Sustainability Challenges of Phosphorus and Food: Solutions from Closing the Human Phosphorus Cycle

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The Green Revolution has led to a threefold growth in food production in the last 50 to 75 years, but increases in crop production have required a concurrent increase in the use of inorganic phosphorus as fertilizer. A sustainable phosphorus supply is not assured, though, and food production depends on mineral phosphorus supplies that are nonrenewable and are being depleted. Phosphorus is effectively a nonsubstitutable necessity for all life. Because mineral phosphorus deposits are not distributed evenly, future phosphorus scarcity may have national security implications. Some projections show economically viable mineral reserves becoming depleted within a few decades. Phosphorus-induced food shortages are therefore a possibility, particularly in developing countries where farmers are more vulnerable to volatile fertilizer prices. Sustainable solutions to such future challenges exist, and involve closing the loop on the human phosphorus cycle. We review the current state of knowledge about human phosphorus use and dependence and present examples of these sustainable solutions.

Keywords: phosphorus, food security, sustainability, human phosphorus cycle, phosphorus limitation

Phosphorus (P) is essential to life and serves multiple roles that sustain cellular vitality. Perhaps most important, P is a key structural component of DNA and RNA—sugar phosphates form the helical structure of every molecule. The element is also critical to ATP (adenosine-5'-triphosphate) and to phospholipids, and thus to cell membranes. Furthermore, P is necessary for the formation and maintenance of bones and teeth in all vertebrates. The average human body contains about 650 grams of P, mostly in bones—roughly 20% of the human skeleton and teeth are made of calcium phosphate, $Ca(H_2PO_4)_2$. Ecologically, P is a highly conserved macronutrient that is tightly cycled in cells, organisms, and ecosystems; P rarely occurs in highly concentrated forms in the Earth's crust and is made available to natural ecosystems mainly as a result of chemical weathering. Thus, P is a widespread limiting nutrient to growth and production in marine, freshwater, and terrestrial ecosystems (Elser et al. 2007). Notably, there is no known chemical or technological substitute for P in either natural ecosystems or in the agroecosystems that produce food and commodities (e.g., cotton, wood products).

The human phosphorus cycle

Agricultural demand during the last 75 years—a result of the Green Revolution—has increased global P mobilization by roughly fourfold (box 1; Falkowski et al. 2000, Villalba et al. 2008). Much of this P has ended up in natural waters, causing costly eutrophication problems (Bennett et al. 2001, Smith and Schindler 2009). Many of the quantitative analyses of human use of P have focused on industrial (e.g., Liu et al. 2008, Villalba et al. 2008) or agricultural and food (e.g., Cordell et al. 2009) aspects. In this article, we continue a broader socioecological analysis of the human P cycle begun by Cordell (2010) that we hope will enable both scientists and nonscientists to engage more actively with the sustainability challenges posed by our dependence on this resource. We organize our review of the human P cycle, and our suggestions for sustainable solutions to close it, around a simplified conceptual diagram (figure 1), and detail each component of this diagram below.

The inorganic P supply. The P cycle is sedimentary, and the ultimate ecological fate of P is burial in aquatic, primarily oceanic, sediments. In geologic time, sedimentary P accumulates as P-rich mineral deposits (phosphorites), many of which have become the target of intense mining activity in the last century. Because of this accelerated extraction, and because these deposits are renewed on time scales of thousands to millions of years, it is possible that economically extractable mineral P resources will become scarce or even exhausted in the next 50 to 100 years (Steen 1998, Smil 2000). Recent analyses using the "peak oil" analogy (Hubbert 1949) have suggested that "peak P" may occur as soon as 2030 (Cordell et al. 2009), or already may

