



Phosphorus in agriculture: global resources, trends and developments

Report to the Steering Committee Technology Assessment of the Ministry of
Agriculture, Nature and Food Quality, The Netherlands,

and in collaboration with the Nutrient Flow Task Group (NFTG), supported by
DPRN (Development Policy Review Network)

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The authors wish to thank for several critical, but fruitful, discussions during the writing of this report. We hope that it will contribute to a more sustainable use of phosphorus in the future.

1. Introduction

Phosphorus (P) is one of the major nutrients needed to sustain life. P-containing compounds are vital in energy metabolism (including ADP, ATP), membranes, structural support (teeth, bones), genetic components (DNA, RNA) and (for plants) the photosynthesis process. For life on earth, photosynthesizing organisms play a crucial role being the life forms which can convert solar energy and carbon dioxide into (energy containing) organic compounds, needed as food for secondary production. The low concentration of P in the soil along with its low solubility makes it a key growth limiting factor for plant growth nearly everywhere on the world. The natural delivery of P by the soil to plants therefore heavily determines the production capacity of unfertilized agro-ecosystems. Soils in entire continents like Africa and Australia and in countries such as Brazil and India have either a low phosphorus content or have soils that release phosphorus at insufficient rates to make high yields possible without external P inputs.

In the past, natural ecosystems and low-input agricultural systems adapted to low P availability by recycling P from litter and other green manure as much as possible. In addition, phosphorus input was raised by collecting manure in stables from animals that had been grazing outside the farm. Hence, P was collected from a much larger area than the arable part of the farms thereby improving the fertility status of the nearby fields of a settlement. This strategy was common all around the world, including the Netherlands, and is still practiced in large parts of the world. The strategy requires, depending on the inherent fertility of the natural lands and the desired production level, at least 20 ha of grazing land per ha of cop land.

Until about the middle of the 19th century also city refuse (human excreta, the dung of city horses etc.) was important to replace the nutrients which were removed from the farm with the products. In Europe, especially in Flanders and Holland this was practiced and sometimes regulated by government (Duncan Brown, 2003).

External P-inputs became available on a large scale in the second half of the 19th century by the mining of phosphate deposits. This induced large ecological and agricultural changes. According to Howarth *et al.* (1995) the widespread use of the P-commodity has decoupled patterns of supply, consumption and waste production from natural nutrient cycles. Its use has rather been governed through economic profitability. The introduction of artificial P (and nitrogen (N)) -fertilizer allowed intensification of agriculture, and can be considered to be one of the determinants for global population to continue its growth from around 1 billion people in 1850 (when mining of phosphate deposits began) to the current 6,8 billion people. Rather than an expansion of agricultural area to provide the increasing amount of food, yield increase provided the largest portion of the increase in food production. Even when the P-fertility status of the soil is considered sufficient for plant growth, artificial P-fertilization appears often to be profitable, which explains the success of P-fertilizer in the past century. The introduction of mineral P-fertilizer also allowed the extension of arable land into regions that were poor in phosphorus. P-fertilization contributed largely to the expansion of soybean cultivation in the *Cerrado* biome in Brazil. The dependency of modern agriculture, and thus global food supply, on artificial phosphorus fertilizer is not commonly recognized.

Attention worldwide is fully focused on the finiteness of fossil fuels, despite the fact that the availability of energy as such is not limiting. New technological options are available and can be made more efficient to capture solar radiation that is readily available at amounts exceeding 10.000 times than required. Moreover other alternatives are available including wind, geothermal, tidal and nuclear energy. In contrast, artificial fertilizer phosphorus is a finite resource that cannot be replaced by another nutrient. Little is known about the distribution of global food production and consumption when phosphorus would be in short supply, but they are likely to be fierce because of the fundamental importance in plant production.

Still, the risk of running out of artificial phosphorus fertilizer and the potentially fierce consequences do not feature prominently on the agenda of global UN and agricultural organizations, nor as an urgent matter on the political agenda of many countries. The governance of global phosphorus resources is left to market forces of supply and demand and no international organizations are active in this respect (Cordell, 2008; Cordell *et al.*, 2009).

Considering the important role of P-availability for the worlds food production capacity, and also the geopolitical aspects associated with the available phosphorus resources, this report presents the current insights in the use of P and identifies the major issues which determine future requirement of P. We will summarize briefly the future and current developments in relation to phosphorus. Future scarcity, due to the finiteness of the phosphorus resources, has strong links with many development related issues through the primary agricultural production, such as the millennium development goals, alleviation of poverty, eradication of hunger and sanitation.

It seems necessary to increase the awareness of a possible P scarcity at various (political and institutional) levels and to explain the possible consequences so that coordinated actions can be undertaken.

In this report we will first provide information on the main global P flows in the human-agricultural environment. In Chapter 3 the worlds known P- resources are compared with the current and future demand, taking into account factors like the increase in the human population, changes in menu (more meat-based) and the possible increase in biomass production for energy purposes. In this chapter also the various losses of P in the production chain from mining to food are treated. In Chapter 4 possibilities for a more efficient use of P are summarized. The report ends with a discussion of the results (Chapter 5), the main conclusions are presented in Chapter 6.

2. The global P-cycle

The global P cycle has four major components (Ruttenberg, 2003): (i) tectonic uplift and exposure of P-bearing rocks to the forces of weathering; (ii) physical erosion and chemical weathering of rocks producing soils and providing dissolved and particulate P to rivers; (iii) riverine transport of P to flood plains, lakes and the ocean; and (iv) sedimentation of P associated with organic and mineral matter and burial in sediments. The cycle begins anew with uplift of sediments into the weathering regime. In this chapter we will briefly treat the global flows of phosphorus, thereby emphasizing the agricultural aspects as well as losses occurring in industry/household rather than on the geochemical aspects, as their temporal dynamics are beyond the time horizon and sphere of influence of human civilization.

2.1 Flows

Figure 1 gives a representation of the main flows of P through the food related human activity system. The thickness of the arrows is proportional to the flow (figures are in Mt¹ of P but are prone in some cases to large uncertainties). The diagram is based on the figure by Cordell (2008) while taking into account also data from other references (Smil, 2000; Smil, 2007; Liu *et al.*, 2008) and our own calculations.

A short description of the major P-flows in global agriculture and human hemisphere.

Fertilizer P

Besides P in animal manure, fertilizer P currently is a major input to arable soil and to intensively managed grasslands.

Erosion and leaching

Especially in arable soil P can be lost by erosion (mainly particulate P) or leaching, after transport by rivers this P eventually ends up in the sediments of the ocean. Compared to crop uptake the losses by erosion are in the same magnitude. In contrast to carbon, nitrogen, oxygen, hydrogen and some other elements, P is therefore not an integral part of global ecological cycles. Because of the fact that in the global context large amounts of P are discharged annually into the oceans the term P-cycle is not an appropriate term according to Howarth *et al.* (1995). Cycling of the phosphorus in the oceans' sediments takes only place in the very long term (millions of years) by the process of tectonic lift.

Crop uptake, offtake and recycling of crop residues

P taken up by crops originates directly from fertilizer P and animal manure or delivered by the soil (including mineralization of previously applied organic P). Part of the P taken up by the crops is recycled back to the soil, the greater part ends up in food and feed although substantial losses can occur before it reaches humans or animals.

Animals

An extra cycle of phosphorus occurs in livestock. Worldwide a large proportion of the arable crops is used for feed, supplemented by P-additives. Non-confined domestic animals can take up phosphorus by grazing in nature or range lands.

Our calculations show that worldwide domestic animals produce around 12-14 Mt of P in manure, but higher values (16-20 Mt P) are mentioned as well (Smil, 2000). Part of this manure is recycled to arable land, part to non-arable soil and part is lost (burnt, discharged to surface water, dumped etc.).

¹ 1 Mt P is 1 million metric tons of P = 10⁹ kg P (1 billion kg P); 1 kg of P = 2.29 kg phosphate (P₂O₅).

Humans

The phosphorus taken up by humans does not exceed 3-4 Mt P; almost the same amount is excreted. Only part of the phosphorus in human excreta is recycled back to agricultural land.

Looking broader than agriculture the planets' global fluxes of phosphorus are indicated in Table 1. The annual rate of uptake by marine biota is a magnitude higher than in the terrestrial plants due to a much slower cycling in the latter. Flux by erosion is estimated between 19 and 30 Mt P annually. According to Smil (2000; 2007) erosion and runoff of phosphorus have increased by at least a factor 2 since the pre-industrial era. The one-directional flow of P towards the ocean can be inferred from the return flow of only 0.3 Mt P which returns to land with fisheries.

Table 1. Major global biospheric fluxes (Mt P year⁻¹) of phosphorus (Smil (2000) and Ruttenberg (2003)).

P-fluxes	Smil (2000)	Ruttenberg (2003)
Atmospheric deposition	3-4	3
Erosion and runoff	25-30	19-22
Plant uptake		
Terrestrial	70-100	71-200
Marine	900-1200	600-1100
Burial in marine sediments	20-35	8-9
Ocean to land (fisheries)		0.3
Minable P to land		12-14 ²

2.2 Reservoirs

Table 2 shows the biospheric P-reservoirs of the global P-cycle. The phosphorus content of the human population (3 Mt P), but also zoo mass (30-50 Mt P) and even phytomass (500-600 Mt P), is small compared to biota in the marine environment (93000 Mt P). For the total P-content of the earth's soil an amount of 50×10^3 Mt P is mentioned by Smil (2000) and $90 \times 10^3 - 200 \times 10^3$ by Liu *et al.* (2008). The latter mentions the amount of P stored in the ocean sediments ($27 \times 10^6 - 840 \times 10^6$ Mt P), far exceeding any other reservoir. The large amount of phosphorus in marine sediments illustrates that the global phosphorus cycle is only a cycle in the very long term: millions of years. In the past millennium and certainly in the last century there is a net flow to the oceans 'with minor interruptions owing to temporary absorption of a small fraction of the transiting element by biota' (Smil, 2000).

The transferred soluble and particulate P to the ocean eventually settles in the sediments. Recycling of these sediments depends on the slow reshaping of the earth's surface as the primary P cycle is dependent on the tectonic uplift. The circle closes after 10^7 to 10^8 years as the P-containing rocks are re-exposed to denudation.

² In 2008 already around 18 Mt P was used as fertilizer.

Table 2. Major biospheric reservoirs of phosphorus (sources: Ruttenberg (2003), Smil (2000), Jasinski (2008)).

P reservoir	Total storage (Mt P)	Reference
R1 Sediments (crustal rocks and soil > 60 cm deep and marine sediments)	800-4,000 * 10 ⁶	1
R2 Soils (0-50 cm)	40,000-50,000	2
Inorganic P	35,000-40,000	2
Organic P	5,000-10,000	2
R7 Minable P	2,400-6,600	3
Ocean	93,000	2
R4 Surface, 0-300 m (total dissolved P)	3000	1
R5 Deep sea, 300-3300 m (total dissolved P)	90,000	1
R3 Terrestrial phytomass	500-550	2
Zoomass	30-50	2
Anthropomass	3	2
R6 Marine phytomass	50-140	1
R8 Atmosphere	0.028	1

1= Ruttenberg, 2= Smil, 3= Jasinski.

