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Until it was treated with phosphorus fertilizers, soil in Brazil's Cerrado region was largely agriculturally unproductive. Maize plants grown on phosphorus-treated soil are much taller than control plants like those in the foreground, which did not receive adequate additional phosphorus. *Credit: D.M.G. de Sousa*

Phosphorus and Food Production

Phosphorus is essential for food production, but its global supply is limited. Better insight is needed into the availability of this non-renewable resource and the environmental consequences associated with its use. Optimizing agricultural practices while exploring innovative approaches to sustainable use can reduce environmental pressures and enhance the long-term supply of this important plant nutrient.

Virtually every living cell requires phosphorus, the 11th most abundant element in the Earth's crust. However, the soil from which plants obtain phosphorus typically contains only small amounts of it in a readily available form. There is no known substitute for phosphorus in agriculture. If soils are deficient in phosphorus, food production is restricted unless this nutrient is added in the form of fertilizer. Hence, to increase the yield of plants grown for food, an adequate supply of phosphorus is essential.

Farming practices that are helping to feed billions of people include the application of phosphorus fertilizers manufactured from phosphate rock, a non-renewable resource used increasingly since the end of the 19th century. The dependence of food production on phosphate rock calls for sustainable management practices to ensure its economic viability and availability to farmers. While there are commercially exploitable amounts of phosphate rock in several countries, those with no domestic reserves could be particularly vulnerable in the case of global shortfalls.

Use of phosphorus in agriculture is associated with several types of potential environmental impacts. Too little phosphorus restricts plant growth, leading to soil erosion. Phosphorus overuse can result in losses to surface waters and eutrophication. More sustainable practices—such as better managed field applications and enhanced phosphorus recycling—can contribute to improvements in productivity and reduce environmental impacts while increasing the life-span of this finite resource. **Figure 1** shows the phosphorus flows in the environment. Although much is known about how to locally enhance soil fertility by adding phosphorus, there is a need for a more comprehensive understanding and better quantification of the global pathways.

Scientists are starting to quantify global phosphorus flows through the food production and consumption system. It is estimated that only one-fifth of the phosporus mined in the world is consumed by humans as food (Schröder et al. 2010). Yet important knowledge gaps remain concerning how much phosphorus is obtained, how much is used in agriculture and retained in soil, and how much is released to the aquatic environment or lost in food waste.

Phosphorus resources and reserves

Resources are concentrations of naturally occurring phosphate material in such a form or amount that economic extraction of a product is currently or potentially feasible.

Reserves are the part of an identified resource that meets minimum criteria related to current mining and production practices, including grade, quality, thickness and depth, and that can be economically extracted or produced at the time of the determination. Use of this term does not signify that the necessary extraction facilities are in place or working.

Source: Adapted from Van Kauwenbergh (2010) and Jasinski (2011)

Supplying a critical nutrient

High crop yields today depend fundamentally on mined phosphate rock, a significant departure from historical food production methods. When the world population was much smaller, farmers could obtain adequate yields by fertilizing soil with phosphorus derived from human and animal excreta. Population growth in the 18th and 19th centuries stimulated food production, resulting in more rapid depletion of soil nutrients. Farmers therefore began to use increasing amounts of off-farm sources of phosphorus, including bone meal, guano and phosphate rock (Jacob 1964). Phosphate rock, which was cheap and plentiful, became the source that was widely preferred

