Human Impact on Erodable Phosphorus and Eutrophication: A Global Perspective

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Human actions—mining phosphorus (P) and transporting it in fertilizers, animal feeds, agricultural crops, and other products—are altering the global P cycle, causing P to accumulate in some of the world's soil. Increasing P levels in the soil elevate the potential P runoff to aquatic ecosystems (Fluck et al. 1992, NRC 1993, USEPA 1996). Using a global budget approach, we estimate the increase in net P storage in terrestrial and freshwater ecosystems to be at least 75% greater than preindustrial levels of storage. We calculated an agricultural mass balance (budget), which indicated that a large portion of this P accumulation occurs in agricultural soils. Separate P budgets of the agricultural areas of developing and developed countries show that the rate of P accumulation is decreasing in developed nations but increasing in developing nations.

Phosphorus accumulation in upland soils may affect freshwater ecosystems. Production in most lakes depends on P input (Schindler 1977). Overenrichment with nutrients can cause excessive production in lakes, a problematic condition known as eutrophication, in which water quality is impaired (see the box on p. 225). Phosphorus generally enters aquatic ecosystems sorbed to soil particles that are eroded into lakes, streams, and rivers (Daniel et al. 1994, Sharpley et al. 1994). Much of this runoff occurs during major erosion-causing storms (Pionke et al. 1997). Potential P pollution of aquatic ecosystems is thus strongly influenced by watershed land use and the concentration of P in watershed soils: Any factor that increases erosion or the amount of P in the soil increases the potential P runoff to downhill aquatic ecosystems (Daniel et al.1994, Sharpley et al. 1994).

INCREASING ACCUMULATION OF PHOSPHORUS IN SOIL THREATENS RIVERS, LAKES, AND COASTAL OCEANS WITH EUTROPHICATION

Phosphorus buildup in upland soils could cause water quality problems in excess of eutrophication seen to date. Many years may pass between accumulation of P in soil and the appearance of adverse effects in freshwater ecosystems (Reed-Andersen et al. 2000). Such adverse effects might appear abruptly if the vulnerability of the system increases gradually until a threshold is passed (Heckrath et al. 1995). Soil P accretion could lead to sudden and unanticipated changes in aquatic ecosystem productivity. It could also cause lags between management actions taken to control eutrophication and the time when results of those actions are realized (Stigliani et al. 1991).

In this article we ask, "Are there changes in the global P cycle that could increase impacts on freshwater systems?" Specifically, we attempt to determine whether there is, in fact, increased P storage in the soils of terrestrial ecosystems. We address this question through synthesis of existing literature and use a budget approach to estimate the increase in P storage in upland ecosystems.

Changes in the global nitrogen (N) cycle have been well described (Vitousek et al. 1997, Caraco and Cole 1999). Human

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Eutrophication

Eutrophication is a widespread problem in aquatic ecosystems around the world (Vollenweider 1968, NRC 1993, Nixon 1995). Eutrophic lakes exhibit many undesirable traits, including excessive growth of algae and other aquatic plants (Figure 1; Smith 1998). In response to overenrichment with nutrients, the phytoplankton community may shift to bloom-forming nuisance algae, which are harmful to other organisms (Smith 1990). Decomposition of algal blooms can lead to foul odors and oxygen depletion, which can in turn lead to fish kills (Carpenter et al. 1998, Smith 1998). Other problems associated with eutrophication include the presence of toxins, unpalatability of drinking water (Lawton and Codd 1991), extirpation of native plants (Gleick 1998, Smith 1998), and loss of biodiversity (NRC 1993, Smith 1998).

Figure 1. Algal bloom on a eutrophic lake, Lake Mendota, in Madison, Wisconsin.

Eutrophication is also a problem in many nearshore marine areas. Eutrophication has been linked to the hypoxic "dead zone" in the Gulf of Mexico (Turner and Rabalais 1991, 1994). Nearshore eutrophication can lead to coral reef death (Smith 1998) or shellfish poisoning of humans (Anderson 1994, Anderson and Garrison 1997). Moreover, the symptoms of eutrophication in both fresh and salt waters can lead to loss of aesthetic, ecological, and economic value of aquatic ecosystems.