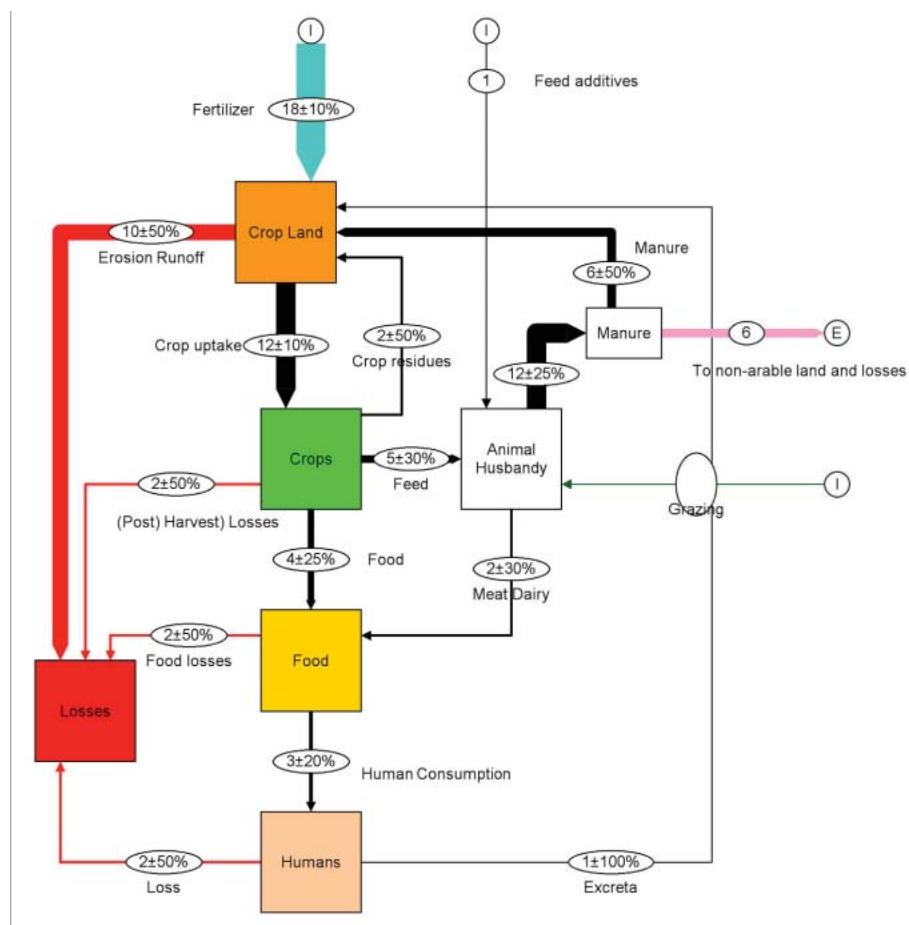


Figure 1. Representation of the major global P-flows in (I), out (E) and through the food production system on arable land (after Cordell (2008; 2009) and taking also into account data by Smil (2000, 2007), Liu et al. (2008) and own calculations.

3. Production and use of P-resources

3.1 P mining

Mined phosphorus deposits are mainly used for agricultural fertilizer (80%), the remainder is used for animal feed additions (5%), while 15% goes to industrial uses such as detergents (12%) and metal treatment and other industrial applications (3%) (Heffer *et al.*, 2006). The fraction used for detergents has decreased in recent years (now not more than 10%).

Resources

Estimated reserves of rock phosphate and production through mining are given in Table 3 (Jasinski, 2008). The reserve base is that part of an identified resource that meets specified minimum physical and chemical criteria related to current mining and production practices, including those for grade, quality, thickness, and depth. Reserves are 'that part of the reserve base which could be economically extracted or produced at the time of determination' (see for more information (USGS, 2009) . Reserve base *includes* therefore those resources that can currently be exploited economically (reserves), marginally economic (marginal reserves), and sub economic (sub economic reserves).

Table 3. Production and reserves of rock phosphate³ (in 1000 metric tons rock phosphate).

	Mine production		Reserves	Reserve base	Reserves (%)	Reserve base (%)
	2006	2007				
United States	30,100	29,700	1,200,000	3,400,000	6.7	6.8
Australia	2,300	2,200	77,000	1,200,000	0.4	2.4
Brazil	5,800	6,000	260,000	370,000	1.4	0.7
Canada	550	500	25,000	200,000	0.1	0.4
China	30,700	35,000	6,600,000	13,000,000	36.7	26.0
Egypt	2,200	2,300	100,000	760,000	0.6	1.5
Israel	2,950	3,000	180,000	800,000	1.0	1.6
Jordan	5,870	5,700	900,000	1,700,000	5.0	3.4
Morocco and W. Sahara	27,000	28,000	5,700,000	21,000,000	31.7	42.0
Russia	11,000	11,000	200,000	1,000,000	1.1	2.0
Senegal	600	800	50,000	160,000	0.3	0.3
South Africa	2,600	2,700	1,500,000	2,500,000	8.3	5.0
Syria	3,850	3,800	100,000	800,000	0.6	1.6
Togo	1,000	1,000	30,000	60,000	0.2	0.1
Tunisia	8,000	7,700	100,000	600,000	0.6	1.2
Other countries	7,740	8,000	890,000	2,200,000	4.9	4.4
World total (rounded)	142,000	147,000	18,000,000	50,000,000	100.0	100.0
In Mt of P ⁴	18.6	19.3	2400	6600		

³ Rock phosphate that is used as a feed stock for phosphoric acid or elemental phosphorus usually is referred to as marketable phosphate rock, regardless of whether it has been beneficiated. The generic term, phosphate rock, can refer to either igneous or sedimentary phosphate-bearing minerals used as an ore.

⁴ The reserve base is not standardized to 30% P₂O₅ but it would be a good estimate of the potential P₂O₅ that may be contained (Jasinski, pers. comm.).

According to Jasinski (2008) the data in Table 3 were derived from information received from government sources, individual companies, and independent sources. Reserve data for China were based on official government data and included deposits of low-grade ore. Production data for China do not include small 'artisanal' mines. Domestic reserve data were based on U.S. Geological Survey and individual company information.

China appears to be an important consumer and producer of phosphorus as well as an important resource location (25-40%). Striking is also the more than 10% increase in mine production in 2006, this increase alone means a 3% increase in the global production.

Phosphate rock resources occur principally as sedimentary marine phosphorites. The largest sedimentary deposits are found in northern Africa, China, the Middle East, and the United States. Significant igneous ('fire rocks': cooled magma) occurrences are found in Brazil, Canada, Russia, and South Africa. Large phosphate resources have been identified on the continental shelves and on seamounts in the Atlantic Ocean and the Pacific Ocean. High phosphate rock prices have renewed interest in exploiting offshore resources of Mexico and Namibia. Continental shelf reserves are not included in the reserve base, as those in the USA can not be economically recovered (Jasinski, pers. comm.). Also continental shelf resources in Mexico and Namibia are not included at this time. Stated resources in Namibia are 196 million tons, with an average grade of 13.4 to 18.1% P_2O_5 . According to the same source it is unlikely that new significant P deposits will be discovered. New projects for exploitation that have been discussed over the past year concern deposits that have already been identified in the past.

Products

The word phosphate rock is used in two ways

- 1) the apatite bearing rock with a content of P high enough to be used directly to make fertilizer or as a furnace charge to make elemental P
- 2) to designate a beneficiated apatite concentrate. *Beneficiation* of the rock phosphate removes much of the clay and other impurities, and raises the P_2O_5 content to 30 – 35%.

According to information from the Potash & Phosphate Institute (PPI, US) after beneficiation, the rock phosphate is finely ground. Although it can be applied directly as rock phosphate fertilizer, the P in it is slowly released and seldom benefits crops during the first two or three years after application. Direct uses of phosphate rock account for 1 Mt of P. Most of the rock phosphate is treated to make the P more soluble.

Fertilizer phosphates are classified as either *acid-treated* or *thermal-processed*. Acid-treated P is by far the most prevalent. Sulphuric and phosphoric acids are commonly used in producing acid-treated phosphate fertilizers.

Sulphuric acid is produced from elemental sulphur (S) or from sulphur dioxide. More than 60 percent of industrial sulphuric acid is used to produce fertilizers. Treating rock phosphate with concentrated sulphuric acid produces a mixture of *phosphoric acid* and *gypsum*. Filtration removes the gypsum, leaving 'green' or 'wet-process' phosphoric acid containing about 54% P_2O_5 . Wet-process acid can be further concentrated to form superphosphoric acid. In this process, water is driven off and molecules with two or more P atoms are formed. Such molecules are called polyphosphates.

Acid-Treated Fertilizer Materials are normal superphosphate, tripelsuperphosphate, ammoniumphosphate, ammoniumsuperphosphate and ammonium polyphosphate. *Thermal phosphoric acid* is produced by first producing elemental P through the reduction of phosphate rock with coke in an electric arc furnace. Elemental phosphorus is oxidized to P_2O_5 which is subsequently reacted with water to form furnace grade phosphoric acid (H_3PO_4). Thermal acid is much more pure than wet-process H_3PO_4 . Its use in fertilizer manufacture is sometimes preferred for the production of liquid fertilizers because of its purity.

Quality

Content and waste

The profitability of mining the deposits depends on factors such as ore grade, impurities, economic conditions, transportation planning. The content of impurities such as aluminum, iron, and magnesium are the most detrimental to processing phosphate rock into phosphoric acid. Marginal resources often contain higher amounts of these compounds and lower P_2O_5 content. The most accessible and higher quality rocks tend to be mined first (Isherwood (2000)); according to IFA statistics the average P_2O_5 content of the 125 Mt of phosphate rock mined in 1980 was 32.7%, whereas that of the 141 Mt mined in 1996 was 29.5%.

Phosphate ore contains Ca, Fe, Al, Mg, Si, Na, K, F and other impurities. Naturally occurring impurities in P-rock ore depend largely on the type of deposit (sedimentary or igneous), associated minerals and the extent of weathering. Major impurities can include organic matter, clay and other fines, siliceous material, carbonates, iron bearing minerals and heavy metals. The beneficiation produces large volumes of waste (Heffer *et al.* (2006).

Beneficiation is required to upgrade the quality and concentration; the P concentration in beneficiated rock phosphate ranges from 7-14% P (16-32% P_2O_5). It is then used for phosphoric acid production. During mining a considerable amount of solid waste is produced (waste and tailings). For phosphate it is also estimated that 33% is lost through mining and an additional 10% is lost in transportation and handling. The overall mining efficiency in China is estimated at only 49% in 2000 (Villalba *et al.*, 2008). We have not found data on the mining efficiency per country.

The *wet* process provides a potential source of fluorine that is not exploited and can cause environmental problems. In the wet process the end products are phosphoric acid and phosphogypsum (see Figure 1 in Villalba *et al.* (2008)). The gypsum byproduct is normally disposed of at sea or in ponds. Apart from the fluorine emissions, the gypsum byproduct from the wet process also presents a major problem.

Radioactivity

Known impurities of the phosphorus deposits include radioactivity. The main product of uranium decay is ^{226}Ra , the uranium is partitioned between phosphoric acid and the by-product phosphogypsum. The radioactivity has raised concern related to potential health hazards during the manufacturing and handling of the byproducts, final products and waste materials from phosphorus processing. Several processes have been developed for the extraction of uranium from P-acid, that are however costly and economic viability depends on the price of uranium.

