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Peak Phosphorus: Implications for Agricultural Production, the Environment and Development

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Abstract

Phosphorus is a key element in food production, but is a non-renewable resource. Recent estimates suggest that global production of P fertilizers will peak in 2033 and will be one third of that peak level by the end of the 21st century. Population and income growth will increase demand for food, and especially animal protein, the production of which will accelerate the rundown in P reserves and the consequential rise in fertilizer prices. The global distribution of current P fertilizer use divides countries into the 'haves' which in many cases face severe pollution problems from excess P, and the 'have-nots' in which low input use annually drains soil P reserves. Coping strategies include improvements in the efficiency of fertilizer P manufacture and use, and the recycling of P in liquid and solid wastes. The latter approach offers win-win solutions by reducing the environmental pollution of water in highly populated areas. Future utilisation of scarce P reserves requires policy decisions that take account of equity, productivity, environmental and trade considerations. Biological solutions designed to increase P use efficiency, such as improving crop varieties and mycorrhiza associations, and the use of P accumulating plants as green manures, are also considered.

1   Introduction

Life without P is hard to see
No bones, no teeth no ATP
       H.L.S. Tandon (1995)

"only matters if you want your grandchildren to have bones."
       James Elser (Quoted in the New Yorker, January 2010)

The essential role of phosphate (P) in all living things derives from its role in several vital processes. The adenosine triphosphate produced in mitochondria provides the chemical energy upon which life depends. P is also a component of DNA through which life reproduces and grows. For vertebrates the structural role of P in bones and teeth is also vitally important. In 2010, the United Nations International Year of Biodiversity, it is sobering to consider that one of the by-products of the near extinction of the North American bison in the 19th Century was the gathering - on the prairie, or at the base of cliffs over which these animals were stampeded - of the bones of the bison which were crushed and sent east to be sold as fertilizer (Hornaday 2009). Unlike the other essential nutrient, nitrogen, which is abundant, albeit largely inert, in the atmosphere, P is a non-renewable resource the future scarcity of which is the focus of this paper.

Pile of Bones in the Canadian Prairies

The 20th Century saw massive increases in food production that generally kept pace with a global population increase from 1.6 billion to 6 billion. Some of the production increase was due to opening new land for cultivation, but the green revolution in the high-potential areas, particularly in Asia, contributed significantly to productivity increases in those countries with major population growth. During that century, as modern fertilizer-responsive rice, maize and wheat became widely available, use of P fertilizers increased 3.5-fold (Tilman1999). By contrast in sub-Saharan Africa the 20th century saw declines in per capita food production and very limited use of fertilizers (Vlek 1990). In Latin America large areas of land in the Cerrados were opened to productive agriculture only after adequate fertility management based on liming and P application was developed. P fertilizers also played a key role in agricultural production gains made in North America and Australia.

As one of the three major essential elements for plant growth, P supplies have asserted and will continue to assert significant influence on efforts to expand food production. Importantly, plants concentrate P in the grains and fruiting bodies, which when harvested and removed from the farm create a significant drain of P reserves in soil. High yielding systems therefore require P inputs at a minimum level that replaces harvest losses. Unlike nitrogen, which can be fixed from the atmosphere, the main source of P currently must be mined from limited deposits. Furthermore, to the extent that energy-intensive industrial N fixation can be replaced by legume nitrogen fixation, this process relies heavily on the availability of adequate P supplies.

Bruinsma (2009) estimated that to feed a projected population of 9 billion in 2050 will require a 66% increase in crop production from the base level in 2005/2007, while during the same period meat production will have to increase 85%. The latter projection is high because it takes account of increased incomes, particularly in the more populous countries of Asia. Future supply of P fertilizers will therefore have to accelerate to sustain the quantity and quality of food and feed grain production needed by this up-and-coming population, aside from that required to meet the basic food needs of less prosperous regions. However, P is a non-renewable resource with finite reserves; recent concerns about the future availability of P fertilizers (Cordell *et al.* 2009) have presented this as a major global challenge.

This paper reviews the global distribution of P use, transfers between regions, rates of soil P depletion and prospects for improving the P fertilizer efficiency and P re-cycling, in the context of peak P production.

