GLOBAL BIOGEOCHEMICAL CYCLES, VOL. 23, GB0A04, doi:10.1029/2009GB003576, 2009

Human alteration of the global nitrogen and phosphorus soil balances for the period 1970–2050

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Received 19 May 2009; revised 25 August 2009; accepted 9 September 2009; published 18 December 2009.

[1] The Millennium Ecosystem Assessment scenarios for 2000 to 2050 describe contrasting future developments in agricultural land use under changing climate. Differences are related to the total crop and livestock production and the efficiency of nutrient use in agriculture. The scenarios with a reactive approach to environmental problems show increases in agricultural N and P soil balances in all developing countries. In the scenarios with a proactive attitude, N balances decrease and P balances show no change or a slight increase. In Europe and North America, the N balance will decline in all scenarios, most strongly in the environment-oriented scenarios; the P balance declines (proactive) or increases slowly (reactive approach). Even with rapidly increasing agricultural efficiency, the global N balance, ammonia, leaching and denitrification loss will not decrease from their current levels even in the most optimistic scenario. Soil P depletion seems to be a major problem in large parts of the global grassland area.

Citation: Bouwman, A. F., A. H. W. Beusen, and G. Billen (2009), Human alteration of the global nitrogen and phosphorus soil balances for the period 1970–2050, *Global Biogeochem. Cycles*, *23*, GB0A04, doi:10.1029/2009GB003576.

1. Introduction

[2] During the past five decades, global population, food production, and energy consumption have increased approximately 2.5-fold, threefold and fivefold, respectively [*FAO*, 2008; *Grübler et al.*, 1995]. Through activities such as fertilizer use, fossil fuel consumption and the cultivation of leguminous crops, humans have more than doubled the rate at which biologically available nitrogen (N) enters the terrestrial biosphere compared to preindustrial levels [*Galloway et al.*, 2004]. The global phosphorus (P) cycle has also been altered by human activity. Mining of phosphate rock and subsequent production and use as fertilizer, detergent, animal feed supplement and other technical uses has more than doubled P inputs to the environment over natural, background P from weathering [*Mackenzie et al.*, 1998; *Tiessen*, 1995; *United States Geological Survey*, 2008].

[3] The changes in global nutrient cycles have had both positive and negative effects. The increased use of N and P fertilizers has allowed for producing the food necessary to support the rapidly growing human population [*Galloway and Cowling*, 2002]. However, significant fractions of the anthropogenically mobilized N and P in watersheds enter groundwater and surface water and are transported through freshwater to coastal marine systems. This has resulted in numerous negative human health and environmental impacts such as groundwater pollution, loss of habitat and biodiversity, an increase in frequency and severity of harmful algal blooms, eutrophication, hypoxia and fish kills [*Diaz and Rosenberg*, 2008; *Howarth et al.*, 1996; *Rabalais*, 2002; *Turner et al.*, 2003; *Vollenweider*, 1992; *Vollenweider et al.*, 1992].

[4] Describing the biogeochemical linkages between changes in land use and river nutrient export to coastal ecosystems at continental and global scales, requires spatially explicit, multielement, multiform predictive models of riverine nutrient export appropriate for use at regional and global scales. The Global Nutrient Export from Watersheds (Global NEWS) work group of the UNESCO–Intergovernmental Oceanographic Commission (IOC) has addressed many of these issues [*Seitzinger et al.*, 2005].

[5] The Global NEWS work continued with the analysis of past (1970) and possible future changes in nutrient export by rivers to coastal marine ecosystems. The four scenarios of the Millennium Ecosystem Assessment (MEA) [*Alcamo et al.*, 2006] describe contrasting pathways for the future development of human society and ecosystems. The MEA scenarios are therefore a good basis for expanding them with scenarios for future agricultural nutrient inputs and outputs and nutrient cycling in natural ecosystems.

[6] Soil balances for N and P are generally regarded as useful indicators of the losses to the environment. The aim of this paper is to develop spatially explicit soil balances for N and P, the primary drivers of the Global NEWS models [*Seitzinger et al.*, 2009]. We first discuss the processes of N and P in soil-plant systems. Subsequently, we describe spatially explicit N and P soil balances for agriculture and natural ecosystems with a 0.5 by 0.5 degree resolution developed with the Integrated Model to Assess the Global

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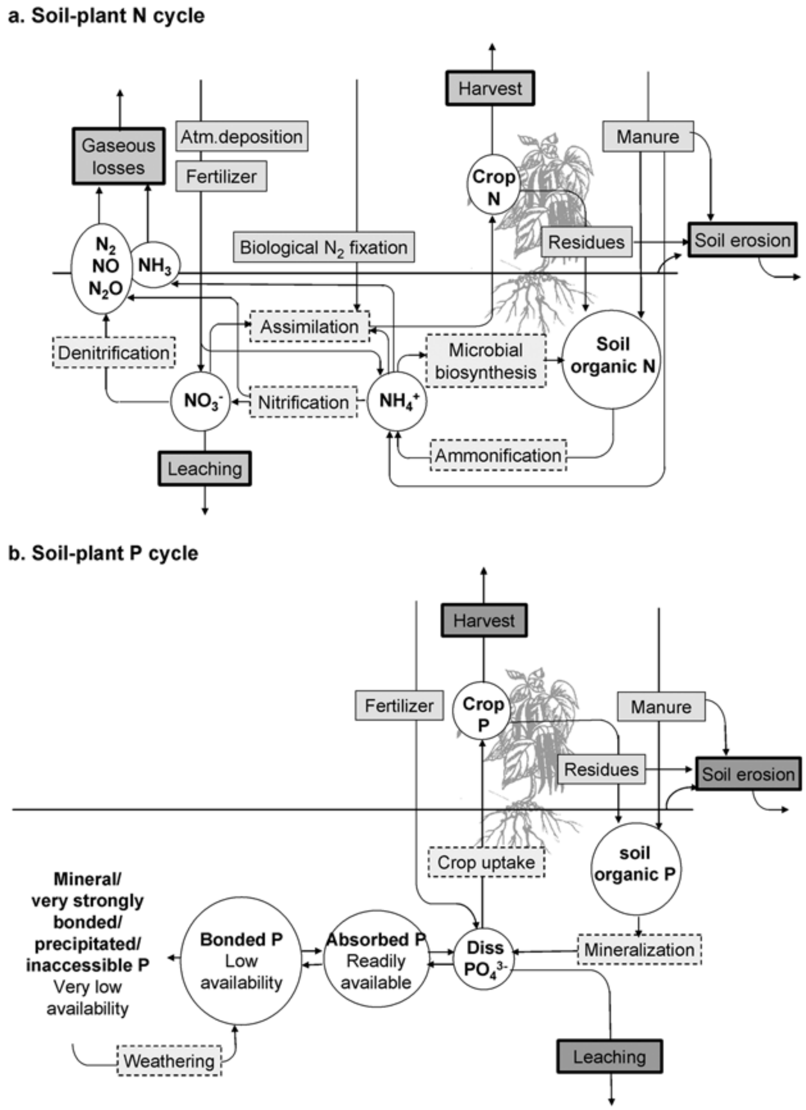

Figure 1. (a) Nitrogen and (b) phosphorus cycle in soil-plant systems. Circles indicate pools, boxes with dashed lines are processes, light-gray boxes with solid lines are inputs, and dark-gray boxes with bold lines represent outputs.

Environment (IMAGE) [*Bouwman et al.*, 2006] for the MEA scenarios, and discuss the consequences for the global N and P cycle.

2. Processes of Nitrogen and Phosphorus in Soil-Plant Systems

2.1. Nitrogen

[7] Nitrogen is most often limiting plant growth in both natural and agricultural systems and the rate of internal nitrogen cycling in soil (Figure 1a) is a crucial factor for plant production. In this cycle organic N is transformed by mineralization, ammonification, and nitrification, so that N may at any one moment be present as NH_4^+ or NO_3^-; these forms are prone to losses through (1) denitrification, the reduction of nitrate (NO_3^-) to nitrite (NO_2^-), nitric oxide (NO), nitrous oxide (N_2O) and N_2; (2) leaching of NO_3^- and dissolved organic nitrogen; (3) ammonia volatilization; and (4) soil erosion [*Brady*, 1990].

[8] In natural ecosystems these N losses are compensated through biological N_2 fixation by leguminous plants living in symbiosis with Rhizobium and other N_2 fixing bacteria, or free-living bacteria, as well as through nitrogen deposition. A number of factors limit symbiotic N_2 fixation in ecosystems. The process of N_2 fixation requires energy for the construction of specialized structures, protection against oxygen and breaking the triple bond of the N_2 molecule [*Vitousek et al.*, 2002a, 2002b]. With this high energy requirement it is not surprising that leguminous species are more widespread in the tropics than in temperate climates [*Cleveland et al.*, 1999; *Crews*, 1999]. In mature ecosystems legumes may have a further disadvantage because of their shade intolerance [*Vitousek et al.*, 2002a]. The demand of leguminous species and free-living N_2 fixers

for P and other elements like molybdenum exceeds that of non N_2 fixers; in many ecosystems with low availability of P, biological N_2 fixation may be constrained, leading to N limitation. Finally, grazing of protein-rich tissues of leguminous plants may control biological N_2 fixation [*Vitousek et al.*, 2002b].

