SCOPE Newsletter visions for sustainable phosphorus tomorrow contributions received May 2014

Visions for sustainable phosphorus tomorrow

The European Sustainable Phosphorus Platform's call for texts for a 'vision for sustainable phosphorus in tomorrow's world' received 110 contributions. A selection of 25 are printed in the SCOPE Newsletter special edition n°106.

Both these and all the other contributions received are published in this document and present a wide range of ideas and opinions.

They are printed as sent, and the opinions expressed are those of the authors, and not of the European Sustainable Phosphorus Platform.

Towards a more efficient use of soil phosphate by crop plants

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Soil Phosphate (P)

In many developed countries high application rates of fertilizer P has led to an accumulation of P in agricultural soils. With increasing time of reaction of soil P and the soil solid phase P availability decreases because of the diffusion of P into internal particle surfaces and perhaps precipitation reactions at the soil solid phase. Soil P fractions with differing availability accumulate in soil.

Plant acquisition of P

P is the macronutrient with the lowest solubility in soil.

It is transported to the roots nearly exclusively by diffusion in the soil solution. The acquisition is mainly restricted by the low soil solution activities of P which restricts the diffusion gradient.

The interaction of soil P availability and plant root P acquisition by di-or tricaboxylic acid anions

To overcome the problem of low P solubility/ P availability and the resulting small P acquisition even at high content of total soil P several plant species developed strategies to increase P solubility in the rhizosphere by the excretion of P mobilizing (P dissolving) agents. The by far most successful way of P mobilization is the excretion of organic anions such as oxalate, citrate and possibly malate and some other carboxylic anions by the roots.

The knowledge of the reactions controlling the P mobilization in soil is essential for the knowledge of its effect on P acquisition by mobilizing plant species. Fundamental research in this field of soil-plant interaction is required.

The interaction of excretion of carboxylates with other root parameters e.g. rooting density, root-shoot ratio, the formation of root hairs, and its number and length is largely unknown.

Research at the field scale

The interaction between P mobilizing plants and non- mobilizing plants is largely unknown. The effect of P mobilizing field crops on the P acquisition in mixed cropping or on subsequent crops is unknown.

Plant breeding

Plant breeding is a useful tool to find and select species with efficient P mobilization features

a. High excretion intensity of organic anions.

b. Changes of root architecture: a higher number and length of roots, root branches like cluster roots and root hairs would increase P mobilization and diffusion into the roots by shortening diffusion ways.

c. The internal P efficiency of crops (kg dry matter / g absorbed phosphorus) should be clearly increased.

Precision Farming & Smart Equipment

>>>The 'Know-How per cm^{2}' Revolution to Master the Phosphorus Challenge

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A game changing technology revolution is underway poised to make a difference in achieving sustainable phosphorus use in the years ahead: the rapid evolvement and growing uptake of smart equipment and advanced precision farming systems. Already today, cutting-edge machinery is a key solution for farmers to achieve more resource-efficient phosphorus use. Combining high-precision satellite guidance, sensor technology and smart, algorithm-based application techniques, agricultural machines can optimize farm operations so as to achieve average reductions in fertilizer use of 5% to up to 32% – and we ain't seen nothing yet…In fact, we have every reason to believe that the full potential for such savings is still to be unleashed.

Much as the IT revolution in the 1980s took off with the arrival of the first personal computers (PCs), the next years will witness a fundamental paradigm shift towards a new farming reality driven by smart and integrated machines. This shift will not only push up the boundaries of our knowledge per cm^{2} field to new, unprecedented dimensions. It will also provide us with user-friendly tools to turn this knowledge into practical intelligence which can easily be managed and actually applied in the field. As was the case with the IT revolution and the PC, the development is likely to turn into a virtuous circle driven by two key factors: mass uptake and constantly evolving technology.

Regarding mass uptake, certain precision farming technologies are becoming mainstream features today. This wide-spread uptake is driving down purchasing costs for farmers and will, in turn, accelerate and increase user levels even further. This development can already be observed for GPS receivers sold for agricultural use and is set to continue with new and more advanced products as the technology evolves – which brings us to the second point: technological progress. This, too, is set to accelerate and increase. The untapped potential still is enormous. Many new frontiers are about to be crossed and conquered in the years ahead. Just take the example of robotic solutions: already well-established in the form of feeding and milking robots in livestock farming, it is still in its infancy for arable crops. But is set to hit the fields in the years ahead and allow for an even better and more targeted use of inputs – and thus for more sustainable use of phosphorus. The other key point – familiar to us from so-called optimized search results on Google or suggested friends on Facebook – is the inherent learning aspect of smart IT systems. Ever more advanced algorithms will allow to connect and use the growing agronomic data streams generated by modern machinery in an ever more targeted and precise manner.

So imagine the farm of 2040: will it still need phosphorus? Most certainly yes. Will phosphorus be applied in the same way as today? Most certainly not. What will be the key application tool? The smart, integrated machine, probably robotic. So what about the quantities of phosphorus used? Much less. And what about environmental protection and farm productivity? A good deal more.

Sustainable phosphorus fertilisation in agriculture

>>>How to promote sustainable phosphorus fertilisation in agriculture

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Increasing phosphorus (P) content in agricultural soils stimulates crop yield but also increases phosphorus losses to surface waters and groundwater (Figure 1). Adequate P availability in the soil is necessary for crop growth but above a certain soil P content, yields do not increase. Below a certain threshold soil P content, P losses are limited, but losses can increase exponentially when the soil P content exceeds the threshold. A small 'target zone' soil P content with optimal crop yields and limited P losses can be defined (Tunney, 2002; McDowell, 2012). Soils with low soil P content (A in Figure 1) can receive net P inputs (= P fertilisation input minus crop P output) without large increases in P losses, whereas soils with large soil P contents (B in figure 1) can have several years of net P export without compromising crop yields. Soil P content should evolve in the next 10-30 years towards the target zone. This sustainable choice is optimal for both the environment and yields. Measures for reaching this goal are (1) an adapted fertilisation legislation and (2) adequate fertilisation recommendations. Figure 1 presents a simplified picture that does not take hydrology, connectivity or soil characteristics into account. Moreover, the method to measure soil P content must be appropriate because results often depend upon soil characteristics.

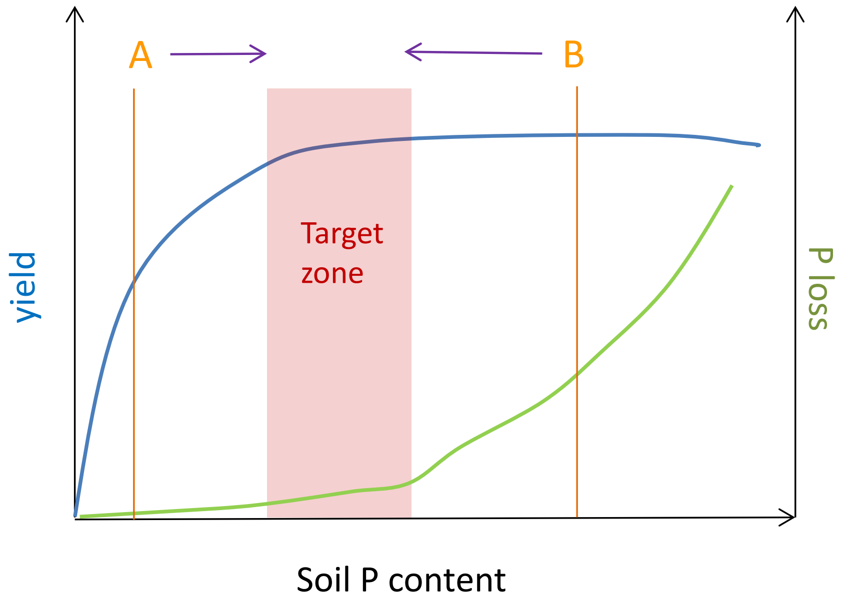

Figure 1. Yield and P loss evolutions at increasing soil P content, with an optimal agro-environmental target zone.

1. Legislation regarding phosphorus fertilisation in European countries and regions varies from no direct regulation to strict maximum phosphorus application rates (Amery & Schoumans, 2014). By taking the risk for soil P losses into account for identifying the maximum phosphorus application rate, evolution towards the target zone can be promoted (Figure 1). Some European countries already have P application limits that depend upon the soil P content, stimulating evolution towards the target zone. Further progress could be made by using an environmental instead of an agricultural soil P measurement, and also by taking hydrology and connectivity into account. To optimise yields and minimise P losses, legislation regarding P fertilisation within and outside Europe should include maximum P application limits differentiated to soil P content and P loss risk.
2. The soil P content is generally taken into account when formulating P fertilisation recommendations. But even for similar soil-crop situations, fertilisation advice differs more than threefold in Europe (Jordan-Meille et al., 2012). New recommendation systems in some European countries are flowing from updated models and data, more appropriate safety margins and new insights into P availability measurements. The new P recommendations are generally lower than before (Albertsson, 2008;

Krogstad et al., 2008; Bussink et al., 2011). New environmentally friendly recommendation systems can largely limit P fertilisation and costs while maintaining crop yields (Csathó et al., 2009). Additional research on and development of new P fertilisation advice that guarantees optimal yields while limiting P losses should therefore be encouraged.

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P in Agriculture

>>>Nanoparticles can play a vital role in Phosphorus Nutrition

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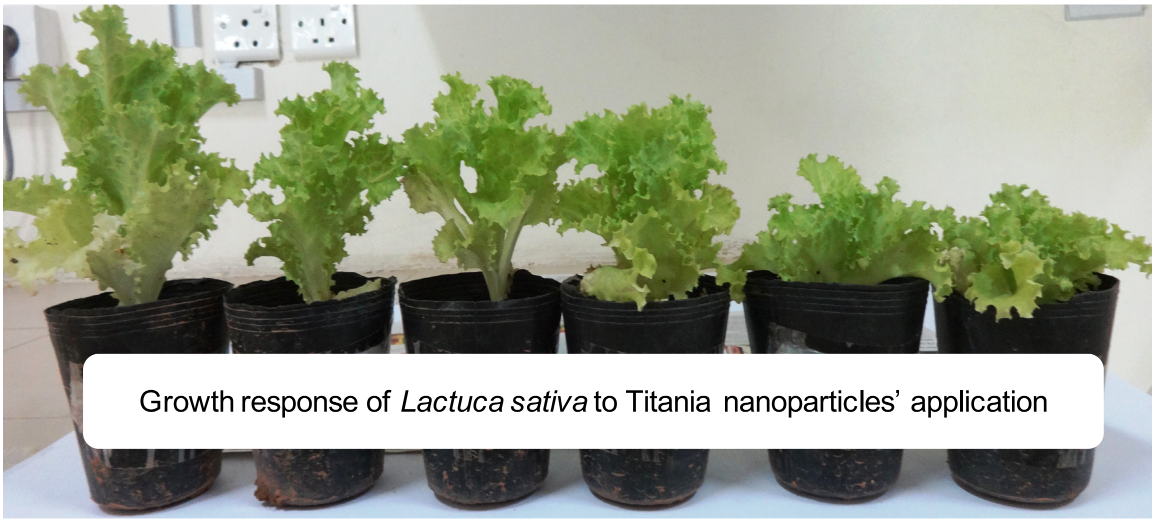
Phosphorus has the status of fuel for life on our planet – The Earth. Without adequate availability of P, sustainability cannot be achieved. In future, judicious and efficient use of P will be much more important as compared to the present. Recent work by a few researchers has reported the ability of nanoparticles to improve availability and efficiency resulting into increase in biomass production. But this work is at very initial stage. There are many relevant questions unanswered. These reported and unreported results are only from lab scale studies. Adequate combinations considering levels of nanoparticles, complementary fertilizer dose, types of crop plants and varieties, soil texture and structure interferences, kinds and size of these particles, product composition and digestibility, economic assessments, etc. still need to be explored and require extensive research before successful application into the field. If successful, this can also lead to development of nano-fertilizers, probably developed by coating of nanoparticles on P granules that will result into effective release and uptake by the plant. These nanoparticles can act as a delivery system for P within soil-plant continuum. However, there may be certain problems as well with the application of these tiny particles, particularly the toxicity issues. Certain kinds of nanoparticles can be toxic for rhizosphere bacteria and/or for crop plants. So there is need for an integrated approach in order to have safe and sustainable use of nanoparticles for P management for food security and sustainability.



Growth response of *Lactuca sativa* to Titania nanoparticles' application

Phosphorus Flow

>>>Nutrient Recycling Through Land Application of Biosolids

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The non-gaseous environmental cycle of phosphorus (P) is extremely vulnerable to anthropogenic impacts. World's high grade phosphate rock reserves are being depleted rapidly to produce phosphate fertilizers that underpin modern agriculture. The biggest challenge for the next few decades would be to minimize the impact on natural cycle and ensure efficient use of this scarce natural resource through recovery and recycling from farm and nonfarm systems. Utilization of the secondary P sources (e.g., biosolids, animal manure) will play a key role in this regard.

Biosolids are a valuable source of nutrients although it contains lower nitrogen (N) (2–8%) and P (1.5–3%) compared to high-grade commercial fertilizers (with ~5-10% N and 10% P). Land application of biosolids is a very effective way to not only recycle the essential plant nutrients (N and P) but also to reduce the reliance on inorganic P sources. Due to a lack of synergy attributable to economic and social drivers, currently, just over half of the biosolids produced in the United States are applied to farmland.

Economic Driver: Transporting biosolids economically, scheduling their applications that are compatible with the timing of agricultural planting and harvesting operations as well as weather conditions are the main challenges faced by the land recycling programs. Government programs targeted towards creating interdependence and synergies between wastewater treatment facilities (WWTFs) and farmers will help alleviate these problems. Geographic Information System (GIS) can be used as a support tool to develop maps of collection and application points and data analysis for site-specific management. Furthermore, technologies concentrating biosolids (e.g., granular or 'pellet' form) would help reduce volume and transportation expenses.

Social Driver: Despite being a crucial ingredient of modern agriculture, P has received very little general public attention as a non-renewable natural resource. Making the latest P research more accessible will change the public attitude towards underappreciated P sources (e.g., biosolids). The success of sustainable agricultural practices such as organic farming will have a direct impact on the P cycle. Organic farming will promote the use of organic sources of P and reduce the reliance on inorganic P sources.

The fertilizer value of biosolids depends on the potential plant availability of the nutrients. It is important to note that plant-available P content of biosolids is a function of secondary/tertiary processes used in municipal WWTFs. For example, traditional tertiary chemical precipitation (using Fe or Al salts) systems produce biosolids with low P availability, which necessitates higher application amounts to increase labile soil P levels. The emerging high-performance P recovery systems (e.g., struvite) have the potential to cause significant changes in biosolids characteristics and management practices, which in turn would impact the current land application practices. Initial data from our local WWTF, the Madison Metropolitan Sewerage District Nine Springs Facility (Madison WI, USA), reveal a considerable decrease (~50%) in soluble P levels (from biosolids) after the installation of a struvite harvesting system. The effect of enhanced P removal or P recovery systems needs to be evaluated from the context of changes in environmental P mobility after land application of associated biosolids.

Increased P recycling through biosolids land application systems would require an excellent cooperation between WWTFs-Government-Farmers. The success of these programs will help reduce our over-exploitation of the finite P reserves, which is only going to become more important in the coming decades.

P in agriculture, soils, crops, animal feeds, forage crops, sustainable farming systems

>>>The Fertile Grounds Initiative: an integrated approach to increase nutrient availability and nutrient use efficiency.

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Every year more than €3 thousand million is lost due to soil degradation. Soil fertility decline that comes with soil degradation limits food production and economic growth. To unlock the potential of soils, nutrients need to be used more efficiently. This holds in particular for P, because it has the lowest nutrient use efficiency of all nutrients required by crops. Although several pathways of change have been proposed already to increase the productive capacity of soils, new approaches are necessary to cope with the current trends of globalization, urbanization, growing resource scarcity and climate change. Such approaches should be based on Integrated Soil Fertility Management (ISFM), which combines the application of both mineral fertilizers and organic manures with other aspects of agronomic management (seed, crop protection, soil and water management).

With the Fertile Grounds Initiative (FGI) we aim for a coordinated strategy of collaboration between actors in nutrient management at various spatial scales and in time. It is based on eight components, which bring together the supply and demand of nutrients within a specific geographical area to make optimum use of available nutrients by means of site-specific interventions, supplemented with external imports. The FGI could make a significant practical contribution to sustainable development in areas with limited soil fertility and P availability. At the same time it turns residual streams into economic assets, thus alleviating environmental problems arising from nutrient emissions near urban centres of the country.

The main goal of the FGI is to bring together organic and mineral nutrient flows to increase nutrient availability, nutrient use efficiencies and nutrient value, so that new economic activities can be based on the nutrient value chain, and the ownership of nutrients in various forms, and independence of smallholders can be strengthened.

The Fertile Grounds Initiative consists of the following eight components:

1. Inventory: farmers communicate their nutrient demand, preferably on the basis of their Integrated Farm Plan, and potential suppliers communicate what they can supply, both in terms of amount and quality.
2. Product formulation and processing: converting and combining diverse resources, both mineral and organic into valuable fertilizer products.
3. Brokerage: nutrients in natural resources and fertilizer products are given a value and a commercial agreement is arranged between suppliers and clients.
4. Site-specific fertilizer recommendations: calculating the real nutrient demand, based on e.g. soil and crop data and agro-ecological zones (or projected/expected potential yields).
5. Trade and logistics: business case design, nutrient trade and transport.
6. Capacity building: farmers, extension workers, brokers and salesmen receive training in best practices for optimal nutrient management.
7. Institutional arrangements: cooperating with existing farmers' organizations and/or setting up farmers' cooperatives, defining the role of a nutrient bank, legal and institutional embedding, as well as government and policy support.
8. Creating an enabling environment for economic growth: mobilising support for market access, micro-credits, insurances, etc. for smallholders.

Nutrient supply and demand are brought together by brokerage, physical transport and the valorization of nutrients through a Nutrient Stock Exchange (NSE) platform. Nutrient brokerage is based on matching the amount and quality of supply with the nutrient demand of the farming system and the ambitions (i.e. targets) of the farmer.

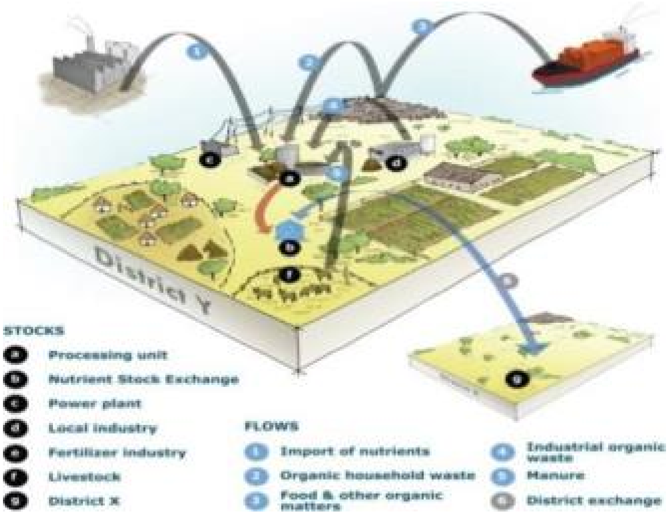

Figure 1. Elements of the proposed nutrient cycling mechanisms at the district level.

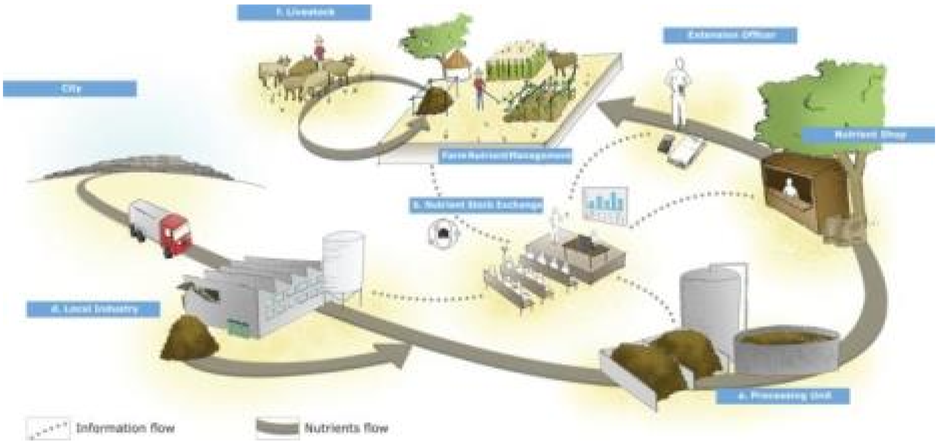

Figure 2. Information and nutrient flows in the proposed nutrient cycling mechanism of the Fertile Ground Initiative.

Soil phosphorus in sustainable farming systems

>>>Designing the crop rhizosphere for sustainable phosphorus use in agriculture

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The productivity of cropping systems is dependent on the use of phosphorus (P) as fertilizer; however when fertilizer P is added to soils only a small proportion is immediately available to plants, with much of it becoming either strongly bound to the soil or incorporated into a range of organic forms. These sequestration mechanisms have meant that fertilizer P is generally applied in excess of crop needs resulting in an accumulation of a largely unavailable soil P pool, as well as enhanced P leaching and contribution to the eutrophication of receiving water courses. One strategy for improving agricultural nutrient efficiency and the sustainable use of P resources is to increase the ability of plants to access the naturally unavailable soil P fraction.

A large proportion of soil P can occur in organic forms, constituting as much as 80% of the total soil P. Soil organic P (P_o) is not easily available to plants, but finding ways to utilize this store of P is imperative to improving agricultural sustainability. The two fundamental problems associated with the poor utilisation of soil P_o by plants are: a) soil P_o forms, specifically phytate, are strongly adsorbed by soil mineral particles and precipitated as insoluble forms; and b) P_o must first be converted to inorganic orthophosphate prior to plant uptake. Many plants exude compounds that increase the bioavailability of soil P through the solubilization and mineralization of P_o. These include, but are not limited to (a) organic acids (e.g., citrate, malate), which release P from the solid phase, and (b) phosphatase enzymes (e.g., phytase), which hydrolyse P_o to plant-available orthophosphate. Examples of organic acid-exuding plants include genotypes of barley (*Hordeum vulgare* L.), wheat (*Triticum* spp.) and lupins (*Lupinus* spp.). Several plants naturally produce phosphatase enzymes (*Medicago* spp.) or have been genetically engineered to express genes for extracellular phytases taken from a range of soil fungi, such as a subterranean clover (*Trifolium subterraneum* L.) capable of secreting phytase. Recent evidence suggests that management of plant and soil microbiome interactions could be designed to promote plant utilization of the P_o fraction through the proper selection and combination of these rhizosphere traits. In order for this approach to be realized, further work is required to improve our understanding of P_o bioavailability as influenced by plant genotypic variation, soil type, rhizosphere conditions, and the resident microbial community.

A three year project has recently been funded by Biotechnology and Biological Sciences Research Council (BBSRC) in the UK to explore cropping strategies to target the use of recalcitrant soil P_o. This consortium includes researchers from Lancaster University (Lancaster, UK), James Hutton Institute (Aberdeen and Dundee, UK) and Rothamsted Research (Devon, UK). The overarching hypothesis of the project is that cropping systems selected to combine favourable root exudate properties will facilitate sustainable agricultural production through improved access to soil P_o (Fig. 1). For any further information please contact us.

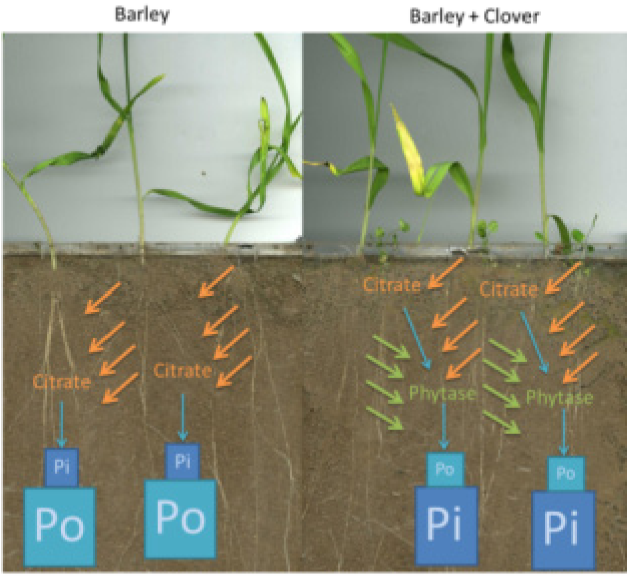

Fig.1. A conceptual model for improving plant access to soil P_o. In this example, citrate-exuding barley and phytase-exuding clover enhances soil P_o mineralization.

Education will make closed nutrient cycles the next ‘normal’

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In the past years, the idea of establishing a circular economy that enables a sustainable management of materials has found ground. In this context, a lot of attention has been dedicated to the technological innovations to make this possible and the economic conditions to make this viable. However, the societal aspects of this socio-technical transition are of equal importance to ensure a sustainable use of phosphorus in the future. Two main challenges are at the centre of our attention: (1) ensuring public support and (2) having a working population with the right skills and knowledge.

Ensuring public support

Closing material and nutrient cycles by using secondary materials from waste(water) have to become the next “normal”. In order to achieve this, it will be key to involve citizens especially when projects are implemented in areas with dense populations (e.g. cities). Today, too often, technological innovations are implemented in a very “top-down” way. Private actors and governments make an agreement and afterwards inform citizens, having little attention for the fact that citizens are part of the innovation (for example, when secondary P is generated from households, or from buildings that are used by many people) or might experience some hindrance from new plants. By involving citizens more and increasing awareness on the need for a circular economy and sustainable materials management, public support for these innovations will be higher and the use of secondary materials will become common sense.

Having a working population with the right skills and knowledge

A transition to a closed nutrient cycle is only possible by developing the skills, knowledge and competences required by resource-efficient, sustainable processes and technologies; and integrating these into our businesses and communities. Different skills are needed by different industrial players in the nutrient cycle. Early identification of these skills and integrating them in our educational programmes is likely to play a significant role in the seizing of sustainable development opportunities.

Apart from new technological knowledge and skills, the introduction of green emphases into training programmes is an important lever in strengthening the skills of employees to fill the sustainable jobs of the future. More concretely, in relation to the establishment of a circular economy that enables sustainable materials management it will be key to introduce a more integrated approach in many training programmes. It is necessary that in every stage of the nutrient cycle employees are aware of both their own contribution and the contribution of others in other stages to closing the nutrient cycle. This enables to organize the whole cycle in the most efficient and sustainable way.

Well-informed citizens that support innovations and a well-trained working population will make sustainable materials management and closed nutrient cycles the next “normal”.

Phosphorus in sewage treatment and management

>>>Regulating phosphorus recovery from sewage ensures a net benefit?

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Regulatory limits on phosphorus discharges effectively prevent eutrophication of receiving waters. Regulatory targets for phosphorus recovery are being considered to secure a local supply and stabilise prices of this essential nutrient. This paper argues that a regulatory approach to securing phosphorus supplies does not ensure a net benefit unless several factors are considered.

In some jurisdictions, sewage constitutes a small portion of national phosphorus budgets. Observations in Australia, including 3 capital cities, indicated that the phosphorus load per capita declined in 11 of 12 sewage treatment plants by an average of 30% between 1997 and 2012. Additionally, regulating recovery does not consider the associated environmental impacts of resource consumption or the economics of recovery processes. While phosphorus security is important to global food production, it is not the only global sustainability challenge. Global warming is predicted to impact food production due to extreme weather events, rainfall variations and rising temperatures. Increasing adoption of energy and resource intensive processes to recover phosphorus effectively places phosphorus security above other sustainability challenges.

Consequently, if phosphorus security is achieved by a regulatory approach, it must be done in the context of national phosphorus budgets and the environmental impacts of recovery processes. Regulation must be designed to maximise the potential benefits and minimise burdens. This could be achieved by using life cycle assessment to select treatment plants to target for recovery, or by designing regulation with mechanisms to favour these plants.

Selection of treatment plants and processes would consider the quantity, location, form and bioavailability of recovered phosphorus in order to determine the reduced demand for fertiliser produced from phosphate rock. A recent life cycle assessment of decentralised and centralised treatment plants indicated that phosphorus recovery may have a net environmental benefit when the energy or resource consumption of the existing treatment process is reduced. Discharges to the environment would also be considered, since not all plants are required to remove phosphorus and treatment facilities may require upgrades or new infrastructure to facilitate phosphorus recovery. Each jurisdiction would need to consider how these factors apply to local treatment plants and available recovery processes.

Near complete phosphorus recovery from sewage is technically feasible. Furthermore, where sewage collection infrastructure already exists, recovery could be integrated with existing treatment facilities. However, utilities' adoption of these processes will likely occur either due to regulation or if recovery becomes more economical than current discharge or treatment practices.

Regulation would be designed to ensure that adoption of the most economical recovery process by water utilities also incorporates the environmental impacts as an included cost. Alternatively, regulation would include mechanisms to favour processes with reduced environmental impacts in regions where they could not be included as an economic cost. Targeting plants for recovery or regulation designed to maximise benefits would acknowledge that while phosphorus recovery from sewage may be beneficial to society, complete recovery may not be the most beneficial to the environment or economy and should be considered in the context of national phosphorus budgets and the environmental impacts of recovery.

