Chapter 5
Use: What is Needed to Support Sustainability?

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Abstract Increased demands for agricultural output per unit of land area must be met in a way that encourages improved efficiency and better stewardship of natural resources, including phosphate rock. Modern crops remove between 5 and 35 kg P/ha, with P removal exceeding 45 kg P/ha for high-yielding maize. In situations such as Sub-Saharan Africa, where soil fertility is low and P removal exceeds average inputs of 2 kg P/ha/year, the resulting nutrient depletion severely restricts yields (e.g., maize yields $<$ 1,000 kg/ha/year) and accelerates soil

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degradation. In other regions, excessive P inputs produce economic inefficiencies and increase the risk of P loss, with negative environmental consequences. During the year of application, plants recover 15–25 % of the added P, with the remaining fraction converting to less soluble forms or residual P which becomes plant available over time. Improving P efficiency requires a balance between the imperatives to produce more food while minimizing P losses. Utilizing transdisciplinary approaches, a number of social, economic, and environmental goals can be simultaneously achieved if progress is made toward short- and long-term food security and global P sustainability. This chapter provides an overview of efforts to improve P use efficiency in agriculture ranging from promising germplasm, improved crop, and soil management scenarios, additives in animal diets to reduce P inputs and surplus P in the manure, and opportunities for P recycling in food and household waste. Challenges and opportunities associated with each option are discussed and transdisciplinary case studies outlined.

Keywords Phosphorus and the food chain · Integrated nutrient management · Phosphorus recovery · Phosphorus losses from use · Improving access to phosphorus

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1 Introduction

1.1 Phosphorus and the Food Chain

Phosphorus (P) is essential in every cell of living organisms. As a limited earth mineral, it is well accepted that greater efforts must be made to improve the use of P in global ecosystems. In addition to avoiding unnecessary losses, the time is right to manage all aspects of the P cycle as a whole process, not just as single pieces that are poorly connected (Fig. 1). To ensure long-term sustainability, consideration needs to be made on how to use P as efficiently as possible, minimize losses and waste, and promote recycling as much as economically feasible. Transdisciplinary approaches are especially suited to this venture, as they allow integration of scientific knowledge with insights gained in everyday practices.

Phosphorus does not become "lost" as it dissipates and cycles through geochemical processes, but the concentration becomes diluted to a point where it is too difficult or expensive to recover using current technology. Phosphorus loss to the ocean is a "natural" and unavoidable process. For example, an uncultivated soil from the Canadian prairies has lost up to 40 % of its total P within 10,000 years of pedogenesis (St Arnaud et al. 1988). However, human activities (including phosphate rock mining, soil tillage, animal production, and industrial/urban discharges) have greatly accelerated the rate and the quantity of P lost to water (Fig. 1). It is clear that excessive P loss to water bodies can have a strong negative impact on water quality, whereas P enrichment in terrestrial systems can cause a shift in native plant species.

Improving P recovery and efficiency while reducing negative environmental effects are the urgent short-term goals, but reducing irrecoverable losses of this finite natural resource will not keep pace with the geological concentration of P supplies without a shift in current approaches to P stewardship. Although P scarcity is not a pressing issue at this time, improving the efficiency of P use would extend the lifetime of global mineral reserves. However, long-range efforts need to converge with the ultimate goal of economic efficient P recovery and recycling.

Projections of global population growth anticipate the need for far more food, feed, and fuel to be produced on a limited amount of productive land. This pressure to increase agricultural output must be done in a way that encourages improved efficiency and better stewardship of natural resources. Appropriate applications of P fertilizer are an essential part of maintaining crop yields by minimally replacing the nutrients removed during harvest. It is reasonable to expect the requirement for P additions to grow in importance as crop intensification increases.

Improving the efficiency of P use in the human food chain will require cooperation of the P mining and fertilizer industry, the agricultural and forest production sectors, the food-processing industry, industrial P users, urban wastewater

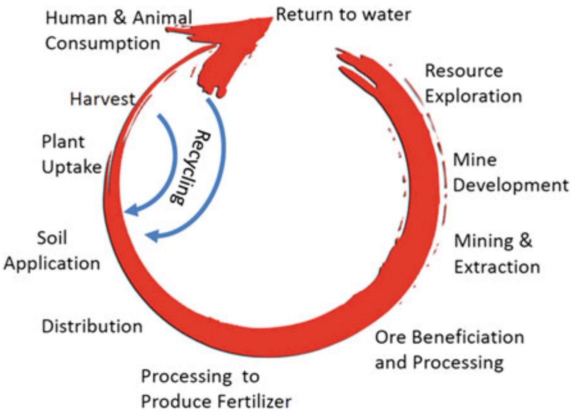

Fig. 1 The primary pathways of P extraction, use, and loss. Opportunities exist at each step for improved P use efficiency

treatment operators, and individual consumers (Hilton et al. 2010). There are significant economic and biological barriers to improving P use efficiency, thus this endeavor will require cooperation of many stakeholders.

The human recommended daily intake is 1 g P/person for maintaining proper health. This translates to an annual global requirement of over 2.5 Mt P (or nearly 6 Mt of P_2O_5 fertilizer equivalents). The actual amount of P consumed in daily diets is often much greater than this, so providing a reliable assessment on the world level is difficult. But since the average consumption is likely 3 g P/person/day (Smil 2000; Smit et al. 2009; Scholz and Wellmer 2013), the conversion of mined phosphate rock to edible human food is low and amounts only to 15–20 % (Schröder et al. 2011; Suh and Yee 2011), leaving ample room for improved efficiency. The unutilized P most commonly ends up stored in soil for subsequent crops or is transferred to water bodies through runoff, erosion and, to a lesser extent, leaching (Granger et al. 2010).

1.2 The Use of Chemically Processed Phosphorus Fertilizer

The majority of mined phosphate rock (>80 %) is processed to produce soluble fertilizers for plant nutrition. The insoluble phosphate rock (apatite) is first reacted with a strong acid to dissolve the raw mineral and form water-soluble compounds that will be available for plant uptake in the soil. Without the reaction with acid, apatite is very slow to dissolve in most agricultural soils and the rate of soluble P release is too slow to be of significant value for plant nutrition. There are, however, some sources of phosphate rock that dissolve sufficiently rapid in acidic soils to be a valuable source of P plant nutrition without first treating it with acid (Smalberger et al. 2006).

The discovery of this acid-treatment process in the 1840s marked the beginning of the modern P fertilizer industry and was a major advance in understanding plant nutrition. Since that time, considerable progress has been made to better understand P chemical reactions and plant nutrition. During the 20th century, the P fertilizer industry emerged as a fundamental partner in supporting the global food production system. As the demand for crop production increases, the global demand for additional P fertilizer also increases.

Since an inadequate concentration of P limits plant growth in many parts of the world, the chemistry of P fertilizer is one of the most studied topics in soil and plant nutrition (Hedley and McLaughlin 2005). Numerous global studies have repeatedly demonstrated that only a relatively small proportion of P annually added to agricultural soils ends up in the harvested product in the year of application (Syers et al. 2008).

Efficiency is commonly determined by measuring the amount of material "going in" (a field, watershed, or a nation) and comparing that with the quantity removed (such as a harvested crop). The quantities of soluble P added in excess to plant needs and remaining in the soil profile can react with Al and Fe oxides or with Ca and Mg carbonates depending on the soil pH and mineralogical properties of these sorbents. These reactions result in the conversion of soluble P to less soluble residual P forms that are not immediately available to the annual crop. The value of this accumulated residual soil P is difficult to quantify, but it makes an important contribution to plant nutrition for many years following the initial fertilizer application.

The high crop yields desired for food security, economic profitability, and farm sustainability place a significant demand on soil nutrient reserves. Modern crops remove between 15 and 35 kg P/ha for cereals, 15–25 kg P/ha for many leguminous and root crops, and 5–15 kg P/ha for vegetables and fruits. Phosphorus removal of over 45 kg P/ha can be seen in high-yielding maize and sugar crops. Modern high-yielding cultivars remove more P during harvest than during the mid-twentieth century. For example, Edwards et al. (1997) showed that English wheat removed about 7 kg P/ha in 1950, 13 kg P/ha in 1975, and about 20 kg P/ha in 1995.

Many regions of the world have soils that are P deficient. For example, there are many smallholder farms in East, Central, and Southeast Asia and Sub-Saharan Africa, where the lack of access to P fertilizers (MacDonald et al. 2011) and prolonged nutrient mining has led to severe land degradation (Craswell et al. 2010). Moreover, unsustainable agroecosystem management in these areas, such as burning or feeding of crop residues and shifts to more nutrient-demanding crops, results in severe soil erosion and drains on soil nutrient capital (Quinton et al. 2010; Vitousek et al. 2009). Large areas of once-productive soils have been abandoned due to soil degradation. At the same time, many farming areas in East Asian floodplains, North America, Europe, and parts of Latin America have a history of repeated P use, resulting in a buildup of the soil P reserve (IPNI 2010; MacDonald et al. 2011).

Calculating a P balance is a common way to estimate whether soils are becoming enriched or depleted in nutrients over time. All the nutrient inputs added to a field, watershed, or country are compared with the nutrients removed in the harvested portion of the crop and the P lost through erosion and surface runoff. Vitousek et al. (2009) conducted a P balance for three regions and found that they ranged to positive in North China (>50 kg P/ha/year), to neutral (Western Kenya) to negative balances in the Midwest USA (−9 kg/ha/year). The negative balance in the USA reflects current nutrient removals exceeding inputs following a history of P fertilizer and manure applications during 1970–1995 where additions were in excess of crop removal. Differences in current P balances in these three regions clearly demonstrate the need for targeted management strategies to sustain productivity.

A study by Richards and Dawson (2008) examined the P balance of the 27 European Union countries. They estimated that net imports to agricultural soil in these countries were 2 Mt P/year. This input is equivalent to an addition of 18 kg P/ha, with an average removal of 10 kg P/ha/year, resulting in an average surplus of 8 kg P/ha/year. This surplus does not mean that all soils in the EU are receiving an annual excess of P, but raises awareness that there are areas where P is accumulating and that those soils should be monitored to avoid excess P accumulation and potential negative environmental impacts. Positive P balances of agricultural systems are necessary during the soil-building phase, but the inputs of P will likely decrease over time as soil P concentrations reach the optimum level for crop production. Most farmers would not invest money in P fertilizer if the soil already contained adequate P and the likelihood of a return on investment was low. The surplus P situations most frequently occur as a result of livestock production and the difficulty of transporting manure to areas that would benefit from the nutrients. In these surplus-manure regions, government policies are often helpful to provide incentives for improved P management. For example, the introduction of nutrient subsidy schemes in Switzerland contributed to a decrease of the P surplus in agriculture from about 27 kg P/ha/year in 1980 to about 5 kg P/ha/year in 2008 (Spiess 2011; Lamprecht et al. 2011).

1.3 Phosphorus and Forestry

Forests cover about one-third of the total land surface of earth (FAO 2009). Besides providing fuelwood, which is still the largest use of wood worldwide, forests provide a number of timber and non-timber products. Forests also provide a range of vital environmental services (such as a reserve of biodiversity, C sink, protection against natural hazards, water fluxes regulations, and water purification). In the next decades, the demand for forest products will grow, and the provision of environmental services from forests will still be crucial.