[9] Agricultural production systems differ from natural systems by the regular harvesting of the largest part of produced plant biomass and often by the soil disturbance through tillage. Except in N_2 fixing leguminous crops (pulses, soybeans), N_2 fixation is actively excluded in agricultural systems. Nitrogen losses from the system through harvesting, denitrification, leaching, volatilization and soil erosion thus have to be compensated by application of synthetic N fertilizers and animal manure. Only about half of these anthropogenic N inputs are taken up by the crops [*Smil*, 1999] while the remainder is lost to the environment, at a much higher rate than in natural ecosystems [*Van Drecht et al.*, 2003]. Although in experimental fields the efficiency of N use may be much higher than the global average of 50% [*Balasubramanian et al.*, 2004], under practical conditions it is difficult to match the N supply from fertilizer and from soil organic matter mineralization with the dynamics of crop N uptake demand [*Dobermann and Cassman*, 2005]. Improved synchrony can be achieved using simple rules for splitting N applications according to phenological stages, or by using more complex approaches to diagnose soil and plant N status during the growing season, thus improving agricultural N efficiency.

2.2. Phosphorus

[10] Phosphorus occurs in small quantities in the earth's lithosphere, biosphere and hydrosphere. In terms of mass, P ranks at the 11th place in the lithosphere, and 13th in seawater [*Smil*, 2000]. The Earth's biomass contains small amounts of P. In the three polymers that make up most of woody phytomass, P is absent in cellulose, hemicellulose and lignin. It is also absent in N-rich amino acids that make up proteins of living organisms [*Smil*, 2000]. Despite its scarcity, P is essential for formation of carbohydrate polymers, proteins and nucleic acids. The energy needed for synthesis of all complex molecules of life is supplied by energy released by the P bond that reversibly moves between adenosine diphosphate (ADP) and adenosine triphosphate (ATP) [*Purves et al.*, 2004].

[11] Unlike natural C and N cycles, which are driven by microorganisms and plants, and have an important atmospheric component, there is only a very small atmospheric reservoir of P [*Mackenzie et al.*, 1998; *Smil*, 2000]. On a time scale of thousands of years, the natural P cycle appears to be a one-way flow, with an important role of living organisms. Weathering of parent material generally containing small amounts of P, uptake by plants, mineralization of organic P, erosion, and runoff (Figure 1b) transfer soluble and particulate P to the ocean where it is eventually buried in sediments [*Mackenzie et al.*, 2002]. Given the low solubility of phosphates in soils, leaching of P generally occurs at low rates, apart from P-saturated soils in some industrialized countries [*Smil*, 2000]. Cycling of organic P has rapid turnover times, and is driven by decomposition, mineralization and assimilation by autotrophic production.

[12] The cycling of P in natural ecosystems is efficient. There is no biotic mobilization of P (equivalent to biological N_2 fixation); the P that is lost from the soil-plant cycling is replaced by the slow process of rock weathering (Figure 1b). P in rocks is present in poorly soluble forms. Apatite, a calcium phosphate mineral, contains 95% of all P in the Earth's crust. In soils, soluble P released by weathering is usually rapidly immobilized into insoluble forms [*Brady*, 1990]. Precipitation of phosphates with alumina occurs at low pH, and with calcium in calcareous soils. As a result, only a miniscule fraction of P in soils is directly available to plants as dissolved phosphate (PO_4^{3-}).

[13] The two main factors controlling the availability of P to plant roots are the concentration of phosphate ions in the soil solution and the P-buffer capacity, i.e., the ability of the soil to replenish these ions when plant roots remove them [*Syers et al.*, 2008]. Root length and diameter and the efficiency of P uptake by the roots determine the rate and extent of P uptake. In soils, inorganic P can become absorbed by diffusive penetration into soil components. This may result in a reversible transfer of P between plant-available and nonavailable forms. P is retained in soil components with a continuum of bonding energies with varying degrees of reversibility (Figure 1b). These pools can be related to the availability of P to plants. P is the growth limiting nutrient in many terrestrial ecosystems in general, particularly tropical forests [*Vitousek*, 1984]. Soils rich in soluble iron or alumina, clay minerals like kaolinite, or with a high calcium activity, react with P to form insoluble compounds inaccessible to plant roots [*Brady*, 1990]. This is often referred to as P fixation, which is particularly relevant in many weathered tropical soils, such as Ultisols and Oxisols, and volcanic ash soils (Andosols) [*Fairhurst et al.*, 1999; *Sanchez*, 1976].

[14] Since the readily available pool provides most of the plant-available P, it is necessary in agricultural systems to maintain a certain critical amount of P in this pool to obtain good crop yields [*Syers et al.*, 2008]. Fertilizer P recovery in crops is often only 10–20% in the short term. Part of the P added to soil in fertilizer and manure is used by the plant in the year of application. A varying but substantial part 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. Where the amount of readily available P is below the critical level, the rate of P release from residual P may not be sufficiently rapid to sustain optimal crop yields. While building up the soil P status to the critical value, the crop P recovery may slowly increase to values up to 90%. In an ideal situation, when P is present in the readily available pools in adequate amounts, annual P inputs from fertilizer equal to the plant P uptake may be adequate to maintain good crop yields [*Syers et al.*, 2008].

3. Data and Methods

3.1. General

[15] Four scenarios were developed in the Millennium Ecosystem Assessment (MEA) [*Alcamo et al.*, 2006], Global

Orchestration (GO), Order from Strength (OS), Technogarden (TG) and Adapting Mosaic (AM). A number of general features of the scenarios are summarized in Table 1. Brief descriptions as well as the changes of the main drivers of change in agriculture, i.e., population, economy and food demand for the MEA scenarios are in the auxiliary material (Figures S1–S10 and Text S1).[1]

[16] We consider the historical period 1970–2000 and implemented agricultural production data for the period 2000–2050 from the MEA study (Figure 2) for simulating spatial land use and nutrient distributions with the IMAGE model [*Bouwman et al.*, 2006]. Compared to the original MEA (where IMAGE version 2.2 was used) here we apply an update (version 2.4) with improved simulation of livestock production systems, land cover, land use and N and P soil balances. A summary of the IMAGE 2.4 model framework is presented in section S2 of Text S1.

[17] Although IMAGE 2.4 is global in application, with data and scenarios at the scale of 24 world regions (Figure S4), it performs many of its calculations on a terrestrial 0.5 by 0.5 degree resolution (crop yields and crop distribution, land cover, land-use emissions, soil nutrient balances and C cycle). Data from many different sources are used to calibrate the energy, climate and land use variables over the period 1970–2000.

[18] For calculating spatially explicit soil nutrient balances for the MEA scenarios, a downscaling procedure is used (section S2.9 of Text S1) which results in 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) [*Bruinsma*, 2003].

[19] The soil balances are calculated for each grid cell as the sum of all inputs minus the sum of the removal of nutrients in the harvested crops and grazing (Figure 3). A negative balance indicates depletion of the soil stocks, while a positive balance can accumulate in the soil or be lost to the environment. The overall system efficiency is calculated as the sum of the removal of nutrients in the harvested crop and grazing, divided by the sum of the inputs.

[20] Here we describe the components of N and P soil balances, starting with land use (section 3.2), spatial distributions of N and P from animal manure (3.3), human excreta (3.4), fertilizer use (3.5), biological N_2 fixation (3.6), atmospheric N deposition (3.7), and crop uptake (3.8).

3.2. Land Cover and Land Use

[21] Grid cells are either agricultural land or natural vegetation. The distribution of 14 natural land cover types is simulated with the BIOME model [*Prentice et al.*, 1992]. Agricultural grid cells have fractions of different crops and grass (section S2.3 of Text S1). Harvested areas, cropping intensities, arable land and grassland areas are calibrated for the period 1970–2000 with *FAO* [2008] data on the scale of the 24 world regions of IMAGE. From the data on domestic food, feed and energy crop production taken directly from MEA for the period 2000–2050 [*Alcamo et al.*, 2006], IMAGE calculates the required harvested area by using cropping intensities and crop yields (Figure 2a). Crop yields may increase as a result of technological progress, climate change and increasing atmospheric CO_2 concentration (section S2.3 of Text S1). Total arable area (including fallow land) is calculated from the harvested area and cropping intensity (number of crops per year) (Figure 2a). The way in which expansion or abandonment of agricultural land is simulated is discussed in section S2.3 of Text S1.

[22] Consumption by animals of feed crops, crop residues, grass, and other feedstuffs is calculated from animal productivity, feed efficiency (kg feed per kg product) and feed ration (Figure 2b). Grassland areas are calculated on the basis of the grazing intensity, which is the grass consumption: production ratio within a country or world region (Figure 2b).

[23] For allocating nutrient inputs, the crop groups of IMAGE (section S2.3 of Text S1) are aggregated to form five broad groups, including grassland, wetland rice, leguminous crops (pulses, soybeans), other upland crops and energy crops (Figure 3). Areas of grassland receiving synthetic fertilizers are within the mixed agricultural system.