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Putting a Phosphorus Bounty on Society's Bad Behaviour

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Phosphorus (P) mining and fertiliser application has enabled increased food production, disrupted the global P cycle by 400% (Filippelli 2008) and caused widespread eutrophication. Eutrophication is the planets greatest cause of water quality deterioration (Smith & Schindler 2009). Efforts to reduce P accumulation in the ecosphere have focused on increasing agricultural P use efficiency and the recycling of P from wastes. However, this will not be sufficient to achieve P sustainability. These advances should be viewed as components of the whole system. We argue here that focus on the behaviour of the consumer (i.e. society) is just as important as improving behaviour of the producers (i.e. agriculture).

The global P cycle (Figure 1) is driven by the motor of human consumption. P demand is increasing due to an increasing population, with an expanding middle class with growing P requirements, largely due to increasing meat consumption (Childers et al. 2011). The responsibility for reducing the human P footprint falls upon the lifestyle choice of the individual. Policy makers, industry, scientists and educators can therefore play key roles in creating a future in which P sustainability is a societal aspiration. To achieve this, integration of natural and social sciences is required (Ulrich et al. 2013), and is currently not common place (Holm et al. 2013). In this respect, the Global Transdisciplinary Processes project (TraPs) leads the way (Scholz et al. 2014).

Encouraging behaviours that support low P lifestyles offer significant reductions in our P footprint (Figure 1). Ecosphere accumulation will continue (3.1-38.2 MT yr^{-1}) if P mining (15.9-44.4 MT yr^{-1}) and P rock weathering continue to exceed depositional retention (6.2-12.8 MT yr^{-1}). Improvements in behaviour offer emission reductions up to 1.8 MT yr^{-1}. Whilst reducing consumption of foods with high P footprints will propagate further reductions within the global P cycle (i.e. reduced fertiliser demands).

Food labelling regulations do not enforce the declaration of a product's P content or footprint. Such labelling would enable consumers to make informed decisions regarding their dietary P footprint. As obesity in the developed world increases (Cameron et al. 2012), it is necessary to consider not only how dietary P effects individual health (serum P may be a predictor risk factor of mortality, cardiovascular morbidity and bone metabolism (Onufrak et al. 2008), but also environmental health (Sutton et al. 2013).

In the US, 44% of the bestselling groceries contain P additives; furthermore products with P additives are cheaper (León et al. 2013). Policy may promote lower P diets by restricting P additive use by the food industry. Based on estimates for US diets, globally this represents 1.2–2.5 MT P yr^{-1} (Uribarri & Calvo 2003). Policies to reduce detergent P concentration have shown success (US EPA 2002a; EC 2011). In sixteen US states, bans on sales of detergents with more than 0.5% P resulted in a 40-50% reduction of P in wastewaters (US EPA 2002b).

Quantifying the impact of behavioural change on P emissions both directly and through feedback loops, will allow environmental benefits to be realised.

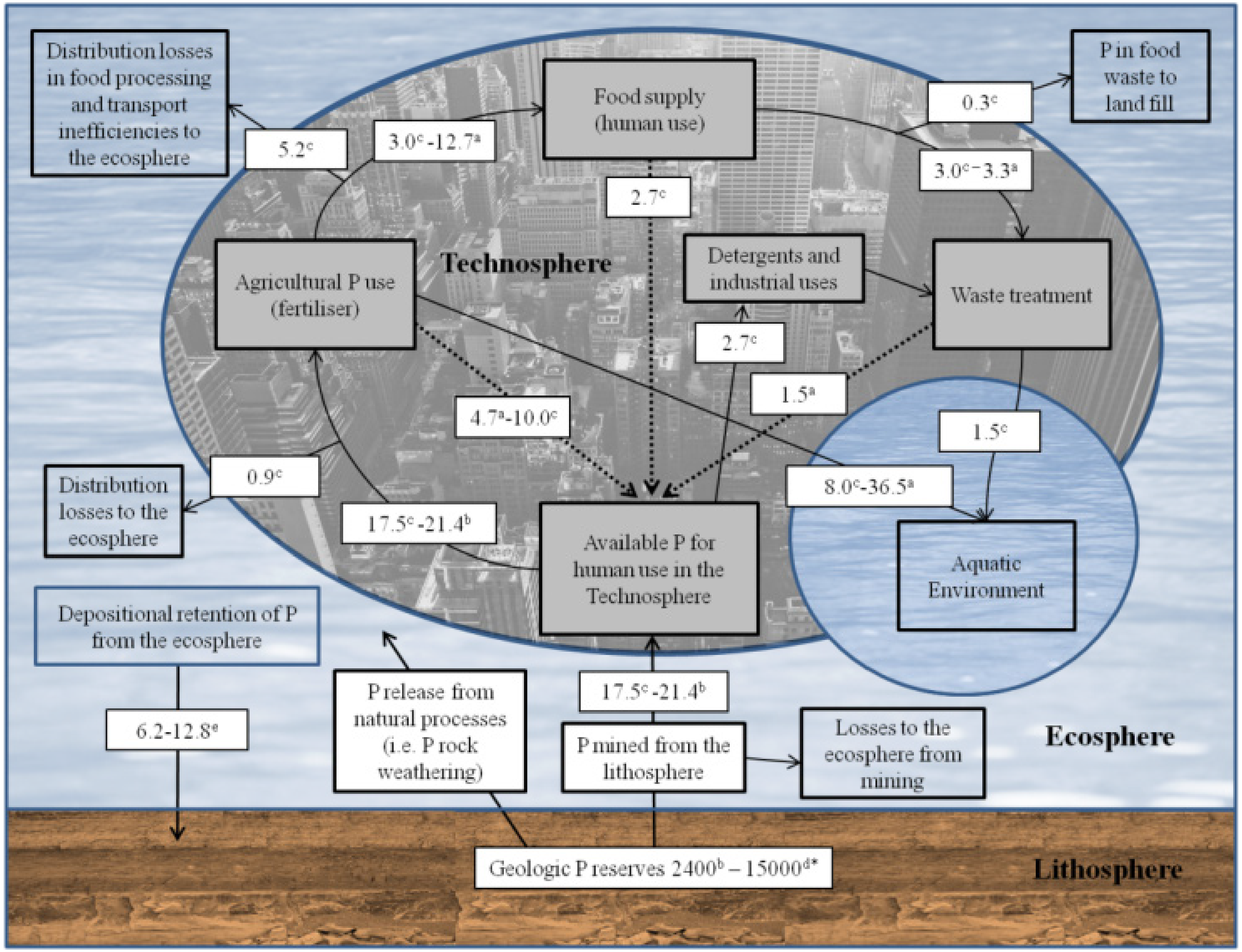

Figure 1. The global P cycle. Solid arrows represent flows of phosphorus (P), dashed lines represent recycling of P within the technosphere (grey area). Figures in boxes represent estimates of P flows in million tonnes (MT) year-1 (*estimated P reserves in MT). Superscripts correspond to the data source for each P flow estimate: a) Liu et al. 2008, b) Villalba et al. 2008, c) Cordell et al. 2009, d) Gilbert 2009 e) Pierrou 1976. P accumulation in the ecosphere (blue area) is equal to the sum of all losses from the technosphere (grey area), the rate of P release from natural processes (i.e. P rock weathering) and losses from P rock mining, minus the rate of depositional retention into the lithosphere (brown area).

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P resources and their use

>>>And why not phosphates from animal origin?

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Only recently have geologists begun to point out that geologic phosphates are a non renewable resource, that the heavy metals content is an increasing problem for food and fertilizers. On an other hand, animal phosphates wastes (carcasses, bone meals) cannot be slowed down as the mondial population is still being increasing, and countries as China, Africa and India being in full growth are more and more meat consumers.

Our idea is to select and preserve animal phosphate wastes (carcasses from slaughterhouses, bone meals) to be valorized into calcium phosphate resources. For this, the valorization of such wastes must be strongly imposed. For such a valorization, must be forbidden the pollution of these wastes by the addition of sludges, the co-incineration of these wastes into the clinker industry, the use of these wastes as road layers. As a matter of fact, the bone meals producers often pollute the animal phosphates with their industrial sludges wich contain Si, Fe, Al, Zn, Cr, Ni, V and others. Moreover, the animal phosphates wastes can contain Na and Cl input, if an industrial leather production is done in the bone meals plants.

Since 1998, we have tested this idea to valorize animal phosphate wastes, at the laboratory scale. We have work to adjusted the calcination step in the aim to recover mineral ashes made of 98% of hydroxyapatite, a very pure calcium phosphate with 38% P_2O_5 and in the same time, to recover energy. We propose to promote small calcination unities, close to slaughterhouses, or close to bone meals plants. They will become new calcium phosphates producers and new energy distributors.

We have compared the chemical compositions of geologic phosphates (from Marocco and from Israel) with that of ashes from bone meals from different French plants. We have elaborated crude phosphoric acids, obtained from these different phosphates. Compare to geologic phosphates, the animal phosphates are P_2O_5 rich phosphates (38%), free Fluorine phosphates (0%), As, Cd, U and heavy metals poor phosphates. They contain K, Sr and Mg which are bone components. The crude phosphoric acids from the different calcium phosphates show that only are recovered the elements contained in the phosphates (Table 1). Pure animal calcium phosphates allow to obtain pure phosphoric acid which will need, through refining, the elimination of K, Sr and Mg.

Origin	**Mg**	**K**	**Sr**	**F**	**As**	**Cd**	**REE**	**Pb**	**U**
ANIMAL	**526**	**837**	**2.59**	**0**	**10.9**	**7.65**	**15.3**	**20.1**	**6.96**
MAROC	292	74.9	17.8	4821	2559	2938	11944	56.7	25939
ISRAEL	180	7.69	32.5	866	995	2155	1362	13.1	7604

Table 1: Chemical analyses of the crude phosphoric acids elaborated from calcium phosphates from animal origin and geological origin (Marocco and Israel) (ppm for Mg, K, Sr, F; ppb for As, Cd, REE, Pb, U). The presence of REE, lead, cadmium, in animal phosphates, is certainly due to the animal feed (grass, flour) which contains pollutants brought by the phosphate fertilizers.

Towards phosphorus security for a food secure future

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Substantial progress has been made with respect to research and awareness on the global phosphorus challenge in the last five years alone. The 2008 fertilizer and food price spikes were a wake up call, reminding us of the inextricable link between phosphorus and humanity, and, exposing the fragility of the world's phosphorus and food system to even temporary perturbations. New research has analyzed national phosphorus flows, global phosphate reserves and market dynamics and risks. Phosphorus recovery trials have increased and numerous global and national phosphorus platforms have been established. There is now consensus that increased phosphorus recycling and efficiency are required regardless of the longevity of remaining phosphate rock.

However there is still much work to be done to shift the current precarious trajectory of phosphorus use and governance onto a more sustainable path to ensure food and nutritional security for a growing global population, fertilizer access and sustainable livelihoods for billions of the world's farmers and ecological integrity of the planets rivers, lakes and oceans.

Like other complex or wicked sustainability problems, the global phosphorus challenge has fuzzy/contested boundaries and multiple co-existing agendas and goals. A sustainable phosphorus future will need to directly address these goals, in addition to the legacy of our current systems (weights the past) and future drivers or mega-trends (figure 1).

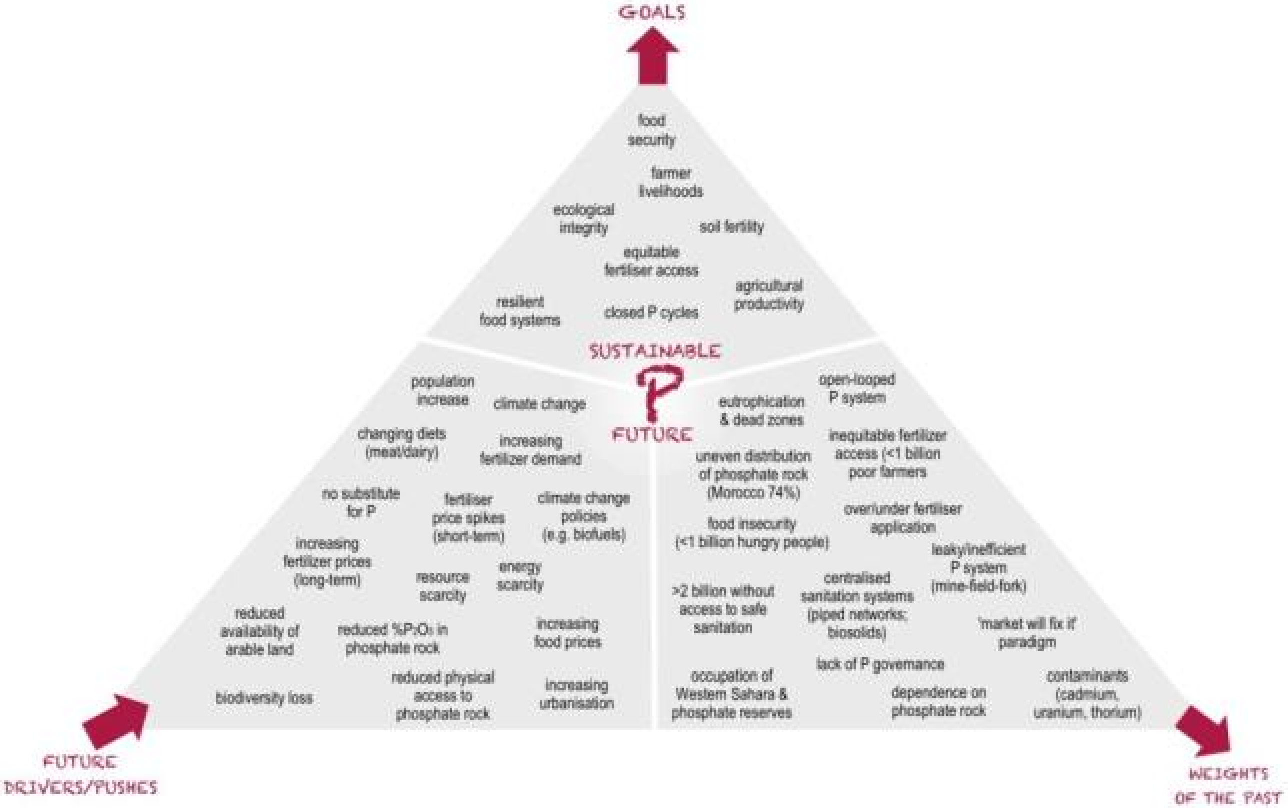

Figure 1: Defining sustainable phosphorus futures are informed by weights of the past, future drivers (mega trends) and aspirations (future goals).

Collective goals for phosphorus security might include:

- *Agricultural productivity*: Increase overall phosphorus use efficiency of the food system (beyond the farm) by increasing the number of people fed per tonne P input, or reduce total P demand while maintaining food/agricultural output;
- *National security*: Reduce dependence on phosphorus imports through diversification of sources, to buffer against price fluctuations and geopolitical risks in producing countries;

- *Soil fertility*: Ensure soils are fertile in terms of total bioavailable phosphorus and C:N:P ratio, organic matter, moisture;
- *Farmer livelihoods*: Ensure farmers' needs are met by ensuring access to affordable phosphorus fertilizers and in a bioavailable and manageable form;
- *Environmental integrity and productivity*: Close phosphorus cycles by reducing losses and wastage of phosphorus throughout the food system, from mine to field to fork; and
- *Ecological integrity*: Reduce leakage of phosphorus from land to avoid eutrophication & pollution of rivers, lakes and oceans.

So how do we get from where we are now, to where we want to go? There is a whole 'toolbox' of phosphorus recycling and efficiency measures available to us in all sectors from increasing efficient practices in mining and agriculture to low- or high-tech phosphorus recovery in the sanitation sector to changing diets. Key will be taking an integrated, context-specific approach that responds to local/regional drivers to avoid investing in ineffective or partial measures. What works in Europe will be different to Australia, China or Ethiopia. Finally, technologies and practices don't implement themselves: effective policy instruments (regulatory, economic, facilitation) are required to stimulate and support such measures. Accountability means independent monitoring of transparent phosphate data is required. Shifting the current trajectory towards more desirable futures is possible if all key goals and associated stakeholders are included, to co-define and implement more scientifically credible, policy salient and legitimate phosphorus strategies.

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Comparative Life Cycle Analysis of two detergents: 1) Phosphated and 2) Phosphate free

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Detergents are formulated in general with the following components: surfactants, builders, pH buffers, optic whiteners, enzymes, colorants and fragrances. For the manufacturing of phosphated detergents, a builder of historically sustained efficiency is used: sodium tripolyphosphate. It's properties are: 1) keep on solution the hardness of water, 2) remove and prevent incrustation from fibers, 3) generally improve the whole washing process. The main concern over the adverse effects associated with the use of sodium tripolyphosphate in detergents is based on the increase of the phosphorous load in the environment, every time in which the effluent doesn't gets tertiary treatment. Aluminum silicates (zeolites) are utilized as substitutes for phosphates. They have the capacity of forming a strong bind with metal ions like calcium.

When comparing the Mexican infrastructure of wastewater treatment on its main cities with the one of countries in which wastewater is integrally treated, a hypothesis was constructed which stated that the use of phosphated detergents, in comparison with phosphate free products, doesn't represent a higher environmental impact in Mexico. The main objective was to quantify the environmental impact of phosphated detergents in comparison with the phosphate free alternative using Life Cycle Analysis. Detergents, as products that are part of daily life, have received special attention, especially because of their high usage globally. The Life Cycle Analysis tool, indicated on the ISO 14040 standard, integrates four phases: objective and scope of the study, inventory analysis, impacts evaluation and interpretation of results.

For the purposes of this study, a functional unit was defined as the kilograms of each powder detergent (phosphated and phosphate free) needed for the function of 1,000 washing cycles. The CML, 2000 life cycle impact evaluation model was used. At this stage of the Life Cycle Analysis impact categories were selected, and the results of the inventory were assigned to these, in a way that the potential impacts per category could be calculated and evaluated by the SimaPro 7.3.2 software.

Between the phosphated and phosphate free detergents, there's a difference of 3% on their energy consumption, reflected on the environmental impact of the second in the category of climate change. Notwithstanding the low significance between the water consumption of each, the solid waste generated by the phosphate free product is 12% higher. The impact category with the highest difference between both detergents is eutrophication, with a 60% difference. In contrast, the category of abiotic resources depletion only differentiates by 2%. Regarding the environmental impact of the nine categories evaluated, the phosphated detergent contributes with a lower impact on six of them (abiotic resources depletion, climate change, stratospheric ozone depletion, human toxicity, water toxicity and soil toxicity). The phosphate free product contributes with a lower impact on three categories (acidification, eutrophication, and photochemical oxidation). As a sensibility analysis was performed, the hypothesis was confirmed, due to the lower environmental impact of phosphated detergents and the strong correlation between the environmental impact of both products and the influence of the level of wastewater treatment with tertiary treatment and P removal when disposed after the use phase.

Sustainable P Management Inspired by Nature

>>>A novel perspective beyond phosphorus stewardship

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Like other grand sustainability challenges of our time, the phosphorus issue roots in false perception. Human consciousness fails to accommodate the bond between man and nature in its full holistic dimension. Evolutionary forces, intrinsic to the global sustainability effort, are at work to raise awareness. We call this half-conscious development a transition, and focus mainly on challenges and achievements without: phosphorus, food, water, energy.

Yet the road to phosphorus sustainability, as much as it will hopefully improve management skills without, will at the same time enhance awareness within. Individual and collective cognitive transformation steps will change our basic attitude to nature and behavior. The current, anthropocentric stewardship paradigm will make place for a more ecocentric world order, in which mankind consciously, functionally and integrally partakes.

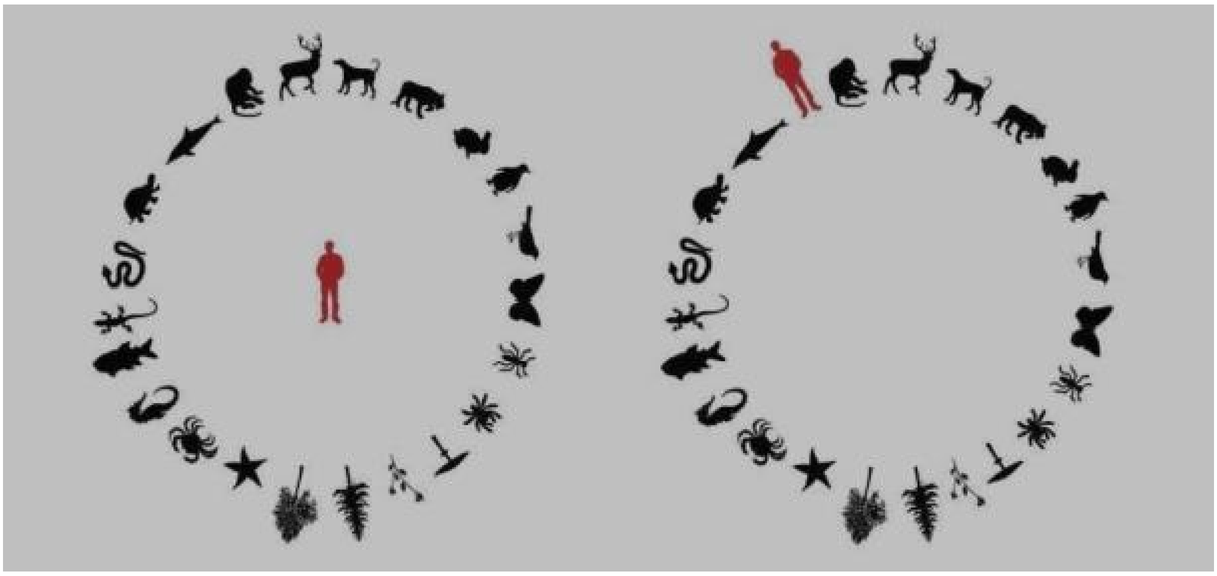

Figure 1: In the anthropocentric view (left) humans dominate the natural world; in the bio- or ecocentric view (right) man is part of and participates in the natural world.

Change is underway indeed, the planet growing greener every day. When deliberately transiting to sustainability, people look for roadmaps: coherent visions of a world that works and practical ways to get there. Biomimicry's claim and miracle is that it provides both. Biomimicry? Yes: the conscious emulation of nature´s genius [1]. Imagine how the near future might look with biomimicry seeds for sustainable innovation already being sown around the globe, from kindergarten to university, and in all sectors of society.

In 10-25 years time the biomimicry movement will change landscapes radically, fading out the idea of P stewardship. Instead a simple, humbly posed question echoes everywhere: "how does life manage phosphorus?". Turning to the natural world as model and benchmark for sustainability is now driving successful P management.

Biomimetic action frameworks surface to carefully replicate nature´s effective and efficient P strategies. As we learn to quiet our human cleverness and welcome nature as a mentor, new scientific truth on phosphorus comes to light. A re-interpretation of existing data and constitution of novel theories help to re-map the biogeochemical P cycle, our blueprint for action.

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[1] The word „biomimicry" was coined by Janine Benyus in her book „Biomimicry: Innovation Inspired by Nature" first published in 1997.

P technologies adapt to these changing conditions by self-renewal: rejecting heat-beat-and-treat processes and re-modelling to multi-functional designs that use life-friendly, water-based (bio)chemistry for even more resource and energy efficiency. Locally attuned and responsive P management improves considerably, shortening feedback loops between use and re-use cycles and sustaining cooperative relationships among all actors in the value chain.

The 2007 Phosphorus movement that initially spread so swiftly, survived by integrating development with growth. It now thrives through the freedom of self-organization. Alternating bottom-up and top-down leadership fosters nodes of biomimetic activity connected in strong networks that cooperate to globally tackle the P challenge.

For now let us stick to P for Phosphorus – Unexpected manifestation of light at the end of the tunnel comes from recognition of biomimicry's realism. After 3.8 billion years of R&D, species that surround us have learned how to manage phosphorus and survive. The art of asking nature for advice, biomimicry design informed by living systems thinking is the way forward.

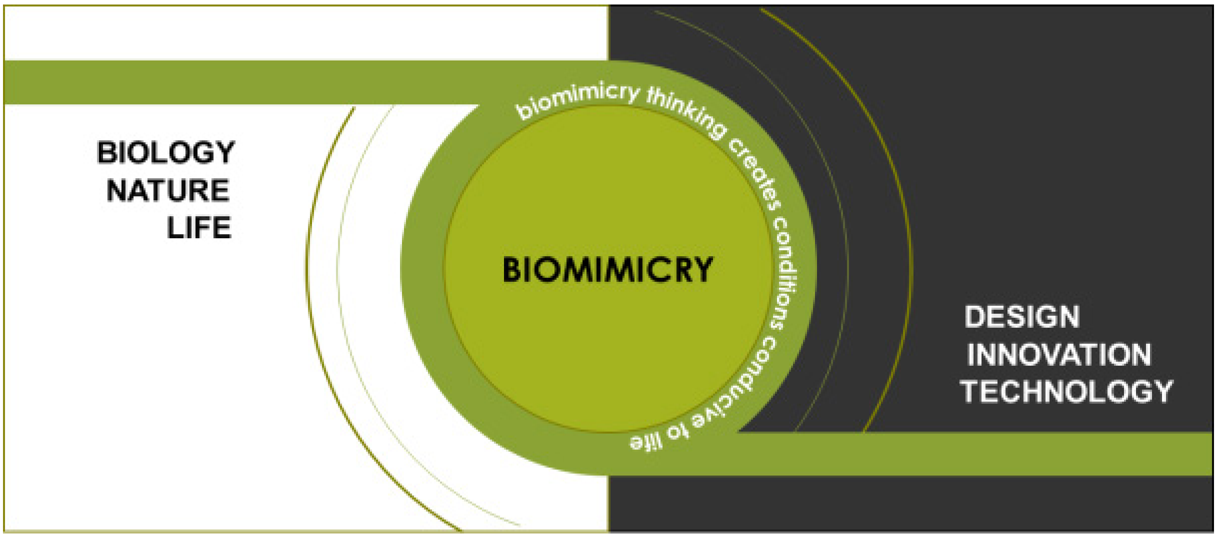

Figure 2: Biomimicry connects two living worlds: man and nature, and biomimicry operates at the interface between fundamental and applied science.

Illustration credits

Figure1: adapted from http://kindredspiritus.wordpress.com/2013/09/25/challenging-the-dominant-paradigm/

Figure 2: modified from Biomimicry Resource Handbook, Biomimicry 3.8, Missoula MT, USA

A mature market for recycled nutrients in 2030

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The phosphorus challenge is deeply rooted in the way we produce our food and manage our waste. By mining useful resources from our waste streams, we are able to mitigate the potential risks of scarcity, geopolitical dependency and environmental pollution. Eventually we might become self-sufficient in our nutrient supply by smart routing of organic waste streams back into our food and feed production system.

Solutions to *recover* nutrients are already rapidly emerging. We are well capable of extracting phosphorus from wastewater, animal manure and other types of organic waste. Not always, however, are these nutrients actually *recycled*. To genuinely close the nutrient cycle it is essential to match the supply side to the demand of the end-user.

One key to successful recycling is to start at the end of the value chain, at the ultimate customers of recycled nutrients. Potato farmers naturally demand an entirely different composition of fertilizer than a tomato horticulturist, and a pig feed producer compiles its product differently from a chicken feed producer. The requirements in quality and quantity of individual nutrients like phosphorus, nitrogen and potassium are widely varying, and are not always taken into account by the part of the value chain that is responsible for nutrient recovery.

Therefore, on top of explicating the different kinds of demand for recycled nutrients, we also need to pro-actively couple the tail end with the rest of the value chain. This approach asks not only for technical innovations, but above all for an organizational change. How do we re-design the value chain in a way that is beneficial for all parties? If we are able to create dedicated products that match the demand of specific end-users, we might be making fast steps in actually closing nutrient cycles.

Of course there are several other hordes to be taken that currently prevent the rapid advance of a European market for recycled nutrients, including legislative and financial factors. By harmonizing legislation of waste treatment throughout Europe, by creating incentives for companies to create value out of organic waste streams and by involving green investors in nutrient recycling we might be able to accelerate our current activities.

However, we need to look further ahead. On the long term we envision a system in which organic waste streams are fully separated into re-usable components, upgraded to valuable products and brought back into our food and feed system, without wasting a single nutrient. It is our aim to recycle 40% of recoverable nutrients by 2020, and to recycle 100% by 2030. Nutrients can both be recycled on a local scale in a decentralized set-up as well as be exported to nutrient-scarce regions through a centralized system, as long as the design of the value chain is tailored to the demand of the end user. For that purpose it is essential to bring together all parties throughout the value chain and keep developing innovative ways of recycling. We are looking forward to it.

Securing Phosphorus in Tomorrow's World

>>>Phosphorus – At the crux of agricultural and demographic transition

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Phosphorus is essential for life and its biological role proves to be vital in aquatic systems. However a vast majority of phosphorus compounds are consumed as agricultural fertilizers, replacing natural phosphorus plants remove from the soil, and the annual demand is rising nearly twice as fast as the growth of the human population. Proven reserves of phosphorus could be exhausted within a century putting at risk ecosystems and human welfare.

As for many other societal and ecological issues, answers concerning phosphorus depletion will depend on agricultural and demographic evolutions. Both trends are dramatic ecological and societal drivers of our common future. The way they will be managed during the century will deliver a better life for all or cause increasing threats, poverty and social unrests.

