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.

www.pnas.org/cgi/doi/10.1073/pnas.1206191109

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)."

www.pnas.org/cgi/doi/10.1073/pnas.1321091110

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

Lex Bouwman[a,b,1], Kees Klein Goldewijk[a], Klaas W. Van Der Hoek[c], Arthur H. W. Beusen[a], Detlef P. Van Vuuren[a,d], Jaap Willems[a], Mariana C. Rufino[e], and Elke Stehfest[a]

[a]PBL Netherlands Environmental Assessment Agency, 3720 AH, Bilthoven, The Netherlands; [b]Department of Earth Sciences–Geochemistry and [d]Utrecht Centre for Earth and Sustainability, Faculty of Geosciences, Utrecht University, 3508 TA, Utrecht, The Netherlands; [c]Centre for Environmental Monitoring, National Institute for Public Health and the Environment, 3720 BA, Bilthoven, The Netherlands; and [e]International Livestock Research Institute, Nairobi 00100, Kenya

Edited by Mario Herrero, International Livestock Research Institute, Nairobi, Kenya, and accepted by the Editorial Board April 15, 2011 (received for review August 30, 2010)

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

---

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.

The authors declare no conflict of interest.

This article is a PNAS Direct Submission. M.H. is a guest editor invited by the Editorial Board.

[1]To whom correspondence should be addressed. E-mail: lex.bouwman@pbl.nl.

This article contains supporting information online at www.pnas.org/lookup/suppl/doi:10.1073/pnas.1012878108/-/DCSupplemental.

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 $Tg{\cdot}y^{-1}$ up to 2000 (Table 1). P excretion increased from 6 to 9 $Tg{\cdot}y^{-1}$ to 17 $Tg{\cdot}y^{-1}$ 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 $Tg{\cdot}y^{-1}$ 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 $Tg{\cdot}y^{-1}$ in 1900 and increased to 13 $Tg{\cdot}y^{-1}$ in 1950 and to 35 $Tg{\cdot}y^{-1}$ 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 $Tg{\cdot}y^{-1}$ of N and from 17 to 26 $Tg{\cdot}y^{-1}$ of P (Table 1). The manure that ends up outside the agricultural system by 2050 will amount to 21 $Tg{\cdot}y^{-1}$ 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, $Tg{\cdot}y^{-1}$									
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	60
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.

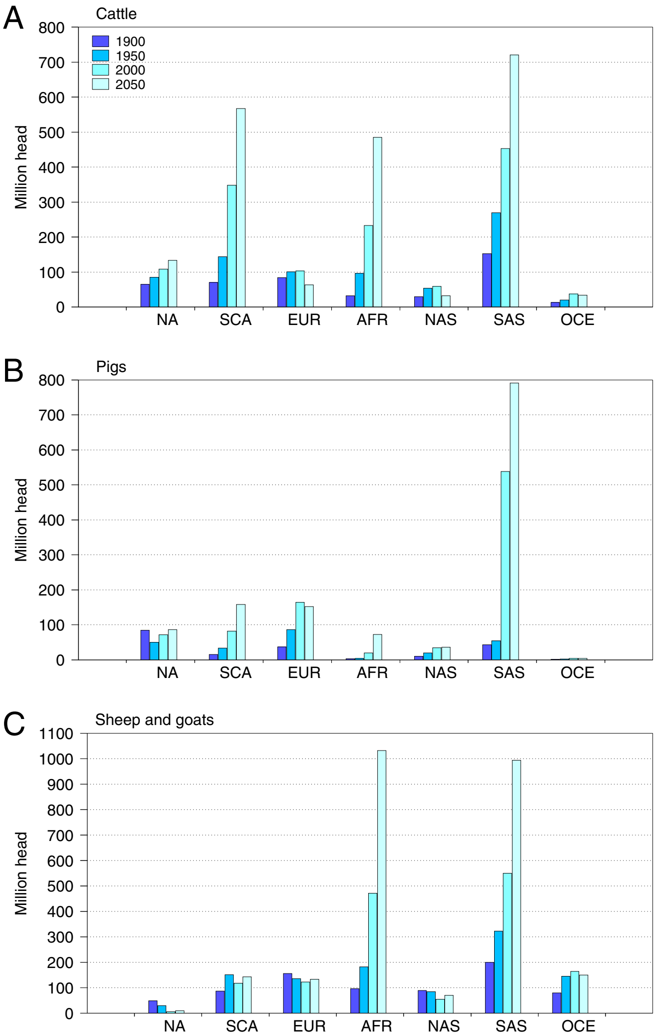

Fig. 1. Global animal stocks for 1900, 1950, 2000, and 2050 for cattle (*A*), pigs (*B*), and sheep and goats (*C*). AFR, Africa; EUR, Europe; NA, North America (Canada, United States); NAS, North Asia (Russian Federation, Belarus, Ukraine, Republic of Moldova); OCE, Oceania (Australia and New Zealand);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

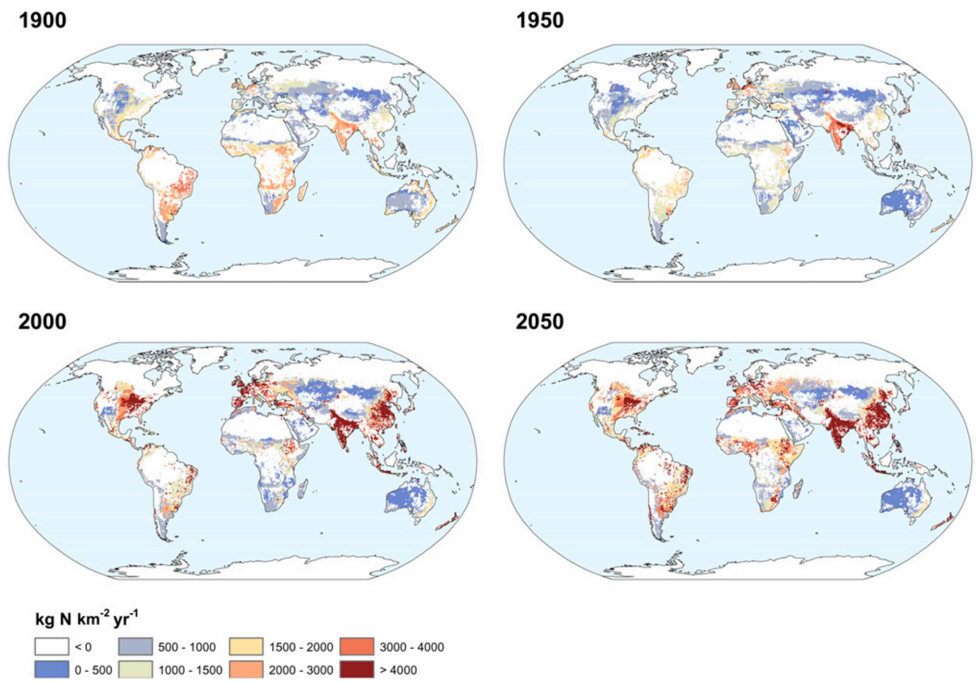

Fig. 2. Agricultural soil N budget for 1900, 1950, 2000, and 2050 (baseline scenario). The soil N budget is calculated using Eq. **1**.