Excess P input from point sources such as sewage treatment plants has been curtailed in freshwaters of the developed world since passage of the Clean Water Act and similar laws. However, nonpoint source pollution, which originates from diffuse, intermittent sources that are difficult to identify, is still an important water-quality problem (NRC 1992, Duda 1993). In fact, the major source of P in freshwater in the United States is nonpoint source flux from land to water (NRC 1993, Sharpley et al. 1994, Daniel et al. 1994).

impacts on the global P cycle are less clear (see, however, Howarth et al. 1995, Tiessen 1995). Nevertheless, instances of human impact on the P cycle leading to accumulation of P in upland systems have been discovered both locally and regionally. For example, Lowrance and colleagues (1985) found that imports of P exceeded exports by 3.7 to 11.3 kg · ha^{-1} · yr^{-1} in four subwatersheds of the Little River in the Georgia Coastal Plain, with human fertilizer inputs to the four subwatersheds far exceeding natural precipitation inputs. Similarly, a P budget of the upper Potomac River Basin revealed that over 60% of imported P was retained within the watershed (Jaworski et al. 1992). In this case, P retention was caused by an excess of fertilizer and animal feed inputs over outputs of agricultural products. In a Florida study, Fluck and colleagues (1992) found that less than 20% of P input to the Lake Okeechobee watershed in fertilizers was output in agricultural and other products. A P budget of the Lake Mendota watershed also showed a human-caused increase in P storage. Net P storage in the 686-square-kilometer watershed was found to be over 500,000 kg in 1996 (Bennett et al. 1999). Natural P movement (in dry and wet deposition and hydrologic outputs) accounted for less than 5% of all P movement into and out of the watershed.

Some national and regional studies reveal similar human impacts and increased P storage in terrestrial ecosystems. Runge-Metzger (1995) calculated net fertilization (fertilizer input minus crop removal) of 0.7 to 57.2 kg P ha^{-1} · yr^{-1} in 25 countries in Europe. The average imbalance of P in countries in the European Economic Community was 12.8 kg · ha^{-1} · yr^{-1} (Runge-Metzger 1995). No country studied showed a net loss of P; all countries were P accumulators. In every case, P accumulation was caused not by a natural imbalance in P inputs and outputs but by inputs of fertilizer and animal feeds that exceeded outputs in agricultural products (Runge-Metzger 1995). Tunney (1990) discovered an eightfold increase in average available P in the soils of Ireland between 1950 and 1990. In 1990, P inputs in fertilizers to Ireland were more than double the outputs (Tunney 1990). Isermann (1990) calculated the P surplus (total application of fertilizers minus net withdrawal by agricultural products) in the Netherlands and Germany to be 88 and 63 kg · ha^{-1} · yr^{-1}, respectively.

A literature search turned up eight published attempts to quantify the global P cycle (Stumm 1973, Lerman et al. 1975, Pierrou 1976, Richey 1983, Smil 1990, Schlesinger 1991, Jahnke 1992, Reeburgh 1997). These authors quantified the movement of P through 7 to 10 global pools, including land,

land biota, minable resources, sediments, ocean, and ocean biota. In general, the authors did not focus on P accumulation or human impacts. Because data for directly calculating a global budget have not been readily available, and because there are numerous ways to calculate global pools and fluxes of P, substantial discrepancies exist. Because many fluxes are difficult to measure accurately at the global scale, and because most of these authors were concerned with only portions of the global P cycle, some scientists completed mass balances by assuming an annual net steady state in the soil compartment. This assumption is debatable, however, as some recent studies show an accretion of P in soil (Fluck et al. 1992, NRC 1993, Bennett et al. 1999).