Because agriculture and demographic development are linked. Demand for food and feed depends on demography. Feed however is linked to livestock and to our diet choices.

Addressing complex and interrelated issues asks for *integrated approaches* to deliver plural dividends. The *integrated strategy* to solve long term phosphorus shortages is to reduce the demographic explosion while modifying our diet by reducing our meat consumption. Fixing both would help to reduce not only the phosphorus problem but many others ones (water eutrophication, bioaccumulation,...). Any other solution is a plaster on a wooden leg.

Nations worldwide have to manage unsustainable trends and to learn moving towards responsible governance. Our 21st century will be a knowledge-based century, a century of collective intelligence, or be a period of disasters, inequalities and wars.

The first act of such a collective intelligence would be to reduce the growth rate of human population and the way to address this sensitive issue is to act at the United Nations level. We should discuss the issue within the UN and have the courage to initiate debates and dialogues and try to find a consensus in terms of common but differentiated capabilities and responsibilities with the aim to table mutually supportive solutions, better lives for all and prosperity for Nations. It is key that Governments around the world commit themselves through economic, social and educational incentives to reduce our population growth rate.

In this debate, historical issues are critical. Saying "the West has an historic responsibility and we have the right to freely develop ourselves" is dangerous. Difficulties that developing countries actually face with demographic growth should be balanced with same difficulties developed countries address nowadays with ageing populations and retirement funding.

The second track is to reduce globally our meat consumption. Here also this solution is expected to deliver many potential gains : cost-efficient health systems, better immunity profile, nutrition as the new medicine, promising biotechnological avenues and last but not least stopping the loss of biodiversity.

Optimizing Phosphorus Recovery during Wastewater Treatment:

>>>Supplementing existing wastewater treatment with electrokinetics

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With current and projected consumption rates, the quality and quantity of primary sources of phosphorus will rapidly decrease in the coming decennia. This will significantly stimulate the need for secondary sources, in the form of waste streams. A high potential secondary source is municipal wastewater and its resulting sewage sludge; however, its value, for example as fertilizer of agricultural soil, is often diminished by insoluble phosphorus complexes and hazardous compounds, both organic and inorganic of nature.

Many of the well-established wastewater treatment methods focus on the production of clean water to meet existing legislative standards, but show certain disregard towards the sludge product. To prevent the release of phosphorus into the environment, many wastewater treatment methods involve precipitation of aqueous phosphorus using iron and aluminum salts. However, this significantly hinders the effective recovery of phosphorus at a later stage.

A change in approach of wastewater treatment is required in order to increase phosphorus recovery meet the future demand. Fully changing existing wastewater treatment methods is a time-consuming and costly endeavor which needs to happen gradually. Innovative treatment techniques supplementing existing wastewater treatment can be the way forward when the focus of wastewater treatment widens from the production of clean water to the recovery of important nutrients.

One example of a technique that could supplement existing wastewater treatment methods is electrokinetics, in the form of electrodialysis (ED). ED is a remediation method in which a direct current and ion exchange membranes are used to extract and concentrate ionic complexes. The technique has the potential to extract phosphorus in the form of phosphates during wastewater treatment without significant intrusion into existing treatment processes. Application of ED during wastewater treatment could eliminate the usage of chemical coagulants altogether, significantly improving the availability of phosphorus in the sludge, and if incinerated, in the resulting sludge ash. Furthermore, it can also reduce sludge production and result in the recovery of a pure fraction of phosphorus during wastewater treatment.

Current research focuses on the combination of ED with existing wastewater treatment methods, investigating the changes in the most important characteristics of wastewater and the influence of these characteristics on the efficiency on ED treatment for the recovery of phosphorus. Research in this area will form the outline for the use of ED as supplementary technique in the near future.

Legislation will change and the focus of wastewater treatment shifts to nutrient recovery in the coming years. Supplementary techniques such as ED can be the solution to increase recovery of phosphorus from secondary sources in the short term without having to significantly change existing wastewater treatment methods.

Phosphorus recycling from cities to arable land

>>>Clean products and efficiency at all levels

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More people, limited resources, higher standards, better health and reduced environmental impact of human activities is desirable and a realistic expectation for the future. This means increased food production due to an increasing population and changes in eating habits.

To reduce the environmental impact a high efficiency at all levels is required, i.e. increased recycling of resources which should be clean and effective in their use. For phosphorus there is an extra dimension relating to independency on import since most regions are dependent on imports. Therefore, an improved recycling of phosphorus from society's waste is particularly important.

Phosphorus-containing wastes are wastewater, slaughterhouse wastes and animal manures. For wastewater, the efficiency of phosphorus recycling starts in the treatment plant. Increased efficiency of phosphorus removal results in a larger amount of phosphorus being available for recovery. For Europe, improved phosphorus removal from wastewater implies that additional thousands of tons of phosphorus become available for recovery.

Increased food production on limited land requires increasing inputs of fertilizers and feed additives. In order not to increase emissions, fertilizers have to be efficient having high plant availability and application synchronized with crop demand.

Phosphorus fertilizers usually contain high levels of impurities from the raw material such as cadmium and uranium, which via fertilizers contaminate soil and crop giving negative consequences for human health. Fertilizers should have a low content of heavy metals otherwise intensive production will contribute to increased accumulation of pollutants counteracting a safe food production.

In future increased incineration of sewage sludge, slaughterhouse waste, and manure will occur to reduce the amounts of wastes. In addition, incineration destroys organic pollutants which if recycled to agricultural land may constitute a health risk. The ashes produced have high phosphate content, between 14 - up to 41 % P2O5, compared with 27 – 37 % P2O5 in rock phosphate.

In our view, sustainable systems for phosphorus recirculation consist of the following characteristics:

- Improved phosphorus removal in wastewater treatment plants, i.e. an increased amount of phosphorus available for recovery
- Phosphorus removal by chemical precipitation giving phosphorus in sewage sludge
- Incineration of sewage sludge, either mono- incineration or co-incineration
- Use of ashes for phosphorus recovery (no other use is permitted)
- Resource-efficient recovery processes producing pure products such as water-soluble fertilizers or feed phosphates
- Disposal of undesirable substances, heavy metals, etc.
- Improved strategies for application of fertilizers on arable land improving the efficiency of phosphorus use

These criteria reduce the consumption of finite resources, contribute to safe food production and improved public health.

Ragn -Sells AB and Easy Mining Sweden AB developed a concept, "Sustainable sludge incineration" meaning co-combustion of sewage sludge, avoiding energy demanding drying, with subsequent phosphorus recovery from the ash. The ash is processed according to the efficient process developed by EasyMining resulting in pure and well-known phosphorus products, ammonium phosphates or calcium phosphates (fertilizers or feed additives), recovery of iron and aluminium in form of precipitation chemicals while heavy metals are separated for disposal.

Efficient Phosphorus Use in Animal Nutrition

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Introduction

Phosphorus (P) is an essential mineral for man and animal. P is involved in bone formation and many metabolic processes.

Animal feeds contain certain levels of P, but often not sufficient to meet animal requirements or not available for the animals. Therefore, animal diets can be deficient in P if not supplemented with inorganic P or supplemented with the enzyme phytase to increase P availability. This statement summarizes some approaches to reduce P supply in animal nutrition and to increase the efficiency of P utilisation.

Potentials to improve the efficiency of P utilisation

There are various possibilities to improve P-efficacy in animal nutrition such as:

Meet P-requirements of animals more precisely

One of the most relevant objectives of animal nutritionists is to identify energy and nutrient requirements of food producing animals depending on animal species and categories, their yield, physiological stage, health and welfare and safeguarding the quality of food of animal origin. Metabolic studies and dose-response studies were carried out to deduce P-requirements since many years. Scientific committees (e.g. GfE-Germany; NRC-USA) analyse available data and report requirements, which are updated every 10 to 20 years. Such committees also suggest criteria and methods to evaluate P availability of feedstuffs.

Use of phytase as feed additive

Phytate (phytic acid) is the major storage form of P in plant seeds and in this binding form P is only to a very limited extend available to nonruminant species. Six P-atoms and some bivalent major and trace elements (e.g. Mg, Ca, Fe, Zn, Cu) can be found in phytic acid (Johnson and Tate, 1969). About 50 to 80% of the total P is present in many seeds as phytate-P (Rodehutscord et al., 1996). Supplementation of microbially produced phytases can increase the availability of P and further minerals for pigs and poultry remarkable.

Possibilities of plant and animal breeding

Some opportunities in plant and animal breeding exist to improve the P availability as recently summarized by Flachowsky (2013).

Plants low in phytate

Reduction of phytate synthesis in plants via plant breeding to create low-phytate hybrids or varieties of maize, barley, rice or soybeans may improve P availability. In a study with pigs low-phytate maize showed the same results as traditional maize supplemented with inorganic P per kg feed, but a significantly lower P excretion

2.3.2. Plants express phytase

Most cereal seeds contain only low concentrations of the enzyme phytase. In pigs, grains with relatively high phytase concentration (e.g. wheat) have a higher P availability than grains with low phytase concentration (e.g. maize). Some animal nutritionists tested a phytase transgenic feed and found similar results as with microbial phytase for enhancing the utilization of phytate P.

Animals express phytase

First studies showed that genetically modified pigs and poultry are also able to express phytase via saliva. The so-called “environmental friendly pig” (Enviropig) carries a bacterial phytase gene under the transcriptional control of a gland-specific promoter, which allows the animals to digest certain amounts of plant phytate.

P-recovery from animal bones and other waste

Most of the P accreted by the animal is contained in the skeleton and disappears from the food chain in countries not allowing to feed processed animal proteins. Therefore, P utilization from animal bones (e.g. Abel et al. 2003) and other by-products incl. sewage sludge is a real challenge for animal nutritionists for effective P use.

Conclusions and Summary

There are many opportunities for a more efficient use of P in animal nutrition, such as more precise estimates of the P requirement of animals, improved feedstuff evaluation, use of feed additives, and breeding of plants with a low phytate and/or a high phytase content.

Phosphorus applications in Industry – A high potential of achieving "positive materials´ criticality"

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Industrial applications of phosphorus can be made both, by the wet chemical route to produce purified phosphoric acid (PPA) out of merchant grade acid and the electro thermal route to produce white phosphorus (P_4) and its downstream derivates. Depending on the route a partial (PPA) or full range (P_4) of industrial applications can be achieved. As raw material for industrial application it is regardless, whether primary rock phosphate or secondary phosphates are used, as the high purity requirements make the refining on a high standard indispensable. Facing the outstanding country concentration on the supply side of P_4 derivates in Asian countries, there have been no appreciable supply restrictions yet. The PPA production in contrast is more relaxed, but the delivery of basic phosphorus derived substances is a question of concern for the short global market balance.

Beneath its tremendous variety of uses for industry, phosphorus is mostly used as an additive. Thereby phosphorus acts as specific functional substance to optimize product or material performance. By substituting or excluding phosphorus additives substantial performance losses have to be taken into account. Keeping in mind the increase of raw material consumption since the industrial revolution along with the rapid surge of material diversity, industrial applications of phosphorus take an essential part in ensuring a more efficient use of resources and materials. Thinking in this broad and global context, a phase out for phosphorus in industrial purposes, that accompanies the peak phosphorus debate, is neither necessary nor reasonable for the future. Quite the contrary is the case by adding value to the application fields. With a relatively constant overall growth at about 2% on a yearly basis no significant increase can be expected particularly in terms of the predicted growth in fertilizer consumption.

One example is the emerging application area of batteries for a variety of electric and electronic devices that will be dominated by the lithium ion technology in the future. For this technology multiple electrode materials can be employed, in particular lithium cobalt dioxide ($LiCoO_2$), lithium iron phosphate ($LiFePO_4$) or lithium hexafluorophosphate ($LiPF_6$). Cobalt is assessed as a highly critical material in several studies such as critical raw materials for the EU. The $LiFePO_4$ that can be obtained by the PPA and P_4 route and the $LiPF_6$ that can only be gained by the P_4 route can decrease materials´ criticality of cobalt. Aside from this the safety standards and price structures are more advantageous. Indeed this phosphate technology can´t replace all cobalt related battery uses, as it isn´t suitable for mobile devices but it is likely predominated for electro mobility that is currently endorsed by the EU.

Phosphorus can help to tread a positive pathway to materials´ criticality, offering a moderate and stable criticality for high ranked strategic functional materials as well as extending material and product life.

Harnessing sequestered phosphorus from abandoned feedlots: A feasible alternative to depleting phosphorus

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Feedlot operations over the years have recorded revenue increases in the United States, with the marketing of cattle and calves increasing eight percent, from $63.0 billion in 2011 to $70 billion in 2012 (USDA NASS, 2013). Apart from providing employment, products from these operations have help improve soil conditions (Rotz, 2004), and also provided materials to feed the energy sector in heat and electricity production (Flesch et al., 2011).

Cattle feedlot operations generate enormous amount of wet manure, ranging from 1.2 to 1.4 billion tons per year in the United States (USEPA, 1998; USEPA, 2004). Manure generated consists of gas, fiber, nutrients (Marino et al., 2008), and other constituents depending on the feed, supplement, and medications consumed by the livestock. Wet manure excreted per dairy cow per day equals that of 20 to 40 people (USEPA, 2005). It is estimated an average dairy cow excretes 166 kg of nitrogen and 29 kg of phosphorus in manure annually while an average beef cow excretes 59 kg of nitrogen and 10 kg of phosphorus (Van Horn, 1998). Roughly 25 to 50% of manure nitrogen (Hristov et al., 2011) is lost to the atmosphere (Van Horn et al., 1996) in the form of nitrogen gases including ammonia (Hristov et al., 2011) and nitrogen oxides (Rotz, 2004). Although most of the nitrogen is lost to the atmosphere, the remnant phosphorus and nitrogen in the manure is transported by runoff (Swanson and Mielke, 1973), leached (Van Horn et al., 1996), or incorporated into the soil after decomposition. Studies on soil from abandoned feedlots revealed elevated concentrations of sequestered phosphorus (e.g. Gbolo and Gerla, 2013a), which may be released during periods of anaerobic conditions when soils are saturated (Richardson, 1985) causing spikes of elevated concentrations in groundwater.

Numerous studies and articles including Cordell et al. (2009) and Fixen (2009) have indicated a depletion of minable phosphorus reserves within the 21st century due to high demand of phosphorus for crops. In addition, phosphate mining can have deleterious environmental effects (Pearce 2011). Can phosphorus be recovered from feedlots abandoned more than a decade or more? Soils from newly abandoned feedlots have high salt content compared to the older abandoned feedlots (Eghball and Power, 1994). Most feedlots are simply abandoned: erosion occurs and invasive native and exotic plants often germinate thrive, especially during the wet seasons. Agronomists, soil scientists, hydrologists, other scientists, and major stakeholders in agriculture and food security should take a holistic approach in assessing the viability of abandoned feedlots as a source of phosphorus. Phytoremediation of phosphorus using graminoids should be encouraged, but these plant species should be used as forage for livestock consumption. Other practices such as prescribed burning, ploughing, and irrigation should also be encouraged to help release and recycle immobilized phosphorus. The use of abandoned feedlots to supplement the primary sources of phosphorus used in fertilizer can delay the depletion of these critical reserves.

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P Stewardship for Food and Fuel: Would You Rather Eat or Drive?

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It's common enough to want to drive to go out to a restaurant for dinner. But future demand for phosphorus (P) may make it infeasible to both eat and drive. Biofuels increasingly appear to be part of a sustainable future with regards to climate change and fossil fuels. The biostocks required to produce those fuels, like corn and sunflower, require vast amounts of P based fertilizer to grow. Even next generation microbial-based biofuel requires a great deal of aqueous nutrient inputs. These fertilizers are of course the same ones we rely on to produce enough food to feed the people on our planet, credibly creating competition between global food and energy systems. We have previously seen a drastic spike in food prices after the widespread adoption of corn based ethanol. This spike was based on a sudden demand increase for a single crop. The shock would be even worse and more widespread if the item in demand was the P in fertilizer needed for production of every food item. Clearly, a sustainable future cannot create conflicting interests between food and energy production. Use of low P demand crops and P recycling are two practices that biofuel production can undertake as their industry grows to help meet this goal.

First, utilizing low P demand crops can significantly reduce the amount of P required to produce the necessary biostocks. Genetically modified crops can require only half the P to produce the same yield. However they have faced fierce public backlash when used for food, from labeling requirements to outright bans. This presents an opportunity to instead use these low P demand crops for biofuel production. As widespread production of biostocks for fuel are produced, these should be selected from the most nutrient efficient crop strains science has to offer.

Second, P recycling can easily be introduced to biostock production. While biostock crops and algae require P to grow, the extracted ethanol and fatty acid chains fuel is refined from do not. That means all of the consumed P is left in the organic byproducts. It is a critical opportunity to recognize the nutrients embodied in these residuals can be recaptured and reapplied to subsequent crops. The residuals should be broken down through chemical or physical means, then the P recaptured and concentrated into a reusable fertilizer. P recovery technologies have been developed, but full scale application and widespread adoption are vital opportunities to reduce the P demand of biofuel production. A sustainable future for biofuel production incorporates P recycling from biostock residuals.

Use of low P demand GMOs for biostock production, and recycling of the P in the residuals after biofuel refining are critical visions for future P stewardship. The biofuel industry has an opportunity today to incorporate these technologies so that they are standard as biofuel becomes more widespread over the coming decades. This will avoid future competition between food and fuel, allowing us to drive *and* eat when we go out to dinner.

P losses to surface waters, eutrophication and water catchment management

>>>Prevent incidental losses of phosphorus by erosion from agricultural fields

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It is beyond doubt that eutrophication of surface water bodies is partly due to diffusive losses of the nutrients N and P from agricultural land. It also becomes increasingly clear that frugality is needed with our phosphorus resources. An unwanted phenomenon from both sides is incidental loss of phosphorus by erosion from agricultural fields to the surface water system. Incidental losses are losses by incidental erosion events. Such erosion events are often related to rain storms but river bank failure due to cracking under dry conditions may also be held responsible for incidental losses. These incidental losses are overlooked in a country like The Netherlands, while the Netherlands has a dense surface water drainage network, a strong tradition in intensive agriculture and, therefore, agricultural soils that are very rich in phosphorus. Sufficient international research has indicated that the phosphorus load of surface water systems by incidental losses related to erosion may amount to 50% or more. The majority of the load may even be related to a single heavy rain storm. From a sustainability perspective, a need exists to retain phosphorus on the agricultural land and to prevent it from loss to surface water. Once lost in the surface water system, it is technically difficult and financially unattractive to reclaim phosphorus. Increasing attention should thus be paid to soil management techniques that prevent environmental losses of phosphorus from agricultural fields. Some countries like Denmark and Belgium have established soil erosion policies for this, but this is no common practice in the European Union or more worldwide.

Figure. Overland flow from a flat agricultural field and quickflow of surface water rich in iron hydroxides as suspended matter with related phosphorus (photos by Joachim Rozemeijer).

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High Temperature Reactors (HTRs) for energy neutral phosphorus production

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The International Atomic Energy Agency (IAEA) with its overall vision of atoms for peace is promoting the use of "safe, secure and peaceful nuclear technologies". One potential application area is to study energy neutral phosphorous production. Elemental phosphorous can be produced using energy intensive thermal processing methods that are presently not favored due to high energy costs. High Temperature Reactors (HTRs) could provide the required energy economically using direct process heat applications.

Within Phosphate Rock (PR), the basic resource for phosphorous, considerable concentrations of uranium/thorium are found as accompanying elements. As first proposed by *Haneklaus et al.* ("Using high temperature gas-cooled reactors for greenhouse gas reduction and energy neutral production of phosphate fertilizers"-Annals of Nuclear Energy) HTRs can deliver process heat for thermal PR processing with integrated uranium/thorium recovery. The extracted uranium/thorium can be used as nuclear reactor fuel to operate HTRs powering the process or other nuclear power plants. Figure 1 shows a brief illustration of the proposed energy neutral process chain.

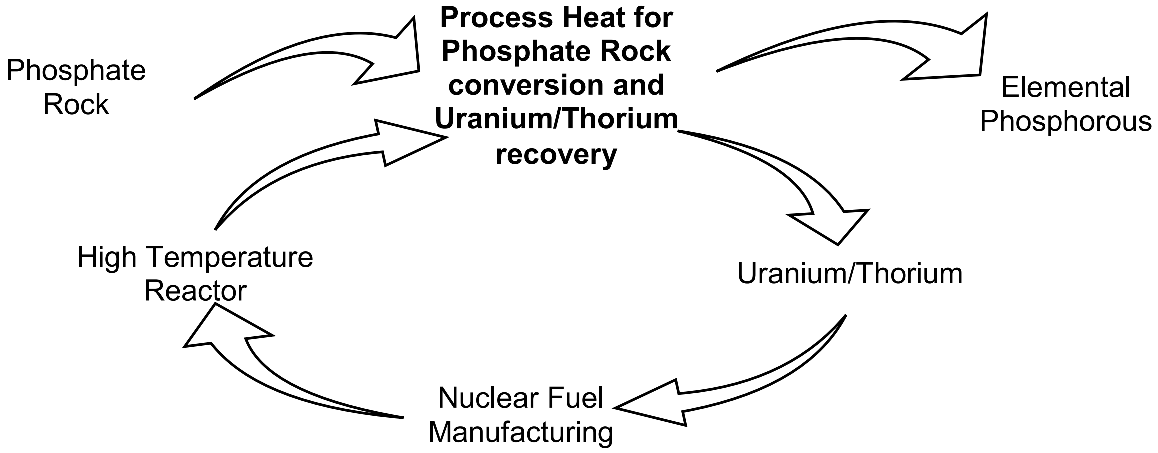

Figure 1: Energy neutral phosphorous production using high temperature reactors

Thermal PR processing generates elemental phosphorous that can be used directly (e.g. as food additives) or can be further processed to high purity thermal phosphoric acid (e.g. for phosphate fertilizer production). It is a well-developed process that dates back to the 1930s. In fact in 1950 production of phosphoric acid by the thermal process using conventional energy supply and the presently predominant wet process was about equal in the USA, the largest phosphate fertilizer producer at that time. The thermal process is in many ways more desirable than the wet process. Its ability to process low-grade PR and to separate impurities from PR generating high quality end products in one process, makes it attractive from an environmental point of view. Impurities of value (e.g. uranium/thorium, rare earth elements) and/or hazardous material (e.g. cadmium) can be separated. The relatively low quantity of waste is another attractive characteristic of the thermal process. In the wet process 4-6 tons of phosphogypsum is accrued as a waste product for each ton of phosphate fertilizer. Today approx. 5 % of all phosphate acid is produced using thermal processing techniques. Economically sound energy for thermal PR processing could be generated by High Temperature Gas-cooled Reactors (HTGRs) a specific type of HTR. A commercial demonstration plant the HTR-PM is presently under construction in Shandong Province China. The technology is well established and numerous HTR research reactors and demonstration plants have been operated in the past; UK (Dragon 1973-1976), USA (Peach Bottom 1967-74, Fort St. Vrain 1976-89), Germany (AVR 1976-88, THTR 1986-89), Japan (HTTR since 1998) and China (HTR-10 since 2000).

First estimates show that energy produced by a HTGR of average size would be more than sufficient to power thermal PR processing with integrated uranium recovery. The amount of recovered uranium ore would be larger than the amount needed to manufacture reactor fuel to operate the HTGR (assuming average uranium concentration of 100 mg U_3O_8 per kg PR as for instance found in Florida and large parts of Morocco). The applicability and potential of using HTGRs for thermal phosphate rock processing will be further elaborated on as part of a proposed IAEA Coordinated Research Project (CRP) regarding energy intensive mineral development processes ("Using HTGRs for energy neutral mineral development processes – a proposed IAEA-CRP" – URAM2014).

Financial incentives to drive circular economy

>>>Dredging and flexible pollutant fees keep phosphorous on land

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Like many places around the world, aquatic environments in Sweden are suffering under levels of loading of nutrients, including phosphorous, that are causing eutrophication and expanding anoxic sea-beds. Decades of emissions to the Baltic Sea have brought it to the point where internal leakage is now many times larger than the current inflow. Similar situations exist for example around the Conowingo Dam in the USA.

Two things about phosphorus (P) make it a priority. Firstly, it is a limiting factor. The more P that is removed the lower the threat of algal blooming. Secondly, it is scarce. Today we rely on mining which in turn relies on cheap energy. A true sustainable, circular, economy uses a soil to soil perspective for P, eliminating the need for mining. As the concentration of P in living things is several magnitudes larger than in the environment our very survival rests on this circular economy functioning properly.

There is a good business case for restoring these aquatic environments by removing sediment rich in P. Where some see mud, others see a potential gold-mine of resources including sources for biogas, fertilizers, land cover materials and valuable trace metals and minerals.

New dredging technology and new approaches to the economy could just save the day

Density Sorting Dredging, developed in Sweden by KTH, the Royal Institute of Technology, works like a giant vacuum cleaner, gently extracting different fractions from the seabed without stirring up sediment to release nutrients. Cheaper, cleaner sources of P are promised.

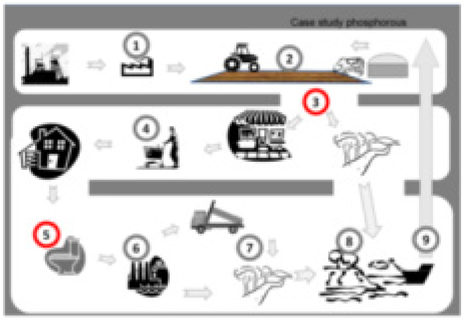
But cleaning up the pollution of past generations is not enough. We need investment in new kinds of infrastructure to usher in the soil to soil age of P. Once retrieved, we need P to circulate and never to leak again.

Flexible Pollutant Fees from The Swedish Sustainable Economy Foundation provide a control mechanism for P. Where P enters the economy it is subject to a fee. The fee is raised until the market responds, either by not taking in P or ensuring it never leaves the economy. Suitable places to levy a fee include on import and on discharge to waste systems or discharge direct to the environment.

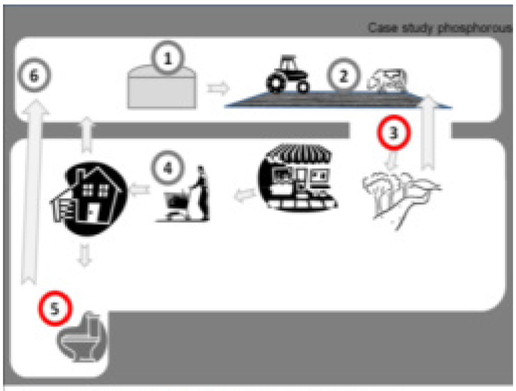
Everyone gets to share the income from fees

Should the market not respond, some hefty fees might rack up. But the fee does not all go to the government. On the contrary, the revenue from the fee, minus dredging and other costs, is returned to tax-payers to further stimulate the economy and distribute costs in a fair and democratic way.

The technology exists to circulate P. The scientific arguments are sound. A relatively minor fee can set the change in motion, putting P back on the land and making sure it stays there. For ever.



1. Phosphorus is mined and processed into fertilizer along with other nutrients like potassium and nitrogen.
2. Applied to the fields, it is incorporated into vegetables and sold direct or into animal feed. Animal manure is reapplied to the fields, or in some gases goes via biogas production and then back to fields as fertilizer.
3. Phosphorus leaks from agriculture into waterways and is exported to shops as food.
4. Consumers purchase food for consumption.
5. Phosphorus leaves the body mainly as urine.
6. Sewage is processed at water purification plants.
7. Some phosphorus is dumped as waste from purification, some ends up in waterways.
8. Eventually phosphorus travels to the sea where a large proportion is unrecoverable.
9. Some retrieval of phosphorus from the seas is possible from, for example, seaweed harvesting and dead zone dredging



1. Digested remains from biogas return to the fields
2. Organic agriculture releases only small amounts to surface water
3. Surface water is cleaned naturally and nutrients returned to the soil
4. Domestic and shop waste is composted and returned to the soil
5. The toilet system returns P to biogas and agriculture
6. Recycling technology closes the loop

P-recovery: Looking Beyond Struvite for P–Recovery

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Phosphorus (P) recovery from wastewater and livestock waste has been widely regarded as a strategic solution towards the potential P-depletion in the future. And struvite ($MgNH_4PO_4 \cdot 6H_2O$) is generally considered as the optimal phosphate mineral for recovery as it contains 51.8% of P_2O_5 (based on $MgNH_4PO_4$) and can be used directly as a slow release fertilizer. If the economic and life cycle costs are taken into account, however, it becomes clear that P recovery as struvite is likely not the best approach, for the following reasons: 1) production of P-mineral with a high content of struvite from real wastewater is a difficult and costly process; and 2) struvite is not superior to other phosphate-based compounds in fertilization efficiency, nor is it an exclusive form of raw materials favoured by the fertilizer industry.

In literature and practice, struvite precipitation is usually performed under alkaline conditions (pH 9.0-10.7). It is often taken for granted that these precipitates are struvite-like compounds when there are appropriate molar ratios among magnesium, ammonium and phosphate. However, in our recent studies, it is revealed by element analyses that the extensively reported struvite produced at high pHs (>9.0) could actually be some phosphate-based compounds containing a lower content of struvite or no struvite at all. The reason is that at high pH ammonia-N mainly exists in the form of NH_3 instead of NH_4^+ ions and phosphate is more likely to form precipitates with Ca^{2+}. Precipitates with a high struvite content (>95%) were only obtained at neutral pH rather than the alkaline pHs usually cited in literature.

