Responsible phosphorus use

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 fertiliser. **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.

Making the best use

In this vision, we make sure that our vital nutrients are used in the best possible way. **In fertiliser 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.

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Towards phosphorus security for a food secure future

Substantial progress has been made with respect to research and awareness on the global phosphorus challenge in the last five years alone. The 2008 fertiliser 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**.

Fuzzy boundaries and contested agendas

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, fertiliser 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).

Goals for phosphorus security

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 fertilisers 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.

Backcasting to the future

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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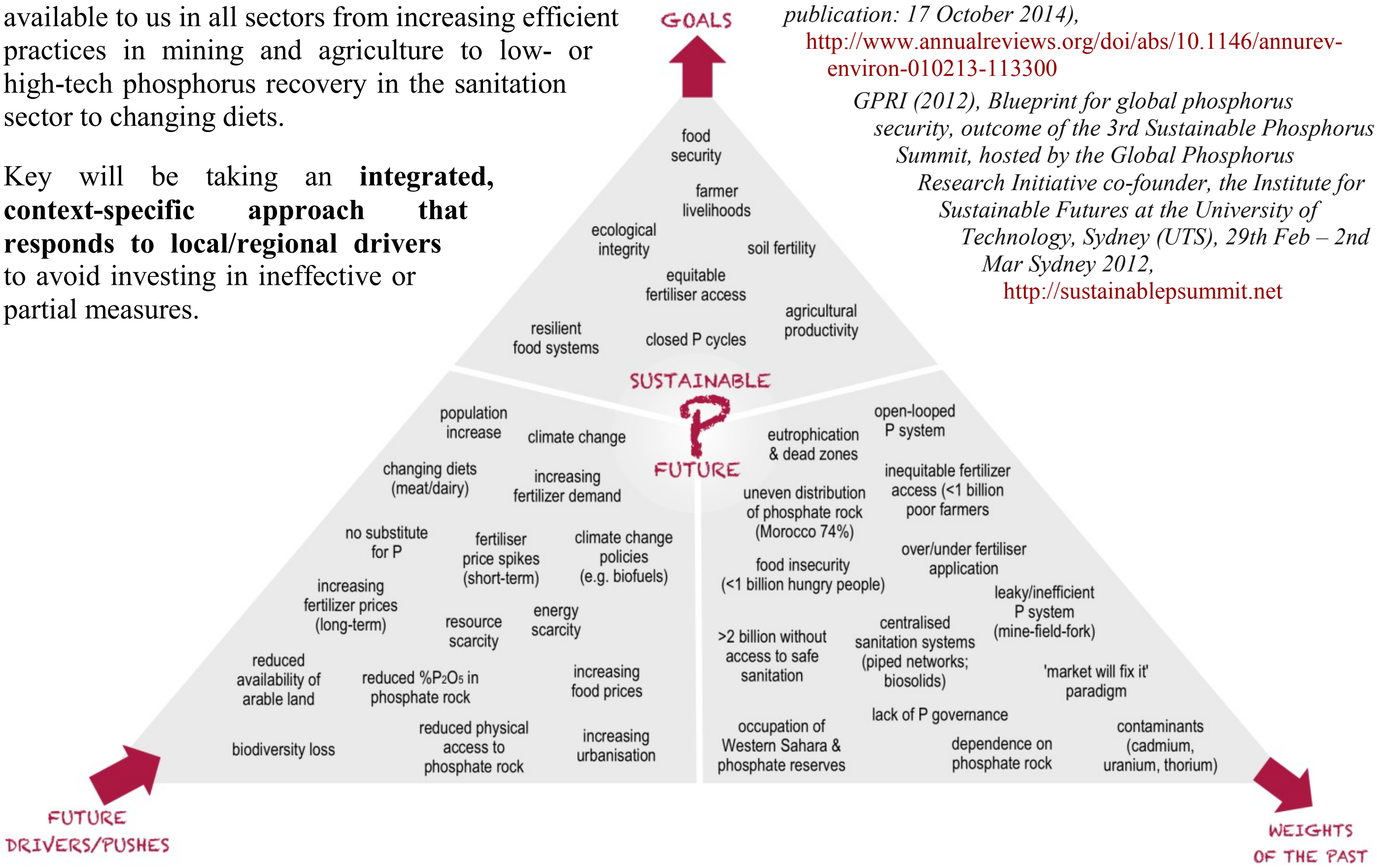

Figure 1: Defining sustainable phosphorus futures are informed by weights of the past, future drivers (mega trends) and aspirations (future goals).