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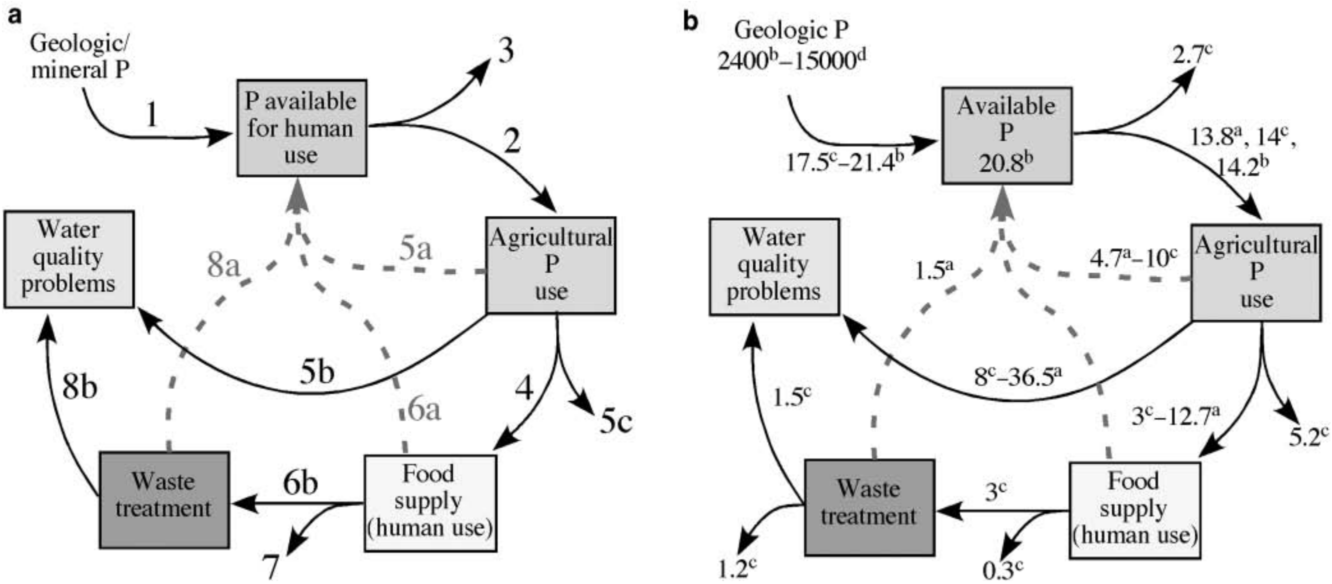

Figure 1. A conceptualization of the human phosphorus (P) cycle. (a) Solid arrows represent key P flows and dashed red arrows represent flows that close the human P cycle through sustainable solutions: (1) P mining and refining, (2) agricultural P use and efficiency, (3) nonagricultural P uses, (4) P in food, (5a) P recycled to agricultural production at the farm, (5b) P lost from farm fields, (5c) P lost in food processing and transportation inefficiencies, (6a) P in composted food waste, (6b) P in human excreta, (7) P in food waste lost to landfills, (8a) P from sewage treatment that is recycled to agricultural production, and (8b) P discharged from ineffectively treated sewage. (b) Estimates of P flows (arrows, in millions of metric tons [MMT] P per year) and P stocks (boxes, in MMT P). Superscripts correspond to the data sources: a, Liu and colleagues (2008); b, Villalba and colleagues (2008); c, Cordell and colleagues (2009); and d, Gilbert (2009). Note the large variability (and uncertainty) in many of the P flow estimates. Geologic supply is based on readily available mineral P reserves. Recycled agricultural P (dashed red arrow 5a) includes the reapplication of crop residues (2 to 2.2) and animal wastes (2.5 to 8) to fields. Agricultural P losses to water bodies (arrow 5b) include estimates of runoff and erosion.

Box 1. 1938 Address to the US Congress.

The constraints on food production have been widely recognized for some time. In a message to Congress in 1938, President Franklin D. Roosevelt underscored the importance of phosphorus (P) to agriculture and people: "The phosphorus content of our land, following generations of cultivation, has greatly diminished. It needs replenishing. I cannot overemphasize the importance of phosphorus not only to agriculture and soil conservation but also to the physical health and economic security of the people of the nation. Many of our soil deposits are deficient in phosphorous, thus causing low yield and poor quality of crops and pastures."