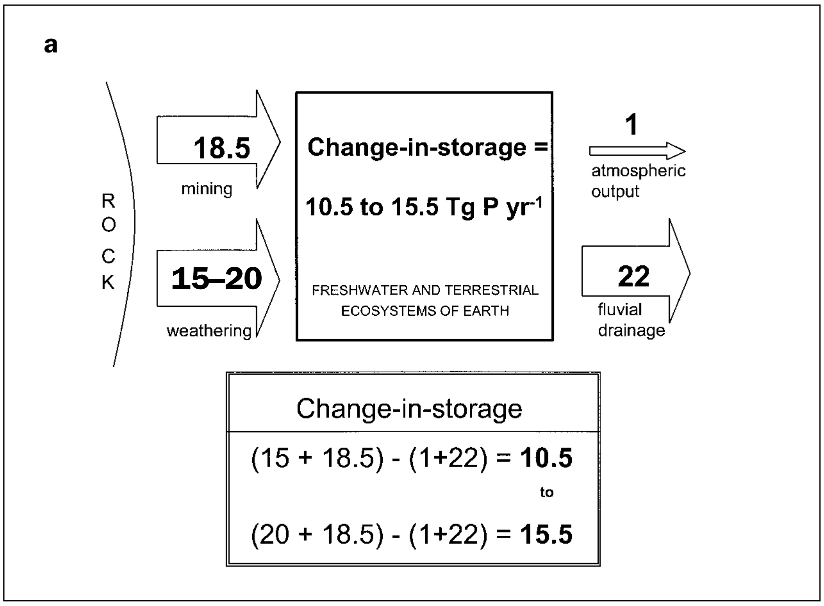
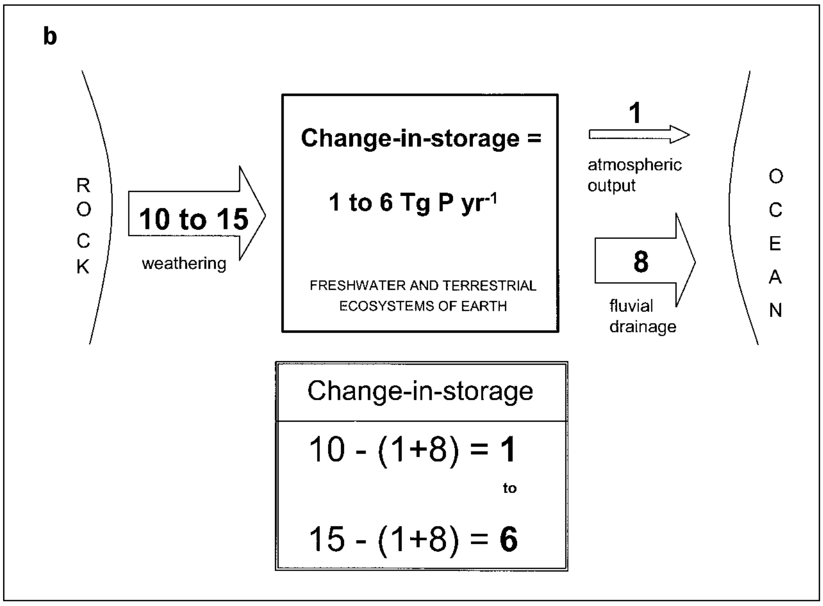


Figure 2. (a) Terrestrial phosphorus fluxes, current estimate, in Tg · yr^{-1}; (b) terrestrial phosphorus fluxes, preindustrial estimate, in Tg · yr^{-1}.



Global phosphorus budgets

How has the global P cycle changed since the onset of large-scale mining for P? We used a mass-balance approach to estimate yearly inputs to, outputs from, and change in storage of P in the surface soils of all terrestrial ecosystems and all freshwater ecosystems on the Earth (Figure 2). We examined these P levels for both the current and the preindustrial (before global-scale human impact) eras. Phosphorous accumulation was calculated as inputs minus outputs in both periods. The inputs were P added to surface soils and freshwater ecosystems through mining and weathering, and the outputs were P removed from this system through net output to the atmosphere and fluvial transport to the oceans.

We compared the global budgets to a similar budget calculated for agricultural lands only. For the agricultural budget, inputs were fertilizers and manure; outputs were harvested crops, animals and animal products, and runoff. We then separated the agricultural budget results by developing or developed nation status (FAO 2000) to determine whether the pattern of global P accretion is uniform throughout the world.

Values for inputs and outputs for all budgets were determined through literature search. Wherever we found ranges of numbers, we chose the more conservative estimate to minimize current annual P accretion. Weathering estimates are highly variable, so we report a range of estimates.

Calculating the current global P budget. We calculated annual input of mined P to surface soils to be about 18.5 Tg · yr^{-1} (1 teragram = 1 million metric tons). Production of phosphate rock in 1995–1996 was 19.8 Tg · yr^{-1}; however, not all of this P enters surface soils (FAO 1950–1997). About 4% of mined P is used to produce products such as flame retardants, paper, glass, plastics, rubber, pharmaceuticals, petroleum products, pesticides, and toothpaste, which are not added to surface soils (RISL 1994). We considered only those products that readily enter surface soils or freshwater ecosystems as P input—agricultural fertilizers, animal feed supplements, and detergent builders, for example—and therefore did not include the 4% (0.8 Tg · yr^{-1}) of phosphate rock that was mined for industrial uses (RISL 1994). Additionally, not all mined P that is used to produce animal feeds will be incorporated into surface soils directly: Some will be incorporated into animal tissue. To avoid double counting, we used manure production to estimate input from animal feed to soil. Thus, the amount of mined P that is included as an input in our budget is 19.8 Tg P mined – 0.8 Tg for industrial uses – 2.0 Tg in animal feeds (RISL 1994) + 1.5 Tg in manure (Isermann 1990) = 18.5 Tg · P yr^{-1}