3.3. Animal Manure

[24] Historical country data on animal stocks and production per animal are obtained from *FAO* [2008] and subnational data for some countries (section S2.4 of Text S1). Livestock production estimates for 2000–2050 are taken directly from MEA [*Alcamo et al.*, 2006]; IMAGE computes the animal stocks based on the production per animal (Figure 2a).

[25] Total manure production within pastoral and mixed and landless systems is computed from the animal stocks and N and P excretion rates (Figure 2c). We obtained N excretion rates per head for dairy and nondairy cattle, buffaloes, sheep and goats, pigs, poultry, horses, asses, mules and camels from *Van der Hoek* [1998]. P excretion rates are based on various sources [*Midwest Plan Service*, 1985; *Sheldrick et al.*, 2003; *Smith*, 1991; *Van Horn et al.*, 1996; *Wilkerson et al.*, 1997]. We assume that excretion rates are constant, so that the N and P excretion per unit of product decreases with increasing milk and meat production per animal.

[26] For each country, the animal stocks and N and P in the manure for each animal category are spatially allocated within mixed and pastoral systems (section S2.4 of Text S1). Within each system, the manure is distributed over different management systems (Figure 2c). The fraction grazing is derived from the ratio of grass to total feed in the ration of each animal category [*Bouwman et al.*, 2005a]. Pig and poultry manure is assumed to be stored or collected in mixed and landless systems.

[27] Animal manure available for application to crops and grassland is all stored or collected manure (Figure 2c), excluding (1) manure excreted outside the agricultural system, for example in urban areas, forests and along roadsides [*Bouwman et al.*, 2005a]; (2) manure used as fuel or for other purposes according to *Mosier et al.* [1998]; and (3) NH_3 volatilization from animal houses and manure storage systems [*Bouwman et al.*, 1997].

[28] We assume that in most industrialized countries, 50% of the stored and available animal manure is applied to

[1]Auxiliary materials are available in the HTML. doi:10.1029/2009GB003576.

Table 1. Main Drivers of Ecosystem Change for the MEA Scenarios[a]

	Global Orchestration (GO)	Order From Strength (OS)	Technogarden (TG)	Adapting Mosaic (AM)
Keywords	Globalization, economic development, reactive approach to environmental problems	Regionalization, fragmentation security, reactive approach to environmental problems	Globalization, environmental technology, proactive approach to environmental problems	Regionalization, local ecological management with simple technology, proactive approach to environmental problems
World population (billion)	Low 2000: 6.1 2030: 7.7 2050: 8.2	High 2000: 6.1 2030: 8.6 2050: 9.7	Medium 2000: 6.1 2030: 8.2 2050: 8.9	High 2000: 6.1 2030: 8.5 2050: 9.6
Income (annual per capita GDP growth rate)	High 2000–2030:2.6% a^{-1} 2030–2050:3.0% a^{-1}	Low 2000–2030:1.6% a^{-1} 2030–2050:1.3% a^{-1}	High 2000–2030:2.1% a^{-1} 2030–2050:2.6% a^{-1}	Medium 2000–2030:1.8% a^{-1} 2030–2050:2.2% a^{-1}
Global GHG emissions (GtC-eq a^{-1})	High 2000: 9.8 2050: 25.6	High 2000: 9.8 2050: 20.3	Low 2000: 9.8 2050: 7.1	Medium 2000: 9.8 2050: 18.0
Global mean temperature increase (°C)	High 2000: 0.6 2030: 1.4 2050: 2.0	High 2000: 0.6 2030: 1.3 2050: 1.7	Low 2000: 0.6 2030: 1.3 2050: 1.5	Medium 2000: 0.6 2030: 1.4 2050: 1.9
Per capita food consumption	High, high meat	Low	High, low meat	Low, low meat
Agricultural productivity increase	High	Low	Medium-high	Medium
Energy crops	4% of cropland area in 2050	1% of cropland area in 2050	28% of cropland area in 2050	2% of cropland area in 2050
Fertilizer use and efficiency	No change in countries with a surplus; rapid increase in N and P fertilizer use in countries with soil nutrient depletion (deficit)	No change in countries with a surplus; slow increase in N and P fertilizer use in countries with soil nutrient depletion (deficit)	rapid increase in countries with a surplus; rapid increase in N and P fertilizer use in countries with soil nutrient depletion (deficit)	Moderate increase in countries with a surplus; slow increase in N and P fertilizer use in countries with soil nutrient depletion (deficit); better integration of animal manure and recycling of human N and P from households with improved sanitation but lacking a sewage connection.

[a]From *Alcamo et al.* [2006] and our assumptions for the fertilizer use. MEA, Millennium Ecosystem Assessment.

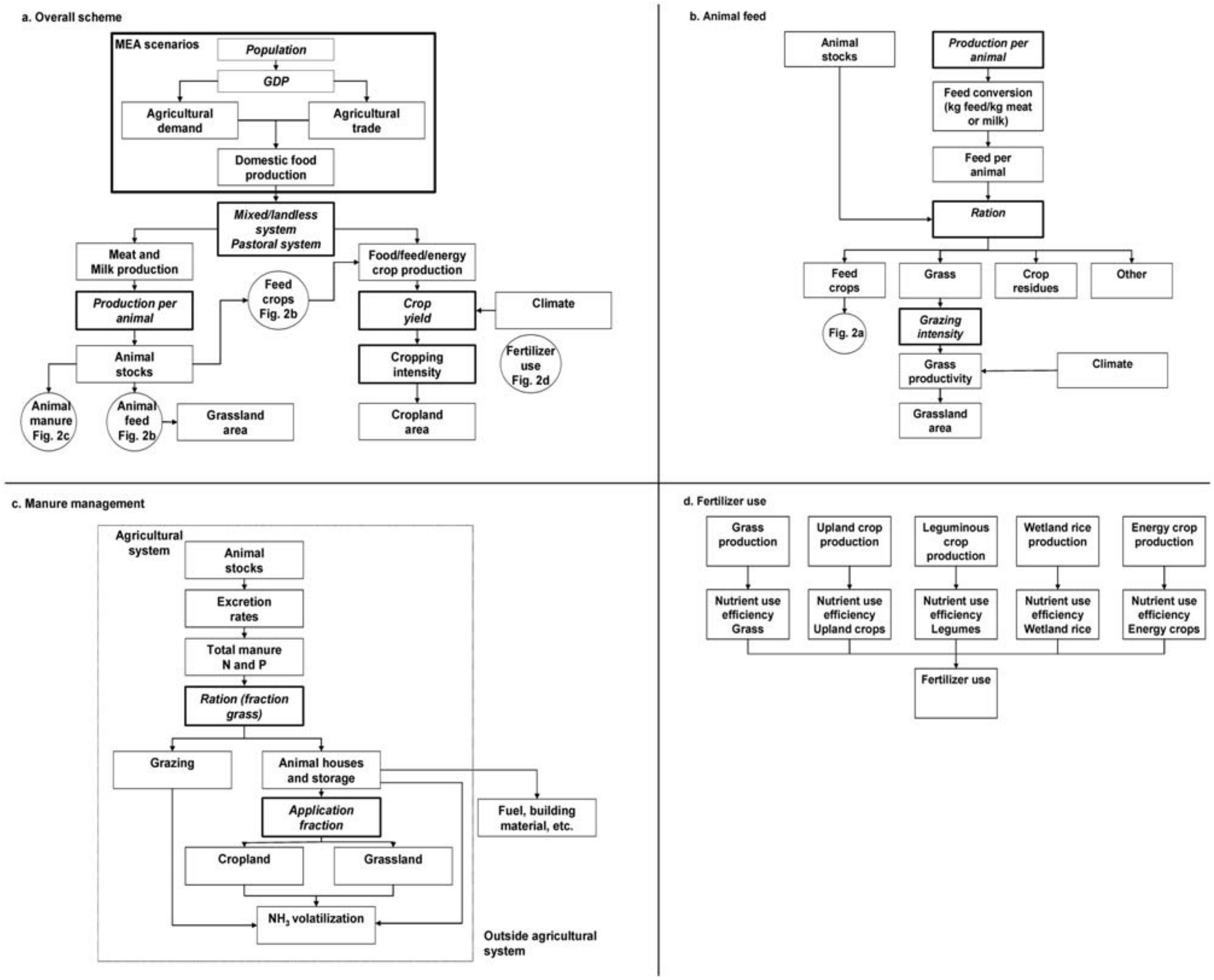

Figure 2. Simplified scheme of the Integrated Model to Assess the Global Environment (IMAGE) model calculation of (a) areas of arable land and grassland in pastoral and mixed and landless systems; (b) the use of different feedstuffs and calculation of grassland area; (c) the distribution of N and P from animal manure over grazing, animal houses and storage, application to cropland and grassland, other uses, and NH_3 volatilization from animal houses and manure storage; and (d) fertilizer inputs for grassland, upland crops, leguminous crops, wetland rice and energy crops. Boxes with bold lines and text in italics are scenario assumptions, or data for the historical period. Data on food demand and trade of agricultural products were provided by the Millennium Ecosystem Assessment (MEA) study [*Alcamo et al.*, 2006].

arable land and the remainder to grassland [*Lee et al.*, 1997] (application fraction in Figure 2c). 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 on croplands, and the lower importance of grass compared to crops in developing countries [*Seré and Steinfeld*, 1996]. For EU countries we use maximum application rates of 170–250 kg N ha^{-1} a^{-1} based on existing regulations.