Figure 1: The biogeochemistry of P (Chen *et al.* 2008)
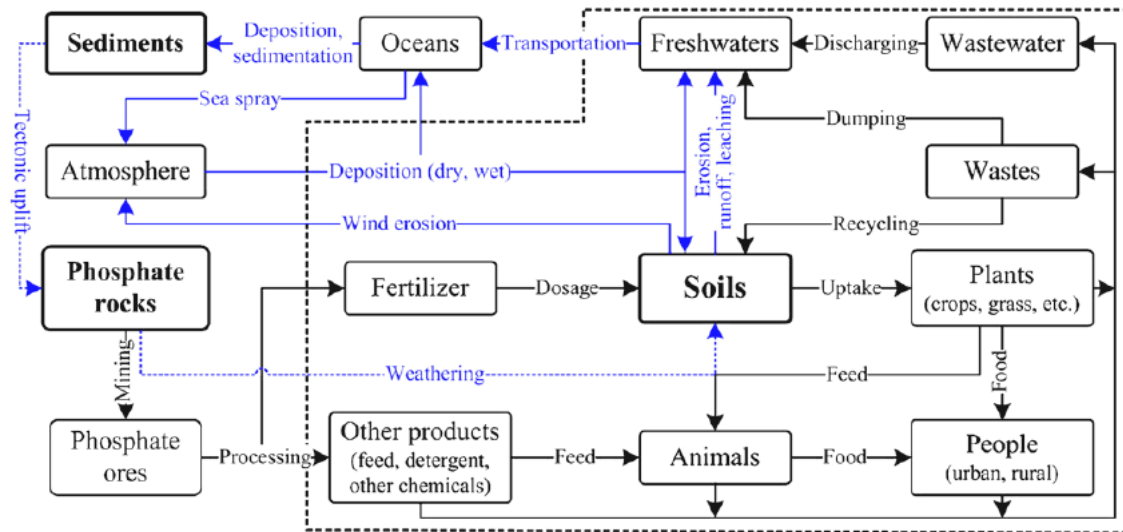
The biogeochemistry of P is illustrated in Figure 1, which provides an overall framework for the discussion of P resources, the use of P in agriculture and the environmental processes that can cause concern. Human perturbation of the P cycle drives the P mainly in the one direction from phosphate rocks through fertilizer and the soil to plants, livestock and people to wastewater discharged into freshwater and Ocean sinks.

2 P Resources, Uses and Transfers

2.1 P Resources

Most P fertilizer is produced from P rock which is either igneous or sedimentary. The sedimentary rock makes up 80% of production and limited quantities are used on acid soils of the tropics for direct application. Fine grinding of the less reactive before application may increase the availability of the P to plants in the short term. Beneficiation of some igneous P rocks reduces transport costs and makes them more effective as sources of P (Fixen, 2009). Igneous rocks that have a high P content and low levels of impurities do not require much beneficiation. World phosphate rock production has varied considerably over the past 25 years (Figure 2). The major changes have been the decline of production in 1997 after the breakup of the Soviet Union, the large expansion in Chinese phosphate rock production and the emergence of Brazil, Jordan and Tunisia as small but significant producers.

Figure 2: World phosphate rock production 1981–2008 (Fixen, 2009). (For 1992 to 1997 Soviet Union includes Kazakhstan and Russia, afterwards Russia only).
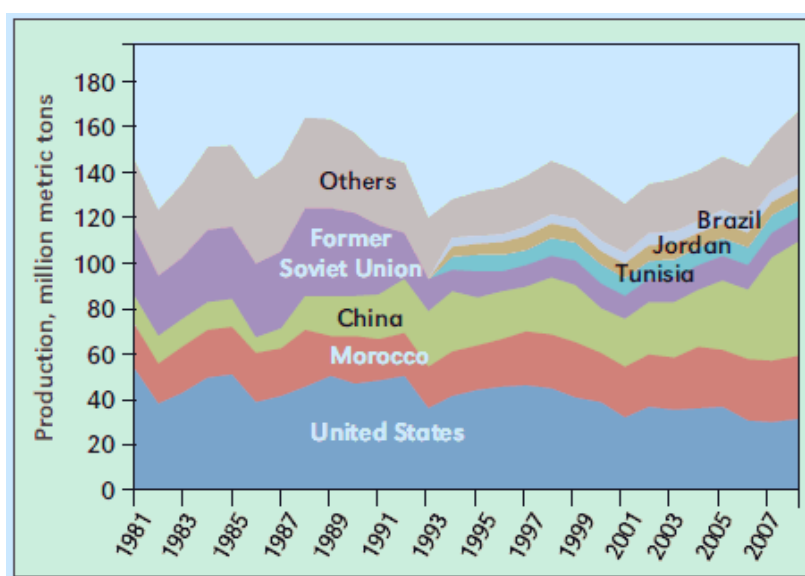
Annual global production of P rock in 2008 was 167 million tons, with China, the USA and Morocco and Western Sahara as the main producers (Table 1). Global reserves total 15,000 million tons but the country rankings in terms of reserves are not the same as for annual production – the data for the USA indicate an annual rate of use of 19% of global production with only 7-8 % of the worlds' reserves. On the other hand, China's production is proportional to

its reserves. Morocco and Western Sahara are conservative in their P extraction, as are minor producers such as Jordan and South Africa. Overall, about 70% of total reserves are in Africa, including Sub-Saharan Africa, and the location and nature of these deposits are shown in detail below.