Farmers listened, and global P fertilizer use increased roughly fourfold by the turn of the century. The resulting increase in crop productivity—the Green Revolution—dramatically increased the food supply and coincided with a 50% growth in the human population.

have occurred (Déry and Anderson 2007). Regardless of the particulars of peak-P analyses, the availability and affordability of P for fertilizer may begin to limit food and commodity production shortly after peak P is reached. In fact, in some parts of sub-Saharan Africa, the price of fertilizer is already too high for many farmers. As a major sustainability challenge, peak P is difficult to ignore.

The global distribution of mineral P reserves and mines is extremely uneven. In 2007 nearly 90% of the global P supply of 20.8 million metric tons (MMT) (figure 1b) was supplied by five countries (figure 2a; Villalba et al. 2008, USGS 2010). In the United States, domestic P reserves will most likely begin to be depleted within 25 years (Stewart et al. 2005, Jasinski 2010); the United States already imports roughly 10% of its P (figure 2b). This patchy geographic distribution and early signs of resource scarcity have begun to produce sociopolitical complexities. For example, the United States imports most of its P from Morocco, and in 2004 the two countries signed a free trade agreement. Much of Morocco's P reserves are in disputed, independent territory in the Western Sahara. Morocco also supplies most of the P needs of Europe, Indonesia, and India. China briefly imposed a 135% tariff on mineral P in 2008–2009, effectively stopping P exports; Brazil may nationalize its P mining operations. The objective in both cases is apparently to secure domestic agricultural production. In 2007, global demand for mineral P was dominated by the United States (24%), China and nearby Asian countries (18%), and Africa (17%), with the rest of the world consuming the remaining 41% of mineral P supplies (figure 2b; Villalba et al. 2008). If the human population grows by 2 billion to 3 billion people and is more affluent by 2050 (as is projected), global

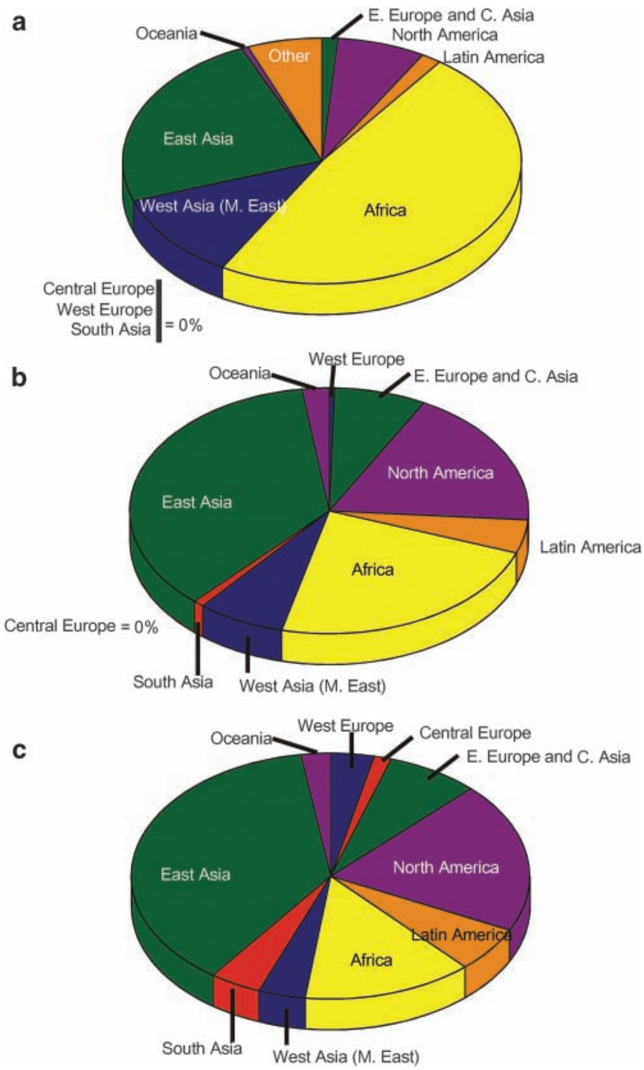

Figure 2. Global mineral phosphorus data by region. (a) Reserves (Jasinski 2010), (b) production (IFA 2008), and (c) consumption (IFA 2008).

food production will need to increase by 70% to 100% (not including added agricultural demand from biofuels production). In a future in which mineral P resources may become more scarce and expensive, the implications for global food security, and international security in general, are significant.