Forest trees, like all organisms, need P to grow. For instance, the annual P needs of *Pinus* plantations have been estimated to be 10 kg P/ha to maintain leaf area index for optimal growth (Fox et al. 2011). However, apart from forest plantations where fertilization is common, forests rarely receive any fertilizers (Fox et al. 2011). In Switzerland, it is almost forbidden to apply any kind of fertilizers to forests. Although forest vegetation has developed very sophisticated mechanisms to survive and in some instances thrive on low P soils (Reed et al. 2011), there are signs that non-fertilized forests might become P limited in the next future. For instance, a significant decrease in P concentration has been observed in Eastern France in the leaves of 118 beech stands between 1970 and 1996 (Duquesnay et al. 2000). This can be related to the accelerated rates of P depletion from forest soils due to an increased use of wood for energy, to excessive N loads from atmospheric deposition (Genenger et al. 2003) leading to P limitation of tree growth (imbalanced nutrition), and to soil acidification which can increase P sorption on soil and decrease root growth. For example, in 1999, Switzerland was producing 25,000 t/yr of wood ash that could not be applied back to forest soil. Finally, climate change may also lead to an increased P requirement, as trees need higher P concentration to resist to drought (Duquesnay et al. 2000). In conclusion, the need for P fertilization might also increase in forest systems in the future.

1.4 Phosphorus in the Food Chain

When studying the whole global food chain, inefficiencies of P occur both during and after the production process. These apparent inefficiencies include accumulation in soil (4.5 Mt/year), erosion (8 Mt P/year); crop losses due to pests, diseases, and natural destruction (3 Mt P/year); post-harvest losses (0.9 Mt P/year); and losses at distribution, retail, and household level (1.2 Mt P/year) (Cordell et al. 2009). It is important to distinguish between true P losses (at a defined scale, such as erosion) and temporary factors that influence short-term P efficiency (such as drought-induced crop failure). Worldwide, the total amount of P consumed directly by humans has been estimated to be about 3 Mt P/year (Cordell et al. 2009).

Crop losses due to pests, diseases, and natural destruction account for 12 % of food in developed and for 22 % of the food in the developing world (Kader 2005). In some developing countries, this loss increases up to 40 % at the farm itself and 15 % during processing and storage. A close examination of P recovery of these post-harvest losses is needed in order to improve overall efficiency. In particular, appropriate mechanisms relevant for developed and developing countries should be considered.

At the retail and household level, food losses account for about 20–30 % of total production in developed and 10 % of total production in developing countries

(Kader 2005). A study in the UK showed that of the food (7 Mt/year) and drink (1.3 Mt/year) waste generated yearly in the UK, about 4.5 Mt (food) and 0.8 Mt (drink) would be potentially avoidable, and an extra 1.5 Mt (food only) would be possibly avoidable (Parfitt et al. 2010). In addition to the P savings that the reduction in food losses would confer, significant economic savings would also be expected.

1.5 Non-fertilizer Phosphorus Uses

About 10 % of the 24.5 Mt/yr of elemental P, which is currently mined, is used for non-fertilizer purposes (Jasinski 2011; Prud'homme 2010). This non-fertilizer P is used (a) as animal feed additive (about 7 %), which becomes part of the agricultural food chain, (b) as an additive of processed food and beverages such as dark sodas (1–2 %) [e.g., Coca Cola making up 0.01–0.02 % of total P consumed in Switzerland, Binder et al. (2008)], or (c) as an element of pharmaceutics and industrial uses such as detergents, metal treatment, and other industrial applications 9 % (Prud'homme 2010; Schröder et al. 2010).

2 Opportunities to Improve Phosphorus Use

With the complexities and challenges associated with improving the use of the global P supplies, three concurrent strategies can be proposed. The first approach suggests that the mining of phosphate rock and the processing of fertilizer can be improved to extend the known resources. The second path entails improving the efficiency of P use in agricultural production, food processing, industrial applications, and recovery from waste streams. The third approach is to change the demand for P use in various applications. Of these options, this chapter highlights some of the bottlenecks to improving P use in agriculture. We look first at different components of agricultural systems (mineral fertilizer, manure, plant) and then at the system in its entirety. This is done in the frame of integrated nutrient management (INM), which is presented thereafter. Some of the barriers for improving P use efficiency are constrained by scientific knowledge, by economics, or by social and political barriers—once again highlighting the need for transdisciplinary solutions.

2.1 Integrated Nutrient Management

INM is a comprehensive approach taken for improving nutrient use efficiency by crops and animals while decreasing nutrient losses to the environment (Frossard et al. 2009). To achieve these goals, INM must consider all the components involved in nutrient cycling (climate, soil, plants, animals, all inorganic and organic nutrient sources) as well as the relevant socioeconomic factors such as the production preferences of farmers, the food preferences of consumers, markets, and trade. From a biophysical standpoint, INM can include the input of exogenous nutrients that deliver available nutrients to plants when and where necessary, the use of crops with a high nutrient acquisition efficiency, nutrient recycling through the introduction of improved green manures, proper reuse of animal manure and urban wastes, and the decrease in nutrient losses by minimizing erosion, leaching, and runoff. Most of these points are discussed below for improving P use efficiency.

2.2 Soil Testing and Phosphorus Recommendations

It was estimated that crop growth on about two-thirds of farmland in the world is limited by insufficient P concentrations in soils (Cakmak 2002). To overcome this limitation, farmers have adapted many ways to provide the needed P, including using mineral fertilizer, animal wastes, composts, and various recycled materials to compensate for the P removed in the harvested crops and animals.

A fundamental issue is how to determine the appropriate amount of P to add to soil to meet crop production goals? Insufficient P fertilization risks a loss of crop yield and quality, while excessive fertilization poses economic inefficiency and a heightened risk of P losses with negative environmental impacts.

Chemical analysis of agricultural soils is widely accepted in developed countries as the primary technique to predict the need for additional P. There are many techniques and interpretations, which are adapted to local crop and soil properties. Unfortunately, costs associated with soil sampling and laboratory analysis, as well as access to laboratories limits this important tool in many parts of the world. Where chemical tests are not feasible, local research using the "omission plot" technique can identify the probability that P will improve plant growth.

Without access to information on the need for P on specific fields, farmers are left to guess the likelihood of P response based on factors such as historic fertilization practices, the amount of P required to compensate for crop removal, the quantity of P fertilizer that is affordable, and generalized soil fertility recommendations for the region. All of these factors can lead to either under- or over-fertilization. Modern fertilization practices should not rely on "insurance" doses of P, but should be based as much as possible on site-specific information of the local needs.

Soil testing is helpful to estimate the amount of P that will likely be available for plant uptake during the coming growing season, but less useful as a predictor of the long-term value of P held in relatively insoluble soil compounds.

2.3 Fertilizer Placement and Residual Phosphorus

Improving the placement of P fertilizer can benefit short-term P recovery by plants. For example, in the Netherlands, according to fertilizer recommendations, for a similar yield response twice as much P is needed if the fertilizer is broadcasted on the soil surface rather than positioned at the subsurface close to seed rows (Schröder et al. 2010). Since P is relatively immobile in most upland soils, it should be placed as close to the roots as practical. Specialized equipment that allows P to be injected (or knifed) into the soil increases the short-term recovery of P; placing P on the soil surface separates it from the active root zone and leaves it vulnerable to loss with runoff water. Tilling the soil to incorporate P deeper into the root zone carries the heightened risk of erosion if sediment is carried off the field. Compromises are sometimes made in deciding where P placement is optimal. Repeated P application onto the soil surface produces a stratified zone of nutrients, which may not be accessible to the deeper roots of many plants and pose a greater risk of P loss in runoff.

Plants only assimilate a small proportion of the fertilizer P in the first year following application. Most of the fertilizer remains in the soil in association with the mineral and the organic fractions of soil, largely unavailable for short-term plant uptake. Traditional soil testing only measures the P associated with the inorganic fraction, while soil organic matter can be an important reservoir for a large proportion of the total soil P.

During the year of application, plants may only recover 15–25 % of the added P. This low apparent recovery has caused considerable concern about P efficiency. Recovery is typically calculated as follows (Chien et al. 2012):

$$\mathbf{\%\ P\ recovery = [P\ in\ the\ fertilized\ plant - P\ in\ the\ unfertilized\ plant] / P\ applied \times 100}$$

However, the remaining fraction of freshly added P (75–85 %) remains in the soil, where it is slowly released over time. Once adequate P has accumulated in the soil, high-yielding crop production can often be maintained for several years without requiring further P additions. Many examples are available that demonstrate maintenance of high yields with reduced P inputs once an adequate supply of P has been accumulated (Gallet et al. 2003).

Results from long-term research suggest that P efficiency can exceed 90 % when a “balance method” is used for the calculation (Syers et al. 2008). The balance method considers the ratio of P uptake from a fertilized soil divided by the amount of P applied. This approach yields valuable information regarding P accumulation or depletion, but does not consider the amount P mined from soil without the addition of fertilizer (Chien et al. 2012).

2.4 Fertilizer Products

Most of the P added for plant nutrition comes from highly soluble fertilizer sources such diammonium phosphate (DAP), monoammonium phosphate (MAP), and triple superphosphate (TSP). The high degree of water solubility that is provided by these fertilizers is not always justified from an agronomic viewpoint (Engelstad and Hellums 1992). It would be feasible in many conditions to use P fertilizer materials with a lower degree of solubility (measured with water and citric acid) and still achieve the same agronomic results. This would allow more of the lower-grade phosphate rock to be used for plant nutrition and result in less P discarded in the processing waste.

Unprocessed phosphate rock can be a useful source of nutrients in certain conditions (IFA 2013). The best predictor of agronomic performance for phosphate rock is its solubility (usually measured in a dilute solution of ammonium citrate or citric acid). Direct use of phosphate rock is best in acid soils ($pH < 5.5$) that have a high capacity to retain P. A low calcium concentration and high soil organic matter will enhance the agronomic performance of phosphate rock. Unlike water-soluble P fertilizers, there are specific factors (such as the rock reactivity, soil properties, management practices, and crop species) that must be considered before using phosphate rock (Smalberger et al. 2006).

2.5 Plant Recovery

Efforts to modify crops to be more efficient in recovering soil P also hold promise. Young plants and some plant species have limited root length and surface area that hinders the acquisition of P. Genetic research is underway to select plants that have more effective root architecture and abundant root hairs. The organic exudates excreted from roots play an essential role in solubilizing soil P. The release of organic acids solubilizes a portion of the inorganic P compounds for uptake. Root-excreted phosphatase enzymes are thought to hydrolyze organic P-containing compounds to inorganic phosphate.

Continuing work is underway with microbial additives that can assist with P nutrition, including promoting the association of mycorrhizal fungi with plant roots. This fungal symbiosis is an important mechanism for supplying P to plants, but limited progress has been made on improving this process for major food crops. This topic was thoroughly reviewed by Richardson et al. (2011).

2.6 Bioenergy Crops

The increased cultivation of bioenergy crops puts an additional drain on soil P reserves (CAST 2013). When crop biomass and residues are removed from the field in addition to grain or oilseed to produce bioenergy, there is less opportunity for nutrient recycling. The P removed in plant biomass should be returned to the cropland where the feedstocks were produced whenever possible. If bioenergy crops are grown on poor or marginal land in order to avoid competition with food production, it is probable that there will be a need for additional P fertilization to meet the crop requirements.

When grain or oilseeds are used for ethanol or biodiesel production, most of the P is concentrated in the coproducts (such as dried distiller's grain with solubles or canola meal). These P-rich by-products make excellent feed materials for animals. When this P is excreted in manure, it should be properly managed, like all P sources.

2.7 Increasing Phosphorus Use Efficiency at the Cropping System

Recent reviews have summarized how different components could be combined to improve P use efficiency at the cropping/grassland system level (Oberson et al. 2011; Simpson et al. 2011). This includes using adapted plant germplasm, better crop rotations to improve soil structure and plant health, appropriate use of both mineral and organic fertilizers, and appropriate soil preparation techniques to reduce erosion.