Putting a phosphorus bounty on society's bad behaviour

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.

Consumer behaviour

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**. As the global population grows so too does its P-demand. This is compounded by the relatively large population increase of the middle class whose P-demand continues to grow, largely due to **increasing meat consumption** (Childers et al. 2011).

The responsibility for reducing the human P footprint falls upon the **individual whose lifestyle must be changed**. Policy makers, industry, scientists and

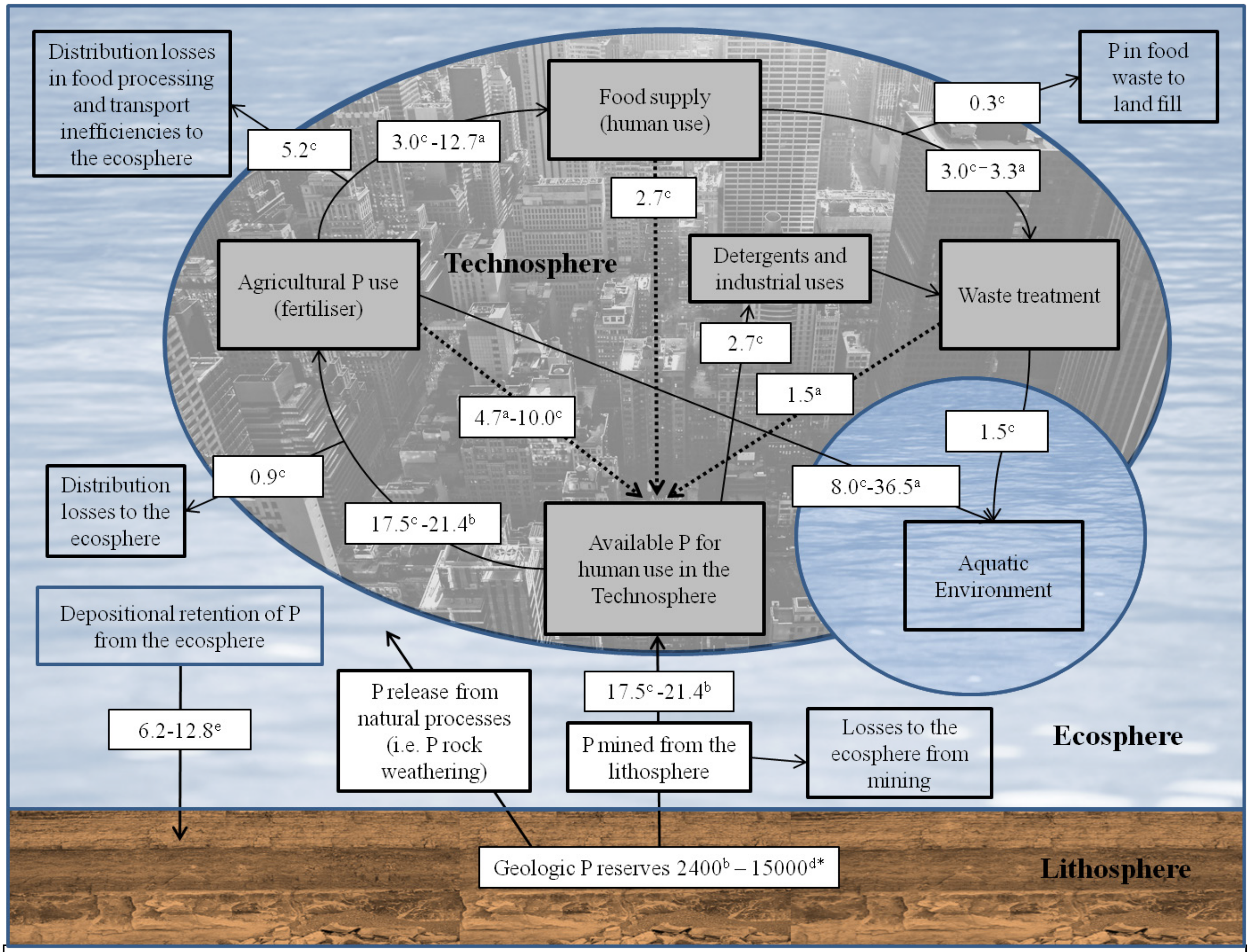

*Figure 1. The global P cycle. Solid arrows represent flows of phosphorus (P), dashed lines represent recycling of P within the technosphere (grey area). Figures in boxes represent estimates of P flows in million tonnes (MT) year-1 (*estimated P reserves in MT). Superscripts correspond to the data source 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, 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).*

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).

Individual choices

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 information

Food labelling regulations do not currently 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 measures for reducing the **impacts of dietary P on both human health** (serum P may be a predictor risk factor of mortality, cardiovascular morbidity and bone metabolism, Onufrak et al. 2008) and environmental health (Sutton et al. 2013).