Cadmium

Most phosphate rock processed for fertilizer use (roughly 85%) is derived from sedimentary rock while the remaining 15% originates from igneous deposits. In general sedimentary P-rock contains higher concentrations of potentially hazardous elements, such as cadmium, than igneous P rock. Concentration is several times higher than in igneous rock. Moreover, the cadmium content of sedimentary rock varies much more. In igneous rock average phosphate content is 38% P_2O_5 with 1.5 ppm Cd (0.5-5) whereas sedimentary rock with on average 32% P_2O_5 contain 21 ppm Cd, (0.5-150).

In the *wet* process phosphoric acid production, part of the Cd present in phosphate rock goes into the phosphogypsum waste. The way single superphosphate (SSP) is produced implies that all of the impurities in the phosphate rock, including Cd, are transferred to the SSP fertilizer. This holds also for the production of triple super phosphate (TSP). The level of Cd may be higher in triple than in super. Direct use of ground rock phosphate as a fertilizer means that all impurities will be input to agricultural land. Cadmium concentration varies considerably, also within countries. In the US phosphate rock from Florida (locations which are prone to be exhausted) has relative low contents (6-9 ppm Cd) whereas in Idaho and North Carolina, average Cd content is 92 and 38 ppm resp. In Morocco average Cd contents of 4 different locations varied between 15 and 38 ppm Cd (Heffer *et al.*, 2006)

For the removal of Cd there are two approaches i) before processing and ii) removal from phosphoric acid. For decadmiation of phosphoric acid, several processes are available such as co-crystallization with anhydrite, precipitation with sulphides, removal by ion exchange resins or liquid ion exchange, removal by solvent extraction and separation by membrane technology. Costs related to the separation of Cd from phosphoric acid are not well understood at present, however, the cost per ton of P_2O_5 using co-crystallization seems to be far less compared to the other methods mentioned (Heffer *et al.*, 2006). In 1998 (Steen, 1998) estimated that Cd removal could result in 2-10% higher phosphate fertilizer prices. Worldwide 130 Mt of phosphogypsum (with cadmium and radioactivity) per annum is produced, the disposal of the material is increasingly becoming a global issue. Management of phosphogypsum disposal is a costly process and reach up to 5€ per ton (as indicated by (Heffer *et al.*, 2006).

It is expected that in the not too distant future fertilizer manufacturers need to anticipate on not only a reduced supply but that also the quality of the resource will deteriorate (P-content, radioactivity, heavy metals). This will have its consequences for mining efficiency as well as waste disposal.

Geopolitics

It may appear from Table 3 that the resources of phosphate rock are found all over the world as in most continents important deposits are available. However, within a continent the total reserves are dominated by the reserves of a few countries and sometimes only one country (Figure 2).

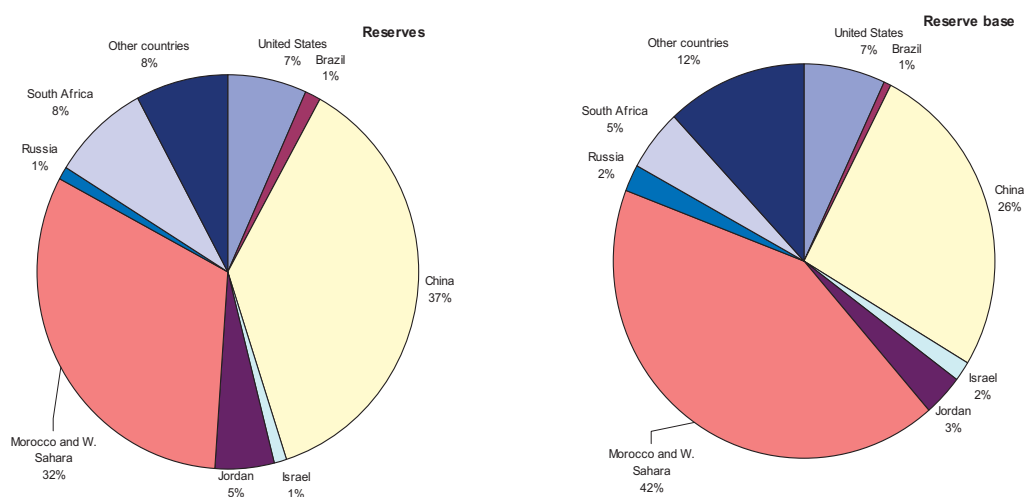


Figure 2. Major P-resource locations with respect to reserves (left) and reserve base (right).

The United States has the major part of the resources of North America, while the former Soviet Union is the sole European country. In the Middle East and Mediterranean area several countries with deposits are found, Morocco holds by far the most resources. In sub-Saharan Africa only South Africa has substantial deposits. The reserves of South America are dominated by Brazil. China has the major sources in Asia, and Australia of Oceania however the latter currently at a rather limited production (Anonymous, 1998).

Mining of phosphate rock is thus restricted to a few countries: Morocco (including West Sahara), the US (resources are depleted in a number of decades) and China (the country that has recently imposed an export tariff on phosphate rock to secure domestic supply).

The conclusion can be drawn that large part of the world, including Europe, India and Australia, are almost totally dependent on the import of phosphate from a limited number of countries. On top of that the import from Morocco

can raise concern because of the disputed mandate of Morocco in the West –Sahara. Importing phosphate rock from this location is condemned by the UN (www.phosphorusfutures.net).

3.2 Future demand for P

Current use of fertilizer P

Global

In Table 4 fertilizer global consumption in Mt y^{-1} is indicated for N, P en K_2O . When dividing the production/ consumption of P-fertilizer (Table 4) by the global area for crop land, currently estimated at 1.4 billion hectare, a fertilization rate of almost 13 kg P ha^{-1} is found. The table shows that in 4 years an increase in P-demand of 10% is foreseen.

Table 4. Global Fertilizer Consumption in Mt y^{-1} (Heffer and Prud'homme, 2008).

	2007	2008	2008 (kg ha^{-1})*	2012	Annual change over 2008**
N	99.4	102.9	74	114.9	+2.8%
P	17.6	17.8	13	19.8	+2.7%
K ₂ O	29.1	29.8	21	32.8	+2.4%

* use per ha cropland (currently estimated at 1.4 billion ha).

** based on estimates of future demand in 2008 and 2012.

Compared with the removal of 10-12 kg P with the average global yield of a wheat crop of 3400 kg ha^{-1} (FAOSTAT for 2007), the input of P with artificial fertilizer (additional to input with manure) is quite substantial. It illustrates how modern agriculture, triggered by an increasing population, has become dependent on P-fertilizer. In many regions P input with artificial fertilizer will be higher than the mentioned 13 kg P ha^{-1} because of the fact that millions of hectares on the continent of Africa are not receiving any phosphorus fertilization at all.

Table 5 shows that three countries China, India and the US already consume more than half of the global use of P fertilizer. Most (50%) of the fertilizer P is going to cereal crops (Heffer, (2008): wheat (18%, rice (13%), maize (13%) and other cereals (5%).

Table 5. Phosphate fertilizer use by country as a percentage global use (100% = 17.6 Mt P).

China	30%
India	15%
USA	11%
EU-15	7%
Brazil	8%
Pakistan	2.4%

Table 6. Characteristics of some continents (and N. America) with respect to area of arable land (including permanent crops), yield and area of total cereals, P-fertilizer consumption and rate (on arable land). P off-take with cereals is calculated assuming a content of 3.5kg P/t (FAO statistics 2005/6, the P-rate is calculated for total arable area including permanent crops (not just cereals).

Continent	Area Arable+	Total Cerals		P-fertilizer applied (Mt P)	Offtake Cereals (Mt P)	Cereal yield (t.ha ⁻¹)	Aver. P-rate (kg.ha ⁻¹)	Cereal P offtake (kg ha ⁻¹)	
	Perm. Crops (Mha)	Area (Mha)	Area (%)						Production (Mt)
Africa	239	105	44%	146	0.4	0.5	1.4	2	5
Asia	577	327	57%	1141	10.0	4.0	3.5	17	12
Europe	296	121	41%	395	1.8	1.4	3.3	6	11
N. America	229	78	34%	463	2.5	1.6	5.9	11	21
Oceania	55	19	35%	23	0.4	0.1	1.2	8	4
World	1562	700	45%	2342	17.2	8.2	3.3	11	12

Table 6 shows (FAO –statistics) for some regions the total available arable land (including permanent crops), the absolute and relative area of cereals, and the consumption of P-fertilizer (both absolute and on a hectare base). For cereals, worldwide the most important crop, also the P removed from the field was calculated. On the global scale more than twice the amount of P in the harvested cereal crop is applied as P fertilizer, with large differences between the continents.

The average rate for Africa is around 2 kg P ha⁻¹ but with a skewed distribution. Most countries have a fertilization rate of less than 1 kg P ha⁻¹ whereas a few countries (South Africa, Egypt, Kenya) have a large contribution to the average P-consumption.

In Africa P-off take with cereals is per hectare higher than the average P fertilizer rate, this is also the case for Europe and North America. However for Europe and North America an above average P-fertility level in addition to an abundant use of animal manure, both necessitating less P-fertilizer, might be the explanation whereas for Africa the figures indicate a depletion of the soil for phosphorus. Both Asia and Oceania show a high fertilization rate relative to off take with cereals.

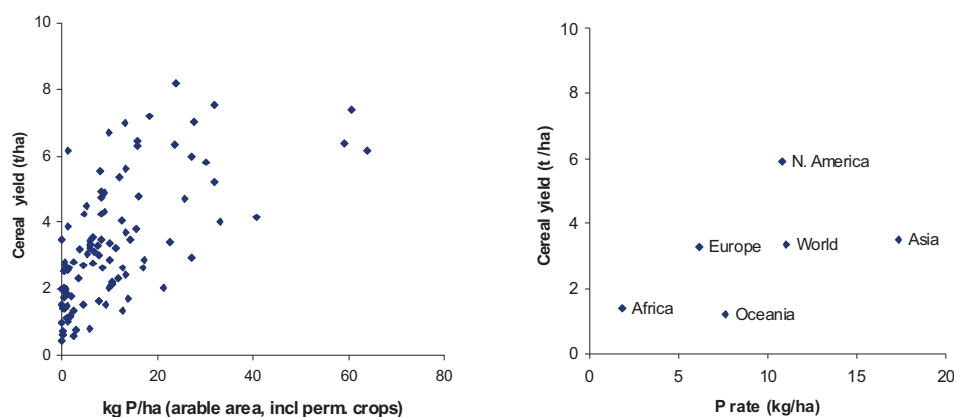


Figure 3. The relationship between average (national) P-fertilizer application rate and national cereal yield (average yield for countries producing more than 350kt cereals, left) and averaged for selected regions (right). Note: the effect of P-rate is very probably correlated with the nitrogen fertilizer application rate.

It is difficult to estimate the sole effect of phosphorus fertilization on food production. If nitrogen (or any other nutrient) is at minimum there will be no effect of a phosphorus fertilization. If on the other hand phosphorus is the limiting factor for growth (which is in many regions the case) also a nitrogen fertilization will have no effect (see e.g. Bindraban *et al.*, 2009b). Figure 3 is calculated on the basis of available FAO statistics. This figure gives on the left side the relationship between national fertilizer P-rates and national cereal yields (a selection is made for countries with a production > 350 kt) and on the right side the same relation but pooled for continents. However, as there will be a positive correlation between P and N fertilization rates in many countries, the whole positive effect on cereal yield cannot be attributed to phosphorus alone. Vice versa in many regions the potential positive effect of nitrogen fertilization would not occur without a phosphorus fertilization.