For example, Johnston and Dawson (2010) showed that organic matter additions improved soil structure, which promoted root health and greater P availability. In their Rothamsted field experiments, a 60 % increase in soil organic matter content (raised from 15 to 24 g kg^{-1} reduced the critical P concentration (from 46 to 17 μg P kg^{-1}) needed to achieve maximum yields. The soil organic matter improved the soil structure, so that root growth improved and acquired additional plant-available P.

Balanced nutrition, where the soil's nutrient-supplying capacities are maintained in relative balance to crop needs, is also essential for getting maximum P use efficiency. Phosphorus is just one of the many essential mineral nutrients that are supplied from soil. There are many examples where a shortage of one nutrient limits the uptake of several other nutrients and stunts overall growth. Phosphorus cannot be viewed in isolation from other factors that stimulate growth including maintenance of soil organic matter content and soil pH. Soil pH affects the availability of all plant nutrients, but has the greatest effect on P and several micronutrients.

2.8 Decreasing Phosphorus Loss from Soil

Soil erosion is the greatest source of P loss from cropped soils, while grassland soils lose more P through surface water runoff. Management practices that limit the loss of sediment-bound P will help avoid P-induced water quality problems. There are many cultural practices that can reduce soil and P losses including retention of crop residues on the surface, reduced tillage practices, subsoil tillage to improve water infiltration, terracing and contour tillage, use of cover crops, and conversion to perennial crops. Chemical additives, such as polyacrylamide, are effective at reducing sediment loss from fields by binding soil particles together.

Changing land use and management practices can limit P losses to water. Grassland and forests have the benefit of a permanent canopy that helps reduce runoff and enhance infiltration. Various management practices, such as planting field-edge vegetative buffer strips (riparian or grassland), have been shown to reduce P loss in runoff from agricultural land.

2.9 The Use of Phosphorus for Livestock Production

When crops and nutritional supplements are fed to animals and converted into animal products, there is a large inefficiency in P recovery. Only a fraction of the P present in the animal feed is converted into economic products such as milk, meat, eggs, or wool. The remaining P is excreted in manure and urine where it can be used as a valuable resource if it collected and applied back to cropland (Tarkalson and Mikkelsen 2003; Nelson and Mikkelsen 2005).

To avoid potential limitations to growth, animal producers in developed nations routinely add mineral P supplements to the feed ration to insure against deficiencies. Globally, between 5 and 8 % of the P use goes toward animal nutrition products (Schröder et al. 2010). Adjusting the amount of mineral P added to animal diets to reflect the actual P present in the feedstuffs can minimize the P excreted in manure and urine, but requires an advanced understanding of animal nutrition. Decreasing the quantity of P added to the diets as animals mature (phased feeding) also limits P excretion. The addition of phytase to the diets of nonruminant animals can enhance the nutritional availability of relatively indigestible organic P compounds present in plants (especially phytic acid present in seeds and grains). New plant varieties have been developed that contain less phytic acid in the seed. Such dietary adjustments can greatly reduce P inputs in the animal feed and the surplus of P in the manure (Cromwell 2005).

A major hurdle with intensive animal husbandry is to effectively use manure to sustain all plant nutrients in the sufficiency range for plant growth (Mikkelsen 2000a). The relatively low nitrogen to P ratio in most manure is the reverse of the plant requirement, which frequently leads to P accumulation in soils when manure is applied to meet the N needs of crops. Manure application rates need to be adjusted to meet the P requirement to avoid this accumulation. Uniform application of bulky and nonhomogenous material can also pose challenges.

Recycling organic manures in agricultural operations should be a fundamental principle in sustaining productive agriculture in mixed crop–animal production systems; however, this can be difficult to achieve in practice (Mikkelsen 2000b). The major problem with P for intensive animal production in North America is the separation of the feed-production areas from the animal-production areas. Since the challenge and expense associated with transporting manure over significant distances is difficult to overcome even with government regulatory or financial incentives, manure is too frequently applied to the most convenient fields.

Animal manures serve as a large pool of potentially recoverable P. Manure and animal waste products annually generate over 20 Mt P. When the animals are raised in confined areas, there is reasonable expectation to collect the manure and uniformly distribute it back on to crop production fields when possible, which is currently the case for about 50 % of the manure produced (Cordell et al. 2009). For the other 50 %, mostly free ranging or grazing animals, it is not generally feasible to collect manure, which leads to uneven distribution of manure and P. Additionally, grazing animals tend to congregate near water or shelter, leaving manure poorly distributed across the field. The fertilizer industry has repeatedly looked at how animal-derived nutrient sources can be incorporated into wide-scale crop production, but a suitable economic model has not yet been developed.

Various approaches have been proposed or tested to reduce P losses from manure-amended soils. For example, chemical treatments such as aluminum chloride (alum) added to manure have been shown to reduce soluble P and losses in runoff. Chemical additives might, however, have only a short-lasting effect (Schärer et al. 2007). Regardless, their additions cannot solve the problem of P inputs added in excess to crops' needs observed in systems with a high density of animals.

Experimental pigs have been genetically modified to produce more salivary phytase, allowing them to use the grain P much more efficiently ("enviropigs," Golovan et al. 2001). The public acceptance of these animals is not yet known, and whereas this genetic modification indeed significantly reduces the concentration of P in the manure, it does not address the emission of other nutrients which can be problematic in intensive swine production.

The P in animal wastes and composts is present in variable proportions of soluble P and scarcely soluble inorganic and organic P compounds (Oberson et al. 2010). The organic P compounds require microbial transformation for conversion to plant-available forms. The time required for the mineralization can range from days to years, depending on environmental factors and the type of organic compounds present.

A number of techniques have been developed to extract and recover P from animal manure. Several companies currently treat animal wastes and produce inorganic P compounds (such as calcium phosphates and magnesium ammonium phosphate or struvite) that can be used as commercial fertilizer.

From an efficiency view, the key issue is that P that is not retained in the animal should be recovered and returned to the field where the feed originated. There are many global examples where this is not being properly done, resulting in excessive P accumulation and potential water quality problems near the animal farms. Nutrient depletion is inevitable in the crop-producing areas unless the soils are supplied with supplemental P to replace the harvested P. There are a number of issues including economic constraints (such as expense and energy required to transport relatively dilute manure or to concentrate or dry it) that challenge the full recycling potential of animal wastes and pose a serious hindrance to improving global P efficiency.

3 Opportunities to Improve Phosphorus Use at the Societal Level

3.1 Postharvest, Retail, and Household Level

Large-scale food processing in developed countries is frequently contained in a closed process, making it easier to recover P. In less developed countries, it may be more challenging to recover P from food-processing residues and utilize them in a productive way. However, in both scenarios, there are multiple opportunities to reduce nutrient losses during food storage, processing, and transportation.

After harvest, crops are processed into final products for food, feed, fiber, and fuel. Losses occurring during storage from pests and disease can often be reduced by better management practices. Parts of food that are discarded during processing (such as husks or damaged and under-grade products) also represent a "loss" of P unless they are returned to the fields. Improving this may necessitate additional infrastructure, better management by the processor, and more thoughtful food handling by consumers.

With long and sophisticated food delivery systems that frequently stretch across the globe, care should be taken to minimize food losses. The challenge of dealing with wastes from a global food chain could be simplified by producing food as closely as possible to where it is consumed and then returning the waste products to the agricultural production fields. However, there are serious economic, social, technological, and logistic issues that need to be resolved to implement this ideal.

Huge quantities of food are regularly disposed at the retail level due to spoilage or elapsed expiration dates. To avoid unnecessary wastage, a balance between excessive disposal and food quality and safety must be maintained. Food that is slightly beyond its peak freshness or contains minor cosmetic blemishes should not be automatically disposed.

The loss of food and nutrients in the home is very high in some countries. It is estimated that over 50 % of food waste in some countries is still edible and could be used with better meal preparation and planning. Reasons for food being wasted in the UK are: (1) poor pre-shop planning; (2) not sticking to the shopping list; (3) not understanding the "use by" date and "best before" date; (4) food not stored correctly; (5) no meal planning; (6) cooking too large portions; and (7) poor skills in combining left-overs with fresh food (Parfitt et al. 2010). Thus, a cultural shift to create awareness among consumers is needed at different levels and might start with educational programs in school.

Projections of human population growth estimate that much of this increase will occur in peri-urban areas of developing countries where recycling could still be improved (Kiba et al. 2012a, b). Recycling urban wastes is easier where a large concentration of people is living. By reducing the quantity of food and nutrients going to landfills and sewers, compost or other organic products could be developed to beneficially reuse this resource (Kader 2005).

Recovery of P in household waste is not simple. The food wastes need to be collected and processed at a collection area. The P in human waste can be separated in specialized toilets prior to entering the sewer, but this technology is not widely adopted. Biosolids from waste treatment plants can provide a valuable P source for crops, but issues with public acceptance, sanitation, and the residual constituents must be considered. Phosphorus in sewage sludge ash can be recycled to cropland, but technologies to recycle this P are not widely adopted. In addition to the nutrients contained in biosolids, the organic matter can also be useful for soil improvement. While technologies to treat and recycle waste exist, socioeconomic constraints limit widespread adoption.

The ideal P cycle involves removal of nutrients from the soil by plants, harvest, and ultimate replacement of nutrients back to the soil without any losses. However, a perfectly closed P cycle has never existed (even in unfertilized ecosystems), and there will be some inevitable loss from the relatively leaky biological process of food production. However, the current system of moving large quantities of P from farms to the city without consideration of returning the P and other nutrients to the crop-producing area is short sighted and inefficient. Restoring this linkage is essential for making significant progress in improving P use efficiency.

3.2 Issues of Scale

As the long-term implications of poor utilization of P become better appreciated (such as water quality impacts, land degradation, and potential rock P depletion), a fresh examination of how P is used is timely, but the potential for improving P use efficiency in agriculture and food systems varies significantly by location. Countries that export significant quantities of agricultural products will necessarily have a different P balance than countries that rely on significant quantities of imported food and feed.

Improving P efficiency will involve careful examination of the entire biogeochemical process of this essential nutrient. Solutions to this issue require a balance between the imperatives to produce more food each year while minimizing losses that have wasteful and adverse impacts. The urgency to improve management practices is spurred by the recognition that P is a limited natural resource that plays an irreplaceable role in sustaining plant, animal, and human life. The social acceptance of changes that are made to improve P recycling, recovery, and efficiency will require a significant educational effort and knowledge of transition processes. A number of social, economic, and environmental goals can be simultaneously achieved as progress is made toward short-term and long-term food security and global sustainability. The complexity and regional specificity of the different practices influencing P use can benefit from a transdisciplinary approach to better understand and promote sustainable P use practices.

4 Work in Global TraPs

4.1 Knowledge Gaps and Critical Questions

Although a great deal of technical knowledge exists on ways to efficiently use and recycle P in agriculture, too few studies seek to understand how agricultural policy, financial services, farming technologies, and local capabilities interactively affect decisions about nutrient use and management (Hazell et al. 2007). Additionally, how such decisions affect soil fertility, food productivity, and profitability of the whole farm have not been sufficiently investigated. Human decision making at multiple levels, interactions between agroecosystem's components, and their dynamics over time and space is key to understand sustainable P use. An important first step toward promoting sustainable agriculture is incorporating region-specific parameters, such as how inorganic P fertilizers are being introduced to world regions at different times and with significantly different economic impacts (Elsner 2008).

The challenge of improving P use efficiency highlights important questions that need to be addressed:

- What potential does INM have for supporting soil fertility, improved food production, preservation of water quality, and eventually better livelihoods?
- What strategies can support more effective use of P resources (including manure and fertilizer) in market-oriented farms, so as to decrease vulnerability to fluctuating fertilizer prices and reduce negative environmental impacts?