In the US, 44% of the bestselling groceries contain P additives and these 'high-P' products are cheaper (León et al. 2013). In the future, policy may promote lower P diets by restricting P additive use by the food industry. By extrapolating from data on diets in the USA (Uribarri & Calvo 2003) this measure would achieve a reduction of 1.2-2.5 MT P/year at the global scale.

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.

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A vision for sustainable phosphorus use in tomorrow's world

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 microorganisms, animals and plants.

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. **World reserves will last 100 to 200 years or more 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 about 300 years (1850-2150), without consideration for the 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.

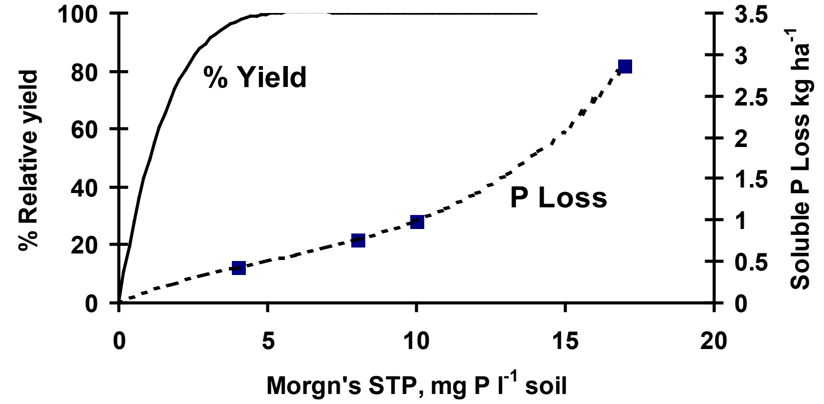
Developed countries and countries with high phosphate rock resources have a **special responsibility** to help others. Many developed countries import more than double what they export, building up soil P with implications for loss (Figure 1) and eutrophication. The time horizon in farming and politics 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 fertiliser 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 30 years, to the order of 10% to 25% of what is used today or as soon as practically possible.