Once mined, mineral P is typically refined and purified into phosphoric acid. This is done using either wet acid or thermal acid production techniques; P fertilizer production uses the former (Villalba et al. 2008). To generate 1 metric ton (MT) of phosphoric acid, the wet acid process requires more than 3 MT of phosphate rock, 1.4 MT of sulfuric acid, and 11 cubic meters of water, and produces 5.4 MT of phosphogypsum as a by-product (Ayres and Ayres 1998). The process also requires substantial inputs of fossil-fuel energy (as does the mining process itself). The price of fertilizer thus reflects the interplay of energy costs (associated with P mining and processing and with nitrogen fixation through the Haber-Bosch process) and global supply and demand for mineral P. In 2007–2008 the price of fertilizer grew by between 500% and 700% in a 14-month period (Cordell et al. 2009, Gilbert 2009), and much of this increase was caused by similar increases in the price of mineral P. This spike in fertilizer prices coincided with a global food crisis that had disparate regional consequences. As mineral P becomes scarce, volatile fertilizer and fossil-fuel costs are likely to make efficient food production prohibitively expensive in substantial regions of the globe.

Agricultural P uses and demand. Early farming relied on P already in soils, on natural P inputs (such as sedimentation associated with flooding), and on tight and efficient recycling of P (such that the P cycle was much more closed than in modern agroecosystems). This low-impact food production was largely sustainable for thousands of years. When these farm ecosystems mixed crop and animal production, crop residues were returned to the soil or fed to livestock, and nutrients, in the form of manure, were returned to fields. In much of eastern Asia, even human wastes were largely recycled back into food production (in ancient China, this was known as "night soil"; Ebrey et al. 2006). There was little need for outside nutrient supplies until humans began to concentrate in population centers, and demand for food began to exceed the productivity of these small, mixed agroecosystems. One of the first supplemental P fertilizers was bird guano, but economically viable deposits were concentrated in only a few areas around the world (mainly in Peru and islands in the South Pacific), and these were depleted by the late 1800s (Stewart et al. 2005). Without a major new supply of cheap fertilizer, food production was effectively nutrient limited during this time (per Liebig's "mineral theory" of 1840).

Today, fertilizer production accounts for 80% (Lauriente 2003) to 90% (Smil 2002) of the worldwide demand for phosphate rock (figure 1b). Averaged globally, agricultural fertilization rates are 10 kilograms (kg) P per hectare (ha), but this ranges from about 3 kg per ha in Africa to more than 25 kg per ha in parts of Europe (Liu et al 2008, Vitousek et al. 2009). The United Nations Food and Agriculture Organization (FAO) estimated that only 15% to 30% of P in fertilizer is actually taken up by crops, often because fertilizers are applied far in excess of plant demand (FAO 2006). Considerable advances in fertilizer application technologies and in crop nutrient-uptake efficiencies are being made, though, and much of the excess P will remain in the soil as a resource for future crop yields (assuming soil erosion is minimal). Today, however, only about 20% of all mined P is actually consumed in food—the remaining 80% is lost from the human P cycle (figure 1). Beyond P losses at the point of farm production, about 55% (global average) of the P in food is lost to inefficiencies "between farm and fork," including wastes in processing, transportation, and storage (Cordell et al. 2009).

Another product of the Green Revolution, particularly in developed countries, was the move from relatively small, mixed agroecosystem farms (i.e., the family farm) to commercial agriculture (of both crops and meat; figure 3). During the same time, global demand for meat products increased, and continues to increase. Estimates suggest that the global livestock population is about 65 billion animals, but only about 50% of P consumed by livestock is returned as animal wastes to fields where food is grown (figure 1b; Smil 2000, Gilbert 2009). In the United States, the shift to industrial agriculture and concentrated animal feeding operations coincided with a regional shift in livestock production away from where crops are grown. Cattle production moved from the upper Midwest (i.e., the Corn Belt) to Kansas, Oklahoma, and Texas, and chicken and pork production moved east. Separating by hundreds of kilometers the production of animals and their wastes from food grain production makes transporting animal wastes back to fields (which would close a key component of agricultural P cycle; dashed arrows in figure 1) energy intensive and thus economically impractical.

