expected decrease in costs of animal products is related to the increasing share of production in more energy- and nutrient-efficient mixed and industrial production systems and a decreasing share of traditional pastoral systems (16).

Here, an analysis is presented of the historical and possible future changes in N and P cycles in global crop-livestock production systems. The focus is on soil N and P budgets and the fate of these nutrients. Soil nutrient budgets are the difference

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Author contributions: L.B. and E.S. designed research; L.B., K.K.G., K.W.V.D.H., A.H.W.B., D.P.V.V., J.W., and E.S. performed research; L.B., K.K.G., K.W.V.D.H., A.H.W.B., D.P.V.V., J.W., and M.C.R. analyzed data; and L.B. and M.C.R. wrote the paper.

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between nutrient inputs from fertilizer and animal manure and the withdrawal through harvesting crops and grazing or mowing of grass. A positive budget is a surplus, which represents a potential loss to the environment or accumulation in the soil; a negative budget indicates a deficit (i.e., soil nutrient depletion). A varying but substantial part of surplus P accumulates in the soil as residual P. This reserve can contribute to P in soil solution and be taken up by crops for many years (17).

The analysis consists of three parts: (*a*) changes in N and P soil budgets at a 0.5° × 0.5° resolution over the 20th century; (*b*) N and P budgets based on the International Assessment of Agricultural Knowledge, Science, and Technology for Development (IAASTD) baseline scenario (18) for the 2000–2050 period; and (*c*) variants of this scenario to assess the consequences for N and P budgets from a number of modifications in livestock production, including (*i*) extensification (EX), (*ii*) increased FE, (*iii*) improved manure storage (ST) systems, (*iv*) integrated manure management (IM) systems, and (*v*) change in human diet, with beef production partly being replaced by that of poultry (DI).

Results

Nutrient Soil Budgets Between 1900 and 2000. We estimate that the global recycling of manure N in agricultural systems (excluding manure that ends up outside the agricultural system, such as when used as fuel or building material) increased from 34 to 51 trillion grams (Tg)/y^{-1} between 1900 and 1950 and to 92 Tg·y^{-1} up to 2000 (Table 1). P excretion increased from 6 to 9 Tg·y^{-1} to 17 Tg·y^{-1} over the same period. The increase in nutrient excretion is slower than in animal stocks (Fig. 1). N and P fertilizer use was negligible in the year 1900 (Table 1) and increased slowly between 1900 and 1950. In the period between 1950 and 2000, N fertilizer use increased more than 20-fold for N and sevenfold for P. Biological N_2 fixation by legumes and in soils increased much less, from 14 to 39 Tg·y^{-1} between 1900 and 2000. Our estimate for 2000 is the low end of the range presented elsewhere (19). However, the contribution of N_2 fixation to crop N demand is uncertain (19, 20). Atmospheric N deposition onto agricultural land was 6 Tg·y^{-1} in 1900 and increased to 13 Tg·y^{-1} in 1950 and to 35 Tg·y^{-1} in 2000. The global total N and P surplus increased by about 80% and more than a factor of 7, respectively, between 1900 and 1950 and by close to factors of 4 and 5, respectively, between 1950 and 2000. The N surplus in arable land doubled between 1900 and 1950, whereas in the 1950–2000 period, there was a rapid increase by a factor of more than 7.

Soil Nutrient Budgets for 2050. The IAASTD baseline projection shows a rapid increase between 2000 and 2050 in manure recycled in the global agricultural system, from 92 to 139 Tg·y^{-1} of N and from 17 to 26 Tg·y^{-1} of P (Table 1). The manure that ends up outside the agricultural system by 2050 will amount to 21 Tg·y^{-1} of

Table 1. Global input terms (fertilizer, manure excluding NH_3 emission from animal houses and storage systems, biological N_2 fixation, and atmospheric N deposition), soil budget (total, arable land, and grassland) and the various loss terms for N [NH_3 volatilization, denitrification (excluding N_2O and NO), and N_2O and NO emission], nitrate leaching and runoff, and P runoff for 1900, 1950, 2000, and 2050 for the baseline and five variants