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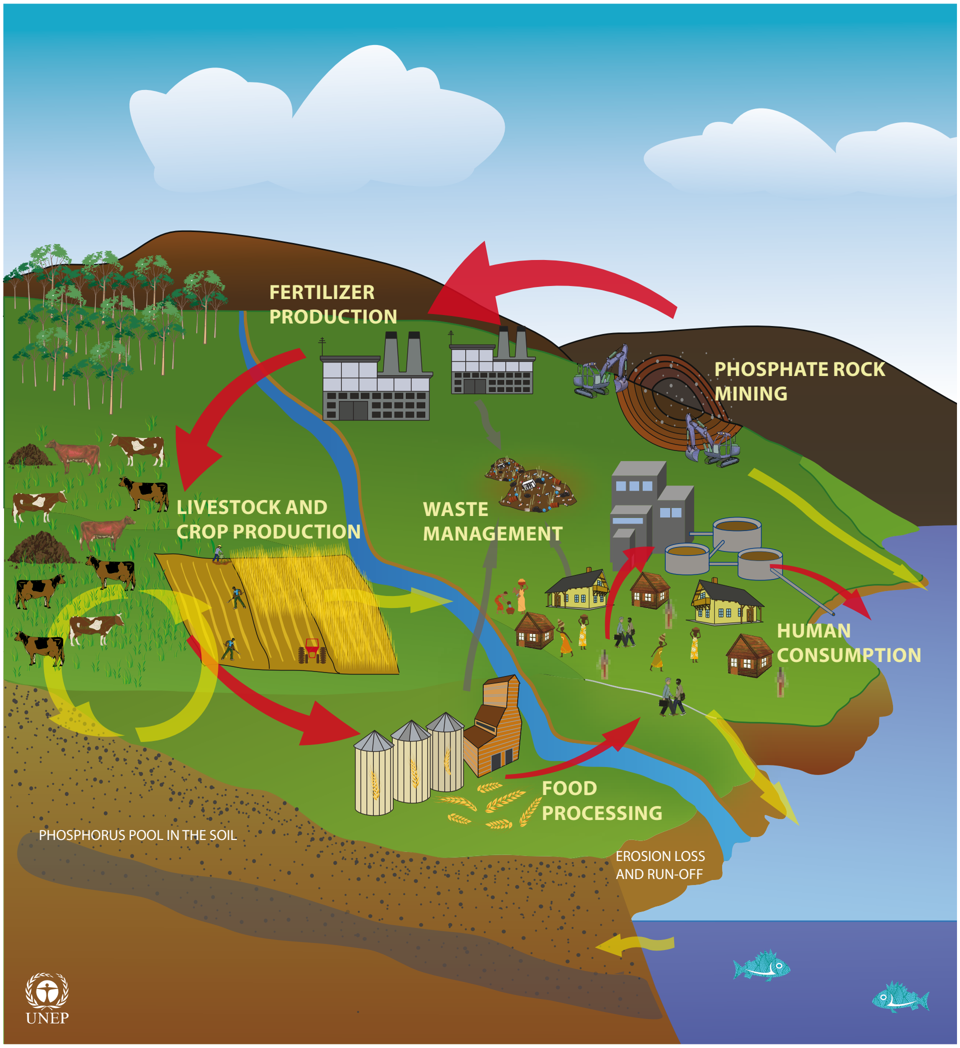

Figure 1: Phosphorus flows in the environment. To enhance food production, phosphorus is added to soil in the form of mineral fertilizer or manure. Most of the phosphorus not taken up by plants remains in the soil and can be used in the future. Phosphorus can be transferred to surface water when it is mined or processed, when excess fertilizer is applied to soil, when soil is eroded, or when effluent is discharged from sewage treatment works. Red arrows show the primary direction of the phosphorus flows; yellow arrows the recycling of phosphorus in the crop and soil system and movement towards water bodies; and grey arrows the phosphorus lost through food wastages in landfills.

(Smil 2000) (**Figure 2**). Farmers also adopted new methods, such as planting high-yielding crop varieties and then applying nutrients—notably nitrogen, phosphorus and potassium (NPK)—and other inputs such as pesticide (Fresco 2009). Scientific progress continued in the last half of the 20th century with the Green Revolution. Although it staved off a great deal of world hunger in the face of significant population growth, the Green Revolution has been criticized for causing environmental damage by encouraging excessive or inappropriate use of fertilizers and other inputs (IFPRI 2002).

To sustain agricultural productivity at current and predicted future levels, it is crucial to determine the full extent of the supply of this finite resource. Thirty-five countries currently produce phosphate rock and it is estimated that 15 others have potentially exploitable resources (IFA 2009). Phosphate rock's value depends on various factors, including physical accessibility,