Table 1:   **Production of P rock and reserves in main producing countries (Jasinski 2009)**

|	Proportion of global total P rock (%)		
Country	2008 annual production	Reserves	Reserve base[1]
China	30	28	21
United States	19	8	7
Morocco/Western Sahara	17	38	45
Russia	7	1	2
Tunisia	5	<1	1
Brazil	4	2	<1
Jordan	3	6	4
South Africa	1	10	5
Global total P rock (Mt)	167	15,000	47,000

[1] Reserve base: P rock with a 'reasonable potential for becoming economically available within planning horizons beyond those that assume proven technology and current economics'

A simple calculation (reserves divided by annual extraction rate) of the life of the P rock reserves at current rates of global production results in a 90 year lifespan for the USGS-classified reserves plus 281 years for the 'reserve base' (see Table 1 footnote for the definition). The calculation of future rates of production and peak P requires an understanding of the future rate of increase in demand, market price movements, and potential improvements in technology, especially to remove impurities economically. As prices rise, the incentive to use P judiciously will increase, as will the economic feasibility of improving technology not only for refining P rocks, but also for increasing the recycling of P from wastes. Fixen (2009) points out that the most recent USGS reserve estimates are based on fertilizer prices several years old and therefore may underestimate the extent of reserves. Cordell et al. (2009) have utilized a methodology originally used by M. King Hubbert of the Shell Company to define peak oil production, i.e. analysis of production of a finite resource as a symmetrical bell-shaped curve which rises, peaks then falls as the resource dwindles in supply. Defining the height and timing of the peak when 50% of the total has been mined, is the critical element in the analysis. In the case of oil, new reserves have been explored and new technologies for extraction developed, as the price has increased over the past decades. The Hubbert curve devised by Cordell et al. suggests a peak in P production of 29 Mt P/year in 2033 (see Figure 3). According to their analysis, the rate of production will be reduced to 10 Mt P/ year in 2100. Bouwman et al. (2009) foresee a large increase in P fertilizer use on cropland in developing countries and estimate that 36% to 64% of P reserves will be utilized by 2100. World trade issues, price rises that make it economic to mine lower grade deposits, and market forces will all significantly influence the life of P resources. A critical factor that is already changing markets and distorting availability is cadmium legislation. For example, a Finnish proposal to pass on new limits to the European Union would render much

of North African P no longer importable, as long as cadmium removal remains an expensive technology. Currently Austria, Finland and Sweden regulate the cadmium content of phosphate fertilizers (IFA 2010).

The overriding reality is that since rock P that can be utilized as a fertilizer is a finite resource, there will be a peak, but the timing is difficult to pinpoint. New more detailed studies of the issue, that take account of economic aspects such as the effects of rising prices, as well as the potential impacts of new technologies on estimates of the extent of reserves, are in progress by agencies such as the International Fertilizer Development Center in Alabama (A. Roy, personal communication 2009). Nevertheless, current evidence suggests that peak P will become a serious problem facing the next two generations of humanity and beyond.

Figure 3: P curve showing actual and projected P production (Cordell *et al.* 2009).
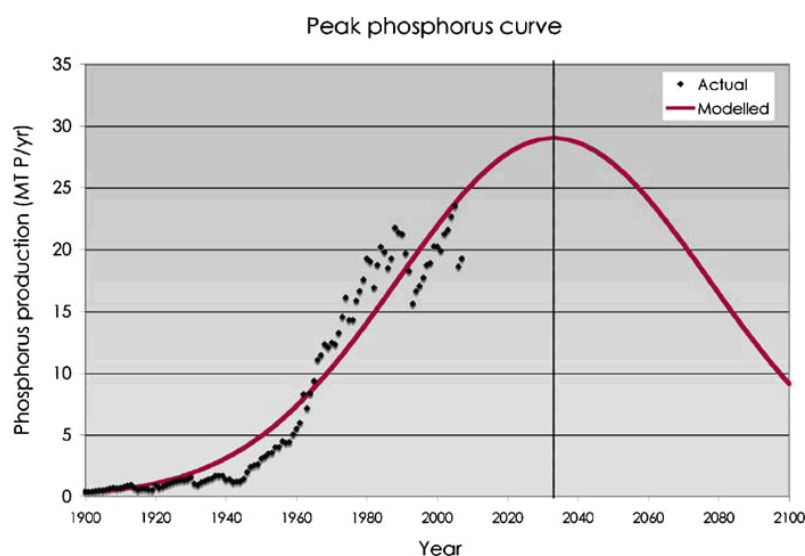
2.2   P Use