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

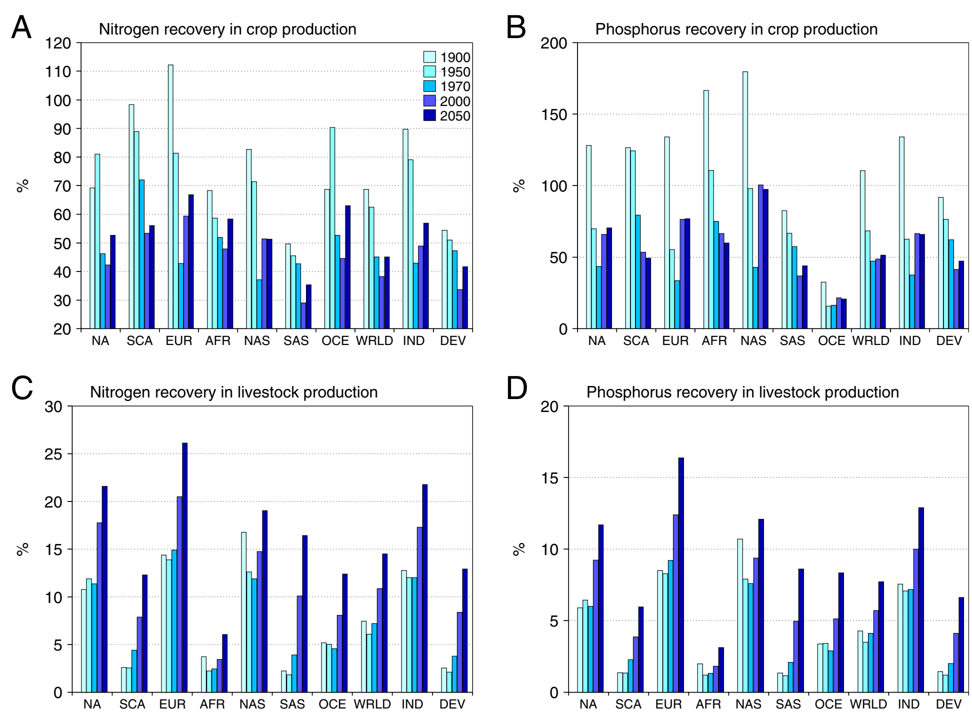

Fig. 3. Global recovery of N and P in crop (*A* and *B*) and livestock (*C* and *D*) production for 1900, 1950, 1970, 2000, and 2050 (IAASTD baseline scenario). Recovery is calculated using Eq. **S5** (crop) and Eq. **S6** (livestock).

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 including N_2O and NO emissions) (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 north-western 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:

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

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.

1. Galloway JN, et al. (2008) Transformation of the nitrogen cycle: Recent trends, questions, and potential solutions. *Science* 320:889–892.
2. Galloway JN, Cowling EB (2002) Reactive nitrogen and the world: 200 years of change. *Ambio* 31:64–71.
3. Diaz RJ, Rosenberg R (2008) Spreading dead zones and consequences for marine ecosystems. *Science* 321:926–929.
4. Howarth RW, et al. (1996) Regional nitrogen budgets and riverine N and P fluxes of the drainages to the North Atlantic Ocean: Natural and human influences. *Biogeochemistry* 35:2235–2240.
5. Vollenweider RA, Marchetti R, Viviani R, eds (1992) *Marine Coastal Eutrophication* (Elsevier, Amsterdam), p 1310.
6. Vollenweider RA (1992) Coastal marine eutrophication: principles and control. *Science of the Total Environment, Supplement 1992: Marine Coastal Eutrophication*, eds Vollenweider RA, Marchetti R, Viviani R (Elsevier, Amsterdam), pp 1–20.
7. Turner RE, Rabalais NN, Justic D, Dortch Q (2003) Global patterns of dissolved N, P and Si in large rivers. *Biogeochemistry* 64:297–317.
8. Rabalais NN, Turner RE, Wiseman WJ, Jr. (2001) Hypoxia in the Gulf of Mexico. *J Environ Qual* 30:320–329.
9. Liu J, et al. (2010) A high-resolution assessment on global nitrogen flows in cropland. *Proc Natl Acad Sci USA* 107:8035–8040.
10. Steinfeld H, et al. (2006) *Livestock's Long Shadow. Environmental Issues and Options* (Food and Agriculture Organization of the United Nations, Rome).
11. Bouwman AF, Beusen AHW, Billen G (2009) Human alteration of the global nitrogen and phosphorus soil balances for the period 1970-2050. *Global Biogeochem Cycles* 23:GB0A04 1–16.
12. Galloway J, et al. (2010) The impacts of animal production systems on the nitrogen cycle. *Livestock in a Changing Landscape. Drivers, Consequences and Repsonses*, eds Steinfeld H, Mooney HA, Schneider F, Neville LE (Island Press, Washington, DC), pp 83–95.
13. Seré C, Steinfeld H (1996) *World Livestock Production Systems. Current Status, Issues and Trends* (Food and Agriculture Organization of the United Nations, Rome), p 83.
14. Van der Hoek KW (1998) Nitrogen efficiency in global animal production. *Nitrogen, the Confer-N-s*, eds Van der Hoek KW, Erisman JW, Smeulders S, Wisniewski JR, Wisniewski J (Elsevier, Amsterdam), pp 127–132.
15. United Nations (2009) *World Population Prospects: The 2008 Revision* (United Nations Department for Economic and Social Affairs, New York) Available at: http://esa.un.org/unpp/. Accessed February 2, 2011.
16. Delgado C, Rosegrant M, Steinfeld H, Ehui S, Courbois V (1999) *Livestock to 2020. The Next Food Revolution* (International Food Policy Research Institute, Food and Agriculture Organization of the United Nations, International Livestock Research Institute, Washington, DC).
17. Syers JK, Johnston AA, Curtin D (2008) *Efficiency of Soil and Fertilizer Phosphorous Use. Reconciling Changing Concepts of Soil Phosphorous Behaviour with Agronomic Information* (Food and Agriculture Organization of the United Nations, Rome), p 110.
18. McIntyre BD, Herren HR, Wakhungu J, Watson RT (2009) *International Assessment of Agricultural Knowledge, Science and Technology for Development (IAASTD): Global Report* (Island Press, Washington, DC), p 590.
19. Herridge DF, Peoples MB, Boddey RM (2008) Global inputs of biological nitrogen fixation in agricultural systems. *Plant Soil* 311:1–18.
20. Salviagiotti F, et al. (2008) Nitrogen uptake, fixation and response to fertilizer N in soybeans: A review. *Field Crops Res* 108:1–13.
21. Grigg D (1987) The industrial revolution and land transformation. *Land Transformation in Agriculture*, eds Wolman MG, Fournier FGA (John Wiley and Sons, New York), pp 70–109.
22. de Wit C, Huisman H, Rabbinge R (1987) Agriculture and its environment: Are there other ways. *Agric Syst* 23:211–236.
23. Olson RA (1987) The use of fertilizers and soil amendments. *Land transformation in agriculture*, eds Wolman MG, Fournier FGA (Wiley, New York), pp 203–226.
24. Smil V (2001) *Enriching the Earth: Fritz Haber, Carl Bosch, and the Transformation of World Food* (MIT Press, Cambridge, MA).
25. FAO (1951) *Yearbook of Food and Agricultural Statistics 1950. Production* (Food and Agriculture Organization of the United Nations, Washington, DC), Part I, Vol. IV.
26. FAO (2008) FAOSTAT Database Collections (Food and Agriculture Organization of the United Nations, Rome).
27. Dobermann A, Cassman KG (2005) Cereal area and nitrogen use efficiency are drivers of future nitrogen fertilizer consumption. *Sci China C Life Sci* 48 (Suppl 2):745–758.
28. Giller KE, et al. (2004) Emerging technologies to increase the efficiency of use of fertilizer nitrogen. *Agriculture and the Nitrogen Cycle*, eds Mosier AR, Syers JK, Freney JR (Island Press, Washington, DC), pp 35–51.
29. Dobermann A, Cassman KG (2004) Environmental dimensions of fertilizer nitrogen: What can be done to increase nitrogen use efficiency and ensure global food security. *Agriculture and the Nitrogen Cycle*, eds Mosier AR, Syers JK, Freney JR (Island Press, Washington, DC), pp 261–278.
30. Stehfest E, et al. (2009) Climate benefits of changing diet. *Clim Change* 95:83–102.
31. Rosegrant MW, Cai X, Cline SA (2002) *World Water and Food to 2025: Dealing with Scarcity* (International Food Policy Research Institute, Washington, DC).
32. Bouwman AF, Kram T, Klein Goldewijk K (2006) *Integrated Modelling of Global Environmental Change. An Overview of IMAGE 2.4* (Netherlands Environmental Assessment Agency, Bilthoven, The Netherlands) Publication 500110002/2006, p 228.
33. Abelson PH (1999) A potential phosphate crisis. *Science* 283:2015.