Global release of P to surface soil caused by weathering ranges between a minimum of 15 and a maximum of 20 Tg · yr^{-1}. By combining the mechanical and chemical denudation rates (20,000 Tg · yr^{-1}; Garrels and Mackenzie 1971) with the mean P content of the Earth's crust (0.1%; Taylor 1964), Lerman and colleagues (1975) calculated current P weathering to be 20 Tg · yr^{-1}. Judson and Ritter (1964) calculated and Gregor (1970) corroborated a pre–human-impact mechanical and chemical denudation rate of 10,000 Tg · yr^{-1}; this denudation rate suggests a pre–human-impact weathering rate of 10 Tg · yr^{-1}. Because global weathering estimates vary widely due to differences in methodology or difficulties scaling up from local studies to arrive at a global estimate, we use a range of values in our budget (Gardner 1990, Newman 1995). For the minimal estimate of current weathering rates, we average the published values for global weathering noted above for an estimate of 15 Tg of P released per year. As a maximum estimate, we use the current weathering rate estimate (20 Tg · P yr^{-1}) alone.

Graham and Duce (1979) found that 3.2 Tg · yr^{-1} of P moves from the atmosphere to land and 4.2 Tg · yr^{-1} from the land to the atmosphere. The excess P (1 Tg · yr^{-1}) entering the atmosphere from the land—net atmospheric output in our model—is eventually deposited in the ocean (Duce et al. 1991).

Modern fluvial P flux, the amount of P discharged from the world's rivers to the ocean, is estimated to be 22 Tg · yr^{-1} (Howarth et al. 1995). Fluvial P flux is calculated as the total of dissolved and particulate riverine P flux. Using data from 20 rivers worldwide, Meybeck (1982) found dissolved P flux to be 2 Tg · yr^{-1}. An extensive literature review led Howarth et al. (1995) to estimate particulate P flux to the ocean to be 20 Tg · yr^{-1}. This estimate was based on Milliman and Meade's (1983) estimated total riverine sediment flux of 15×10^{15} g · yr^{-1} and an average concentration of P in riverine suspended sediment of 1275 mg kg^{-1} (Martin and Meybeck 1979, Meybeck 1988). Total dissolved and particulate flux to the oceans of 22 Tg · yr^{-1} falls within the published range of 17 Tg · yr^{-1} (Pierrou 1976) to 32 Tg · yr^{-1} (GESAMP 1987).

Inputs of P to terrestrial soils and freshwater ecosystems in the current budget are between 33.5 and 38.5 Tg annually. Approximately 23 Tg of P is output annually. Total accumulation of P in surface soil and freshwaters in the modern budget was between 10.5 and 15.5 Tg · yr^{-1} (Figure 2a). A little over one-quarter of the P input is stored in upland soils and freshwaters, according to this budget.

Calculating a preindustrial global P budget. In the preindustrial budget, weathering input of P ranged between 10 and 15 Tg · yr^{-1}. Mining input was negligible. As a minimal estimate for preindustrial weathering rates, we use the published preindustrial weathering rates (Judson and Ritter 1964, Gregor 1970) to calculate a P weathering rate of 10 Tg · yr^{-1} (see earlier discussion of current weathering rate estimates). As a maximal estimate, we assume that the preindustrial and current weathering rates are identical and we average the published values for global weathering for an estimate of 15 Tg P released per year.

