Chapter 18
Phosphorus and Global Change

Holm Tiessen, Maria Victoria Ballester, and Ignacio Salcedo

18.1 Human Appropriation of P Deposits

Phosphorus (P) is related to the issues of global change in two ways: the approximately 1,000 million tonnes (t) of P that have been mined and added to the environment over the past 150 years are part of environmental change at a global scale; and global climate and land use changes affect how P is being moved and used in the environment.

Prior to the middle of the nineteenth century, phosphate was largely derived by recycling bones, and its use was necessarily limited. In the 1840s, John Bennett Lawes patented the production of superphosphate, treating a phosphate ore found in Britain with sulfuric acid. By the 1870–1880s British superphosphate production reached some 15,000 t of P and the large phosphate ore deposits of South Carolina and Florida were being discovered, which are now responsible for about 20% of world production. The history of industrial phosphate use is therefore very similar to that of petroleum, which had been used for thousands of years in limited applications (such as asphalt) but was first transformed into liquid fuels at industrial scale in the middle of the nineteenth century. Like oil use, P use has increased exponentially and played a major role in human development. Phosphate deposits are unevenly distributed around the globe: Western Sahara, Morocco and China

H. Tiessen (✉)
Inter-American Institute for Global Change Research, Av. dos Astronautas 1758, 12227-010 São José dos Campos, SP, Brasil
e-mail: htiessen@dir.iai.int

M.V. Ballester
Centro de Energia Nuclear na Agricultura, Universidade de São Paulo, Av. Centenário 303, 13416-000 Piracicaba, SP, Brasil
e-mail: vicky@cena.usp.br.

I. Salcedo
Departamento de Energia Nuclear, Ignacio Salcedo. Universidade Federal de Pernambuco, Centro de Tecnologia, Av. Prof. Luiz Freire 1000, Cidade Universitária, 50740-540 Recife, PE, Brasil
e-mail: salcedo@ufpe.br

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have the largest economic minerable reserves (5,700 and 6,600 million t, respectively, followed by South Africa, USA, and Jordan with 1,500, 1,200, and 900 million t, respectively. Brazil has reserves of 260 million t of mostly sedimentary deposits, but India does not have sizeable reserves (USGS 2007). For some countries, the reserve base can be two to four times greater than the actual reserves (USGS 2007) and it includes those resources that are currently economic (reserves), marginally economic (marginal reserves), and some of those that are currently subeconomic (subeconomic resources).

The Government of China has already imposed limits on exports of phosphate rock to maintain supply for domestic consumption (Jasinski 2004), and other phosphate-producing countries may follow suit in the near future. Hence, phosphate has been classed as a strategic resource. The "International Strategic Minerals Inventory Summary Report" on phosphate published by the US Geological Service (USGS Circular 930-C) in 1984 was prepared by a group of earth science and mineral resource agencies from Australia, Canada, Germany, South Africa, and the USA (Krauss et al. 1984). This report still remains the source for most assessments on the future availability of phosphate, and for arguments on "peak phosphorus," although numbers were reviewed in 2007 and the International Fertilizer Association is now in the process of compiling new data. It is an indication of phosphate's strategic importance that the USGS report was prepared as part of the first series of strategic mineral assessments that included P, Cr, Mn, and Ni – the latter all essential to metallurgy and therefore to military and industrial applications. The potential for geochemical constraints of these and additional elements has also been analyzed by Pickard (2008).

