Global Phosphorus Flows and Environmental Impacts from a Consumption Perspective

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Summary

Human activities have significantly intensified natural phosphorus cycles, which has resulted in some serious environmental problems that modern societies face today. This article attempts to quantify the global phosphorus flows associated with present day mining, farming, animal feeding, and household consumption. Various physical characteristics of the related phosphorus fluxes as well as their environmental impacts in different economies, including the United States, European countries, and China, are examined. Particular attention is given to the global phosphorus budget in cropland and the movement and transformation of phosphorus in soil, because these phosphorus flows, in association with the farming sector, constitute major fluxes that dominate the anthropogenic phosphorus cycle. The results show that the global input of phosphorus to cropland, in both inorganic and organic forms from various sources, cannot compensate for the removal in harvests and in the losses by erosion and runoff. A net loss of phosphorus from the world's cropland is estimated at about 10.5 million metric tons (MMT) phosphorus each year, nearly one half of the phosphorus extracted yearly.

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Introduction

The root of the deep conflicts between modern society and the environment derives from anthropic interventions in material flows. It has been argued that human-induced material flows in modern economies are much more intensive than those in natural cycles (Klee and Graedel 2004). Moreover, the paths and transformations of the societal processing of materials are far more complicated. Because rapid economic development is not yet in harmony with natural ecosystems, the underlying conflict between them has become one of the most important factors influencing an increase in social welfare. To reconcile economy and ecology, it is essential to systematically reflect on the societal mechanism of material flows, thus ecologizing the economy by shifting production and consumption paradigms to improve the overall efficiency of material throughput (Liu 2005).

Phosphorus is one of the most common elements on earth and is essential to all living organisms. A nonrenewable mineral, phosphorus reserves exist only at the earth's crust in the form of phosphate rock, which is currently being mined. In nature, phosphorus flows can be defined as a series of biogeochemical processes involving both mechanical transference and physical, chemical, and biological transformations. The natural phosphorus flows occur very slowly (one single loop of the natural cycle can take place over 1 million years), remain relatively constant in quantity, and contribute to a stable closed loop. The situation has been significantly changed by human activities, however, in particular since industrialization. Historically, as one of the main plant nutrients, phosphorus was recycled in agricultural communities: Food was consumed close to its place of production, and the resulting animal and human manures were applied to the same land. The growth of cities and the intensification of agriculture have depleted soil nutrients, which has increased the need for synthetic phosphorus fertilizers. This has broken open the originally closed loop of the phosphorus nutrient and has caused an increase in phosphorus in human societies. As a consequence, the natural balance of production and consumption in the food chain is disturbed, which usually leads to algae becoming the dominant form of life in water. This, in turn, shapes one of today's challenges: responding to the increasing demand for food and agriculture's growing need of nutrients without exhausting phosphate mineral resources and threatening surface water quality.

This study analyzes and characterizes global phosphorus flows. We examine both the natural cycle and the societal cycle, by using a statistical substance flow analysis method, which has been widely applied to quantitatively describe the physical profiles of modern societies (e.g., Klee and Graedel 2004). In doing so, we give special attention to phosphorus movement in the soil system, which constitutes the largest phosphorus pool (reservoir) within our economy and contributes to the majority of phosphorus losses into the environment. The related environmental issues caused by irrational, inappropriate, or inefficient phosphorus uses are subsequently discussed. The article closes with a discussion on the ecological shifting of the societal phosphorus flows.

The Human-Intensified Phosphorus Cycles

The Natural Cycle

Inorganic Cycle

Phosphorus circulates through the environment in three natural cycles. The first of these is the inorganic cycle, which relates to phosphorus in the crust of the earth. Over millions of years, phosphorus has moved through the inorganic cycle, starting with the rocks, which slowly weather to form soil, from which the phosphorus is gradually leached from the land into rivers and onward to the sea, where it eventually forms insoluble calcium phosphate and sinks to the sea floor as sediment (Follmi 1996). There it remains until it is converted to new sedimentary rocks as a result of geological pressure. On a timescale of hundreds of millions of years, these sediments are uplifted to form new dry land, and the rocks are subject to weathering, completing the global cycle (Schlesinger 1991). In addition, some phosphorus can be transferred back from the ocean to the land by fish-eating birds, whose droppings have built up sizable deposits of phosphate as guano on

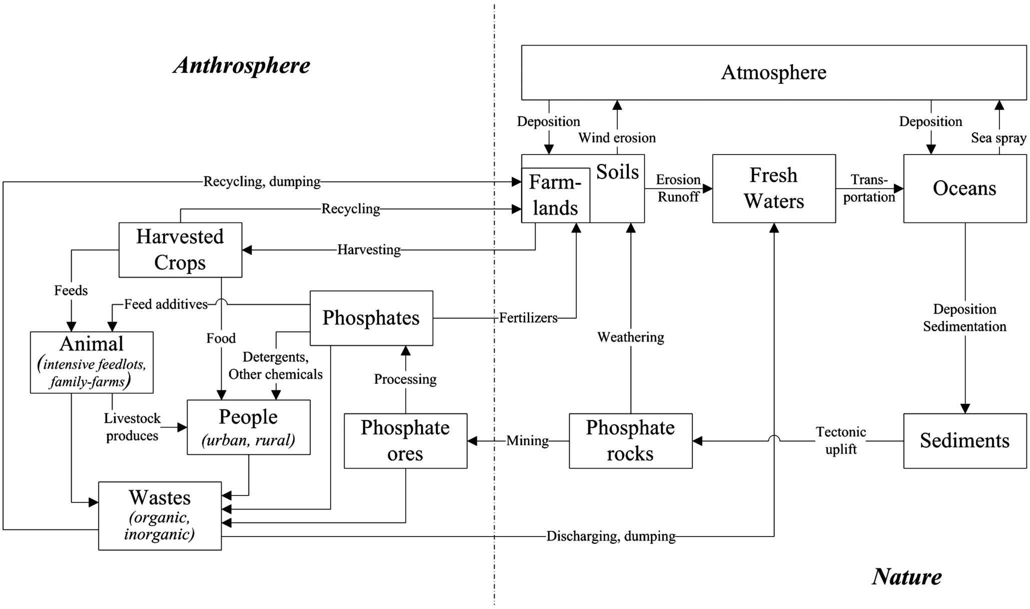

Figure 1 The human-intensified global phosphorus cycles.
Sources: modified from Liu et al. 2004a; Richey 1983; Smil 2000.

Pacific coastal regions and islands, and by ocean currents that convey phosphorus from the seawater to these regions. A simplified schematic of the global phosphorus cycle is presented in figure 1.

