Supporting Information

Supporting Information Corrected February 19, 2013

Bouwman et al. 10.1073/pnas.1012878108

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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:

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

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:

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

$N_{vol,sto}$ 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}·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 $kg{\cdot}km^{-}2{\cdot}y^{-1}$ 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 ($N_{vol,spr}$):

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

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:

$$N_{den} = f_{den}\, N_{pot} \qquad \textbf{[S4]}$$

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:

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

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:

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

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).

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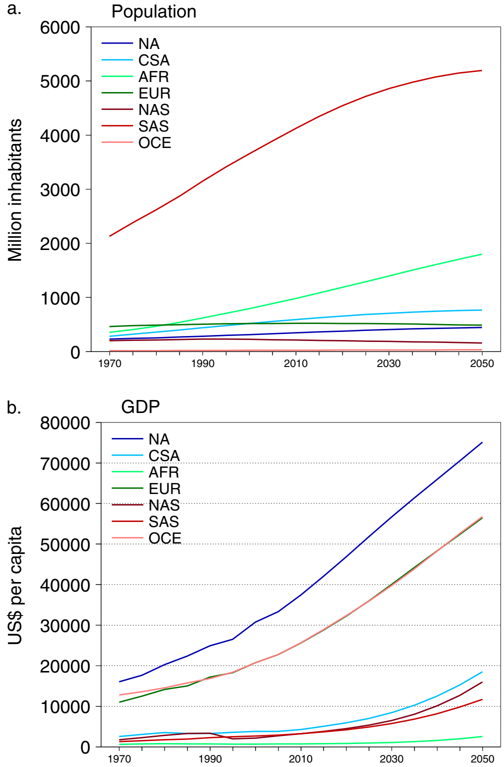

Fig. S1. Population (*A*) and income (*B*) projections. Regions are as shown in Fig. 1. Caput = head.

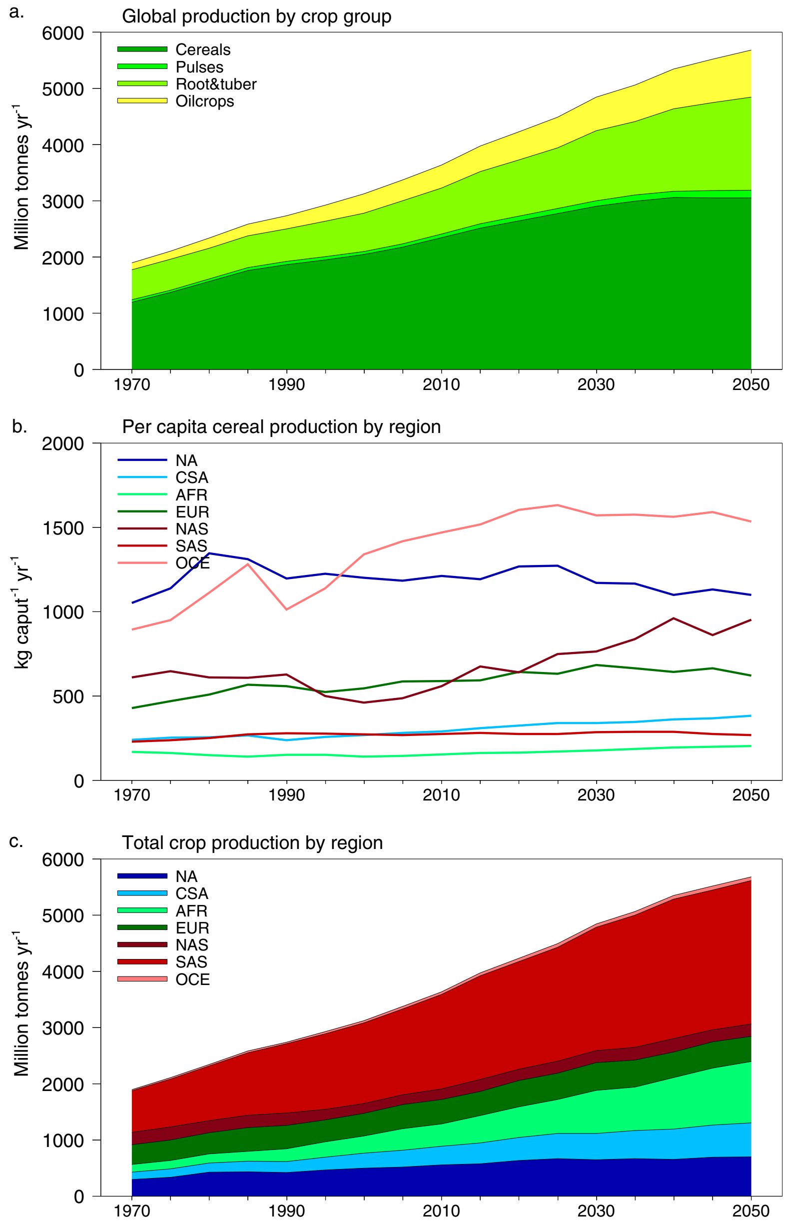

Fig. S2. Crop production by crop (*A*), per capita (*B*), and total crop production by world region (*C*). Regions are as shown in Fig. 1. Tonne = metric tonne = 10^6 g; caput = head.