3.4. Human N and P

[29] We neglect the direct use of human N and P in agriculture for the period 1970–2000 (section S2.5 of Text S1). For future decades, we consider the AM scenario as one where human N and P will play a role in agriculture. In AM, the focus is on local, simple and economically feasible options for socioecological management. This strongly contrasts with TG, where the focus is on environmentally sound technology and engineering solutions. The AM scenario uses the concept of ecological sanitation, which aims at closure of local material flow cycles [*Langergraber and Muellegger*a, 2005]. We assume that the N and P contained in urine and faeces collected from households will be used in agricultural production systems in the same way as animal manure, to substitute synthetic fertilizers. From the assessment of the point sources for the AM scenario [*Van Drecht et al.*, 2009], we use the country estimates of the human N and P from inhabitants with

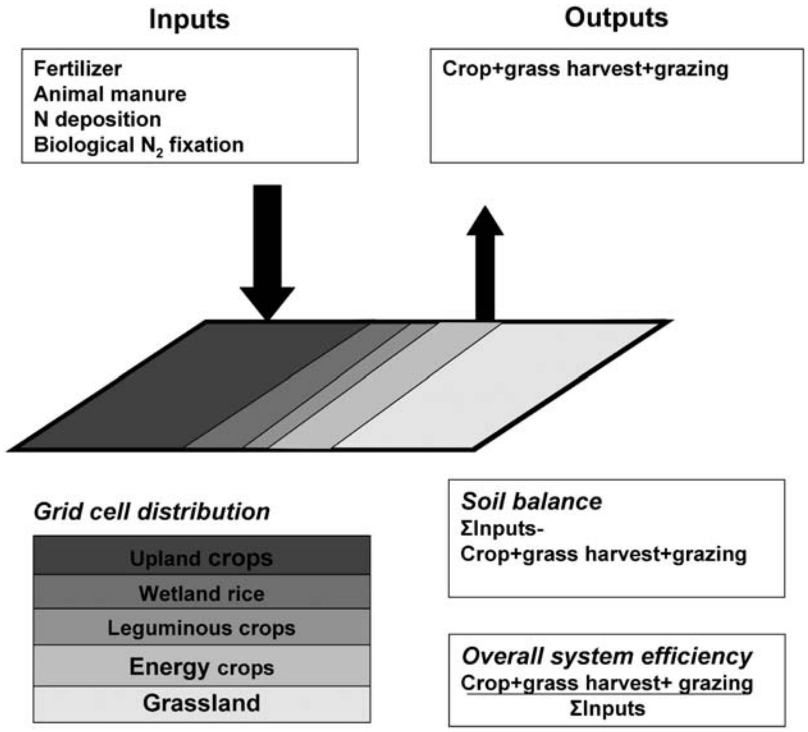

Figure 3. Soil N and P inputs and outputs for fractions of 0.5 by 0.5 degree grid cells covered by upland crops, wetland rice, leguminous crops, energy crops, and grassland.

access to improved sanitation, but excluding households with a flush toilet and a connection to sewage systems. Together with animal manure, human N and P are used to substitute synthetic N and P fertilizers (section 3.5).

[30] We ignore the use of sewage sludge. In developing countries this source of N is probably not important, because of the low degree of wastewater collection and treatment, while in industrialized countries the use of sewage sludge may be restricted because of environmental regulations related to the pathogens and heavy metals in sludges.

3.5. Fertilizer Use

[31] We use historical country data from *FAO* [2008] on total synthetic fertilizer consumption and crop production and N and P fertilizer use by crop from *International Fertilizer Industry Association/International Fertilizer Development Center/Food and Agriculture Organization* (*IFA/IFDC/FAO*) [2003]. For crops and grass, we use the concept of fertilizer N and P use efficiency (NUE and PUE, respectively), which represent the production in kg dry matter per kg of fertilizer N or P (Figure 2d). This is the broadest measure of N use efficiency, also called the partial factor productivity of the applied fertilizer N [*Dobermann and Cassman*, 2005]. NUE and PUE incorporate the contribution of indigenous soil N, fertilizer uptake efficiency and the efficiency with which the N uptake is converted into the harvested product. NUE and PUE vary between 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 (Figure 4). Following the analysis of *Dobermann and Cassman* [2005], we excluded animal manure N and P in the NUE and PUE values.

[32] For constructing the scenarios, we use data from *Bruinsma* [2003] as a guide (Figure 4). We divided the world into countries with inputs exceeding the crop uptake (positive balance or surplus) and countries with current deficit. Generally, in TG and AM, farmers in countries with a surplus are motivated to be increasingly efficient in the use of fertilizers, while in GO and OS we assume a slower efficiency increase (Table 1). In deficit countries, we assume that NUE and PUE for upland crops will gradually decrease to a varying degree (Figure 4). 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. The data in Figure 4 for the category upland crops represent 75% of global N and 80% of global P fertilizer use. N and P fertilizer inputs for wetland rice, leguminous crops and grassland are computed in a similar way (section S2.6 of Text S1).

[33] *Janssen and Oenema* [2008] concluded that the use of synthetic fertilizers may be reduced by better integrating animal manure in cropping systems. The current availability of animal manure for application in cropping systems is limited, because of spatial separation of intensive livestock and crop production. In AM we assume that farmers in all

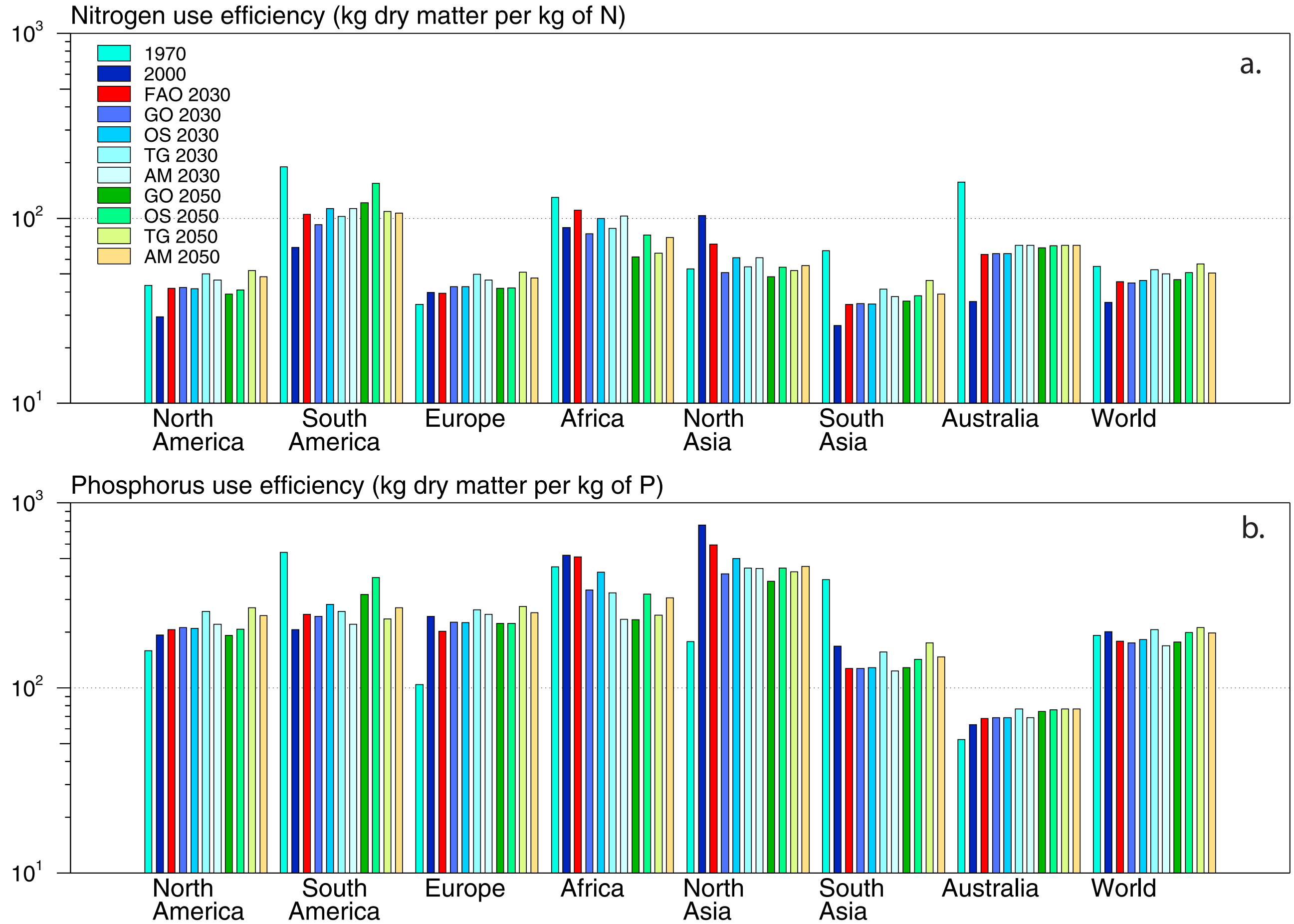

Figure 4. (a) Nitrogen use efficiency (NUE) and (b) phosphorus use efficiency (PUE) for the category upland crops, for aggregated world regions and the years 1970, 2000, and 2030 according to the FAO Agriculture Toward 2030 study [*Bruinsma*, 2003] and for 2050 for the four MEA scenarios (Global Orchestration (GO), Order from Strength (OS), Technogarden (TG), and Adapting Mosaic (AM)).

countries will partly substitute N and P fertilizers by the extra available animal manure that is generated in animal houses and storage systems since 2000, and human N and P. Since 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, adds to the soil N reserve or is decomposed gradually and lost through leaching and denitrification [*Janssen and Oenema*, 2008]. For human N, we assume that 25% of the N in the excreta is lost by ammonia volatilization during storage. This is based on the high N content of urine, containing 80–90% of the N in human excreta. We assume that 100% of manure and human P is effectively available.