EU27

For the European Union (EU27 countries) Richards and Dawson (2008) recently made a phosphorus balance. They calculated that net import of P fertilizer/rock phosphate by the EU27 amounted to 1.3 Mt P, total net import in the EU27 was 1.6Mt of P this figure included 0.3 Mt P imported as feed additives.

P enters the EU in imported crop products such as soybean, oil cakes for food and feed, whereas P is exported mostly in cereals and cereal products. Net import with crop products was estimated at 0.052 Mt P and with food and feed products at 0.137 Mt.

When taken into account all imports and exports (consumables, textiles, metals etc. etc.) total net import of phosphorus in the EU27 was estimated at 1.83 Mt P in 2006. The EU27 appears to be a significant sink for traded phosphorus. Fertilizers and their raw materials dominated with 72% of net imports of traded material. When taking into account internal additions, uptake from soils, immigration, deposition and subtractions by application to soil and discharge to sea, the net addition reduced to around 0.85 Mt P. Total sequestration of phosphorus in durable structures and products was estimated to be around 0.6 Mt P, so after sequestration the balance was estimated at 0.24 Mt P.

When calculating a balance for *agricultural soil* in the EU27, the authors estimated the total application of P in manures to be 2.06 Mt of P. In addition fertilizer around 1.3 Mt (already mentioned above) and 0.23 Mt of P from other sources was applied. All this would amount to 18 kg P ha⁻¹ as agricultural area was estimated at almost 200 Mha. Offtake by crops, livestock etc. was estimated at around 10 kg P/ha, therefore the average net balance for agricultural soil in the EU27 is around 8 kg P ha⁻¹ (surplus). The data from Richards and Dawson (2008) confirm that the EU in order to maintain the soil P-fertility is dependent from resources outside the EU (either from (raw) fertilizer material or from feed).

NL

For the Netherlands the main figures with respect to the agricultural soil phosphorus balance were in 2005 (source: CBS):

Fertilizer consumption:	0.021 Mt P
Net import with crop products for feed (e.g. soybean)	0.051 Mt P
Imported P feed additives	0.006 Mt P

Animal manure produced in the NL contains approximately 0.065Mt of P, with additional fertilizer etc. total input is much higher than taken of by harvested crops, livestock etc. It leads to an accumulation of more than 20 kg P ha⁻¹ year⁻¹ for agricultural soils in 2005, far exceeding the average accumulation of P for the EU27 as indicated above. Since 1950 the strong increase in landless intensive livestock (esp. pigs and poultry) combined with imported feed (35% grain, 35% byproducts from oil seeds like soybean etc. and the rest citrus pulp, tapioca etc.) an accumulation of P in soils at an average rate of 36 kg P ha⁻¹ year⁻¹ took place, cumulating to 2000 kg P ha⁻¹ during this period of time (CBS-data). Even so, P-fertilizer is used in the Netherlands at an average rate of 10 kg P ha⁻¹ (arable and grassland).

Like the EU27 the Netherlands is dependent for crop production (food and feed) on import of P from outside Europe. However, different from the rest of Europe, in the Netherlands four times as much P is net imported with feed and P-additives than with fertilizer while the reverse is true for the EU27.

Although a large amount of phosphorus is stored in the Dutch soils, the following aspects are relevant when considering dependency, vulnerability or the impact of calamities with respect to agricultural activities:

- Even within the Netherlands, accumulation is localized, concentrated in the southern part of the Netherland with intensive livestock, but to a lesser extent and at farm level dairy farms also accumulate phosphorus in the rest of the country.
- A reduced input of P (fertilizer/manure) can, despite the current high P-fertility status, lead to lower yields. Current Dutch fertilization recommendations suggest that this will be especially the case for short growing vegetables.
- Producing feed in the EU in stead of importing from outside the EU will have consequences for :
 - the demand of P-fertilizer
 - the current surplus of P (but not necessarily lowering it)
 - land use (pulses shall compete with current crops)
 - quality of the feed, e.g. the N/P ratio differs between pulses and soy.
 - These aspects will have to be elaborated further in combination or as follow up with other studies, e.g. Bindraban *et al.* (2009c)

Trends in demand for P fertilizer

Next to the growing world population and the increasing meat, milk en egg consumption in the world (necessitating a larger feed volume) also the growing demand for *bioenergy crops* affects the future P-use, in particular when grown on additional marginal land with a low P-fertility status.

Recently Heffer and Prud'homme (2008) mentioned some of the trends which can influence the consumption of fertilizer and will have to be anticipated on, some of them being related to bioenergy:

- a large maize area replacing other crops in the USA
- more soybean, sugar cane and maize in Brazil
- more soybean and cereals in Argentina
- the end of the set-aside of agricultural land in the EU
- more cereals, oilseeds and sugar beet in the Commonwealth of independent states
- more cash crops in India
- more maize , fruits and vegetables and less wheat and rice in China
- more oil palm in Indonesia and Malaysia
- increasing areas in Argentina, Brazil, Indonesia, Malaysia, Russia and Ukraine

Also the higher demand in recent years is seen owing to higher commodity prices, and to policies promoting fertilizer use in many Asian countries. Fertilizer demand was especially strong in Latin America (+12.8%), Eastern Europe and Central Asia (+6.3%), East Asia (+6.1%) and South Asia (+3.4%).

Drivers responsible for the increase in P demand are therefore the increased production of biofuels together with the world population increase and average income growth in emerging Asia. Heffer and Prud'homme (2008) suggest that the impact of biofuel production on world fertilizer demand is mostly *indirect* through its influence on international cereal, oilseed and sugar prices, which provide strong incentives for increasing fertilizer application rates on crops grown for food or feed. In June 2008 they predicted *short* term growth in demand to be stronger for nitrogen (+3.6%) than for phosphate (+2.7% and potash (2.2%). Consumption growth would be modest in Western and Central Europe, in all the other regions demand would be up by 3-4%.

For the *medium* term a steadily growth is projected. In 2012/13 global demand is perceived to increase by 3.1% annually, also here nitrogen demand would be rising slightly faster (+3.2% p.a.) than consumption of potash (+3% p.a.) and phosphate (+2.8%)

Duration of resources

First estimates using annual growth percentage in demand

Guano (bird droppings) was first used as a source to compensate for the P off-take with crops. These resources were exhausted in about 35 years. A first estimate of the duration of current resources (rock phosphate) to be depleted is simply by using the data of Table 3 and assuming a yearly growth percentage for current consumption of P. Table 7 shows the number of years presented at growth rates of 0, 1, 2 and 3% being in the range of the current growth rates of 2-3%. At a growth percentage of 2%, even the reserve base which includes resources not economically minable at this moment, is depleted in 100 years. While this approach is commonly used to arrive at a first indication for the duration of depletion, the assumption of a fixed yearly growth (= continuous exponential growth!) is questionable.

If population growth would be 2% annually, a world population of 15 billion would be reached in 2050, while 1% growth arrives at a more realistic estimate of about 10 billion people. A growth of 0.7% would result in a population of 9.2 billion people in 2050 (this number is conform the medium variant as indicated at <http://esa.un.org/unpp/>). Continuous exponential growth for estimating developments in the long term appears, therefore, not realistic, and is probably the main reason why the predictions of the Club of Rome (Meadows, 1972) did not materialize for several resources. Therefore we made a modification to this methodology by assuming an exponential growth percentage until 2050, as population growth is then assumed to level off. In this way phosphorus consumption will keep pace with the growth of the world's population. Hereafter, the consumption of phosphorus is kept constant, i.e. assuming a growth percentage of 0%. Now reserves would be depleted in 70-100 years and the reserve base in between 170 and 264 years (Table 7). Of course growth of population and growth of P demand do not necessarily have to coincide, P demand until 2050 could increase faster than population growth due to changing diets etc. The table just gives an indication of the timeframe.

Table 7. First estimates of duration in years of the resources at various growth percentages in P-consumption (Table 4) and resources as in Table 3

Source	Growth %				Growth until 2050 (afterwards 0%)		
	0	1%	2%	3%	0.70%	1%	2%
Reserve	125	80	60	50	100	91	69
Reserve base	340	150	100	80	264	237	167

Earlier estimates of the duration of phosphate rock, were presented by Günter (1997). In 1976 one of his references calculated the duration of depletion between 249 and 714 years. Other authors at later dates reported durations of depletion between 120 and 154 years. Major differences in these predictions basically result from differences in assumptions related to the economically exploitable reserves. In 1998 when annual global production of P was around 17 Mt P, including 14 Mt of P for fertilizer, the global reserves were estimated at 3600-8000 Mt P₂O₅ whereas the potential reserves were estimated at 11-22000 Mt P₂O₅ (Steen, 1998). Her assumptions (population growth, changing diets) resulted in the estimate of a final annual consumption rate of around 31 Mt of P. She concluded that depletion of current economically exploitable reserves can be estimated at about 60-130 years and that phosphate reserves would last for at least over a 100 years.

In the Fertilizer Manual (Anonymous, 1998) other estimates of the duration of depletion have been reported. Herring and Fantel (cit.) considered in 1993 various scenario's of unconstrained growth with no future additions to reserves. They indicated that world reserves will be depleted in about 50 years from 1990, and additional resources, i.e. a modified reserve base that may or may not be economically minable, would be depleted in perhaps another 50 years. It is unclear whether the cited references take account of *mining losses* in their calculations. This could imply that the duration of the resources is substantially shorter than indicated

Effect of increasing global population and urbanization

In predicting the growth of the world population and the consequential food requirement (Rosegrant *et al.*, 2001), P is not considered in the analysis, despite the fact that P-fertilizer is an essential resource for food production. The predictions assume implicitly an ample supply of phosphorus as is currently the case. This might not be true for the mid-term and long term. Also in the short term undesired changes can occur because supply is dependent on a few countries only, which implies that political instability/war or unrest might interfere with supply.

Estimates of population growth made by the United Nations mostly rely on assumptions about demographic factors like mortality/fertility rate, international migration and the spread of diseases such as AIDS. For the year 2050, for a medium and high variant, a world population of respectively 9 and 11 billion people is foreseen (Anonymous, 2007). Compared with the current 6.8 billion people this is an increase of 30-50%. The implication could be that global phosphorus consumption must increase with at least the same percentages, assuming that the efficiency of P-fertilization will remain the same. And yet not taking into account changing diets (more meat, vegetables, dairy and eggs), increased bioenergy crops etc.. These aspects will be considered separately in the following paragraphs.

Another trend in global development that will also affect consumption of phosphorus is the increasing *urbanization* because this is associated with a lower recycling of human waste. According to Liu *et al.* (2005) the application of human waste is common in Asia and (was common) in Europe but less prevalent elsewhere. In urban areas human waste is less recycled than in rural areas. In China the percentage recycling of human waste for agricultural purposes from urban areas dramatically decreased from 90% in 1980 to less than 30% in the late 1990s. In 1990 in rural areas about 94% was returned to crop land. It is estimated that in Europe the recycling rate of urban sewage averaged about 50% over the 1990s. Liu, *et al.* (2005) assumed that globally about 20% of urban human waste and about 70% of rural waste are recycled at present, amounting to 1.5 Mt P annually. This might be too optimistic as according to Cordell (2008) only 0.3 Mt P returns to crop land.