4.2 Role, Function, and Kind of Transdisciplinary Processes

In order to comprehensively tackle knowledge gaps associated with improving P use, a collaboration of various disciplines (e.g., agricultural and soil sciences, biology, hydrology, environmental science, industrial ecology, economics, water engineering, sociology) and different societal fields/stakeholders (including administration, individual farmers and farmer organizations, fertilizer industry, NGOs, society/consumers) is essential.

Given the diverse tasks/targets of these groups, it is inevitable that decisions on P management can neither be understood nor managed by academia, industry, government, or international organizations alone. There is a need for close collaboration between these groups to create comprehensive knowledge and develop robust strategies. Transdisciplinary case studies allow for addressing highly complex societal problems such as P use, which need multi-perspective approaches and require the ability to deal with different knowledge cores, diverse interests, values, and norms. Through transdisciplinary case studies, optimizations related to closing different P cycles can be achieved, considering critical feedbacks with other cycles and P-related issues. They are especially suited on local/regional level, where the production of place-specific and application-oriented knowledge and transition abilities can be linked. The following examples provide illustrations of transdisciplinary case studies that could help with P sustainability issues at various scales.

4.3 Potential Case Studies

Bavarian P strategies: *Sustainable use of P in Bavaria and integrative transdisciplinary analysis*. Sustainable P management at a regional level implies a balance between processing, agricultural production, food consumption, and waste management. Focusing on key agricultural production and food consumption issues of relevance include: (a) the interrelation of P used for food and energy production, (b) the need for P in food production, (c) the regulatory framework with respect to the use of by-product-generated P, and (d) lifestyles affecting consumer behavior, such as diet (meat versus vegetarian) and the demand for certified food products.

This transdisciplinary case study focuses on the Federal State of Bavaria, Germany. Key research issues are: at which spatial scale of P balancing and trading among farmers should be fostered to reduce the risk of decreasing fertility of the soils, and what is the level of acceptance of “by-product fertilizers” among farmers? Further, the role which various food production systems could play in closing the P loop by linking consumption, waste management, and sustainable production will be examined.

P from animal manure: *Social and institutional constraints for integrating P from intensive animal production into crop production*. A large amount of research has been done to understand the behavior of P derived from animal manure in diverse cropping systems. When utilized properly, manure P can be an excellent nutrient source for sustainable agriculture. However, there are multiple examples where mismanagement of animal manure has resulted in excessive P loss to surface water, with an accompanying degradation of water quality and environmental services.

This case study will compare and contrast various approaches to incentivize more efficient P management in animal manure. Management approaches that involve institutional and government controls will be compared with technological remediation approaches. This will be done through a multi-stakeholder discourse by which the appropriate role of various private and public institutions in successful P management strategies will be assessed.

Modifying cropping systems: *Modifying cropping systems to improve P efficiency*. A number of practical on-farm agronomic techniques have been shown to improve the efficiency of P use. For example, the use of intercropping, cover crops, proper rotations, and integrated soil fertility management have all been demonstrated to have the potential of improving P use efficiency. In addition to the P benefits, the environmental value of these techniques has not been well quantified yet. These cropping system modifications are well suited for small-scale farmers who could immediately benefit from improved P management. However, there are a number of social, cultural, economic, and agronomic factors that can limit the widespread adoption of these practices. There are significant regional differences in farming and social conditions that can also pose significant barriers to adoption.

Appropriate P sources: *Identifying and delivering the most appropriate P source*. Many soils in the world contain insufficient P to sustain high crop yields. When a source of P is available to farmers in these P-deficient regions, it may not be the most appropriate material since they are often forced to rely on whatever P fertilizer is available in the market or is subsidized by the government. Market availability of P does not always equate to the most agronomically desirable material to meet economic, environmental, or production goals.

An analysis of what P fertilizer materials are currently available in the market along with a report on the most agronomically favorable P fertilizers would allow a better match in supply and demand. This would involve a transdisciplinary exchange between fertilizer companies, brokers, traders, and farm groups in developing countries where P deficiencies are common. However, other factors including cost per unit of nutrient, associated transport costs, storage and handling characteristics, availability, total tonnage all have to be considered. Involving market players will allow for better understanding and insight into factors that affect fertilizer demand beyond agronomic performance.

East African P management: *Phosphorus management in East African wheat, potato, and coffee smallholder farms*. Phosphorus management will be evaluated on smallholder farms with three different commodities (wheat, potato, and coffee) in three different agroecological and sociocultural regions of East Africa. Each commodity presents a unique challenge with P use. The case study aims at joint stakeholder research to understand and develop sustainable P management strategies at the farm level considering local conditions (such as local environmental, economic, market, social, and cultural conditions). Farm-specific learning processes and stakeholder interactions will be emphasized.

In the case study, three farmer groups will be engaged to develop insights to current P management in wheat, potato, and coffee production and then explore options for improvement. Based on best practices, recommendations for improved P efficiency may be extrapolated for a commodity within a broader regional context where constraints are similar. However, extrapolation to other commodities may be limited. For example, potato and coffee farmers typically have strong market linkages, but they may face labor constraints while wheat producers may have limited access to adequate markets.

Appropriate P in Vietnam: *Multi-actor strategies for avoiding P overuse (peri-urban) and P underuse (remote uplands) in Vietnamese smallholder farms*. Phosphorus fertilizer management challenges for Vietnamese farmers fall into two categories. (1) Many farmers engage in intensified production to meet market demand for food by applying P fertilizer at adequate or excessive rates to maintain production. However, these farmers frequently fail to use management practices to minimize P losses through runoff and erosion. This group includes smallholder farmers engaged in intensified agricultural production of cereals, fruits, and vegetables and who often produce two to three crops (e.g., rice, vegetables) per year on the same land area. (2) A second group includes poor subsistence farmers who cannot gain access to P fertilizer, leading to poor crop yields, soil degradation, and a cycle of poverty. Therefore, viable options for economically and environmentally efficient P use and recycling in these two agroecosystems need attention. The study considers Vietnam's smallholder systems in the Red River delta (available P fertilizer, market-oriented) and in the Northwest Mountain Region (no P fertilizer access, subsistence) as cases for the two contrasting P use regimes.

The case study will follow a transdisciplinary process focusing on P use in smallholder agroecosystems to form a better integration of scientific and stakeholders' knowledge. This will facilitate stakeholders' understanding about achieving sustainable P use. Stakeholders involved with P management (e.g., national and policy-makers, fertilizer companies, rural development donors and farmer groups) can benefit by improving their understanding of the role of P in long-term approaches to sustainable food production.

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References

Binder CR, Wittmer D, Mouron P, Bieler P, Herren M (2008) Phosphorflüsse in der Schweiz: Stand, Risiken, Optionen, Schlusspräsentation Modul 1, BAFU

Cakmak I (2002) Plant nutrition research: priorities to meet human needs for food in sustainable ways. Plant Soil 247:3–24

Council for Agricultural Science and Technology (CAST) (2013) Food, fuel, and plant nutrient use in the future. Issue paper 51. CAST, Ames, Iowa, USA

Chien SH, Sikora FJ, Gilkes RJ, McLaughlin MJ (2012) Comparing of the difference and balance methods to calculate percent recovery of fertilizer phosphorus applied to soils: a critical discussion. Nutr Cycl Agroecosyst 92:1–8

Cordell D, Drangert JO, White S (2009) The story of phosphorus: global food security and food for thought. Glob Environ Change 19:292–305

Craswell ET, Vlek PLG, Tiessen H (2010) Peak phosphorous—implications for productivity and global food security. In: Proceedings of 19th world conference for soil solutions for a changing world, Brisbane, Australia

Cromwell GL (2005) Phosphorus: agriculture and the environment, Agronomy monograph. In: Sharpley AN et al (eds) Phosphorus and swine nutrition, vol 46. American Society of Agronomy, Madison, pp 607–634

Duquesnay A, Dupouey JL, Clement A, Ulrich E, Le Tacon F (2000) Tree Physiol 20:13–22

Edwards AC, Withers PJA, Sims TJ (1997) Are current fertiliser recommendation systems for phosphorus adequate? Int Fertiliser Soc 404:1–23

Elsner H (2008) Stand der Phosphat-Reserven weltweit (Status of phosphate reserves worldwide). Braunschweiter Nährstofftage. Julius Kühn-Institut, Hannover, Germany, Electronic Presentation, Bundesanstalt für Geowissenschaften und Rohstoffe

Engelstad OP, Hellums DT (1992) Water solubility of phosphate fertilizers: agronomic aspects a literature review. International Fertilizer Development Center (IFDC) paper series P-17, p 27

FAO (2009) State of the world's forest 2009. Food and Agriculture Organization of the United Nations, Rome, Italy

Fox TR, Miller BW, Rubilar R, Stape JL, Albaugh TJ (2011) Phosphorus nutrition of forest plantations: the role of inorganic and organic phosphorus. In: Bünemann E et al (ed) Phosphorus in action. Soil biology 26, Springer, Berlin Heidelberg, pp 317–338

Frossard E, Bünemann E, Jansa J, Oberson A, Feller C (2009) Concepts and practices of nutrient management in agro-ecosystems: can we draw lessons from history to design future sustainable agricultural production systems? Die Bodenkultur 60:43–60

Gallet A, Flisch R, Ryser JP, Frossard E, Sinaj S (2003) Effect of phosphate fertilization on crop yield and soil phosphorus status. J Plant Nutr Soil Sci 166:568–578

Genenger M, Zimmermann S, Hallenbarter D, Landolt W, Frossard E, Brunner I (2003) Fine root growth and element concentrations of Norway spruce as affected by wood ash and liquid fertilisation. Plant Soil 255:253–264

Golovan SP, Meidinger RG, Ajakaiye A, Cottrill M, Wiederkehr MZ, Barney DJ, Plante C, Pollard JW, Fan MZ, Hayes MA, Laursen J, Hjorth JP, Hacker RR, Phillips JR, Forsberg CW (2001) Pigs expressing salivary phytase produce low-phosphorus manure. Nat Biotechnol 19:741–745

Granger SJ, Bol R, Anthony S, Owens PN, White SM, Haygarth PM (2010) Towards a holistic classification of diffuse agricultural water pollution from intensively managed grasslands on heavy soils. Adv Agron 105:83–115

Hazell P, Poulton C, Wiggins S, Dorward A (2007) The future of small farms for poverty reduction and growth. International Food Policy Research Institute Washington, DC

Hedley M, McLaughlin M (2005) Reaction of phosphate by products in soils. In: Sharpley AN et al (eds) Phosphorus: agriculture and the environment, Agronomy monograph, vol 46. Madison, Madison, pp 181–252

Hilton J, Johnston AE, Dawson CJ (2010) The phosphate life-cycle: rethinking the options for a finite resource. Int Fertiliser Soc 668:1–42

International Fertilizer Association (IFA) (2013) Direct application of phosphate rock. http://www.fertilizer.org/ifacontent/download/97688/1430905/version/3/file/2013_ifa_darp.pdf

International Plant Nutrition Institute (IPNI) (2010) Soil test levels in North America. 30-3110. Norcross, GA, USA

Jasinski SM (2011) 2010 minerals yearbook—phosphate rock. U.S. Geological Survey, Washington DC

Johnston AE, Dawson CJ (2010) Physical, chemical and biological attributes of agricultural soils. Proc Int Fertiliser Soc 675:1–40

Kader AA (2005) Increasing food availability by reducing postharvest losses of fresh produce. In: Mencarelli F, Tonutti P (eds) Fifth international Postharvest symposium, Acta Horticulturae

Kiba DI, Lompo F, Compaore E, Randriamanantsoa L, Sedogo PM, Frossard E (2012a) A decade of non-sorted solid urban wastes inputs safely increases sorghum yield in periurban areas of Burkina Faso. Acta Agric Scand Sect B: Plant Soil Sci 62:59–69