The evidence reviewed above shows that P reserves are being utilized at an unsustainable rate, i.e. the high rate exploitation of the finite reserves of P rock cannot be sustained in the long term. While the distribution of P rock reserves across countries of the world is uneven, the rate of use of the P is also extremely uneven. Figure 4 shows the 2005 annual consumption of P as fertilizer broken down by region, as well as projections to the year 2030, which is approximately when Cordell et al. (2009) expect P production to peak. Note that the global total consumption in 2030 that Tenkorang and Lowenburg-DeBoer (2009) project is 23 Mt of P, whereas Cordell et al. 's projection of peak production is 29 Mt. The highest level of P consumption in 2005, and projected to 2030, is in Asia, which reflects the high population as well as the intensive cropping systems, based on the use of irrigation and modern high-yielding varieties. In Asia, as in Latin America another important factor will be the expanded demand for P for biofuel crops such as cassava, soy bean and sugar cane. Europe, North America and Latin America utilize

proportionally less fertilizer, but the most striking contrast is the low consumption of P in Sub-Saharan Africa, and the low trajectory of the projected future use.

Figure 4:   The annual consumption of P fertilizer in different world regions in 2005 and projections to 2030. Adapted from Tenkorang and Lowenburg–DeBoer (2009).
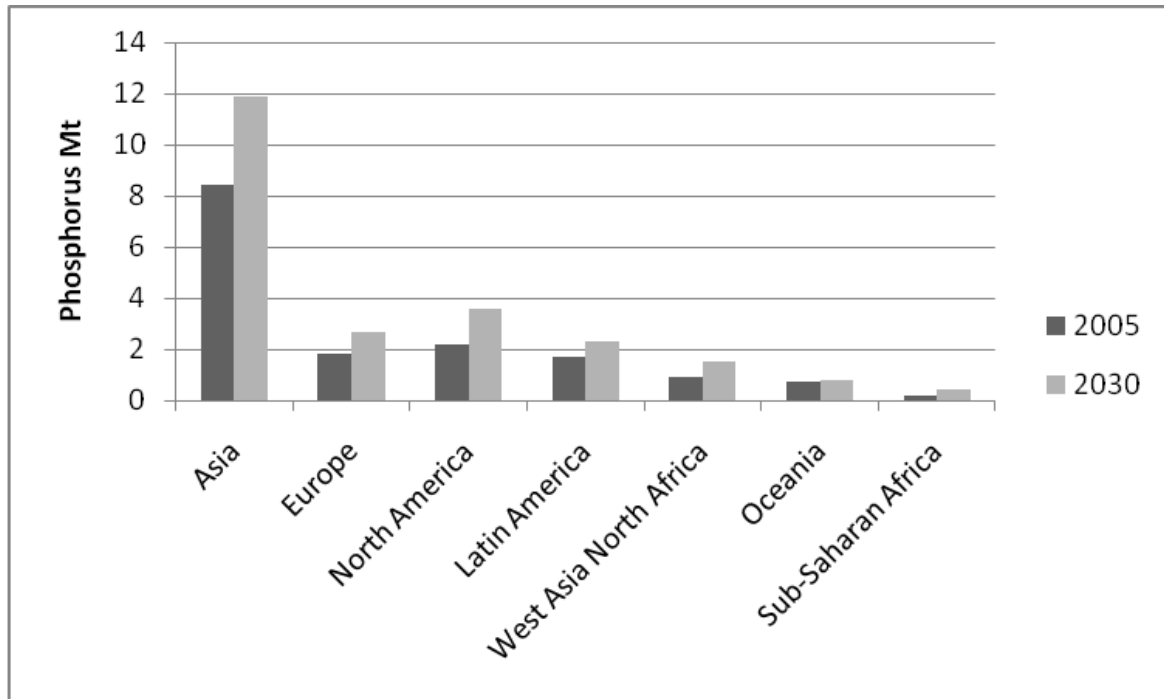
2.3   P balances