In addition urbanization generally occupies intensively managed soils with a good P status and may require reclamation of soils with a low P status, needing a P investment.

Until now the trend of urbanization means less recycling, however it can be argued that here also opportunities become apparent. A concentration of phosphorus in urban areas could also improve the possibilities to collect. Standard sanitation in urban areas usually implies that human excreta are vastly diluted with water which makes recycling more difficult (apart from the aspect of contamination with pharmaceuticals, heavy metals etc..). However, in the Netherlands by various precipitation methods nearly all the P originating from households ends up in the sewage sludge. This gives feasible possibilities for recovery, even after incineration, as new technologies are emerging (referring to the EU-project SUSAN (www.susan.bam.de) and see also chapter 4; (W. Schipper, Thermphos pers. comm)).

Effect of changing diets

Increased production of feed

World wide around 30% of the cereals is used as cattle feed (Steinfeld *et al.*, 2006), in Europe this is 60%.

A changing diet towards more meat consumption in the developing countries will therefore translate in an increasing demand for cereals. According to the data as published in Rosegrant *et al.* (2001) in 2020 an additional 650 Mt of cereals will be produced, of which only 15% in developed countries. This would require an *additional* input of minimal 1.95 Mt of fertilizer P just to compensate for the removal from the field with the harvested cereals (assuming a P content of 0.3%). This additional P approximates more than 10% of the current world use of fertilizer P.

Table 8. Global production of cereals in 1997 and 2020 in Mt (Rosegrant *et al.*, 2001).

	1997	2020
Developed countries	725	822
Developing countries	1118	1675
World	1843	2497

For soybeans a similar calculation can be made. A recent prognosis (ABIOVE,2005) shows an increase in global soybean volumes from 235 to 307 Mt in 2020. In Brazil production of 57 Mt of soybean on 21 Mha in 2007 will increase to 108 Mt in 2020⁵. On average P-fertilization in Brazil on soybean is 28 kg P ha⁻¹ whereas 25 kg ha⁻¹ is removed with the crop. The implication is that in 2020 at least 0.8 Mt of P must be the input to meet the prognosis. This amount of fertilizer will then be at least 4.5% of the current global use of fertilizer P, a substantial amount for one crop in one country.

More meat in the diets

Retention of P in the human body is limited (Liu *et al.*, 2008), so P consumption by man can be calculated from data on the amount and composition of human excrements or from data on diets. According to the first method, estimates of excretion range from 0.5 kg P per capita per year (Smil, 2000; Liu *et al.*, 2008) to 1.2 kg P per capita per year (Kirchmann and Pettersson, 1995). As indicated, P consumption can also be approximated by combining diet compositions (<http://faostat.fao.org>) and the P concentration of the constituents (Beukeboom, 1996). According to this method average excretion in 2003 would have been 1.0 kg P per capita per year, ranging from 0.9 kg P in less developed countries to 1.4 kg P in developed countries (Table 9). These differences appear to result from the more affluent diets in modern societies in which P in dairy, eggs and meat represents 50% of the total P consumption compared to 23% in less developed countries. Global P consumption and excretion according to these calculations would be 6.52 MMT P per year. This intake is far above the consensus of around 3 Mt P global excretion (e.g. see Figure 1)

Table 9. Apparent annual human consumption of P (kg P per capita per year) in 2003 through the dietary constituents in developed and less developed countries (if based on production data from: <http://faostat.fao.org>; P-contents after Beukeboom, 1996).

Constituent	Developed countries	Less developed countries
Cereals, potatoes, vegetables	0.55	0.62
Milk, butter, cheese, eggs	0.26	0.07
Meat	0.44	0.15
Fish	0.15	0.11
Total	1.39	0.94

An explanation could be that P concentrations in Beukeboom (1996) may not apply to crops grown on soils with a low P status. The discrepancy may arise also from the fact that FAO estimates are based on harvested amounts which will be (much) higher than the amounts processed, marketed and eventually eaten. Losses are substantial in developed as well as in developing countries. Whereas in developing countries losses are mainly in the trajectory field to consumption, the losses in developed countries may be substantial in the retail or household area.

⁵ E.g. <http://www.nets.iwr.usace.army.mil/docs/LongTermForecastCommodity/ACE061804final.pdf>

Because of this discrepancy we used the relative ratio between P-intake in developed and developing countries and calculated that a P-intake for humans at resp. 0,64 and 0,43 kg capita⁻¹year⁻¹ ha⁻¹ would lead in 2003 to a global intake of 3 Mt of P (Table 10). As the global use of P-fertilizer in that same year was around 16 Mt of P, a ratio of fertilizer use to consumption of 5.4 can be derived. Assuming the same ratio for 2020, a world population of 7.7 billion people (<http://esa.un.org>) would, without change in diets, raises the need for P fertilizer input to about 19 Mt P, an increase of nearly 20%. If on the other hand, people in developing countries would by then have the same P intake as in the developed countries, then the demand for fertilizer P would raise to nearly 27 Mt; an increase of 64%. For 2050 with a global population of 9 billion people P demand would raise 40 and 96% respectively for current and affluent diets.

The table also shows the anticipated fertilizer use when a more favorable ratio of 4.3 would be attained instead of 5.4. Such a decrease in ratio has a large impact on P-demand, but implies large changes in the way P fertilizer is used as well as an improvement of the way organic wastes, including manure, are recycled.

Table 10. Anticipated global P fertilizer use in 2020 (in Mt P and relative to the use in 2003), as function of diets and the ratio between P-consumption and P fertilizer use.

Year	Population (10 ⁹)			Diet	P -cons. (kg/capita/y)		Total glob cons. (Mt P)	Ratio Cons./Fert. use	(Anticipated)	
	Developed countries	Devel- oping	Total		Developed countries	Develop- ing			Fertilizer P-use	Relative
2003	1.21	5.15	6.36	current	0.64	0.43	3.0	5.4	16.24	100%
2020	1.27	6.41	7.68	current	0.64	0.43	3.6	4.3	15.5	96%
				affluent	0.64	0.64	4.9	4.3	21.4	132%
2020	1.27	6.41	7.68	affluent	0.64	0.64	4.9	5.4	26.7	164%
								4.3	18.3	113%
2050	1.28	7.87	9.15	current	0.64	0.43	4.2	4.3	18.3	113%
				affluent	0.64	0.64	5.9	4.3	25.4	157%
2050	1.28	7.87	9.15	affluent	0.64	0.64	5.9	5.4	31.8	196%
								4.3	22.8	141%

Effect of bioenergy crops

Biofuel/energy production has been increasing rapidly over the past few years. Decision makers in the USA and in the European Union (EU) have recently adopted new policies on renewable energy sources. These policies set new mandatory blending targets for biofuels that are more ambitious than previous ones. Next to biofuels, also unprocessed (raw) biomass can be used to produce electricity and heat and is seen as another source to supply renewable energy to the world. Heffer and Prud'homme (2008) estimated fertilizer use for growing biofuel crops in 2007/8. From their graph the total fertilizer P requirement can be derived at around 0.34 Mt of P (Table 11).

Table 11. Global P use on Biofuel crops in 2007/08 (derived from a graph in Heffer and Prud'homme (2008)).

Destination	Mt of P
USA maize for ethanol	0.24
Brazil, cane for ethanol	0.05
EU, rapeseed for biodiesel	0.01
Other	0.04
Total	0.34

Scenario analyses project that a large part of this biomass will be sourced directly from energy crops, i.e. crops that are purposely grown for energy production. Also these crops need phosphorus for yield formation, and with the harvested biomass phosphorus is removed. Compensation for the off-take is minimally required to maintain soil fertility at the same level.

When assuming that in 2020 10% of the world's transport fuels (= around 9 EJ) is produced with biofuels and that a mix of 1st generation biofuels crops is used (wheat, sugar beet, sugar cane, maize, rapeseed, palm, soybean, miscanthus (Bindraban *et al.*, 2009a) then roughly 2.7 Mt of P will be removed from the agricultural fields by crop harvest, which translates into 0.3 kg P per GJ of biofuel.

If additionally 10% of the global energy consumption (10% will be around 68 EJ in 2020), will be supplied by biomass for use in the power and heat sector, then another 2.3 Mt of P is removed by harvesting (this will require 0.033 kg P/GJ combustion energy). In comparison to transport fuels the P demand is lower, because (woody) biomass contains much lower amounts of P. Together 5 Mt of P is contained in the biomass used for both the bioenergy (heat and electricity) and biofuel scenario.

Smeets and Faaij (2006) also studied the future demand of fertilizer in relation to biofuels/bioenergy. They calculated scenarios in which the future use of bioenergy (derived from woody bioenergy crops) varied from 50 EJ year⁻¹ to even more than 400 EJ year⁻¹ in 2050 (combustion energy). Although they did a prognosis on total fertilizer demand (N, P, K) it can be derived from their data that an increase in P-fertilizer use can be expected of up to 1.2 Mt P in 2020 and of 0.9-3.6 Mt P in 2050, depending on the scenario applied

Bio energy in general can increase the demand for artificial P in the future but it strongly depends on whether the phosphorus left in residues (ashes, organic material etc.) can be recycled back to the sites of production. Producing biodiesel probably leaves more room for recycling than the production of heat and electricity with (woody) bioenergy crops.

Aquaculture

The rapidly increasing aquacultural production of seaweeds and fish (Einarsson and Emerson, 2009), may also require additional phosphorus. In addition to that it is proposed that algae species with a high oil content can be used for energy production (Chisti, 2007). Following the same calculation procedure as this author, an oil content of algae of 50% and a P-content of 0.6% (dry mass fraction) would result in a factor of 0.36 kg P/GJ energy from algae.

If 10% of the global transport fuel is to be replaced (approximately 9 EJ), it would need at least the amount of 3.3 Mt of fertilizer P (around 20% of the current global use). Recycling of P in residues is then important.

If, after extraction of the oil content, the residue cannot be re-used as input in the production process the demand for artificial fertilizer will be permanent. In addition, it will also be crucial whether the residue can be recycled for agricultural purposes (feed, organic fertilizer etc.). As with bioenergy and biofuel crops the degree of recycling is a key-issue with respect to prognosis of future demand of fertilizer P.

Pooled estimate for future demand

In Table 3 it is calculated that the currently economically exploitable resources will be depleted within 125 years with today's consumption. However, according to the same table, China increased its production of phosphate by 10% in 2007 and also in 2008. Table 7 shows that when P-consumption keeps pace with the expected global population the currently estimated economically minable P-resources will be depleted within 70-100 years.

In addition to the effect of an increasing global population *per se* the effect of a more affluent diet and the use of biomass for energy purposes can lead to an increased consumption of P. Table 12 gives a summary for two basic

assumptions with respect to i) the ratio between fertilizer P and food P intake and ii) the extent of recycling P in the produced biomass. Considering the amount of P involved, both the ratio and the recycling will have to be improved.

Table 12. Summary of current and anticipated additional use of fertilizer P as influenced by efficiency and recycling (see also Table 10).