Kiba DI, Zongo NA, Lompo F, Jansa J, Compaore E, Sedogo PM, Frossard E (2012b) The diversity of fertilization practices affects soil and crop quality in urban vegetable sites of Burkina Faso. Eur J Agron 38:12–21

Lamprecht H, Lang DJ, Binder CR, Scholz RW (2011) The trade-off between phosphorus recycling and health protection during the BSE crisis, in Switzerland, A “Disposal Dilemma”, GAIA 20, pp 112–121

MacDonald GK, Bennett EM, Potter PA, Ramankutty N (2011) Agronomic phosphorus imbalances across the world’s croplands. PNAS 108:3086–3091

Mikkelsen RL (2000a) Beneficial use of swine by-products: opportunities for the future. In: Proceedings of beneficial uses of agricultural, industrial, and municipal by—products, Soil Science and Society of American Specialists Publication, pp 451–480

Mikkelsen RL (2000b) Nutrient management for organic farming: a case study. J Nat Resour Life Sci Educ 29:88–92

Nelson NO, Mikkelsen RL (2005) Balancing the phosphorus budget of a swine farm: a case study. J Nat Resour Life Sci Educ 34:90–95

Oberson A, Bünemann E, Frossard E, Pypers P (2011) Management impacts on biological P cycling in cropped soils. In: Bunemann E (ed) Phosphorus in action. Soil biology, vol 26. Springer, Berlin Heidelberg, pp 431–458

Oberson A, Tagmann HU, Langmeier M, Dubois D, Mäder P, Frossard E (2010) Fresh and residual phosphorus uptake by ryegrass from soils having different fertilization histories. Plant Soil 334:391–407

Parfitt J, Barthel M, MacNaughton S (2010) Food waste within food supply chains: quantification and potential for change to 2050 Phil. Trans R Soc B 365:3065–3081

Prud'homme M (2010) Peak phosphorus: an issue to be addressed. Fertilizers and agriculture, International Fertilizer Industry Association (IFA), Feb 2010

Quinton JN, Govers G, van Oost K, Bardgett RD (2010) The impact of agricultural soil erosion on biogeochemical cycling. Geo Nat 3:311–314

Reed SC, Townsend AR, Taylor PG, Cleveland CC (2011) Phosphorus cycling in tropical forests growing on highly weathered soils. In: Bünemann E (ed) Phosphorus in action. Soil biology, vol 26. Springer, Berlin Heidelberg, pp 339–369

Richards IR, Dawson DJ (2008) Phosphorus imports, exports, fluxes and sinks in Europe. Int Fertiliser Soc 638:1–28

Richardson AE, Lynch JP, Ryan PR, Delhaize E, Smith FA, Smith SE, Harvey PR, Ryan MH, Veneklaas EJ, Lambers H, Oberson A, Culvenor RA, Simpson RJ (2011) Plant and microbial strategies to improve the phosphorus efficiency of agriculture. Plant Soil 349:121–156

Schärer M, Stamm C, Vollmer T, Frossard E, Oberson A, Flühler H, Sinaj S (2007) Reducing phosphorus losses from over-fertilized grassland soils proves difficult in the short term. Soil Use Manage 23:154–164

Scholz RW, Wellmer FW (2013) Approaching a dynamic view on the availability of mineral resources: what we may learn from the case of phosphorus? Glob Environ Change 23:11–27

Schröder JJ, Smit AL, Cordell D, Rosemarin A (2010) Sustainable use of phosphorous. Report No. 357. Plant Research International, Wageningen, NL

Schröder JJ, Smit AL, Cordell D, Rosemarin A (2011) Improved phosphorus use efficiency in agriculture: a key requirement for its sustainable use. Chemosphere 84:822–831

Simpson RJ, Oberson A, Culvenor RA, Ryan MH, Veneklaas EJ, Lambers H, Lynch JP, Ryan PR, Delhaize E, Smith FA, Smith SE, Harvey PR, Richardson AE (2011) Strategies and agronomic interventions to improve the phosphorus-use efficiency of farming systems. Plant Soil 349:89–120

Smalberger SA, Singh U, Chien SH, Henao J, Wilkens PW (2006) Development and validation of a phosphate rock decision support system. Agron J 98:471–483

Smil V (2000) Phosphorus in the environment: natural flows and human interferences. Annu Rev Energy Environ 25:53–88

Smit AL, Bindraban PS, Schroder JJ, Conijn JG, van der Meer HG (2009) Phosphorus in agriculture: global resources, trends and developments. Plant Research International B. V, Wageningen

Spiess E (2011) Nitrogen, phosphorus and potassium balances and cycles of Swiss agriculture from 1975 to 2008. Nutr Cycl Agroecosyst 91:351–365

St Arnaud RJ, Stewart JWB, Frossard E (1988) Application of the "pedogenic index" to soil fertility studies in Saskatchewan. Geoderma 43:21–32

Suh S, Yee S (2011) Phosphorus use-efficiency of agriculture and food system in the US. Chemosphere 84:806–813

Syers JK, Johnston AE, Curtin D (2008) Efficiency of soil and fertilizer phosphorus use. FAO fertilizer and plant nutrition bulletin 18. Food and Agriculture Organization of the United Nations, Rome, p 108

Tarkalson DD, Mikkelsen RL (2003) A phosphorus budget of a poultry farm and a dairy farm in the Southeastern U.S. and the potential impacts of diet alterations. Nutr Cycl Agroecosyst 66:295–303

Vitousek PM, Naylor R, Crews T, David MB, Drinkwater LE, Holland E, Johnes PJ, Katzenberger J, Martinelli LA, Matson PA, Nziguheba G, Ojima D, Palm CA, Robertson GP, Sanchez PA, Townsend AR, Zhang FS (2009) Nutrient imbalances in agricultural development. Science 324:1519–1520

Appendix: Spotlight 6

Health Dimensions of Phosphorus

James J. Elser

Phosphorus is an essential element for all living things, needed (in the form of phosphate, PO_4) in cells for construction and renewal of DNA & RNA, of phospholipids, and of energy transduction molecules such as ATP. In vertebrates, PO_4 (P_i, hereafter) is a main component of the mineral apatite (a form of calcium phosphate) in bones. Thus, human health depends on an adequate dietary supply of P every day (DACH 2008, Reference Values for Nutrient Intake): 700 mg for an adult, 500–1,250 mg for children and youth). The body tightly regulates P_i homeostasis, primarily by modulating P_i excretion in the kidney, closely in concert with calcium (Ca) due to their joint role in bone formation.

Deficiency

Deficiencies of P are well studied in association with Vitamin D metabolism, as Vitamin D regulates levels of Ca and P in the bloodstream and thus controls bone growth and remodeling (Perwad and Portale 2011). Vitamin D deficiency leads primarily to bone fragilization (“rickets”), a relatively rare condition in the modern world. Direct deficiency of P (“hypophosphatemia”) is also relatively rare for humans nowadays, as P_i is relatively abundant in many foods and easily assimilated in the gut. However, it can occur independent of Vitamin D deficiency in, for example, cases of general malnutrition, alcoholism, damage to the gastrointestinal tract, or tumors that produce the P_i-regulating hormone FGF23.

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Excess

Elemental P: Nearly all P on Earth is in the oxidized form, as phosphate (PO_4). However, various industrial processes involve production and use of two molecular forms of elemental P: white phosphorus (P_4) and red phosphorus (a polymer based on the P_4 unit). These forms of P are used in production of matches, munitions, and illicitly methamphetamines. Elemental P is highly unstable and reactive, readily reacting with oxygen. Thus, exposure to elemental P is damaging to tissues, and use and exposure in industrial settings are usually subjected to close regulation.

Dietary PO_4 and kidney dialysis: A significant challenge facing kidney disease patients is proper regulation of body PO_4 because existing dialysis methods are relatively inefficient in removing PO_4 (Kuhlmann 2007). Thus, patients with kidney disease often exhibit excess serum phosphate ("hyperphosphatemia") that must be addressed using PO_4-binding medications and/or by reducing levels of dietary P intake. The latter can be challenging because foods with high P content are often the same as those with high protein content (thus patients can become protein deficient) and because many foods contain PO_4 additives used as preservatives (e.g., deli meats, many processed foods) or flavorants (e.g., phosphoric acid in some soft drinks).

Dietary PO_4, cardiovascular disease, aging, and cancer: The health risks of P are well established for elemental forms and for patients with kidney disease. However, tentative epidemiological and animal data also suggest link between P_i intake (both high and low) and certain degenerative diseases and cancers. For example, P_i has been called the "new cholesterol" (Ellam and Chico 2012) due to evidence linking high P_i intake to cardiovascular disease via a mechanism in which P_i reacts with Ca in formation of mineral plaques that contribute to atherosclerosis ("hardening of the arteries"). The reader should bear in mind, however, that such epidemiological studies cannot conclusively establish such links and considerably more work is needed. Some data connecting elevated P_i intake to accelerated aging have recently appeared, in the form of studies of mice-bearing mutations in the gene Klotho (John et al. 2011), which acts with FGF23 to regulate kidney P_i transport. Mice lacking either FGF23 or Klotho show hyperphosphatemia and develop multiple aging-like symptoms. This work is in a preliminary stage and has not been extensively evaluated for its relevance to humans. Finally, it has recently been proposed that dietary P_i has a mechanistic link to tumor progression because of the high P demands needed to construct ribosomal RNA in rapidly growing tumor cells (Elser et al. 2003). Tentative support for this hypothesis has appeared from comparative study of human tumors (Elser et al. 2007) and experimental dietary P manipulations in mice (Wulaningsih et al. 2013). As with P_i's possible association with aging, much further work remains to confirm or reject a putative connection to human cancer.

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References

Camalier CE, Young MR, Bobe G, Perella CM, Colburn NH, Beck GR, Jr. (2010) Elevated Phosphate Activates N-ras and Promotes Cell Transformation and Skin Tumorigenesis. Cancer Prevention Research 3 (3):359-370. doi:10.1158/1940-6207.capr-09-0068

DACH (2008) Referenzwerte für Nährstoffzufuhr, 3rd edn. http://www.sge-ssn.ch/de/ich-und-du/rund-um-lebensmittel/Referenzwerte-fuer-die-Naehrstoffzufuhr/

Ellam TJ, Chico TJA (2012) Phosphate: the new cholesterol? The role of the phosphate axis in non-uremic vascular disease. Atherosclerosis 220(2):310–318. doi:10.1016/j.atherosclerosis.2011.09.002

Elser JJ, Kuang Y, Nagy J (2003) Biological stoichiometry of tumor dynamics: an ecological perspective. BioScience 53:1112–1120

Elser JJ, Kyle M, Smith M, Nagy J (2007) Biological stoichiometry in human cancer. PLoS ONE 10:e1028. doi:10.1371/journal.pone.0001028

Jin H, Xu C-X, Lim H-T, Park S-J, Shin J-Y, Chung Y-S, Park S-C, Chang S-H, Youn H-J, Lee K-H, Lee Y-S, Ha Y-C, Chae C-H, Beck GR, Jr., Cho M-H (2009) High dietary inorganic phosphate increases lung zumorigenesis and alters Akt signaling. American Journal of Respiratory and Critical Care Medicine 179 (1):59-68. doi:10.1164/rccm.200802-306OC

John GB, Cheng CY, Kuro-o M (2011) Role of Klotho in aging, phosphate metabolism, and CKD. Am J Kidney Dis 58(1):127–134. doi:10.1053/j.ajkd.2010.12.027

Kuhlmann MK (2007) Practical approaches to management of hyperphosphatemia: can we improve the current situation? Blood Purif 25(1):120–124. doi:10.1159/000096410

Perwad F, Portale AA (2011) Vitamin D metabolism in the kidney: regulation by phosphorus and fibroblast growth factor 23. Mol Cell Endocrinol 347(1–2):17–24. doi:10.1016/j.mce.2011.08.030

Wulaningsih W, Michaelsson K, Garmo H, Hammar N, Jungner I, Walldius G, Holmberg L, Van Hemelrijck M (2013) Inorganic phosphate and the risk of cancer in the Swedish AMORIS study. Bmc Cancer Unsp 13:257. doi:10.1186/1471-2407-13-257

Appendix: Spotlight 7

Phosphorus in the Diet and Human Health

Rainer Schnee, Haley Curtis Stevens, and Marc Vermeulen

A minimum of phosphorus in human diets is essential for health, because the body needs phosphorus (P) for bones, teeth, DNA, energy metabolism and many other functions. The recommended daily requirement for health (DV) for P is 1,000 mg/day (Council for Responsible Nutrition 2013, based on US Food and Drug Administration data). However, modern Western diets often have higher levels of P, because of improved diets, increased meat and dairy product intake (rich in P, calcium and other minerals) and food phosphates used to ensure safety (bacteria free preservation) or processing of many modern foods, such as cakes, soft cheese, cold meats, pre-prepared meals. Today in Europe, dietary P intake is around 1.3–2.7 g P/day (Flynn et al. 2009). The balance between P and dietary calcium is important.