Phosphate is a finite resource and irreplaceable as an essential nutrient for all living organisms. The 1984 USGS strategic inventory report provides a summary of production and deposit information that may guide understanding of "how finite" phosphate ore deposits are and therefore how urgent conservative and renewable technologies are. The earth's crust contains on average 0.12% P. Mined deposits contain 2–20% P, i.e. 15–150 times the crustal average. In 1945, world P production was 1.8 million t P increasing to 21 million t P by 1981 (11 and 142 million t phosphate concentrate respectively, Krauss et al. 1984). Based on these numbers, and assessments by Cordell et al. (2009) and Tenkorang and Lowenburg-DeBoer (2009), Craswell et al. (2010) quote peak production estimates of 23–29 million t around the year 2030. The 1984 report estimates supply in known deposits and their extensions to last for about 100 years, assuming 5% consumption growth per year. These estimates depend on a large number of economic and regulatory assumptions, transport costs, elasticity of the agricultural input markets, and mandated limits on contaminants such as cadmium or fluoride. Significant reductions in P use occurred after the collapse of the Soviet Union with its centrally mandated fertilizer applications, and overall consumption has leveled off since the 1980s, particularly in richer countries where soil P reserves have been built up during 30 years of applications in excess of replacement levels (MEA 2005). A 7% drop in sales in 2008 is an indication of economic pressure on P use, which is likely to cause a re-evaluation of P needs over several years. Fixen (2009) estimates reserves to last for potentially another 300 years, although that includes currently uneconomic ores. Regardless of when peak production is expected and when mined P will become too expensive to serve as an input to crop production at present costs of food, P needs to be treated as a finite resource that is not renewable, only recyclable.

18.2 P Cycling in Natural and Agro-Ecosystems

In natural terrestrial ecosystems, P is relatively closely cycled between soils and biota (Smil 2000). The absence of a gaseous phase, the low solubility of calcium-bound P, the relatively strong retention of the orthophosphate anion by Fe and Al oxy-hydroxides, and the limited soil erosion under good vegetation cover, are key determinants in this close cycling. In such natural systems, mineralization and immobilization transformations between inorganic and organic forms are relatively more important than transport processes. In agro-ecosystems, human intervention opens the P cycle and transport processes become relatively more important. Fertilizer, livestock feeds, manure and/or bedding, agricultural products, human wastes, and P leaching and runoff have become important global P flows (Smil 2000; Liu et al. 2008). In addition to such transfers, P transformation processes also occur in managed lands, particularly in soils that receive continuous manure applications, which modify the proportions of organic and inorganic soil P fractions (Galvão and Salcedo 2009; Hao et al. 2008).

P pollution of surface waters by farming activities is largely due to soil erosion and surface runoff (overland flow) from croplands (Sharpley et al. 1995; Liu et al 2008). Grazing of pastures can also be a source of significant P pollution, particularly when stocking rates are high (Soupir et al. 2006; Chardon et al. 2007; Bilotta et al. 2008). Subsurface transport or leaching is a lesser but still important route for water pollution (McGechan et al. 2005; Kleinman et al. 2006). P overloads from manures and fertilizers, which enrich the surface layers of soil, contribute to pollution of surface waters. On the basis of data collected between 1998 and 2000 in Southern and Eastern Asia, Gerber et al. (2005) estimated that almost 40% of the cropped area had P overloads of 4.4–16 kg ha^{-1}. These two regions of Asia have the world's highest P consumption while Africa's consumption is the lowest (Table 18.1). Rates in Table 18.1 were calculated using total agricultural areas (arable + pasture lands), which certainly underestimate fertilizer use in croplands because in many regions pastures are less fertilized, if at all. Asia is the least favored region when the ratio of population to arable land was considered (Table 18.1) and therefore has the most fertilizer-intensive land management.

In addition to enhanced transport processes at the agro-ecosystem scale, P enters global transfers involving agricultural and industrial commodities (grains, meat, fruits, vegetables, seeds, phosphate rock, etc), processed food, fertilizers, and biofuels. Part of this global circulation is beneficial to people (Beaton et al. 1995; Villalba et al. 2008). However, excessive or uncontrolled transfers of P that occur as a consequence of intensive animal husbandry based on imported feeds result in contamination of lakes, rivers (Sharpley et al. 1995) and, ultimately, estuaries (Salcedo and Medeiros 1995) and coastal seas (Howarth et al. 1995), resulting in the environmental dispersion of P at a

Table 18.1 World mineral fertilizer-P consumption, population, arable land, meadows and pastures areas subdivided by continents and main regions (data for 2007)