A neutral pH level favours the formation of pure struvite, but the precipitation rate is significantly reduced. We acquired a single crystal of struvite (99.7% in purity) in a process taking approximately three months under ambient temperatures (25−30 °C). Obviously, such a long reaction time will hamper the application of struvite production in practice. There are several methods, such as electrochemical deposition, introducing crystal seeds and increasing thermodynamic driving force (controlling K^+ concentration), to accelerate the struvite formation. However, these methods demand extra energy & costs, and further increase the complexity of the P-recovery process.

From a practical application viewpoint, P recovery is unnecessarily oriented to struvite. Previous studies have indicated that struvite is approximately equal to monocalcium phosphate ($Ca(H_2PO_4)_2 \cdot H_2O$) and dicalcium phosphate ($CaHPO_4 \cdot 2H_2O$) in fertilization efficiency; however, the cost of producing struvite is much higher than that of producing these two compounds. In addition, the fertilizer industry finds no favour with struvite as long as the feedstock contains an appropriate content of P_2O_5 (30−40% favoured).

In conclusion, P recovery should not be too strongly focused on struvite, and could be aimed at any acceptable forms of phosphate-based compounds by the fertilizer industry, depending on onsite circumstances. Accordingly, efforts should also go to develop technologies based on other phosphate based compounds in future research.

Expanding the understanding of nutrient management

>>>Consideration of quality hierarchy in sustainable nutrient management

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Terms quality and quantity are ubiquitously used when nutrient management is discussed, particularly for phosphorus. The picture is confounded by specific disciplines or consumer groups that define these terms differently.

Universally the nutrient quantities can be measured in normed concentrations, but what about qualities? Food is tasty but fertilizers are judged by their grade or plant availability. Considering the global view, fertilizer production serves to produce food and feed, thus, agricultural output is the highest desired nutrient quality. The embedded nutrients in food can enfold their dedicated potential – keeping us alive. Considering this formulation, we can develop a rough hierarchy of the nutrient potential along the food chain:

1. Food and feed - nutrients consumed by humans and animals
2. Fertilizers, in the broad context - nutrients that can be applied to fields and taken up by plants, such as compost, digestates, sewage sludge and TSP
3. Other sources - nutrients are present but in a form which is not allowed or cannot be applied in tiers 1 or 2, because of low grade, pathogens or undesired metals or other, such as MSW, sewage sludge, diffuse run-off sources, phosphorus rock

Depending on the regulatory framework, the nutrient-containing materials can be divided into these categories differently (e.g. sewage sludge). The energy and natural resources consumed for production tend to intensify at each tier. For example water and energy footprint increases from mining to agricultural production and human consumption. The resources of the lowest tier are typically accounted for in the production of the main-product or discarded as externalities.

Further, the tiers can be divided into different grades, high grade sources representing “cleaner”, more concentrated materials. The normative understanding of our nutrient quality is that the higher in the hierarchy, the more potential it can provide as a nutrient. Further, the higher the grade the easier the potential can be enfolded.

By planning thoughtful nutrient use, recovery and reuse processes, where the quality of the nutrient is enhanced at each hierarchy level and additionally retained at that level for as long as possible, more sustainable nutrient management is possible. New recovery processes, which enable nutrient recycling but require additional effort, should be applied to concentrated and continuous nutrient streams, however not before the nutrients have used up their potential.

In contradiction to this understanding, food is still being used for production of biodiesel, food waste as feed for pigs was banned in EU and digestates are often perceived as waste. Not only resource efficiency, recovery and reuse matter, but importantly also how the quality of the resources is taken into account during its usage.

The concept of considering both the quality and quantity of energy sources has lead to a revolution in energy efficiency. Why not promote this in the agricultural sector to enhance the efficient nutrient management as well? While the waste-sector generally acknowledges the hierarchy of abatement, recycling and recovery, no difference is made between nutrient rich and other waste.

Our vision is that this overarching concept would be a guideline in future decisions on nutrient management at the legislative level and in practice. This conception of nutrient quality can be coherently evaluated with risks, such as health and environmental hazards, related to the management of nutrient sources. We argue that the question whether a certain risk is high enough to abandon the nutrient reuse at the each hierarchy level, should be raised. In this way the global nutrient management would take a step towards more sustainability.

Phosphorus and Bone Health

>>>Synergy with Calcium and Essential Human Health

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Phosphorus and calcium are two minerals which are essential at several critical periods of human growth and development, including in utero and during childhood. The presence of these two minerals in the diet assists in proper development of bone mass which is vital throughout life and can help to deter adverse health outcomes, such as bone fractures.

Many people consider intake of calcium essential to bone health, but without also consuming adequate dietary phosphorus, proper development and re-mineralization of bones and teeth cannot occur. Most people consume sufficient amounts of phosphorus due to its common presence in many foods and beverages, including dairy products, meat products and fruit juices.

During infancy and childhood, deficiencies in phosphorus and calcium can lead to poor health outcomes, including Kwashiorkor and rickets. Severe deficiencies during these critical periods have also been associated with increased infant and child mortality.

There are other populations, including the elderly, which may not meet the recommended daily intake of phosphorus and consider calcium supplementation to aid in prevention of bone fracture or osteoporosis. But if supplementation does not contain phosphorus, it will not help with prevention of osteoporosis as both minerals are required to build bone mass. As the bioavailability of phosphorus and calcium is not complete, it is vital that individuals, especially those in special populations such as infants and the elderly, consume adequate amounts of both minerals to ensure proper bone and overall health.

Sustainable Future Phosphorus Management:

>>>Optimum P-Supplies of agricultural Soils to meet Sufficiency, Efficiency and Consistency

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Like generally sustainable development of all life styles sustainable phosphorus (P) management has to meet simultaneously over the long term the basic needs both for biomass use / consumption **(Social component: Sufficiency**), corresponding production **(Economic component: P and monetary efficiency**) and for the natural environmental resources **(Ecological component: Consistency)** referring here mainly to the production and use of food and bioenergy. Within these general sustainable aspects especially of P management corresponding sustainable P supplies of the agricultural soils have fundamental importance. It is shown exemplary for Germany.

As consequences of till now non-sustainable official P recommendations for arable and grassland soils in Germany i.e. by VDLUFA (Tab. / A)) influenced by lobby mainly to promote mass consumption and corresponding production of animal food (i.e. 68% more meat than tolerable) actually about 73% of the agricultural soils of Germany are hypertrophied with P (and 78% with K). This has lead to a not tolerable surplus of about 755 kg P / ha in the agricultural soils during 1950 to 2005 and doubled their total P (and K) contents. While P efficiency in agriculture is actually about 55%, **P efficiency** of the total system human nutrition is only about 3% but 92% is stored in agricultural soils and "only" 5% are P input into the hydrosphere. Nevertheless corresponding average 5fold too high input of 772 g P/ha · yr from agriculture into the surface waters of Germany has not changed during 1983 to 2005.

Tab.: A) Till now non-sustainable and B) Future sustainable P-recommendations for arable and grassland soils in Germany (1988-2014)

Till now non-sustainable official P-recommendations (VDLUFA 1997 -2014) (5-Classes-System)			**Future sustainable P-recommendations (Isermann 1988 -2014) (3-Classes-System)**		
Soil-Test-Classes (P-Supply)	**Soil-Test values (mg CAL- / DL-P / 100 g soil)**	**P-Input vs. P-Output yields**	**Soil-Test-Classes (P-Supply)**	**Soil-Test values (mg CAL- / DL-P / 100 g soil)**	**P-Input vs. P-Output yields**
A (very low)	**< 2.1**	**>> P-Output**	**A (too low)**	**< 3.0**	**> P-Output**
B (low)	**2.1 - 4.4**	**> P-Output**	**B (optimum)**	**3,0 – 5,0**	**= P-Output**
C (optimum)	**4.5 – 9.0**	**= P-Output**	**C (too high)**	**> 5,0**	**0**
D (high)	**> 9.1 - 15.0**	**0.5 P-Output**	**-**	**-**	**-**
E (very high)	**> 15.0**	**0**	**-**	**-**	**-**

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On the other hand for some future decades there is no need for any P input into these P (and K) hypertrophied soils: Agriculture can and must use these soils as future "P (and K) bank". Correspondingly the future P recommendations for arable and grassland soils (Tab. / B)) will guarantee <u>on long term</u> about 98% of maximum yields changing P surplus from 9.5 to -7.5 kg P/ha · yr and (apparently) "P-efficiency" from 55 to 288%. There is no need for mineral fertilizer P because P input by recycled P form sustainable waste and waste water management is sufficient in future sustainable P balance of agriculture. Additionally the 80% needed reduction of P input into the hydrosphere resp. into the surface waters by agriculture will be reached (**consistency**) and - if other comparable countries will follow these future P recommendations – also to maintain the world´s mineral P reserves considerably longer than about 100 years (**Consistency and Sufficiency**) .

But an absolute prerequisite to meet not only these future aims of sustainable P management but simultaneously also those of sustainable C, N, K and S managements is to abolish immediately mass consumption and corresponding production of animal food esp. of meat with:

1. a maximum tolerable life stock of 0.1 GWU (gross weight units) = 50 kg life weight for 60 kg life weight of the inhabitants within a definite region. This means the reduction of animal production of about 60%. (**Sufficiency**)
2. and a maximum tolerable animal density of 1.0 GWU per ha agricultural area supply able with C, N, P and K [i.e. referring to P soil test classes A and B (Tab. / B)].

In this way not only about 60% of all environmental problems nutrient caused like eutrophication, acidification, climate change, decline of bio diversity caused by German agriculture will be solved but last not least also a healthy human nutrition especially with animal food.

We don't need to reinvent the wheel!

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"Knowing is not enough, we must apply! Willing is not enough, we must do!" These words of Johann Wolfgang von Goethe reflect perfectly the current situation. After decades of problem analyses and research in the field of sustainable use of phosphorus, we are now at the brink of transferring our knowledge and experience into proper action. But, who in our highly spezialized society decides what action is proper or not. The fundamental question everyone has to ask her- or himself is: What do I really need instead of what do I want? And, it is in the responsibility of our policy makers to ask this question: What do we really need for the society?

Looking at phosphorus recycling from waste streams, we have developed many technologies to recover this valuable resource. But, by now, just a hand full of them made it to matured industrial scale application. Besides the rather virtual question of cost, most important success criteria are operational issues and the properties of the recovered material. What good is a high-tech recovery process for, when nobody is able to valorize the obtained material? These points reveal the weakness or vulnerability of highly specialized or very complex systems. We need to reconnect the different links along the value chains or around the nutrient cycle. And where, if not on local or regional level? In my hometown Berlin, more than 3400 Mg of phosphorus annually end up in different waste streams and only 8% are currently recycled. The biggest quantity of more than 2700 Mg P still waits to be tapped from the wastewater/sewage sludge. This quantity would be sufficient to cover roughly 70% of the mineral P fertilizer demand of the surrounding state of Brandenburg. Since all the sludge from Berlin is incinerated, more than 95% of the total P freight from the sewer system could be recovered from the ash, if all the sludge were mono-incinerated. Complementing this, struvite recovery can provide some more percent of the ready to use fertilizer "Berliner Pflanze". My future vision for this region is a closed P cycle, where all the P waste from the German capital is recycled on the surrounding farmland, providing regional food for the city dwellers, who supply the nutrients to grow their own food.

Toward More Sustainable Livestock Feeding Systems:

>>>Barriers to Adoption of Precision Phosphorus Feeding of Ruminants

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With the worldwide population projected to reach 9 billion by 2050, animal scientists are challenged to double animal protein production while satisfying the three pillars of sustainability: economic, environmental, and social [1]. Issues surrounding phosphorus (P) challenge all three pillars. Livestock excrete 60 to 80% of consumed P [2, 3] and P excretion increases with overfeeding [3, 4]. Because feed contributes most of the P imported to farms [5] 'precision P feeding' is a powerful approach to improve P balance on livestock farms. How can this be made more sustainable?

Precision feeding is the process of providing adequate nutrition without overfeeding. The environmental benefits are clear but there are barriers to its full adoption. For decades P was overfed to livestock primarily because of inaccurate perceptions of benefits to reproduction and performance. Addition of mineral P to traditional diets elevated P intake to 30-100% above requirements [6-10], resulting in increased manure P and also increased soluble P, the fraction most vulnerable to runoff [11]. Significant progress has been made in the past 20 years through education of producers and their advisors. National surveys indicate markedly less overfeeding, with 99% of the nutritionists responding to a national (U.S.) survey feeding less P now than 5 years earlier [12]. Respondents were from 40 states and were collectively responsible for feeding ~20% of the U.S. dairy herd.

Mistrust of availability of feed P is one remaining barrier [12]. Current feeding standards for ruminants assume homogenous absorption of P from feed [13, 14]. In contrast, we and others have demonstrated effects of grain processing [15, 16], grain type [17-19], and exogenous enzymes [20] on digestion of organic P by ruminants. Recently our research group has developed advanced analytical techniques for quantification of organic P fractions in feed and feces [21]. These measurements allow better representation of P digestion and excretion in mathematical models [22, 23]. Update of ration formulation programs to include these will address variation in P availability, increasing user confidence.

The significant remaining barrier to adoption of precision P feeding is the high and highly variable P content of popular byproduct feeds (e.g., distillers grains, corn gluten feed, and brewers grains at 0.5 – 1.0% P) [24, 25]. Most ruminant nutritionists are no longer adding mineral P to ruminant rations [12] but the use of by-products is nearly universal. This increases manure P [26] and aggravates whole farm P imbalances [9, 27]. Thus an obvious next step in precision P feeding will be wide implementation of technologies to remove P from these feeds. Approaches include pre-fermentation fractionation to remove the high P endosperm [25] and struvite formation or chemical treatments as used to remove P from liquid manure [28]. For widespread implementation, incentive or regulatory programs will be needed to motivate producers to reduce P imbalance. The resulting market pressure will create economic incentive for wide-spread implementation of these technologies in ethanol plants. Development and implementation of these technologies will conserve P for tomorrow's world and contribute to the sustainability of animal agriculture.

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Sustainable Agricultural NP Turnover in the 27 European Countries

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A deep contrast of NP balances, water nitrate contamination, soil P and rural development has appeared between Western and Eastern European countries since the implementation of the European nitrate directive in 1991 (91/676/EEC). In an economy ruled by free market rich countries become richer and poor countries become poorer from the point of view of water nitrate contamination and soil P overloads. There is a need for a paradigm shift in the European agro-environmental protection legislation. Instead of speaking about it, agro-environmental protection, social, and rural development principles should gain real priority. According to the principle of subsidiarity, the present problems can be solved only at the highest European-level, i.e., in the legislation and in the administration. We reviewed the anomalies in the NP turnover of the European countries. The major points are: (1) instead of some agronomic factors such as soil NP status, added farmyard manure, and expected yield level, per capita gross domestic product and population density were the major factors affecting the magnitude of mineral and organic NP application. (2) Countries with the highest livestock densities do not take into account previous farmyard manure application and soil P status as mineral NP dose diminishing factors. This practice contradicts to the basic principles of sustainable crop nutrition. As a result, between 1991 and 2005, highest P surpluses, the most positive P balances were reached in the countries with the highest soil P level, further enhancing their agricultural P load to the environment. (3) Similarly, the European countries with the highest organic NP application, The Netherlands, and Belgium, were those who applied most mineral NP fertilisers reversely to the agronomic principles, and, resulting in most positive NP balances, and, as a consequence, the most severe environmental threat, the most severe agronomic NP

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Nutrient cycling as a means for sustainable agriculture and healthy water systems

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Phosphorus and Nitrogen along with other mineral nutrients are essential to life. Crop nutrition enables the crop to grow to its genetic potential and to produce good crop yields. Currently, the influx of phosphorus to agriculture and the food chain occurs primarily through mineral fertilizer.

The world´s population growth and the changing eating habits have been estimated to demand a 70 percent growth in food production by 2050.

The world´s supply of fossil Phosphorus resources is shrinking and nitrogen fertilizers are being produced in a highly energy intensive process with a negative impact on climate change.

At the same time nutrients leak from arable land to water courses to cause eutrophication and nitrogen compounds originating from nitrogen fertilizers are emitted to the atmosphere to cause global warming instead of being available for plant growth. Valuable nutrients contained e.g. in organic household waste, in manure and municipal wastewater are wasted. Because of the leaks from different stages of the nutrient chain only 20-25 % of the mined P-rock ends up in the food we eat.

The EU should focus on transition towards sustainable nutrient management by nutrient cycling. It is important to invest in better management of nutrient applications, and to develop the science, technology and market necessary to keep improving nutrient use efficiency and best agricultural practices. The measures would provide EU with higher self-sufficiency of nutrients and thus contribute to ensuring food security. They should, of course, be implemented on a global level, too.

Given the multidisciplinary character of knowledge and variety of practical skills needed in agricultural applications, interdisciplinary cooperation and efficient communication between different stakeholders in the field is crucial. To get a holistic picture of the complicated area of agronomy, we need scientific skills in analytical chemistry, microbiology, soil chemistry, hydrology, providing monitoring equipment etc. Expertise and measures on how to maintain good soil condition are of utmost importance.

Development and promotion of technologies and knowledge to enable optimal nutrient cycling and nutrient use are to be encouraged and supported by public funds.

Piloting the most potential technologies would be of great importance. The piloting should include the whole line from raw material to a product as well as use and marketing of the products. The structure and application of public financial instruments and subsidies as well as the need for potential changes in legislation to promote nutrient cycling should be considered based on the results of the piloting.

The innovative skills of business life are needed to solve the technological challenges of productive and sustainable agriculture based on nutrient cycling. Solving the problems would create new business opportunities and significantly help in creating new competitive clean technology in Europe for domestic market and for export.

All nutrient chain related stakeholders should be involved to understand the necessity of nutrient cycling. Nutrient issues, including nutrient cycling should become common knowledge.

EU needs acutely a nutrient cycling strategy.

Vision

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As phosphate rock reserves worldwide will reach for the next 3-400 years, phosphates should not become a limiting factor in nutrition chain. But Europe has to rely on imports mainly from North Africa/Middle East and thus must develop recycling alternatives for phosphates, e.g. waste water, animal bones and agricultural waste. These efforts shall be focused on the human nutrition chain and not “wasted” for biofuels, etc. Phosphorus is too important for fertilizers, feed and food. Therefore, uses in the nutrition chain up to phosphates in people`s food should be the favorable direction.

Industrial phosphates are also widely used, mainly because of their high performance and low risks, but compared to the nutrition chain volumes are much smaller and slightly growing. Performance should be the driver for such developments, as eutrophication of slow moving waters can be solved by adequate waste water treatment, even being a future source of recycling phosphates.

Phosphate mining, an alarming situation in lower Himalayas

>>>P losses to surface waters, eutrophication and water catchment management

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Unmanaged Phosphate mining is an alarming situation especially in watershed area of lower Himalayas at an altitude of 4300 feet in Pakistan, not only because of excessive extraction but due to lack of proper management and efficient use. Pakistan has an installed capacity of one million tons for production of all types of phosphate fertilizers, these, primarily, include di-ammonium phosphate (DAP), single super phosphate (SSP) and nitro-phosphate (NP) fertilizers. Rock phosphate, a major source of phosphorous is being extracted from mining area located in lower Himalayas, Hazara district and especially in Kakul and Tarnawi Abbottabad Pakistan.

This watershed area receives annual rainfall of about 1366 mm which contribute to largest water reservoir “Tarbela” of Pakistan. Phosphorus gets into water in both urban and agricultural settings. Tri calcium phosphorus tends to attach to soil particles and, thus, moves into surface-water bodies from runoff. Since groundwater often discharges into surface water, such as through stream banks into rivers, there is a concern about phosphorus concentrations in groundwater affecting the water quality of surface water. About 1 km2 area is exposed to mining results in deforestation which ultimately leads to excessive phosphate concentration in runoff.

Excessive runoff of phosphate to Tarbella is causing eutrophication, loss of biodiversity, and problems in this water catchment management.

Despite the bitter reality concerns the need of phosphate fertilizer, we cannot stop the extraction of this non-renewable resource. It is essential for agriculture practices and agriculture is the back-bone of Pakistan’s economy however we can reduce the P loses from the surface water runoff of this watershed area through management of mining and reforestation on affected area.

Photo 1. of model representing lower Himalayas i) mountain without forests extensively mined causing P in water through runoff which passes through fields and urban settings to largest ii) water reservoir Tarbella Pakistan.

Keeping in mind this serious issue, a model was prepared on topic “Phosphate mining, an alarming situation in lower Himalayas” by students of Bachelor of Science Environmental Sciences of COMSATS Institute of Information Technology, Abbottabad Pakistan. The purpose of this model was to aware the community residing that area, politicians and students about the problems being created by this uncontrolled and unmanaged phosphate mining activity.

Photo 2. Actual mining site showing removal of trees from for making paths and roads for transporting raw Rock phosphate.

Vision 50 by ’50

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Nutrient use efficiency is a key indicator of Food Security, and P is a (the) key nutrient. Our vision for P is by 2050 to reach an efficiency target of 50% in the management of P resources across the full life cycle – from mine to soil nutrient, whether as primary or secondary (or tertiary) resource. We currently estimate life-cycle efficiency at 5-15%.

To get there we must learn how to close the P cycle in an economically and environmentally acceptable way. The sustainable balance between economic and environmental objectives and benefits will deliver what John Nash calls a new, cooperative point of equilibrium. Finding where that new point of equilibrium is necessarily involves all stakeholders - food consumers as much as phosphate producers or farmers – and behavioural change from all parties. Supply and demand factors need to be rethought and modified.

This in turn means defining the critical control points at which efficiency can be measured: resource discovery and classification; mining and beneficiation; manufacture, distribution, agronomic use; identification and maintenance of critical P values in soils; recovery and reuse from waste streams and waste water; prevention of avoidable wastes from foods that are grown or processed but not consumed and simply go to landfill; review of sell-by and use-by dates on product labelling and their role as waste generators; landfill mining; global flows of P across the global food supply chain…

Metrics from these critical points ; will help define an efficient, sustainable and socially acceptable fertilizer and food production/ consumption policy, something as a society we have not properly reviewed and updated since the end of World War 2. This includes substitution of biosolids and other secondary sources of P as part of the resource conservation process.

Any such change begins with communications, bringing awareness to the general population of the importance of and need to conserve P supplies. As we head to a global population of 9 billion by 2050, each of us can play a part in the intergenerational sustainability contract in regard to better use of P resources in securing sustainable food production . Hence as a key enabler Vision 50% P life-cycle efficiency by 2050.

Phosphorous disposal by the land application of animal waste: Virginia

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In Virginia, "…inorganic nutrient sources shall not exceed crop nutrient needs…" (Commonwealth of Virginia, 2005, Section IV). Three methods exist to manage organic phosphorus (P). The "Soil Test" method can be summarized by the formula: pounds P_20_5 per acre = 120 - (2.18 * M1) where M1 is the Mehlich 1 soil test P in ppm. No P application is allowed if the soil test exceeds 55 ppm. The "Environmental Threshold" method is less restrictive, allowing N-based application (P is ignored) if the M1 soil test is less than 55 ppm. If the M1 soil test is between 55 and 135 ppm, P application is permitted up to "1X crop removal." No P application is allowed if the M1 soil test level exceeds 135 ppm. The "P-index" method is complicated, subjective and typically even less restrictive. According to Beegle (2006) "…the critical level for soil test P for the Mehlich 3 soil test is around 30 ppm for Mid-Atlantic soils. If the test is below 30 ppm we would expect a profitable increase if we add P. However, if the soil test is above 30 ppm, no yield response is expected.'' (p. 164). A Mehlich 3 soil test of 30 ppm P corresponds to a Mehlich 1 soil test of 10.5 ppm P. Virginia's regulations sanction organic P disposal at rates far in excess of crop nutrient needs. Poultry litter causes the most P pollution (Land, 2012).

According to Sims (p. 66) "...much of the crop land in the Chesapeake Bay watershed is now considered 'optimum' (or 'excessive') in P from an agronomic perspective and hence needs little additional P, from any source, to ensure that economically optimum crop yields are attained." Despite these facts, the over-application of P continues and regulations continue to favor the lobbying efforts of the wastewater, poultry and agricultural sectors. Cheap waste disposal trumps improved Chesapeake Bay water quality in the eyes of legislators. There exists no agronomic reason to apply P in excess of crop removal rates. If Virginia's regulations required P disposal according to crop needs, more acreage would be required to dispose of the waste and additional nitrogen fertilizer would be needed, reducing the profits of the concerned sectors.

America's P reserves will be mined out in the lifetimes of children being born today (e. g. Vaccari, 2009). Just as is true of many aspects of modern society, the costs of externalities (pollution in this case) are ignored. America will incur costs, both financial and political, when P must be imported from the Middle East. There are large, real costs associated with the nutrient pollution of Chesapeake Bay, mostly caused by inefficient agricultural fertilization practices (Chesapeake Executive Council, 2004). We would be wise to ban the disposal of animal waste by land application in favor of using the waste for energy and recovering the nutrients, expecially P, for application in a much more efficient manner than is true today.

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The Future for Phosphorus in England

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The future for phosphorus in England

The Environment Agency is responsible for protecting and improving the water environment in England. One of our major water quality challenges is phosphorus (P).

Alongside the concerns about sustainability of supply and uses, **P is the most commonly failing water quality parameter under the Water Framework Directive** (WFD)[2]. 45% of assessed river water bodies and 74% of lake water bodies currently exceed their P standard for good ecological status, designed to control freshwater eutrophication[3].

Phosphorus and eutrophication

Eutrophication occurs when excess nutrients cause algal proliferation, adversely affecting the ecology and water uses/benefits including drinking water supply, recreation, conservation and tourism. Eutrophication became recognised as a national water quality issue in the late 1980s[4]. River P concentrations had increased significantly between 1950 and 1990. These increases have been considerably reversed, through **P-reduction at sewage treatment works and reductions in detergent-P, fertiliser use and livestock numbers.**[5]

Despite this progress, analysis suggests that **further major reductions (c.40-60%) in P-loadings to rivers** from sewage works and agricultural sources, with further national source control measures, would be needed to achieve good status for P, and getting there may not be possible in populous areas[6].

Further major P emission reductions needed

The Environment Agency is engaging with stakeholders over the **effectiveness and cost-benefit of further actions** for the next Water Framework Directive River Basin Management Plans, finalised December 2015[7].

Sewage treatment works remain the largest source of P in English rivers[8]. The Environment Agency has recently agreed a programme of sewage works P-reduction trials with the water companies. This aims to identify technologies, suited to UK conditions, **which can achieve very low levels of effluent P**, , enabling more ambitious future measures for waters affected by eutrophication.

Complementary action to reduce agricultural P losses is needed. Uptake of effective measures will be crucial. Advisory schemes (e.g. currently Catchment Sensitive Farming) and incentive-based approaches (eg the New Environmental Land Management scheme) will help. The collaborative Catchment-Based Approach shows increasing promise and ideas such as nutrient trading warrant consideration.

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[2] Freshwater Eutrophication: a nationally significant water management issue. Environment Agency briefing note for 10.12.2012 stakeholder workshop on phosphorus and eutrophication.

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Other, smaller sources of diffuse pollution including septic tanks and misconnections are receiving further attention[9] [10].

Sustainable phosphorus stewardship

The Environment Agency supports the increasing interest of EU and UK governments in sustainable stewardship of phosphorus. **Potential wider adoption of source control, recovery and recycling is something we wish to explore further with government, sectors and other stakeholders in managing P for the future**.

- **Incentives** such as flexible, catchment-based permitting may be needed to facilitate more ambitious and sustainable practices at sewage works.
- Currently P-removal in England is mainly through **chemical dosing**, precluding P-recovery[11].
- **Tap water dosing, dishwasher detergents and food additives** deserve consideration as regards possible further source control[12].
- **Increasing bio-solids recycling to land**, reducing reliance on artificial fertilisers, may be possible[13].
- **Food waste** is another source where reduction and recycling would improve sustainability[14].
- Thinking more radically, **more sustainable human diets** could reduce this major source of sewage-P[15].

Ecological recovery from eutrophication can be lengthy and uncertain. Our experience from the Norfolk Broads suggests lakes can take 2-3 decades[16].

In addition, **climate change** and **population growth** present future risks from increased nutrient loadings and eutrophication impacts[17, 18].

Phosphorus management seems set to remain a challenge for several decades to come.