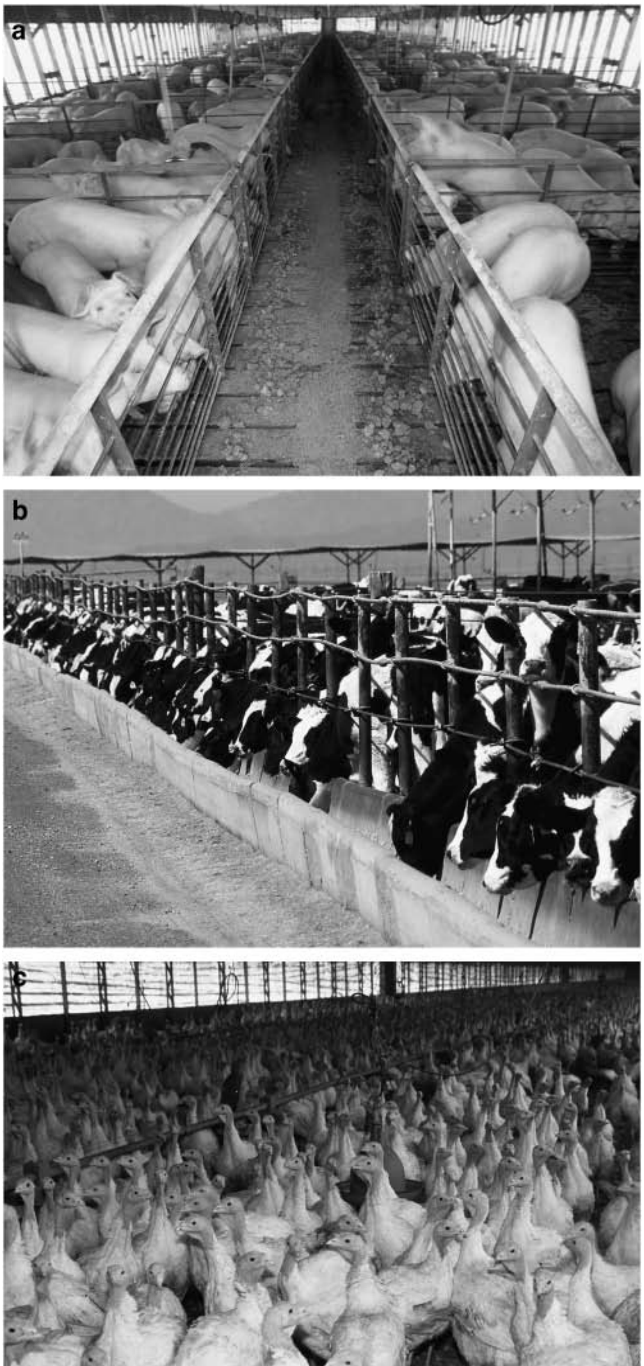

Figure 3. Examples of high-density industrial-scale stock farming as is now common in the United States and other developed countries for production of (a) pork (b) beef and dairy, and (c) turkey. Photographs: (a) Jeff Vanuga and G. A. Lyons; (b) Jeff Vanuga, Yuma, Arizona, US Department of Agriculture Natural Resources Conservation Service (USDA NRCS); (c) Jeff Vanuga, USDA NRCS.

The human P cycle. There are considerable social and environmental costs of P being lost from the currently "open" human P cycle. In the United States alone, economic damages resulting from eutrophication of freshwaters total $2.2 billion annually (Dodds et al. 2009). Nearly 25% of the 250 billion MT of P mined since 1950 has ended up in water bodies or landfills (Rosmarin 2004). Humans excrete about 3 MMT P per year, only about half of which is recycled back to food production (figure 1b). Liu and colleagues (2008) estimated that about 20% of urban human wastes (as high as 50% in European cities; Farmer 2001) and 70% of rural human wastes are returned to food production. In China, about 30% of urban human waste and 94% of rural wastes are recycled (Pan et al. 1995, Chen 2002), whereas Bangkok recycles about 10% of its human dietary P (Barles 2010). Notably, cities are growing in size whereas rural populations are shrinking. Phosphorus from human excreta that is not recycled to food production largely winds up in waterways after varying degrees of treatment, causing myriad water quality problems and eutrophication.