The historically low rate of fertilizer use is Sub-Saharan Africa is well documented (Batiano *et al.* 2006). Over fifteen years ago, Vlek (1993) raised concerns about nutrient exports from sub-Saharan Africa. In 2007, the export of stimulant crops alone removes around 50,000 tons of P from this region or one-fifth of the annual P use. This amounts to a doubling in P exports against a stagnant use of P fertilizer over the past 20 years. Over 30 years of repeated harvests without matching fertilizer applications has resulted in an estimated depletion of 75 Kg P/ha from 200 million ha of cultivated land in 37 African countries. This estimate is consistent with the figure of 3.3 kg P/ha/yr published by Sheldrick and Lingard (2004), who projected a rise in depletion rates to 6 kg P/ha/yr in 2020 unless rates of growth of fertilizer P use increased to 7% per year. There is a clear case for urgent action to address this problem, particularly viewed against a background of peak P. Fortunately a significant number of countries in Sub-Saharan Africa have native deposits of P rock that could be developed locally for direct application to help solve the problem if the fertilizer sector develops (van Straaten, 2002). Figure 5 shows the type and distribution of the deposits, but to date the commercial development of these P resources is limited to only a few countries. The reactivity of the P rocks varies according to the mineral composition, which, along with the soil pH and other factors affect the effectiveness of

direct application. A decision support system for phosphate rock has been developed that helps developing countries assess the suitability of indigenous phosphate rocks for direct application by integrating the complex series of major factors involved (Chien *et al.* 2009). An updated PRDSS that can be used to predict the initial and residual agronomic effectiveness of P rocks is soon to be published (Norman Chien, personal communication, 2010)

At the other end of the scale are 'nutrient surplus' countries (Craswell *et al.* 2004) in Western Europe, especially countries such as Belgium, Denmark, and the Netherlands, which import feed grains for livestock production creating a surplus of nutrients in the environment, and therefore face serious pollution problems. The same applies to some of the intensive production systems in North America and Asia. Excess P use can cause eutrophication of waterways and toxic algal growth that can cause red tides and oxygen-depleted "dead zones" in coastal seas. This is a key area for environmental policy action, including international agreements; Bach and Frede (1998) report progress in reducing P surpluses in agricultural land in Germany by 60% in the last decade of the 20th century. The OECD (2008) reported that the use of P fertilizers in OECD countries declined by 10% during the 1990s, but livestock manure remained a major source of P surpluses for most countries. Amongst the countries reported to have high accumulations of P in agricultural soils were Japan-51, Belgium-23, and the Netherlands -19 KgP/ha per annum. The accumulation of P in agricultural soils is considered a serious problem because of potentially serious pollution to surface waters.

Figure 5:   Distribution of known P rock deposits in Sub-Saharan Africa (Buresh *et al.* 1997)

■ Igneous
● Sedimentary
▲ Guano

Angola
  1 Cabinda
  2 Longonjo
  3 Lucunga
Benin
  4 Mekrou
  5 Pobe
Burkina Faso
  6 Arly
  7 Diapega-Kodjari
Burundi
  8 Matongo
Cameroon
  9 Douala
Cen. Africa Rep.
  10 Bokouma
Congo Republic
  11 Comba
  12 Holle
  13 Offshore
Ethiopia
  14 Bikilal
  15 Gorrahei
Gabon
  16 Iguela
Guinea Bissau
  17 Saliquinhe
Kenya
  18 Mrima Hill
  19 Rangwa

Ghana
  20 Sekondi
Liberia
  21 Bambuta-Bomi Hill
Madagascar
  22 Iles Barren
Malawi
  23 Chilwa Island
  24 Tundulu
Mali
  25 Assakerei
  26 Tilemsi
Mauritania
  27 Bofal-Loubboira
Mozambique
  28 Maputo
  29 Muambe
Niger
  30 Aschia Tinamou
  31 Tahoua
  32 Tapoa
Nigeria
  33 Abeokuta
Senegal
  34 Gambia Namel
  35 Matam
  36 Taiba-Thies
  37 Ziguinchor
Somalia
  38 El Bur

Namibia
  39 Empembe
  40 Kalkfeld
  41 Offshore
Sudan
  42 Halaib
  43 Sherelk
Tanzania
  44 Minjingu
  45 Panda Hill
Togo
  46 Akoumape-Hahotoe
Uganda
  47 Busumbu
  48 Sukulu
Zaire (now Congo Dem. Rep.)
  49 Bingo
  50 Lueshe
Zambia
  51 Rufunsa
  52 Nkombwa
Zimbabwe
  53 Dorowa
  54 Shawa

Harrison et al (2009) have recently published estimates of the flows of P from various sources in surface waters within different regions and river basins. In contrast to the major role of excess fertilizer nitrogen in pollution of coastal waters, direct P flows from fertilizer to the oceans are a relatively small component even from regions such as the USA and Europe where fertilizer use is high (see Figure 6). An exception is the highly impacted semi-enclosed waters such as the Baltic Sea or Chesapeake Bay. On the other hand, the flows of P from sewage point

sources to the oceans are high, particularly in Asia, and indicate a high potential for recycling that would reduce pollution of coastal zones. Deng *et al.* (2010) have assessed the flows of inorganic P and other pollutants from the Yangtze River in China. Reducing P outflow levels to an allowable level of 18,000 t per annum, in order to combat the serious problem of toxic red tides, will require the addition of dephosphorization facilities to existing waste water treatment plants and the building of new plants, both involving major investments. The productive use of the P recovered will be a further challenge, depending on health and other environmental considerations.