Continents and regions	Consumed P ($t \times 10^3$)	Population (Inhabitants $\times 10^6$)	Arable land (ha $\times 10^6$)	Meadows and pastures (ha $\times 10^6$)	P consumed in agricultural land[a] (kg ha^{-1})	Population per arable land (Inhabitants ha^{-1})
Africa	348	943	219	911	0.3	4.3
Northern	182	300	56	239	0.3	5.3
America	5,396	900	364	803	4.5	2.5
North	2,677	336	215	253	5.6	1.6
South	2,461	379	113	454	4.2	3.4
Asia	9,871	3,983	504	1,089	5.9	7.9
Eastern	5,464	1,530	150	515	7.9	10.2
Southern	3,116	1,612	217	78	10.1	7.5
Europe	1,963	731	277	180	4.1	2.6
Eastern	751	296	194	116	2.4	1.5
Western	452	187	34	198.2	5.5	5.5
Oceania	671	34	45	393	1.5	0.7
World	18,250	6,593	1,411	3,378	3.7	4.7

Source: FAOSTAT (2009)
[a]Arable land plus meadows and pastures

massive scale. This highlights one fallacy of the literature on P. The often repeated statement that P is "not mobile" and the inference that excess P additions to agricultural land will eventually all contribute to residual fertilization effects is wrong. P is indeed relatively immobile compared to other elements such as N, but it does move in and through soils (Letkeman et al. 1996). Phosphate does dissolve, is found in ground and surface waters, and gets delivered to the oceans. When global reserves and global budgets are being assessed, that mobility is an important issue.

Transfers of P into aquatic environments can be classified by the nature of the P source as point (industrial, urban, feedlots), diffuse (agriculture and atmospheric deposition) and background (natural land) sources (EEA 2005). About 73% of the total P load (60 kt year^{-1}) in waters of Great Britain was attributed to households, 20% to agriculture, 3% to industry and 4% to background sources (White and Hammond 2009). The agricultural share in most source apportionments in Europe varies between 25 and 75% of the total load (0.3–2.5 kg ha^{-1} year^{-1}). The reason for this variability is the uneven point source share, which involves differences in population density, industrial activities, and wastewater treatment among the various catchments (EEA 2005). Comparison of area-specific indices to compute P loads into the aquatic system places Belgium and Netherlands at the top, with approximately 2.5 kg P ha^{-1} (EEA 2005). Over all land uses, China's area-specific P load was estimated at 1.4 kg ha^{-1} (Chen et al. 2008) but when only arable land was considered, it attained 2.8 kg P ha^{-1}. On the high end of area-specific P loads, analysis of the total suspended solids (TSS) load in 126 rivers pointed to 15 basins with particulate phosphorus (PP) loads greater than 20 kg P ha^{-1} year^{-1}, eight of which with loads above 30 kg P ha^{-1}: the Purari and Fly (New Guinea), Ord (Australia), Ganges and Tapti (India), Mahakam (Indonesia), and Irrawady (Myanmar) (Beusen et al. (2005)). Most of this will be from agricultural sources, although some of these basins also release PP by erosion of non-agricultural areas.

Estimates of world P transfers into the aquatic system from all sources vary between 12 and 21 million t year^{-1} (Liu et al. 2008; Beusen et al. 2005; Smil 2000; Howarth et al. 1995; Meybeck and Helmer 1989). The almost twofold variability in the estimates is due to the complexity of large scale data integration (Krueger et al. 2007). The relevant point is that estimated P losses are of the same order of magnitude as the annual world consumption of fertilizer-P (18.3 million t year^{-1}, Table 18.1). Two highly negative aspects of P flows into aquatic ecosystems are (1) the enhancement of biological activity in fresh water bodies (eutrophication), impairing water quality (USEPA 1996), and (2) the loss by burial of P in sediments of coastal ocean waters, except for a small fraction that is harvested in fish catch (Howarth et al. 1995).