Runoff from agricultural fields and from animal production facilities also contributes to water quality problems. Bennett and colleagues (2001) estimated that the P content of freshwater systems worldwide is at least 75% greater than preindustrial levels, and that P fluxes to oceans have increased from 8 MMT per year to 22 MMT per year during the same period. Coincident with these trends, more than 400 coastal dead zones have been identified worldwide (Diaz and Rosenberg 2008). Coastal dead zones are often associated with excess nitrate in river discharge, but P also contributes to these hypoxia and anoxia events (CENR 2010). Closing the human P cycle at both agricultural and wastewater stages will generate substantial societal and economic savings in environmental costs alone.

Social, economic, and security implications of P-induced famine

The economic, social, and political challenges of P scarcity will most likely begin well before mineral P reserves run out. These challenges may be unprecedented because, unlike fossil-fuel energy (which generates similar global challenges), there is no biological or technological substitute for either food or P. The FAO defines food security as the condition in which "all people, all the time, have access to sufficient, safe, and nutritious food to meet their dietary needs for an active and healthy life" (FAO 2006). Limitations on food production will begin when the cost of P fertilizers increases (supply < demand). The economic challenges of expensive P may disproportionately affect food production in countries that have no P mineral reserves, in countries that are politically conflicted with mineral P exporters, and in poor countries. Complicating matters is that in developed countries only a small fraction of grocery store food costs (about 20%) are actual "farm costs" (i.e., the costs, including fertilizer, incurred by farmers to produce the food). In the developing world, where people eat mainly local and unprocessed foods, a much larger fraction of food costs reflects farm costs. Thus, the market signals of P scarcity will be weaker in the developed world (where most P consumption is taking place), and traditional market forces (e.g., food prices) may not begin to enforce P conservation until there is considerable food scarcity in the developing world. These economic challenges may translate into food shortages, perhaps even localized or regionalized famine, and the political instability that often accompanies such adversity. The implications of a P shortage (real, economic, or both) for national and global security are complex. This link between food shortages and political instability is not contrived. The global food crisis of 2008 was a complicated situation with many direct and indirect causes, including (a) a dramatic increase in the price of fossil-fuel energy, (b) a five- to sevenfold increase in the price of P fertilizer, and (c) demand for fertilizers and other agricultural resources by a burgeoning biofuels industry (in 2009, 32% of all corn grown in the United States was used for ethanol production, representing 10% of all P fertilizer used in the United States in that year; CENR 2010). In 2008, food price increases led to violent food riots in 40 countries, including major unrest in Bangladesh, Haiti, India, and Mexico (among others). Similar phenomena occurred in mid-2010, when increases in food prices caused deadly riots in Mozambique, Egypt, and Pakistan (MacFarquhar 2010). These price spikes were not driven by food scarcity per se, but the results demonstrate the volatility of human response to real or perceived threats to food access.

To detect the approach of a major P shortage tipping point (a precursor to global sociopolitical challenges), Cordell and colleagues (2009) proposed monitoring key indexes of "P accessibility." For example, Africa is the world's largest exporter of mineral P (from Morocco and the Western Sahara) but is also the continent with the largest food shortages. Compared with Europe, P fertilizer is more expensive in sub-Saharan Africa—in real price and as a proportion of a farm's budget—yet sub-Saharan farmers have relatively less purchasing power. This means that P accessibility for a sub-Saharan African farmer is considerably lower than for a European farmer, even though both are using mineral P from the same source (Cordell et al. 2009). Soils depleted in P are already responsible for lower crop yields and increased interannual variability in food production in sub-Saharan Africa (Vitousek et al. 2009). Decreases in future P accessibility may well portend near-term problems with food supply and regional stability in time for them to be ameliorated or perhaps even prevented.