The global cycle of phosphorus is unique among the cycles of the major biogeochemical elements in having no significant gaseous compounds. The biospheric phosphorus flows have no atmospheric link from ocean to land. A small quantity of phosphorus does get into the atmosphere as dust or sea spray, accounting for 4.3 million metric tons[1] of phosphorus per year (MMT P/yr) and 0.3 MMT P/yr (Richey 1983), respectively, but the amounts are several orders less important than other transfers in the global phosphorus cycle. The amount of 4.6 MMT P/yr of atmospheric phosphorus deposition, being balanced by the phosphorus carried by the wind and the sea spray, cannot offset the endless drain of this element from the land due to erosion and river transport (Schlesinger 1991). Fortunately, increased anthropogenic mobilization of the element has no direct atmospheric consequences.

Nearly all the phosphorus on land is originally derived from the weathering of calcium phosphate minerals, especially apatite $[Ca_5(PO_4)_3 OH]$. Around 13 MMT P/yr of this is released to form soils each year (Emsley 2000). This amount cannot offset the annual losses of phosphorus from the land, however. If we take into account all four forms of phosphorus (dissolved and particulate, organic and inorganic), the global annual phosphorus losses from the lithosphere into freshwaters are estimated at 18.7 to 31.4 MMT P/yr (Compton et al. 2000).

The uncertainty in the estimate is mainly due to a lack of knowledge of the biogeochemical processes of the particulate inorganic phosphorus (PIP), which constitutes the major component in the total loss. Not all of the eroding phosphorus can eventually reach the ocean. About 3.0 MMT P/yr is carried away by wind into the atmosphere, and at least 25% of that is redeposited on adjacent cropland and grassland or on more distant alluvia (Smil 2000). Consequently, the amount of phosphorus transported by freshwaters into the ocean is probably in the range of 12 to 21 MMT P/yr. This result agrees with the most likely value of 17 to 22 MMT P/yr given by some previous estimates (Emsley 1980; Meybeck 1982; Richey 1983; Sposito 1989; Howarth et al. 1995). The riverborne transport of phosphorus constitutes the main flux of the global phosphorus cycle. The loss, as a result of erosion, pollution, and fertilizer runoff, must be considerably higher than it was in prehuman times. It can be argued that the human-intensified phosphorus flux caused by wind and water erosion is at least double (Compton et al. 2000) or even three times (Smil 2000) its prehistoric level.[2]

Organic Cycles

Imposed on the inorganic cycle are two organic cycles that move phosphorus through living organisms as part of the food chain. These are a land-based phosphorus cycle that transfers it from soil to plants, to animals, and back to soil again and a water-based organic cycle that circulates it among the creatures living in rivers, lakes, and seas. The land-based cycle takes a year, on average, and the water-based organic cycle only weeks. The amount of phosphorus in these two cycles governs the biomass of living forms that land and sea can sustain.

The amount of phosphorus in the world's soils is roughly 90×10^3 to 200×10^3 MMT P, according to various estimates (Emsley 1980; Meybeck 1982; Richey 1983; Filippelli 2002). Although the total phosphorus content of soils is large, only a small fraction is available to biota in most soils. This constitutes an available phosphorus pool containing 1,805 to 3,000 MMT P (Grove 1992), most likely 2,000 to 2,600 MMT P (Emsley 1980; Richey 1983). A larger amount, in the range of 27×10^6 to 840×10^6 MMT P, can be found in the oceans. The sea water contains 80×10^3 to 120×10^3 MMT P, and the rest is accumulated in sediments (Emsley 1980; Richey 1983; Grove 1992; Filippelli 2002; Smil 2002).

The ocean water loses phosphorus continually in a steady drizzle of detritus to the bottom, where it builds up in the sediments as insoluble calcium phosphate. Despite the geological remobilization, there is a net annual loss of millions of tons of phosphate a year from the marine biosphere. Thus, the ocean sediments are by far the largest stock in the biogeochemical cycles of phosphorus.

The Societal Cycle

Global Phosphate Consumption

Phosphate rock is initially converted to phosphoric acid (P_2O_5) by reaction with sulfuric acid (see the companion article on phosphorus production by Villalba et al. [2008]). The phosphoric acid is further processed to produce fertilizers, food-grade and feed-grade additives, and detergents. Other marginal applications include metal surface treatment, corrosion inhibition, flame retardants, water treatment, and ceramic production. Despite such widespread use, the latter applications represented only about 3% of the total consumption of various phosphates in the 1990s (CEEP 1997).

The global consumption of all phosphate fertilizers surpassed 1 MMT P/yr during the late 1930s. After reaching 14 MMT P/yr in 1980, the world consumption of phosphate fertilizers has been relatively stable. It was 14.8 MMT P (34 MMT P_2O_5) in statistical year 2002–2003, and it slightly decreased to 13.8 MMT P (31.5 MMT P_2O_5) in statistical year 2003–2004 (FAO 2005) roughly accounting for 78% of the global production of phosphorus from phosphate rock. As the top fertilizer-processing country, China contributed 22% and 28%, respectively, to the world production and consumption; the top three economies (China, United States, and India) accounted for one half of the world consumption. The area of the world's current cropland is about 1.4 billion hectares[3] (FAO 2005), which implies that the global fertilizer application intensity averages 10 kg P/ha. The application rate varies significantly among continents, ranging from about 3 kg P/ha in Africa to over 25 kg P/ha in Europe. Among western European countries, application levels range from 8.7 kg P/ha in Denmark and Sweden to 34 kg P/ha in Ireland (Johnston and Steen 2000).

Crop Harvests

The use of phosphates to nourish agricultural soils aims to replenish the removal of phosphorus from soil by harvests and erosion losses. Adopting the average phosphorus contents in crops and the harvest index (Smil 1999), the global crop production harvested 12.7 MMT P from soils in 2005, as shown in table 1, on the basis of the world agricultural production database (FAO 2006a). A study of Chinese phosphorus flows suggested that the national harvest in 2000 removed 3.4 MMT P from croplands, on the basis of a set of domestic data for the phosphorus contents and the harvest

Table 1 Allocation of phosphorus in world harvest in 2005

	Harvested crops			*Crop residues*		
Crop	*Fresh weight (MMT)*	*Dry matter (MMT)*	*P in grains (MMT P)*	*Residues (MMT)*	*P in straws (MMT P)*	*Total P uptake (MMT P)*
Cereals	2,239	1,968	5.9	2,947	2.9	8.9
Sugar crops	1,534	476	0.5	370	0.7	1.2
Roots and tubers	713	143	0.1	219	0.2	0.4
Vegetables	882	88	0.1	147	0.1	0.2
Fruit	505	76	0.1	126	0.1	0.2
Pulses	61	58	0.3	61	0.1	0.4
Oil crops	139	102	0.1	92	0.1	0.2
Other	100	80	0.1	200	0.2	0.3
Forages		500	1.0	0	0.0	1.0
Total	**6,173**	**3,491**	**8.2**	**4,163**	**4.5**	**12.7**

Sources: Harvest data are derived from FAO (2006a); conversion coefficients are adopted from Smil (1999).
Note: MMT = million metric tons; P = phosphorus.

index (Liu 2005). These two estimates agree that (1) cereals accounted for a major part of the harvested phosphorus (i.e., 70% at the global level and/or 68% in China) and (2) about two-thirds of the annually harvested phosphorus is contained in grains, and the rest is contained in straw and other agricultural waste.