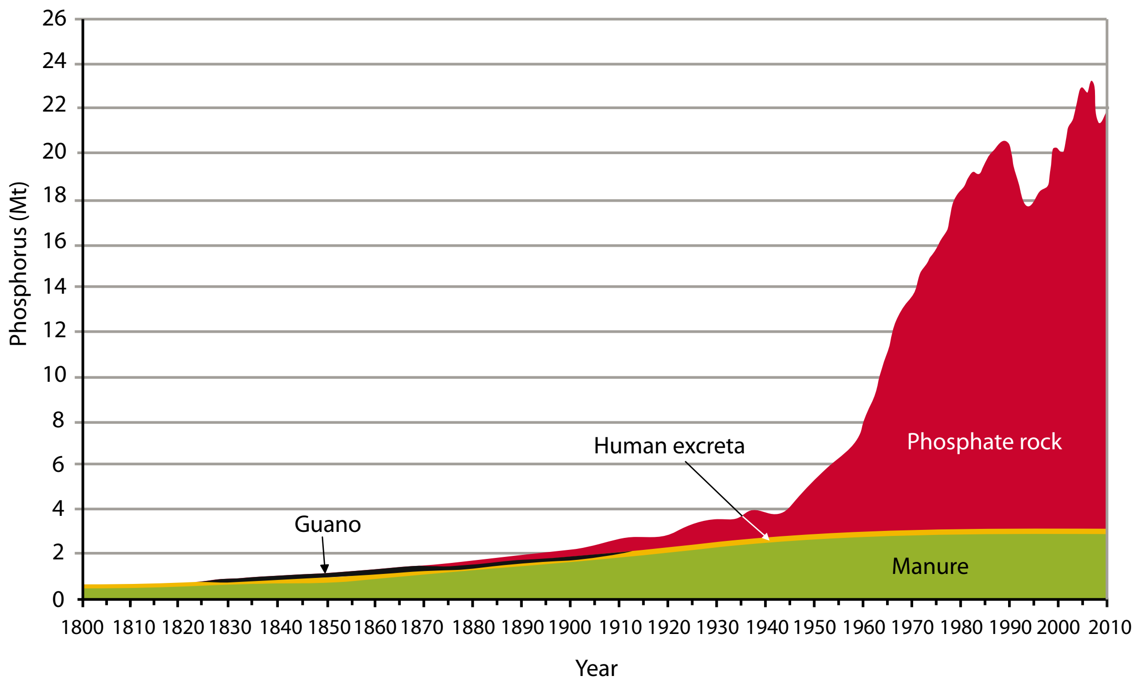

Figure 2: Global sources of phosphorus fertilizer. Since the mid-1940s, population growth accompanied by greater food demand and urbanization have led to a dramatic increase in the use of mined phosphate rock compared with other sources of phosphorus. *Source: Cordell et al. (2009)*

level of impurities and phosphate content. The known supply of cheap, high-grade reserves is becoming increasingly limited while demand continues to increase. The remaining amount of commercially viable phosphate rock, particularly the lifetime of reserves, has been the subject of vigorous debate among experts during the last few years (Vaccari 2009) (**Box 1**).

New phosphate rock mines have been commissioned in several countries, including Australia, Peru and Saudi Arabia, while undiscovered deposits are being widely sought, including in seafloor sediments off the coast of Namibia (Drummond 2010, Jung 2010, Jasinski 2010 and 2011). Although estimates of the extent of known reserves are increasing, the quality of these reserves requires further evaluation. If the phosphate concentration in the rock declines and larger volumes of ore are needed in order to obtain a given amount of phosphorus, production costs will likely increase. Such changes could also lead to greater energy requirements and more waste in phosphate rock mining. In an open market these factors might well raise the price of phosphorus fertilizers, limiting their accessibility to many farmers and having negative effects on yields. If these were to occur, food security could be threatened in countries that are highly dependent on phosphorus imports.

The eradication of hunger and poverty is Goal 1 of the Millennium Declaration, adopted by the United Nations General Assembly in 2000. A 2010 review of progress towards achieving the Millennium Development Goals reported that hunger and malnutrition increased between 2007 and 2009, partially reversing earlier progress (UNGA 2010). Many of the world's estimated 925 million undernourished people are small-scale farmers (IAASTD 2009, FAO 2010). Phosphorus-based fertilizers are often unobtainable by these farmers, whose productivity could be improved with better access to this input (Buresh et al. 1997).

Greater appreciation of the role and value of phosphorus could be the basis for increased co-operation on research and development to acquire a more comprehensive understanding of this essential nutrient—including how it can best be recovered, used and recycled to meet future food demand. Research has already demonstrated the importance of building up and maintaining a critical level of plant-available phosphorus in soil to optimize plant uptake of this nutrient; anything lower than this level would represent a loss of crop yield, and anything higher an unnecessary expense for farmers and a potential cause of phosphorus run-off to receiving waters (Syers et al. 2008). Good

Box 1: The 'peak phosphorus' debate: how long will global phosphate rock reserves last?

The extent of global phosphate rock reserves is difficult to ascertain. Knowledge of phosphate rock deposits is evolving, along with technology and the economics of production (IFDC/UNIDO 1998). How long reserves will last depends on their size, quality and rate of use.

Researchers have raised concern about 'peak phosphorus', the proposition that economic and energy constraints will set a maximum level for phosphate rock production, which will then decrease as demand for phosphorus increases. Many scientists and industry experts contest the specific assertions that have been made regarding when such a peak is likely to occur. For example, Cordell et al. (2009) estimated that peak production of current reserves (that is, phosphate rock known to be economically available for mining and processing) would occur between 2030 and 2040. That estimate was based on United States Geological Survey (USGS) data for global phosphate reserves (Jasinski 2006, 2007 and 2008). Increasingly experts now consider the extent of these reserves to have been underestimated (Van Kauwenbergh 2010). The most recent USGS estimates have been revised upward (Jasinski 2011). Proponents of the peak phosphorus theory argue that even if the timeline may vary, the fundamental issue, that the supply of cheap and easily accessible phosphorus is ultimately limited, will not change.

A recent report from the International Fertilizer Development Center (IFDC) on reserves and resources provisionally revised the estimate of phosphate rock reserves from the USGS estimate of around 16 billion to approximately 60 billion tonnes (Van Kauwenbergh 2010), which is roughly consistent with the most recent USGS report (Jasinski 2011) (**Figure 3**). These reserves would last 300 to 400 years at current production rates of 160 to 170 million tonnes per year. Since phosphorus fertilizer production is expected to increase by 2 to 3 per cent per year during the next five years, the life expectancy of reserves could be less than that (Heffer and Prud'homme 2010). The IFDC report also estimates that the world's overall phosphate resources amount to approximately 290 billion tonnes and potentially as much as 490 billion tonnes (Van Kauwenbergh 2010).