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[9] https://www.gov.uk/government/consultations/small-sewage-discharges-new-approach-to-how-we-regulate-in-england

[10] https://www.gov.uk/government/consultations/tackling-water-pollution-from-the-urban-environment

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Phosphate recovery: Study of economic chances and Opportunities

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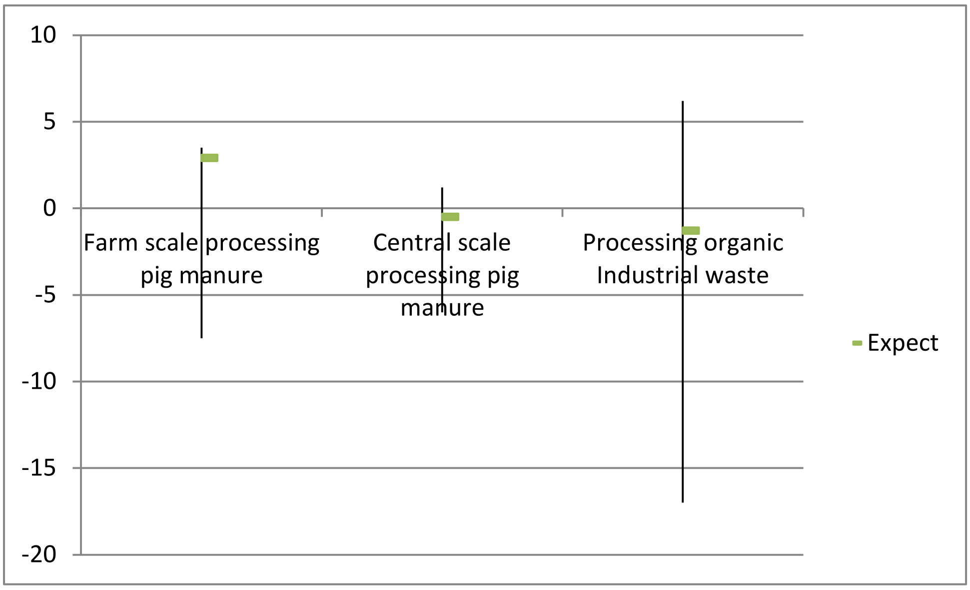
S.1 Key findings

Recycling phosphate from the ash from sewage sludge incineration is economically and practically feasible. The economic prospects for recycling phosphate from pig manure and organic industrial waste are highly uncertain. The extraction of struvite from organic waste flows is not economically interesting for phosphate recycling. With the current high prices for phosphate ore, it is economically feasible to recover phosphate from sewage sludge incineration ash. At least several dozen million kg of phosphate are potentially available, and only two important parties are involved in the final stage: Slibverwerking Noord-Brabant (SNB) and Thermphos. If a single party pulls out, this can slow the process down for years to come. Thermphos declared bankruptcy in late 2012, making this slowdown a reality.

Small positive results can be achieved with processing plants making exportworthy products from manure and organic industrial waste if they are running at high technical and economic efficiency (Figure S.1). However, the uncertainties, and therefore the risk of negative returns, are high. Uncertainties which could have a significant influence on returns are:

- the purchase price of the incoming products (manure, co-products);
- government subsidies, in particular for processes which generate sustainable energy;
- regulations relating to selling the final products;
- the selling price ex-factory of the final manure pellet product on the global market.

Figure S.1 Profit/loss in euros per kg of phosphate recycled from pig manure and organic industrial waste



Source: LEI.

S.2 Complementary findings

- The largest amounts of recycled phosphate can be recovered from incinerated ash. This is followed by the processing of pig manure into exportworthy products. Of the five cases investigated, struvite extraction generates the smallest amount of recovered phosphate.

- In Europe, regions with excess phosphate and regions with phosphate shortages are often only a few hundred kilometres apart. In order to keep distribution costs as low as possible, these distances can only be bridged by using fertilisers with a relatively high phosphate content.

- It is possible to achieve relatively high phosphate levels while maintaining organic content with small-scale or large-scale manure processing. There are significant economic uncertainties involved in this.

Government intervention is necessary in order to buffer these uncertainties, for instance by making manure processing a requirement.

- The potential market in Europe for dried Dutch manure and manure pellets is more than large enough. A survey of the market for large amounts of manure pellets from pig manure must still be carried out

- Struvite extraction is only interesting in the context of preventive maintenance of pipes, valves and cut-off valves for transport pipes for organic waste flows. In this situation, struvite is a by-product.

- In order to further develop co-fermentation, a technological and/or financial breakthrough is necessary which will enable higher financial returns. The operators of the existing cofermentation plants in the Netherlands are only barely keeping their heads above water. They are extremely dependent on government subsidies and on the price and availability of co-products.

Unlock Phosphorus from Soils Based on Molecular Level Mechanisms

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An agricultural practice without input of phosphorus (P) fertilizer might be promising in tomorrow's world from the perspective of soil scientists. In addition to runoff and erosion, more than half of applied P has been trapped within soils. We envision a revolution in soil science to replenish bioavailabile phosphate (PO_4) by unlocking soil P rather than by adding chemical fertilizer.

Soil is a superior repository for P, wherein P is locked through adsorption and/or precipitation. While adsorption regulates the retention and dissolution of PO_4 at low soil P contents, precipitation of P minerals controls the P solubility at high soil P contents. Adsorption capacity of PO_4 in soils is primarily provided by clay minerals, particularly the amorphous Al and Fe (hydr)oxdies. Soil scientists have found a positive correlation between P sorption capacity and concentrations of ammonium oxalate-extractable Al and Fe in acidic, neutral to calcareous, and even slightly alkaline soils. Regarding solubility of PO_4 from P minerals, the equilibrium of PO_4 dissolution is generally controlled by Al- and Fe-P minerals in acidic soils and by Ca-P in neutral and alkaline soils.

As a result, distinguishing P species is critical to predict and evaluate PO_4 dissolution and bioavailability in soils. This is also the prerequisite for the method development to unlock soil P.

Our research trend leaps into molecular mechanism development for soil P. This is achievable with application of X-ray absorption spectroscopy (XAS). XAS is an element-specific technique that provides nondestructive and direct determination of local molecular bonding environment between P and the surrounding atoms. The spectral features also allow us to differentiate adsorbed P versus precipitated P. An understanding of speciation at this level would improve models for chemical reactivity, solubility, and mobility of P in soils environment.

So, what is our perspective in releasing soil-trapped P for sustainable agricultural use?

A pragmatic scenario is to find a direct evidence for the mobilization and transformation of individual P species taken place at mineral-plant interfaces, i.e. the PO_4 hotspot for crop uptake. Mapping for the spatial-temporal distribution of P species may give us clues on how P is transformed into crops-available species in natural environments, or what chemical species is preferable for P mobilization. This sort of observation may proof the hypothetical stepwise pathway of P transformation, and show potential mechanisms that regulate mobility. Even though there is no guarantee for manipulating P-releasing process via this approach, the bottom line is, technical support available today is sufficient in generating comprehensive view of P distribution at this critical interface.

Our vision is that molecular-level mechanisms for soil P behavior could provide a solution for the expected P deficiency in agricultural systems by virtue of liberating the repository of PO_4 that was locked in soils.

A case study of biological phosphorus removal from municipal wastewater in warm countries

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Introduction: our vision

Phosphorus recovery from municipal wastewater is a key issue to focus on since rock mining sources are unevenly spread over the world and risk to deplete in the following 50 years (IFDC, 2011), whereas on the other hand, phosphorus continuous discharge in water bodies has been recently reported in different European countries (SCOPE newsletter December 2012). Physico-chemical solutions are efficient but present some economical drawbacks as the higher costs linked to the external chemicals dosage and higher amount of low valuable sludge waste produced, compared to Enhanced Biological Phosphorus Removal (EBPR). The latter lays on the capacity of Polyphosphate Accumulating Organisms (PAO) for cumulating phosphorus over the bacterial growth needs under subsequent anaerobic and aerobic conditions, resulting in a net phosphorus removal in the secondary treatment layout in a conventional municipal wastewater treatment plant, which receive in average 2.1g/d/p.e. (Stricker and Heduit 2012) constituting a potential source for the high value-added product recovery. However, the biological mechanisms involved are complex and become instable within several factors (high temperatures, nature of carbon sources, nitrate presence…). Due to the urgent call from governments and the European Environmental Agency, stringent regulations targeting phosphorus arise in the coming years, stressing the need to asses more efficient and sustainable solutions for decreasing the phosphorus concentration in the rejected effluents beyond 1 mg/L.

A demonstrator pilot plant for biological phosphorus removal at high temperature (30°C):

Veolia Environment Research and Innovation (VERI) has included since many years ago, the study of biological phosphorus removal process within their different research and development projects.

For example, recently encouraging results have been obtained at pilot scale within a process treating simultaneous carbon, nitrogen and phosphorus removal at high temperatures (30°C). After 6 months of trials with a municipal raw wastewater, performances up to 97%, 87% and 85% of total COD, nitrogen and phosphorus removal respectively have been successfully reported without any external carbon or chemicals addition. The process consists on an innovative layout based on different continuous stirred tanks recirculated and operated as a way that favours PAOs development over Glycogen Accumulating Organisms (GAOs), being these last responsible for many failures of EBPR processes. Not only phosphorus but carbon and nitrogen high performances are achieved thanks to the key operating conditions (redox, sludge recirculation and hydraulic retention time) imposed in the different compartments. External disturbances like rainy periods causing COD limitation and nitrate appearance are addressed and microbiological analysis have been compared in order to focus on EBPR mechanisms and populations still not referenced in the literature data bases. Although analyses are on course, first sequencing samples at VERI showed that PAOs accounted for a 2-4 % of the total bacteria, in the range reported in good full scale wastewater treatment plants at low temperatures (Mielczarek et al., 2013). The higher phosphorus removal efficiencies during the pilot run were correlated to the increase of PAOs presence, and by the same way, the higher GAOs proliferation ratios were correlated to pilot dysfunction periods.

These promising results could gain insight the applicability of this process in warm countries were biological phosphorus efficiencies are limited due to the GAOs proliferation, opening new roads for easier phosphorus recovery from the produced sludge. A full scale pilot has been recently constructed in India and first stable results will be obtained after the commissioning phase (around July 2014).

Maximizing phosphorus investments with soil management

>>>Amplifying phosphorus use efficiency by site-specific soil fertility management

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The majority of soils in sub-Saharan Africa (SSA) are highly weathered with limited intrinsic soil fertility. Smallholder farmers face crop production challenges and consequently food insecurity as a result of soil phosphorus (P) deficits. Investing in the P capital of these regions by increasing P inputs is a recognized strategy for lifting P limitations to agricultural productivity. However, this strategy has met difficulties as infrastructure, economic, and soil-based challenges tend to limit access, affordability, and efficiency of P investments, and thus the average adoption of P fertilizer (and any other type) is low. The forecasted global limitation of rock phosphate reserves may further exacerbate availability and economic barriers to P transfers into regions where building P capital is most needed.

To address the issue in a holistic way, P investments must go hand in hand with site-specific soil fertility management. We describe the multiple advantages of such management as the key to success of current and future investment strategies toward P security. This reflects strong soil controls on the fate and crop use of P, and the potential to capitalize on the ‘master variable’ of soil pH to promote efficient use of added P, i.e. to increase agricultural P use efficiency (PUE). Resources for soil fertility management to improve PUE may be more abundant regionally and accessible locally relative to minable P deposits. Such integrated management also has the potential to lower the risk perceived by farmers to invest in P fertilizers given the increased return from such investment.

The strong propensity of acid soils prevalent in SSA to fix or ‘lock up’ P in unavailable forms undermines P investments in this region. Liming agents can be used to correct soil acidity, thereby increasing PUE of inputs. Unlike global rock phosphate reserves, lime deposits are generally more common and widely distributed. For example, calcium carbonate reserves recently identified in several SSA nations could be used as a lime source, improving availability of added and existing P in soils. Treating soil acidity can also improve PUE indirectly by alleviating non-P constraints on crop production, most notably aluminium toxicity and nutrient deficiencies like molybdenum—a critical element for legume crops to fix atmospheric nitrogen. Furthermore, using a regional resource like lime to achieve higher PUE offers an opportunity to improve P security by lessening dependence on imported P inputs.

Finally, improved PUE by soil management requires basic but long-lasting investments in knowledge of soils, particularly at sub-regional scales. For example, P fertilizer recommendations in Kenya are highly generalized and overlook significant variability in soils that dictate efficient use of added P by crops. This is largely due to incomplete and poor-resolution soil maps of the region. Building information and knowledge infrastructure through soil mapping and basic soil testing are necessary to appropriately target P and supporting PUE investments spatially and over time.

Silicon-rich substances and future of phosphate fertilizers practice

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Phosphate fertilizers are one of the most important agrochemicals in the modern agriculture. The efficiency of this type of fertilizers are naturally limited by P leaching from sandy soils and by strong chemical fixation by Ca, Al and Fe in neutral or alkaline soils. On the other hand numerous environmental problems like eutrophication of the natural waters and soil pollution by heavy metals related with phosphate fertilization as well. It is necessary new approach in the resolving of these problems, which must have base on the understanding natural processes – chemistry, biochemistry and geochemistry.

Literature and our results of the numerous laboratory, greenhouse and field testing in USA, Russia, Australia, China and other countries showed that combined used of the traditional P fertilizers with Si-rich materials (fertilizers or soil amendments) may resolve these problems. Si and P have complex physical-chemicals interactions thought several mechanisms, which can be used on practice. First, monosilicic acid can react with slightly soluble phosphates (Ca, Mg, Al, Fe). This is the exchange reaction of the phosphate-anion displacing by silicate-anion can be occurs in the soil. In the result the content of plant-available P in the soils treated by active forms of Si can be increased on 20-100% and more. It is important that treatment of the phosphate rock by monosilicic acid increase the content of plant-available P. At the same time, because monosilicic acid controls heavy metal mobility, the part of these pollutants (which may present phosphate rock or in cultivated soils) can be neutralized by active forms of Si as well.

Secondary, usually Si-rich soil amendments has high adsorption capacity to phosphate anions. In the result, the application of the Si-rich soil amendments can increase soil physical adsorption to phosphorus, which reduces P leaching from sandy soil (up to 90%) and keep P in plant-available forms. Except P the applied Si-rich soil amendment also reduces N, K and other elements leaching. The demonstration tests, which was conducted in USA showed that the concentration of P in the local surface waters (rivers, lakes) after application of the specific Si-rich soil amendments was reduced on 30-80%.

The analysis of the obtained and literature data showed that today is available about 3-4 million tons of Si fertilizers and Si-rich soil amendments, which can be used for improvement of P fertilizers efficiency. During next 10 years the volume of joint fertilization P and Si-rich substances can be increased on 2-3 times. Such countries like China, South Korea, Australia are leading in practical application of the new P-Si technologies. The European countries initiate several programs for application of Si-base products to modern agriculture. The technologies, which can be adapted for any soil-climatic conditions are available and successfully tested.

Phosphorus in agriculture, soils and crops

>>>Understanding the bioavailability of new and old phosphorus to crops

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Today, sufficient availability of phosphorus (P) for agriculture is considered one of the main constraints for global food security, thus P resources need to be used more efficiently. Our vision for future P stewardship is that we need to understand the bioavailability in soils of P already present in our soils, existing fertilisers and manures, and in new or recycled P products.

Soil-crop-fertilizer systems differ

In P fertilization recommendation systems throughout the world, soils are generally treated as the "same", but the amount of P that has built up in soils and the physico-chemical conditions of soils vary strongly. In any one year, most crops take up a small proportion of their P from the P applied in the form of fertilizer and manure, so most has to be supplied to the crops from the soil reserves. However, the forms and bioavailability of this "legacy-P", i.e., P already present in soils from long-term inputs to soils are still insufficiently understood. Also, new P-recycling technologies produce products for which fertilizer values and environmental impacts are as yet unknown. This means that we need to understand the way that P is bound in different soils with, for example, different new products applied and with different organic matter inputs, to enable long-term bioavailability of P to be modelled and predicted for various crops. It is a misconception that current soil P tests allow such predictions of P bioavailability to be made.

Vision

Decades of research effort on P has been related to the problem of excess P in soils. However, the situation is changing and current mineral P fertilizer use for example in the EU27 is about 4 times less than it was in 1980 (International Fertiliser Association statistics, 2012). There is a very large heterogeneity in P balances among European regions with excess P in the intensive animal farming regions and other regions that are in deficit. Assessing long-term residual effects of applied P, avoiding the loss of soil fertility due to a decrease in availability of soil P, and providing more accurate fertilization advice schemes that are tailored to specific soil conditions will result in more efficient use of P, both in regions with negative and positive P-balances.

Better soil management and soil-specific P fertilization for defined soil conditions are of paramount importance for the long-term sustainability of the entire intensive crop production sector. A comprehensive approach that includes wide geographical areas, agricultural systems and soils under different conditions is required to understand and predict the bioavailability of the soil-P and to refine P fertilization recommendations.

Advances in our understanding of the forms and long-term dynamics of P in soil systems and the new P products are needed. We must combine the latest analytical techniques such as ^{31}P NMR and synchrotron spectroscopies, with existing long-term field experiments to determine the dynamics of P in soils. This new knowledge must then be quickly transferred into practice to enable the efficient use of scarce P resources for future crop production and environmental quality.

Image 1. Many agricultural and other materials are good sources of P, but their effect on P bioavailability is insufficiently understood (photo courtesy of Rothamsted Research ©).

Image 2. In Europe there are more than 50 long-term field epxeriments that can be used to deteremine the long-term bioavaiability of P in different soils (photo courtesy of Rothamsted Research ©).

P resources and their use

>>>Cities as key components of sustainable food-system P cycling

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In 25 years cities are no longer be viewed as the last stop for P on its journey from mines to the ocean. Cities will be viewed as an integral part of a sustainable P management scheme in our food system. Food waste has been reduced, and P losses through runoff and erosion have also been reduced significantly. These reductions are not simply the result of P management guidelines or laws, but part of a larger urban sustainability practice aimed at social equality, resource use reduction, and a clean local environment. As such, greening of the city is accompanied by limited fertilizer use, quality compost production, fewer impervious surfaces and increased buffer zones between laws, fields, and waterways where these buffer zones are used as recreation areas. The human waste and food waste produced by urban environments is used as fertilizer in urban and peri-urban agriculture, and in some cases even more distant farms. Urban and peri-urban agriculture allows for low technology P reuse and contributes to limiting food waste. This local recycling in agriculture also creates a buffer capacity for urban food security to global energy and P prices shift. Urban consumers eating less meat and animal products, and when they do eat meat citizens are sensitized to sustainable P and agricultural management and make purchasing decisions accordingly. Waste management and food production planning is part of a holistic approach to reducing landfills and decreasing resource use. These local waste reduction and increased P recycling practices do not however halt the need for global trade of food or fertilizer and, as such, cities redesigning waste management have made it possible to create high-quality and concentrated P fertilizer for export further away.

Specific technologies and food and waste-management schemes will vary to adapt to local context. In developing countries with limited sanitation, urine diverting and composting toilets would become prevalent. In developed countries, wastewater treatment plants would extract P, and would limit contamination by diverting industrial waste to separate facilities. Similarly, organic waste collection may be more centralized, but would aim to produce high-quality compost where residents separate organic waste. New developments would not necessarily be linked to existing centralized systems, but operate on a neighborhood scale, where P fertilizer products are picked up to be redistributed to users.

Integrating cities into our conceptual understanding of the food system is necessary because urban residents and decision-makers play important roles as consumers, waste-producers, and catalysts for change across scales. As we move forward to realize our vision(s) of sustainable P management, we must include cities, taking account of the unique context of each city by creating P management plans for different urban context. As the urban context changes over time, we must also make sure we monitor urban P flows to allow for iterative and reflexive decision-making processes to enhance sustainable P management. Cities can and should be epicenters of sustainable P management.

Urban garden in Montreal, Canada using local compost as a source of phosphorus.

Sourcing waste and low grade resources for Phosphorous

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Currently known high grade easily-acquirable phosphate rock reserves required by the fertilizer industry may be depleted within a few decades. Although there will undoubtedly be more phosphate discoveries after current identified reserves are depleted, they will require progressively more effort and expense to extract and refine.

Currently, the EU imports virtually all its phosphorus with the import dependency rate of approximately 92% and, as reserves diminish, this will be the case for other countries that have large unsustainable phosphorus demands.

Current world phosphate rock reserves, concentrated in a few countries mainly China and Northern Africa, will decline forcing the- more costly - extraction of lower grade sources which are burdened by levels of heavy metal and radioactivity contamination. Geopolitical tensions and a globally increased demand of P have already resulted in highly fluctuating and simultaneously increasing trend in the phosphorous price development As the need for phosphorous will increase globally, due to increasing food and energy crop production, these tensions are not likely to disappear. The need to develop phosphorous recovery also from unconventional sources is unavoidable.

Currently only phosphate rock containing relatively high amounts of phosphorous has been utilized effectively. Waste amounts of lower grade rock is considered as overburden and not utilised.

Phosphate extraction from sub-economic reserves and other under-utilized sources will mitigate the pressure of global and regional phosphorus shortages. Further, utilising this phosphorus-containing mine waste will contribute to diminishing the environmental footprint of mining.

In addition to subeconomic rock phosphate reserves, waste rock from iron ore mining and steelmaking by-products enriched in phosphorus are largely unexploited potential sources of phosphorus.

Steelmaking slag and blast furnace slag are by-products of steel and iron production process. Global blast furnace slag generation in 2002 was close to 190 million t and in Europe ca. 40 million t in 2004. Another fairly unexploited source are ashes from biomass incineration, the P-content of which varies between 1 % (wood pellet ash and straw) and ~ 20 % (municipal sludge), depending on the fuel.

We foresee during the next your targeted development and deployment of new technologies   that can efficiently utilise these secondary materials For instance Microbiological processes are potentially a cost efficient option to traditional chemical processes for material containing lower concentrations of phosphorus. When phosphorus is recovered from waste materials and side streams, their phosphorus content and subsequently the risk of unwanted leakage of phosphorus from wastes is diminished. In addition to the phosphorus, the accompanying metals could be recovered for better utilization of natural resources

This will ease the foreseen future situation where the physical limitations of the resource will become increasingly important.

Necessity for a Phosphorus Recovery Chain

>>>Spilling phosphorus by flushing the toilet?

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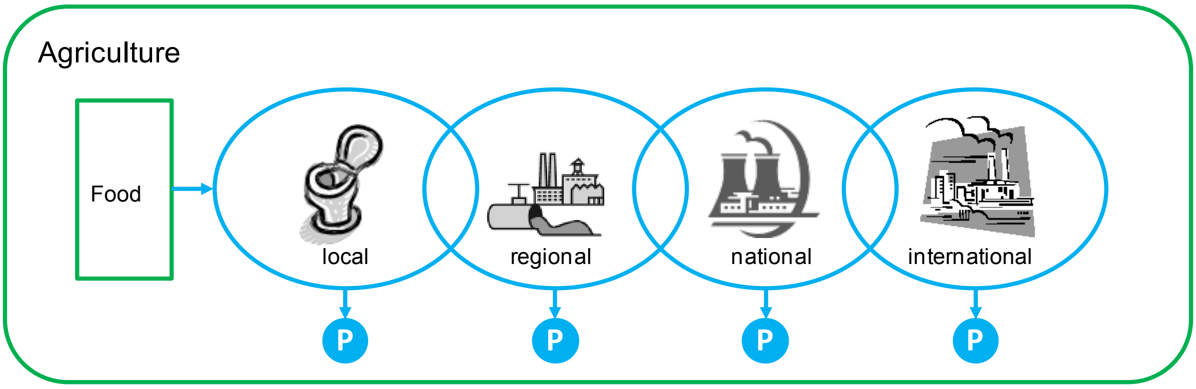
Toiletwater acts as a sink of phosphorus in times of importing phosphorus from outside Europe. The phosphorus chain starts with using fertilizer, which is uptaken by food, passing human bodies and ends in waste streams (in the Netherlands a 12 Gg P/a can be recovered from wastewater, Notenboom et al. (2013)). No matters what will happen with the phosphorus?!

Toiletwater will be a source of phosphorus in times that phosphorus rock is scarce and difficult assessable for Europe. It will become more common to use technologies to recover phosphorus from wastewaters (in the Netherlands already the amount of P from wastewater could replace the import of chemical fertilisers of the year 2008 (amount is decreasing with the years), Notenboom et al. (2013)).

Wastewater, biological solid wastes and animal manure will in the future fill the gap of phosphorus needs, since these streams are highly potential for recovery. Europe will have his own phosphorus production sides in various scales through closing the loop of phosphorus production – consuming – wasting.

Phosphorus Recovery Chain



The phosphorus recovery chain must be tailor made for the users, varying in scale and location. The prospect will be the most sustainable scale and place to recover phosphorus. This can be directly at the source, in one household or a small residential district; or at regional wastewater treatment plants; or implemented at national level, i.e. from mono-incineration ashes of sewerage sludge. For small countries in Europe the size might not be efficient, it can be better to take a look beyond the national borders and to solve the recovery question together with other countries.

The scale of the recovery side depends on the inter-action between the technologies and the demand of recovered phosphorus. The leading question should be: Who needs the phosphorus and in which constitution? Regarding this, it will be determined at which point of the chain phosphorus should be recovered. This will not end in any exclusion of recovery on other scales – no, the different scales interact and complete each other towards the most sustainable supply chain of recovered phosphorus.

References: Notenboom, G., Vergouwen, L., Morgenschweis, C., Schöll, L., Postma, R. (2013): Fosforhoudende Producten uit de Communale Afvalwaterketen, STOWA 2013-32, November 2013

Sustainable Phosphorus Management

>>>Practical Site-Specific Measurements for Phosphorus Risk Assessment

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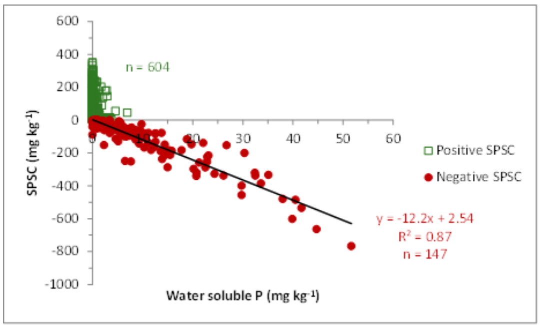
Extant phosphorus (P) risk assessment approaches such as degree of P saturation (DPS) and soil test measures provide information as to whether an application site constitutes an environmental concern. However, they do not capture the amount of P that could be applied safely or that would continue to be lost as a legacy source after excessive P application. Predictions for safe P application require that the P retention capacity of a soil be taken into account, and that the remaining capacity (prior to environmental detrimental P risk) be determined. A concept called the Soil Phosphorus Storage Capacity (SPSC) that is based on a threshold phosphorus saturation ratio (PSR) has been developed; the PSR is the molar ratio of P to iron (Fe) and aluminum (Al), and SPSC is a PSR-based calculation of the remaining soil P storage capacity that captures risks arising from previous loading as well as inherently low P sorption capacity of a soil. Zero SPSC amounts to a threshold value below which P runoff or leaching risk increases precipitously; SPSC can be calculated using the following equation:

SPSC = (threshold PSR-soil PSR)*(molar extractable Al & Fe)*31 (mg kg^{-1}) where the threshold PSR = 0.1, corresponding to a DPS of 20%. The relationship of SPSC to water soluble P based on data generated from over 750 soil samples of the Suwannee River Basin in Florida, USA, illustrates the practical application of this concept.



A DPS value of 25% is the critical DPS that would support a P concentration of 0.1 mg P L^{-1} in groundwater as proposed by researchers in the Netherlands. Recently, scientists in Switzerland identified a DPS value of 23.5% as their threshold above which P losses increase substantially. The calculation of DPS as originally proposed requires determination of oxalate-extractable P, Fe, and Al concentrations in a soil. Substituting a more readily determinable extraction (e.g., a soil test procedure) for oxalate-extractable P and metals has practical advantage and has already been proposed in various parts of the USA. If a common method of determining the threshold PSR could be identified across various locations in Europe, the USA and elsewhere, we would have a simple tool (SPSC) that could be used to manage P losses from agricultural soils across a range of soil types and P source applications to address P losses to surface waters that can result in eutrophication. Site-specific SPSC determinations can be extrapolated to a catchment scale. With the advantage of SPSC being additive such that a single value can be obtained for a given soil profile to any desired depth, it should be possible to identify locations within a catchment that are subject to P loss either via surface or subsurface pathways, or through leaching. The approach would be useful to identify locations of legacy P accumulation and address the issue via appropriate best management practices (BMPs).

What are You waiting for ? We can use the Phosphorus in the Wastewater Stream

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EU27 imports 92% of phosphate rock and derivatives for agriculture[19], equivalent to 1'250'000 t of phosphorus per year[20]. More than 50% of the phosphorus in the sewage sludge from the wastewater stream is lost in landfills[21], which corresponds to 12% of the phosphorus provided by mineral fertilizers and feed additives in agriculture. The phosphorus lost in the wastewater stream in the EU27 could substitute phosphorus imports for fertilizer and feed worth over 0.2 billion € (in equivalent TSP prices).

Recovery technologies running in pilot or full-scale (see Figure[22]) are capable of recovering phosphorus from the wastewater stream at very competitive prices. For example, a full-scale applicable technology produces fertiliser raw material by purification of sewage sludge ash at estimated 2.20 €/kg phosphorus[23]. Direct replacement of phosphate rock with sewage sludge ash in the fertilizer industry is technically feasible and the use of existing processes and equipment should lead to low costs. Taking into account necessary investments and the available technologies it can be concluded that the phosphorus in the ash of incineration plants could be recycled at a cost of less than 10 €/capita in the concerned region. As a comparison, typical costs of wastewater treatment in the EU range from 40 to 140 €/capita. The investment necessary for regional or national implementation of high rates of recovery is thus reasonable.

My future vision is that authorities will work together with early movers in the waste treatment and fertilizer industry as they have already started:

- ICL Fertilizers plan to replace 15% of rock phosphate feedstock with ash until 2015.
- Ecophos, a leading technology and feed phosphate provider are planning a plant for production of feed phosphates in Dunquerque, France for 2016, which should partly use sewage sludge ash.
- The planned revision of the Swiss federal Technical Ordinance on Waste prescribes recovery of phosphorus from sewage sludge starting in 2020.