	Year scenario or variant[*]								
Input/output balance term	1900	1950	2000	2050 base	2050 EX	2050 FE	2050 ST	2050 IM	2050 DI
N, Tg·y^{-1}									
N fertilizer	1	4	83	104	103	109	104	82	104
N manure[†,‡]	33	48	92	139	143	130	142	153	133
N_2 fixation	14	23	39	54	55	56	54	55	53
N deposition	6	13	35	49	51	49	49	49	48
Total N inputs	54	89	248	347	352	344	350	340	337
N withdrawal	34	52	110	176	183	180	178	184	172
N budget	20	36	138	170	169	165	172	156	165
Arable land	6	12	93	119	117	114	121	104	116
Grassland	14	24	45	52	52	51	51	51	49
NH_3 volatilization	4	7	24	36	34	34	37	33	33
Denitrification (N_2)	7	15	66	82	81	79	83	73	80
N_2O emission[§]	3	4	7	9	9	9	9	9	9
NO emission	1	1	2	3	3	3	3	3	3
N leaching + runoff	5	9	39	42	42	41	43	38	41
NH_3 emission from animal houses and storage systems[‡]	2	4	10	15	15	14	11	18	15
P, Tg·y^{-1}									
P fertilizer	0	3	14	23	23	24	23	18	23
P manure[†]	6	9	17	26	27	25	26	29	25
Total P inputs	6	11	31	49	50	49	49	47	48
P withdrawal	6	9	19	31	32	31	31	31	30
P budget	0	2	12	18	18	17	18	16	18
Arable land	0	2	11	16	16	15	16	14	16
Grassland	1	1	1	2	2	2	2	2	2
P runoff	1	1	4	6	6	6	6	6	6

[*] IAASTD projection serves as the base; EX, 10% of the production in mixed systems is moved to pastoral systems; FE, 10% lower excretion rates in mixed and industrial systems; ST, 20% reduced emissions from animal houses and ST systems; IM, recycling of animal manure that is used as fuel or building material or is unused manure in the baseline and with better integration of animal manure in mixed systems in countries where manure contributes less than 25% total N or P inputs in crop production; DI, as in IAASTD projection but with 10% of ruminant meat production replaced by poultry meat.

[†] Excluding manure that is not recycled in the agricultural system, such as manure stored in lagoons or manure used as fuel.

[‡] Excluding NH_3 emission from animal houses and storage systems, which is presented separately.

[§] N_2O emissions include direct emissions and indirect emissions from leached N and atmospheric N deposition.