Phosphate rock is the only new source of phosphorus entering the food production chain. The consistency and volume of food production therefore depend on the accessibility of phosphorus to farmers. Given the difficulties of estimating the longevity of phosphate rock reserves and the vital importance of decision-making based on reliable and transparent information concerning world phosphate rock resources and reserves, IFDC recommends establishing an international, multi-disciplinary network to regularly update a definitive database on phosphate rock deposits (Van Kauwenbergh 2010).

Country	Phosphate rock reserves, millions of tonnes
Morocco	5 700
China	3 700
South Africa	1 500
Jordan	1 500
United States	1 100
Brazil	260
Russia	200
Israel	180
Syria	100
Tunisia	100
Other countries	1 660
World total (rounded)	16 000

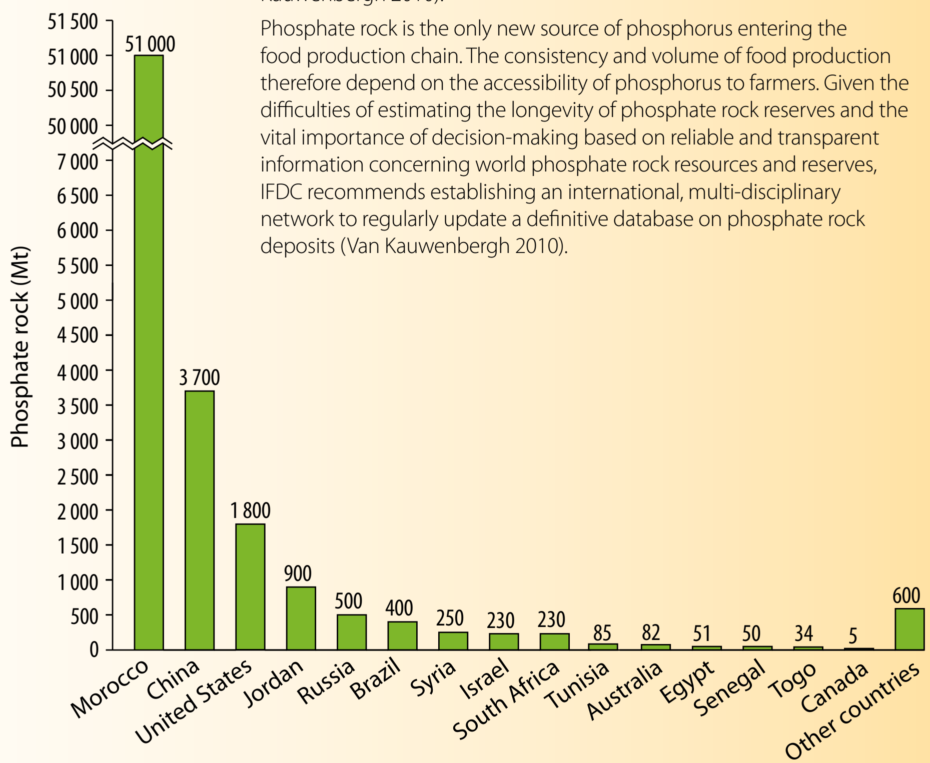

Figure 3: Recent estimates of the distribution of world phosphate rock reserves, as reported by the United States Geological Survey (left) and the International Fertilizer Development Center (right). Most potentially viable phosphate rock reserves are concentrated in a few countries. *Sources: Jasinski (2010) and Van Kauwenbergh (2010)*

Note: The United States Geological Survey's Mineral Commodity Summaries 2011, published on 21 January 2011, revised the USGS estimate of world phosphate rock reserves to 65 billion tonnes. Its revised estimate of Moroccan reserves is 50 billion tonnes, based on information from the Moroccan producer and IFDC. The top ten countries in the 2011 report are Morocco, China (3 700 Mt), Algeria (2 200 Mt), Syria (1 800 Mt), Jordan (1 500 Mt), South Africa (1 500 Mt), the United States (1 400 Mt), Russia (1 300 Mt), Brazil (340 Mt) and Israel (180 Mt). Source: Jasinski (2011) management practices for fertilizers and agricultural waste products are advocated by many organizations and initiatives, including the International Plant Nutrition Institute and the Global Partnership on Nutrient Management (GPNM 2010).

More sustainable use of a finite resource

Almost 90 per cent of global phosphate rock production is used to produce food and animal feed (Prud'homme 2010). The need for increased agricultural productivity will create higher demand for fertilizer to meet crop requirements by improving supplies of phosphorus, nitrogen and potassium. The specific amounts required will vary with soil type. Phosphorus fertilizer consumption has stabilized in much of the developed world, but it is expected to continue to increase steadily in developing countries (**Figure 4**) (**Box 2**). Population growth will drive much of this demand, but so will increased consumption of meat and dairy products and the cultivation of crops for non-food purposes such as biofuel feedstock (FAO 2008, IFA 2008, Van Vuuren et al. 2010).