The existing sludge use in agriculture will be complemented by the processing of ash and also other recovery paths. Closing the phosphorus loop will reduce imports and introduce new technologies and services which create new jobs. The environment will benefit from replacement of fossil resources with renewable ones and Europe will be more independent from external influences from the labile phosphorus market24.

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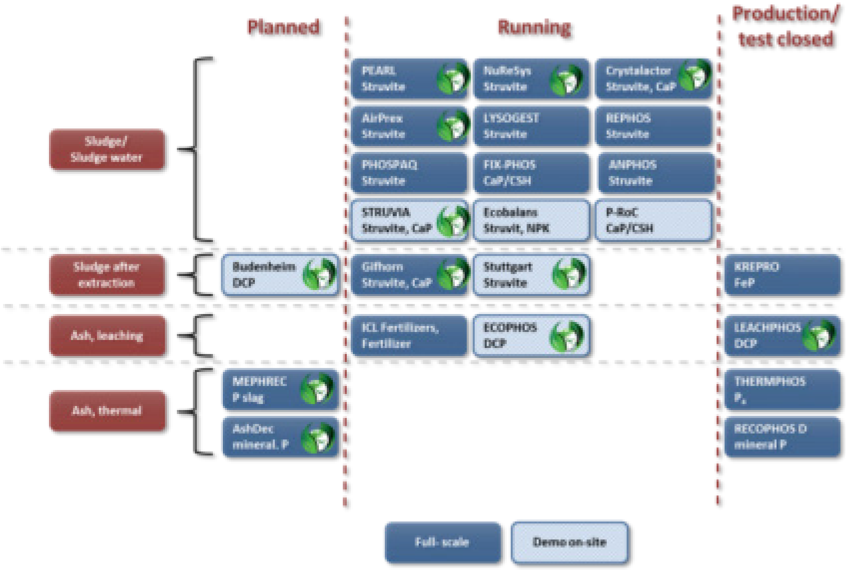
Planned
Running
Production/ test closed
Sludge/ Sludge water
PEARL Struvite
NuReSys Struvite
Crystalactor Struvite, CaP
AirPrex Struvite
LYSOGEST Struvite
REPHOS Struvite
PHOSPAQ Struvite
FIX-PHOS CaP/CSH
ANPHOS Struvite
STRUVIA Struvite, CaP
Ecobalans Struvit, NPK
P-RoC CaP/CSH
Sludge after extraction
Budenheim DCP
Gifhorn Struvite, CaP
Stuttgart Struvite
KREPRO FeP
Ash, leaching
ICL Fertilizers, Fertilizer
ECOPHOS DCP
LEACHPHOS DCP
Ash, thermal
MEPHREC P slag
AshDec mineral. P
THERMPHOS P_4
RECOPHOS D mineral P
Full- scale
Demo on-site

Inorganic phosphate & cheaper anticancer therapies

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Inorganic phosphate (Pi) is an essential nutrient to the living organisms. It is required as a component of energy metabolism, kinase/phosphatase signaling and in the formation and function of lipids, carbohydrates and nucleic acids and, at systemic level, it plays a key role for the normal skeletal and dentin mineralization. Pi represents an abundant dietary element and its intestinal absorption is efficient and minimally regulated. The kidney is a major regulator of the Pi homeostasis and can increase or decrease its Pi reabsorptive capacity to accommodate the Pi need. Relevantly, Pi is emerging as an important signaling molecule capable of modulating multiple cellular functions by altering signal transduction pathways, gene expression and protein abundance in many cell types (1).

Recently, a series of articles aimed at determining the consequences of elevated Pi on the behaviour of human osteosarcoma cells has been published. Overall, evidence has been accumulating that enhances the proposal of Pi as a signaling molecule and indicates that Pi may act as a potent antitumor agent in osteosarcoma cells (2).

New drug delivery systems have been developed that incorporate anticancer drugs into phosphate containing nanoparticles to maintain high concentrations of anticancer drugs at bone local site. Very interestingly, the release of inorganic phosphate by phosphate containing nanoparticles and its retention in bone microenvironment is predicted to occur, thus affecting locally the Pi concentrations (3).

In addition, keeping in mind that phosphate is the most abundant anion in the cell with a high intracellular concentration (of about 100 mmol/L), it is easy to imagine that an increase of extracellular Pi can be found in the tumor microenvironment upon its release from death cells during the chemotherapy.

The combination chemotherapy is receiving particular attention in order to find compounds that could increase the therapeutic index of antineoplastic drugs while limiting their potential toxicity.

Notably, the burden of the cancer is growing and becoming a major financial issue. The number of cancer patients and the cost of their treatment are constantly increasing. Thus, the charge of anticancer therapies in the developed world is spiraling and its economic impact is increasingly becoming more relevant for National Health Services (4).

Efficacious and cheaper anticancer strategies compatible with a public National Health System are strongly warranted.

The findings that the inorganic phosphate, very simple "naturally occurring molecule", can have antitumor effects on osteosarcoma cells and can achieve additive cytotoxic effects when combined with relevant chemotherapeutic agents illustrates its potential for clinical applications.

Further positive results from this research might provide the rationale for the rapid development of novel and cheap modalities for therapeutic intervention in osteosarcoma, and possibly in other tumors, based simply on increasing the concentrations of inorganic phosphate at local sites.

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Key challenges for future research on Phosphorus in Europe

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More than 164,000 scientific papers have been published worldwide about phosphorus (P) since the early 70s. A brief overview of the literature shows that P was first studied as a nutrient by agronomists. P fertilisation recommendation systems have been improved, which has led to lower mineral P fertiliser rates in most western European countries. Later P was studied as a pollutant triggering eutrophication of water bodies and mitigation options have been proposed. More recently, phosphorus as an essential non-renewable resource has received attention from the scientific community (figure 1).

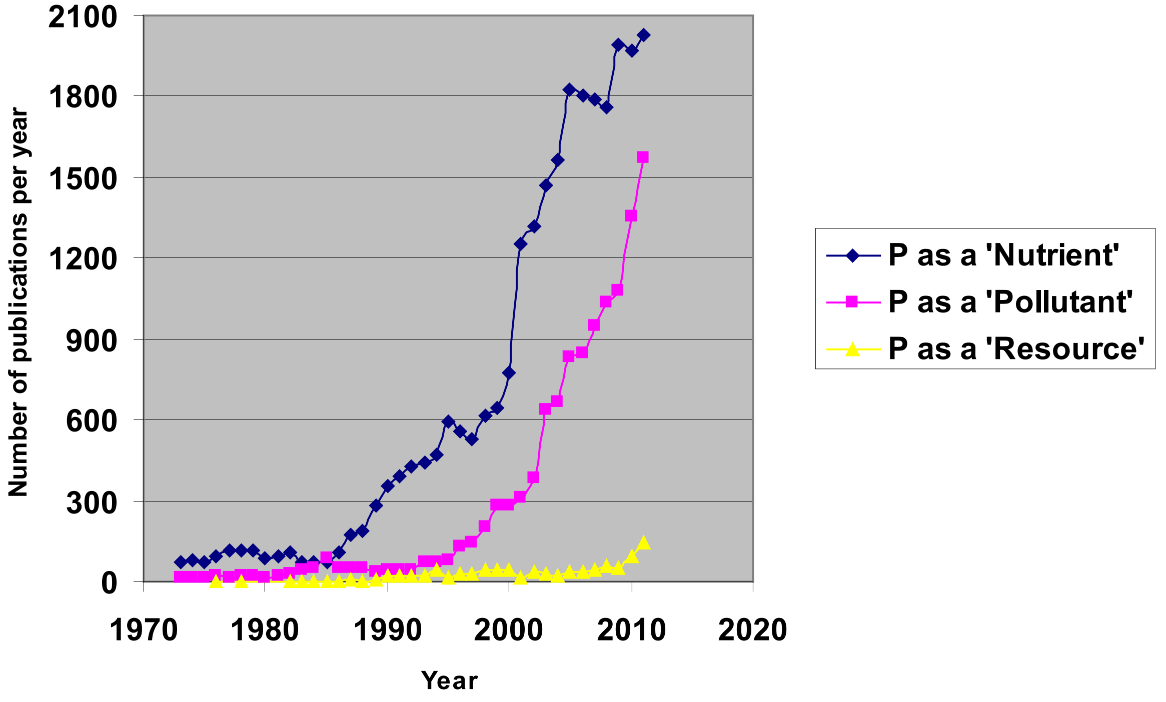

Figure 1: Number of scientific publications per year on Phosphorus (Web of Sciences)

In Europe, these three issues are now closely interconnected, but not addressed in a coordinated way at the EU level. The European Union has negligible natural P resources. Soil fertility and agricultural production in Europe rely on P imports (1500 Gg P per year of mineral P fertilisers). Phosphorus circulates within and between different industry sectors: agriculture, food/feed and detergent processing industry, households and waste. Calculated P budgets at European and national levels show that only a small fraction (ca. 20%) of the P entering the food chain via fertilisers ends up in food on the plate of consumers (Figure 2). The P cycle is characterized by limited recycling, low P use efficiency, accumulation in agricultural soils in some areas and losses to water bodies and landfill. Sustainable P management is urgently needed to ensure agricultural productivity, to secure food production and to protect our environment.

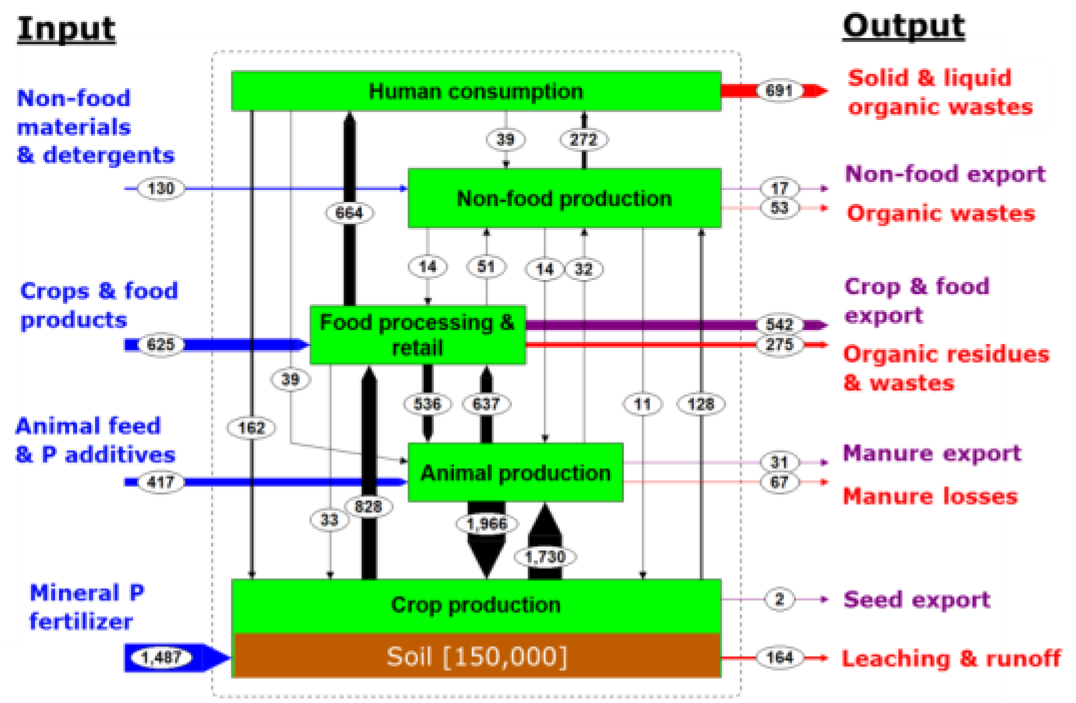

Figure 2: Phosphorus flows in the food production – consumption chain of the European Union (EU-27) in 2005. Inputs are shown on the left-hand side, output and losses on the right-hand side. Flows are indicated by arrows, pools and stocks are indicated by boxes. The size of flows and pools are presented in Gg = Mkg = kton P per year (from van Dijk K, 2013)

Innovations can make Europe less dependant on P imports by: re-aligning P use to more precisely match crop and animal requirements, reducing P losses, reusing P from manures and residues more effectively, recycling P from wastes and redefining the food chain where needed. A wide range of such innovations has been suggested in different segments of the P cycle, including more P efficient cropping systems, direct use of P-rich by-products as fertilisers, improvement of fertiliser and manure recommendations and application techniques, P-recovery from wastes and wastewater, etc. Many on-going research projects in Europe aim at preparing these innovations, but questions remain as to where and at which points in the food production-processing-consumption-waste recycling chain should recovery and recycling occur and with which technology? Possible options and burgeoning innovations are rarely assessed in an integrated way. This is limited by a lack of appropriate and harmonized approaches and tools for this, and a tendency of disciplines and sectors to work in isolation.

We argue that future research on P in Europe should increasingly span multiple disciplines, including social and natural sciences and featuring multi-disciplinary projects. Beside efforts to understand P dynamics at micro and meso-scales, there is an increasing need to identify drivers of P flows in the society and model the P cycle at large scales (regional, national, continental and global level). A common conceptual framework and accepted indicators (e.g. P footprint) are needed for a quantitative understanding of the P flows and cycling in the food production-consumption-waste management chain, harmonized calculations of P use efficiency, monitoring of progress, dynamic modelling and scenario analyses. This integrated approach will provide the appropriate framework to determine the critical flows, processes and factors and to assess how individual and combined innovative strategies can improve P recycling and P use efficiency in the society. Moreover, it will enable interactions with other issues to be assessed such as food safety and C and N cycles.

P-recovery from food-grade animal bones

>>>REFERTIL ABC: Animal Bone bioChar organic-P-fertilizer

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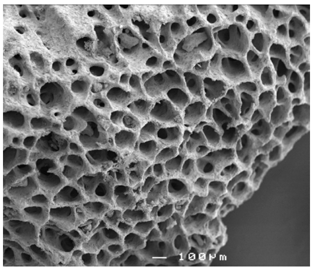
Today the EU agriculture relies on phosphorus fertilizers mostly processed from mined phosphate rock from Western Sahara - Morocco, which is a non-renewable resource that takes 10-15 million years to form. The technologically enhanced heavy metals and Uranium as fertilizer-associated elements are target contamination in phosphate rock. The current known reserves are likely to be depleting 50-100 years, but the low Cadmium and Uranium content phosphate rock reserves depleting far sooner, likely 10-25 years. The rate of production of economically available phosphate reserves will soon reach a peak, followed by a rapid steep decline and subsequent ongoing decline of productivity. Demand for phosphorus fertilizers is expected to increase by 50-100% over the next 50 years due to increased population, increased demand for meat and dairy-based diets and increased demand for non-food crops like biofuel crops. Industry statistics indicate that annual world production of P_2O_5 from low cadmium igneous rock is of the same magnitude as the total EU consumption. However more than 90% of this low Cadmium phosphate is consumed outside the EU. It is therefore unrealistic to suppose that the whole of the EU could be supplied with low Cadmium phosphate from existing production capacity. Global trade of phosphate commodities is extremely energy intensive and currently relies on cheap fossil fuel energy for mining, processing and particularly freight.

There is an increasing economical, environmental and ecological need for recycling and reuse of the phosphorus resources, all in order to improve P-supply stability and food security. The targeted streams for P recycling are harvested biomass, food industrial and animal wastes (food grade bone-meal), which are reach in phosphorus into natural Phosphorus fertilizers and sewage sludge. However, all in order to maintain efficient agri productions, the high P_2O_5 concentrated recycled phosphorous products in economical intersting production dimensions are the most interesting. One of the few high P_2O_5 concentrated (30%) recycled phosphorous product availability is the „ABC" Animal Bone bioChar, made from food grade animal bone, that is an extracted byproduct part of the EU animal waste rendering industry with over 20 million tons/year throughput total capacity.

Biochar is plant and/or animal biomass by-product or organic waste based stabile carboniferous substance for conservation agriculture applications. Plant based biochar is soil improver while ABC is organic P-fertilizer.



macroporous ABC

ABC is high calcium phosphate apatite mineral and low carbon content macroporous slow release natural organic P-fertilizer safe product. ABC is produced from food grade animal bones at 650°C reductive thermal processing and negative pressure conditions with advanced zero emission environmental performance. ABC is highly macroporous, formulation optimized for significant enhancing of soil microbiological life, having high water holding and macromolecular organic nutrient retention with sequenced release P- fertilization effect.

ABC fertilizer efficiency test

The sustainability criteria for all biochar is that the feed matrials are not competing with human food, animal feed and plant nutrition production.

The REFERTIL project also provides strong policy support to the European Commission for revision of the Fertiliser Regulation (Reg. EC No. 2003/2003.). ABC films: http://www.euronews.com/2014/04/21/richer-soil-from-old-bones/

and http://www.euronews.com/2014/04/21/do-you-know-do-plants-eat-skeletons/

P resources and their use

>>>Phosphorites in the Republic of Estonia

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Estonia is a small country with the surface area of 45 thousand km^2 and population number about 1.3 mln. The Estonian phosphorite (EP) deposits belong to Baltic-Ladoga phosphorite basin and are located close to North-Estonia – St Petersburg district clint. Lithologically, phosphorite is represented by yellowish-light to dark-grey so-called obolus sandstone with P_2O_5 content 10% and more. It is a sedimentary rock with enhhanced content of *Brachiopoda* valves (Figure) rich in phosphorus (~30-36% P_2O_5).The content of valves ranges in the ore from 5-10 to 80-90%. Phosphorite is easyly enrichable and characterized by low content of cadmium (< 2ppm in concentrate). The phosphorite bearing sediments are united into Kallavere formation, which lies in monoclinally bedded sedimentary bedrock complex on the border of Upper Cambrian and Lower Ordovician and belongs mostly to Ordovician. There are several deposits (Maardu, Toolse, Aseri, Rakvere etc) with recources of about 865 milion t P_2O_5 .

In 1924-1991 about 25 mln t of ore was excavated, being then partially enriched by different ways. During Soviet period the concentrate was mainly used as a direct fertilizer. In collaboration of Estonian Geological Survey (www.egk.ee; R. Raudsep, V. Petersell, H. Liivrand et al), Tallinn University of Technology (TUT, www.ttu.ee; M.Veiderma, R.Kuusik, E.Aasamäe, et al) and other institutions the complex geological characterization of deposit as well as enrichment conditions of ores and technological properties of concentrates have been worked out. The chemistry of apatites and mining problems have been of continuous interest in TUT (K.Tõnsuaadu, E. Reinsalu, I. Valgma). The respective publications have been involved in two biblipgraphies (*Phosphorites of Baltic Basin. Bibliography 1829-1990. Tallinn1992, 232 p*. and *Inorganic Chemisty and Technology Research Group. Bibliography 1960-2002. ISBN 9985-95-416-9.TTÜ Kirjastus, 97 p.* (both in Estonian with English preface).

Currently, in order to take into accunt developments on processing technologies during the last 20 years, by oil shale processing enterprise VKG (www.vkg.ee) several issues are initiated, being in primary stage of study. These include hydrogeological conditions (Estonian Geological Survey), distribution of Mg and Fe impurities in phosphorite rock (Tartu University, Geology Section), rock beneficiation and reactivity testing (partner in USA), underground mining technology of phosphates (TUT, Mining Institute) and economics of fertilizer production (VKG). While the EP deposits are mostly located in economically advanced agricultural regions, the future possible activities related to phosporites are widely discussed.

The Governance Gap Surrounding Phosphorus

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How could phosphorus (P), an essential dietary element, that limits the productivity of ecosystems, and that exists as fossil rock reserves in mainly one country in the world remain a low global governance priority? That the UNEP Global Partnership on Nutrient Management deals essentially only with nitrogen, that the EU has a Nitrogen Directive but nothing for phosphorus and that the entire UN has no structure in place to monitor and regulate the extraction of phosphate rock all say that a serious gap exists. That phosphorus prices rose 800% in 2008 is common knowledge. Yet, neither P nor fertilizers were mentioned as issues of concern during the ensuing three UN Food Security Summits. In fact the Food Security Summits only discussed expanding the World Food Program. They did not address the need for fertilizer and self-sufficiency. The problem of P governance is complex, exists at multi-level scale and strengthens regional and global disparities. Whereas deprived smallholder farmers in most African countries cannot afford today's chemical fertilizers to improve the quality of their soils, heavy subsidies to the agricultural sector in the North has ingrained a common perception that P is limitless and hence food should remain cheap. When we subsidize agriculture in the EU with 1 billion Euros per week, should this be a surprise? The extraction of nitrogen from the atmosphere (Haber-Bosch process) has been the most important factor in the provision of fertilizer that has fueled the first green revolution and makes it possible to feed 6 of the 7 billion people. P extraction from fossil deposits has very quietly kept pace. But who is managing this finite resource? Are the geopolitics of dependency on 4-5 countries being adequately addressed? That the EU's sole source is from one mine in Finland that has about 30 years of commercial life left is apparently a non-issue. Path-dependent ways of managing P around the world leaves little room for improving efficiency and optimizing reuse. As Duncan Brown coined it, the present way we use phosphorus is more like driving a car at top speed down the highway with no fuel indicator on the dashboard, and we will do nothing until we first run out of gas. This calls for a concerted effort to develop the global and regional governance of this finite resource. An action plan with several stages is required:

1) global conference including stocktaking and suggestions for sustainable practices

2) non-partisan monitoring and regulatory program on extraction of phosphorus rock set up by the UN

3) global convention erected whereby milestones in sustainable practice are set up including limits to extraction and minimum levels of reuse

4) new generation of best practices that optimize the quality of waste systems (liquid and solid) be set up in order to promote reuse

5) economic instruments developed whereby wasteful practices are taxed and reuse promoted.

6) communications strategies initiated to help make the P question more household and better understood.

Sustainable P use

>>>Efficiency – pollution -- social responsibility: Keys for sustainable phosphorus use and food security

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Producing more with less environmental impacts is a general challenge of sustainability. Against this background, efficient use of non-renewable resources such as phosphate rock (PR) used in the production of phosphorus (P) fertilizers is central to achieving sustainable agriculture. Considering that approximately 3 Mt P is consumed in food compared to the 20-22 Mt of mineral P fertilizer used in food production, annual food related P use efficiency appears to be low. This efficiency is further reduced if one considers an additional 2-3 Mt P released by anthropogenic land use [1]. Within each component of the P value chain (e.g. exploration, mining, processing, use, and recycling), opportunities for improving efficiencies exist. For example, P fertilizer production may be considered inefficient as 30-50% of the P_2O_5 equivalents in mined ore is not recovered in the finished product [2]. Globally, perennial nutrient use efficiency (PNUE), if defined as the ratio of edible crop divided by the mineral and manure fertilizer used would be a low 40% [3]. The remaining 60% would include both stored nutrients (e.g. soil, crop residues,) and nutrients lost *via.* runoff, erosion, etc. Thus, the sole use of efficiency parameters creates confusion. For instance, from a regional perspective, Africa has the highest PNUE for P because the soil is exploited for P, but exploitation translates into low yields. Therefore, high efficiency is not sufficient for sustainability. There is also limited knowledge about the efficiency of sewage recycling technologies. Here, the economic efficiency for recycled P relative to P fertilizers seems lower, in part because there is no consensus regarding indirect or external costs. Sustainable P management requires properly relating efficacy and efficiency on different scales. Our **first vision** is that this knowledge will develop in future transdisciplinary processes.

As humans have more than tripled the natural P flows, the associated losses (from runoff, erosion, overuse of P etc.) have contributed to eutrophication, hypoxia or anoxia in surface waters. There is also evidence that overuse of P affects terrestrial biodiversity [4]. Despite specific environmental issues (e.g. cadmium contamination) associated with P fertilizers, P should not be looked at as a single element, since ecosystem balance is dependent on all nutrients and other elements [5]. Our **second vision** is that profound environmental system knowledge is developing about critical planetary boundaries of P use and that an assessment of the global patterns of P management and its impact on the biotic earth system will be conducted.

Finally, much has been published on the scarcity of PR reserves and the 2008 price peak. Comparative analysis with other commodities, geoeconomic analysis on the dynamics of reserves, and geotechnical considerations (e.g. on offshore mining) have shown that there will be no physical scarcity in the foreseeable future [6]. PR is an abundant low cost commodity. Each person is consuming about 30 kg PR yr^{-1} at a price of USD 6. Given the relative abundance of PR (present in 57 countries), significant long-term supply interruptions could be managed. However, PR reserves are finite and eventually there will be a peak. This reality calls for increasing the efficiency of PR and mineral P use. Furthermore, smallholder farmers are highly vulnerable to any price increase. Providing access to P fertilizers for poor farmers may be seen as a global social responsibility. Our **third vision** is that we will keep or establish a resilient global supply chain that provides supply security and access to P for the poor.

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Phosphorus recovery from wastewaters

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Globally, clean water for domestic, agricultural, and recreational uses, and for potable supply, is increasingly endangered due to water pollution. Phosphorus (P) is a major nutrient contaminant in water causing this pollution. Excessive P in wastewater sources must be removed to avoid eutrophication of receiving waters such as rivers and lakes. Phosphorus removed from water can be a source of raw material for the phosphate industry, especially for the production of phosphate fertilizers. If a successful method is developed for effective and economical recovery of P, the present thinking that P is a contaminant will change to one that deems it is a resource. This view has increased in recent past because some have argued that P is a limited and non-renewable resource and the reserves of high-grade phosphate rock that are used to make phosphate fertilizers will be mosty exhausted before the end of this century, unless another source of high-grade phosphate is identified.

The daily amount of wastewater generated in Sydney, Australia is over 1200 ML. Assuming a typical raw sewage P concentration of 11 mg/L, Sydney's wastewater system generates 13.2 tonnes of P on a daily basis or 482,000 tonnes of P annually. As a nation, Australia consumes more than 300,000 tonnes of P a year from import of phosphate fertilisers. If even a part of the P in wastewater in Sydney and other cities in Australia is recovered, it can meet the national P requirement.

Adsorption is an effective water treatment process for the removal of P (Loganathan et al. 2014). Adsorbents are used as filter media in filter-based systems and as bed media in constructed wetlands. After a period of usage they become saturated with phosphate and their efficiency of phosphate removal decreases. At this point the adsorbent needs to be regenerated by removing the adsorbed phosphate. The phosphate so removed can be recovered by precipitation with calcium/or magnesium salts and employed as phosphate fertilizers.

A recent study in our laboratory has shown that phosphate was effectively removed from synthetic wastewater by adsorption onto an iron oxide impregnated strong base anion exchange resin (Purolite FerrIX A33E) (Nur et al. 2014). Greater than 90% of adsorbed phosphate was desorbed by leaching with 1M NaOH and the adsorbent was regenerated after each of three adsorption/desorption cycles by maintaining the adsorption capacity at >90% of the original value. Greater than 99.5% of the desorbed P was recovered by precipitation using $CaCl_2$. The P content of the dried precipitate was 15-16% which was similar to that in commercial phosphate rocks (apatites) used to produce phosphate fertilisers. Our proposed vision is to optimise conditions for the removal of P from real wastewaters and recover the P in the form of apatite or struvite using cost-effective and efficient adsorbents at the pilot-plant scale and make recommendations for commercial use.

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Legacy of phosphorus: Agriculture and future food security

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Introduction

Global food demand is on a trajectory to increase by 70% in 2050. However, sustainable food supply may be challenged by availability of natural resources (1, 2), among which phosphorus (P) as a low-rate recoverable source with finite availability (3, 4) and a major limiting nutrient in agriculture (5).

P scarcity has five dimensions, including physical, geopolitical, institutional, economic and managerial scarcity (6). While the time scale of P depletion is debatable (7-10), a critical question beyond the physical scarcity is whether P resource depletion can be managed by more sustainable P consumption.

Our innovative vision for sustainable P in tomorrow's world has two major components:

Residual phosphorus

About 10-20% of the P fertilizer can be taken up by crops in the first year, while the rest accumulates in the soil as "residual P" that can be taken up by crops for many years (11, 12). Following a traditional misconception that P accumulation/fixation is dominant and irreversible, P has been used excessively in agricultural systems for decades (13). The importance of the residual P shall be considered seriously in the projections of P demand.

Our results show that accounting for the role of residual soil P leads to lower projections of P demand in 2050 even with increase of global production and yield.

The average global P fertilizer use on cropland must change from the current 17.8 to 16.8-20.8 Tg yr^{-1} in 2050, which means up to 50% less than existing estimates in the literature (14).