Supporting Information

Supporting Information Corrected February 19, 2013

Bowwman et al. 10.1073/pnas.1012878108

SI Text

Data Availability. The following data are available (www.pbl.nl/en/publications/2011/exploring-global-changes-in-nitrogen-and-phosphorus-cycles-in-agriculture-induced-by-livestock-production-over) for all years (1900, 1950, 2000, and 2050), the baseline, and variants: (*a*) 0.5° × 0.5° land cover maps (upland crops, legumes, wetland rice, grassland in mixed systems, and pastoral grassland), (*b*) input files (nutdata_year_scenario.csv and uptake_year_scenario.csv), and (*c*) execution and documentation of the nutrient budget and emission model. The complete datasets of the Integrated Model to Assess the Global Environment (IMAGE) as published in the IAASTD reports can be requested from the corresponding author.

The data are provided for reproducing the results presented here. Anyone can use these files for noncommercial academic research only. If you want to make a buck off of these files, get in touch and we will talk. We would appreciate a short description of what you are planning to do with the data. If you feel that this dataset is a major contribution to your research, we would like to be coauthor on any manuscript. If the data are being included in a published manuscript, we would like to see a preprint before submission to make sure the data description is correct.

Calculation of N and P Budgets. ***General.*** Because we focused on the geographical distribution of the fate of N and P in the environment, the soil budget approach considering all relevant input and output terms for a given land area is more appropriate than a farm-gate or system budget (1).

Livestock rations (consisting of feed crops, crop residues, grass, and other feedstuffs) are calculated from animal productivity, FE (kilograms of feed per kilogram of product), and feed ration (2). Grassland areas are calculated on the basis of the grazing intensity, which is the grass consumption/production ratio within a country or world region.

For allocating nutrient inputs, the crop groups of IMAGE (temperate cereals, rice, maize, tropical cereals, pulses, roots and tubers, oil crops, and other crops) are aggregated to form five broad groups, including grassland, wetland rice, leguminous crops (pulses, soybeans), other upland crops, and energy crops. Areas of grassland receiving synthetic fertilizers are within the area of mixed agricultural systems.

We used the nutrient budget and emission model of IMAGE (3), which has been used to develop the land cover and climate scenarios for the IAASTD land cover projection. This model is spatially explicit, with a 0.5° × 0.5° resolution in this study, and uses country-specific for all countries and subnational for the United States and China data to estimate N and P soil budgets according to Eq. **1** and gaseous emissions of NH_3, N_2O, NO, and N_2 and NO_3-N leaching. We used the model to analyze the impact of changes in management in the livestock and crop production system on the N cascade (4) and the fate of P for the historical years 1900, 1950, and 2000; for the period 2000–2050, data on land cover and data on food and livestock production from the IAASTD study (5) are used.

For calculating spatially explicit soil nutrient budgets for the IAASTD scenarios, a procedure is used to downscale regional data to country estimates for fertilizer use and livestock production varying around the projection "Agriculture Towards 2030" of the Food and Agriculture Organization of the United Nations (FAO) (6). With this method, the scenarios will have the same distribution for countries within a world region as in the FAO study.

The calculation of the individual terms of the soil nutrient budget and the historical data used are discussed below.

Animal manure. Total manure production within pastoral and mixed and industrial systems is computed from the animal stocks and N and P excretion rates. We used N excretion rates per head for dairy and nondairy cattle, buffaloes, sheep and goats, pigs, poultry, horses, asses, mules, and camels (1, 7). P excretion rates are based on various sources (8–12). We used constant excretion rates (except for 1900 and 1950, as discussed in the section on historical data), such that the N and P excretion per unit of product decreases with increasing milk and meat production per animal. For the years 1900 and 1950, we assumed that excretion rates for all countries are equal to those of developing countries in 2000, reflecting the low levels of animal productivities in the first part of the 20th century (13).