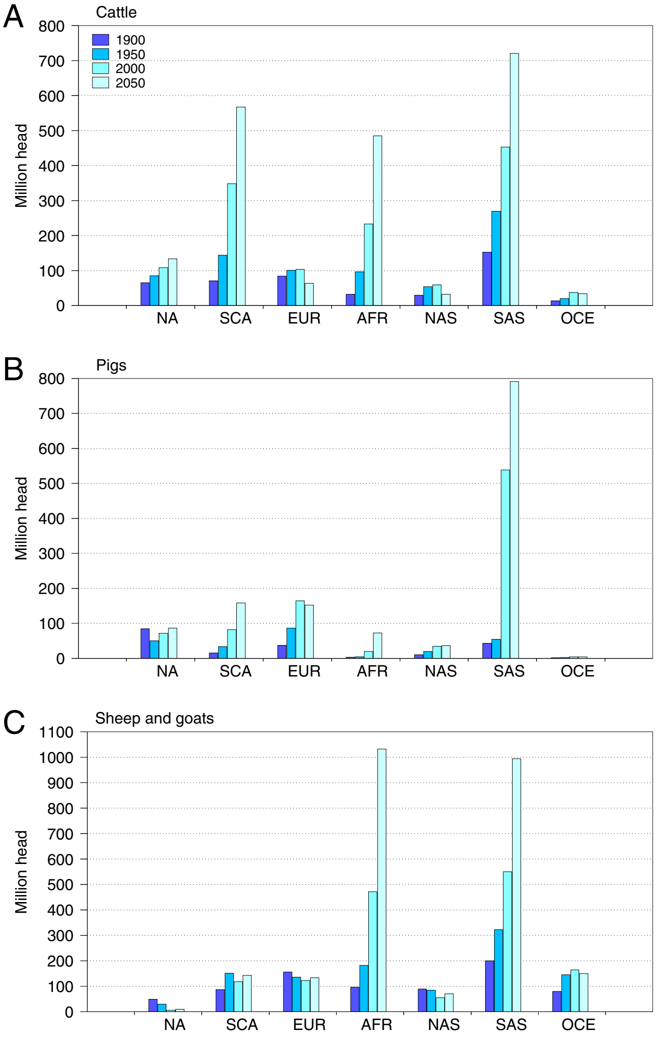

Fig. 1. Global animal stocks for 1900, 1950, 2000, and 2050 for cattle (*A*), pigs (*B*), and sheep and goats (*C*). AFR, Africa; EUR, Europe; NA, North America (Canada, United States); NAS, North Asia (Russian Federation, Belarus, Ukraine, Republic of Moldova); OCE, Oceania (Australia and New Zealand); SAS, South Asia (rest of Asia); SCA, South and Central America.

N and 3 $Tg{\cdot}y^{-1}$ of P. For fertilizer use, we see a similar increase, from 83 to 104 $Tg{\cdot}y^{-1}$ of N and from 14 to 23 $Tg{\cdot}y^{-1}$ of P. In the baseline scenario, there is a rapid increase in biological N_2 fixation to 54 $Tg{\cdot}y^{-1}$ and in atmospheric deposition to agricultural land to 49 $Tg{\cdot}y^{-1}$. By 2050, the N surplus will increase by 23% to 170 $Tg{\cdot}y^{-1}$ and the P surplus will increase by 54% to 18 $Tg{\cdot}y^{-1}$.

Soil Nutrient Budgets for the Variants. The 2050 EX variant shows that a slower transformation of the livestock sector from pastoral to mixed and industrial systems results in a slight increase in manure production and total surplus (+1%), which is related to an increase in the surplus in grasslands (Table 1). Changes in gaseous emissions and nitrate leaching compared with the baseline scenario are small. The improved feeding (2050 FE) variant shows a 6–7% decrease in manure production, a decrease in the total surplus in both arable land and grassland, and hence also decreasing emissions, especially of NH_3. Reduction in the NH_3 loss from animal housing and storage systems by 20% (2050 ST) results in a 4% reduction in the total NH_3 emissions. Although 5% more N would be available in the manure used for spreading, the N surplus would be slightly higher than in the baseline scenario, because lower overall NH_3 emissions are offset by larger losses attributable to denitrification and leaching. Recycling in primarily crop production systems of 21 $Tg{\cdot}y^{-1}$ of N and 3 $Tg{\cdot}y^{-1}$ of P in manure that ends up outside the agricultural system (2050 IM) in the baseline scenario and improved integration of animal manure in the agricultural system result in a significant decrease in fertilizer use (−22%) and smaller N (−9%) and P (−13%) surpluses. A 10% shift from beef to poultry consumption and production leads to a reduction in fertilizer use (−1%), manure production (−4%), atmospheric N deposition (−4%), and total N surplus (−3%), mainly in grassland (−5%) and less so in arable land (−2%).