Given that natural weathering and atmospheric deposition, as discussed elsewhere, cannot compensate for the amount of phosphorus uptake from soils, application of phosphates, in both inorganic and organic forms, becomes essential to sustain today's harvests. Although most inorganic phosphates applied to soils come from chemical fertilizers, the means of organic phosphorus reuse are diverse. The most direct means is to recycle crop residues *in situ*. If we assume that roughly half of the annual output of crop residues (mostly cereal straw) is not removed from fields, the amount of the direct reuse of crop residues is about 2.2 MMT P/yr.

Livestock and Animal Wastes

Animal wastes have been applied as organic manure in traditional farming and remain a relative large source of recyclable phosphorus in modern agriculture. A rough estimate of global production of animal wastes is needed, because detailed inventories of nutrient budget of livestock husbandry are not available for most countries. According to the latest national survey data from the United States, beef cattle, dairy cattle, swine, and poultry produced 1.7 MMT P contained in animal manures in 1997, of which about half was produced by confined animals (Kellogg et al. 2000). The livestock population in the United States accounted for 7% of the world total in 1997, and the proportion has remained fairly constant. On this basis, the global production of animal wastes would be 24.0 MMT P/yr. However, the real figure may be somewhat smaller, because the animals in United States are exceptionally well fed. For this reason, Smil's (2000) estimate of global production of 16 to 20 MMT P/yr in animal wastes, obtained by applying an average concentration of 0.8% to 1% of phosphorus for both confined and unconfined animal wastes, is probably more accurate.

Only the phosphorus in wastes from confined animals is considered to be recyclable for croplands, whereas unconfined animal wastes mainly return to pastures. If we assume that animal biomass remains relatively constant, the amount of phosphorus in animal wastes is equal to the consumption of phosphorus contained in all kinds of feeds. According to the global Food Balance Sheet (FBS) in 2003, livestock consumed 36% of the harvested cereals (excluding the amount of cereals processed for beer), 21% of the harvested starchy roots, and 20% of the harvested pulses (FAO 2006b). Consequently, the annual livestock consumption of phosphorus in the harvests accounted for about 2.9 MMT P/yr.

Some part of crop residues is used as animal fodder. The reuse ratio of crop residues as fodder varies considerably, however. For instance, it was reported that the percentage of crop residues—mostly the straws of rice, wheat, and corn (maize)—used as fodder ranged from 3.6% in Shanghai to 42.8% in Gansu province in 2000 in China, depending on crop and livestock species, farming and feeding traditions, and local economic profiles, and averaged 22.6% across the nation (Gao et al. 2002; Han et al. 2002). Given that over 70% of world livestock are raised in developing countries, where commercial feeds are less used, the global recycling rate of crop straws as fodder is probably about 25%, leading to an absolute quantity of 1.1 MMT P/yr.

Another major source of animal daily phosphorus intake is via feed additives. Around 6% of the global yield of phosphoric acid has been processed as animal feed-grade additives since 2000 (Brasnett 2002; PotashCorp 2004). This constitutes an annual phosphorus flux of 1.0 MMT P/yr input to livestock husbandry.

If we add all three sources above, the global livestock consumption of phosphorus amounts to about 5.0 MMT P each year. When we take into account the recycling of various industrial byproducts and kitchen organic wastes (which is prevalent in rural family-based farms in developing countries), this figure could be as much as 20% higher, resulting in a total of 6.0 MMT P/yr. Of course, the phosphorus flux to livestock of 6.0 MMT P/yr is mainly consumed by animals in confined facilities, whereas the world's cultivated and natural pastures provide a major source of phosphorus for unconfined animals. If we assume that 1.0 MMT P/yr goes to unconfined animals in pastures, about 5.0 MMT P/yr consumed by confined animals gives an approximation for the maximum potential of recoverable phosphorus for croplands. If one half of the organic phosphorus in confined animal wastes is subject to recycling, animal manure is responsible for about 2.5 MMT P/yr returns to global croplands.

Food Consumption and Human Wastes

The third source of organic phosphorus available, in principle, for cropland is human waste. If we assume that the world human body mass averages 45 kg/capita (reflecting a higher proportion of children in the total population of low-income countries) and phosphorus content in the human body averages 470 g P/capita, this implies a global anthropomass (i.e., aggregate mass of humankind) that contains approximately 3.0 MMT P. The typical daily consumption is about 1,500 mg P/capita for adults (CEEP 1997). This is well above the dietary reference intake (DRI), the amount a human individual should take in each day, as recommended by the Food and Nutrition Board of the Institute of Medicine, a part of the U.S. National Academy of Science. The U.S. recommended intakes are 700 mg/capita for adults over 18 years of age, 1,250 mg/capita for young adults between 9 and 18 years of age, and 500 mg/capita for children.

A similar estimate for China is derived from the PHOSFLOW model (a static phosphorus flow balance based on a substance flow analysis approach): The individual daily intake of phosphorus was 1,400 mg P/capita for urban residents and 1,470 mg P/capita for rural residents in 2000 (Liu 2005). This exceeds the DRI of 1,000 mg/capita recommended by the Chinese Nutrient Society. In addition, livestock products provided 30% of the daily phosphorus intake for Chinese urban residents and 14% of that for the rural population (Liu 2005).

Although the phosphorus content of anthropomass is marginal in comparison with that of soil biota or ocean biota, the environmental consequences can still be significant. Given the annual world population growth of 78.4 million since 2000 (UN 2004), the net accumulation of phosphorus in the global anthropomass is around 0.04 MMT P/yr. Compared with the global consumption of phosphorus in foods, the slight increase of phosphorus in the anthropomass stock implies a low assimilation rate of about 0.5%. If we assume a global average dietary consumption of 1,400 mg P/capita, human excreta contains about 3.3 MMT P/yr, of which urban and rural populations generate 1.6 MMT P/yr and 1.7 MMT P/yr, respectively.