For each country, animal stocks and N and P in the manure for each animal category are spatially allocated within mixed and pastoral systems. For the period 2000–2050, the distribution over these systems is provided by the IAASTD study. To obtain the distribution over these systems in 1950, we assumed that the shift of the production from pastoral to mixed and industrial systems during the period 1950–1970 is one-half of that estimated for 1970–2000 (2). For 1900, we assumed that the change during 1900–1950 is one-half of that during 1950–1970. Within each country and system, the manure is distributed over different management systems: (*i*) grazing or excretion in the meadow or field (N_{gra} and P_{gra}), (*ii*) storage in animal housing and storage systems (N_{sto} and P_{sto}), and (*iii*) manure ending outside the agricultural system (N_{out} and P_{out}). N_{out} and P_{out} include manure excreted outside the agricultural system, for example, in urban areas, forests, and along roadsides or manure collected in lagoons (2) and manure used as fuel or for other purposes (14). Total N excretion, N_{exc}, is thus:

$$N_{exc} = N_{gra} + N_{sto} + N_{out} \qquad \textbf{[S1]}$$

Animal manure available for application to crops and grassland (N_{man}) includes all stored or collected manure, excluding NH_3 volatilization from animal houses and storage systems. Finally, we have to correct for NH_3 volatilization from animal housing and ST systems ($N_{vol,sto}$) (15). The input of manure for the soil budget (Eq. **1**) therefore excludes N_{out} and P_{out} as well as $N_{vol,sto}$. N_{man} is calculated as follows:

$$N_{man} = N_{exc} - N_{out} - N_{vol,sto} \qquad \textbf{[S2]}$$

$N_{vol,sto}$ is 20% of the N in the manure in animal housing and storage systems (15). We assumed that in most industrialized countries, 50% of the available animal manure from storage systems ($N_{sto} - N_{vol,sto}$) is applied to arable land and the remainder to grassland (16). In most developing countries, 95% of the available manure is assumed to be applied to cropland and 5% to grassland, thus accounting for stubble grazing and manure excretion in croplands as well as the lower economic importance of grass compared with crops in developing countries (17). For European Union countries, we used maximum application rates of 17,000–25,000 kg of N $km^{-2} \cdot y^{-1}$ based on existing regulations.

For substitution of fertilizer by animal manure, we assumed an effectivity. Because the N in animal manure is partly present in organic form, we assume that 60% is effectively available for plant uptake. The remainder is lost through NH_3 volatilization, is added to the soil N reserve, or is decomposed gradually and lost through leaching and denitrification (18).

Fertilizer. 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), which represents the production in grams of dry matter per gram of fertilizer N or P (19–21). This is the broadest measure of NUE, also called the partial factor productivity of the applied fertilizer N (19, 20). NUE and PUE are apparent fertilizer use efficiencies because they incorporate the contributions of indigenous soil N, fertilizer uptake efficiency, and the efficiency of conversion of uptake to harvested product. NUE and PUE vary among countries because of differences in the crop mix, their attainable yield potential, soil quality, amount and form of N and P application, and management. For example, very high values in many African and Latin American countries reflect current low fertilizer application rates; in many industrialized countries with intensive high-input agricultural systems, the NUE and PUE values are much lower. In contrast, countries in Eastern Europe and the former Soviet Union had a rapid decrease in fertilizer use after 1990, causing a strong apparent increase in the fertilizer use efficiency (Fig. S5).

We aggregated fertilizer use and production data to calculate NUE and PUE for the broad categories of wetland rice, leguminous crops, upland crops, and energy crops (Fig. S5). For constructing the fertilizer scenarios for these crop categories, we use data from Bruinsma (6) as a guide. We divided the world into countries with inputs exceeding the crop uptake (positive budget or surplus) and countries with current deficit. Generally, in the IAASTD scenarios, farmers in countries with a surplus are motivated to be increasingly efficient in the use of fertilizers. Especially for China, we assumed a rapid decrease of the use of P fertilizers to levels comparable to Europe and North America. In countries with nutrient deficits, we assumed that NUE and PUE for upland crops will gradually decrease to a varying degree, which portrays a decrease of soil nutrient depletion attributable to increasing fertilizer use.

Biological N_2 fixation. Biological N_2 fixation by pulses and soybeans is calculated from crop production data (22) and N content. Total biological N_2 fixation in biomass during the growing season of pulses and soybeans is calculated by multiplying the N in the harvested product by a factor of 2 to account for all above- and below-ground plant parts (23). Any change in the rate of biological N_2 fixation by legumes is thus the result of the development of yields of pulses and soybeans.

We used a rate of nonsymbiotic biological N_2 fixation of 500 $kg{\cdot}km^{-2}{\cdot}y^{-1}$ of N for nonleguminous crops and grassland and 2,500 kg·km−2·y−1 of N for wetland rice (24). The total biological fixation of N_2 thus depends on the total production of pulses as well as the areas of grassland and cropland.

Our estimate for total biological N_2 fixation for 2000 is the low end of the range presented elsewhere (25). However, the contribution of N_2 fixation to crop N demand is uncertain (25, 26).

Atmospheric deposition. Atmospheric N deposition rates (including dry and wet deposition of NH_x and NO_y) for the year 2000 are obtained from an ensemble of atmospheric chemistry-transport models (27). Deposition rates for historical and future years are calculated by scaling the N deposition field for the year 2000 using emission inventories for the historical period and emission scenarios for N gases from the implementation of the IAASTD scenarios with the IMAGE model. Historical emissions from agriculture are generated according to calculations described below. For all other sources, we used data from an emission inventory made for the historical emission pathways and new scenarios for climate research (Representative Concentration Pathways) (28). We ignored atmospheric P deposition.

Nutrient withdrawal. N and P withdrawal in harvested crops is based on country crop production data; for the United States and China, subnational data are used. The withdrawal of N and P in the harvested products is calculated from the crop production and N and P content for each crop (2) and then aggregated to the broad categories of wetland rice, leguminous crops, upland crops, and energy crops. We also account for uptake by fodder crops. N withdrawal by grass consumption and harvest is assumed to be 60% of all N input (manure, fertilizer, deposition, and N fixation), excluding NH_3 volatilization (21). P withdrawal by grazing or grass cutting is calculated as a fraction of 87.5% of fertilizer and manure P inputs. The complement is assumed to be lost through surface runoff, which is obtained from the increase of total P river export (excluding the contribution of sewage) between 1970 and 2000 (29), wherein this increase is entirely attributed to agricultural activities. This estimate is corrected for the global average P retention of 20% in river systems (30) to arrive at a field loss by surface runoff of 12.5% of fertilizer and manure inputs of P.

Potential N loss. The potential N loss from the plant-soil system to the soil-hydrological system, N_{pot}, is calculated as the difference between N_{budget} and the NH_3 volatilization (N_{vol}) from excretion during grazing ($N_{vol,gra}$) and from spreading of manure ($N_{vol,spr}$):

$$N_{pot} = N_{budget} - N_{vol,gra} - N_{vol,spr} \quad \text{[S3]}$$

NH_3 volatilization in the field. NH_3 volatilization for grazing systems ($N_{vol,gra}$) (depending on animal category and climate) is based on emission factors for 10 animal categories (15). Volatilization from the spreading of animal manure ($N_{vol,spr}$) is calculated with an empirical model based on crop type, fertilizer type, manure or fertilizer application mode, soil cation exchange capacity, soil pH, and climate (31). As a default, we assume that all manure applied to crops is incorporated and that manure applied in grassland is broadcast. In the model, incorporation leads to considerable reductions of NH_3 loss of up to 50% compared with broadcasting (31).