Import and use of P (Mt/y)	Global	EU27	NL
P use in fertilizer	19.3	1.3	0.021
Net import with feed additives, crops, feed	-	0.5	0.051

Extra demand for fertilizer P (in Mt P)	Global demand	
	A ¹	B
2020: 7.7 billion people	+3.2	-0.7
2020: + developing world adopts western diet	+10.5	+5.2
2050: 9.2 billion people	+ 6.6	+2.0
2050: + developing world adopts western diet	+15.6	+9.2
10% of transport fuel by biofuel crops	+2.7	+0.5
10% of global energy by bioenergy crops	+2.3	+1.2
10% of transport fuel by algae	+3.3	+0.7

¹ Scenario A: Assuming the current conversion fertilizer P to food P (factor 5.4) (see also Table 10)
 Scenario B: Assuming P fertilizer /P food of 4.3; and recycling of P in biofuel crops, bioenergy crops, and algae of resp. 80%, 50% and 80%

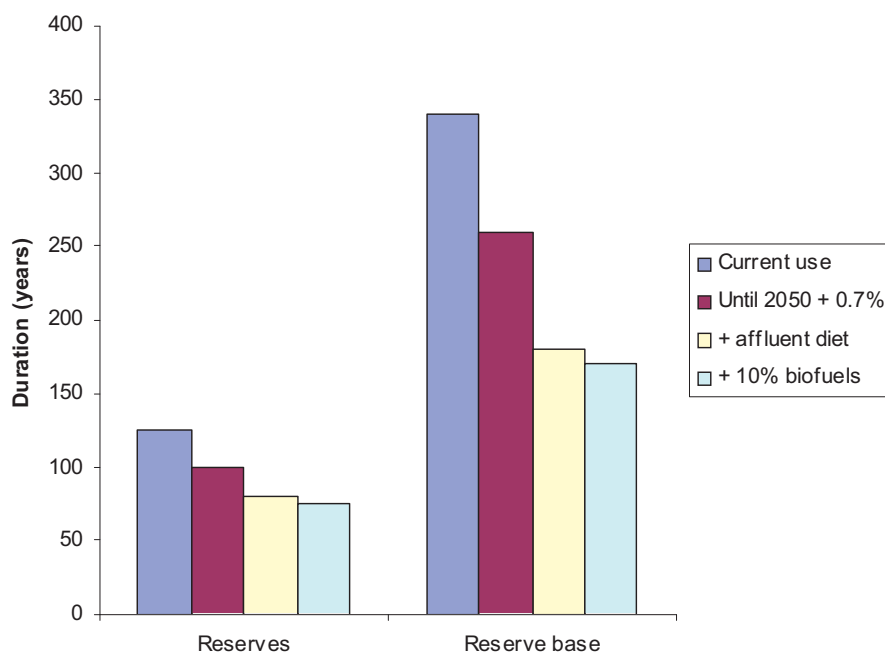


Figure 4. Duration of reserves and reserve base as the cumulated effect of current use, growth of 0.7% until 2050 (see Table 7), an affluent diet (see Table 10 and Table 12) and the effect of using biofuels (Table 12).

What will be the effect of increased fertilizer P consumption *on the duration* of the known reserves? In Table 7 it was indicated that with the *current* P use, reserves and reserve base would last for 125 and 340 years resp.

Figure 4 gives an indication of the cumulating effect of the increase in world population, diet changes and using bio-fuels for 10% of the global transport. It is assumed that P-demand and population will increase both with 0.7% (see Table 7) until 2050 and then remain constant. From 2050 onwards, the effect of a more affluent diet as well as the use of biofuels is taken into account. The combined effect leads to an exhaustion of the reserves in 75 years and the reserve base in 170 years from today.

3.3 Losses in the P-cycle

Considering that P-resources are finite as well as important for food production there is every reason to consider in more detail the global P-cycle to find out whether the available resources are used efficiently and to what extent losses could be avoided. Taking into account that the global amount of P-fertilizer (17-20 Mt of P) far exceeds the amount that eventually ends up in food consumed by the human population (3 Mt of P) the major losses in the global cycle will be discussed.

Losses during mining, by erosion, runoff and leaching are not solely responsible for the fact that global use of P-fertilizer largely exceeds the amount of P in our food. There are several factors that contribute to this apparently inefficient use of fertilizer P:

Mining losses

First loss already occurs during mining of the deposits where losses occur in a range from 30-50% (Villalba *et al.*, 2008; Zhang *et al.*, 2008) Identifying the nature of these losses and options to diminish them seems vital as a first step to prolong the duration of the known resources, and also concerning the environmental problems caused by the waste products of the mining process.

Erosion

From the global P-cycle as described the conclusion was drawn that a major flow of P (25-30 Mt P (Smil, 2000) or 19-22 Mt P (Ruttenberg, 2004)) ends up annually in the ocean sediments, with current technology this cannot be recovered. These data are from a few references and verification seems to be appropriate, especially in to what extent agricultural activities are the main cause for erosion. In general anthropogenic (agricultural) activities play an important role.

Although the transfer to the oceans could be considered as the result of natural processes (erosion and run-off) it is however accelerated by human activities such as arable agriculture, concentrated animal husbandry and direct anthropogenic discharges. Smil estimated that the loss through erosion nowadays is twice as high as in the pre-industrial era, i.e around 1800 (Smil, 2000; Smil, 2007).

Well managed grasslands and forests have less soil erosion due to the protective influence of permanent canopy, litter layer and rooting which are however lost when soil is taken in production for arable crops. Current estimates of P-losses by erosion amount to 10 kg P ha⁻¹ totaling 15 Mt P globally per year from crop fields. Additional erosion from *overgrazed* pastures and undisturbed land is estimated by Smil annually at 15 Mt P. Total loss of P by erosion amounts therefore up to 30 Mt P year⁻¹ (Table 1). Compton *et al.* (2000) arrive at comparable estimates of annual P-losses from the lithosphere into freshwater at 19-31 Mt P year⁻¹. Not all of the eroding P reaches the ocean, this is estimated by these authors at 12-21 Mt P year⁻¹. Losses by erosion therefore seems to be globally an important flux, but it must be kept in mind that the number of references quantifying this flux, especially the agricultural part of it, is small.

Depending on crop type more erosion and loss of P will occur when natural vegetation is replaced by annual bio-energy crops. According to Pimentel and Kounang (1998) and Pimentel (2006) each year 75 billion tons of soil are

eroded. They mention that most agricultural lands are losing soil at rates from 13 t to 40 t ha⁻¹ year⁻¹. Each ton of fertile soil contains about 1 – 3 kg of phosphorus (this seems however an overestimation, our data suggest 0.5 – 1 kg of P per ton soil to be more realistic) and that conversion of rangelands into arable land will increase erosion considerably. In the USA, for instance, erosion rates in some cases increased 200 times as the amount of ground cover decreased (with rates up to 20 t ha⁻¹ year⁻¹). The references above mention a worldwide erosion on cropland to be around 30 t ha⁻¹. As a result about 30% of the worlds arable land has become unproductive and has been abandoned. Lowest erosion rates are found in US and Europe but are on average about 13 t ha⁻¹. Erosion rates are highest in agro production systems in Asia, Africa and South America. Also for pastures in the USA a rate of about 6 t ha⁻¹ is mentioned but much more if overgrazed (Pimentel and Kounang (1998)) . In forest lands stable erosions rates are as low as 0.05 t ha⁻¹ year⁻¹.

Considering the above, the implication is that P-offtake and fertilizer use is only one aspect with respect to the future phosphorus demand. It is due to be overshadowed by the effect of crops (at least the non-perennial crops) on worldwide erosion. The effect of erosion and runoff is not only that P is eventually lost for agriculture but also, if the land is not abandoned after all, that fertility levels have to be restored. In such a situation usually much more phosphorus is needed than just to compensate off-take.

The P- balance on crop land and fertilization

Despite the fact that input of fertilizer P for food production is high compared to P ending up eventually in food, the P-balance for global crop land (Table 13) is negative or only slightly positive (Smil, 2000; Liu *et al.*, 2008).

At the global scale accumulation and losses/depletion are balanced by the application of P-fertilizers. This, however, is certainly not the case on a more regional scale. Deviations from the average seem to be mainly attributed to erosion and to the fact that in certain regions P is accumulating (NL, US) and in other areas the soil is depleted, e.g. in Africa (Smaling *et al.*, 1993; Stoorvogel *et al.*, 1993).

Table 13. Phosphorus budgets for the worlds cropland (after Smil (2000) and Liu *et al.* (2008)).

Flows	Annual fluxes in Mt P per year	
	Smil (2000)	Liu <i>et al.</i> (2008)
	Reference mid-1990s	Reference 2004
Inputs	24-29	23
• Weathering	2	1.6
• Atmos.deposition	1-2	0.4
• Org. recycling	7-10	6.2
• Crop residues	1-2	2.2
• Animal manure	6-8	2.5
• Human waste	?	1.5
• Fertilizers	14-15	14.7
Removals	11-12	12.7
• Crops	8-9	8.2
• Crops residues	3	4.5
Losses	13-15	19.8
• Erosion		19.3
• Runoff		0.5
Balance	0-2	-9.6

Accumulation of phosphorus on crop land occurs because of the fact that livestock in a specific region produces more manure than the surrounding crop land should accept for good agricultural practices. Another reason for accumulation is that application rates of phosphorus (either with manure or with fertilizer) often exceeds removal by the crop in order to bring the P-status of the soil at a higher level. In some regions phosphate fixation also increases the P rates.

In comparison to nitrogen for phosphorus the relationship between off take and fertilization (or crop demand) is less straightforward and depends on the P-fertility level of the soil. At low fertilities much more, and at high fertility less than off take is needed as fertilization. This is due to the P-fixing or P-adsorbing properties of the soil. Phosphate anions in soil solution may be rapidly immobilized in the soil through precipitation and adsorption reactions, resulting in forms of phosphorus that are unavailable to plants. Especially in the past the observed (short term) low recovery of P-fertilizer was balanced with high application rates.

Fertilizer rates have been determined empirically as doses-response curves. In general this led in the developed world to rates *exceeding off take* and hence to *accumulation* of phosphorus in soil into a low available or unavailable pool. Usually recommended P rates are (much) higher than the off take at low P soils, in this case fertilization is done also to improve the P-status.

In the past it has been often found that the recoveries of P-fertilizer (the part of the P-fertilization which is taken up by the crop) were low. This has led to a preoccupation about the fixing characteristic of P in soils. According to Syers et al (2008) it caused an abundant use of phosphorus fertilizer in the past. However, analyzing data from long term field experiments they made clear that P not taken up in the first year is not *irreversibly* fixed in the soil and can become available later on. In the long term a recovery as high as 90% has been observed in some situations

Crop characteristics such as rooting pattern and length of growth period play an important role in this respect. Cornish (2009) signals a new attitude by considering soils not as P-deficient but as soils containing significant 'potentially available P', to emphasize that soluble fertilizers are expensive, that some of the plant P requirement can be drawn from soil P reserves and that high productivity demanding high P inputs increases environmental risks.

In this context it is important to know at which point a P-fertility level of the soil is adequate and at which level yield depressions can occur. In a recent review of recommendation strategies for P-fertilizer Römer (2009) concluded that 70-80% of the area in European countries has an average or high level P-status. He concluded that at these locations it would be possible to maintain yields even without P-fertilization and that fertilization does not bring a yield increase. In Germany, as in most other countries, a recommended range of soil fertility is in use. Usually the P-fertility of the soil is assessed by extraction with weak acids or water, giving an indication of the amount of plant available phosphorus. Römer concluded that *within* this recommended range, to bring the soil from the lowest to the highest recommended fertility level, already 500 kg P ha⁻¹ was needed, an amount taken off by crops in around 20 years. To arrive at a more efficient use of fertilizer P he suggested a critical revision of the recommendation system.