Application of human excreta as organic fertilizer is common both in Asia and in Europe but less prevalent elsewhere in the world. The nutrient linkage between farmers and croplands has been relatively stable, but the human wastes in urban areas are less recycled than in rural areas. In China, less than 30% of human waste in urban areas was recycled for agricultural uses in the late 1990s (Chen 2002). This percentage dramatically decreased from 90% in 1980 (Chen and Tang 1998). In contrast, about 94% of human wastes in rural areas were returned to croplands in the 1990s (Pan et al. 1995). In European countries, the recycling rate of urban sewage averaged about 50% over the 1990s (EEA 1997; Farmer 1999). Globally, it could be appropriate to assume that about 20% of urban human wastes and about 70% of rural human wastes are recycled at present. Therefore, recycled human wastes amount to 1.5 MMT P/yr.

When we add the quantities of the phosphorus recycled as crop residues, animal manures, and human wastes, the total organic fertilizers applied to croplands amount to 6.2 MMT P/yr. This is equivalent to 45% of the amount applied in the form of inorganic fertilizers. Thus, the global input of phosphorus to croplands is probably 20 MMT P/yr in total, or 1.6 times the amount of the phosphorus removed from the soil by harvesting. This leads to a net accumulation of 7.3 MMT P/yr or 4.7 kg P/ha/yr in global soils, disregarding erosion and runoff losses.

Phosphates in Soil and Losses

Phosphates in Soil

The distribution, dynamics, and availability of phosphorus in soil are controlled by a combination of biological, chemical, and physical processes. These processes deserve special attention, as a considerable proportion of the applied phosphate is transformed into insoluble calcium, iron, or aluminum phosphates. On average, only a small proportion, perhaps 15% to 20% of the total amount of phosphorus in the plant, comes directly from the fertilizer applied to the crop. The remainder comes from soil reserves (Johnston and Steen 2000). For most of the 20th century, farmers in western countries were advised to add more than double the amount of phosphate required by a crop, because these immobilized calcium, iron, and aluminum phosphates had been assumed to be permanently unavailable to plants.

The primary source of phosphorus taken up by plants and microorganisms is dissolved in water (soil solution). The equilibrium concentration of phosphate present in soil solution is commonly very low, below 5 μMol (Condron and Tiessen 2005). At any given time, soil water contains only about 1% of the phosphorus required to sustain normal plant growth for a season (Emsley 2000). Thus, phosphates removed by plant and microbial uptake must be continually replenished from the inorganic, organic, and microbial phosphorus pools in the soil. These continuous processes dominate contemporary agricultural production to remove about 8.2 kg P/ha from cropland each year on a world average (based on our own estimate) and commonly 30 kg P/ha from the U.S. and European fertile agricultural soils (Johnston and Steen 2000).

Each phosphate mineral has a characteristic solubility under defined conditions (Burke et al. 2004). The solubility of many compounds is a function of acidity (pH). A typical solubility diagram that illustrates phosphate solubility against pH is shown in figure 2. An increase in pH can release sediment-bound phosphorus by increasing the charge of iron and aluminum hydrous oxides and therefore increasing the competition between hydroxide and phosphate anions for sorption sites. Also, organic acids can inhibit

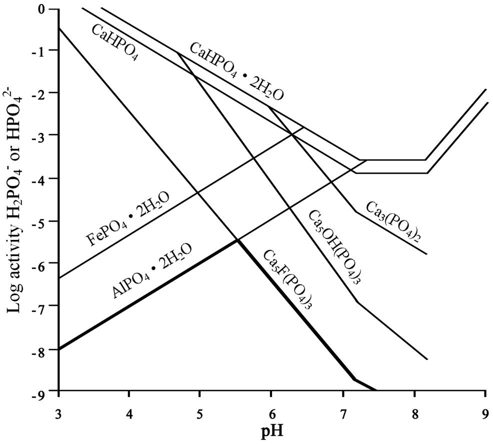

Figure 2 The solubility of phosphorus in the soil solution as a function of pH. The thick line indicates the minimum boundary of the solubility of phosphorus given a certain pH.
Source: adapted from Schlesinger 1991.

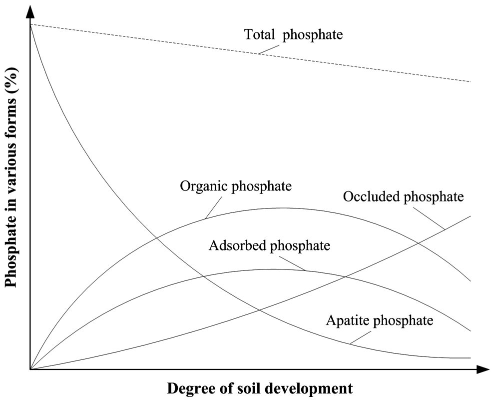

Figure 3 Phosphates in the soil vary with soil development.
Source: adapted from Emsley 1980.

the crystallization of aluminum and iron hydrous oxides, reducing the rate of phosphorus occlusion (Schlesinger 1991). The production and release of oxalic acid by fungi explains their importance in maintaining and supplying phosphorus to plants.

The relative sizes of the sources and stocks of phosphate in soil change as a function of soil development, as shown in figure 3. The buildup of organic phosphates in the soil is the most dramatic change. As time goes on, this becomes the chief reservoir of reserve phosphate in the soil. In most soils, organic phosphates range from 30% to 65% of total phosphorus, and they may account for as much as 90% of the total, especially in tropical soils (Condron and Tiessen 2005).

The reasons for this are organic phosphates' insolubility and chemical stability. Several authors have noted that acidic soils tend to accumulate more total organic phosphorus than do alkaline soils. This is almost certainly because organic phosphates react with iron and aluminum under acidic conditions and become insoluble (Harrison 1987). Being the salts or metal complexes of phosphate esters, they release their phosphate by hydrolysis, but only very slowly. Phosphate esters can have half-lives of hydrolysis of hundreds of years. This process can be greatly speeded up by the action of phosphatase enzymes in the soil, whose function is to facilitate reaction by catalyzing it (Quiquampoix and Mousain 2005).

At later stages of soil development, phosphorus is progressively transformed into less-soluble iron- and aluminum-associated forms, and organic phosphorus contents of the soil decline (Tiessen and Stewart 1985). At this stage, almost all available phosphorus is found in a biogeochemical cycle in the upper soil profile, whereas phosphorus in lower depths is primarily involved in geochemical reactions with secondary sediments (Schlesinger 1991).