Denitrification and N_2O and NO emission. Denitrification in soil is calculated as an empirical fraction, f_{den}, (32) of N_{pot} according to:

$$N_{den} = f_{den}\, N_{pot} \quad \text{[S4]}$$

We use default emission factors (33) for estimating the N_2O emission from animal manure storage and grazing systems and indirect emissions of N_2O from groundwater and surface water stemming from N leached from soils.

Direct N_2O and NO emissions from fertilizer application and spreading of animal manure are calculated with residual maximum likelihood (REML) models (34). For N_2O, the REML model is based on 846 series of measurements in agricultural fields; for NO, the REML model is based on 99 measurements (34). For N_2O, the model is based on the following: (*i*) environmental factors [climate, soil organic C content, soil texture, drainage, and soil pH (35, 36)], (*ii*) management-related factors (N application rate per fertilizer type and type of crop, with major differences between grass, legumes, and other annual crops), and (*iii*) factors related to the measurements (length of measurement period and frequency of measurements). The factors used for calculating NO emissions include the N application rate per fertilizer type, soil organic carbon content, and soil drainage.

Uncertainties. The budget calculations and individual input terms for the year 2000 were found to be in good agreement (21), with detailed country estimates for the member countries of the Organization for Economic Cooperation and Development (37). However, it is clear that the uncertainty in some of the budget terms is larger than for others. Data on N and P fertilizer use reported by countries to the FAO (22) are more reliable than N and P excretion by animals, which is calculated from production data (22) and excretion rates. Crop nutrient withdrawal is less certain than crop production reported by the FAO (22). That is because the withdrawal is calculated with fixed global nutrient contents of the harvested parts for marketed crops. Apart from the uncertainty in nutrient contents, major uncertainties arise from lack of data; data on crops that are not marketed but are used on-farm, such as many fodder crops, and on the use of crop residues are not available, and this probably causes major uncertainties in the nutrient withdrawal.

The model used to calculate NH_3 emissions from manure and fertilizer application is based on a large dataset covering a range of environmental and management conditions (31). A sensitivity analysis of the manure distribution and NH_3 emission calculations in IMAGE (38) showed that the most important determinants of the uncertainty in the global agricultural NH_3 emission comprise five parameters: (*i*) N excretion rates, (*ii*) NH_3 emission rates for manure in animal housing and storage systems, (*iii*) the fraction of the time that ruminants graze, (*iv*) the fraction of nonagricultural use of manure specific to mixed and industrial systems, and (*v*) animal stocks.

The remainder of the surplus in the N budget is lost by denitrification or leaching. The uncertainty in our denitrification and leaching estimates is probably larger than in the NH_3 emissions, primarily because of the difficulty in measuring denitrification and lack of monitoring datasets (39).

In the case of a small difference between the sum of inputs and the sum of outputs (e.g., as in many countries in 1900 and 1950), a small change in one of the terms can cause a shift from a positive budget to a negative one, or vice versa.

Nutrient recovery. Various ways to analyze efficiency of nutrient use are available (40). Here, we use nutrient recovery, which can be applied to both crop and livestock production for comparison. The nutrient recovery in crop production is calculated as the withdrawal of nutrients in the harvested crop divided by the sum of the inputs from fertilizer and manure applied to crops (40). For N, the equation for the N recovery, N_{rec}, is:

$$N_{\mathrm{rec,crop}} = \frac{N_{\mathrm{withdr,crop}}}{N_{\mathrm{fert,crop}} + N_{\mathrm{man,crop}} + N_{\mathrm{fix,crop}} + N_{\mathrm{dep}}} 100 \qquad \text{[S5]}$$

We calculate the withdrawal as the sum of all crops, including legumes (Fig. 3). The nutrient recovery in livestock production is calculated as the nutrients in milk and meat production for all animal categories divided by the intake of nutrients. Milk is assumed to have a protein content of 4% of fresh weight, and meat is assumed to have a protein content of 20% of fresh carcass weight. Protein is assumed to have an N content of 16%. The excretion is for the total animal stock, whereas the production represents the meat from slaughtered animals and milk from lactating cows, buffaloes, sheep, and goats. For N, the equation is:

$$N_{\mathrm{rec,livestock}} = \frac{N_{\mathrm{exp,livestock}}}{N_{\mathrm{exc}} + N_{\mathrm{exp,livestock}}} 100 \qquad \text{[S6]}$$

For P, we use values for the different meat and milk categories (41). For cattle meat, pork, poultry meat, and mutton and goat meat, a P content of 0.2% of the production is used, and for milk, a P content of 0.09% is used.

Human excreta. We ignored recycling of human excreta and other waste materials containing nutrients. Human excreta were probably an important source of nutrients in many parts of the world. For example, in China, human excreta may have contributed 0.6 $Tg{\cdot}y^{-1}$ of N in 1900 from the 400 million inhabitants, assuming an excretion rate of 2 $kg{\cdot}y^{-1}$ of N per inhabitant (42) and an NH_3 loss of 20%. This would add to the 3.6 $T{\cdot}y^{-1}$ of N in animal manure in China.

Historical data. Country animal stocks for 1900 and 1950 are taken from Mitchell (43–45). Complete datasets are available for cattle, buffaloes, pigs, sheep and goats, horses, asses, and mules. To obtain the stocks of beef cattle and milking cows, we used the same ratios to total cattle as in 1970 (22). Data for poultry and camels are scant. We therefore used human population data for 1900 and 1950 from HYDE (46) to scale the animal stocks for these categories. For both animal categories, this yielded a fair agreement with the incomplete data from Mitchell (43–45). Land cover data are taken from HYDE (47) as a basis for distributing the animal stocks and nutrients. Crop uptake for calculating the nutrient budgets for 1900 and 1950 is obtained by scaling the 1960 crop production data for temperate cereals, rice, maize, tropical cereals, pulses, roots and tubers, oil crops, and other crops with population numbers from the HYDE data (46). For livestock production, we used data from the FAO (13) for 1950 (except for the former Soviet Union and Africa, for which we scaled the 1960 production data), and for 1900, the data were downscaled using population numbers. Results thus obtained are in good agreement with the data for 1950 from the FAO (13). Fertilizer use for 1950 is taken from the FAO (13). For the year 1900, we used country data on the use of fixed N (industrially produced N fertilizer, Chili nitrate, guano, coke-oven ammonium sulfate, calcium cyanamide, and electric-arc calcium nitrate) for 1913 (48) and assumed that the use in each country in 1900 is 80% of that in 1913. For the year 2000, we used country data on total synthetic fertilizer consumption and crop production and animal stocks (22) and N and P fertilizer use by crop (49).