Figure 6:   River export of dissolved inorganic phosphate (Tg P yr^{-1}) from continents and to ocean basins (Harrison *et al.* 2010)
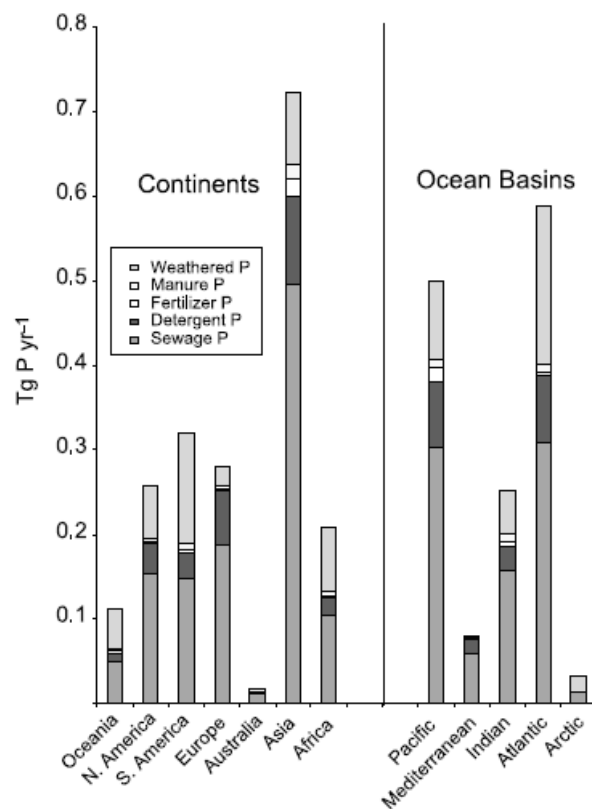
2.4   P transfer

The transfer of P and other nutrients in agricultural commodities in international trade is an area of increasing interest (Craswell *et al.* 2004), because like 'virtual water' trade it provides insights into whether particular countries should choose to grow their own food or import it (Grote *et al.* 2006). In many cases grounds for such a decision may be dominated by water availability but the consequences in terms of P flows are real, not virtual, and will become more important as P resources decline. Figure 7 shows the positive and negative balances of P in traded agricultural commodities projected to 2020. Major food exporting countries and regions, especially the Americas, have large P deficits whereas importers show P accrual. Interestingly,

sub-Saharan Africa has a positive P balance due to food imports, however little of this P ever finds its way to agricultural land.