In the preindustrial budget, P outputs were net atmospheric output and riverine flux to the oceans. Preindustrial net atmospheric output was the same as in the current budget, 1 Tg · yr^{-1} (Graham and Duce 1979). Howarth and colleagues (1995) estimated preindustrial fluvial output of P to the oceans to be 8 Tg · yr^{-1}, based on a dissolved P flux of 1 Tg · yr^{-1} and a particulate flux of 7 Tg · yr^{-1}. Data collected from 20 relatively undisturbed rivers was used to determine the 1 Tg · yr^{-1} preindustrial riverine dissolved P flux (Meybeck 1982). Riverine particulate flux, 7 Tg P yr^{-1}, was calculated by multiplying the suspended sediment flux, 7×1015 g · yr^{-1} (Milliman et al. 1987) by the average P concentration of these sediments, 1000 mg · kg^{-1} (McKelvey 1973). The lower estimate for suspended sediment P concentration (compared to current estimates) is reasonable because it is likely that agricultural fertilization has increased the P concentration of eroding material (Avnimelech and McHenry 1984).

Preindustrial budget inputs of P ranged from 10 to 15 Tg · yr^{-1}. Approximately 9 Tg · yr^{-1} is output. Thus, preindustrial P accumulation in soil was approximately 1–6 Tg · yr^{-1} (Figure 2b). Preindustrial accumulation was probably variable in time and space, depending on factors such as glaciation and age of the soil. The excess P accumulation in the modern budget compared to the preindustrial budget is 4.5 to 14.5 Tg · yr^{-1}, which represents at least a 75% increase in P storage since preindustrial times.

Accumulation location. Our budgets address both terrestrial soils and freshwater ecosystems. While most of the excess P is probably accumulating in upland soils, some of the excess P may be accumulating in freshwater sediments. We calculate the amount of P accumulating in freshwater sediments to have been between 1 and 1.2 Tg · yr^{-1} preindustrially and between 1 and 3.1 Tg · yr^{-1} at the present time. Based on global freshwater area of 10.4 by 1012 m^2 (FAO 1998), an average sediment accumulation of 0.1 cm · yr^{-1} (Filippelli-Gabriel and Ruttenberg 1997), and an average sediment P content of 3 mg g^{-1} dry weight (Nürnberg 1988), global P sedimentation in freshwater is at least 1 Tg · yr^{-1}. Behrendt (1996) estimated that for the global average hydrologic output (0.3 m · yr^{-1}; Berner and Berner [1987]), a 20% P retention in surface waters is expected. This suggests P retention of 1.2 Tg · yr^{-1} in freshwater ecosystems preindustrially and about 3.1 Tg · yr^{-1} in these systems now. Phosphorus that is accumulating in freshwaters can be resuspended or mobilized to contribute to downstream eutrophication. Therefore, this P is included in our estimates of P accumulation in terrestrial and freshwater sediments globally.

We also calculated a global agricultural P budget to determine the amount of P accumulation that occurs in agricultural areas. This budget included only agricultural inputs (fertilizer and manure) and outputs (agricultural products such as meat and eggs, and runoff). Fertilizer inputs were calculated based on global estimates of fertilizer use and P content of fertilizer (FAO 1950–1997). Manure inputs were calculated as in the current global budget. Outputs were calculated based on agricultural production data (FAO 1950–1998) and the percentage of P of these products (Pierrou 1976). The results presented in Figure 3 are budgets calculated for 1958–1998 at 5-year intervals.

The agricultural P budget indicated that the average annual P accumulation in agricultural areas of the world was 8 Tg · yr^{-1} from 1958 to 1998. This figure lies within the range of excess P accumulation in the modern budget as compared with the preindustrial one. This result suggests that a considerable fraction of the excess P in the current global budget is being stored in agricultural soils, which occupy 11% of the terrestrial area of the Earth (World Resources Institute 1998).

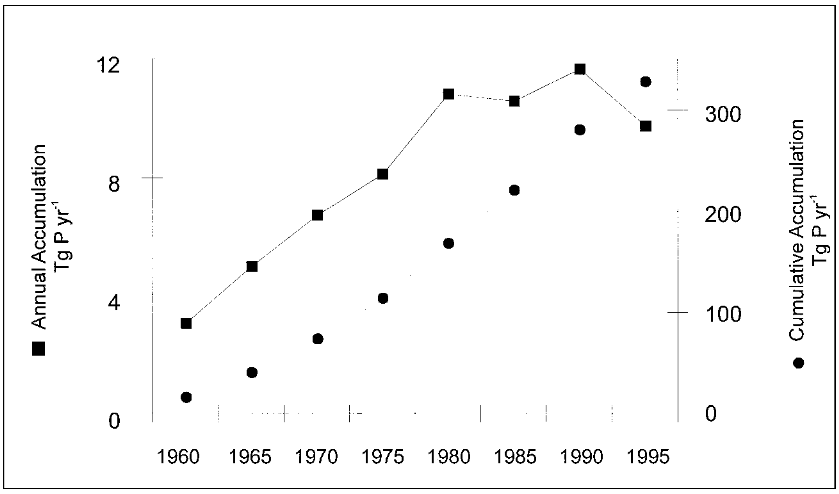


Figure 3. P accumulation in agricultural soils worldwide, 1958–1998, in Tg · yr^{-1}, as determined by global agricultural budget. Squares indicate annual P accumulation based on 5-year averages. Circles indicate cumulative P accumulation.