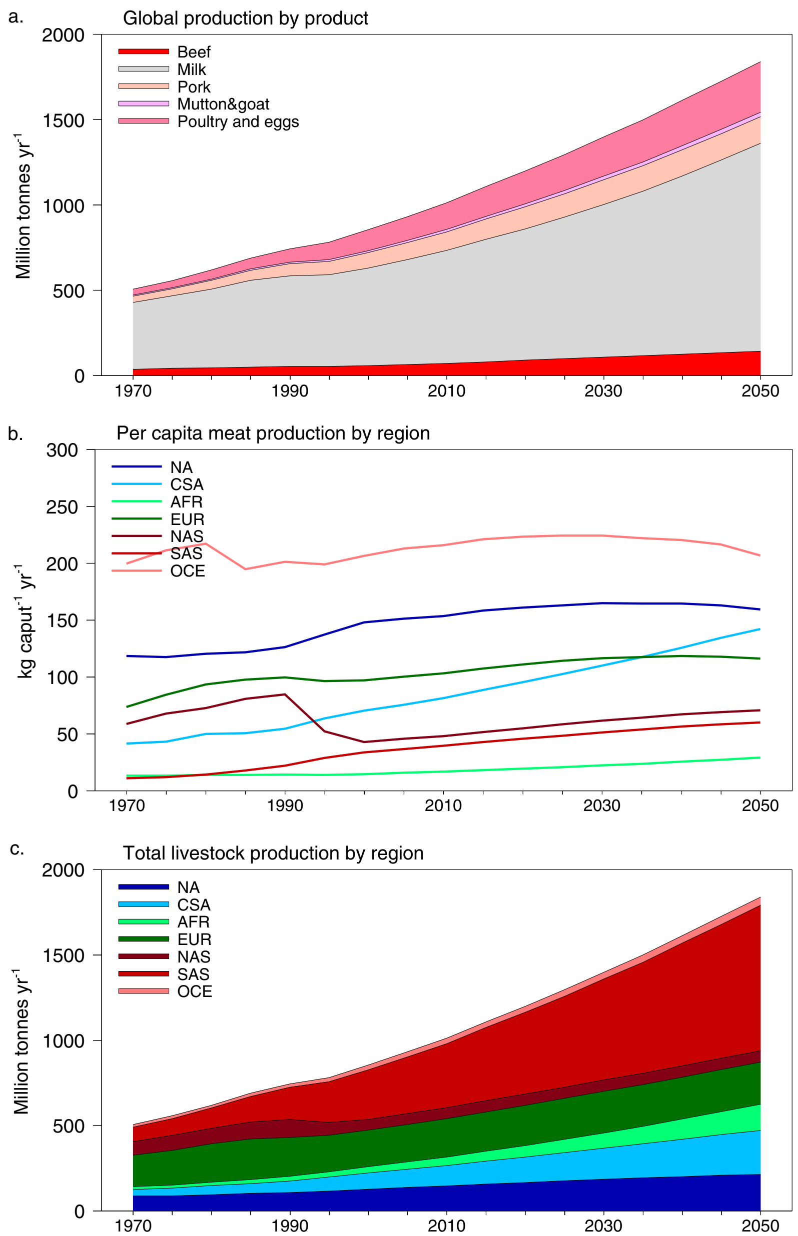

Fig. S3. Livestock production in by category (*A*) and per capita (*B*), and total livestock production by world region (*C*). Regions are as shown in Fig. 1. Tonne = metric tonne = 10^6 g; caput = head.

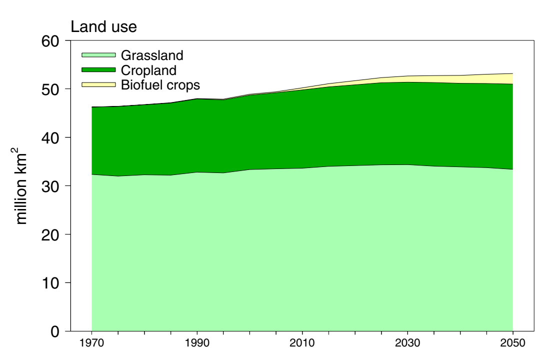

Fig. S4. Global land area for agriculture production.

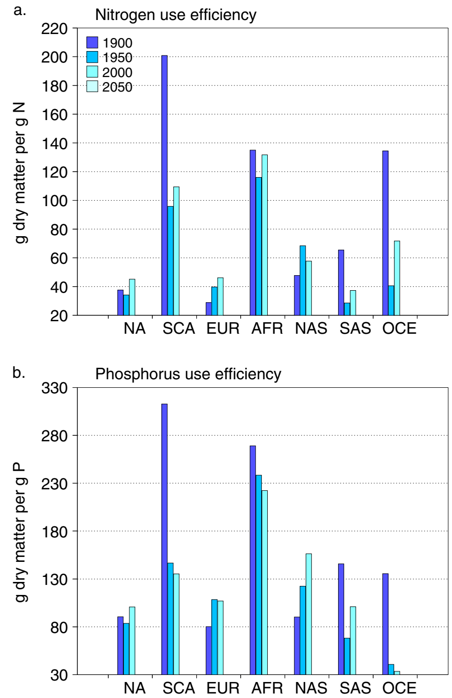

Fig. S5. N (*A*) and P (*B*) fertilizer use efficiency for different regions of the world. The data for 2050 represent the IAASTD baseline. Regions are as shown in Fig. 1.

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.