Figure 7:   Projected regional flows of P in net trade of agricultural commodities in 2020. (Craswell *et al.* 2004)
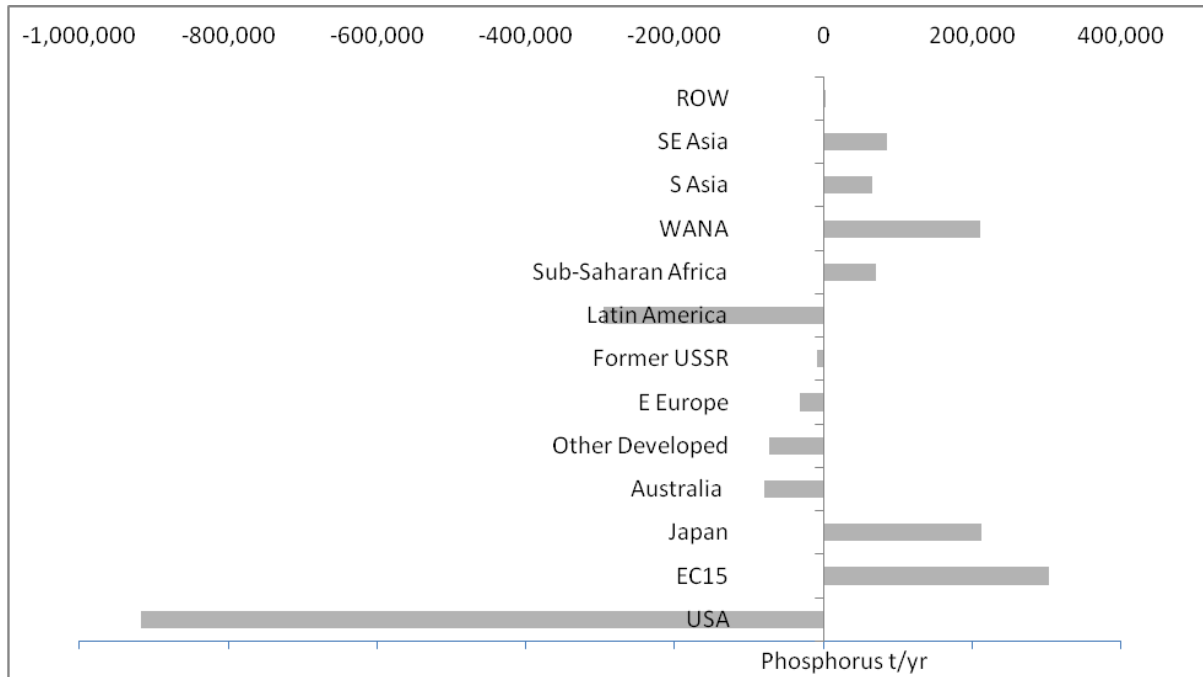
Since food imports to countries in Sub-Saharan Africa are largely consumed in cities, the opportunity for the use of P in municipal and animal wastes to improve peri-urban agriculture has been advocated by Cofie *et al.* (2001) and Drechsel et al (2007). This approach would help address the major problem of soil nutrient mining that is widespread in Africa where fertilizer use by farmers is very low relative to the export of nutrients in harvested products. (Craswell *et al.* 2003). The data in Figure 8 show that currently the rural and peri-urban areas have negative P (and N and K) balances whereas the P and other nutrients accumulate positively in the cities. The opportunity to utilize the P in wastes for peri-urban agriculture is obvious, although biological and abiotic health hazards such as fecal coliforms and heavy metals are still major obstacles to the recycling of sewage P. The same applies to large cities in other regions such as Bangkok where Faerge *et al.* (2001) showed that only 10% of P is recovered and recycled whereas 41% of the P losses could be accounted for by elevated levels in the Chao Phraya River. In the Swedish study by Neset *et al.* (2008) the levels of P in the diet increased significantly during the period 1870 to 2000 largely due to increased meat consumption. Thus an increase in P in the environment due to animal wastes was compounded by the increase in P with which the human waste management system had to cope.

Figure 8: Nutrient balance between imports and exports on a per capita basis averaged for Accra, Kumasi, Tamale and Ougadougu in West Africa (Drechsel *et al.* 2007).
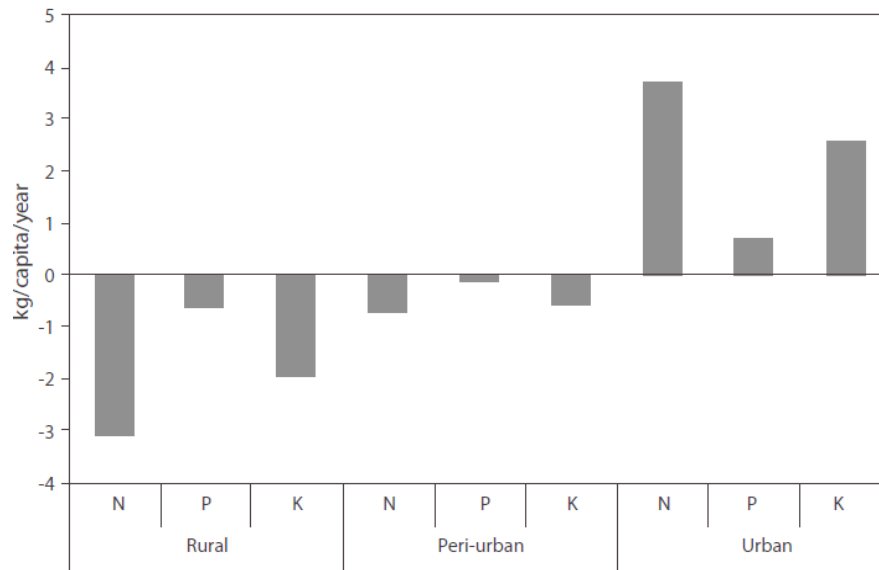
3   Preparing for Peak Phosphorus