The dietary contribution of food phosphate additives is around 0.15 g P/day, based on an estimate by the Phosphoric Acid and Phosphates Producers Association of 25,000 t P/year in food additives for EU25 in 2006. This is well below the MTDI (Maximum Tolerable Daily Intake) for food phosphates considered safe (JECFA 1982). The large majority of P in diets comes from natural sources, such as milk and dairy products, meat and many other foods.

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For patients with kidney problems, it is generally recognized that P accumulation in the body can cause significant health damage. This is because P is normally balanced in the body by excretion of unneeded intake by the kidneys.

A number of studies suggest a statistical relationship between blood phosphorus concentrations (serum P) and indicators of cardiovascular disease (CVD) in the general population. Some recent studies (Westerberg et al. 2013; Itkonen et al. 2013), however, show no link after taking into account other factors. It is thus unclear whether P and/or other minerals (e.g., calcium) contribute to these risks, or whether both are consequences of other factors such as unhealthy diet, obesity, undeclared kidney insufficiency, or other body metabolism problems.

While it is recognized that deterioration of kidney function leads to increased blood P (serum P), there is no evidence that higher dietary P levels lead to increased serum P (except immediately after the P containing meal) in persons not suffering from kidney function deficiency. Indeed, correctly functioning kidneys normally maintain an optimal serum P level. Analysis of the numerous studies available comparing P intake to serum P show that many do not contain relevant data (diet not known, data only for very short term such as one dose of high dietary P), and that those containing useful data do not enable any conclusion because they reach conflicting conclusions.

Very few studies are available comparing dietary P levels directly with heart disease (as opposed to comparing P intake to serum P or serum P to heart disease), and the studies which do exist show contradictory results, some suggesting a correlation and others suggesting no correlation or an inverse correlation (dietary phosphorus inversely related to heart disease symptoms) (Alonso et al. 2010; Elliott et al. 2008; Joffres et al. 1987).

Thus scientific data does not at present indicate that the P content of Western diets increases heart disease risk. Further investigation is warranted to better understand the roles of diet and life style in the etiology of heart disease.

Although several publications suggest a possible link between dietary P and other health impacts these are based on metabolic hypotheses, with very little in vitro basis and virtually no experimental evidence. Because there are very few experimental data, it must be considered that these may be caused by artifacts. The experimental evidence regarding cancer concerns only genetically modified mice, artificially susceptible to cancer. It can be considered that these results cannot be reliably extrapolated to normal mice, or to humans (IFAC 2009). In the most cited case (Jin et al. 2009) a later similar experiment by the same authors with the same genetically modified mice produced the contrary result: a *low* phosphate diet increased lung cancer (Cheng-Xiong et al. 2010). We face the problem of extrapolation of experimental findings to human in vivo conditions also with a study suggesting that high dietary P in Drosphila flies reduced their lifespan (aging), which again cannot be reliably extrapolated to humans, has been completed by a further study suggesting that this is due to impairment of flies' equivalent to kidneys (Bergwitz et al. 2013).

A few epidemiological or in vitro studies with humans suggest a statistical relationship between dietary P and cancer occurrence, but others show no relationship (Berndt et al. 2002; Chan et al. 1998; Giovannucci et al. 1998; Tavani et al. 2005), and others an inverse relationship (increased dietary P related to lower cancer incidence; Brinkman et al. 2010; Chan et al. 2000; Kesse et al. 2005; Spina et al. 2012; Takata et al. 2013; van Lee et al. 2011) or positive/negative relationships for different forms of cancer (Wulaningsih et al. 2013). Other recent publications suggest a possible link between low dietary P and obesity (Celik and Andiran 2011; Lindegarde and Trell 1977; Haglin et al. 2001; Lind et al. 1993; Obeid 2013) or between dietary P and reduced cholesterol (Kim et al. 2013; Ditscheid et al. 2005; Lippi et al. 2009; Trautvetter et al. 2012). There are many other studies which indicate that P intake is safe at current levels (see e.g., JECFA 1982; Weiner et al. 2001).

Based on the current scientific evidence, it can be concluded that normal Western levels of dietary P intake are safe: no studies have reported a clear link to human health risks. This is to conform to the conclusions of the European EFSA scientific panel (EFSA 2005).

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References

Alonso A, Nettleton JA, Ix JH, de Boer IH, Folsom AR, Bidulescu A, Kestenbaum BR, Chambless LE, Jacobs DR Jr (2010) Dietary phosphorus, blood pressure, and incidence of hypertension in the atherosclerosis risk in communities study and the multi-ethnic study of atherosclerosis. Hypertension 55 (3):776–U109. doi:10.1161/hypertensionaha.109.143461

Bergwitz C, Wee MJ, Sinha S, Huang J, DeRobertis C, Mensah LB, Cohen J, Friedman A, Kulkarni M, Hu Y, Vinayagam A, Schnall-Levin M, Berger B, Perkins LA, Mohr SE, Perrimon N (2013) Genetic Determinants of Phosphate Response in Drosophila. Plos One 8(3): e56753. doi:10.1371/journal.pone.0056753

Berndt SI, Carter HB, Landis PK, Tucker KL, Hsieh LJ, Metter EJ, Platz EA (2002) Calcium intake and prostate cancer risk in a long-term aging study: the Baltimore longitudinal study of aging. Urology 60(6):1118–1123. doi:10.1016/s0090-4295(02)01991-x

Brinkman MT, Karagas MR, Zens MS, Schned A, Reulen RC, Zeegers MP (2010) Minerals and vitamins and the risk of bladder cancer: results from the New Hampshire study. Cancer Causes Control 21(4):609–619. doi:10.1007/s10552-009-9490-0

Celik N, Andiran N (2011) The relationship between serum phosphate levels with childhood obesity and insulin resistance. J Pediatr Endocrinol Metab 24(1–2):81–83. doi:10.1515/jpem.2011.116

Chan JM, Giovannucci E, Andersson SO, Yuen J, Adami HO, Wolk A (1998) Dairy products, calcium, phosphorous, vitamin D, and risk of prostate cancer (Sweden). Cancer Causes Control 9(6):559–566. doi:10.1023/a:1008823601897

Chan JM, Pietinen P, Virtanen M, Malila N, Tangrea J, Albanes D, Virtamo J (2000) Diet and prostate cancer risk in a cohort of smokers, with a specific focus on calcium and phosphorus (Finland). Cancer Causes Control 11(9):859–867. doi:10.1023/a:1008947201132

Cheng-Xiong X, Hua J, Hwang-Tae L, Yoon-Cheol H, Chan-Hee C, Gil-Hwan A, Kee-Ho L, Myung-Haing C (2010) Low dietary inorganic phosphate stimulates lung tumorigenesis through altering protein translation and cell cycle in K- rasLA1 mice. Nutr Cancer 62(4):525–532

Council for Responsible Nutrition (CRN) (2013) Vitamin and mineral recommendations. http://www.crnusa.org/about_recs.html

Ditscheid B, Keller S, Jahreis G (2005) Cholesterol metabolism is affected by calcium phosphate supplementation in humans. J Nutr 135(7):1678–1682

EFSA (2005) Opinion of the scientific panel on dietetic products, nutrition and allergies on a request from the commission related to the tolerable upper intake level of phosphorus. EFSA J 233:1–19 (http://www.efsa.europa.eu/de/efsajournal/doc/233.pdf)

Elliott P, Kesteloot H, Appel LJ, Dyer AR, Ueshima H, Chan Q, Brown IJ, Zhao L, Stamler J, Grp ICR (2008) Dietary phosphorus and blood pressure—international study of Macro- and Micro-nutrients and blood pressure. Hypertension 51(3):669–675. doi:10.1161/hypertensionaha.107.103747

Flynn A, Hirvonen T, Mensink GBM, Ocke MC, Serra-Majem L, Stos K, Szponar L, Tetens I, Turrini A, Fletcher R, Wildemann T (2009) Intake of selected nutrients from foods, from fortification and from supplements in various European countries. Food Nutr Res 53:20–20. doi:10.3402/fnr.v53i0.2038

Giovannucci E, Rimm EB, Wolk A, Ascherio A, Stampfer MJ, Colditz GA, Willett WC (1998) Calcium and fructose intake in relation to risk of prostate cancer. Cancer Res 58(3):442–447

Haglin L, Lindblad A, Bygren LO (2001) Hypophosphataemia in the metabolic syndrome. Gender differences in body weight and blood glucose. Eur J Clin Nutr 55(6):493–498. doi:10.1038/sj.ejcn.1601209

IFAC (2009) Statement of the international food additives council and the European chemical industry council. www.cefic.org/Documents/Other/Backgrounder_of_et_al_1-21-09.doc

Itkonen ST, Karp HJ, Kemi VE, Kokkonen EM, Saarnio EM, Pekkinen MH, Karkkainen MUM, Laitinen EKA, Turanlahti MI, Lamberg-Allardt CJE (2013) Associations among total and food additive phosphorus intake and carotid intima-media thickness—a cross-sectional study in a middle-aged population in Southern Finland. Nutrition J 12:94. doi:10.1186/1475-2891-12-94

JECFA (World Health Organisation Joint Expert Committee on Food Additives) (1982) International programme on chemical safety, WHO food additives series 17. http://www.inchem.org/documents/jecfa/jecmono/v17je22.htm

Jin H, Xu C-X, Lim H-T, Park S-J, Shin J-Y, Chung Y-S, Park S-C, Chang S-H, Youn H-J, Lee K-H, Lee Y-S, Ha Y-C, Chae C-H, Beck GR Jr, Cho M-H (2009) High dietary inorganic phosphate increases lung zumorigenesis and alters Akt signaling. Am J Respir Crit Care Med 179(1):59–68. doi:10.1164/rccm.200802-306OC

Joffres MR, Reed DM, Yano K (1987) Relationship of magnesium intake and other dietary factors to blood-pressure—the Honolulu heart-study. Am J Clin Nutr 45(2):469–475

Kesse E, Boutron-Ruault MC, Norat T, Riboli E, Clavel-Chapelon F, Grp EN (2005) Dietary calcium, phosphorus, vitamin D, dairy products and the risk of colorectal adenoma and cancer among French women of the E3N-EPIC prospective study. Int J Cancer 117(1):137–144. doi:10.1002/ijc.21148