3.6. Biological N_2 Fixation

[34] Biological N_2 fixation by pulses and soybeans is calculated from crop production data [*FAO*, 2008] 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 two, to account for all above and belowground plant parts [*Mosier et al.*, 1998]. 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.

[35] We use a rate of nonsymbiotic biological N_2 fixation of 5 kg ha^{-1} a^{-1} of N for nonleguminous crops and grassland and 25 kg ha^{-1} a^{-1} of N for wetland rice, as proposed by *Smil* [1999]. The total biological fixation of N_2 thus depends on the total production of legumes, and the areas of grassland and cropland.

[36] Biological N_2 fixation in natural ecosystems is estimated on the basis of *Cleveland et al.* [1999] combined with the spatial distribution of the 14 types of natural ecosystems in IMAGE (section S2.2 of Text S1). Any change simulated by IMAGE in the ecosystem distribution caused by climate change or forest conversion to agriculture results in a change in N_2 fixation rates.

3.7. Atmospheric N Deposition

[37] Atmospheric N deposition rates (including dry and wet deposition of NH_3 and NO_y) for the year 2000 were taken from *Dentener et al.* [2006]. Deposition rates for historical and future years are obtained by scaling the deposition fields for the year 2000, using emission scenarios

Table 2. Overall Efficiency of N and P Use for the Total Agricultural System[a]

Year/Scenario	North America	Central and South America	Europe	Africa	North Asia	South Asia	Oceania
			Nitrogen				
1970	0.27	0.47	0.44	0.35	0.39	0.39	0.35
2000	0.43	0.52	0.55	0.40	0.46	0.30	0.34
2030-GO	0.51	0.56	0.57	0.46	0.42	0.34	0.41
2050-GO	0.53	0.56	0.58	0.44	0.42	0.36	0.43
2030-OS	0.49	0.58	0.56	0.47	0.45	0.34	0.41
2050-OS	0.51	0.60	0.57	0.46	0.43	0.35	0.43
2030-TG	0.58	0.57	0.63	0.47	0.45	0.39	0.42
2050-TG	0.62	0.63	0.66	0.45	0.46	0.43	0.43
2030-AM	0.55	0.61	0.62	0.49	0.48	0.40	0.43
2050-AM	0.59	0.63	0.64	0.49	0.46	0.42	0.44
			Phosphorus				
1970	0.31	0.64	0.42	0.64	0.49	0.56	0.41
2000	0.61	0.55	0.69	0.62	0.81	0.40	0.37
2030-GO	0.62	0.57	0.68	0.55	0.78	0.34	0.38
2050-GO	0.63	0.56	0.69	0.49	0.80	0.35	0.37
2030-OS	0.62	0.59	0.68	0.59	0.87	0.34	0.38
2050-OS	0.63	0.59	0.70	0.53	0.88	0.35	0.37
2030-TG	0.70	0.58	0.74	0.56	0.81	0.39	0.40
2050-TG	0.74	0.53	0.77	0.50	0.83	0.41	0.37
2030-AM	0.71	0.64	0.80	0.63	1.07	0.40	0.42
2050-AM	0.74	0.64	0.83	0.57	1.06	0.40	0.41

[a]See Figure 3. Regions are as follows: North America is Canada, United States, and Mexico; North Asia is Russian Federation, Belarus, Ukraine, and Republic of Moldova; South Asia is rest of Asia; and Oceania is Australia and New Zealand.

for N gases for the corresponding years from the implementation of the MEA scenarios with the IMAGE model.

3.8. Crop Uptake

[38] N and P export in harvested crops is based on country crop production data; for some countries subnational data are used (section S2.7 of Text S1). The removal of N and P in the harvested products is calculated from the crop production and N and P content for each crop [*Bouwman et al.*, 2005b] and then aggregated to the broad categories wetland rice, leguminous crops, upland crops and energy crops. We also account for uptake by fodder crops (section S2.7 of Text S1). N removal by grass consumption and harvest is assumed to be 60% of all N or P inputs (manure, fertilizer, deposition, N fixation), excluding NH_3 volatilization [*Bouwman et al.*, 2005b]; P removal results from the N:P ratio in grass.

4. Results and Discussion

4.1. Agricultural N and P Balance

[39] For the discussion we aggregated the results from the grid scale to the level of seven world regions (Table 2). A detailed discussion of inputs, outputs and balances of N and P at the level of these regions is in section S4 of Text S1. Here we concentrate primarily on the global changes in nutrient balances.

[40] At the field scale, uptake of N fertilizer by crops is commonly about 50% [*Peoples et al.*, 1995], while the uptake of P fertilizer is 28 to 50%; in field trials with long-term NPK application, P recoveries increase with time [*Syers et al.*, 2008]. The values for overall system efficiency for N are lower in many parts of the world (Table 2), because they include both crop and livestock production systems; livestock production systems have low efficiencies [*Van der Hoek*, 2001]. Our values for the P use efficiency for the agricultural system as a whole are on the high end of this range (Table 2), because of P recycling as animal manure and P from crop residues being returned to crops. In regions with vast areas of P fixing soils, the P recovery values may be lower.

[41] Crop N uptake in 1970 for industrialized countries (26 Tg a^{-1}) and developing countries (32 Tg a^{-1}), implied overall efficiencies of 51% and 66%, respectively. In the year 2000, crop N uptake amounted to 33 and 59 Tg a^{-1} for industrialized and developing countries, with efficiencies of 63% and 50%, respectively. The reason why developing countries faced a decrease of the efficiency, was the low level of inputs in 1970, with possible depletion of nutrients, and a rapid increase of fertilizer inputs between 1970 and 2000. This reduced the problem of N and P depletion in many countries, but thus also decreased efficiency [*Bouwman et al.*, 2005b]. For example, China changed from a deficit to a surplus country, during this period, resulting in rapidly decreasing NUE and PUE. In the scenarios, the efficiency of N use increases most rapidly in the AM scenario because of the substitution of N fertilizer by animal and human manure.

[42] The N balance in the global agricultural system increased from 101 Tg a^{-1} in 1970 to 157 Tg a^{-1} in 2000 (Figure 5a). Despite the increasing efficiency in N use, the scenarios show further increasing balances. In GO, the global N balance will grow to 231 Tg a^{-1} by 2050. In OS, balances are somewhat smaller than in GO, and in TG there is an increase to 172 Tg a^{-1}, while in AM the global N balance in 2050 remains close to the 2000 level.

[43] For P, a similar picture arises, except for 1970 when efficiency was low in industrialized countries (Table 2). This was caused by intensive use of P fertilizers in the