When the dissolved phosphates supply to growing biomass is abundant, a net immobilization of inorganic phosphorus into organic forms will occur. Conversely, inadequate inorganic phosphorus supply will stimulate the production of phosphatases and the mineralization of labile organic forms of phosphorus for microbial uptake (Tiessen and Stewart 1985). A continuous drain on the soil phosphorus pools by cultivation and crop removal will rapidly deplete both labile inorganic and organic phosphorus in soils.

Allowing soil reserves of readily available phosphorus to fall below a critical value, determined by field experiments, can result in a loss of yield. The turnover of available phosphates by plants in soil solution is determined by rates of releases of phosphorus from insoluble forms to soluble phosphates. All kinds of soil particles can contribute to this process, and in some cases it is not only chemical balance that maintains the supply but the action of microbes and enzymes that release phosphate from organic debris in the soil. It is believed that the biogeochemical control of phosphorus availability by symbiotic fungi is a precursor to the successful establishment of plants on land (Schlesinger 1991).

Our existing knowledge, however—briefly discussed above—cannot yet provide a comprehensive understanding of the complex movements and transformations of phosphorus, especially of its organic forms (Turner et al. 2005). This hampers the efficient application of phosphate fertilizers and the efficient control of phosphorus losses.

Phosphorus Losses

Phosphorus is lost from croplands via erosion or runoff. Quantifying phosphorus losses in eroding agricultural soils is particularly uncertain, as erosion rates vary widely even within a single field. Another cause of uncertainty is that few nations take comprehensive, periodic inventories of their soil erosion.

The phosphorus loss from croplands can be roughly estimated on the basis of the amount of topsoil erosion and average phosphorus content. A crop takes up the majority of the nutrients it requires from topsoil. The topsoil is often identified as the "plough layer"—that is, the 20 to 30 cm depth of soil that is turned over before seedbed preparation. The volume of topsoil in the plough layer is around 2,500 cubic meters[4] (m^3) per hectare and weighs approximately 2,000 tons (Johnston and Steen 2000). A ton of fertile topsoil can contain 0.6 to 3.0 kg of phosphorus, mainly based on U.S. and European agricultural practices (Troeh et al. 1991; Johnston and Steen 2000).

It has been estimated that the annual soil erosion from agricultural systems of the United States, China, and India was 3,000 MMT/yr, 5,500 MMT/yr, and 6,600 MMT/yr, respectively (Pimentel 2006). As these three countries hold 23% of global agricultural lands, the global soil erosion could reach 66,600 MMT/yr. Some of the most serious soil erosion takes place in the agricultural systems of Southeast Asia, Africa, and South America (Yang et al. 2003). Hence, the real global soil erosion loss could be even higher, perhaps as much as 75,000 MMT/yr (Myers 1992).

The erosion intensity from croplands varies considerably among countries, ranging from 0.5 to 400 t/ha-yr (Pimentel et al. 1995). Worldwide, soil erosion is highest in Asia, Africa, and South America, averaging 30 to 40 t/ha-yr of soil loss (Taddese 2001). Smil (2000) has suggested that the global average erosion rate is at least 20 t/ha-yr. The lowest erosion rates occur in the United States and Europe, where they average about 10 t/ha each year (USDA 2000a, 2000b). It is evident that soil erosion in the United States has been reduced by soil conservation policies: A national survey showed that the total soil erosion between 1982 and 1992 decreased by 32% (Uri 2001). The annual sheet and rill erosion rate in the United States fell from an average of 10 t/ha in 1982 to 7.7 t/ha in 1992, and the wind erosion rate fell from an average of 8.1 t/ha-yr to 5.9 t/ha-yr over the same period.

Assuming a global erosion rate averaging 25 t/ha gives the soil loss of 38,500 MMT/yr from cropland (cf. table 1). Furthermore, most of the loss is permanent and may not be replenished by weathering. For instance, the excessive soil loss, a rate that would impair long-term crop productivity, was estimated at about 25,400 MMT/yr around 1980 (Brown and Wolf 1984).

Erosion from pastures is commonly less intensive than that from ploughed fields. Soil losses, however, have been greatly increased by overgrazing, which now affects more than half (i.e., at least 1,720 million hectares) of the world's permanent pastures, with a high erosion rate of 15 t/ha each year (Smil 2000). This leads to 25,800 MMT/yr of the soil loss from overgrazed pastures. Together with the amount of soil loss from cultivated grassland, the world's permanent pastures lose their topsoil at an annual rate of 34,400 MMT/yr. When we add the losses from cropland and pastures, the world soil erosion from agricultural areas amounts to 72,900 MMT/yr in total, or 15 t/ha/yr on average. This is similar to previous estimates, as discussed above.

Allowing for the poor condition of topsoil in developing countries, it might be appropriate to assume that the global phosphorus content in topsoil averages about 0.5 kg P/t, or 1.0 t P/ha. This gives world phosphorus losses at 19.3 MMT P/yr from cropland and at 17.2 MMT P/yr from pastures, respectively, as shown in table 2.

The surface runoff loss of applied inorganic phosphate fertilizer varies significantly with a number of agronomic factors. Typical runoff rates of phosphorus in European countries range from 0.2% to 6.7%, an average of 3.5% (Haygarth 1997; Hart et al. 2004). Worldwide, the maximum rate can reach 10% under certain soil characteristics and climatic conditions (Waddell and Bower 1988). Roughly, the world total phosphate fertilizer application can lead to a loss of 0.5 MMT P/yr in surface runoff.

Phosphate Balance in Cropland

The national phosphorus balance varies significantly from one country to another, due to differences in the use of mineral fertilizers and manure and differences in animal husbandry practices. Broadly speaking, in developing countries soils tend to be deficient in phosphorus, whereas

Table 2 Global soil erosion and phosphorus losses from agricultural land (2003)

		Permanent pasture	
Contents	*Cropland*	*Overgrazed*	*Ordinary*
Total area (million ha)	1,540	1,720	1,720
Soil erosion			
Erosion rate (t/ha/yr)	25	15	5
Erosion quantity (MMT/yr)	38,500	25,800	8,600
Phosphorus loss			
P content in topsoil (kg P/ha)	0.5	0.5	0.5
P loss (MMT P/yr)	19.3	12.9	4.3

Note: MMT = million metric tons; P = phosphorus.