Kim WS, Lee D-H, Youn H-J (2013) Calcium-phosphorus product concentration is a risk factor of coronary artery disease in metabolic syndrome. Atherosclerosis 229(1):253–257. doi:10.1016/j.atherosclerosis.2013.04.028

van Lee L, Heyworth J, McNaughton S, Iacopetta B, Clayforth C, Fritschi L (2011) Selected dietary micronutrients and the risk of right- and left-sided colorectal cancers: a case-control study in Western Australia. Ann Epidemiol 21(3):170–177. doi:10.1016/j.annepidem.2010.10.005

Lind L, Lithell H, Hvarfner A, Pollare T, Ljunghall S (1993) On the relationships between mineral metabolism, obesity and fat distribution. Eur J Clin Invest 23(5):307–310. doi:10.1111/j.1365-2362.1993.tb00779.x

Lindegarde F, Trell E (1977) Serum inorganic phosphate in middle-aged men I. Inverse relation to body weight. Acta Medica Scandinavica 202:307–311

Lippi G, Miôntagna M, Salvagno GL, Targher G, Guidi GC (2009) Relationship between serum phosphate and cardiovascular risk factors in a large cohort of adult outpatients. Diab Res Clin Pract 84:e3–e5

Obeid OA (2013) Low phosphorus status might contribute to the onset of obesity. Obes Rev 14(8):659–664

Spina A, Sapio L, Esposito A, Di Maiolo F, Sorvillo L, Naviglio S (2012) Inorganic phosphate as a novel signaling molecule with antiproliferative action in MDA-MB-231. BioRes doi:10.1089/biores.2012.0266

Takata Y, Shu X-O, Yang G, Li H, Dai Q, Gao J, Cai Q, Gao Y-T, Zheng W (2013) Calcium intake and lung cancer risk among female nonsmokers: a report from the Shanghai women's health study. Cancer Epidemiol Biomark Prev 22(1):50–57. doi:10.1158/1055-9965.epi-12-0915-t

Tavani A, Bertuccio P, Bosetti C, Talamini R, Negri E, Franceschi S, Montella M, La Vecchia C (2005) Dietary intake of calcium, vitamin D, phosphorus and the risk of prostate cancer. Eur Urol 48(1):27–33. doi:10.1016/j.eururo.2005.03.023

Trautvetter U, Ditscheid B, Kiehntopf M, Jahreis G (2012) A combination of calcium phosphate and probiotics beneficially influences intestinal lactobacilli and cholesterol metabolism in humans. Clin Nutr 31(2):230–237. doi:10.1016/j.clnu.2011.09.013

Weiner ML, Salminen WF, Larson PR, Barter RA, Kranetz JL, Simon GS (2001) Toxicological review of inorganic phosphates. Food Chem Toxicol 39:759–786

Westerberg P-A, Tivesten A, Karlsson MK, Mellstrom D, Orwoll E, Ohlsson C, Larsson TE, Linde T, Ljunggren O (2013) Fibroblast growth factor 23, mineral metabolism and mortality among elderly men (Swedish MrOs). Bmc Nephrol 14:85. doi:10.1186/1471-2369-14-85

Wulaningsih W, Michaelsson K, Garmo H, Hammar N, Jungner I, Walldius G, Holmberg L, Van Hemelrijck M (2013) Inorganic phosphate and the risk of cancer in the Swedish AMORIS study. Bmc Cancer 13:257. doi:10.1186/1471-2407-13-257

Appendix: Spotlight 8

Technological Use of Phosphorus: The Non-fertilizer, Non-feed and Non-detergent Domain

Oliver Gantner, Willem Schipper, and Jan J. Weigand

Out of a total of 191 million tons phosphate rock mined yearly (2011 figure; Jasinski 2012), a large part is used to make fertilizers, via merchant grade phosphoric acid (MGA), and only a small part, typically 10–15 %, is used for non-fertilizer applications (IFA 2011).

Accurate figures for non-fertilizer uses are not available. IFA (2008) estimates about 7 % is used to make detergents, 10 % to make feed supplements for livestock, and 3 % is used in other applications. Recent estimates (CRU 2013) put feed usage at 5 %, detergents at 2 % and all other uses at 3 % combined. Most of these other applications, as well as a fair part of the detergent phosphate production, involve the manufacturing of elemental, white phosphorus P_4 (“thermal route”) which constitutes the only other relevant processing route for rock besides MGA/fertilizer (“wet acid route”).

The authors estimate a very approximate breakdown for world use of phosphorus (P) as follows:

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- 85–90 % fertilizer
- ±5 % animal feeds
- 1 % food
- 2 % detergents
- 1 % glyphosate
- 1 % other P_4 derivatives
- 1 % other technical phosphates

These numbers are estimates reflecting the uncertainties and differences between published data and are given to the best of knowledge of the authors for the years 2010–2012. They serve above all to demonstrate the relative importance of each use segment. This spotlight focuses on the non-fertilizer uses of P, which include both MGA derived and P_4- derived products, hereafter referred to as the "technological use of P." These include ortho- and polyphosphates, from either MGA (usually) or P_4, as well as a large catchall category of organophosphorus compounds and inorganic phosphorus derivatives that can only be manufactured from the element, P_4.

As MGA contains up to 5 % of sulfate and metallic impurities originating from the rock and manufacturing conditions, phosphates derived from MGA usually need some form of purification of the acid, by extraction, precipitation or crystallization, thus essentially forming a product that competes with high-purity acid and its derived phosphates as obtained through oxidation of P_4 and subsequent hydrolysis ("thermal acid"). Applications include technical fields (detergent, firefighting, flame retardants, water treatment, and many others), feed and food uses, and these determine the amount of purification needed.

Feed phosphates are added to livestock feed, typically as mono-, dicalcium, and several sodium phosphates. As purity requirements are not as strict as for human consumption, these are routinely made from partially purified MGA. This also includes a number of phosphates used in the pet food industry (pyro/polyphosphates).

Food phosphates and food grade phosphoric acid perform a host of functions, such as moisture retention, sequestering, and acidulation. These are made either from highly purified MGA or from thermal acid, with soda ash or caustic soda in most cases. Ammonium, calcium, magnesium, aluminum, and potassium salts are also commercially relevant.

Technical phosphates such as detergent sodium tripolyphosphate (STPP) or phosphates for water treatment, firefighting compositions, and ceramics can be made either from MGA (usual) or via the thermal route. The choice between the two routes is above all cost driven, as a higher quality requires more rigorous purification and hence additional cost (Table 1).

The remaining P compounds all necessarily need to be made through the most reactive allotrope of the element, i.e., white phosphorus (P_4). This is

Table 1 Overview of phosphate containing applications (non-exhaustive) *References* Budenheim (2013), Emsley (2000), Phosphate Facts (2013), Prayon; Villalba et al. (2008)

Phosphate containing applications	Chosen examples for a finished product	Ingredients	Phosphate function
Agrochemicals	Glyphosate	Glycine phosphonate	Herbicide
Beverage	Cola	Food grade phosphoric acid	Acidulant
Building/construction	Cement	Sodium tripolyphosphate, tetrasodium pyrophosphate, Sodium monofluorophosphate	Retarding agent for cement
Cleaning agents	Heavy duty cleaner	Trisodium phosphates, tetra sodium and potassium pyrophosphates, sodium potassium pyrophosphate	Remove oils and greases
Coloring and coating	Intumescent coating	Polyphosphates	Flame retardant
Flame protection	Fire extinguisher	Mono- and diammonium phosphates	Fire retardants
Flame retardants	Automotive polyurethane foam	Phosphate triesters (tricresyl phosphate, etc.)	Flame retardant
Food processing	Dairy, Seafood, Meat	Polyphosphates (sodium tripolyphosphate, potassium tripolyphosphate, etc.)	Moisture retention, emulsifier, shelf life
Glass and ceramic	Ceramic	Tricalcium phosphate	Impart opalescence
Lighting	Neon tubes	Halo phosphates	Phosphor (fluorescent substance)
Lubricant additives	Car engine protectors	Sulfur compounds (zinc dialkyl thiophosphates, etc.)	Protection
Medical engineering	Dental cement	Magnesium phosphate, ammonium phosphate	Dental investment, binding agent
Military use	Fire bomb	White phosphorus	Destruction by fire
Pharmaceutical articles and cosmetics	Toothpaste	Tetrasodium pyrophosphate, tetrapotassium pyrophosphate, etc	Cleaning agent, polishing agent
Phosphoric acid for industrial use	Circuit board	Phosphoric acid	Metal surface treatment
Polish	Polished aluminum	Phosphoric acid	Chemical polishing
Storage technology	Lithium-ion batteries	Lithium iron phosphate	High energy density, rapid charging, and discharging abilities
Textile and leather	Dying wool	Diammonium phosphate	Control of pH in dye bath to allow even penetration of dye through the wool

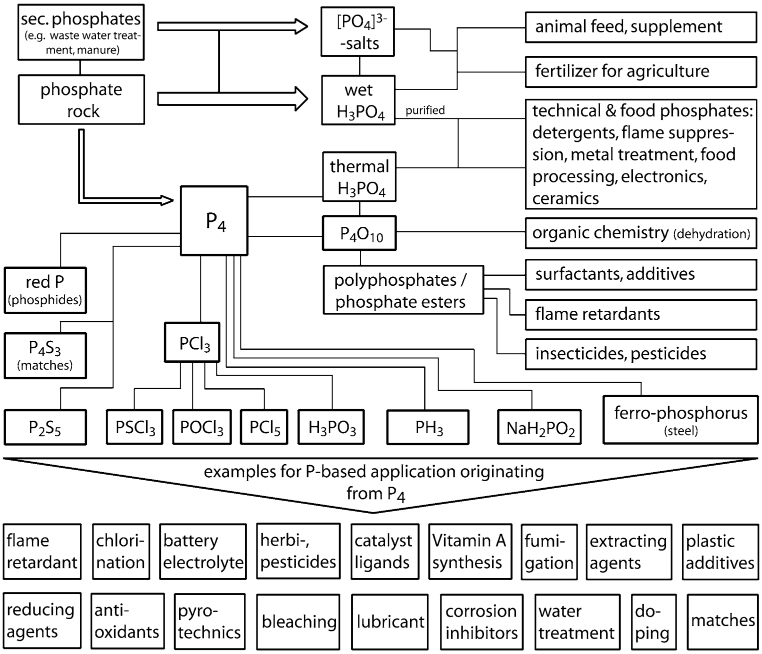

Fig. 2 Technical use of P

obtained through electrothermal reduction of phosphate rock (apatite) in an electric arc furnace at 1,600 °C with coke (reducing agent) and gravel (slag former). White phosphorus as such has limited applications in military incendiaries, but otherwise serves as the father compound to a large palette of (organo) phosphorus compounds (OPCs) through its first derivatives: P chlorides (PCl_3, $POCl_3$, and PCl_5), sulfides (P_2S_5 and P_4S_3) and oxides (P_2O_5 and polyphosphoric acid; see Fig. 2). These consist of mono-, di- and tri-esters of phosphoric and phosphonic acid (phosphates and phosphonates).

Applications include crop protection agents, flame retardants, lubricant additives, extracting agents (e.g., uranyl salts for the fuel production for nuclear power plants), pharmaceuticals, biocides, battery electrolytes and many more. Glyphosate, an organic P compound, the largest volume agrochemical worldwide is a derivative of PCl_3. For 2017 this application will use 250,000 t of P which is 1 % of total P usage (PRWeb 2011).

Apart from these derivatives involving oxygen, chlorine and sulfur, sodium hypophosphite and red phosphorus play a role in respectively nickel electroplating and flame retardant compositions.