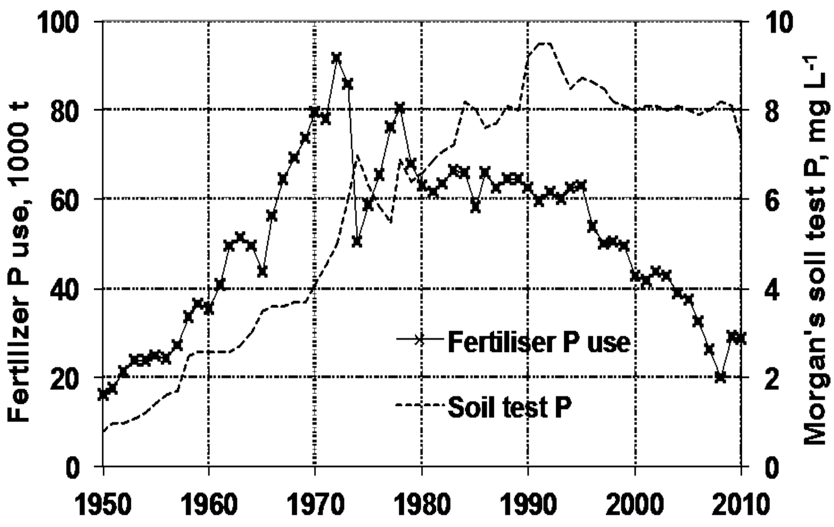


Figure 1. Example of relationship between Morgan's soil test P and relative crop yield and P loss to water (updated from Tunney, 2002; International Association of Hydrological Sciences, publication no. 273:63-69). Morgan's P x 3 = Olsen P approximately.

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).

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.

- **Small quantities of soluble P sprayed on growing crops** low in P may be more efficient than applying P to some soils.
- 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, 30 to 100 years, it will be necessary to reduce P use further to a fraction of that used today but still compatible with sustainable food production, based on cooperation, advanced research and technology. This may seem impossible today but will not be in the future.

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 but less than known minable P rock reserves. The P reserves in sea water and sediments are higher.
- **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.

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.

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Cities as key components of sustainable food-system P cycling

In 25 years cities will 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 fertiliser 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 fertiliser 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.

Greening the city and local recycling

This local recycling in agriculture also creates a buffer capacity for urban food security to global energy and P prices shift. Urban consumers are 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 fertiliser and, as such, cities redesigning waste management have made it possible to **create high-quality and concentrated P fertiliser** for export further away.

Appropriate local solutions

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 fertiliser products are picked up to be redistributed to users.

Thinking city food systems

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.

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Policy

P stewardship for food and fuel: would you rather eat or drive?

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 fertiliser to grow**. Even next generation microbial-based biofuel requires a great deal of aqueous nutrient inputs.

These fertilisers 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**.

Food prices and fertilisers

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 fertiliser 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 growing biofuel production can undertake to help meet this goal.

Crop choices

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 labelling 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.

Phosphorus recycling

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 fertiliser. 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.

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Key challenges for future research on phosphorus in Europe

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 (fig. 1).

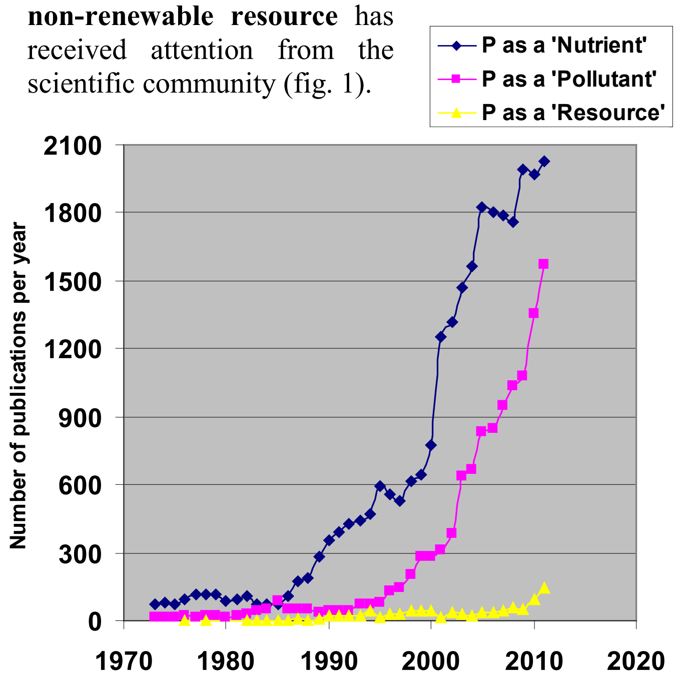

Figure 1: Number of scientific publications per year on Phosphorus (Web of Sciences)

Coordinated P management is needed

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).