Discussion

1900–1950. Up to the beginning of the 20th century, the increase in agricultural production was achieved without synthetic N fertilizers. Potassium and P fertilizers had already come into use by about 1850 in several parts of the world (21). Agricultural production relied heavily on fallow periods to restore soil fertility, and legumes (N_2 fixing crops) were gradually introduced in crop rotations. The input from N_2 fixation by legumes would never have been sufficient to increase yields to the extent that the continuing population growth demanded. For example, wheat yields without major N fertilizer inputs increased by only 0.3–0.5 $g{\cdot}m^{-2}{\cdot}\ y^{-1}$ between 1900 and 1950 in the United States and United Kingdom (22). A second major input of nutrients came from recycling of animal manure from the fast-growing animal stocks (Table 1). A third major source of nutrients was human excreta and household waste (23), but because of lack of data, we ignored this nutrient source. The recycling of human waste has been practiced for centuries in Asia (China, Korea, and Japan), enabling the maintenance of high crop productivity in rice cultivation (*SI Text*). In Europe, the need to increase agricultural productivity also induced trade in all kinds of wastes containing nutrients, including human waste (23).

In 1909, the Haber–Bosch process for converting atmospheric N_2 to NH_3 was discovered, and fertilizer production on an industrial scale began in 1913 (24). N fertilizer use slowly increased in North America and Europe. Still, the low level of external nutrient inputs is reflected by the nutrient soil budgets for 1900 and 1950 (Table 1). Nutrient removal, generally, was more or less in balance with the inputs, and nutrient surpluses were small. However, we see a large variation among countries (Fig. 2), with more intensive nutrient use and increasing surpluses in northwestern Europe and South Asia between 1900 and 1950. China also accelerated its nutrient cycling considerably in this period, although fertilizer use was still limited in 1950 (Fig. 2). Agricultural productivity in much of Asia, Africa, and Latin America continued to grow slowly in the 19th century and first half of the 20th century (25), as reflected by slow changes in soil nutrient budgets.

1950–2000. Between 1950 and 2000, the stocks of cattle increased rapidly (Fig. 1), particularly in developing countries, where productivity increased slowly. For example, in Africa, the annual milk yield did not increase at all during this period (25, 26). In contrast, annual milk production per cow in The Netherlands increased from 3,670 kg in 1949 (25) to more than 7,400 kg in 2000 (26). Another phenomenon was steadily decreasing N and P excretion per unit of meat or milk as a result of more efficient nutrient conversion from feed to meat and milk, mainly in industrialized countries (Fig. 3 *C* and *D*). Total nutrient excretion increased along with production, although less rapidly than the number of animals.

The fast growth between 1950 and 2000 of nutrient inputs from fertilizers, biological N_2 fixation, animal manure production, and NO emissions from industrial activities and fossil-fuel combustion led to a rapid increase in atmospheric N deposition (Table 1). In industrialized countries, total inputs increased rapidly, whereas

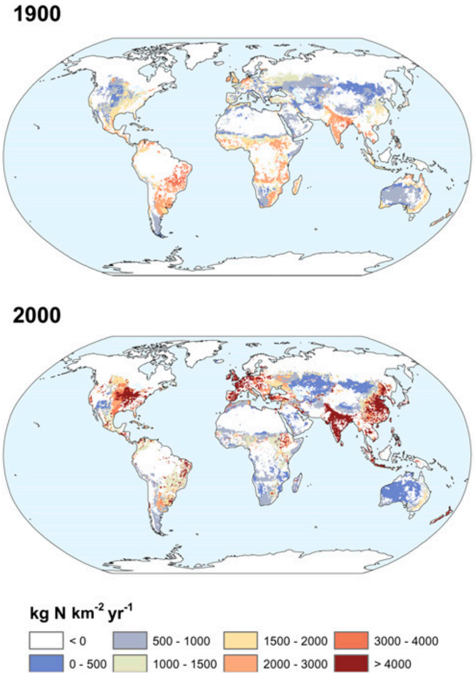

Fig. 2. Agricultural soil N budget for 1900, 1950, 2000, and 2050 (baseline scenario). The soil N budget is calculated using Eq. **1**.

the N and P recovery in crop production decreased (because of increasing fertilizer use; *SI Text*) and that in livestock production increased (Fig. 3). The decrease in nutrient recovery in crop production systems in all countries has been related to a continued change from a low-input system that relied heavily on “natural” inputs, such as animal manure and biological N_2 fixation (1900), to one that relies on synthetic fertilizers (2000). Initially, this led to a drop in nutrient recovery in crop production (Fig. 3 *A* and *B*), as also observed for cereals (27, 28). Since the 1970s, this change has already begun to reverse in many industrialized countries (29) (Fig. 3 *A* and *B*).