Human excreta

The recycling of human waste (containing globally 3-3.5 Mt P year⁻¹) to crop land is diminishing and is estimated globally at 50% (Liu *et al.*, 2008) or at 10% (Cordell *et al.*, 2009). Reuse of P in human excreta would decrease more and more if the current sanitation technology of the western world is adopted by developing countries. More households connected to a sewer system will lead to increased losses towards the oceans sediments. It calls for either new sanitation methods to facilitate reuse of human excreta directly in agriculture or for the development of technology to precipitate P in such a way that recovery in the resulting sewage sludge or ashes is possible.

In the Netherlands where almost every household is connected to a sewer system, P ends up in the sewage sludge which is dewatered or dried ('composted') and eventually is incinerated in energy plants. 20% of the sewage sludge is used as a base material in the cement industry (W. Schipper pers. comm.). In contrast to the UK (where around 70% of the sludge is reused in agriculture (ScopeNewsletter73, 2009) it is not recycled in the Netherlands, due to

concerns related to contaminants. The P-rich ashes after incineration were until recently not recycled (but see chapter 4 for new developments). However, even a complete recycling of human excreta worldwide will not be sufficient for a sustainable use of phosphorus considering the other losses in the food chain and losses caused by erosion.

Slaughter waste

One major loss of P, at least for the Netherlands seems also the destruction of slaughter waste, especially the P-rich bones. Because of sanitary regulations (due to the BSE-disease) bones of slaughtered animals are incinerated now completely, making the P content not directly suitable for use in agriculture. At this moment Wageningen UR institutes (Plant Research International, Animal Science Group and Applied Plant Research (PPO)) are quantifying P flows in the Netherlands to arrive at a complete picture of the fate of imported P. A first estimate showed that the amount of P lost in this way could be as high as 17 million kg P (0.017 Mt P). In comparison to the total use of P-fertilizer (0.021 Mt P) a considerable quantity.

Animal manure

The annual flow of P in manure returned to crop land is estimated differently, varying from 6-8 Mt P (Smil, 2000), or 8 Mt (Cordell *et al.*, 2009) to only 2.5Mt (Liu *et al.*, 2008).

Probably the introduction of artificial P-fertilizer in the past eventually led to a lower recycling of manure. Production of food and feed no longer was dependent on animal manure. In combination with concentration of livestock near cities it also more or less decoupled the places where food (or feed) is produced from where it is consumed.

Also by other developments in the last century a production system emerged *without feedback* (Duncan Brown, 2003). The observation that nowadays a large flow of P is not recycled back with manure to the sites of food production is alarming considering the finiteness of phosphorus resources. There is a difference between phosphorus and nitrogen or energy cycling. For nitrogen and energy, producing meat for food is far less efficient than producing food for a vegetarian diet as it needs another cycle (in domestic animals) to produce protein. During this extra cycle there is an inevitable loss of energy, at the same time nitrogen is withdrawn from the cycle by gaseous losses (ammonia, nitrous oxide etc.).

For phosphorus, however, no gaseous losses occur and with a perfect recycling of manure an affluent diet with more meat should not necessarily lead to a greater demand for phosphorus fertilizer. However, with most of the P intake being excreted (Abelson, 1999), worldwide a far from complete recycling of manure can be observed. The consequences are either losses by leaching or runoff to water streams or accumulation of phosphorus in the soil. For China (Liu, 2005) estimated that more than 50% of the P-load to surface water (total P-load being 1.1 Mt of P in China) could be attributed to livestock production systems (and mentions that in the EU14 this was 36%).

In many cases the technology is available for effective P utilization, including nutrition, manure storage, manure application and recently also manure processing. Legislation should however be put in place for implementation of these practices.

4. Possibilities for efficient use and re-use

Increase efficiency in agricultural production systems

Animal production systems usually have a surplus in the P balance and an apparent inefficient use of P in feed. Non-ruminants such as poultry, swine, and people do not have an efficient digestive system for making phosphate available from phytate, the major P form in many cereals. Addition of exogenous *phytase enzymes* added to the feeds can improve efficiency and reduce losses (Smith *et al.*, 2004). P efficiency and reduction of losses might be further increased with phase feeding, limiting *the safety margins* (implying lower P-additions to feed), good animal management and manure amendments.

A too *high concentration of livestock* in relation to available area of crop land is now one of the major causes for an inefficient use of manure phosphorus in Europe and the US. Unfortunately the same trend can be seen now in developing regions in Asia where meat production increasingly takes place in the neighborhood of cities.

Römer (2009) noticed recently that that phosphorus *fertilization recommendation* schemes should be reconsidered critically taking into account higher prices, the finiteness of phosphorus and the apparent low efficiency of fertilization. Instead the potential of the soil (the formerly considered unavailable P) probably can be used better, although this must be considered as a 'time-buying' option.

Anticipating on a future scarcity (and higher prices) of P fertilizer and considering the surplus of animal manure in some regions, it would be sensible for e.g. European countries to make a cost–benefit analysis of accepting a somewhat lower P fertility status of the soil. The trade off, possibly lower yield and quality of some crops, should balance the prospect of being less dependent of imported fertilizer in the future. As has been indicated before, to improve the P-fertility status of the soil requires a high input of P, whereas observed yield depressions at a lower fertility status in many cases were minor.

Cornish (2009) mentions *plant breeding* to introduce properties which can improve the uptake of this so-called unavailable P, including

- an altered root morphology or function or root hair structure,
- the ability of roots to release organic acids (e.g. citrate, malate) in order to acquire phosphorus (lupins and other legumes have this property)
- increase of rhizosphere volume

Associations between crops and arbuscular mycorrhizal (AM) fungi can play an important role in phosphorus acquisition by plants. Grant *et al.* (2005) attribute this to an effectively enlarged root system rather than to an enhanced solubility of P by the fungi. Plant breeding might be a technique to promote these associations but Grant *et al.* also mention rotation, minimum tillage and seed inoculation as relevant factors.

Römer (2009) observed that the internal P utilization of arable crops (kg dry-matter production/g P uptake) has a considerable range of variation. This could leave room for breeding to arrive at a higher efficiency.

In agro-production systems *recycling* of phosphorus should be the general principle. This holds for manure, crop residues, and other organic rest products. This aspect is particularly relevant for bioenergy and biofuels crops when the acreage of these crops will increase. When P-containing biomass for energy production is removed from the field and processed elsewhere (digested or burnt), the residues, or at least the nutrients, should be returned to the location of production. As with livestock, also here concentration and accumulation should be avoided.

In the case biomass is incinerated the P in the ashes usually is not suitable for reuse in agriculture, but the residues of biofuel crops such as rape (oilseed) can be used as feed because of their high nutritional value. The P in the produced manure can then return to crop land. For bioethanol the residues of the fermentation process, e.g. Distiller's Dried Grains with Solubles (DDGS) a co-product of the distillery industries, have a lower suitability as feed

(less than soybean and rapeseed meal). Because of the increased demand for ethanol, the production of DDGS is expected to double within the next few years. DDGS contains 0.8% P on dry weight basis (<http://www.ddgs.umn.edu/overview.htm>).

Especially the cattle feedlot industry can be a market for DGGS, unless DGSS are processed further into gluten feed, gluten meal, and corn oil. Burning is sometimes suggested as a possibility when more co-products are produced than cattle feedlots and dairies can use (Cassman *et al.*, 2006). Like with sewage however, burning implies that phosphorus contained in this biomass would become ineffective.

Co-products can also be used as organic fertilizer. This can only be efficient if the transport distances of biomass and effluent are small. Ports where massive biomass imports are foreseen for processing into bioethanol have the disadvantage that all nutrients are removed from the soils of origin and accumulate in the country with the (large) bioethanol plants. Therefore similar problems with regard to nutrient imbalances will arise as in countries with too much livestock (or feed import) in relation to the area of crop land. The fertilizer and bioenergy industry should explore together the possibilities to produce fertilizer products from the raw material (residues) left at the bioethanol plants. In Brazil a fluid fertilizer venasse is made from after processing sugar cane into ethanol (Fixen, 2006). All in all a careful analysis will have to be made of the fate of nutrients being removed from the field with bioenergy and biofuel crops.

Recovery from seawater

Mining of the ocean sediments is not seen as a feasible operation at this moment, taking into account that most of these sediments are at a depth of more than 300 meters. Sometimes it is suggested to recover phosphorus from ocean water. This however is not a realistic option, the concentration of phosphorus in seawater is too low to recycle P in a chemical or technological approach. Duncan Brown (2003) calculated that with the average concentration of phosphorus of $70 \mu\text{g L}^{-1}$ sea water would have to be processed at a rate of $2.4 \times 10^5 \text{ km}^3 \text{ year}^{-1}$ if the current use of P-fertilizer were to be obtained. This would be more than 70 times greater than the total global annual consumption of freshwater.

Can plants play a role to recover phosphorus from seawater? Currently it is investigated whether a large-scale production of sea weeds for energy purposes in the North Sea would be feasible (Reith *et al.*, 2005). Although in principle lost phosphorus could be recovered in this way, the authors mention that commercially attractive production levels will necessitate the application of nutrients. Therefore a precision nutrient dosage technology should be developed to prevent eutrophication.

Currently around 2 Mt dry matter is produced annually worldwide with seaweeds for commercial use (Reith *et al.*, 2005), with a P-content of 0.3% P this results in 0.006 Mt of P (a small amount compared to the current losses with erosion or with fertilizer use).

A substantial production of seaweeds is probably constrained by the low phosphorus concentration in seawater. In upwelling zones (along the coast of Chili, East Africa etc) this could be different. However, because of the vulnerability of these zones (marine biota depend for the greater part on the nutrients in these upwelling zones) it is not recommended to start large production systems there (W. Brandenburg, PRI pers. comm). The possibilities to recover phosphorus from rivers and streams in estuaries with seaweeds or algae are probably larger and can be explored.

Recovery from sewage sludge and slaughter waste

From humans connected to a sewer system most of the P excreted ends up in sewage sludge. Reuse of this sewage sludge in agriculture (thereby recycling the P to the sites where the food is produced) is diminishing.

Römer (2009) estimates that in Germany around 2.4 Mt dry sewage sludge is produced containing 48 million kg P (0.048 Mt P). In 2003 only 33% was recycled in German agriculture, 38% was burnt and the rest ended up in landfill or landscape building. The projection is that incineration will increase to as much as 71%. Slaughter waste (dead animals, bones etc.) contain around 22 million kg P (0.022 Mt). For Germany it is estimated that 90% of the in total

0.070 Mt P in rest products could be recycled, more than half of the current German consumption of 0.108 Mt P artificial fertilizer.

In the Netherlands, where practically every household is connected to wastewater treatment plants (WWTP), the use of (phosphorus rich) sewage sludge for agricultural purposes is not allowed. Instead it is used in the cement industry or is incinerated, the remaining ashes with the phosphorus is for the greater part not recycled due to contaminants (heavy metals) and the fact that P is in insoluble compounds.

At this moment promising efforts, needing a different precipitation method at WWTP's (Fe to be replaced with Al), are carried out by Thermphos (production of phosphorus) and SNB (Slibverwerking Noord Brabant) to recycle and reuse the P in the ashes of incinerated sewage sludge (Schipper and Korving, 2009). Since mid-2008 already 550 ton P y⁻¹ has been recycled and an increase is expected.