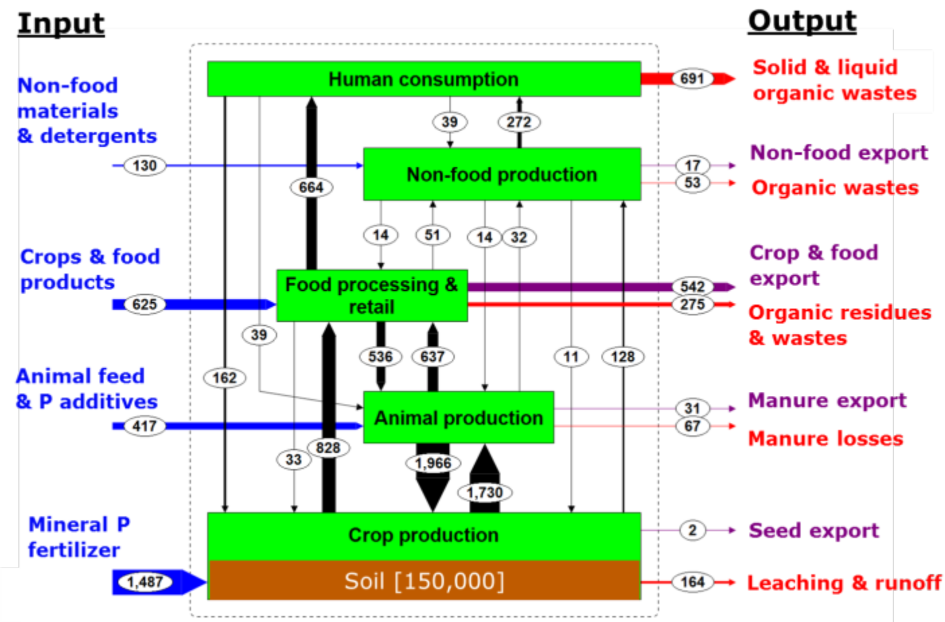

Figure 2: Phosphorus flows in the food production – consumption chain of the European Union (EU-27) in 2005. Inputs are shown on the left-hand side, output and losses on the right-hand side. Flows are indicated by arrows, pools and stocks are indicated by boxes. The size of flows and pools are presented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

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.

Innovation

Innovations can make Europe less dependent 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.

Questions

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).

Framework and indicators

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**.

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The governance gap surrounding phosphorus

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.

Question of concern ?

That phosphorus prices rose 800% in 2008 is common knowledge. Yet, neither P nor fertilisers 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 fertiliser 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 fertilisers 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?

Governance ?

The extraction of nitrogen from the atmosphere (Haber-Bosch process) has been the most important factor in the provision of fertiliser that has fuelled 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**.

Action plan

An action plan with several stages is required:

- **global conference** including stocktaking and suggestions for sustainable practices
- **non-partisan monitoring and regulatory program** on extraction of phosphorus rock set up by the UN
- **global convention** erected whereby milestones in sustainable practice are set up including limits to extraction and minimum levels of reuse
- new generation of **best practices** that optimize the quality of waste systems (liquid and solid) be set up in order to promote reuse
- **economic instruments** developed whereby wasteful practices are taxed and reuse promoted.
- **communications** strategies initiated to help make the P question more household and better understood.

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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)[1]. 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[2].

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[3]. 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**[4].

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[5].

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[6].

Sewage treatment works remain the largest source of P in English rivers[7]. 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.

Other smaller sources of diffuse pollution including septic tanks and misconnections are receiving further attention [8, 9].

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[10].
- **Tap water dosing, dishwasher detergents and food additives** deserve consideration as regards possible further source control[11].
- **Increasing bio-solids recycling to land**, reducing reliance on artificial fertilisers, may be possible[12].
- **Food waste** is another source where reduction and recycling would improve sustainability[13].
- Thinking more radically, **more sustainable human diets** could reduce this major source of sewage-P[14].

Ecological recovery from eutrophication can be lengthy and uncertain. Our experience from the Norfolk Broads suggests lakes can take 2-3 decades[15].

In addition, **climate change** and **population growth** present future risks from increased nutrient loadings and eutrophication impacts [16, 17].

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

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Phosphorus' declining availability in an emerging bio-economy

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:

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.

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.

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.