Sustainable solutions: Closing the human P cycle

The challenges of human dependence on P (and biotic P dependence in general) are of fundamental importance because P is required to produce food. A primary goal of this article is to present viable solutions to P dependence, and the common denominator of the solutions we propose below is the need to close the human P cycle (shown as dashed red arrows in figure 1). Many solutions to sustainability challenges involve technology, and often the goal of technological answers is finding artificial substitutions for natural capital (what Ayres [2007] called "weak sustainability"). Indeed, some of the solutions we propose below involve this kind of technological substitution, and such substitutions are possible for most agricultural commodities. However, the nonsubstitutability of P for food production, coupled with the fact that P is effectively a nonrenewable resource, requires "strong sustainability" solutions (Ayres 2007) that go from thinking outside the box to transformational "thinking of a new box." Our list of solutions is far from exhaustive and is meant to entice biologists and nonbiologists alike into the necessary conversation about the sustainability challenges of the human P cycle.

One option that does not involve closing the human P cycle is locating new sources of mineral P. Many economists and technologists argue that markets respond to scarcity and higher prices by creatively finding new sources of, or viable substitutes for, a product, and that this creativity is driven by commodity price. Although we cannot envision a viable substitute for elemental P, the former scenario is likely with mineral P, particularly when it becomes more scarce and expensive. There is considerable disagreement about the global extent and location of untapped mineral P reserves (see broad range of estimates in figure 1b). New P deposits in Peru, Australia, and off the coast of Namibia are currently being explored (Gilbert 2009). Advances in processing and purification techniques may allow exploitation of less-pure mineral P reserves, though this will increase the volume of nonmarket by-products that are often toxic or even radioactive. Much of the P that is currently lost from the human P cycle ends up in aquatic sediments (arrow 8b in figure 1a; Bennett et al. 2001), and although the reextraction of P from reservoirs, rivers, and coastal oceans may one day be economically viable, the environmental impacts may be extreme. The pursuit of new sources of mineral P is clearly part of the solution, but it seems foolhardy simply to wait for these new sources of this critical nonrenewable resource to be found—particularly if the market trigger for this exploration is P scarcity or volatile fertilizer prices.

Closing the human P cycle at agricultural production. There are numerous opportunities to close the human P cycle at the agricultural and food production stage (in figure 1a, enhancing arrow 5a while reducing 5b and 5c). Some solutions are relatively simple, whereas others will require wholesale transformations in the way we grow, fertilize, process, and transport food. Relatively easy solutions include (a) applying fertilizer in amounts that better align with growth and stoichiometric needs, (b) bioengineering crop strains that require less P for the same crop production or that more efficiently take up P from soils, (c) better control of erosion losses of P-rich soil from farm fields, and (d) returning nonconsumable crop residue to soils or feeding it to livestock. Options a–c have the added benefit of reducing nutrient-rich runoff from farm fields (arrow 5b in figure 1).

However, the industrialization of agriculture has created challenges to closing the human P cycle that may require more transformative thought. For example, reducing meat consumption would reduce the amount of P flowing through the human P cycle. Nonetheless, if we assume that meat will remain a substantial component of the human diet, the best opportunity for on-farm P recycling is to produce crops and livestock in the same places (arrow 5a in figure 1) and reduce waste. Notably, this is not necessary with pasture-based animal production because waste P is already recycled in the fields. The transformation challenge discussed above, though, is that crop and animal production are not collocated in many places (particularly in the United States). Considerable geographic, institutional, and infrastructural inertia will need to be overcome to bring these together.

Agricultural advances are helping to close this component of the human P cycle. For example, researchers at the University of Guelph have developed a transgenic Yorkshire pig that excretes 30% to 65% less P than its precursors. Pigs are unable to digest phytate (a P compound that makes up 50% to 75% of their diet). The transgenic "enviropig" contains the *Escherichia coli* gene for phytase; the pigs produce phytase in their saliva, allowing them to fully digest phytate (Feedstuffs 2010). New technologies are also emerging for recycling animal wastes into usable forms of energy, including the use of algal-based systems that use animal-based farm nutrients to produce algal biofuels and on-site energy from methane and hydrogen (figure 4). These kinds of approaches will not recycle the P directly back into food production, but they may help close the human P cycle by reducing the need for P to grow biofuel crops that are far less efficient at energy conversion than algae (e.g., corn and sugarcane).