18.3 Drivers of Changes in Reservoirs and Fluxes

One major global change process is the increasing urbanization of human populations. Changes to P flows in moving from rural to urban societies are illustrated by the city of Linköping, Sweden, whose population increased from 7,300 in 1870 to

130,000 in 2000 (Neset et al. 2008): increasing amounts of P reaching consumers and hence the waste handling system; increasing flow of products of animal origin, which are the main sources of P; and, most notably, increasing inputs of fertilizer-P in peri-urban areas.

Projections of world population are 9,100 million by 2050. Almost all of the increase will occur in developing countries (UN 2004) with much of the growth concentrated in urban areas (Steinfeld and Wassenaar 2007). The consequence of this urban population growth will be the expansion not only of food crops, but also of feed crops to satisfy demand for livestock products because increases in urbanization are correlated with increases in per capita consumption of animal products (Delgado et al. 1999). Although the projected increase in population for the next 40 years is approximately 50%, meat and milk productions are expected to double, reaching 465 million t of meat and 1,043 million t of milk. These projections are based on the expansion observed between 1980 and 2002, when the annual per capita consumption of meat in developing countries tripled and milk production more than doubled (Steinfeld et al. 2006).

Traditionally, the distribution of livestock production, particularly ruminants, was determined by the availability of natural pastures and crop residues. Pigs and poultry were typical of smallholders, and still are in some regions, because they re-process wastes. Market concentration has largely disengaged livestock production from grazing systems and replaced them with “landless” meat production systems that depend on outside supplies of feed (Steinfeld and Wassenaar 2007; Tamminga 2003). Poultry and pig production, ruminant feedlots and large-scale dairy production are examples of such landless systems (Seré and Steinfeld 1995). Nowadays, livestock production is more associated with access to output and input markets than the availability of grazing lands (Steinfeld et al. 2006). Almost 44% of the P fertilizer consumption in the USA was used for maize production and more than half of this crop production went into livestock feed (Steinfeld and Wassenaar 2007). The large soybean production of Brazil and Argentina is based on imported P fertilizer (42% of total fertilizer P consumption in the case of Brazil, Table 18.2) and most of the grain and by-products are exported (2nd and 3rd world exporters, respectively, FAO, 2009) since the nomenclature refers to the classification given in the FAO publication. These exports represent P flows mostly directed to animal production; they are examples of how globalization drives land-use changes and P fertilizer use at the national level.

The livestock sector is expanding at a faster rate than the rest of agriculture in almost all countries (Steinfeld and Wassenaar 2007). The shift of diets towards more meat and other animal products increases land and fertilizer needs beyond the compensation for growing population numbers. Case studies of the effects of increasing world consumption of beef for Queensland, Colombia and Brazil led McAlpine et al (2009) to point to the global beef market as a driver of regional and global change and to the need for reducing beef consumption, a view also shared by other authors (McMichael et al. 2007). The proximity of landless animal production to urban centers, particularly in Asia (Gerber et al. 2005), determine that large amounts of P contained in the feed drawn from agricultural land end up in the sewer

Table 18.2 Amount of mineral fertilizer-P (%) used for different crops in the world, selected countries, and the European Union, and the percentage mineral fertilizer-P consumption of these regions in relation to the world consumption (data for 2007)

Crop	World	China	India	USA	Brazil	EU-27	Egypt
Wheat	16.2	16.0	20.0	14.7	2.1	21.8	14.5
Rice	12.3	15.0	25.0	1.1	3.9	0.5	8.5
Maize	12.4	7.0	1.5	43.9	20.0	13.0	10.5
Soybean	7.5	3.0	2.5	10.5	42.4	0.3	0.2
Sugar crops	3.9	2.3	4.5	1.1	8.6	3.1	3.0
Fruits and vegetables	17.9	34.0	11.0	6.0	5.0	12.4	45.0
Other	29.8	22.7	36.5	22.7	18.0	48.9	18.3
% of world consumption[a]	100	30.5	14.6	10.4	9.3	8.8	0.6

Source: IFA (2009)

[a]These percentages allow calculation of the amount of fertilizer-P (t $\times$ 10^3) used by each country, based on the world consumption shown in Table 18.1

systems of cities (Weikard and Seyhan 2009). Citing Schröder (2005), "the ongoing disintegration of agriculture into specialized farms, specialized regions and even specialized countries has disrupted local nutrient cycles."