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Consideration of quality hierarchy in sustainable nutrient management

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 fertilisers are judged by their grade or plant availability. Considering the global view, fertiliser 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. **Fertilisers**, 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.**

Grades of nutrient quality

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.

Nutrient management planning strategies

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**.

Learning from energy and waste policies

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 **global nutrient management would take a step towards more sustainability**.

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Recycling

We don't need to reinvent the wheel!

"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 specialized society decides what action is proper or not.

Real needs

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 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 handful 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?

Reconnecting value chains

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 fertiliser 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 fertiliser "Berliner Pflanze".

Vision for a closed cycle

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.

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A mature market for recycled nutrients in 2030

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*.

End-user demand

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 fertiliser 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.

There are several other factors 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.

Long term vision

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.

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What are you waiting for ? Use the phosphorus in the wastewater stream

Europe (EU27) imports 92% of phosphate rock and derivatives for agriculture (1), equivalent to 1 250 000 t of phosphorus per year (2).

More than 50% of the phosphorus in the sewage sludge from the wastewater stream is lost in landfills, road construction similar (3), which corresponds to 12% of the phosphorus provided by mineral fertilisers and feed additives in agriculture. **The phosphorus lost in the wastewater stream in the EU27 could substitute phosphorus imports for fertiliser and feed worth over 0.2 billion €** (in equivalent TSP prices).

Technologies now operational

Recovery technologies **running in pilot or full-scale** - see Figure, (4) 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 (5).

Direct replacement of phosphate rock with sewage sludge ash in the fertiliser 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.

Authorities and companies

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

- **ICL Fertilisers** 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 proposed 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 market (6).

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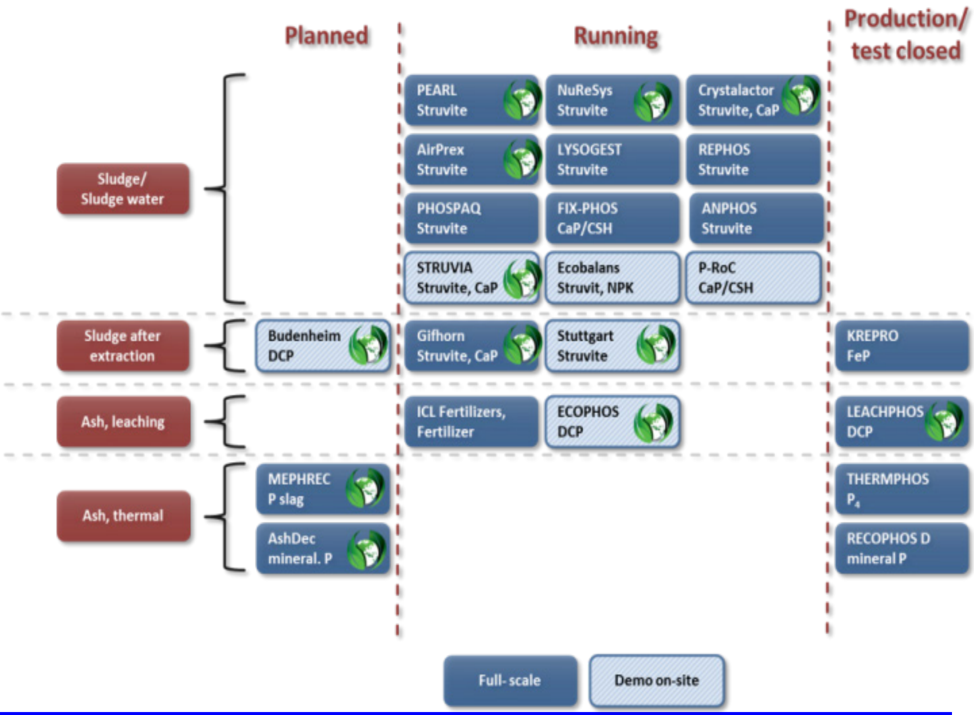

Regulating phosphorus recovery from sewage ensures a net benefit?

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.

Locally intelligent regulation

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 **P- 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 and economics

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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Agriculture

Understanding the bioavailability of new and old phosphorus to crops

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 of P already present in our soils, existing fertilisers and manures, and in new or recycled P products.