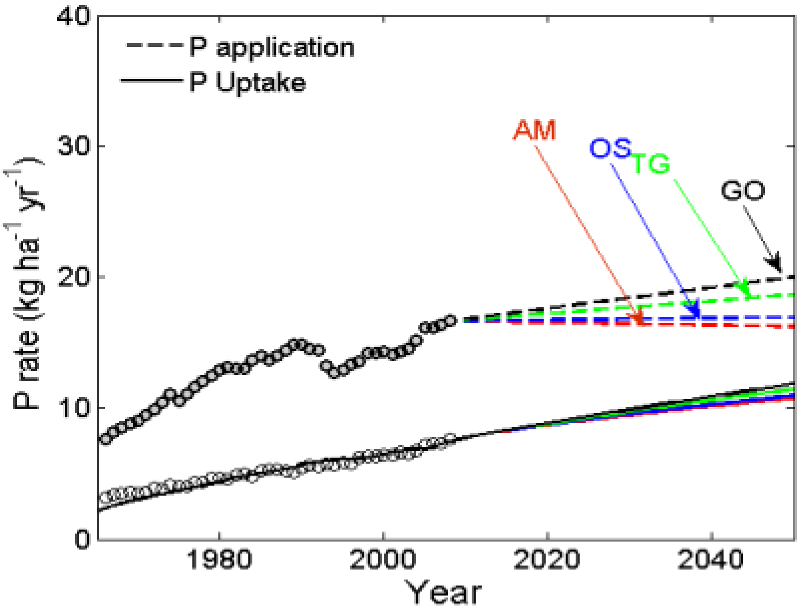

Fig 1. Trends of annual P application and P uptake in cropland for the period 1965 to 2050 on the entire globe according to the four MEA scenarios (15). Long-term FAO data (16) and simulation results are illustrated by circles and lines, respectively. Shaded and open circles refer to P application and P uptake rates, respectively. Dashed and solid lines refer to P application and P uptake rates, respectively.

2. Redistribution of phosphorus

Sustainable use of P can be supported by designing a system of redistribution and balancing of P application through “smart cooperation” (17) between different sectors (e.g. cropland and grassland) and different regions.

2.1 Geopolitical regions

While many industrialized countries move beyond the period of overuse of P fertilizer, in Africa soils are still being depleted over the years due to the low rate of P inputs. Thus in Africa more than five-fold increase in P application is needed to achieve the target P uptake in 2050.

China as the world’s largest producer and consumer of P fertilizer can undeniably play a key role in managing the global P crisis by adapting proper and sustainable P application strategies. Sustainable use of P accounting for the residual P in Chins can reduce the amount of P fertilizer demand by 20% (18) until 2050. This amount is enough to supply half of the required P in Africa, or supply Western Europe’s P to realize the target crop P uptake in 2050 (19).

2.2 Grassland vs. cropland

A large part of the P in animal manure that is recycled in cropland originates from grasslands. Future demand for meat and milk will increase the pressure on grasslands to provide grass and fodder for the animals.

Our results show a large P depletion in grassland soils in all regions in the world except for Eastern and Western Europe, which are currently virtually in equilibrium but have built up residual P in grassland soils in past decades. It is clear that export of manure from grasslands to cropland is primarily responsible for these globally unbalanced budgets. Given the increasing future demand for grass (15), additional fertilizer P and an adequate manure management will be required to maintain soil fertility in the world’s soils under grassland (14).

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Phosphorus, the element we've learned to love

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If we think of a vision for the future, phosphorus certainly has a key role in it. We may not be running out of it soon, as some would have us believe, but we can't afford to get to that point either. If we care about sustainable use of metals, glass, paper and plastic, none of which are as important as phosphorus, we should care much more about a key element that feeds us.

In a way, it's easy to care about phosphorus. If we use it, it's not going to go away after we discard it, because it's a chemical element. It will turn up in places where we don't need it and don't want it, promoting growth of organisms indiscriminately. This may destroy the quality of our surface water. Responsible phosphorus use is all about putting it where we need it most, and only there. In this way we prevent eutrophication and use its tremendous potential where it benefits us. We need to work on the prevention of phosphorus misplacement.

In another sense, it's very difficult to care about phosphorus. We can't see it or touch it, unless we get our hands on a bag of fertilizer. Silently and modestly it plays its role without being recognized. It's all around us and even inside us, invisibly, but we'd sorely miss it if we lost access to it. In this vision for the future, everybody knows about phosphorus, so they can care for it and appreciate its value.

In this vision, we make sure that our vital nutrients are used in the best possible way. In fertilizer production and processing, we will make sure that every gram of phosphorus is used, or failing that, is stored for future use if we need it. We will design our society and systems in such a way that nutrients can be re-used over and over again. Chemistry will play a key role in extracting phosphorus wherever necessary. This should allow us to freely use phosphorus without guilt, in food production but also in industrial and technical applications. As long as we make sure it gets back to us, there's no fundamental restriction to use phosphorus in whichever way we want. With only entropy working against us, we're all set for the future.

P supply stability or vulnerability, adaptive policies, P and food security

>>>Assessing phosphorus vulnerability to inform context-specific adaptive phosphorus strategies

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The scientific discourse on phosphorus as a scarce resource has been dominated by a focus on physical scarcity. While the quality and longevity of global phosphate reserves is indisputably an important issue, the economic, institutional, managerial and geopolitical scarcity of phosphorus require equal attention to ensure sustainable future phosphorus management.

In the same way that regions can experience climate change and water scarcity differently, national or regional food systems are vulnerable to phosphorus scarcity in different biophysical & socio-economic ways. A phosphorus vulnerability assessment can facilitate a context-specific assessment to provide tailored guidance for food and agricultural policy-makers, phosphate producers and farmers to take action to buffer against local and global risks associated with phosphorus scarcity.

A phosphorus vulnerability assessment facilitates the inclusion and integration of a diverse range of phosphorus-related biophysical, technical, geopolitical, socio-economic & institutional stressors and factors relating to exposure, sensitivity and adaptive capacity (figure). Exposure refers to external phosphorus stressors or perturbations (now or in the future) that result in a hazard for the food system. These can be biophysical in nature such as the lowering grade of the world's remaining phosphate rock, geopolitical, such as the uneven distribution of phosphate rock reserves, or economic, such as the price of phosphate commodities. Factors leading to system sensitivity are often endogenous to the national food system (such as a country's dependence on phosphate imports or soil fertility status), and influence the degree to which the system is modified or affected by exposure. Adaptive capacity refers to the potential ability of the food system to cope (short-term) or adjust (longer-term) to the hazard. That is, the preconditions necessary for adaptation. Adaptive capacity is in a similar way influenced by both external and internal factors, and can relate to financial assets, social capital or the ability to exploit natural capital derived from national policies, agricultural structure, or technical and infrastructural capacity to recover phosphorus from waste streams.

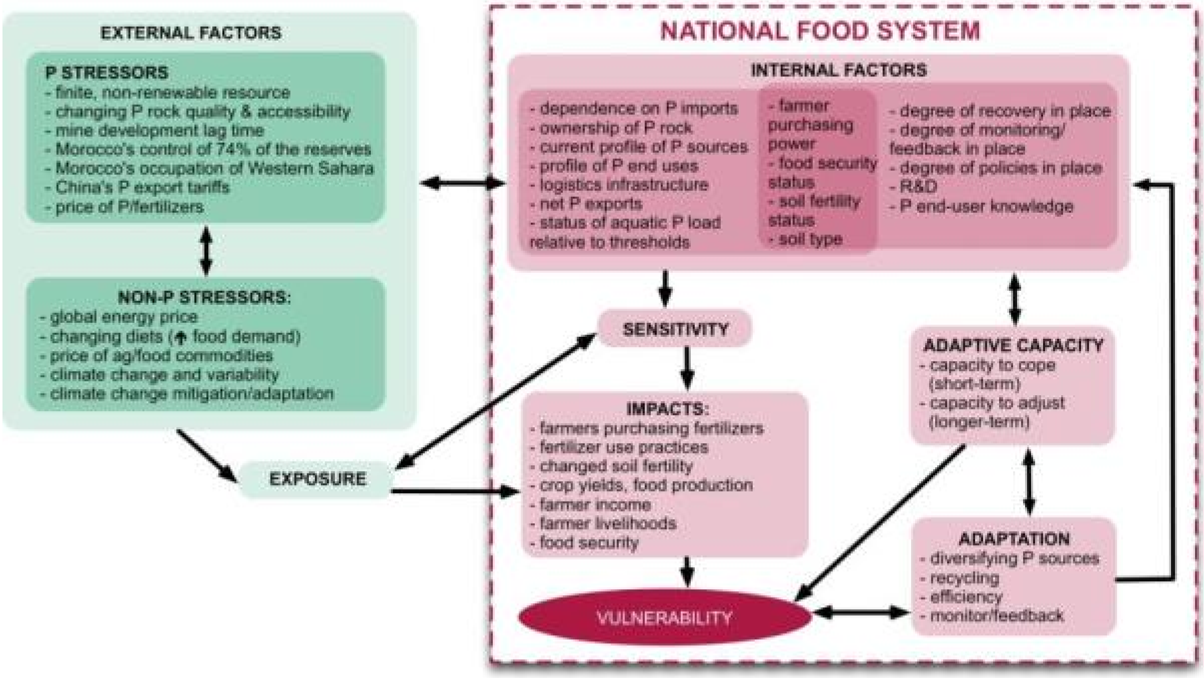

Figure: Assessing phosphorus vulnerability: external and internal factors influence exposure and sensitivity that can lead to vulnerability of the national food system. This can be countered through appropriate adaptation strategies. (Cordell & Neset, 2014)

Importantly, adaptive phosphorus strategies that are feasible in one region may be inappropriate and ineffective in another region. For European countries, key sensitivity factors include the high dependency of phosphate fertilizer imports and high susceptibility of receiving waters to eutrophication. Adaptive capacity can therefore be increased through initiatives like the Dutch Value Chain agreement or the Swedish national goal to safely recycle at least 40% of phosphorus in wastewater to agriculture by 2018. As such, both technical and institutional infrastructures as well as awareness of phosphorus as a scarce resource are important factors. In contrast, key sensitivity factors in many land-locked countries in Sub Saharan Africa include low farmer purchasing power, phosphorus-deficient soils, and poor over-land transport infrastructure. Priority strategies may therefore focus on accessible farm-gate fertilizers and more effective fertilizer use practices.

Assessing phosphorus vulnerability enables identification and discussion of the regional preconditions for decreasing vulnerability and informing priority adaptive strategies to increase the resilience of a food system by improving: national security, farmer fertilizer access, agricultural productivity and ultimately food security. Bringing together the expertise of regional planners, food and agricultural policy-makers, the phosphate industry, phosphorus end-users and scientists can enable more legitimate and effective joint action to reduce vulnerability to the global challenge of phosphorus scarcity.

Resources:

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For more information on the Swedish and Dutch initiatives:

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Organics Granulation: Manure to Fertilizer Granules

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Manure granulation has become a valuable opportunity to those in the agricultural industry, as a combination of hardships plagues our farmers in waste management. The rise in competition for land and its resources has forced farmers to oversaturate their crops with unprocessed manure, causing potential groundwater pollution and other environmental concerns. In addition, non-renewable chemical fertilizer costs are increasing and inorganic fertilizer sources are depleting as nutrient resources, like Phosphorus, are mined. Meanwhile, organic waste sources are sent to landfills, or dispersed among already oversaturated land. Many are learning that manure, though, is not necessarily waste, but an unexploited opportunity to transform waste into valuable fertilizer products via organics granulation systems.

FEECO International is an experienced leader in providing clients with organics granulation systems to transform manure into fertilizer granules. In a recent project, FEECO and the University of Wisconsin-Madison's Accelerated Renewable Energy Consortium (ARE) partnered with Maple Leaf Dairy, a farm in Cleveland, WI, to study on-farm technologies that would relieve manure handling problems. The project goal is to improve soil fertility, alleviate environmental impacts of manure, and serve as an experimental ground for defining process scale-up.

Granulation systems utilize several pieces of equipment to transform waste. Prior to the granulation on-set though, a digester may be used to process the organic waste stream. Digesters are not a required component to the granulation process, rather, they provide an option for farmers to remove manure solids and re-use them on the farm for bedding or other miscellaneous purposes. A separation system, a necessary step for granulation, removes solids from the digestate. A screw press first separates course materials from the manure, followed by a DAF system which separates fine materials. After processing, the material output contains 70-80% moisture, similar to pressed sludge. FEECO's granulation system, including process design, succeeds the separation. In the next step, fine solid fractions travel to the paddle mixer for simultaneous mixing and granulating. From there, the material is sent to the rotary dryer to remove additional moisture, with the product output encompassing 5% moisture. The granulation system creates an overall Phosphorus-rich, organic fertilizer granule, 2-4 mm in size.

Granulation systems exemplify organic recycling- the reuse of manure nutrients that may not always be valued or utilized, though they offer numerous benefits. By transforming manure into a granule, farmers gain more control of nutrient contents. Whereas nutrients in unprocessed manure vary greatly, making it a challenge to yield optimal soil results. In addition, pelletized granules are easily stored, so farmers can use them at the right time, as opposed to manure that must be used immediately. In addition, because pelletized granules are dry, they cost significantly less to transport.

The organics granulation system benefits noted above all integrate superior technology and manure management practices, opening the ultimate opportunity for precision agriculture to promote more productive yields with less available land. The easy-to-manage characteristics of granular fertilizer are fundamental to precision agriculture, and provide field management solutions to the agricultural industry of today *and* tomorrow.

Phosphorus Ore: Resource tax reform on phosphorus ore calls for improvement

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According to statistics concerning the tax on phosphorus ore released by the Ministry of Land and Resources of the People' s Republic of China (MLR) in March 2014, the national resource compensation fees on phosphorus ore exceeded USD16.24 million (RMB100 million) in 2013 for the first time. Especially in Hubei Province, the pilot province for resource tax reform in China, the resource tax on phosphorus ore in 2013 reached USD64.98 million (RMB400 million), up by 7.7% year on year. However, as the whole phosphorus ore market in China entered into a downturn in 2013, most enterprises especially enterprises in Hubei Province, witnessed no increase in revenue.

The continuous reform on phosphorus ore resource tax is mainly attributed to the reduction in the use of phosphorus ore. The tax on quantity lead to exploitation of the rich and the abandon of the poor, and further the excess consumption of high-grade phosphorus ore, which together negatively impact the exploitation and utilization of low-grade phosphorus ore.
Since Jan. 2013, the Chinese government has chosen Hubei Province as the pilot province for resource tax reform on phosphorus ore, by replacing tax on ad valorem (tax rate of 10%) with tax on quantity.

Transition to Sustainable Phosphorus Use

>>>Transdisciplinary processes for consent-based policy options on sustainable phosphorus management

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The transition from the current practice of phosphorus use to an era of sustainable phosphorus management is a complex societal issue. Transdisciplinary processes [1] may

serve **capacity building** by relating and integrating experiential knowledge from practice with academic and technology knowledge from science,

launch **consensus building** processes on the most urgent issues that have to be dealt with, including efficiency considerations and the implications of strong or weak resistance of specific stakeholder groups,

provide **mitigation** among affected key stakeholders, who may benefit or become disadvantaged by sustainability-oriented change (e.g., analytic mediation, multi-stakeholder discourse), and

enable **legitimization** of (governmental) decision makers as they may refer to options that have been elaborated both by mutual learning among science and practice, by a multi-stakeholder discourse and by a dialogue between science and practice with decision makers.

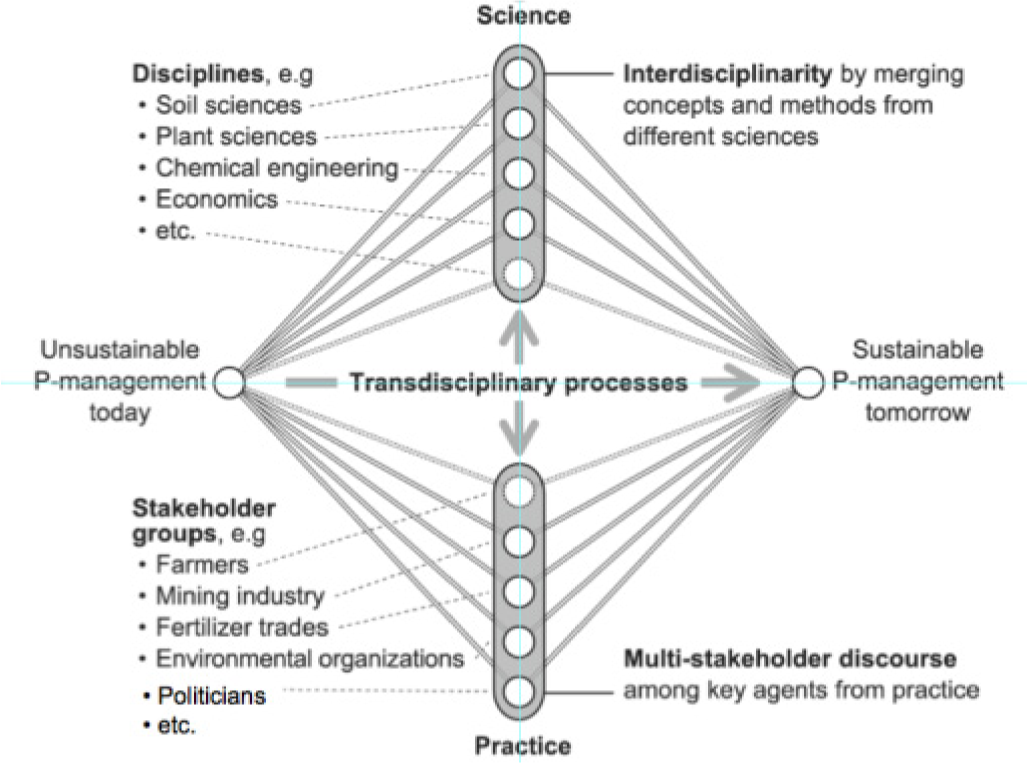

Figure 1: Transdisciplinary processes include interdisciplinary research, mitigation of interests in a multi-stakeholder discourse (Figure taken from [2])

Originating in early 2011, Global TraPs is a significant global-scale transdisciplinary project. After a joint problem definition through agreement on a guiding question among the key stakeholders, the involved scientists and stakeholders elaborated a joint system representation including a Material Flux Analysis (MFA) about the global phosphorus flows. A wide consensus that sustainable phosphorus management must address and resolve critical questions and policy options regarding **accessibility to P**, acceptable **environmental impacts of P production,** and ways **to improve the low efficiency of phosphorus use [3]**.

With respect to **accessibility**, we have to answer:

How may we get reliable knowledge about the current P-reserves? What resources may become reserves under what constraints?

How will the prices of mineral phosphorus increase if the high-grade mines are exploited?

What technology is needed to sustainably mine resources (e.g., by offshore mining) which are currently not sustainable?

What policy means may help that Sub-Saharan farmers will get access to the right type and right amount of phosphorus at the right time?

The **environmental dimension** requires answers to questions such as

What are the planetary boundaries of anthropogenic phosphorus spread?

What role do phosphorus emissions from agricultural use take in the eutrophication and marine dead zones?

Is the biodiversity affected by the anthropogenic tripling of the phosphorus flows?

Is phosphorus mining a sustainable issue or do we face unacceptable land degradation and contamination?

With respect to **efficiency,** the following questions are not sufficiently answered yet:

How may we improve the efficiency of fertilizer use in agriculture?

What losses can be identified along the supply chain? Who is losing what? How efficient is recycling of phosphorus at what part of the supply chain?

Given that we use around 3-4 Mt P each year, but mobilize around 35 Mt mineral P along the supply chain indicates an extremely low efficiency. How can this situation be improved?

Clearly, transdisciplinary processes should support a transition to sustainable phosphorus management soon. It is clear that this is a matter of practice and thus the result of a multi-stakeholder discourse among the representatives of stakeholder groups and politicians (lower Part of Figure 1). But properly answering the complex questions above is impossible without utilizing thorough discipline-based interdisciplinary research. A transdisciplinary process efficiently organizes a process of mutual learning and co-production of knowledge from (A) problem definition, via (B) problem representation to (C) problem solving and the establishment of a future sustainable phosphorus management [4, 5]. Our vision is that transdisiplinary processes will essentially contribute to the transition towards a sustainable phosphorus management.

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Phosphorus in agriculture

>>>Getting local to change global: focus on the nexus between food production and environmental protection

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Our future stewardship of natural resources will be defined in large part by global population growth and by changing dietary patterns within this population. Given these conditions, sustainable phosphorus (P) stewardship will be strongly conditioned by the use of P within agricultural production systems. The history of P stewardship within these systems suggests a disconnect between production-orientated (e.g. input, soil fertility, yield response) and environment-orientated (e.g. risk, export, impact) agendas. This fundamentally limits our ability to understand current P use within agricultural systems, to design appropriate scenarios for future P use, and to realise these scenarios through action. Sustainable stewardship of P urgently requires a re-connection between goals and actions related to food production and to environmental protection. Myopia regarding the primacy of either is destined for failure.

The challenge is to identify and implement solutions that mutually benefit food production and environmental protection. Two examples serve to illustrate the possible nature of such solutions. Firstly, can inorganic P fertiliser input be reduced in some production systems in some areas of the globe without adversely affecting yield, thereby offering an economic benefit to farm businesses whilst concurrently reducing the risk of P export from agricultural land to receiving waters? Secondly, through addressing compaction of agricultural soils, can the risk of P export from agricultural land associated with surface runoff be reduced, whilst at the same time enhancing the trafficability of land for farmers?

The realisation of such solutions relies on ways of thinking and ways of working among researchers, farmers and delivery organisations. Implementation of solutions cannot rely solely on top-down regulation and enforcement, but instead depends on voluntary acceptance by land managers and local authorities of responsibilities and duties for environmental protection under the prevailing law. Both require holistic rather than reductionist approaches at appropriate spatial and temporal scales. Practice and policy must also be informed by credible and accepted science of the highest quality,

Keep away from the edge! Maize production extending down a stream bank to the water edge in the Zhuyu catchment, Zhouzhi County, China. The image crystallises the challenge of securing food production and environmental protection, given increasing human demand on the earth's natural resources.

increasingly delivered through multi-, inter- and trans-disciplinary approaches; the latter achieved by iterative co-production of knowledge through collaboration between stakeholders.

For example, decisions regarding the nexus between food production and environmental protection must be underpinned by analytical frameworks that assess the stocks and flows of P within agricultural systems. In this context, a number of frameworks have emerged from international to farm scales that merit more extensive application (e.g. Oenema et al., 2003; Vitousek, 2009; Carpenter and Bennett, 2011). Ultimately, the aspiration should be to extend such frameworks to consider stocks and flows of P in the broader socio-ecological systems within which the nexus between food production and environmental protection is located (e.g. Ma et al., 2013). However, whilst set within a global systems context, catchment- and agroecosystem-scale perspectives will remain critical for understanding place-specific influences on stocks and flows of P, for identifying feasible means for change in P management, and for engaging and communicating with key actors in the P challenge.

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SyreN Crystal – system for sustainable use of phosphorus

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SyreN Crystal

The essence of a sustainable use of organic fertilizer, is getting a correct N:P ratio and applying the needed amount timely and evenly to an application site. Organic fertilizers have an inherently wrong N:P ratio and it must be corrected to achieve sustainability. This can be done by increasing the N value, decreasing the P value or a combination there of.

Increase of N to P

A very distinct characteristic of a slurry tanker, is that it is only used 2 month pr. year. The slurry tanker has the build in feature of being able to fill itself with slurry or sewage and deliver it to an application site. Add the SyreN system to the slurry tanker, and it is able to increase the N ratio through injection of ammonia to the slurry. This increases the N value to P and solves the problem. Using sulphuric acid to adjust the pH value during application, there is no ammonia emission. Provided that a reduced application rate of slurry is possible in a local area, the sustainability problem is solved.

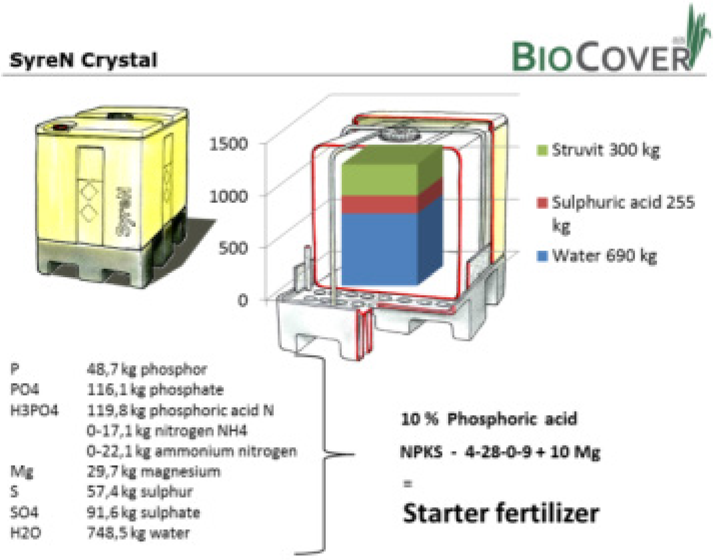
Decrease of P to N

If the requirement is to reduce the P ratio to N, the SyreN Crystal method is used. In the 10 month period where the slurry tanker remains idle, the slurry is loaded batch wise to the tanker. The pH value is adjusted to above 8.0 with SyreN injection of ammonia. Alternatively, CO_2 stripping with a fluid bed can be used and digestrate slurry does not need adjustment of pH. Magnesium chloride is added through the SyreN additive system. The ratio in the slurry between ammonia, phosphorus and magnesium must be 1:1:1. This will cause the slurry P and injected N and Mg to precipitate as struvite crystal and it will build up as a layer inside the slurry tanker. Each batch load is left for 3-4 days with a slow stirring. App. 100 batches are achievable in a season = 2500 m3 slurry.

Depending on the slurry, It is possible to build up 12 – 20 kg P pr. batch load inside the tanker. Thereby up to 2.000 kg P is removed from the slurry. Up to 30% of the total P can be removed in this manner. With the SyreN Crystal method, the P ratio is reduced to N and the application rate of slurry can remain the same, but with a correct N:P ratio. The same volume of slurry can now be used in a local area as the sustainability problem is solved.

A combination of the two methods is possible.

The method



Before and after the precipitation starts, the slurry tanker is measured for weight. The weight increase of the slurry tanker reveals how much struvite is precipitated inside the tanker. The P struvite in the slurry tanker is then dissolved using a 70% sulphuric acid-slurry solution mixed by SyreN system. The ratio must be 3:3:7. This causes the struvite to dissolve into a 10 % phosphorus acid solution or an industry grade fertilizer NPKS of 4-28-0-9 + 10 Mg. This formula is the same as starter fertiliser. With the SyreN system, it can be used directly to replace starter fertiliser for mais and others.

To increase the capacity of precipitation in the slurry tanker, the struvite can be separated through Ekobalance hydro cyclone system. This will change batch flow to a continues flow with up to 3-4 m3 pr. hour. Treatment of up to 15.000 m3 pr. slurry tanker is then possible with a yield of up to 10.000 kg P. If slurry storage capacity is sufficient, the struvite P can be separated by weight in the slurry storage facility and be extracted after slurry application following one to many years.

A unique feature of this method, is that the P is now concentrated in a struvite crystal form, that can be economically transported to- and used in areas with low animal density. Through the SyreN system, the struvite crystal “slow fertiliser” effect is changed to a commercial acid dissolved P grade fertiliser with a very high commercial value. It can be used in all conventional agriculture and facilitate the urgent need for removal of nutrients from the high animal density areas in an efficient and profitable manner.

From human waste to valuable fertilizer

This method and system is not limited to a redistribution of nutrients in agriculture, but can be used at any local sewage plant to precipitate phosphorus. With a co-operation between farmer / contractor and sewage plant, valuable phosphorus can be retrieved from the humane waste system without heavy metals and reused in agriculture without incremental cost for the sewage plants. There are 100.000 slurry tankers in the EU. Deployment of all slurry tankers with above method will close to eliminate import of mineral P to Europe, end airborne eutrophication and save est. 10.000 lives pr. year through reduction in air particle pollution. And it is profitable to do so!

SyreN Crystal

SyreN Crystal – Alternative precipitation to Iron sulphate or aluminium in sewage sludge without investments.

Phosphorus recovery from animal manure

>>>On-site struvite precipitation in pig slurries

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The increasing global population and world food demand lead to a corresponding higher phosphorus (P) demand. Because P is a finite commodity, sustainable and renewable P sources are necessary to ensure continuous supply for current and future generations. The loop could be closed only by recovering and recycling the P lost in both production and consumption chains. Over the past century, P discharge into the environment has grown sharply, the biggest share of it being lost from agro-industrial settlements (agricultural run-offs and animal manure). P losses in run-offs could be minimized by adopting efficient agricultural practices; on the other hand, because manure is a point source, it allows more effective control of P release into the environment.

The amount of P in animal diet could be reduced by avoiding over-enriched feeds; furthermore, technologies should be applied to promote recovery of the unused and excreted P, thus generating a viable source of reusable P. The distribution and amount of P in manure (solids or liquid fractions) depend on the types of breeding (e.g., ruminant or not), nutritional diets, agricultural practices, and post-treatments.

P in pig manure is higher in the solid than in liquid phase, whereas nitrogen (N), the other main element responsible for ground nutrient over-enrichment and water eutrophication, is mainly in the liquid effluent. This is no obstacle to N removal and P recovery because either could be done separately or combined. Sludge can be spread directly to soil depending on environmental permits, presence of available land around farms, and effluent composition. However, strategies combining N and P recovery, for example, via struvite precipitation, would improve effluent control and facilitate management and, because of the higher N content, return a more valuable product than the sludge itself and easy to ship and sell as fertilizer.

If complete N removal is not the target, struvite precipitation could be a feasible technology to remove the surplus P from animal manure, recover it for further reuse, and promote environmental protection by avoiding excessive spread of nutrients.

Struvite precipitation is essentially and technologically simple and encourages on-site treatment rather than shipment of manure to centralized treatment plants. This may be significant in the next decades: avoidance of P waste and the promotion of on-site, sustainable recovery and reuse of P to provide consumers and producers the feasible tools to close the loop locally. However, animal manures are complex matrices, characterized by high organics and solids, high buffer capacity, surfactants, and metals, all of which could hinder P precipitation. Therefore, further research is necessary to determine the applicability of struvite precipitation to different manures and to devise adequate pre-treatments to increase the soluble P content for higher recovery.