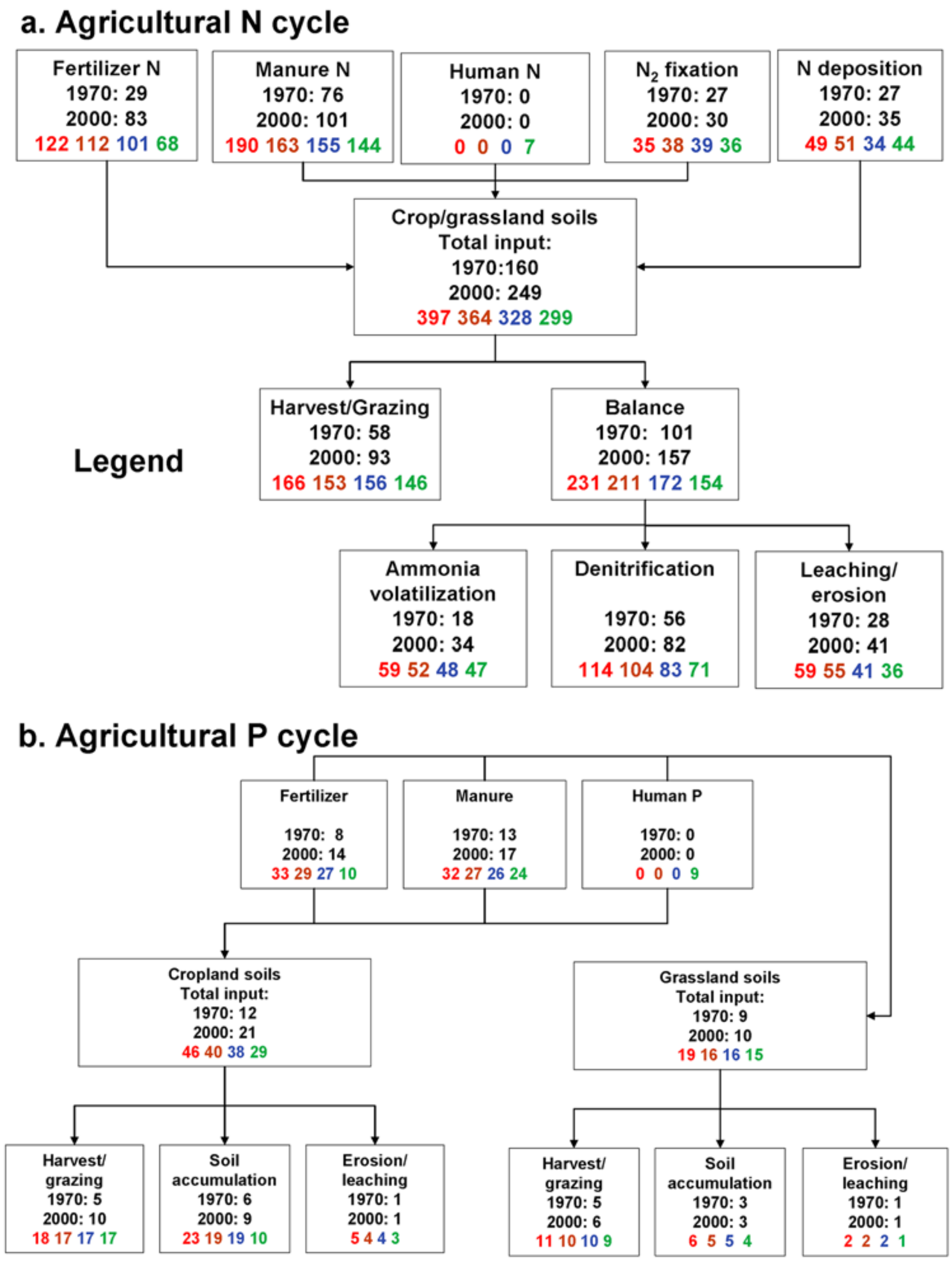

Figure 5. Global fluxes of (a) N and (b) P for 1970, 2000, and 2050 for the four MEA scenarios. Numbers are in Tg N or P a^{-1}.

U.S.A., Europe and the former Soviet Union, which rapidly decreased in the period 1970–2000. With a global fertilizer input of 8 and 14 Tg P a^{-1} and an animal manure production increasing from 13 to 17 Tg P a^{-1} in the period 1970–2000, and given the global efficiency of about 50%, the P balance was 11 and 15 Tg P a^{-1}, in 1970 and 2000, respectively (Figure 5b). Due to the fast increase in P inputs, balances also grow rapidly in GO to 35 Tg a^{-1} by 2050. In OS and TG, the calculated global P balances for 2050 are 30 and 26 Tg a^{-1}, respectively. In AM, the P balance increases to 18 Tg a^{-1} by 2050.

[44] In the AM scenario, oriented toward closing N and P cycles (proactive), the overall global agricultural efficiency for N increases from close to 40% in the period from 1970 to 2000, to values of 50% by 2050, and for P the efficiency increases from the current 50% to 54% by 2050. In scenarios with a reactive approach to environmental problems, the efficiencies for 2050 are somewhat lower (44% for N and 46 to 48% for P) leading to rapidly increasing agricultural N and P balances for all developing countries (Table 3). In the scenarios with a proactive attitude, N balances decrease and P balances show no change or a slight increase. Africa is an exception; African balances increase in all scenarios, as a result of the assumption that land degradation rates by nutrient depletion are reduced or halted (Table 3). In Europe and North America, the N balance declines in all scenarios,

Table 3. Soil Balance of N and P for the Agricultural Area for World Regions[a]

Year/Scenario	North America (Gg a^{-1})	Central and South America (Gg a^{-1})	Europe (Gg a^{-1})	Africa (Gg a^{-1})	North Asia (Gg a^{-1})	South Asia (Gg a^{-1})	Oceania (Gg a^{-1})
			N Balance[b]				
1970	17723	9496	13908	12671	8502	28064	4742
2000	18753	13543	11355	18161	4767	74851	5225
2030-GO	18274	18509	10950	30955	6071	97899	5399
2050-GO	18774	21462	10587	42408	6051	107360	5637
2030-OS	18740	15765	10828	27535	5634	89614	5012
2050-OS	19118	17401	10466	36819	5985	100083	4979
2030-TG	13054	15646	8214	27406	5162	74587	4539
2050-TG	12135	15973	7177	36984	5025	75514	4651
2030-AM	14526	13872	8368	21446	4856	70913	4645
2050-AM	13667	14329	7564	25602	5107	75606	4635
			P Balance[b]				
1970	2815	806	2781	639	1010	2346	580
2000	1656	2023	1029	1235	156	7961	799
2030-GO	2196	3149	1168	3671	217	17291	1092
2050-GO	2393	3904	1127	6098	204	20037	1215
2030-OS	2056	2676	1144	2869	123	15573	1014
2050-OS	2168	3133	1065	4683	108	17616	1080
2030-TG	1415	2712	846	3271	180	13384	889
2050-TG	1264	4056	699	5077	159	13966	1039
2030-AM	1346	2172	595	2053	−49	12628	845
2050-AM	1250	2421	484	3156	−42	14116	903

[a]Regions as in Table 2. For 1970, 2000, and 2030 and 2050 for the four MEA scenarios.
[b]Soil balance in Gg a^{-1} of N or P.

most strongly in the environmentally oriented scenarios; P balances decline (proactive) or increase slowly (reactive approach to environmental problems). In northern Asia, with a strongly declining population in all scenarios, the N balance shows slow or moderate changes, and the P balance increases in globalization scenarios with strong economic growth, and decrease in scenarios with regional orientation (Table 3).

4.2. Comparison of Results With Other Studies

[45] We compared our N and P balances for the year 2000 with country estimates (average 1999–2001) from *Organisation for Economic Cooperation and Development* (*OECD*) [2008] for 29 OECD member countries (Figure 6). Although our data are from globally available statistics, the IMAGE results are in excellent agreement (R values > 0.98) with these national data for N and P soil balances, manure and fertilizer inputs (Figure 6). Important differences in manure production for the U.S.A. are caused by excretion rates, which are 15% higher in the data from *OECD* [2008]. However, since the N and P uptake is calculated from the inputs, the IMAGE soil balance for the U.S.A. is in good agreement with the country estimate. The N balance of 21 Tg a^{-1} for the area of arable land in China estimated by *Zhu and Chen* [2002] is only slightly higher than our 20 Tg a^{-1}. Uncertainty in the calculated nutrient balances is large. For example, although N balances per unit of agricultural area presented by the *European Environment Agency* (*EEA*) [2005] and *OECD* [2008] for the EU15 countries agree fairly well (R = 0.94), the OECD data generally exceed those of EEA. The reason may be inconsistencies and lack of reliable data, particularly on harvested fodder and grass [*EEA*, 2005]. The *OECD* [2008] data is based on a longer experience and includes a larger number of countries.

[46] Although we assumed increases in fertilizer use for many developing countries to a varying degree, the global N fertilizer use in all scenarios for 2030 (103 Tg a^{-1} of N for GO, 96 for OS, 87 for TG and 66 Tg a^{-1} for AM) is lower than the 109 Tg a^{-1} projected by *Bruinsma* [2003]. For P fertilizer, our results for 2030 are similar to the estimate of 22 Tg a^{-1} of P by *Bruinsma* [2003] in TG and AM (23 Tg a^{-1} of P), while P fertilizer use in GO (27) and OS (24 Tg a^{-1} of P) is slightly higher. Our high scenarios for annual P fertilizer use (GO, 33 Tg P; OS, 29 Tg P and TG, 27 Tg P) for 2050 are comparable with the estimate of 30 Tg P a^{-1} presented by *Steen* [1998] for 2050. This 'most likely' estimate of *Steen* [1998] is similar to our scenarios based on assumed increasing P use efficiency in developed countries and increasing use in developing countries.

[47] The *European Fertilizer Manufacturers Association* (*EFMA*) [2009] provides projections of fertilizer use for EU27 countries for the period 2008–2018. Our estimated increase of N fertilizer calculated for EU27 for the period 2008–2018 for the four MEA scenarios (+2% for GO to −5% for AM) is in good agreement with the projected 4% increase by *EFMA* [2009]. For P fertilizer use our scenario results (+38% for GO to 22% for AM) provide a range around the 27% increase projected by *EFMA* [2009] for the eastern European EU members; for the western European EU member countries, *EFMA* [2009] projects a decrease of P fertilizer use of 14%, while our results for the MEA scenarios show a slower decrease of up to 7% in AM and an increase of 3% in GO and OS.