The need for global action to address the need to increase agricultural production while finite P resources continue to decline is clear. The above analysis shows that peak phosphorus will become a reality, only the level and timing are uncertain. The information reviewed also shows that the global distribution of P is both uneven and inequitable. There are high rates of P fertilizer use in countries with advanced agriculture, populations with high purchasing power, and hence diets with high levels of animal protein. The environmental costs of this wastefulness are pollution of surface waters from P in animal and human wastes; the concentration of animals in intensive production systems and the dense human populations in urban areas create hotspots of P accumulation. Van Drecht *et al.* (2009) estimate an increase in global sewage emissions from 1.3 Tg of P per year in 2000 to 2.4–3.1 Tg of P per year in 2050. In the developing countries, sewage-P discharge will likely increase by a factor of 2.5 to 3.5 between 2000 and 2050. This is a combined effect of increasing population, urbanization, and development of sewage systems. In Sub-Saharan Africa with high poverty rates and low consumption of animal protein, soil nutrients are mined as P use in agriculture is very limited. In these countries especially, opportunities exist for re-cycling of P around cities where food imports provide P inputs that can be used to redress imbalance across the rural-urban divide. In the nutrient surplus countries recycling will be driven over time by concerns about environmental pollution as well as by economic necessity, as the scarcity of P due to overexploitation drives the prices of P fertilizer higher.

The assessment by Bouwman *et al.* (2010) of P efficiency - the sum of the removal of nutrients in the harvested crop and grazing, divided by the sum of the inputs - under two different scenarios defined by the Millennium Ecosystem Assessment provides some useful insights. The global orchestration I scenario entails: globalization, economic development, reactive approach to environmental problems leading to no change in P efficiency in countries with a surplus and rapid increase in N and P fertilizer use in countries with soil nutrient depletion (deficit). In contrast the adapting mosaic scenario is based on regionalization, local ecological management with simple technology, proactive approach to environmental problems, leading to moderate increase in P efficiency in countries with a surplus; slow increase in N and P fertilizer use in countries with soil nutrient depletion (deficit); better integration of animal manure and recycling of human N and P from households with improved sanitation but lacking a sewage connection.

The contrasting scenarios suggest that a business as usual global orchestration approach will have little impact on P system efficiency, whereas the adapting mosaic scenarios shows significant opportunity for improvements which will help address the looming problem of peak P.

Coping strategies that could be considered part of the promising adapting mosaic scenario include:

- At the P production level, research is needed to improve the efficiency of processing in P fertilizer manufacture (A. Roy, personal communication 2009). Furthermore, the revision of market regulations, taxation and subsidies for the water soluble P fertilizers will become more important as reserves decline.

- Policy measures are needed that ensure a more equitable global P balance in which measures require both developed and developing countries to take action (Grote et al 2005). Important lessons can be drawn from the recent experience with the collapse of fertilizer use when subsidies are removed or prices rise (e.g. in 2008). Developed countries need to move from production subsidies to direct payments based on environmental incentives and need to regulate nutrient disposal and implement nutrient trading permits. On the other hand, limiting P investment in soils that have other major production constraints (semi-arid Africa for instance) will have to be judged in the light of equity considerations and food security. Nutrient-poor developing countries, such as many in Sub-Saharan Africa, should increase input subsidies, implement credit schemes, and extension and training programs to encourage P consumption and use on high potential land that does not suffer from exessive P fixation. Where possible this should be based on local or regional sources of rock P. Developing countries in Asia such as India, China and Indonesia should re-consider the wasteful and pollution-generating impacts of fertilizer subsidies in high-yielding cropping systems. Major commodity exporting countries need access to P supplies whereas importing countries need to address problems of P excess in large urban areas, especially where peri-urban animal production creates re- cycling problems (Grote et al. 2006).

- In the P accumulating regions, with hotspots such as intensive animal production or urban and peri-urban areas, the emphasis should be on recycling which has the win-win advantage of also reducing environmental pollution, if problems such as harmful pathogens and the heavy metal concentrations in urban wastes can be solved.

- In crop production systems in both high and low potential areas, the efficiency of P fertilizer use should be improved through better timing and placement of P. Plant breeding that improves the yield of crops per unit of P uptake is more sustainable approach than selecting plant varieties that scavenge P in the soil and hasten the decline of soil P reserves. The use of modern tools such as precision agriculture to enhance spatial efficiency of P applications, or decision support systems that help set application rates or provide a systematic basis for assessing the agronomic effectiveness of P rock, taking account of: (1) chemical and physical properties of PR that affect its solubility; (2) soil properties; (3) management practices; (4) climate; and (5) crop species (Chien *et al.* 2009) should be advocated. Biological innovations to improve P uptake, such as inoculation with VA mycorrhiza or the use of P accumulating plants such as *Tithonia spp.* for green manuring may offer niche solutions to this intractable problem (Bunch, 1999).

Sustaining agriculture for generations to come will require a scientific community to remain vigilant in the light of multiple threats such as peak phosphorus, climate change, loss of biodiversity, the emergence of new pests or the invasion of species, some of which are difficult to foresee. In the struggle to be prepared, we should not lose sight of the threats that are easy to predict but may not be any easier to handle.

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