1. Van der Hoek KW, Bouwman AF (1999) Upscaling of nutrient budgets from agroecological niche to global scale. *Nutrient Disequilibria in Agroecosystems*, eds Smaling EMA, Oenema O, Fresco LO (CAB International, Wallingford, NY), pp 57–73.
2. Bouwman AF, Van der Hoek KW, Eickhout B, Soenario I (2005) Exploring changes in world ruminant production systems. *Agricultural Systems* 84:121–153.
3. Bouwman AF, Kram T, Klein Goldewijk K (2006) *Integrated Modelling of Global Environmental Change. An Overview of IMAGE 2.4* (Netherlands Environmental Assessment Agency, Bilthoven, The Netherlands), Publication 500110002/2006, p 228.
4. Galloway JN, et al. (2003) The nitrogen cascade. *Bioscience* 53:341–356.
5. McIntyre BD, Herren HR, Wakhungu J, Watson RT (2009) *International Assessment of Agricultural Knowledge, Science and Technology for Development (IAASTD): Global Report* (Island Press, Washington, DC), p 590.
6. Bruinsma JE (2003) *World Agriculture: Towards 2015/2030. An FAO Perspective* (Earthscan, London), p 432.
7. Van der Hoek KW (1998) Nitrogen efficiency in global animal production. *Nitrogen, the Confer-N-s*, eds Van der Hoek KW, Erisman JW, Smeulders S, Wisniewski JR, Wisniewski J (Elsevier, Amsterdam), pp 127–132.
8. Service MP (1985) *Livestock Waste Facilities Handbook* (Iowa State Univ, Ames, IA), 2nd Ed.
9. Sheldrick W, Syers JK, Lingard J (2003) Contribution of livestock excreta to nutrient balances. *Nutr Cycl Agroecosyst* 66:119–131.
10. Smith LW (1991) Production systems. *Handbook of Animal Science*, ed Putnam PA (Academic, San Diego), pp 280–291.
11. Van Horn HH, Newton GL, Kunkle WE (1996) Ruminant nutrition from an environmental perspective: Factors affecting whole-farm nutrient balance. *J Anim Sci* 74:3082–3102.
12. Wilkerson VA, Mertens DR, Casper DP (1997) Prediction of excretion of manure and nitrogen by Holstein dairy cattle. *J Dairy Sci* 80:3193–3204.
13. FAO (1951) *Yearbook of Food and Agricultural Statistics 1950. Production* (Food and Agriculture Organization of the United Nations, Washington, DC), Part 1, Vol IV.
14. Mosier A, et al. (1998) Closing the global N2O budget: Nitrous oxide emissions through the agricultural nitrogen cycle. *Nutr Cycl Agroecosyst* 52:225–248.
15. Bouwman AF, et al. (1997) A global high-resolution emission inventory for ammonia. *Global Biogeochem Cycles* 11:561–587.
16. Lee DS, et al. (1997) Emissions of nitric oxide and ammonia from grasslands on a global scale. *Gaseous Nitrogen Emissions from Grasslands*, eds Jarvis SC, Pain BF (CAB International, Wallingford, NY), pp 353–371.
17. Seré C, Steinfeld H (1996) *World Livestock Production Systems. Current Status, Issues and Trends* (Food and Agriculture Organization of the United Nations, Rome), p 83.
18. Janssen BH, Oenema O (2008) Global economics of nutrient cycling. *Turk J Agric For* 32:165–176.
19. Dobermann A, Cassman KG (2005) Cereal area and nitrogen use efficiency are drivers of future nitrogen fertilizer consumption. *Sci China C Life Sci* 48(Suppl 2): 745–758.
20. Dobermann A, Cassman KG (2004) Environmental dimensions of fertilizer nitrogen: What can be done to increase nitrogen use efficiency and ensure global food security. *Agriculture and the Nitrogen Cycle*, eds Mosier AR, Syers JK, Freney JR (Island Press, Washington, DC), pp 261–278.
21. Bouwman AF, Beusen AHW, Billen G (2009) Human alteration of the global nitrogen and phosphorus soil balances for the period 1970-2050. *Global Biogeochem Cycles* 23:GB0A04 1–16.

22. FAO (2008) *FAOSTAT Database Collections* (Food and Agriculture Organization of the United Nations, Rome).
23. Mosier AR, et al. (1998) Closing the global atmospheric N2O budget: Nitrous oxide emissions through the agricultural nitrogen cycle. *Nutr Cycl Agroecosyst* 52: 225–248.
24. Smil V (1999) Nitrogen in crop production: An account of global flows. *Global Biogeochem Cycles* 13:647–662.
25. Herridge DF, Peoples MB, Boddey RM (2008) Global inputs of biological nitrogen fixation in agricultural systems. *Plant Soil* 311:1–18.
26. Salviagiotti F, et al. (2008) Nitrogen uptake, fixation and response to fertilizer N in soybeans: A review. *Field Crops Res* 108:1–13.
27. Dentener F, et al. (2006) The global atmospheric environment for the next generation. *Environ Sci Technol* 40:3586–3594.
28. Hurtt GC, et al. (2009) Harmonization of global land-use scenarios for the period 1500-2100 for IPCC-AR5. *iLEAPS Newsletter* 7:6–8.
29. Seitzinger SP, et al. (2010) Global river nutrient export: A scenario analysis of past and future trends. *Global Biogeochem Cycles* 24:GB0A08 1–16.
30. Harrison J, et al. (2005) Dissolved inorganic phosphorus export to the coastal zone: Results from a spatially explicit, global model (NEWS-DIP). *Global Biogeochem Cycles* 19:GB4S03 1–15.
31. Bouwman AF, Boumans LJM, Batjes NH (2002) Estimation of global NH3 volatilization loss from synthetic fertilizers and animal manure applied to arable lands and grasslands. *Global Biogeochemical Cycles* 16:1024 8.1–8.14.
32. Van Drecht G, Bouwman AF, Knoop JM, Beusen AHW, Meinardi CR (2003) Global modeling of the fate of nitrogen from point and nonpoint sources in soils, groundwater and surface water. *Global Biogeochem Cycles* 17:1115 26.1–26.20.
33. IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories. IPCC NGGIP Programme, IPCC-TSU/IGES* (Institute for Global Environmental Strategies, Hayama, Japan on behalf of the IPCC, Hayama, Japan).
34. Bouwman AF, Boumans LJM, Batjes NH (2002) Modeling global annual N2O and NO emissions from fertilized fields. *Global Biogeochemical Cycles* 16:1080 28.1–28.9.
35. Batjes NH (1997) A world dataset of derived soil properties by FAO-UNESCO soil unit for global modelling. *Soil Use Manage* 13:9–16.
36. Batjes NH (2002) Revised soil parameter estimates for the soil types of the world. *Soil Use Manage* 18:232–235.
37. OECD (2008) *Environmental Performance of Agriculture in OECD Countries Since 1990* (Organisation for Economic Co-operation and Development, Environment Directorate, Paris), p 575.
38. Beusen AHW, Bouwman AF, Heuberger PSC, Van Drecht G, Van Der Hoek KW (2008) Bottom-up uncertainty estimates of global ammonia emissions from global agricultural production systems. *Atmos Environ* 42:6067–6077.
39. Hofstra N, Bouwman AF (2005) Denitrification in agricultural soils: Summarizing published data and estimating global annual rates. *Nutr Cycl Agroecosyst* 72:268–278.
40. Ladha JK, Pathal H, Krupnik TJ, Six J, Van Kessel C (2005) Efficiency of fertilizer nitrogen in cereal production: Retrospects and prospects. *Adv Agron* 87:85–156.
41. USDA (2009) *USDA National Nutrient Database for Standard Reference* (United States Department of Agriculture, Washington, DC).
42. Van Drecht G, Bouwman AF, Harrison J, Knoop JM (2009) Global nitrogen and phosphate in urban waste water for the period 1970-2050. *Global Biogeochem Cycles* 23:GB0A03 1–19.
43. Mitchell BR (1993) *International Historical Statistics, The Americas: 1750-1988* (MacMillan, Indianapolis) p 817.
44. Mitchell BR (1993) *International Historical Statistics, Africa, Asia & Oceania: 1750-1993* (MacMillan, Indianapolis), 3rd Ed, p 1113.
45. Mitchell BR (1998) *International Historical Statistics, Europe: 1750-1993* (MacMillan, Indianapolis), 4th Ed, p 817.
46. Klein Goldewijk K, Beusen A, Janssen P (2010) Long term dynamic modeling of global population and built-up area in a spatially explicit way: HYDE 3.1. *Holocene* 20: 565–573.
47. Klein Goldewijk K, Beusen A, van Drecht G, de Vos M (2010) The HYDE 3.1 spatially explicit database of human induced land use change over the past 12,000 years. *Glob Ecol Biogeogr* 20:73–86.
48. Cressy Morrison A (1937) *Man in a Chemical World. The Service of Chemical Industry* (C. Scribner's Sons, New York).
49. IFA/IFDC/FAO (2003) *Fertilizer Use by Crop* (Food and Agriculture Organization of the United Nations, Rome), 5th Ed.