Global use of fertilizers that contain phosphorus, nitrogen and potassium increased by 600 per cent between 1950 and 2000 (IFA 2006). This helped to feed a growing world population, but excessive or inappropriate fertilizer use has also led to significant pollution problems in some parts of the world.

In the last half-century, the phosphorus concentrations in freshwater and terrestrial systems have increased by at least 75 per cent while the estimated flow of phosphorus to the ocean from the total land area has risen to 22 million tonnes per year (Bennett et al. 2001). This amount exceeds the world's annual consumption of phosphorus fertilizer, estimated at 18 million tonnes in 2007 (FAOStat 2009). While much of the phosphorus accumulated in terrestrial systems would eventually be available for plant growth, there is no practical way to recover phosphorus lost to aquatic systems.

In aquatic systems too much phosphorus and other nutrients results in eutrophication, which promotes excessive algal and aquatic plant growth along with undesirable impacts on biodiversity, water quality, fish stocks and the recreational

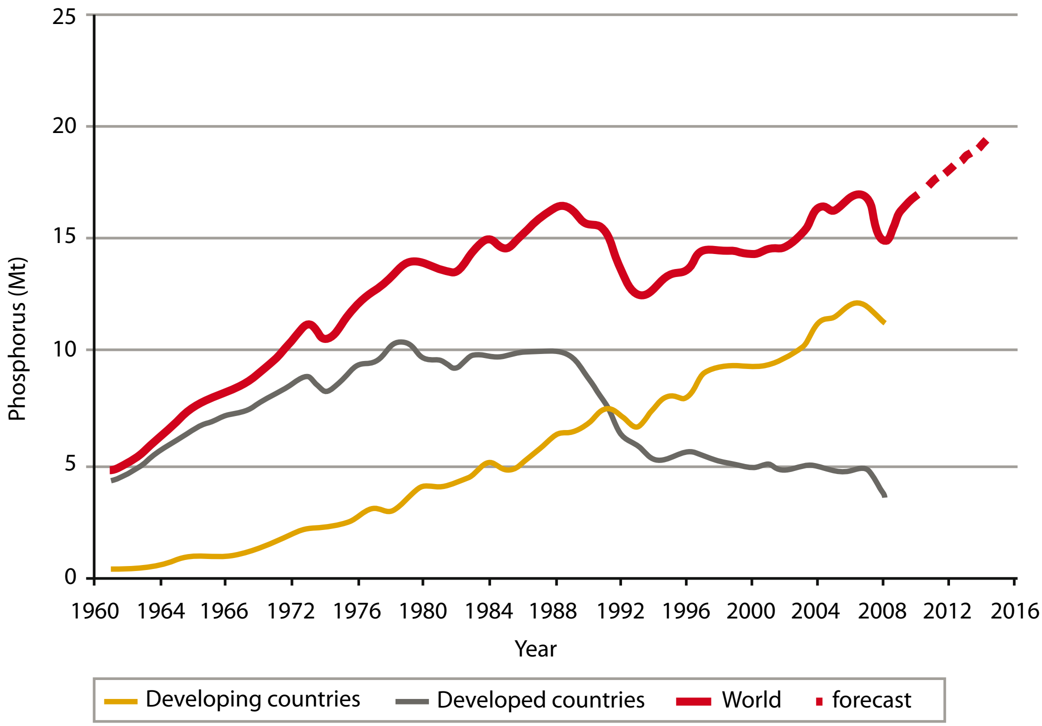

Figure 4: Global phosphorus fertilizer consumption. Demand in developed countries reached a plateau and then declined around 1990. It has continued to increase steadily in developing countries. *Source: Heffer and Prud'homme (2010)*

Box 2: Phosphorus use in African agriculture

Eighty-two per cent of the world's 6.8 billion people live in developing regions (UN 2009). Sixteen per cent of the population in these regions is chronically undernourished (UN 2010), which in some regions can largely be linked to soils' low productive capacity. For example, in Africa nearly three-quarters of farmland is depleted of nutrients, lowering crop yield to one-quarter of the global average (Henao and Baanante 2006). At the same time, more nutrients continue to be removed each year than are added in the form of fertilizer, crop residues and manure.