Closing the human P cycle at food distribution and consumption. It may seem straightforward or even simple to close the human P cycle at the food processing, transportation, and consumption (reducing arrows 6b and 7 in favor of 6a in figure 1) and excretion stages (reducing arrow 8b in favor of 8a in figure 1). One simple step, for example, is to do with less: In 2009 the FAO reported 1.02 billion people worldwide were hungry or malnourished, whereas the World Health Organization (WHO) reported that in 2005 1.6 billion people were overweight or obese (WHO 2007). Many people appear to be getting more food than they need. Composting (arrow 6a in figure 1) returns unconsumed food waste to the soil, though not always to soils where food is grown. Coupling food production and consumption more closely in space saves energy and reduces food wasted in transportation and storage. Cordell and colleagues (2009) estimated that 1.2 MMT P was lost to waste and inefficiency at this stage of the human P cycle.

Figure 4. Portable algal nutrient recovery system cleans farm wastewater while recovering and recycling phosphorus and other nutrients. Photograph: Mark Edwards, Laboratory for Algal Research and Biotechnology, Arizona State University.

Closing the human P cycle at human waste treatment. The other major component of human P transformations is sewage production and treatment. Where treatment wetlands or other ecosystems are being used for tertiary sewage treatment, the plant material and soils from these ecosystems may be periodically harvested and used directly in crop production (a component of arrow 8a in figure 1). Urine is P rich and essentially sterile; the WHO suggests that recycled urine (another component of arrow 8a in figure 1) could provide half of the P necessary to grow cereal crops (WHO 2006). Two Swedish cities now require the use of urine-diverting toilets that separate urine from solids and recover the liquid waste, and the Swedish national government has set a goal of recovering and reusing 60% of all P in sewage by 2015 (Cordell et al. 2009). With the proper infrastructure, P may be efficiently recovered through the direct use of urine or precipitating struvite crystals (ammonium magnesium phosphate) that can be applied directly to farm fields (Cordell et al. 2009, Gilbert 2009).

A major barrier to closing the human waste portion of the P cycle may be psychological. In much of the world, human excreta are perceived not as a resource but as something to be removed (i.e., to be flushed; figure 5). Modern societies invest considerable resources ensuring the rapid removal, treatment, and discharge of human P wastes, and people rarely,

Figure 5. A sewage treatment plant outside Washington, DC, behind a chain-link fence, emblematic of the societal stigma associated with what is actually a resource: excreted phosphorus. Photograph: Craig Brown.

if ever, come in contact with their own wastes. There are clearly public health challenges here, but they are not insurmountable. Fundamentally, overcoming this psychological stigma, to a point at which people recognize that their own waste can be a resource, will be necessary and is far from trivial.

Summary and conclusions

The doubling of the human population over the last 50 to 75 years has been possible largely because of the Green Revolution, and the related increases in crop production have required a concurrent increase in the use of inorganic P. Phosphorus cycles over geologic time scales, making it effectively a nonrenewable resource. Our review of estimates of P recycling in the human P cycle show considerable variability and uncertainty, but today it appears that only about one-quarter of the fertilizer P used in agriculture is recycled back to fields. The rest is lost to the cycle, and much of this loss ends up in waterways, causing expensive eutrophication problems. As with other nonrenewable natural resources, a sustainable P supply is not assured, and some projections show economically viable mineral reserves being depleted within decades. In addition to our review of human effects on the global P cycle, we present a number of sustainable solutions that involve closing the loop on the human P cycle. Some of these solutions are relatively straightforward but many involve overcoming considerable infrastructural or institutional inertia. Fortunately, we have considerable time—perhaps a generation or more—before a business-as-usual future leads to food shortages and global stability issues associated with P scarcity. The scientific community has the potential to assist with the social, economic, and environmental transformations necessary to avert this sustainability challenge before it becomes a crisis.

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