Table 3 Phosphorus budget for the world's cropland (2004)

Flows	*Annual fluxes (MMT P)*
Inputs	22.9
Weathering	1.6
Atmospheric deposition	0.4
Synthetic fertilizers	14.7
Organic recycling	6.2
Crop residues	2.2
Animal wastes	2.5
Human wastes	1.5
Removals	12.7
Crops	8.2
Crop residues	4.5
Losses	19.8
Erosion	19.3
Runoff	0.5
Balance	−9.6
Input shares (%)	
Fertilizer application	64.2
Organic recycling	27.1
Uptake efficiency (%)	64.6

in developed countries the phosphorus content of the soils is adequate or even excessive. If we take into account applications of mineral fertilizers and manure, the balance for some western European countries is positive, particularly in the Netherlands, where it exceeds 39 kg P/ha each year. For the majority of western European countries, the phosphorus balance ranges from 8.7 to 17.5 kg P/ha annually (Johnston and Steen 2000). China, one of the largest agricultural systems in transition, also achieved a positive balance around 1980 at the national level, in parallel with increasing application of synthetic fertilizers (Wang et al. 1996; Jin and Portch 2001). In 2000, the national surplus of phosphorus in Chinese soils was estimated at an average of 16 kg P/ha (Liu et al. 2007).

To balance the phosphorus budget for the world's cropland, two natural inflows of phosphorus to croplands should be taken into account. On the basis of the ratio of cropland area to world total land areas, weathering and atmospheric deposition contribute 2.0 MMT P/yr as inputs to world croplands.

The world phosphorus budget for cropland is summarized in table 3. Although the magnitudes of recycling of animal wastes and soil erosion need further verification, the budget provides a comprehensive overview of the global phosphorus flows associated with the farming sector, which is the most intensive and complicated subsystem of the anthropogenic phosphorus cycle.

Environmental Impacts of Phosphorus Uses

Phosphorus-related environmental issues fall into a broad range. Some are caused by inappropriate use of the material; some are not. Eutrophication, regarded as the most immediate environmental consequence of extensive phosphorus usage in contemporary societies, has received wide attention. It is not the whole story, however, and other issues deserve to be taken into consideration. Here, our discussion is devoted to a broad socioeconomic context, focusing on five phosphorus-related environmental issues: mineral reserve conservation, soil erosion and degradation of soil fertility, animal waste management, sewage and detergent use, and eutrophication.

Mineral Conservation

If the annual mining rate of about 19.5 MMT P/yr remains constant, the world's known phosphate reserves could be exhausted in about 120 years. Moreover, it has been projected that the utilization trend is unlikely to decline in the next 30 years. It will instead probably increase at the rate of 0.7% to 1.3% annually (FAO 2000). This strongly suggests that phosphate rock, as a finite, nonrenewable resource, may be exhausted in a much shorter time. It has been shown that the global average phosphorus content in raw ores dropped to 29.5% in 1996 from 32.7% in 1980 and that global reserves can sustain the current mining intensity for only another 80 years (Isherwood 2000). Some phosphorus-rich deposits around the world could be depleted much sooner. China's phosphorus reserves, for instance, constitute 26% of the world's total reserve base, second only to Morocco and the western Sahara (USGS 2006). With a high intensive extraction activity as well as losses incurred during mining, the basic reserve of the nation's phosphorus resources (i.e., 4,054 million tons with average P_2O_5 content of 17% to 22%) could be exhausted in 64–83 years (Liu 2005). As a result, the Ministry of Land and Resources in China counts phosphorus as one of the unsustainable resources for China's development in this century. Certainly, the larger reserve base and probably more reserves to be discovered in the future guarantee a longer life span of the extraction. Even so, the deposits of phosphorus in the lithosphere will inevitably be depleted before new igneous or sedimentary rocks to be formed via the biogeochemical process at the timescale of millions of years.

Soil Erosion

If our estimates are reasonably accurate, one of the most important results derived from the phosphorus budget is that world cropland is losing phosphorus at a surprising rate of 9.6 MMT P each year. This massive loss from croplands is mainly caused by wind and water erosion of topsoil. Soil erosion has been recognized as one of the most serious environmental crises challenging the world (Brown and Wolf 1984). It is estimated that 10 million hectares of cropland are abandoned annually worldwide due to lack of productivity caused by the soil erosion (Pimentel 2006). Nearly 60% of present soil erosion is induced by human activity, an increase of 17% since the early 1900s (Yang et al. 2003).

In contrast to the erosion loss, a huge amount of phosphorus has been mobilized in cultivated soils. Contemporary scientific knowledge cannot fully explain the complex transportation of phosphorus between plant roots, soil waters, and soil particulates. More complete understanding of these processes might suggest a possibility of controllable remobilization of soil phosphorus that would benefit the environment via reducing both the input of fertilizers and the loss of phosphorus from soils.

Animal Wastes

Livestock husbandry, in particular large, intensive feedlots, has become a major problem both for recycling of organic phosphorus and for emission of phosphorus pollutants. Worldwide, the structure of animal agriculture has changed as livestock are concentrated in fewer but larger operations (GAO 1995; EEA 2003a; Ribaudo et al. 2003). In the United States, in spite of the loss of nearly a fourth of the livestock operations between 1982 and 1997, the total number of animal units[5] has remained fairly constant at about 91 to 95 million (Kellogg et al. 2000). In China, a large number of intensive feedlots appeared in suburbs and rural areas during the last decade. According to a national investigation, the output of hogs, meat chickens (broilers), and egg chickens (layers) produced by intensive feedlots and farms accounted for 23%, 48%, and 44% of the national total in 1999, respectively (SEPA 2002).

As livestock operations have become fewer, larger, and more spatially concentrated in specific areas, animal wastes have also become more concentrated in those regions. This leads to a considerable phosphorus surplus in manure, as the amount of manure nutrients relative to the assimilative capacity of land available on farms for application has grown, especially in specific high-production areas (Steinfeld et al. 1998; Poulsen et al. 1999; OECD 2001; Gerber et al. 2005). Consequently, off-farm manure export requirements are increasing.

But because of its bulk, uneven distribution, and the prohibitive cost of transport beyond a limited radius, a large proportion of manure phosphorus is now subject to disposal instead of recycling. If construction of necessary infrastructures for appropriate disposal of manure lags behind, animal wastes become a major source of phosphorus loads in surface waters. Uncontrolled phosphorus emission from intensive feedlots and farms in China has escalated in parallel with the gradual growth in total animal-feeding operations and the rapid shift in breeding structure (Liu et al. 2004b). The emission of China's livestock was estimated at 36% of its national phosphorus load to aquatic environments in 2000 (Liu et al. 2007). Thus, livestock husbandry is the most significant source of phosphorus flux to surface waters in China, similar to the situation in European countries in the early 1990s (Morse et al. 1993).