Nutrient balance studies in the 1990s suggested average annual depletion rates of 22 kg nitrogen (N), 2.5 kg phosphorus (P) and 15 kg potassium (K) per hectare in Africa. Intensively cultivated highlands in East Africa lose an estimated 36 kg N, 5 kg P and 25 kg K per hectare per year, while croplands in the Sahel lose 10 kg N, 2 kg P and 8 kg K per hectare (Smaling et al. 1997). Average annual fertilizer use in Africa is only about 17 kg per hectare, compared, for example, to 96 kg per hectare in Latin America (**Figure 5**). Even this low rate of consumption is restricted to just a few African countries. Sub-Saharan Africa, excluding South Africa, uses about 5 kilograms of fertilizer per hectare per year, of which less than 30 per cent is phosphorus. These levels are insufficient to balance offtake in crop products.

A combination of high cost and low accessibility prevents many African farmers from acquiring fertilizer. Poor transport, low trade volumes, and lack of local production or distribution capacity result in farm-gate fertilizer prices two to six times higher than the world average. Nevertheless, fertilizer is needed to achieve adequate sustainable crop yields. The Africa Fertilizer Summit (2006) concluded that a lasting solution requires policies to sustain robust distribution networks, including adequate credit sources, retail outlets and transportation, as well as the transfer of technology and knowledge for efficient fertilizer use.

A more sustainable strategy would include integrated soil nutrient management to make the most of organic sources of phosphorus, such as crop residues, animal manure and food waste, combined with more judicious use of mineral phosphorus fertilizers (Alley and Vanlauwe 2009). This would result in multiple environmental benefits, including erosion control. Run-off and erosion combined are responsible for 48 and 40 per cent of phosphorus losses in intensively cultivated highland areas and in parts of the Sahel, respectively (Smaling et al. 1997).

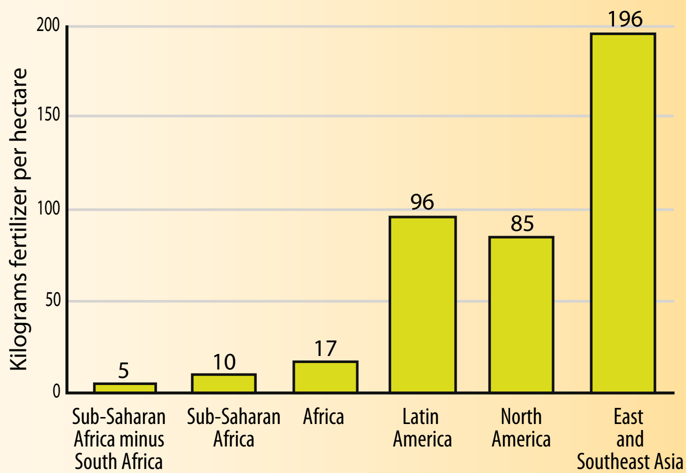

Figure 5: Regional disparities in the application of fertilizers containing nitrogen, phosphorus and potassium. *Source: IFA (2009)*

value of the environment. Algal blooms can include species that release toxins which are harmful to humans or animals, while decomposition of algae can lower dissolved oxygen levels, causing mass mortality among fish (Carpenter et al. 1998, MA 2005). Scientists have warned that human-induced nutrient over-enrichment can push aquatic ecosystems beyond natural thresholds, causing abrupt shifts in ecosystem structure and functioning (Rockström et al. 2009).

The estimated annual cost of eutrophication in the United States alone is as high as US$2.2 billion (Dodds et al. 2009). This problem is exacerbated in countries' large urban centres, where phosphorus from excreta and detergents is concentrated in wastewater streams and discharged along with nitrogen and other nutrients. If local authorities do not invest in facilities to remove these nutrients, they will be discharged with other effluent into rivers and other water bodies (Van Drecht et al. 2009). This is frequently the case in the mega-cities in developing countries, where more than 70 per cent of wastewater enters surface or groundwater untreated (Nyenje et al. 2010).

In many parts of the world, traditional nutrient cycles that were once the basis of local food production, consumption and waste management have changed in response to the need to produce more food in a globalizing world. Over four times as much phosphorus flows through the environment than before phosphorus fertilizer began to be used in agriculture (Smil 2002). Soils that receive phosphorus retain a high proportion, but the variability of the world's soils makes this amount difficult to assess, particularly at large scales. Agricultural efficiency—especially in the expanding area of livestock management—will be essential to optimize phosphorus use, avoid nutrient losses and meet increasingly strict environmental regulations. For example, the European Union's Water Framework Directive requires potential pollutants to be removed from wastewater prior to disposal into surface water. Sustainable land management is important for the prevention of phosphorus loss to water bodies resulting from soil erosion. Improved technologies to remove impurities such as heavy metals from fertilizer products would also minimize their transfer to agricultural soils or surface waters.

Using phosphate rock more sustainably would help ensure its long-term economic viability and the availability of phosphorus to farmers. Because phosphorus flows through the global food system, there are options for enhancing efficiency at each stage of the value chain. They include lengthening the life of reserves through improvements in mining (**Box 3**), in fertilizer production and in fertilizer use efficiency. Recycling phosphorus from excreta or other organic wastes also presents an important opportunity to recover this nutrient. Given the diversity of phosphorus-related issues, an environmentally integrated set of policy options and technical measures is required to ensure more sustainable use of this essential resource.