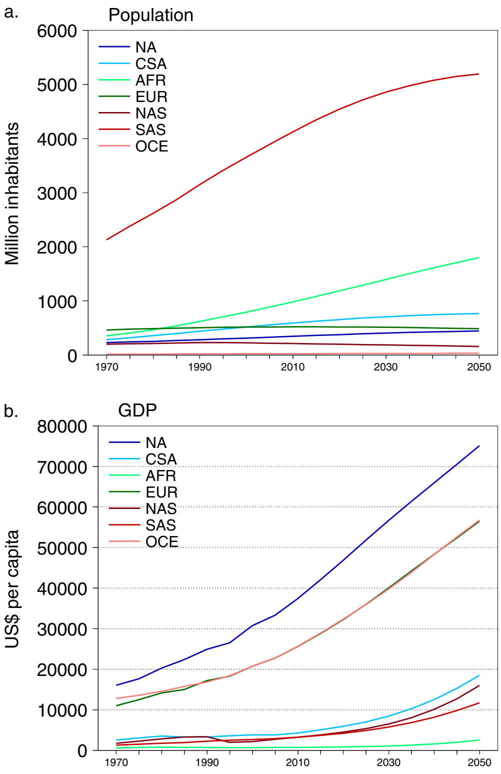

Fig. S1. Population (*A*) and income (*B*) projections. Regions are as shown in Fig. 1. Caput = head.

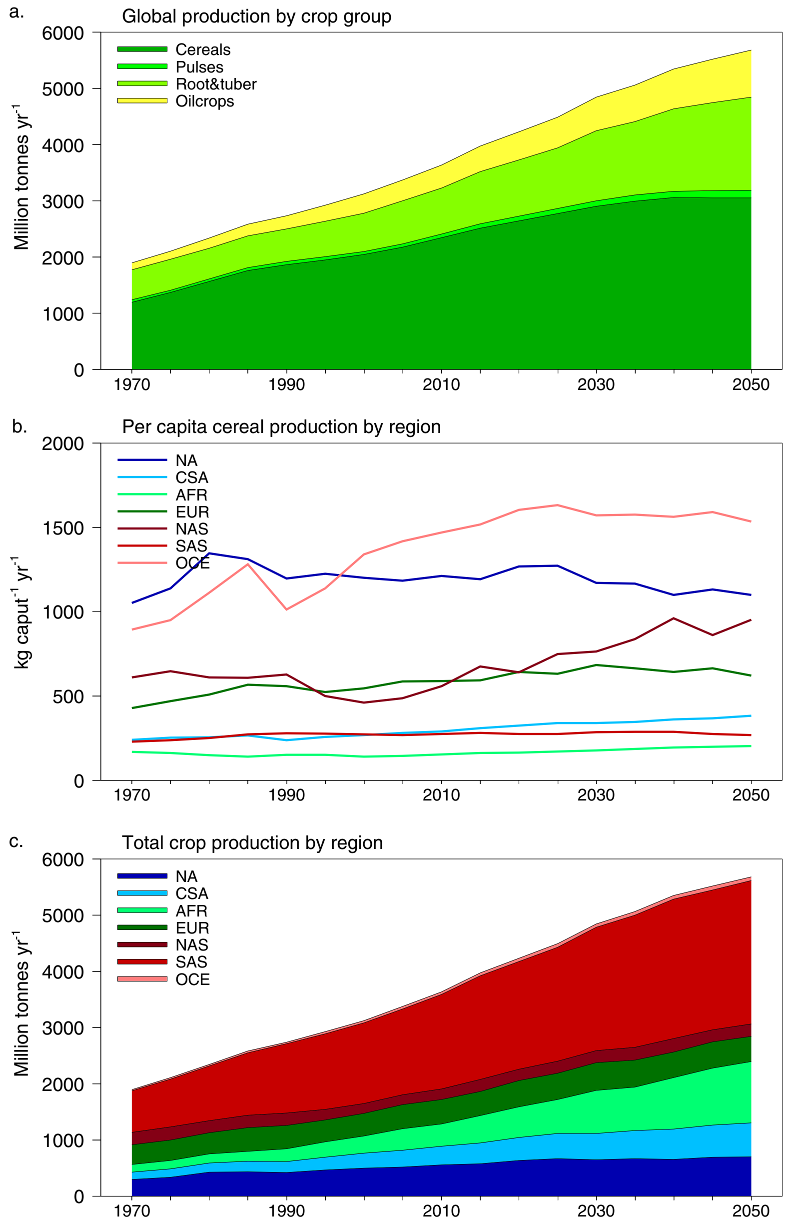

Fig. S2. Crop production by crop (*A*), per capita (*B*), and total crop production by world region (*C*). Regions are as shown in Fig. 1. Tonne = metric tonne = 10^6 g; caput = head.