In the Netherlands around 0.342 Mt of dry matter municipal sewage sludge is produced. The greater part is incinerated, therefore around 12 Mkg of P (0.012 Mt) eventually ends up in the ashes (Geraats *et al.*, 2007). Comparing this to the amount of P-fertilizer used in this country (21 Mkg P) recovery of this source would be worthwhile. Whether or not recycling is possible depends on the Fe/P ratio (which should be <0.2 (Schipper and Korving, 2009)). Potentially a quarter to a third of the P in ashes nationwide could be recycled in this way (Geraats *et al.*, 2007), and for the region covered by SNB a recycling percentage of 46% is mentioned. At this moment it is estimated that potentially more than 90% of the P could be recycled (W. Schipper, Thermphos; pers. comm.).

In other countries the direct use of sewage sludge in agriculture is allowed. In 2005, the UK produced over 1.1 Mt of sewage sludge (dry matter weight), of which around 70% was spread on agricultural land. This corresponds in P content to approximately 40% of total UK phosphate *fertilizer* use. (ScopeNewsletter73, 2009). Note: it must be kept in mind that at least part of the P in sewage sludge is deliberately precipitated (Fe) into insoluble compounds which cannot be taken up by plants. Therefore sewage sludge, apart from the content of heavy metals, probably is not the most appropriate material for a sustainable and efficient use of phosphorus in agriculture.

For the Netherlands recycling of slaughter waste, especially the P-rich bones, could be substantial as the amount of P ending up in the ashes of the energy plants is higher than used in agriculture as fertilizer. Current regulations (NL, EU) which prevent recycling should therefore be reviewed critically.

Other on-going activities in the Netherlands and the EU include the recovery of phosphorus directly from urine. Struvite (a magnesium or potassium ammonium phosphate compound) can be used directly as a fertilizer (Johnston and Richards, 2003). At this moment the agronomic and economic value of struvite as a P-fertilizer is not completely clear and would justify further research (Intern. Conference on Nutrient Recovery from Wastewater Streams, May 2009; Vancouver).

5. Discussion

Strikingly, energy and phosphorus have comparable characteristics. As is the case with known fossil oil and gas reservoirs, phosphorus resources are available in a limited number of countries. This might induce geopolitical instability. Legislation in several countries in the western world is concentrated more on the environmental aspects of P use, such as the reduction of eutrophication of surface and coastal waters, than on the finiteness or the recovery of this resource. Comparably environmental issues like climate change caused by the use of fossil fuel appear higher on the agenda than future scarcity. Until not too long ago, the search for alternative energy sources was minimal.

The difference between energy and phosphorus is that there is no alternative for phosphorus, so solutions will have to come from either less *demand*, a more efficient *use* and *reuse*, or less *losses* in the chain from mining to the dinner table.

Several estimates in the preceding chapter on future demand of P are based on straightforward assumptions about changes in population growth, diet composition, land use etc., but do not take ecological processes related to soil and plant phosphorus explicitly into account. In some regions soils are saturated by now because of the excessive application of manure. In other regions high application rates may be needed to bring or restore the soil to a desired fertility level. If a future increase in world food production must be realized by the expansion of agricultural land with ever less fertile lands, this aspect of P-build up should be explicitly considered. Next, soil P-status should be considered as an important factor for estimating the ultimate impact on food amounts. These divergent conditions suggest the need to look specifically into developments at an eco-regional basis, i.e. at regional level with comparable ecological conditions, rather than at a global level. Hence, estimates of future P-requirements should be made regionally explicit. This will also reveal the geographical changes in future in the gap between the requirement for P and its availability. We therefore recommend the development of a methodology that takes these ecological processes explicitly into account and which estimates future P-requirement at regional rather than global scale. To give an example: in the Netherlands four times as much P is imported with feed & P-additives than with fertilizer whereas for the EU27 the reverse is true (see section 3.2).

Some aspects which need to be quantified for the Netherlands as well as for the EU:

- will an increasing P-fertilizer price impair soybean production in South America, can this eventually lead to protein production in Europe. If so, what will be the consequences for future P-demand, P-surplus, food quality etc.
- to which extent will an increasing P-fertilizer price stimulate better utilization of P in livestock manures and waste?
- what will be the effect of an overall lower availability of fertilizer P in the NL and the EU
 - how long will the current P-fertility sustain the current production volume and quality
 - what will be the effects if a somewhat lower fertility level for P is recommended and, which sectors of agriculture would especially be affected
- quantification of the effects of use, reuse of P in the NL and the EU (inventory of sources and reuse possibilities)

At the global level Cordell *et al.* (2009) recently developed future scenarios based on reuse (including human excreta, manure, industrial waste, food waste etc.), development of new sources (algae, seaweed and ashes) and lowering the demand by measures in mining, agriculture, food processing and retailing and food consumption.

Their conclusion was that the demand for phosphorus can be substantially reduced through measures in the field of changing diets, food chain efficiency and agricultural efficiency but made also clear that there will be lag time before changed measures and policies take effect.

Considering a number of articles which recently appeared on the subject (Cordell *et al.*, 2009; Cordell *et al.*, 2009; Rosemarin *et al.*, 2009; Vaccari, 2009; Weikard and Seyhan, 2009) the awareness on the finiteness of phosphorus

seems to increase in the scientific world, but according to Rosemarin *et al.* (2009) also public awareness of the problem should be improved as most people assume that more resources will be found eventually. Until now global governance is missing, the articles above notice little acknowledgment from governments, UN organizations and international NGOs. Next to the technical solutions as indicated above Rosemarin *et al.* (2009) mention some policies to be considered:

- Higher prices of fertilizer could discourage the inefficient use of phosphate products and promote recycling, but higher prices could also lead to higher food prices which does not seem appropriate.
- Instead a stimulation of recovery and reuse of phosphorus could have a broader perspective. It is argued that with policy reforms promoting the development of recycling technologies the EU could become more or less self sufficient in phosphorus (Note: this seems not very likely if taken into account the amount of phosphorus imported with feed from outside the EU, this feed is also produced with fertilizer P).
- Wide ranging changes in agricultural policy reforms could be effective to reduce the demand for fertilizers
- New incentives such as carbon taxes is seen as an incentive for the fertilizer and phosphate mining industries to become more efficient.

Finally, it seems as if the words 'sustainability' and 'the planets' carrying capacity' are especially meaningful in relation to the finiteness of P-resources. Regardless whether these resources will last for 50 or for 500 years it might be that in the end almost inevitably the world will be confronted with lower potential yields, due to the specific characteristics of P-supply by agricultural soils. So a relevant question might be whether in the *long term* the planet can feed more than the 1 billion people which were on earth *before* P-fertilizer was introduced.

Therefore, next to consider 'time buying options' (such as improving the way fertilizer P and manure is applied, reducing the losses by man-induced erosion, improve recycling etc.) there is the need to find out whether the world can sustain in the long term 10 billion people. Thereby considering explicitly the future availability of phosphorus next to other important resources such as available water and agricultural area.

6. Conclusions & Summary

1. Phosphorus, applied in fertilizer, is important for the world's food production but the resources are finite. With *current* consumption it is estimated that today's economically exploitable resources (the reserves) will be depleted within 125 years and total reserves (the reserve base) within 340 years. If taken into account the expected increase in consumption to the growing world's population, the increasing meat consumption and the increase in biofuel and bioenergy crops, duration of the resources probably will last only 75 years for the reserves and 170 years for the reserve base. Especially the prospect of the global population changing to menus with more meat will have a major effect on the demand for phosphorus.
2. The calculations on duration of the resources may be (much) too optimistic considering the large mining losses which have been reported.
3. Phosphorus deposits are located in just a few countries, Morocco and China control more than 50% of known reserves at this moment. Various countries, including all EU countries, rely heavily on this small number of countries for the import of phosphorus fertilizer products. Imported feed, especially from South America is also an important input of phosphorus for the EU. However, because the soils in e.g. Brazil are known for their low phosphorus fertility this feed is produced with P fertilizer as well.
4. At the global level large losses occur due to soil erosion and runoff. Phosphorus in particulate or dissolved form eventually ends up in the ocean's sediments where it cannot be recovered with current technology. The amount lost in this way exceeds the current use of phosphorus with fertilizer.
5. An increased production of biofuels or bioenergy can effect the demand for phosphorus in several ways:
 - If production takes place on wastelands or marginal lands the P-fertility level usually will have to be improved
 - Losses of phosphorus may increase if bioenergy requires a conversion from rangelands to arable land which is more prone to erosion
 - It is crucial to recycle the phosphorus containing (plant) residues which are produced during the conversion of the biomass into energy, either as feed or as organic fertilizer. If not, it will increase the demand for fertilizer P.
6. Phosphorus intake by the global population is only a fraction (less than 20%) of the amount used in phosphorus fertilizer. This apparent inefficiency has various reasons:
 - Accumulation of phosphorus in soils due to a fertilization which exceeds the crop's removal. This occurs with artificial fertilizer but above all with animal manure in intensive livestock regions
 - Accumulation of phosphorus in the soil also occurs to increase the P-fertility of the soil. Often this is needed to anticipate on the phosphorus fixing properties of the soil, which make that on the short term only a fraction of the fertilization is taken up by the crop.
 - Various losses, next to erosion, in the agricultural chain and in the household area.
7. For a more sustainable use of phosphorus various possibilities can be mentioned:
 - On the global scale measures to prevent erosion seem crucial
 - Livestock concentration (number of animals) should be in balance with the surrounding area of arable land. In this way the excess of animal manure will not lead to an accumulation of phosphorus in the soil and to environmental risks (and losses) for the environment.
 - Next to a more efficient use of manure more technology should be developed to *recycle* the phosphorus in waste streams. Especially in the developed (urbanized) world phosphorus is lost with human excreta, crop residues, slaughter waste & bones and other organic rest streams. In Europe an increasing amount of phosphorus ends up in the ashes of incineration plants. For the major part these phosphorus rich ashes are not recycled. However, feasible technology is available for recycling (mono incineration of P-rich biomass/sewage sludge with a low Fe content). In order to improve the recycling rate current regulations at national and EU level will have to be reviewed critically.
 - A larger global area of crops grown for energy purposes (bio fuels/bioenergy crops) can stimulate the demand for phosphorus (fertilizer) as well as increase losses by erosion. The rationale for these crops is prevention of global warming but sustainability will depend also on recycling of the phosphorus containing residues (back to the land where the crops were grown).

- Critical judgment of current fertilizer recommendation scheme's. The potential trade-off (lower yields or crop quality) when aiming at a somewhat lower phosphorus fertility level should be quantified for various situations. Possibilities to increase the efficiency of phosphorus fertilization strategies within agriculture should be explored. Plant breeding for plant properties to mobilize better phosphorus in the soil should be stimulated.
8. Coordinated global governance on the exploitation of the remaining phosphorus resources will probably not be realized without an increased awareness of the problem . This holds for international organizations and governments but also for 'the man in the street' as aspects of daily life are involved (food certainty , food availability as well as the composition of the menu). For that reason realistic scenario studies will have to be done which quantify the effects of a future shortage on P-fertilizer in various regions. More than in the past century reuse and recycling of phosphorus must be realized, necessitating joined efforts of various disciplines and expertise's.

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