Sewage Treatment

In the 1960s, many developed countries began to alleviate the pollution in surface water by constructing municipal sewage infrastructures and implementing phosphorus discharge restrictions on production sectors (Stauffer 1998; Moss 2000). The giant infrastructure of centralized wastewater treatment has drastically reshaped the phosphorus cycle within modern cities. Despite high economic costs, its environmental benefits in regard to removal of phosphorus from wastewater are far less than satisfactory worldwide. Some progress has been achieved in European countries (EEA 2003b; Farmer 2001) and the United States (Litke 1999), however. As the centralized control strategy just removes "pollutants" into sewage sludge rather than promoting a recovery and recycling of resources, including phosphorus, it does not really solve the long-term problem (Beck 1997; Stauffer 1998). The costly and rigid infrastructures have significantly reduced agricultural reuse of urban human excreta and contributed to a disconnection of nutrient cycles between urban areas and croplands (Foster 1999). Unfortunately, no available technologies for stable recovery and recycling of phosphorus are likely to be successfully commercialized in the near future (Driver 1998; Piekema and Roeleveld 2001; SCOPE 2001). Hence, most of the phosphorus in urban human wastes is not subject to efficient recycling and is permanently lost from the land (EEA 1997; USEPA 1999).

Proposals for recovery of phosphorus via decentralized source-separated strategies have received increasing attention since the mid-1990s (Larsen and Gujer 1996; Beck 1997; Otterpohl et al. 1999; Berndtsson and Hyvonen 2002; Wilsenach and van Loosdrecht 2003; IWA and GTZ 2004).[6] This decentralized and downsized sanitation concept, focused on ecologically sustainable and economically feasible closed-loop systems rather than on expensive end-of-pipe technologies, advances a new philosophy. It departs from the one-way flow of excreta from terrestrial to aquatic environments, as introduced by the conventional flush-and-discharge sewage system. The new alternative separates nutrients and domestic used water at the source and handles both components individually on the basis of material flows approaches. Thus, it avoids the disadvantages of conventional wastewater solutions and enables and facilitates nutrient recycling. Although the reinvention and transition of urban wastewater systems poses a major challenge, it does provide a promising prospect for future phosphorus recovery and recycling in an ecological and economically efficient way (Larsen et al. 2001; Pahl-Wostl et al. 2003).[7]

Detergents Use

The use of sodium tripolyphosphate ($Na_5P_3O_{10}$; STPP), the most widely used detergent additive, has been identified as a significant contributor to eutrophication. STPP was first introduced in the United States in 1946 (Emsley 2000). After reaching a peak in the 1960s, global production has finally fallen to one half of the peak level, about 1.0 MMT P/yr, mainly due to bans on phosphorus-containing detergents in developed countries. According to the estimate by Villalba and colleagues (2008), the total quantity of STPP production was 0.86 MMT P in 2004. In the late 1990s, phosphorus-free detergents accounted for 45%, 97%, and 100% of all detergents, respectively, in the United States, Japan, and European countries (Litke 1999; Moss 2000).

There has been controversy on the environmental impacts of STPP since the middle 1980s

(Lee and Jones 1986; Hoffman and Bishop 1994; Morse et al. 1994; Wilson and Jones 1994; Wilson and Jones 1995; Liu et al. 2004a). Today, it is acknowledged that limiting or banning household consumption of phosphorus-containing detergents would not lead to a significant or a perceivable improvement of eutrophication. It would have little impact on the environment and human health compared to other substitute chemicals (sodium carbonates, sodium silicates or zeolites A, and sodium nitrilotriacetate), from both an environmental and an economic perspective. In parallel with these discoveries, some Nordic countries eco-labeled STPP as an environmentally friendly component of detergents in 1997 and have repromoted the production and consumption of STPP since then.

Eutrophication

Eutrophication is an unwanted explosion of living aquatic-based organisms in lakes and estuaries that results in oxygen depletion, which can destroy an aquatic ecosystem. It has been regarded as the most important environmental problem caused by phosphorus losses. Significant eutrophication took place in the 1950s in the Great Lakes of North America and has been prevalent in many lakes and estuaries around the world (UNEP 1994; ILEC 2003). Phosphorus is often the limiting factor responsible for eutrophication, as nitrogen fluxes to water bodies are relatively large.

Phosphorus losses from industries, croplands, animal farms, and households constitute the main sources. It is helpful to discriminate phosphorus loads from different sources. Normally, point sources refer to the discharges from industry and urban wastewater. Diffuse sources (nonpoint sources) include background losses, losses from agriculture, losses from scattered dwellings, and atmospheric deposition on water bodies. Application of area-specific indicators enables a comparison of phosphorus loads between different geographic boundaries (EEA 2005). Figure 4 illustrates a cross-county comparison of the phosphorus loads in European countries and in China to their domestic aquatic environments. Figure 5 shows a comparative histogram of the phosphorus loads to some main lakes and river basins in Europe and China.

The results show that the phosphorus loads range from 0.2 kg P/ha in Sweden to 2.5 kg P/ha in Belgium at the national level. China lies between Germany and Northern Ireland in terms of the load per unit land area. At the basin level, the phosphorus loads of the three rivers and three lakes[8] in China average 1.7 kg P/ha, 1.3 times the average of the selected European river basins and lakes. These results suggest that the Chinese economy is, in general, processing phosphorus "wastes" less efficiently than developed countries. It is nearly impossible, however, to determine a common benchmark (of a desired phosphorus load) to prevent water bodies from eutrophication. This is because the complex interrelations between the amount of aquatic biomass and the phosphorus load are affected by a number of hydrological, meteorological, and biochemical factors that remain unclear under

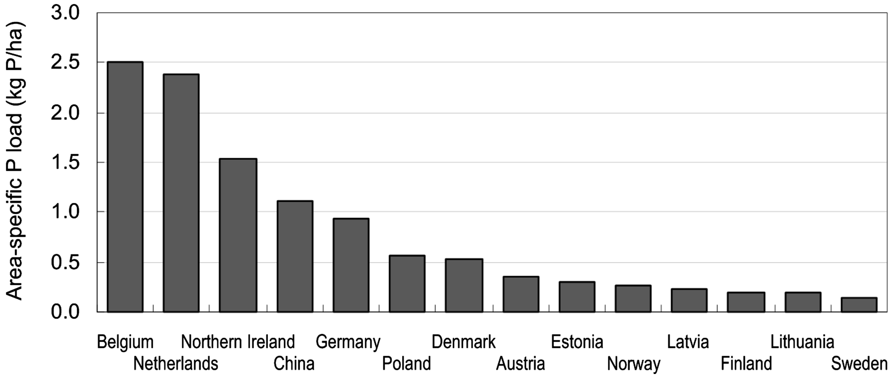

Figure 4 Comparison of phosphorus loads to aquatic environments by country in 2000 (unit: kg P/ha). *Sources:* EEA 2005; Liu 2005.