The rapidly increasing livestock production with its low nutrient recovery (Fig. 3 *C* and *D*) dominates the nutrient budget of the total agricultural system. The net result of fast growth in both

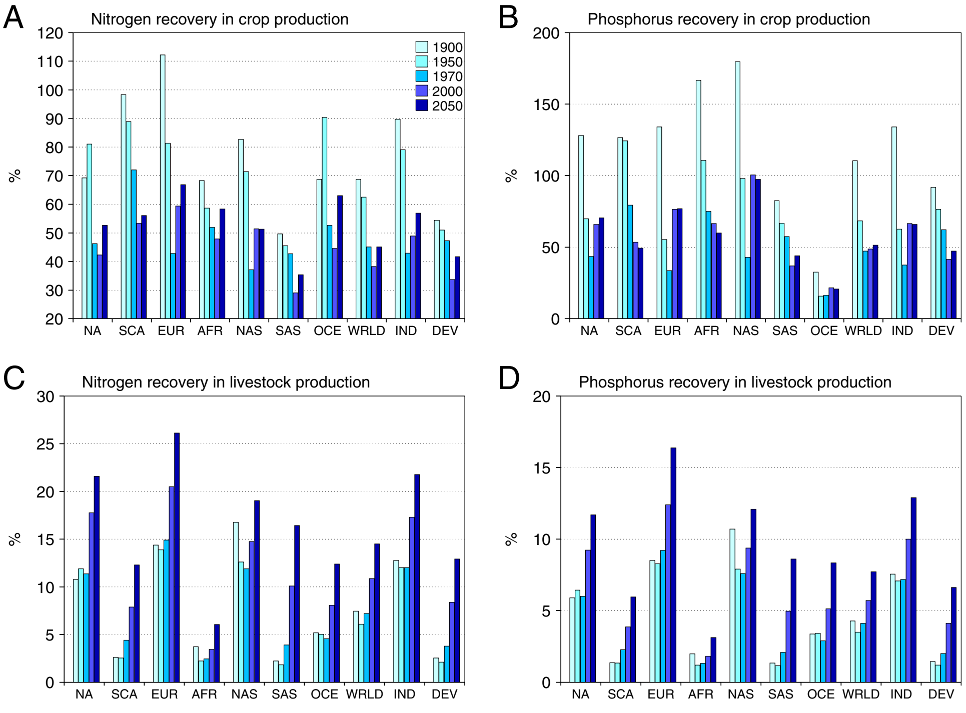

Fig. 3. Global recovery of N and P in crop (*A* and *B*) and livestock (*C* and *D*) production for 1900, 1950, 1970, 2000, and 2050 (IAASTD baseline scenario). Recovery is calculated using Eq. **S5** (crop) and Eq. **S6** (livestock).

crop and livestock production has been a rapid increase in the nutrient surplus in agriculture between 1950 and 2000 (Fig. 2). In 2000, about 50% of the N surplus (138 Tg) was lost through denitrification (67 Tg) (Table 1). Assuming that surface runoff is the only loss pathway for P, considerable amounts of P (surplus of 8 Tg of P in 2000, or one-third of the surplus) (Table 1) are added to residual soil P. The spatial patterns of the soil budgets show a rapid increase in the surplus for North America and a further increase for northwestern Europe and South and East Asia (Fig. 2).