P-recovery from manure

>>>Phosphorus recovery from pig/cow manure: a sustainable approach

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Phosphate's cycle has been modified over the last centuries, as a result of urbanization, deforestation and intensification of stock farming and agriculture (Bergmans, 2011). There is no substitute for phosphorus in nature, as the two main sources for phosphate are guano and rocks containing concentration of the calcium phosphate mineral called 'apatite'. It is estimated to be remaining 7000 million tons of phosphorus rock as P_2O_5 in reserves, which can be economically mined. These P resources could be exhausted in as little as 50-250 years, and the price will increase every year (Liu *et al.,* 2013; Münch & Barr, 2001). Having all these data, the actions for the coming 10-25 years must be focus on the recovery of this necessary nutrient, which is phosphorus, rather than its removal.

Phosphorus recovery as struvite ($MgNH_4PO_4 \cdot 6H_2O$) or K-struvite ($MgKPO_4 \cdot 6H_2O$) from waste streams as a renewable source is considered to be an essential and significant breakthrough for assuring a long-term and cost-effective phosphorus source. Europe produces 1.27 billion tons of manure each year. Its discharge in fields contributes to eutrophication and it is directly related to nitrate vulnerable zones and sensitive areas. There is an opportunity to recover phosphorus from manure as struvite, a valuable slow-release fertiliser that displays excellent fertiliser qualities when compared with standard fertilisers. These qualities include its low solubility, nitrogen and phosphorus components and low heavy metal content when compared to phosphate baring rocks mined (Doyle & Parsons, 2002). Note that the process of traditional N-fertilisers' production, "Haber-Bosch", requires a high demand of energy because higher temperatures and pressures are needed. Through struvite recovery, fossil fuel needs for nitrogen fixation can also be saved.

The ManureEcoMine project, with the subtitle "Green fertilizer upcycling from manure: Technological, economic and environmental sustainability demonstration" is an ambitious FP7 European macro-project (Grant Agreement 603744), that involves many international knowledge partners and companies. This project is led by Ghent University (LabMET), and aims at demonstrating manure technologically and economically as a valuable, mineable resource to upcycle manure nutrients to high-end green fertilizer products through eco-innovative technologies, with all economic, environmental and safety/risk aspects integrally managed.

One of its objectives is the sustainable recovery of nutrients from swine manure, due to its concentration of magnesium (around 400-35 mg $Mg^{2+} \cdot L^{-1}$ in cow-pig manure, respectively), ammonium (around 2000-4000 mg $NH_4^+ \cdot L^{-1}$ in cow-pig manure, respectively), potassium (around 2000-450 mg $K^+ \cdot L^{-1}$ in cow-pig manure, respectively) and phosphate (around 250-80 mg $PO_4^{3-} \cdot L^{-1}$ in cow-pig manure, respectively). In this project, the University of Girona (LEQUIA) will be focus on the selective recovery of phosphorus, nitrogen, magnesium and potassium, from anaerobically digested manure, by precipitation of struvite and K-struvite. Technologies of proven efficacy in the wastewater treatment field will be combined in several process configurations to demonstrate their technological and environmental potential at pilot scale for cow and pig manure (Figure 1). Therefore, the precipitation will take part before and after a biological nitrogen removal, recovering struvite and K-struvite, respectively, as a final product (fertilizer). In summary, the results will allow a better understanding of the underlying fundamentals of nutrient recovery (induction time, secondary nucleation, crystal growth and composition) from waste, which will clearly contribute to improve recovery efficiencies and fertilizer quality and increase its market application.

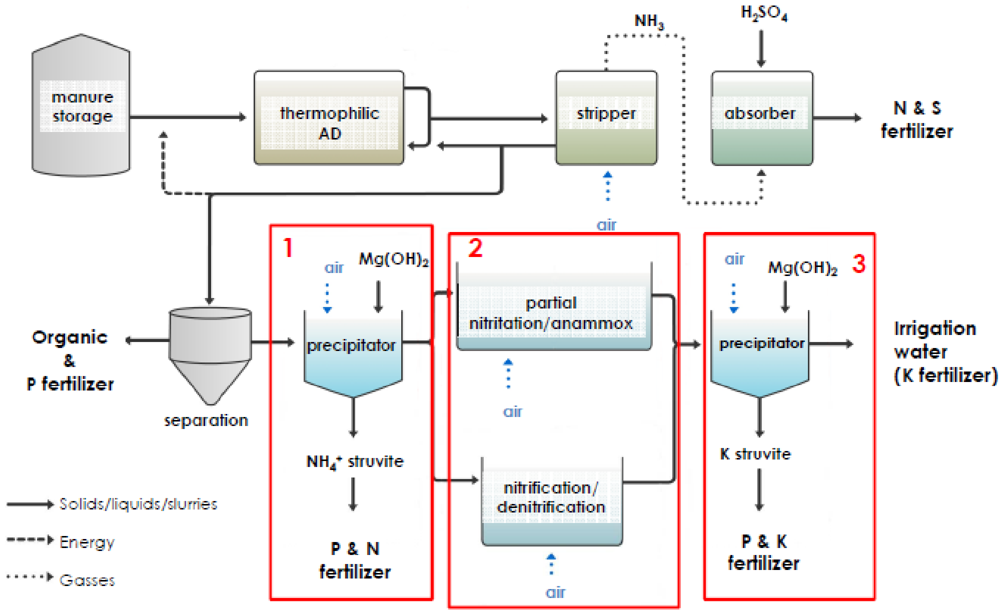

Figure 2. Synergistic coherence of the ManureEcoMine recovery core technologies based on energy recovery (anaerobic digestion) and N recovery (air stripping), with two options indicated for P recovery (1 and 3, struvite and K-struvite, respectively) and residual N removal (2, biological nitrogen removal).

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World phosphorus resources and their use

>>>A vision for sustainable phosphorus use in tomorrow's world

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Introduction

Good leadership requires: a) vision to better mankind and b) importantly, the ability to get stakeholders to buy into the reality of the vision. From the start of life on earth, over 3 billion years ago to 150 years ago, the natural soil phosphorus (P) reserves supplied the demand for this essential nutrient for the needs of plants and animals. Management of the world's diminishing non-renewable P resources is an important challenge for the world today.

Current position

Phosphorus is now in plentiful supply and relatively inexpensive, but this situation will not last. Over 22 million tonnes of P is used annually and peak P mining will occur in the next 25 years. World reserves will last 100 to 200 years and estimates vary. Dates are not as important as the fact that world P is finite. It is not acceptable that world P resources be used up in 300 years (1850-2150), without consideration for future. After about 2040 most P will come from Morocco/Western Sahara and may be vulnerable to geopolitics. Scarcity will impact developing countries most because of low P and high population.

Developed countries and countries with high phosphate rock resources have a special responsibility. Many developed countries import more than double what they export, building up soil P with implications for loss (Figure 1) and eutrophication. The time horizon in farming and politics is short-term, one to five years, but best use of P resources requires long-term vision and leadership. Crop yield is half when P is low compared to adequate, Figure 1 shows an example of the relationship between soil P and yield and also loss to water. Yield increases steeply with small P inputs and then diminishes. In the Republic of Ireland soil P increased ten fold between the 1950's and 1980's in response to fertilizer P inputs that then decreased in response to research and advice to farmers (Figure 2), without impact on production. Photo 1 shows grass on low and medium soil P plots.

Future vision

The vision is to set sustainable targets to progressively reduce use of P rock resources, in the next 25 years, to 10% to 25% of what is used today or as soon as practically possible. The key is to recycle contaminant free P from plant and animal production in an almost closed cycle where little is lost and a minimum needed from P rock. This can be achieved by investment in research into methods and techniques to maximize P recycling and minimize loss. Research will include maximizing uptake from existing soil P reserves, including P in subsoil and in rocks under the soil. The P in world soils is of the same order as minable P rock reserves.

Deep rooting plants and trees can explore P reserves in subsoil for their needs and deposit it in litter on the soil surface for future crops. This P would be more sustainable than mining P rock. Use and breed plants that are most efficient at exploiting soil P reserves; e.g. P use efficiency (PUE) is higher in bananas and potatoes than cereals. Small quantities of soluble P sprayed on growing crops low in P is more efficient than applying P to the soil. Produce good yields of crops low in P and supplement diet with the necessary P rather than high soil P. Reducing animal products in human diet will reduce P needs. One hundred times more edible dry matter can be obtained per hectare from wheat than meat.

In the long-term, 25 to 100 years, it will be necessary to reduce P use to about 1% to 5% of that used today but still compatible with sustainable food production, based on advanced research and technology. This may seem impossible today but will not be in the future.

Conclusion

A multidisciplinary international approach is required to manage limited world P for food security. The best approach is to educate, recover, recycle and change consumption patterns. This will provide challenges and opportunities for health, economics and nature. Aim for flexible P reduction targets that are sustainable and can be updated as new information becomes available.

Photo 1. Forty-year grazed grassland experiment at Johnstown Castle Research Centre Wexford. Plot on left received no chemical fertilizer P between 1968 and 2006 (Morgan's soil test P <2 mg kg^{-1}). Plot on the right received the same treatment as plot on left up to 1998 but received 30 kg P per ha per year between 1999 and 2006 (Morgan's soil test P >4 mg kg^{-1}). Photo 24th April 2006.

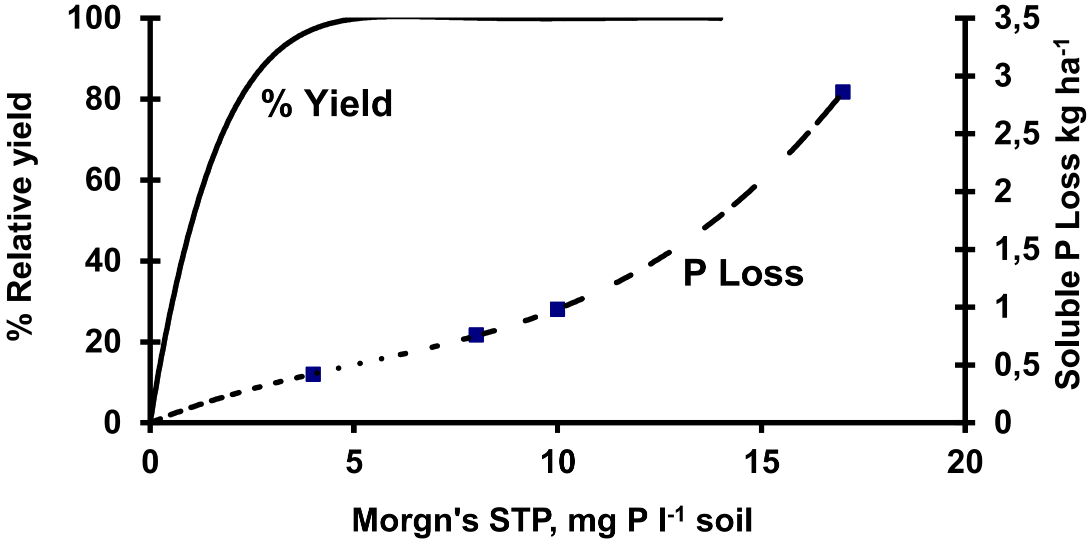

Figure 1. Example of relationship between Morgan's soil test P and relative crop yield and P loss to water (updated from Tunney, 2002; International Association of Hydrological Sciences, publication no. 273:63-69). Morgan's P x 3 = Olsen P approximately.

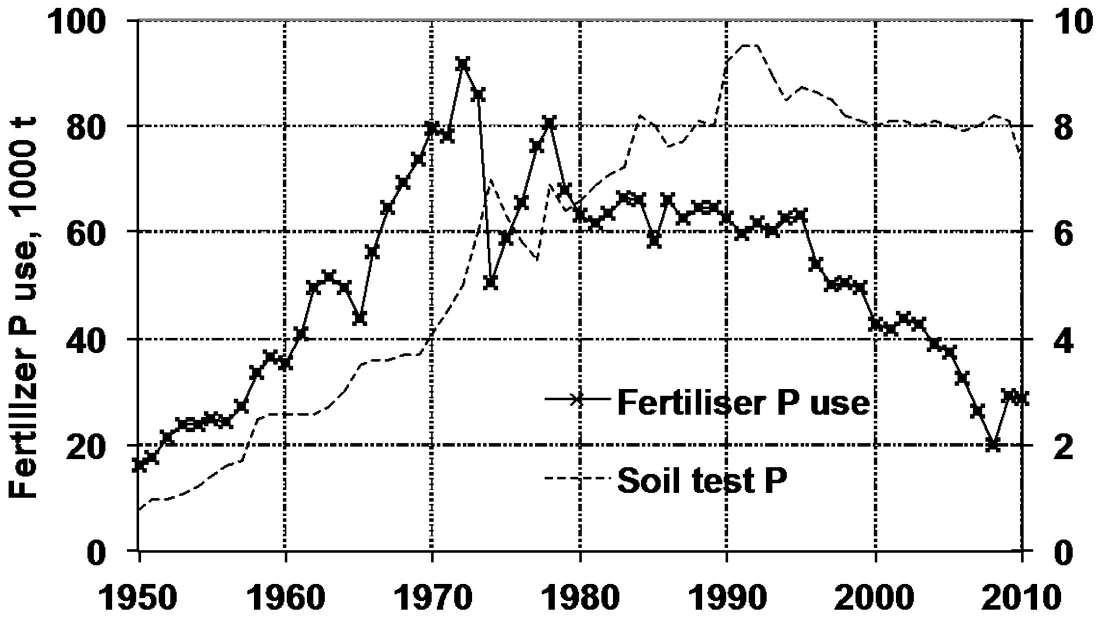

Figure 2. Sixty-year trends in chemical fertilizer P use and average soil test P (on about 50,000 samples per year) analyzed for farmers on the national farm (4m ha) in the Republic of Ireland (updated from Tunney, 1990; Irish Journal of Agricultural Research, 29:149-154).

Phosphorus recovery from urine

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Towards a closed nutrient cycle – phosphorus recovery from urine

Closed nutrient cycle means that all the important nutrients are returned back to the ground instead of nutrients leaking outside the system. The current wastewater treatment is based on an open cycle: crops are grown, food is eaten, defecated, transported by water to be treated (this step is not always taken) and (cleaned) wastewater is released to rivers, lakes and seas. Meanwhile, the nutrients required to grow crops are diminishing from soil and have to be supported by adding chemical fertilizer manufactured from minerals, such as phosphate. This means that the nutrients enter the cycle from one other end and exit the other, instead of circulating within the same cycle [1].

Phosphorus, an important nutrient for plants, can be extracted from phosphate mines. Mining is, often, abusive to the environment and can have serious side effects. According to some researchers, our phosphorus reserves are expected to be depleted in 50–100 years and phosphorus peak to be reached in approximately 2030. The more optimistic estimations reach up to 350 years [2]. Alternative methods for fertilizer sources must be considered, and nutrient recycling is the obvious choice. Especially in cases where raw material is difficult or expensive to extract, using recycled material is often a better option both environmentally and economically.

A renewable and pure form of phosphorus and nitrogen is urine. The majority of nutrients in fecal matters is found in urine (5,7kg N/a and 0,6kg P/a [3]). A lot of the phosphorus in the urine is transformed through wastewater treatment processes to a form that is not bioavailable to plants and/or ends up in water systems causing eutrophication [1]. In the near and more sustainable future this can be avoided by setting up an infrastructure to support the collection of urine from urine-diverting toilets and transportation to a treatment facility.

In addition to the infrastructure, legislative support on national and EU-level is needed in order for urine to be used in commercial farming. The collection, storage and safe methods of urine use as a fertilizer still needs further research. In the future, collection of urine and fertilizer manufacturing offers business opportunities for green economy. For this, cost effectiveness of the whole chain must be further studied.

Urine can be used as liquid or alternatively transformed into a more easily manageable form, such as struvite. Phosphorus in urine can be recovered as a precipitate of struvite (MgNH4PO4•6H2O) by adding magnesium salt under alkaline conditions. Alkaline conditions in the urine can be achieved by storing the urine in a closed container for over two months and seawater and brine are effective magnesium sources [4]. The end result, crystallized struvite is an excellent fertilizer, which can be utilized by households and farmers.

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P in manure management

>>>Manure as low-hanging fruit

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A crisis in phosphorus is not imminent. However, society is not using P sustainably. If that doesn't change, a crisis will come eventually. Currently identified reserves are about 370 times the annual global production. Although this may seem a large amount, phosphorus is nevertheless both a finite resource and one that is absolutely essential for life. But the term "sustainability" implies an indefinite time horizon, and so we are *de facto* not using phosphorus sustainably. Concern for future generations makes it morally imperative that we at least avoid wasting the resource; that is, eliminating losses that are reasonably easily avoidable. We should start transitioning to sustainable practices using measures with the best cost/benefit ratio that are technically feasible and would produce a significant effect on phosphorus use. Recycling of manure as a soil amendment/fertilizer fits these criteria and more. It would be up to authorities to require that almost all animal feeding operations use their by-product on farmland in amounts that suit the agricultural needs and no more. This would require significant changes to practices and infrastructure, but not necessarily new technology. With proper regulatory and financial incentives this could be implemented in a reasonable time frame, certainly within a decade or so. Such an action would be within the scope of government authority. Market forces alone cannot bring this about because the costs of environmental damage and future depletion are externalized (i.e. not borne by the stakeholders). Further justification for taking this step would be provided by a number of other benefits: Water pollution from nutrient runoff that degrade our lakes, streams, and coastal ocean areas would be greatly reduced. Agricultural soil would improve its water- and nutrient-holding capacity, and the organic material would improve its physical properties, reducing erosion losses, and thus increasing agricultural phosphorus use efficiency. Furthermore, if a high proportion of animal waste were recycled, the sensitivity of the food system phosphorus use to dietary quality (i.e. amount of meat in the diet) would be greatly reduced. This would offset the trend to increase meat eating that occurs with alleviation of poverty and which otherwise increases the per-capita phosphorus usage. Converting to effective manure recycling would still not be an easy thing to do; it would just be the best thing to do. That makes it the low-hanging fruit of phosphorus sustainability. Since other conservation measures are harder to do or lack many of the benefits just described, a public commitment to manure recycling will be an indicator of our will to move society towards phosphorus sustainability by taking the first significant step along the way.

Sustainable phosphorus use in agriculture

>>>Towards an optimal choice of phosphorus fertilizers based on soil phosphorus status and crop demand

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The challenge for a sustainable and thus optimal use of P in agriculture is closing the P loop by matching soil P supply and crop demand to fertilizer choice. P fertilizers should be defined as either primary mineral P, as well as organic P or recycled P from secondary waste and residual streams. Currently, specific knowledge to sustainably close this loop is lacking or not available in a form that can be used in agricultural practice. Closing this loop entails an answer to the following structural questions:

- **How to define and maintain an optimal P status of soil?** Defining the P status of a soil is important as studies show that soil P status is more important for crop P uptake than P fertilization. In addition, during a growing season low soil P cannot be compensated for by adding (excess) P fertilizer. An accurate prediction of the soil P status leads to a better usage of P reserves in the soil and is the basis of sustainable fertilizer use, not only concerning dose but also concerning the form in which P is added, timing and placement.
- **How to measure the soil P status in a routine way that does justice to the complex processes that dictates P availability?** In our vision defining the soil P status by using the Intensity – Quantity – Buffer Capacity concept is an effective stepping stone towards achieving these goals. Intensity is the P directly available for crop uptake. Buffer capacity is the resistance of the soil to a change in P intensity and Quantity is the amount of P associated with this buffering and can thus become available over time. This concept can bridge the gap between scientific knowledge and agricultural practice as it does justice to the complex soil processes, can easily be used to define and interpret routine soil analyses and gives information on expected fertilizer response.
- **How do different fertilizers work in the soil, both on the short and long-term?** An accurate characterization of the short and long term functioning of P from fertilizers is important to establish and maintain an optimal soil P target level. Matching the fertilizer type and characteristics to the concepts of soil Intensity, Buffering and Capacity can ensure optimal P supply to crops while minimizing P loss to the environment.
- **How to characterize the fertilizer value of the different secondary P- sources?** This is especially important to optimally embed the use of secondary P streams from agriculture (e.g. bio-slurry from digested manure, compost) or non-agricultural sources (e.g. struvite from sewage water treatment plants or bio-ashes) in agricultural practice.

Answering the previous questions enables the development of decision support tools for fertilizer dose, type, timing and placement that does justice to the P supply from the soil, maintaining sustainable P levels in the soil (ensuring long-term P supply and minimal environmental loss), crop demand and potential yield.

Phosphorus in light of its declining availability in an emerging bio-economy.

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The emerging bio-economy encompasses all sectors that produce, process or use biological resources in whatever form, focusing accordingly on food and non-food biomass. The latter includes feed, energy sources and industrial raw materials. In the raising global demand for biomass, land and water are commonly seen as the major limiting production factors. However, based on Liebig's law of the minimum, the scarcest resource is determining the over-all potential of biomass production. In this context, phosphorus as a very limited non-renewable resource that is essential for biomass production may play a crucial role. Experts report that global phosphorus reserves might be depleted in alarmingly 50 to 100 years, others assume a depletion only after several hundred years. Whatever the case may be, phosphorus extraction will become more difficult and more costly in the future and the precautionary principle compels improving the efficient use of phosphorus and "re-negotiating" its allocation priorities in biomass production. Accordingly, the research agenda has to focus on:

1) Phosphorus allocation for biomass production

Biomass will be increasingly used for non-food produce. In the light of phosphorus scarcity, however, questions will be raised, such as, is it justifiable to use phosphorus to produce bioenergy today and thereby hindering food production in the decades to come? Hence, research has to identify the degrees of phosphorus efficiency in the production of the different types of biomass. Also, alternatives have to be explored: There may be means others than biomass, such as solar power or wind, to more efficiently and sustainably produce energy.

2) Phosphorus allocation for food production

Phosphorus allocation has to be discussed not only in food and non-food biomass production, but also regarding what food should be produced, i.e. which are the most phosphorus efficient food products? This is firstly a question of food energy production (calories), in which major staple crops like rice, maize or potatoes have to be compared to others like sorghum or millet. However, in light that there are one billion calories-undernourished, but over two billion micronutrient-malnourished people, the question arises whether micronutrient-dense food products should be given relative priority in production. Furthermore, the consumption of animal products is increasing with globally increasing income, urbanization and dietary changes. As animal production has a high share on the phosphorus footprint, phosphorus use and dietary behavior have to be harmonized.

3) Phosphorus use efficiency

Biomass production has to improve its phosphorus use efficiency through improved crop varieties to stretch the phosphorus availability as long as possible. Most important is, however, a strong focus on recycling and reusing phosphorus, especially from solid and liquid waste. Furthermore, cascading and coupled uses of biomass, and, hence, of phosphorus have to be explored. Finally, as one good management practice over-fertilization with phosphorus – known from horticulture – has to be avoided.

The finite availability of phosphorus as essential resource for biomass production broadens the bio-economy research agenda. Research-based strategies with clear allocation and priority settings are needed to optimize the use of phosphorus in agriculture and horticulture.

Phosphorus: Its future importance in directing horticultural research

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Phosphate is a vital macronutrient for horticultural crop production -- yet its use in intensive vegetable production systems is often abused by either insufficient application resulting in low yields (Grubben et al. 2014) or excessive application resulting in reduced profitability and environmental damage (Yan et al. 2013). The horticultural sector globally needs research now to come to grips with these contrasting positions to justify its P needs for the future, when competition among various agricultural sectors for declining stocks of this mineral resource will increase.

Tomatoes are among the top ten agricultural commodities produced globally in terms of economic value (FAOStat 2013), and the combined value of all vegetables, fruits and flowers produced by the horticultural sector exceeds many billions of dollars a year. This alone would justify priority allocations of phosphate to this sector. Yet fruit and vegetables are also vital for human health not only in combating malnutrition but also in significantly reducing deaths from cancer and cardiovascular diseases (Keatinge at al. 2011, Oyebode et al. 2014). As there are now approximately twice the number of malnourished humans compared with people experiencing energy-deficient diets, it makes strategic sense to ensure that horticulture is a priority sector for phosphate allocation. Future phosphate distribution will need to be seen not only in terms of ensuring food security for the planet but also in helping to deliver effective nutritional security with suitably diverse, balanced diets for good human health.

Food safety and its implications for P supply to horticulture is a key research topic for the future. The horticultural sector is presently dominant in peri-urban environments in the developing world owing to the short shelf life of fresh fruit and vegetables. As a result, smallholder horticultural production often employs compost, organic fertilizer and irrigation water from urban sources contaminated with either human and animal sewage or heavy metals. Research to solve this key food safety concern is vital if health gains from increased fruit and vegetable consumption are to be realized.

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The Pursuit of the highest value

>>>Community resilience platform

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In the United States of America; I was privileged to contribute to the establishing of a Community Resilience System which was completed in September 2011. The objective of the CRS is to provide a platform for the mitigation of Natural, Man-made Disasters and Economic Dislocation. The project was co-sponsored by Oak-Ridge Laboratories and FEMA (Federal Emergency Management Agency). Over one hundred and fifty citizens participated in the development of the CRS. It is a Sharepoint Platform designed for local and regional communities. Its core provides for the organization of people, processes, and resources; to produce a new normal for any given community or region recovering from disaster. It would be the best tool to utilize for the management of any chemical or mineral resource.

The potential for the CRS is of great value! Although there are reservations. The long-term objective for P sustainability should not be the prime VALUE-FOCUS; it should be the   people. The late Peter Drucker, Management Consultant pointed to a problem with people who struggled with meaning in their work within institutions. He identified this problem as ACIDIA (ACIDIE). If this problem is not brought to a moderate solution, the premium of the sustainability of P can reach a very dangerous tipping point.

Phosphate resources and their use

>>>The "right to know" the geopotential of phosphate resources.

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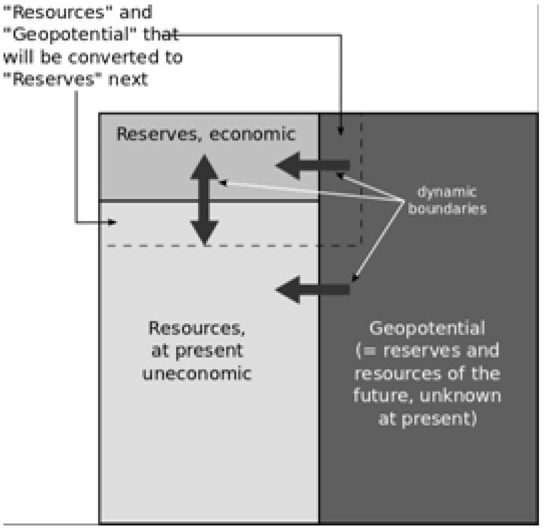
Facts:

1.) Over 80 % of world phosphate production is used as nutrient in fertilizers, the remainder in various industrial applications.

2.) While most commodities fulfill functions which can be substituted either by direct substitution or by indirect substitution via new technologies the nutrient elements are essential and irreplaceable. For potassium and nitrogen there are practically unlimited and exploitable resources (in air resp. sea water) but enriched resources for phosphate are not.

3.) Within the “Total Resource Box” (see Figure) three categories of resources exist: reserves (known and economic), resources in sensu strictu (known, but not economic) and geopotential (unknown so far). The categories are dynamic and so are the boundaries in-between. What are resources today can be reserves tomorrow. Consequently the ratio of reserves to production is **not** the lifetime of reserves but merely a snapshot of a dynamic system. The lifetime ratio can serve as early warning indicator. For phosphate the situation is very comfortable. The ratio is considerably higher than for many metals and has increased during the last 25 years, contrary to metals’ ratios that stayed within a spread of equilibrium values which satisfy mining companies’ planning scope.



Visions:

1.) A peak phosphorous inevitably will occur at some time in the future, but this will not be soon. The phosphorus production curve is and will remain demand driven (as a function of prices and needs) for a long time, not supply driven (example for the latter: oil production in the North Sea). Nonetheless it is important to reduce waste of phosphorus, not only to conserve the non-renewable resource, but importantly because of the environmental effects of phosphorus losses. There is a considerable potential for increasing phosphorus use efficiency in the supply chain.

2.) Wider knowledge on resources will make the general public aware that the reserve/ production ratio is not the lifetime of reserves and the true meaning of a demand driven production curve has been mostly understood, helping to avoid wrong political recommendations and actions.

3.) Since phosphorus is essential and unsubstitutionable it can be argued that the public is entitled to know the size of the Total Resource Box progressively (Fig.) (“right to know”). There is, however, worldwide no authority endowed to accomplish this vision. Reserve data are produced by private or state controlled mining companies. For companies, reserves are their working inventory. They, therefore, normally only gather data and estimate reserves for as many years of production as the cost associated with obtaining the data and their preference for business planning justify.

It seems appropriate to focus on the geopotential as the source of future reserves rather than on dynamically developing reserves. The vision is that there be established maybe under the auspices of the International Union of Geosciences (IUGS) or initially anchored at EuroGeoSurveys (Association of the European Geological Surveys) a solidly funded international standing committee which regularly analyzes the geopotential as done in Project 156 “Phosphate deposits of the world” of the International Geological Correlation Programme from1977 to 1984.