P accretion occurs in both developed and developing nations, but these areas show different patterns of P accumulation over time (Figure 4). We calculated agricultural P budgets as detailed above, but separately for developing and developed nation status (FAOSTAT Agriculture Data, *http://apps.fao.org/page/collections?subset-agriculture*). For developed countries, soil P inputs in fertilizer and manure have exceeded removal of P from crops and animal products, resulting in continual accumulation of P in soil over the past 40 years. For developing nations, P removal in crop yield was greater than P input and there was a slight depletion of P in soils in 1961; by 1996, however, inputs greatly exceeded outputs. Of the 8 Tg of P accumulating in agricultural soils worldwide, approximately 5 Tg are accumulating in the agricultural lands of developing countries.

Clearly, P is accumulating in Earth's surface soils, primarily in agricultural areas and at a faster rate than before large-scale mining for P began. There is also greater throughput of P in the current budget than in the preindustrial estimate. Moreover, P accumulation caused by excess fertilizer may be qualitatively different from an increase in P stock due to weathering: Fertilizer P input changes both the mass and the concentration of P in soil, whereas an increase in weathering changes only the total P mass because it adds both P and other soil constituents. The impact on aquatic ecosystems is therefore likely to be different as well, because the higher P concentration from fertilizers increases the flow of P per mass of soil transported to freshwater. Phosphorus accumulation is no longer a problem just in developed countries; it appears to be of increasing importance in developing nations as well.

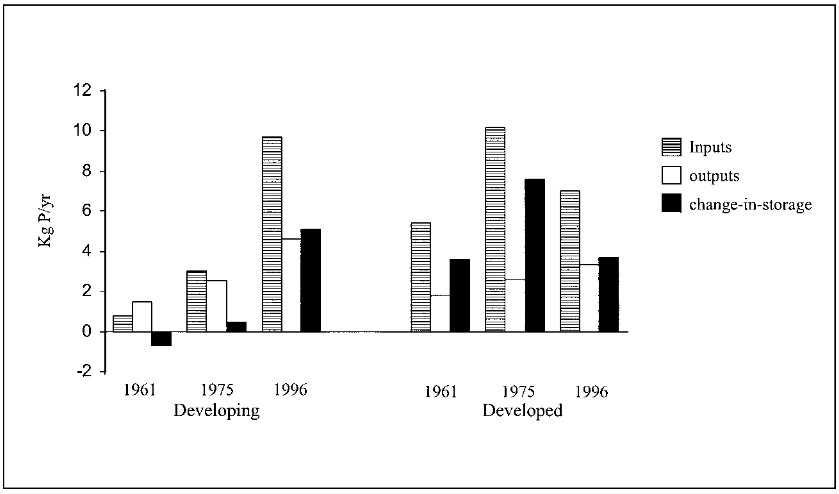


Figure 4. Inputs, outputs, and change in storage of P on agricultural lands in developing and developed countries. Inputs include fertilizers and manure; outputs are runoff and crops harvested. While agricultural lands in developing countries were net exporters of P in 1961, they now accumulate more P per year than developed countries' agricultural areas, making up 5 of the 8 Tg · yr^{-1} total global P accumulation on agricultural lands.

Conclusions

Human-caused changes in the global P budget have caused P to accumulate in upland soils, and greater global accretion of P in soil may lead to the heightened severity and prevalence of culturally eutrophic waters. Increasing soil P levels elevate the potential P runoff to aquatic ecosystems (NRC 1993, USEPA 1996). P is lost from soil in particulate and dissolved forms. Particulate losses, which are the dominant form of loss, occur during erosion and runoff events (Sharpley et al. 1992). Dissolved losses can be significant in some soils, especially if the iron (Fe), aluminum (Al), and calcium (Ca) absorption capacity of the soil is saturated, allowing P to move more readily through the soil toward aquatic ecosystems (Sims et al. 1998). Although the long-term fate of P that accumulates in soils is uncertain (Cassell et al. 1998), it is clear that as soil P content increases, the potential for particulate and dissolved P transport in runoff increases (Sharpley et al. 1981, Daniel et al. 1998). Of particular concern is that large amounts of soil P can be mobilized by exceptional precipitation and erosion events or by changes in land management practices, such as the conversion of agricultural land to residential development (Daniel et al. 1994, Sharpley et al. 1994).