2000–2050. The IAASTD baseline portrays a world with an increasing population, continuous economic growth, increasing per-capita consumption, and important shifts in human diets toward more meat and milk consumption. This induces a continuation of the 1950–2000 trend (i.e., further increasing demand for food and feed crops and livestock products), consequently leading to growing animal stocks (Fig. 1). Nutrient recovery increases rapidly in both crop and livestock production systems in all regions of the world (Fig. 3). Between 2000 and 2050, global N withdrawal by crops increases by 60%, total N inputs in arable land increase by 40%, and the surplus increases by 28%. This indicates that the increase in nutrient recovery cannot balance the impressive increase in nutrient demand to achieve the large increase in crop production. There are important differences among regions of the world (Fig. 2). Industrialized countries show increasing nutrient recovery and often decreasing surpluses. Developing countries with a current nutrient deficit are assumed to increase their nutrient inputs to prevent soil degradation, leading to decreasing nutrient use efficiency (Fig. 3 *A* and *B*), as seen in industrialized countries in the first part of the 20th century. Total nutrient surpluses thus increase rapidly in Africa (+49% N surplus and +236% P surplus) and South and Central America (+75% N surplus and +120% P surplus), and they increase more slowly in South Asia (+27% N surplus and +32% P surplus). Surpluses per unit of area increase by 30% (N) and 194% (P) in Africa (with an expansion of the agricultural area by 14%) and by 34% (N) and 68% (P) in Latin America (with an expansion of the agricultural area of 31%).

With the 117% increase in global livestock production, which is inherently inefficient (Fig. 3) compared with crop production (14), the baseline scenario portrays an increase in global N and P surpluses (23% and 54%, respectively) for the total agricultural system between 2000 and 2050. However, there are large differences among regions (Table S1). According to the baseline scenario, the acceleration of nutrient cycling will continue in North America and Asia and, in contrast to earlier periods, now also in Africa and Latin America (Fig. 2). At this point, it is interesting to analyze the consequences for N and P budgets from a number of modifications in livestock production in the baseline scenario variants.

Variants for 2050. The technical option for reducing NH_3 losses from animal housing and ST systems (2050 ST, improved ST systems) is found to be rather ineffective, probably because it decreases losses at one end of the cascade only to increase them at the other end. However, locally, this may still be a good option for conserving N within the production system and to reduce fertilizer use.

A shift in the production of ruminants from mixed to pastoral systems (2050 EX) leads to an overall decrease in the efficiency of production and nutrient use. This is a result of the larger share of production taking place in the pastoral system compared with the baseline scenario, leading to higher nutrient excretion per unit of meat and milk. The impact on nutrient budgets is small as the result of a decrease in soil budgets of arable land and an increase in those of grassland. Improved feeding strategies to decrease excretion rates (2050 FE, increased feed efficiency) is more successful, because nutrient surpluses can thus be brought down, even with a slight increase in fertilizer use for the larger feed crop requirement.

Recycling animal manure that ends up outside the agricultural system (e.g., manure used as fuel) in the baseline scenario and better integration of animal manure in crop production systems lead to a reduction in fertilizer use and soil nutrient N and P surpluses (2050 IM system). Combining all variants would lead to a major reduction of the global N (−12%) and P (−20%) surplus.

A shift from beef to poultry (2050 DI) leads to a reduction in nutrients cycled within the agricultural system. This is related to various factors. The N excretion per kilogram of meat produced for poultry is 1/10th of that for beef, and this variant thus shows a reduction of total manure production (Table 1), whereas feed crop requirements and associated fertilizer use are not very different in this variant compared with the baseline scenario. However, less grass is needed. Hence, this option is only relevant in regions with intensive ruminant production and intensively managed grassland. In other regions with natural grasslands, shifting from beef to poultry is not an attractive option, because these grasslands are often not suitable for crop production. Shifting from beef to pork will have a similar effect, because pork production is also more N-efficient than beef (14). A reduction in ruminant meat consumption is also an effective strategy to reduce greenhouse gas emissions (30).