18.4 P Cycle and Biofuels

In addition to the expansion of food and feed production for growing populations and livestock production, there is also substantial growth in biofuel production in some countries, further increasing P demand. Interest in biofuels is increasing as a result of growing energy demand, geographical concentration of known petroleum reserves, increasing costs of finding and producing additional oil, and due to concerns about fossil fuel contributions to atmospheric CO_2 and climate change. Bioethanol and biodiesel production to substitute fossil carbon with biologically fixed carbon is being promoted to limit CO_2-driven climate change, because it returns to the atmosphere recently sequestered carbon dioxide (Ruth 2008; Field et al. 2007). A globally escalating demand for biofuels raises concerns about the potential of these biofuels to be sustainable, abundant, and environmentally beneficial energy sources (Tilman et al. 2006) because large areas of forest and grass lands, especially in the Americas and Southeast Asia, are being converted to produce biofuel (Klink and Machado 2005). Concurrently, lands typically used for food production are also being diverted to biofuel production (Fargione et al. 2008).

Most current biofuels are based on food crops: ethanol is produced by fermenting starch or sugar, mainly from corn or sugarcane, and biodiesel is made from oil seeds such as rape, from soybean, or from palm nuts (Ruth 2008). The expansion of biofuel production will result in increased applications of N and P fertilizers when natural or grazing lands are converted to sugarcane, corn, or soybean production. For instance, in 2007 the two main sources for biofuel production in Brazil, sugarcane with 8 million and soybean with 22 million ha (IBGE 2007), were responsible for the consumption of almost 9% (146,000 t) and 42% (712,000 t) of fertilizer-P, respectively (Table 18.2). Of the areas cultivated to these crops 54.6% (IBGE 2010) and 8%, respectively, were for fuel production. Approximately 44% of P consumption in USA is for corn (Table 18.2), some 15% of which is directed to biofuel production. Residue recycling will not greatly reduce P fertilizer demand. For instance, vinasse, a often re-cycled by-product of sugarcane alcohol production has a high organic matter and potassium content, but is poor in P and other nutrients (Ferreira and Monteiro 1987).

Global production of fuel ethanol tripled between 2000 and 2007, with the USA and Brazil accounting for most of the growth (OECD-FAO 2008). In Brazil, 25–30% of road transportation uses sugarcane-derived ethanol (Somerville 2006). In the last 5 years, sugarcane and soybean production have been growing at an annual rate of 7–8 % (IBGE 2007) and the land-use changes to accommodate the expansion of biofuel and feed production have affected large extensions of savannahs and subtropical forests and increased P flows. The increase in P-fertilizer demand to attend this growth resulted not only from the expansion in cultivated area, but is also the consequence of larger investments in fertilizers to improve productivity. According to Brazilian estimates, the average amount of P used per hectare of sugarcane increased from 27 kg in the 1990s to 30 kg in the last decade. These rates are higher than the 16 kg P ha^{-1} that can be calculated from P consumption and planted area information given in Table 18.2 and IBGE (2007). An explanation may be that P fertilizer is often only applied in the first (planting) year of the sugarcane cycle and not for the full 7-year sugarcane cycle. Consumption statistics may therefore be more reliable than estimates based on fertilizer recommendations. During the same period, the annual average amount of P used per hectare of soybean grew from 16 to 26 kg as farmers invested more in fertility management than in new land. Soybean production required an extra input of 6.1 million t of P from 1990 to 2008 (IBGE 2007; ANDA 2010). The 1,200 million L of biodiesel (ANP 2009), consume 3% of the total amount of mineral P fertilizers added to soybean. By 2010, the amount of P fertilizers necessary to supply the projected national biodiesel demand of 1,800 million L will increase proportionally.