Eutrophication of Lake Winnipeg in Manitoba, Canada. Ongoing efforts to improve the lake's health include reducing nutrient inflow from wastewater, eliminating fertilizer use in buffer zones, and reducing phosphorus content in household detergents. *Credit: Lori Volkart*

Soil erosion is a natural process significantly accelerated by human activity, particularly land use changes such as deforestation. Overgrazing or removal of vegetation leaves the soil unprotected and vulnerable to the effects of rain. Soils are particularly prone to erosion in tropical and subtropical regions, where rainfall is usually higher and more intense. Rates of erosion vary with the type of soil and landscape.

A number of measures can be taken to enhance the efficiency of phosphorus use and reduce phosphorus losses, such as effective land management to help reduce losses due to soil erosion (**Box 4**).

Box 3: Improving the sustainability of phosphorus mining

The environmental performance of the fertilizer raw material industry has improved in recent decades, with a greater focus on sustainability in the mining sector. New management systems have been responsible for improved environmental performance, which also yields economic benefits. Increasing phosphorus recovery during mining operations can extend the life expectancy of reserves (Prud'homme 2010).

The area affected by surface mining operations varies with ore-body geometry and thickness. The phosphate content of the ore is upgraded by concentration, or 'beneficiation'. This process removes contaminants such as clay and other fine particles, organic matter, and siliceous and iron-bearing minerals (UNEP/IFA 2001). Such materials are usually removed by crushing/grinding, scrubbing, water washing and screening. They end up in water bodies, mined-out areas or specially designed ponds.

As with many mining activities, the extraction and beneficiation of phosphate rock has potential negative environmental impacts, including damage to the landscape, excessive water consumption, water contamination and air pollution. These impacts are localized and are mostly limited to the mining site (UNEP/IFA 2001). A range of landscaping practices are used to minimize disturbance and accelerate the re-establishment of vegetation, while wastes are confined to a specific area, providing a high degree of management control.

Work is currently under way to recycle process water, reclaim fines, and treat the waste stream to increase the recovery rate. However, information on phosphorus recovery in mining and ore beneficiation is lacking. Reported rates vary widely, with values ranging between 41 and 95 per cent (Prud'homme 2010, Van Kauwenbergh 2010).

Open-cast mining of phosphate rock in Togo. Most of the world's phosphate rock is extracted from open pits, as shown here, or from large-scale mines equipped with drag lines or shovel/excavator systems. *Credit: Alexandra Pugachevsky*

Box 4: Managing soil erosion to minimize phosphorus losses

Since plant nutrients are concentrated in the topsoil, removal of surface soil through erosion can greatly reduce soil productivity. Siltation and eutrophication also damage the aquatic environment. Thus, protecting topsoil from soil erosion maintains soil productivity and conserves water quality.

Measured rates of erosion and sediment transport vary. Topsoil removal rates of 0.47 tonnes per hectare per year have been measured in Africa, compared with rates almost four times as high in Asia (El Swaify et al. 1982). Due to the cost of making measurements, erosion simulation models have been developed. However, these models often provide different results when applied at different spatial scales.

Some 75 to 90 per cent of the phosphorus lost in surface run-off from cropped land is associated with soil particles (Sharpley and Rekolainen 1997). In Africa total annual phosphorus removal by all pathways is estimated at 2.5 kilograms per hectare, while phosphorus loss due to erosion and run-off is approximately 1 kilogram per hectare per year (Smaling et al. 1997).

Several well-recognized practices can minimize soil erosion, such as contour ploughing carried out parallel to the land's contours rather than up or down slopes, and contour planting of hedgerows on steep land. Since it is vegetation cover that principally determines the extent of soil loss by erosion, the long-term solution to control erosion rates is through vegetation protection, including use of mulches, cover crops, and fertility-enhancing systems on low-fertility soil (Stocking 1984). These practices have the potential to be more widely adopted in the developing world, although they are limited by lack of land tenure, the costs of adopting them, limited extension support and other socio-economic factors. Improved farmer education is an important starting point.

Major gains can be made through improving plant nutrient management and recycling phosphorus from waste streams (Syers et al. 2008, Gilbert 2009, Van Vuuren et al. 2010). Technological innovations in waste management can dramatically lower the amount of phosphorus making its way into the aquatic environment (**Box 5**). Such improvements sometimes produce co-benefits such as energy generation from biogas (Van Vuuren et al. 2010). Recycling sewage sludge is another option, although there are some health concerns as sludge may contain high concentrations of heavy metals, pathogens and other contaminants.

Some European countries are already formulating targets for phosphorus recycling. For example, Sweden aims to recycle 60 per cent of the phosphorus in municipal wastewater by 2015 (Swedish Environmental Protection Agency 2010).