Materials and Methods

The annual soil nutrient budget includes the N and P inputs and outputs for 0.5° × 0.5°-grid cells (11). N inputs include biological N fixation (N_{fix}), atmospheric N deposition (N_{dep}), and application of synthetic N fertilizer (N_{fert}) and animal manure (N_{man}). Outputs in the soil N budget include N withdrawal from the field through crop harvesting, hay and grass cutting, and grass consumed by grazing animals (N_{withdr}). The soil N budget (N_{budget}) was calculated as follows:

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

For P, the same approach was used, with P inputs being animal manure and fertilizer. The soil nutrient budget is a steady-state approach, which ignores nutrient accumulation in soil organic matter buildup in case of a positive budget (surplus) and soil organic matter decomposition and mineralization, which is an internal cycle. With no accumulation, a surplus represents a potential loss to the environment (for N, this includes NH_3 volatilization, denitrification, surface runoff, and leaching; for P, this is runoff). Negative budgets indicate soil N or P depletion. Uncertainty in the budget terms is discussed in *SI Text*.

IAASTD Scenario. The baseline scenario used in our study is the reference case of the IAASTD (18). This baseline was developed using several linked models, including the IMPACT agriculture-economy model (31) and the Integrated Model to Assess the Global Environment (32). The scenario depicts the world developing over the next decades in a similar manner as it does today, without anticipating deliberate interventions. For population, the scenario is based on the United Nations medium projection, leading to a total population size of around 9.4 billion by 2050 (Fig. S1*A*). The global economic growth is close to 3% annually over the 2000–2050 period (Fig. S1*B*). Together with a changing trade in agricultural products, these drivers lead to an increasing per-capita and total food crop demand (an increase of about 80% between 2000 and 2050; Fig. S2). Diets are projected to become richer in animal protein, especially in low-income countries (Fig. S3). Global meat demand increases by 115% between 2000 and 2050, with growth rates of around 1.7% (early in the scenario period) to 1.4% annually (in the 2025–2050 period) (Fig. S3). About 70% of the growth in crop production comes from yield increases, implying an expansion of cropland from 15 to more than 16 million km^2 between 2000 and 2050 (Fig. S4). The increase in meat consumption (Fig. S3) leads to increasing animal stocks (Fig. 1). At the same time, there is a gradual shift to more intensive forms of animal husbandry, and although some net expansion of pasture areas will still occur, this will level off soon after 2025 (Fig. S4). For developing scenarios for fertilizer use for crops and grass, we used the concept of apparent fertilizer N and P use efficiency (NUE and PUE, respectively) (Fig. S5), which represent the production in g dry matter per g of fertilizer N or P (27, 29).

Scenario Variants. We developed five variants to the IAASTD baseline scenario to analyze the impact of differences in nutrient management by 2050. Assumptions in all variants were applied globally.

1. EX assumes that 10% of ruminant production in mixed and industrial systems is shifted to pastoral production systems. The overall ruminant productivity is thus lower, with fewer feed crops and more grazing and higher nutrient excretion rates per unit of product. Also, the share of animal ST and manure spreading is smaller than in the baseline scenario.
2. Increased FE assumes a 10% lower N and P excretion for cattle, pigs, poultry, and small ruminants in mixed and industrial systems. This is achieved by tuning the feed composition and increasing the use of concentrates by 18% (3–10% in industrialized countries and up to 65% in developing countries, where use of concentrates is currently limited) to increase the N conversion. Feed P additives in pork and poultry production, and thus P excretion, may be reduced by improving the capability of monogastrics to degrade phytate or to reduce the phytate contents of grain (33).
3. Improved ST considers 20% lower NH_3 emissions from animal housing and storage systems. This means that the animal manure used for spreading contains 5% more N than in the baseline scenario. An associated reduction in fertilizer use is not accounted for.
4. IM assumes that all manure that ends up outside the agricultural system in the baseline scenario (manure used as fuel or building material or unused manure stored in lagoons) is recycled in crop systems; this allows for substituting fertilizer. In addition, there is improved integration of animal manure in crop systems. For those countries where the share of manure in N and P inputs from fertilizer and manure is less than 25%, we assume that fertilizer is substituted for by the available manure, based on 60% effectivity for manure N and 100% effectivity for P. In countries where animal manure dominates the nutrient budget, we assume that manure integration cannot be improved.
5. DI assumes that by 2050, 10% of the baseline scenario's beef consumption is replaced by poultry meat in all producing regions, without accounting for changes in agricultural trade.

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