18.5 Land Degradation

Pastures and arable land, particularly in the tropics, normally are established by conversion of natural vegetation (13 million ha $year^{-1}$, FAO 2007) on P-deficient soils often with high extractable Al and Fe contents. Once the tight nutrient cycling of natural ecosystems is interrupted, sustained agriculture production has to be based on lime and P inputs. Of the 3,400 million ha classified as permanent meadows and pastures (Table 18.1), approximately 532 million ha have potential for expansion of agricultural production, 80% of which are in the southern hemisphere and close to 200 million ha in Brazil (WWF 2009). The report estimates that arable lands in Brazil extend over 70 million ha and that about 30% of its 200 million ha of pasture lands are degraded (WWF 2009). By recovering such degraded soils the country could double its arable land resulting in less intense deforestation in the Cerrado and Amazon (WWF 2009; Field et al. 2007).

However, if the 70 million ha of degraded pasture in Brazil (IBGE 2007) were converted into biofuel fields, assuming an average input of 28 kg P ha^{-1}, this would result in nearly 2 million t of additional P, which is of the same order of magnitude as the current fertilizer P consumption of Brazil (1.7 million t in 2007, Table 18.2). It is not clear how such an expansion in P demand could be satisfied and for how long. World P fertilizer consumption in 2007 amounted to 17.4 million t for a total agriculture area of 4,967 million ha (Table 18.1). The expected growth in world demand for phosphate fertilizers by 2012 is 2.2 million t P compared to 2006 figures (FAO 2008). Unless management policies are developed and environmental regulations implemented to induce P recycling at farm, municipality, and watershed scales, the environmental effects of such a dramatic increase in land conversion are grim.

These additional land pressures are in conflict with environmental goals of preserving ecosystem services, and are accompanied by an historic increase in the intensity and extension of soil degradation at a world scale (EEA 2003; Pimentel 2006; FAO 2007). Actual arable land is approximately 1,500 million ha worldwide (Table 18.1), which is about the same area as has been abandoned due to land degradation since farming began (Lal 1990). Because soil erosion removes surface soil, which normally has a considerably higher P content than the subsoil, this diminishes the potential for food production. Soil erosion rates depend on past and present land uses, soil type, climate, and land-surface forms (Pimentel 2006). The rate of loss of arable land is estimated at 10 million ha $year^{-1}$ (Faeth and Crosson 1994). Estimates obtained from analyzing global river transport of sediments (Beusen et al. 2005) or analyzing soil erosion with reference to land use and climate change (Yang et al. 2003) are coincident in reporting South East Asia as the region suffering the most serious erosion, followed by South America and Africa. Societal response to this situation is inadequate. Most consumers connect meat, fruits and vegetables with agricultural activities, but not with the soil and even less with P. In this context, education must assume a role in reinstating the link between food availability and resource conservation in the understanding of urban societies.

P carried by rivers to be buried in sediments of estuaries and near-shore marine environments of the continental margins (Ruttenberg and Berner 1993) will probably stay out of reach until land reserves of phosphate rock become so depleted that high phosphate ore prices could justify the investment of exploring such dilute marine deposits. However, at this point, P fertilizer prices will be much higher than nowadays and the current perception of an ever-growing food supply will have to be adapted to the new reality. Therefore, optimization of P resource management to minimize its gross transfer into the aquatic system should be a major issue when analyzing sustainable food production.

18.6 Concluding Remarks

Phosphate has been essential to the growth of human populations and their prosperity. But, P has been used in production systems in a way that leaked large amounts of P into down-stream ecosystems. The negative effects on these ecosystems, whose biological productivity are often P or N and P limited, are well known. Detrimental effects from P excess now occur at a global scale, although some regions, particularly in poorer countries, remain P-deficient. Agricultural production will always be P-dependent, and it is becoming increasingly clear that P is a finite resource that, by scarcity or price, will be a limiting factor in future production increases. How to feed growing populations has long been a preoccupation. In addition, there is now growing concern about agricultural expansion for biofuel production to offset fossil fuel use. Balancing arguments of CO_2 emissions versus P limitations on human wellbeing will not be an easy task. It is clear though that P use will have to be accompanied by greater efforts towards re-use, recycling, and strategic targeted applications.

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