Box 5: From waste to phosphorus recovery and recycling

For centuries, animal and human excreta have been added to farmland to supply nutrients for growing crops. Farmers in most parts of the world still consider animal manure a valuable soil amendment. To recover nutrients, including the phosphorus in human excreta, a wide range of technologies are being developed, ranging from low-cost, small-scale systems to expensive high-technology ones.

'Ecological sanitation' recovery systems for human excreta are designed to close nutrient and water cycles. For example, nutrient recycling from human waste can be achieved using urine-diverting dry toilets (Morgan 2007). Such on-site systems are particularly appropriate in rural and peri-urban areas, where households are not connected to sewerage or farmers do not have access to—or cannot afford—chemical fertilizers (Rosemarin et al. 2008). Trials in villages in Niger by Dagerskog and Bonzi (2010) found that an average rural family of nine persons excreted the equivalent of chemical fertilizer worth about US$80 per year. The urine component produced comparable or 10 to 20 per cent higher yields of sorghum and millet, compared to the same amount of nutrients applied as chemical fertilizer.

Interest in recycling phosphorus and other nutrients from sanitation systems has been increasing for several years (Esrey et al. 2001). Responding to this interest, the World Health Organization has developed guidelines for the safe reuse of human excreta in agriculture (WHO 2006).

Other innovations in the area of ecological sanitation have significantly increased the feasibility of extracting phosphorus from municipal wastewater streams (Gantenbein and Khadka 2009, Tilley et al. 2009). The output is the mineral struvite, a white solid formed when bacteria are used to clean up sludge. Struvite has demonstrated value as a source of phosphorus-based fertilizer (Johnston and Richards 2003). First used commercially in 2007, this technology is currently in full-scale use in treatment plants in some major cities in North America and the United Kingdom.

During the past decade, researchers have started to focus on reducing phosphorus losses by developing ways to improve phosphorus uptake by animals. In particular, intensive pig rearing produces massive volumes of phosphorus-rich manure. Monogastric animals such as the pig are unable to break down phytate, the major form of phosphorus in their feed. Phosphorus is therefore added to their diet as an inorganic supplement, but much of it is excreted due to low uptake in the gut. Scientists at the University of Guelph in Canada have developed a genetically engineered *Enviropig* able to digest phytate (Forsberg et al. 2003). This decreases the need for an inorganic phosphorus supplement. Other research groups are developing low-phytate crops or focusing on the production of phytase, an enzyme that helps animals to digest phytate.

Technological innovation has resulted in the development of a pig able to digest phytate. This reduces the need to provide a phosphorus supplement, much of which is excreted. Approval by the Canadian government in early 2010 allowed farmers to begin raising the *Enviropig*, a significant step towards enabling its processing and sale as food. *Credit: University of Guelph*

Scrubbing and washing with seawater of phosphate rock in the coastal area of Togo. *Credit: Takehiro Nakamura*

Population growth and economic development are expected to further increase agricultural production, particularly livestock raising. Future demand for phosphorus will strongly depend on the types of agricultural practices that accompany this increase (Vitousek et al. 2009). Dietary changes and reduction of food waste in the retail sector and households would help reduce phosphorus losses, and would require greater awareness and a change in attitude in order to alter consumption patterns. As promising options emerge, they will call for decision making based on reliable scientific evidence derived from further research on phosphorus availability, product flows and end-uses (Hilton et al. 2010, Van Vuuren et al. 2010).

Looking ahead

Phosphorus has received only limited attention compared to other important agricultural inputs such as nitrogen and water. Because of the vital role of phosphorus in food production, any consideration of food security needs to include an informed discussion concerning more sustainable use of this limited resource. Key themes include the increasing global demand for phosphorus fertilizers, the ongoing debate over the long-term availability of phosphate rock, lack of adequate phosphorus accessibility by many of the world's farmers, prospects for increased recycling and more efficient phosphorus use in agriculture, and minimization of losses through soil erosion control. More detailed research is required to provide reliable, global-scale quantification of the amount of phosphorus available for food production. A global phosphorus assessment, including further insights from scientists and other experts, policy-makers and other stakeholders, could contribute to improving fertilizer accessibility, waste management in urban settings, and recycling of phosphorus from food waste and from animal and human excreta.

The long-term availability of phosphorus for global food production is of fundamental importance to the world population. Given the diversity of issues surrounding phosphorus, only an integrated set of policy options and technical measures can ensure its efficient and sustainable use. Environmental solutions that improve nutrient management and recycling, minimize phosphorus losses due to soil erosion, and foster sustainable production and consumption also promote wise use of a finite resource. This could be the basis for fostering environmental innovation and other actions at local, national, regional and international levels to improve phosphorus management. The future of this resource will also depend on governance with regard to its extraction and distribution around the world. There is a need for accurate information about the extent of global reserves, new technologies, infrastructure, institutions, attitudes and policies to meet the challenge of sustainably feeding a rapidly growing global population while maintaining a healthy and productive environment.

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