[48] Uncertainties in the global N soil balance calculations were assessed by *Van Drecht et al.* [2005] in a comparison of different inventories for the year 1995 [*Boyer et al.*, 2004; *Green et al.*, 2004; *Siebert*, 2005; *Van Drecht et*

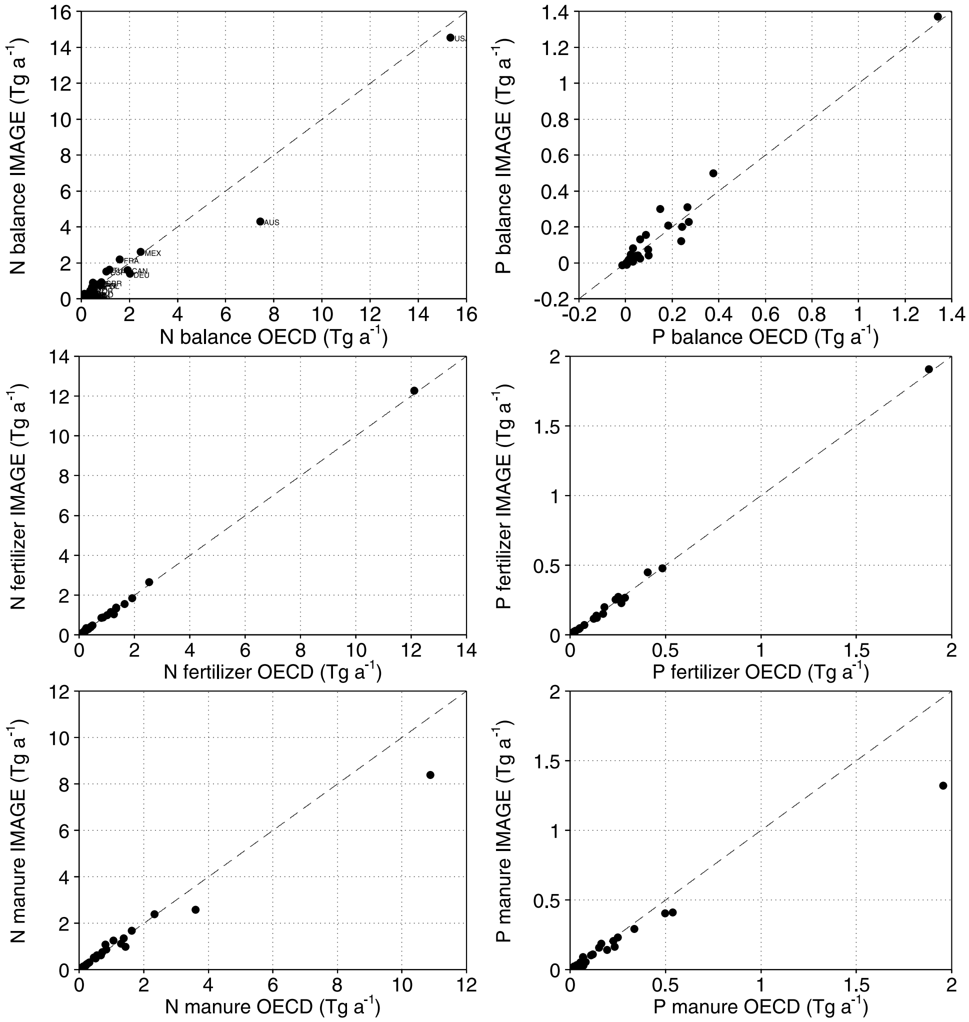

Figure 6. Comparison of IMAGE results with data from *OECD* [2008] for the N and P balance, fertilizer, and manure input for 29 OECD countries.

al., 2003]. The data from *Van Drecht et al.* [2003] were prepared with the same approach used in this study. The results of *Van Drecht et al.* [2005] indicate that the most important differences are in the rates and the spatial allocation for biological N_2 fixation in natural ecosystems, atmospheric N deposition, and N in harvested crops and grass consumption.

4.3. Total N and P Balance

[49] The total N and P balance per unit of land for natural vegetation and agricultural production systems (Figure 7) shows large heterogeneity. Central and South America have small populations and agricultural areas compared to the other world regions. This is more important for N than for P, because biological N_2 fixation in the vast areas covered by tropical forest in Central and South America dominates the N balance. Therefore, the scenarios show a less pronounced total N balance in this region than in the other regions (Table 4). For P, the situation is different, since the P balance is fully determined by agricultural inputs and outputs.

[50] Similarly, population density in North Asia is relatively low, and agricultural areas make up a small part of the total land area. N_2 fixation in natural ecosystems occurs at much lower rates than in Central and South America, and the N balance is smaller than in other world regions (Figure 7).

[51] Despite the fact that Africa has a low population density, we calculate a higher N balance than in, for example, North America (Table 4). This is due to high biological N_2 fixation rates in tropical forest and savanna areas in Africa. In parts of North Africa with intensive agricultural production systems, we see N balances comparable to those in industrialized countries.

[52] Two densely populated world regions, Europe and South Asia, show comparable balance values for the year 2000 (Table 4). The balance per km^2 decreases in all scenarios in Europe. With the population increase projected in the scenarios for South Asia, the N balance per km^2 increases further in the period from 2030 to 2050 in all scenarios. While Europe has increased the efficiency of P inputs in agriculture (Table 2), in South Asia inputs

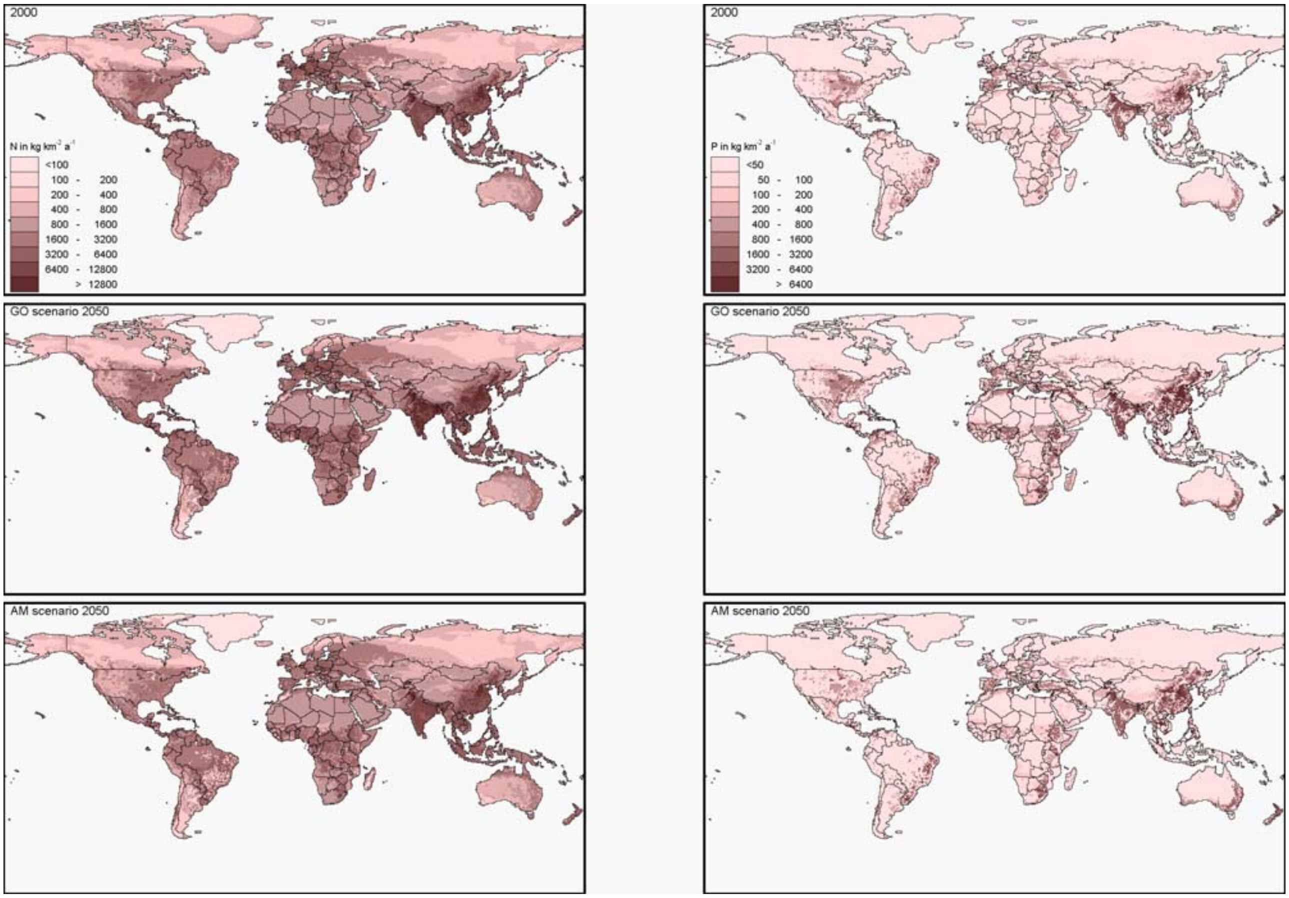

Figure 7. Total balance for (left) N and (right) P for natural ecosystems and agriculture for 2000 and 2050 for the GO and AM scenarios.

increased rapidly between 1970 and 2000, and a further increase is projected. The balances exceed those of other world regions as a result of high fertilization rates associated to multiple cropping. There is a strong concentration of high nutrient input agricultural activities in India and eastern China (Figure 7), and large extensive grassland and desert areas in China and Mongolia having small N and P balances.