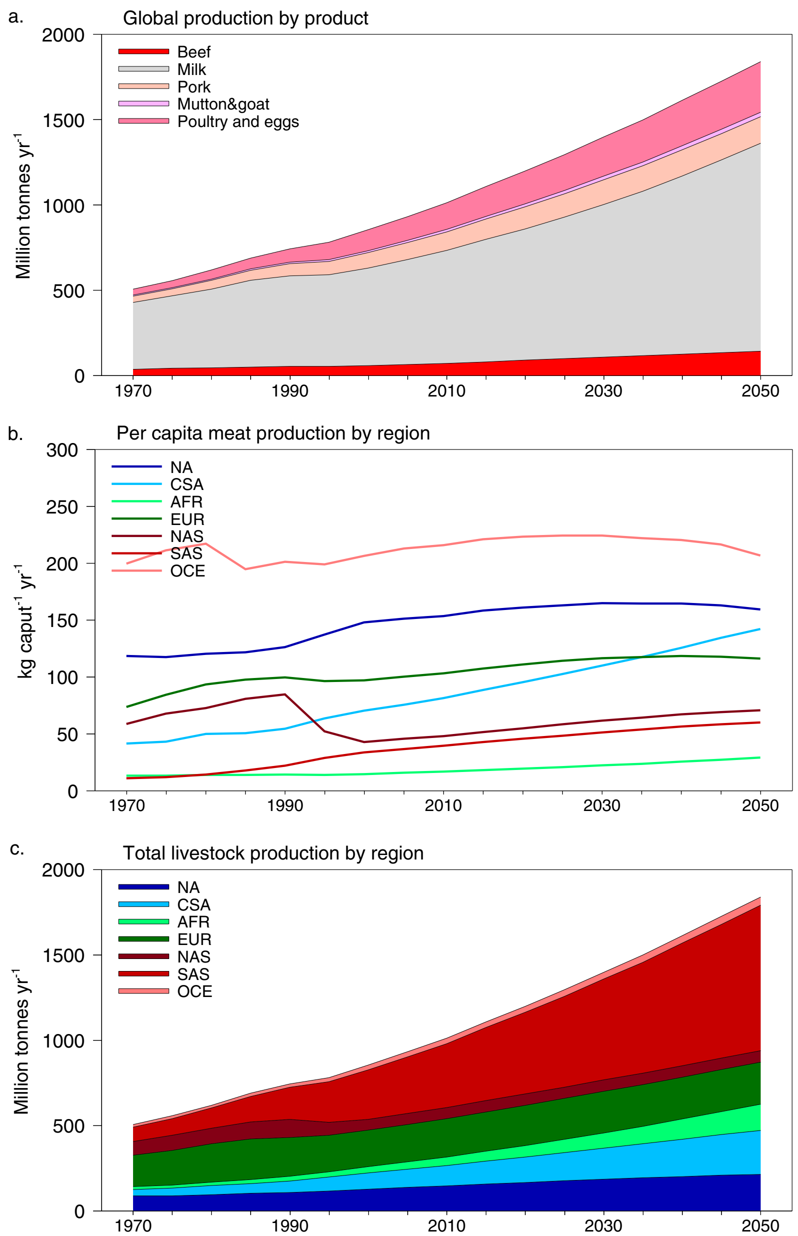

Fig. S3. Livestock production in by category (*A*) and per capita (*B*), and total livestock production by world region (*C*). Regions are as shown in Fig. 1. Tonne = metric tonne = 10^6 g; caput = head.

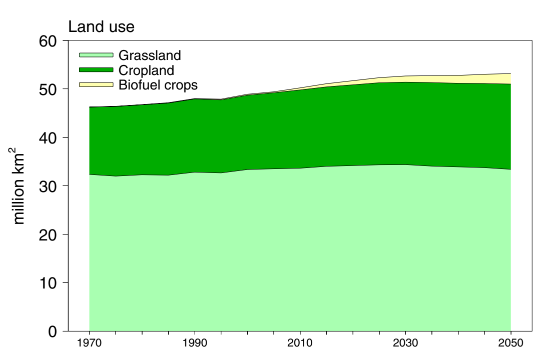

Fig. S4. Global land area for agriculture production.

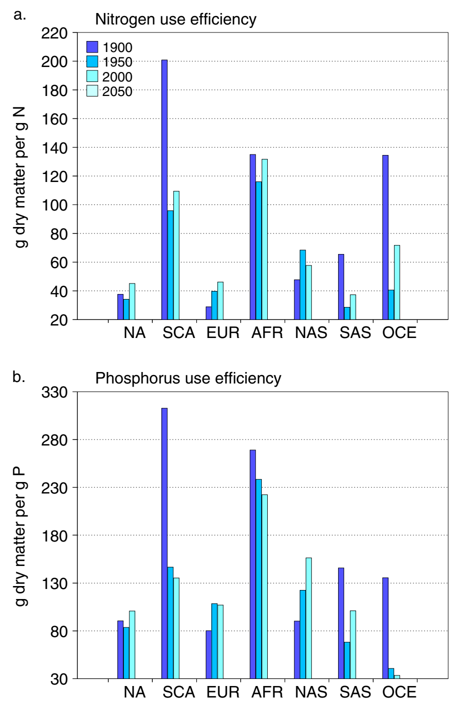

Fig. S5. N (*A*) and P (*B*) fertilizer use efficiency for different regions of the world. The data for 2050 represent the IAASTD baseline. Regions are as shown in Fig. 1.

Table S1. Annual N and P inputs from fertilizer, manure (excluding NH_3 emission from animal houses and storage systems), biological N_2 fixation and atmospheric N deposition, and N and P surplus per square kilometer of total agricultural land for the world and different regions of the world* for the IAASTD baseline for 2050

	World region							
Balance term	North America	South and Central America	Europe	Africa	North Asia	South Asia	Oceania	World
N, $kg \cdot km^{-2} \cdot y^{-1}$								
Fertilizer	2,361	746	5,519	589	988	4,234	308	2,165
Manure	2,010	3,118	3,509	2,839	762	3,561	707	2,880
N_2 fixation	1,458	1,393	774	656	537	1,304	527	1,130
Deposition	656	689	1,030	698	731	1,756	162	1,024
Total N inputs	6,486	5,946	10,833	4,782	3,018	10,856	1,703	7,199
Withdrawal	3,493	3,571	6,477	3,280	1,304	4,165	931	3,662
Surplus	2,993	2,375	4,356	1,502	1,714	6,691	773	3,537
P, $kg \cdot km^{-2} \cdot y^{-1}$								
Fertilizer	476	405	930	165	159	770	273	480
Manure	401	576	668	498	144	714	119	545
Total P inputs	877	980	1,597	662	302	1,484	392	1,025
Withdrawal	668	636	1,295	503	244	744	154	644
Surplus	209	344	303	160	58	739	237	380

*Fig. 1.