Phosphine (PH_3 derived) chemistry is very minor volume-wise but has a huge field of application in such diverse fields as extraction agents, catalyst ligands, fumigation and fine chemistry.

The rationale to choose the energy intensive “thermal” route through P_4 is that it gives access to compounds that could otherwise not be produced. Reasons to make P_4 and its derivatives include:

- creating water soluble molecules that perform a function such as chelating, surface treatment or antiscale action, often as a variation on structurally related carboxylic acids (such as phosphonates and acid organophosphates),
- introducing P into a plastic or other flammable material to obtain flame retardancy, with functional groups around the P atom to create compatibility with the material to be flameproofed, or particles made compatible with the matrix material, (e.g., phosphate esters, DOPO, phosphinates),
- mimicking a molecule from nature to obtain a pesticide/herbicide (such as glyphosate),
- providing functionality to obtain a catalytic action, usually together with a transition metal ion, usually by providing a lone pair, i.e. acting as a Lewis base, such as in hydrocarbonylation (i.e., polymerization and modification of petrochemical building blocks),
- chemical reduction (such as sodium hypophosphite which is difficult to replace in electroless nickel plating),
- certain P compounds provide specific functions, including chlorination (P chlorides) or a strong dehydrative power in reactions (phosphorus pentoxide, polyphosphoric acid) which are difficult to replace with other reagents.

Academic research continues to develop our understanding on different branches of P chemistry, as shown in the recently updated 1,500 page handbook on Phosphorus (Corbridge 2012). This includes superconductivity, interesting thermo-chemistry, and magnetic behavior (Pöttgen et al. 2005). Some compounds are also important in homogeneous and heterogeneous catalysis (Peruzzini and Gonsalvi 2011). With respect to P_4 routes, given the drawbacks of chlorine-based and heavy salt-waste syntheses, stringent, environmental, and transportation regulations increasingly demand not only new ways of P_4 functionalization to useful molecules, but also new economic and ecological ways to meet current challenges also in the non-fertilizer P use. The need to bypass P chlorides, e.g., to obtain OPCs straight from P_4 is a continuing research topic (Caporali et al. 2010). Recycling phosphine oxides as a by-product of the Wittig synthesis, which are currently treated as waste in most cases, is a typical example of smart re-use of P compounds in a small, dedicated loop (Feldmann et al. 2011).

References

Budenheim (2013) Solutions for a better life. Accessed from https://www.budenheim.com/en/

Caporali M, Gonsalvi L, Rossin A, Peruzzini M (2010) P4 activation by late transition metal complexes. Chem Rev 110:4178–4235

Corbridge DEC (2012) Phosphorus: chemistry, biochemistry and technology, 6th edn. CRC Press/Taylor & Francis Group, Boca Raton

CRU (2013) Ashok Shinh (presentation), Phosphates 2013 conference, Monte Carlo

Emsley J (2000) The 13th element: the sordid tale of murder, fire, and phosphorus. Wiley, New York

Feldmann K-O, Schulz S, Klotter F, Weigand JJ (2011) A Versatile protocol for the quantitative and smooth conversion of phosphane oxides into synthetically useful pyrazolylphosphonium salts. ChemSusChem 4(12):1805–1812

IFA (2008) Accessed from http://www.fertilizer.org/

IFA (2011) Global phosphate rock production trends from 1961 to 2010—reasons for the temporary set-back in 1988–1994. Feeding the Earth Series, Oct 2011. http://www.fertilizer.org/ifa/HomePage/LIBRARY/Publication-database.html/Global-Phosphate-Rock-Production-Trends-from-1961-to-2010.-Reasons-for-the-Temporary-Set-Back-in-1988-1994.html

Jasinski SM (2012) Phosphate rock. In: Salazar K, McNutt MK (eds) Mineral commodity summaries 2012. USGS, Reston, p 118

Peruzzini M, Gonsalvi L (2011) Phosphorus compounds: advanced tools in catalysis and material science in catalysis by metal complexes. Springer, Heidelberg

Phosphate Facts (2013) Uses and applications. http://www.phosphatesfacts.org/uses_apps.asp

Pöttgen R, Hönle W, von Schnering HG (2005) Phosphides: solid state chemistry

Prayon (n.d.) Phosphates and phosphoric acid in everyday life. Accessed from http://www.prayon.com/media/pdf/publications/brochure-tech-en.pdf

PRweb (2011) Global glyphosate market to reach 1.35 million metric tons by 2017. http://www.prweb.com/releases/glyphosate_agrochemical/technical_glyphosate/prweb8857231.htm

Villalba G, Liu Y, Schroder H, Ayres RU (2008) Global phosphorus flows in the industrial economy from a production perspective. J Ind Ecol 12(4):557–569. doi:10.1111/j.1530-9290.2008.00050.x

Appendix: Spotlight 9

Phosphorus in Organic Agriculture

Bernhard Freyer

Today, worldwide more than 1.8 million farmers have a total 37.2 million ha of agricultural land that would meet the criteria for organic crop production (FAO 2009; Willer and Kilcher 2011). Organic Agriculture is defined by internationally accepted guidelines, standards, and certification systems (IFOAM-EU 2012). The organic system is built upon vision and understanding of the farm as an organism. With such an understanding, organic farmers seek to close their farm nutrient cycles, to reduce resource input from off farm sources and to increase the efficiency of resources used. These goals lead organic farmers (as well as other farmers) to consider nutrient balances as a management and decision making tool that leads to increased nutrient availability in soils, the efficiency of nutrient uptake in plants. In addition, organic farmers use mixed cropping systems along with the application of organic manures to promote microbial diversity that strengthens the antiphyto-pathogenic potential of the soil. Similarly, some fodder legumes (e.g., alfalfa, clover) improve overall soil fertility by biological fixing nitrogen (some of which is available to the subsequent crop), provide residues to maintain or improve soil physical and biological properties and promote nutrient re-cycling and access to water through deep rooting. The combination of rich root systems, residue production and humus production by legumes, and cropping systems with green manure mixtures, contributes to a permanent soil cover, minimizing soil erosion and thereby the loss of phosphorus (P) and other nutrients. Compost from plant residues and stable manure from livestock permits an efficient internally closed nutrient cycle on the farm.

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Types of Farm External P-Sources

According to the organic guidelines, the readily available mineral fertilizers (e.g., triple superphosphate, DAP, etc.) are excluded, while the application of low soluble phosphate rock (hypherphos) is accepted. The use of Thomas-phosphate is restricted in almost all countries because of Cadmium content. Low energy input for the provision of mineral P-fertilizer is one reason for the use of P-mineral fertilizers with low solubility. A second reason is that the main strategy for ensuring proper plant nutrition in organic farming is to improve the conditions for nutrient mobilization from slightly soluble sources by plant–soil-microorganism interactions instead of directly fertilizing plants with readily available mineral fertilizers. Specifically, in acid soils, liming improves the availability of many nutrients including P. Accepted farm external organic P-sources are: communal biowaste composts (sewage sludge is excluded because of the risk of contamination with heavy metals and organic compounds); mineral fodder including P; diverse organic industrial P-fertilizers (e.g., slaughterhouse waste); fodder and organic manure from organic farms or conventional low input farms, with production intensity limited to the site-specific production potential.

P-Cycles

The amount of external P-sources is strictly regulated through guidelines and control systems. Farmers are required to provide calculations on nutrient balances as a precondition for getting permission to apply farm external P-fertilizers. Negative balances could allow P use from mineral fertilizers limited to approximately 5–15 kg P ha^{-1} y^{-1}. The input of P through industrial organic P fertilizers or from other sources is limited due to the site-specific yield potential. P import through mineral fodder is accepted up to approximately 4 kg P LU^{-1} ha^{-1} y^{-1} (LU = Livestock Unit). P export with respect to farm types increases as follows: grassland farms with cattle < mixed arable farms with livestock < stockless cereal producing farms < stockless root crops producing farms < vegetable farms. Without P imports, P-balances decline by approximately 1 to 5 kg P ha^{-1} y^{-1} in the first farm type to 10–15 kg P ha^{-1} y^{-1} in the last farm type (Berner et al. 1999; Martin et al. 2007). Even under limited P-input conditions, P content in organic products is equal to those in conventional farms (Dangour et al. 2009). In smallholder farms under subtropical conditions, the P balances in low input/organic farms range from highly positive to negative demonstrating a lack of access to P inputs, and possibly awareness of P needs and farm management practices in general (Onwonga and Freyer 2006).

P-Dynamics

Sources of plant-available phosphate (PO_4^{3-}) in many soils are the reserves of labile organic and inorganic soil pools, which have been built up over time through the use of mineral P fertilizers, rock phosphate, or other "organic" amendments including green manure residues, and livestock manure. Species-specific root exudates, microorganisms, and fungal enzymes induce the mineralization processes of phytates (storage of P in organic matter), thereby increasing the phosphate levels in the soils (Hinsinger et al. 2011). The extension of the root surface is highly relevant for plant P uptake. Optimal soil structure and organic manure will increase root growth and mycorrhiza colonization (Muthukumar and Udaiyan 2000) and with that the volume of the soil where P is accessible for uptake by roots. Finally, solubility of phosphate rock is supported by specific legume root exudates (Vanlauwe et al. 2000). To summarize, technologies including—lime for pH-regulation, farmyard manure, compost, phosphate rock and diversified legume based crop rotations are key for sustainable use of phosphorous (Onwonga et al. 2008).

References

Berner A, Heller S, Mäder P (1999) Nährstoffbilanzen im biologischen Landbau. 5. Wissenschaftstagung zum Ökologischen Landbau. Berlin. Retrieved June 10 http://orgprints.org/00002908

Dangour AD, Dodhia SK, Hayter A, Allen E, Lock K, Uauy R (2009) Nutritional quality of organic foods: a systematic review. Am J Clin Nutr 90(3):680–685

FAO (2009) High level expert forum. FAO. Accessed 15 Aug 2013

Hinsinger P, Betencourt E, Bernard L, Brauman A, Plassard C, Shen J, Zhang F (2011) P for two, sharing a scare resources: soil phosphorus acquisition in the rhizosphere of intercropped species. Plant Physiol 156(3):1078–1086

IFOAM (2012) European organic guidelines. Retrieved 16 June 2012. http://www.ifoam-eu.org/positions/publications/regulation/

Martin R, Lynch D, Frick B, van Straaten P (2007) Phosphorus status on Canadian organic farms. J Sci Food Agric 87:2737–2740

Muthukumar T, Udaiyan K (2000) Influence of organic manures on arbuscular mycorrhizal fungi associated with Vigna unguiculata (L.) Walp. in relation to tissue nutrients and soluble carbohydrate in roots under field conditions. Biol Fertil Soils 31:114–120

Onwonga R, Freyer B (2006) Impact of traditional farming practices on nutrient balances in smallholder farming systems of Nakuru district, Kenya. In: Asch F, Becker M (eds) Conference on international agricultural research for development, Tropentag, pp 158–161

Onwonga RN, Lelei JJ, Freyer B, Friedel JK, Mwonga SM, Wandhawa P (2008) Low cost technologies for enhancing N and P availability and maize (Zea mays L.) performance on acid soils. World J Agric Sci 4(2):862–873

Vanlauwe B, Diels J, Sanginga N, Carsky RJ, Deckers J, Merckx R (2000) Utilization of rock phosphate by crops on non-acidic soils on a toposequence in the Northern Guinea savanna zone of Nigeria, response by maize to previous herbaceous legume cropping and rock response by maize to previous herbaceous legume cropping and rock phosphate treatments. Soil Biol Biochem 32:2079–2090

Willer H, Kilcher L (2011) The world of organic agriculture. Statistics and Emerging Trends 2011, IFOAM, Bonn and FiBL, Frick