4.4. Implications for the Global Agricultural N and P Cycle

[53] We also assess the fate of the global N and P balance in agriculture (Figure 1). Ammonia volatilization (section S2.8 of Text S1) makes up ~20% of N balance. Using the model of *Van Drecht et al.* [2003] we estimate that denitrification makes up 50% and leaching the complement (30%) for the situation in 2000 (Figure 5a). The scenarios for the period 2000–2050 are quite different with respect to the calculated N balance. In AM the balance shows only a slight change at the global scale, while in GO there is a continuation of the upward trend seen in the period 1970–2000 (Figure 5a). The loss terms ammonia volatilization, denitrification and leaching runoff show no or slight changes in AM, while in GO all loss terms show a rapid increase. Both the total balance and the leaching and erosion terms are relevant to particularly the river export of DIN, which is the N form most strongly influenced by human activities [*Seitzinger et al.*, 2009].

[54] For the P fluxes in global agricultural land we also see dramatic increases. Total P inputs to agricultural soils increased from 21 to 31 Tg a^{-1} between 1970 and 2000. The withdrawal of P by agricultural crops increased from 5 to 10 Tg a^{-1}, which is in agreement with *Cordell et al.* [2009]; P withdrawal by grass increased from 9 to 10 Tg a^{-1} between 1970 and 2000. In order to estimate the P balance that is added to the various pools of soil P (Figure 1b) we need to know how much of the P is lost through leaching and runoff. For this we used the increase of total P river export as presented by *Seitzinger et al.* [2009] (excluding the contribution of sewage), assuming that this increase can be completely attributed to agricultural activities. This increase was corrected for P retention in river systems. This simple calculation indicates that about 10% of the P inputs to soil are lost to aquatic systems. In the period 1970–2000 this represented 2–3 Tg P a^{-1}. The difference of 9 (in 1970) to 13 Tg a^{-1} (in 2000) between the total inputs, withdrawal by crops and grass and this P loss to hydrosystems, is assumed to accumulate in soils (Figure 5b). This estimate exceeds the estimate of 8 Tg P a^{-1} by *Bennett et al.* [2001] who assumed larger P erosion and leaching fluxes.

Table 4. Total N and P Balance for the Total Land Area[a]

Year/Scenario	Region[b] North America	Central and South America	Europe	Africa	North Asia	South Asia	Oceania
			N Balance[c]				
1970	1564	2337	3925	1708	1135	1902	1229
2000	1615	2419	3541	1852	845	3381	1358
2030-GO	1588	2643	3439	2212	996	4258	1342
2050-GO	1631	2787	3442	2605	1060	4697	1395
2030-OS	1601	2463	3336	2088	939	3906	1294
2050-OS	1595	2492	3224	2366	988	4271	1261
2030-TG	1266	2484	2696	2084	878	3361	1235
2050-TG	1162	2178	2350	2262	873	3284	1119
2030-AM	1365	2351	2773	1883	884	3200	1249
2050-AM	1316	2328	2580	2005	940	3355	1230
			P Balance[c]				
1970	136	44	555	22	57	75	73
2000	80	110	213	42	9	255	101
2030-GO	106	172	233	124	12	554	138
2050-GO	116	213	225	206	12	642	153
2030-OS	99	146	228	97	7	499	128
2050-OS	105	171	212	158	6	565	136
2030-TG	68	148	169	110	10	429	112
2050-TG	61	221	139	171	9	448	131
2030-AM	58	111	116	57	−5	331	106
2050-AM	52	123	94	83	−4	362	114

[a]Including natural ecosystems and agricultural systems for world regions for 1970, 2000, and 2030 and 2050 for the four MEA scenarios.
[b]Regions; see Table 2.
[c]Soil balance in kg km^{-2} a^{-1} of N or P.

[55] An aspect not considered by *Bennett et al.* [2001] and *Cordell et al.* [2009] is that there are important differences in the P balances for cropland and grassland (Figure 5b). P accumulation is important in the world's croplands, with large differences between countries (Figure 6). However, for grasslands the difference between inputs and outputs is much smaller. The use of P fertilizer in global grasslands of 0.3 Tg P a^{-1} occurs in only a few countries. In all other countries the supply of P in grasslands depends entirely on weathering of minerals (Figure 1b). If the withdrawal of P or the erosion and leaching losses from grasslands are underestimated, there may even be a depletion of soil P.

[56] Our estimate for the withdrawal in harvested products and grazing may indeed be underestimated. In many countries, a large share of the animal feed cannot be accounted for, for example roadside grass and food wastes [*Bouwman et al.*, 2005a]. A further possible overestimation of soil P accumulation is the P leaching and erosion term estimated by the Global NEWS models. Many authors use higher values for river total P export [*Mackenzie et al.*, 2002; *Ruttenberg*, 2005; *Smil*, 2000]. *Meybeck* [1982] reported a value for global particulate P river export to coastal seas of 20 Tg P a^{-1} based on global ratios of particulate carbon to phosphorus. *Cordell et al.* [2009] used an estimate for P erosion losses from agricultural soils of 8 Tg a^{-1}, and *Liu* [2006] presented an estimate of 20 Tg a^{-1}. Such high estimates for the erosion loss would imply that the global grassland area has a large P deficit.

[57] At present, phosphate rock is the only global source of phosphate. With the current increase in the use of P, particularly P fertilizers, the global phosphate rock reserve may be depleted within decades [*Cordell et al.*, 2009; *Herring and Fantel*, 1993; *Steen*, 1998]. It is common practice in the literature to distinguish phosphate reserve and reserve base [*United States Geological Survey*, 2008]. The reserve base (50 Pg rock phosphate) is the in-place demonstrated stocks plus estimated existing resource. Reserves (18 Pg of rock phosphate) comprise that part of the reserve base which could be economically extracted or produced at the time of determination. Reserves and reserve base may contain 7–8 Pg of P based on an average P content of 13.5%. We used data from *Van Drecht et al.* [2009] on detergent P use, calculated P feed supplements on the basis of livestock production, and industrial uses of P on the basis of the IMAGE estimate for the volume of industrial production. If we assume a constant global P use between 2050 and 2100, 64% of the reserves would be depleted in 2100 in GO, 52% in OS, 46% in TG and 35% in AM.

5. Conclusions

[58] This is the first study on spatially explicit global trends in N and P soil balances over time. The MEA scenarios allow for describing contrasting future developments in agricultural nutrient use under changing climate for the next five decades. Massive increases in the flows of N and P are expected in all scenarios in the developing countries. In industrialized countries differences between the scenarios indicate that with a proactive approach the N and P use in agriculture can be controlled. Turning to the nutrient soil balances, the scenarios with a reactive approach portray significant increases in N and P balances in Asia, Central and South America and Africa, while they predict no changes in North America, Europe and Oceania. However, in the scenarios with a proactive approach to environ-

mental problems, the increase in N and P balances is much less or even decreasing in North America, Europe and Oceania.

[59] Apart from differences in population, economy, food consumption and production, energy crop production, and climate, the results of our scenarios indicate that agricultural management aimed at closing nutrient cycles has a major impact on nutrient balances. First, the scenarios differ in the efficiency of N and P use in crop and grass production. We also show that recycling of animal manure and human excreta has large potential to substitute fertilizer. Given the strong prejudice and social inhibition against the handling and use of human excreta in many countries, we do not know if this is realistic.

[60] The global N cycle may be accelerated further in the coming decades, with an increase of the balance by up to 50% in the most pessimistic case; however, in the most optimistic scenario the balance will remain constant at the current high level of about 150 Tg a^{-1}. The global soil P balance in crop production systems increases in all scenarios. This is caused by our assumption of a strong rise in the use of P fertilizers in developing countries in cropland. The soil P balance will probably increase the accessibility and availability of soil P for agricultural production. In future this will lead to an increase of P use efficiency. A negative effect is the potential loss of P by erosion. Our analysis suggests that 36–64% of the world's phosphate rock reserves may be depleted by 2100. A large part of the unfertilized global grassland area has a negative P balance.

[61] The data on N and P input and crop export from diffuse sources, in this paper, together with the estimates for N and P in urban wastewater from the work of *Van Drecht et al.* [2009], are used in the Global NEWS model analyses presented in this special issue for predicting the loads of the various N and P compounds in rivers.

[62] **Acknowledgments.** The Global NEWS project has been cofunded by UNESCO-IOC and is a project under LOICZ. We are grateful to Emilio Mayorga for his extensive comments on the text and for carefully checking our results during the implementation in the GNE framework. The work described in this paper is part of the project Integrated Terrestrial Modeling of the Netherlands Environmental Assessment Agency (PBL). We thank Bas Eickhout for rerunning the IMAGE 2.4 model with the original MEA data, Detlef Van Vuuren and Rineke Oostenrijk for providing the Millennium Assessment data on energy crop production, and Annemieke Righart for editing the text.

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