Because it originates from dispersed sources and varies widely with environmental conditions, nonpoint source pollution is difficult to measure and regulate. Policies and regulations have tended to approach P runoff to aquatic ecosystems and eutrophication as a problem of the particular lake, river reach, or estuary in question, rather than as part of a larger pattern. Understanding the global ecological patterns behind eutrophication can affect local decisions and stimulate discussion of large-scale approaches to management.

There are two basic approaches to decreasing the impact of soil P accretion on aquatic ecosystems. We can attempt to bring the P budget into balance by reducing P inputs to soil (controlling sources), and we can try to reduce the transport of P from soils to aquatic ecosystems (increasing sinks). At the same time, it will be important to reduce P concentrations in soils already overenriched with P because of past budget imbalances.

Drawdown of soil P could take decades or longer in many areas (McCollum 1991, Stigliani et al. 1991). Because of the increase in soil P concentrations, the risk of eutrophication will be elevated for a long while (Cassell et al. 1998). Over this time period, changes in farm practices, urban expansion, or climate change could accelerate erosion, thus increasing the rate of transport of P from the soil into aquatic ecosystems. By the time water resources are noticeably impaired, P accretion in terrestrial soils, upstream sediments, rivers, or lakes may already be great enough to maintain high loading to lowland aquatic systems for extended periods of time.

Although there are few data on the long-term fate of P that accumulates in fertilized soils, the slow response times of Fe–P, Al–P, and Ca–P pools may reduce options for later management. When dealing with slowly changing variables such as soil P concentrations, mitigation takes a long time and aggregate costs can be large (Pizer 1996). By controlling soil P accretion now, we may be able to avoid the costs of eutrophication in the future and create flexibility for coping with freshwater problems that could arise.

Delivery of P to receiving waters can be reduced not only by reducing P inputs to soils but also by increasing P sinks in watersheds. Among such sinks are riparian buffers and wetland areas, detention basins, and conservation agriculture practices (NRC 1992, Novotny and Olem 1994, Soranno et al. 1996). However, riparian and wetland buffers have a limited capacity to retain P (Richardson and Qian 1999).

Some areas are at higher risk for increased sediment delivery rates and severity of eutrophication, and these will demand particular management attention. Urban and suburban development—indeed, construction projects in general—expedite erosion of P-enriched soil into aquatic ecosystems (Novotny and Olem 1994). Thus, water quality in areas where human population growth is rapid is likely to decline because of eutrophication. Growing human populations make heavy demands on water supply and freshwater resources, yet diminish these services by increasing eutrophication. Thus, in rapidly urbanizing or suburbanizing areas, particular attention may need to be directed to reducing sediment delivery, drawing down soil P, and balancing the P budgets of surrounding agricultural areas.

Bringing the P budget of agricultural areas into balance by reducing fertilizer use would reduce P accumulation in agricultural soils, but doing so may diminish agricultural output. Global demand for food is predicted to increase as the human population continues to grow (Daily et al. 1998). Increases in food production will most likely derive from increased yields from more efficient water use on land already in production; increasing production may also require triple the amount of nitrogen and P now in use (Daily et al. 1998, Tilman 1999). Some modifications in agricultural practices may allow a reduction in P use without sacrificing food production (Frink et al. 1999). For example, manure and sewage P might be recycled more efficiently, fertilizer might be targeted to meet plant needs at specific times in the crop cycle, and changes in animal production systems might be made (Matson et al. 1998). Experience in developed countries suggests that the rate of P accumulation can be decreased even as crop yields increase (Frink et al. 1999, Sharpley and Tunney 2000).

Methods of agricultural production have developed in response to society's demand for inexpensive, plentiful food (Lanyon and Thompson 1996). Pressured to meet society's need for cheap food without going out of business, farmers have had to make decisions that have led to specialization and intensification of agricultural production systems. At the same time, society has taken for granted a continual supply of cheap, clean water. The two are not compatible unless soil P accretion is controlled.

Acknowledgments

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