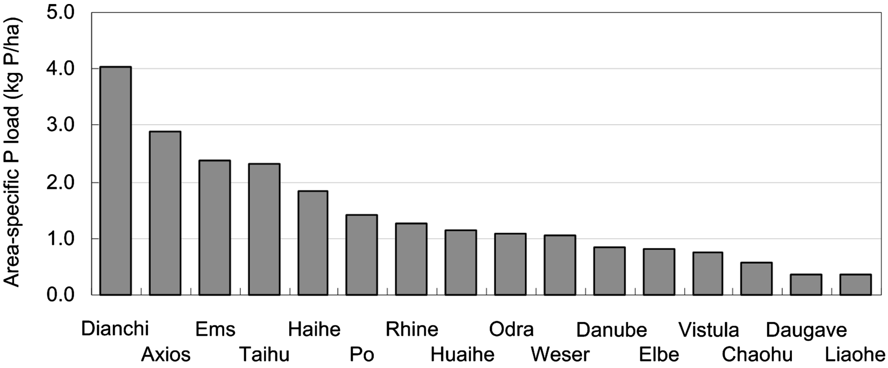

Figure 5 Comparison of phosphorus loads to aquatic environments by river basin in 2000 (unit: kg P/ha). Date for Chinese river basins refers to 2001.
Sources: EEA 2005; Liu 2005; Zhang and Chen 2003.

current knowledge. Nevertheless, the comparison of area-specific phosphorus loads serves as a valuable analysis tool for decision making.

Regulating the Societal Phosphorus Flows

Phosphorous, intensively extracted from the natural sink in the lithosphere and processed through various production–consumption cycles, ultimately deposits in soil or reaches a water body by different pathways. The societal phosphorus flows are characterized by complicated physical interconnections in high intensities among a number of production and consumption sectors. Hence, it is vitally important to connect the phosphorus flows with environmental regulations intended to intervene in social practices and human behaviors.

Instead of continuously trying to limit the growth of phosphorus use (e.g., the bans of detergent phosphorus), there is a great need to reconstruct the physical structure of phosphorus flows, in particular by redirecting the crucial phosphorus flows with highly negative environmental impacts. The most remarkable feature of the societal phosphorus flows is that, on the one hand, the current global reserves may sustain the current mining intensity for perhaps less than 1 century. On the other hand, massive losses of phosphorus from the economies take place annually, and only a few of them have been subject to recycling.[9] Currently, most of the phosphorus regulatory measures focus on the reduction of various phosphorus losses to the water body, aiming to mitigate extensive eutrophication. Nevertheless, management of the phosphorus in soils and recovery and recycling of phosphorus in various wastes, which are vitally important to reconstruct the societal phosphorus flows as a whole, are comparatively disregarded.

The ecological restructuring of the current once-through mode of societal phosphorus metabolism is thus desired, leading to a sound structural shift in the societal production and consumption of phosphorus. The ecologically rational switch, differing from the current eutrophication-driven regulatory regime, can contribute to sustained phosphorus uses and a substantial reduction of phosphorus emissions, by minimizing phosphorus input and maximizing phosphorus recycling. Given that ecologizing the phosphorus flows only succeeds when measures are institutionalized into the economy and society as a whole, this process will most likely be a gradual one rather than a radical revolution.

Notes

1. One million metric tons (10^6 t) = 1 teragram (Tg) = 10^9 kilograms (kg, SI) ≈ 1.102 × 10^6 short tons. All tons mentioned in this article refer to metric tons.
2. Some authors disagree. Schlesinger (1991), for instance, assumed that this flux may be only slightly higher than in prehistoric time.

3. One square kilometer (km^2, SI) = 100 hectares (ha) ≈ 0.386 square miles ≈ 247 acres.
4. One cubic meter (m^3, SI) ≈ 1.31 cubic yards (yd^3).
5. We apply the term *animal unit* acknowledging that animals are considerably different in manure production. It serves as a common unit for aggregating animals across farms and across animal types and thus provides a measurable basis for environmental regulation. One calculates animal units by multiplying the number of animals by an equivalency factor based on nitrogen or phosphorus emission.
6. Such systems (e.g., dual-flush toilets) separate nutrients and domestic used water at the source and handle all components individually on the basis of material flows approaches. The holistic alternatives, which avoid the disadvantages of conventional wastewater solutions, allow the segregation of urine and feces in plumbing and thus ultimately enable and facilitate nutrient recycling. Moreover, by decentralizing and downsizing the entire urban wastewater infrastructure, this approach does not favor specific technologies and meanwhile does not cause hygiene or odor problems.
7. Detailed studies are essential as a first step, *inter alia*, of technological, organizational, economic, and social aspects. In addition, the involvement of multistakeholders, such as residents, building owners, farmers, politicians, officials, and other interested parties, from the start seems essential. All these problems cannot be solved overnight, as the solution requires nothing less than a paradigmatic change of a large sociotechnical system.
8. *Three rivers* refers the Huai River, Hai River, and Liao River, and the three lakes include Taihu Lake, Chaohu Lake, and Dianchi Lake. All of them are regarded as national key areas for water environmental protection. These six watersheds were upgraded as the national key environmental protection areas at the Fourth National Environmental Protection Conference in 1996.
9. The estimation of the depletion times of phosphorus reserves on the basis of the ratio of current reserves to current usage rates is controversial. Reserves are defined as the resources economically available to extract given current prices and technology. It is argued that when reserves become scarce, the market prices tend to rise, and a variety of societal responses (e.g., substitution, more efficient use, increased exploration, investment in improvements in extraction technology) could occur. Because there is definitely no substitute for phosphorus, improvements in (re-)extraction technology and usage efficiency can provide promising ways to sustain future demands of human society for a longer period. For instance, as discussed elsewhere in this article, the phosphorus that has been mobilized in soils over time, especially after industrialization of chemical fertilizer production and application, forms a tremendous source for remining. Due to significant uncertainties in technological trajectories as well as market mechanisms, however, it is almost impossible to predict exact depletion times of a certain resource. Our estimation provides a baseline scenario for phosphorus depletion. The result warns us that if we do nothing on investments in advanced technologies for phosphorus (re-)mining and recycling today, we will suffer very soon.

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Supplementary Material

The following supplementary material is available for this article:

Appendix S1.

This material is available as part of the online article from:
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