Soil-crop-fertiliser systems differ

In P fertilization recommendation systems throughout the world, soils are generally treated as the "same", but **the P bioavailability varies strongly due to variation in the amount of P that has built up in soils and the soil physico-chemical conditions vary strongly**. In any one year, most crops take up a small proportion of their P from the P applied in the form of fertiliser 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 are still insufficiently understood.

Also, **new P-recycling technologies** produce products for which fertiliser 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 in Europe and **current mineral P fertiliser use is about 4 times less than it was in 1980** (EU27, International Fertiliser Association statistics, 2012).

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 experiments that can be used to determine the long-term bioavaiability of P in different soils (photo courtesy of Rothamsted Research ©).

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.

Precision soil and fertiliser management

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 soils 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 improved environmental quality.

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Legacy of phosphorus: agriculture and future food security

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:

1. Residual phosphorus

About 10-20% of the P fertiliser 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 fertiliser 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).

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 fertiliser, **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 fertiliser 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 China can reduce the amount of P fertiliser 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 fertiliser 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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Prevent incidental losses of phosphorus by erosion from agricultural fields

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.

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).

An unwanted phenomenon from both sides is **incidental loss of phosphorus by erosion from agricultural fields** to the surface water system.

"Incidental" soil erosion events

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.

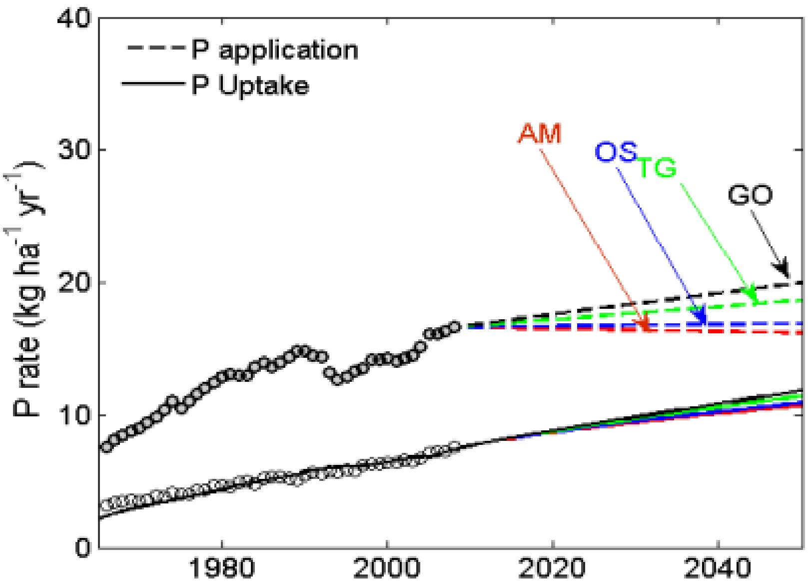

Fig 1: Trends of annual P application and P uptake in cropland for the period 1965 to 2050 on the entire globe according to the four MEA scenarios (15). Long-term FAO data (16) and simulation results are illustrated by circles and lines, respectively. Shaded and open circles refer to P application and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

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 not common practice in the European Union or more worldwide.

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Sustainable livestock: barriers to precision feeding of ruminants

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

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 traditiona l 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].

Phosphorus removal and recovery

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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Unlock phosphorus from soils based on molecular level mechanisms

An agricultural practice without input of phosphorus (P) fertiliser 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 fertiliser.

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.**

Phosporus forms in soils

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.

Molecular understanding

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** taking 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.

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Sustainable P use in agriculture: towards an optimal choice of fertilisers

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 fertiliser choice.

P fertilisers include primary mineral P, organic P as well as recycled P from secondary waste and residual streams.

Agronomic knowledge needs

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 fertiliser. 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 fertiliser 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 fertiliser response.
- **How do different fertilisers work in the soil, both on the short and long-term?** An accurate characterization of the short and long term functioning of P from fertilisers is important to establish and maintain an optimal soil P target level. Matching the fertiliser 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 fertiliser 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 fertiliser 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.

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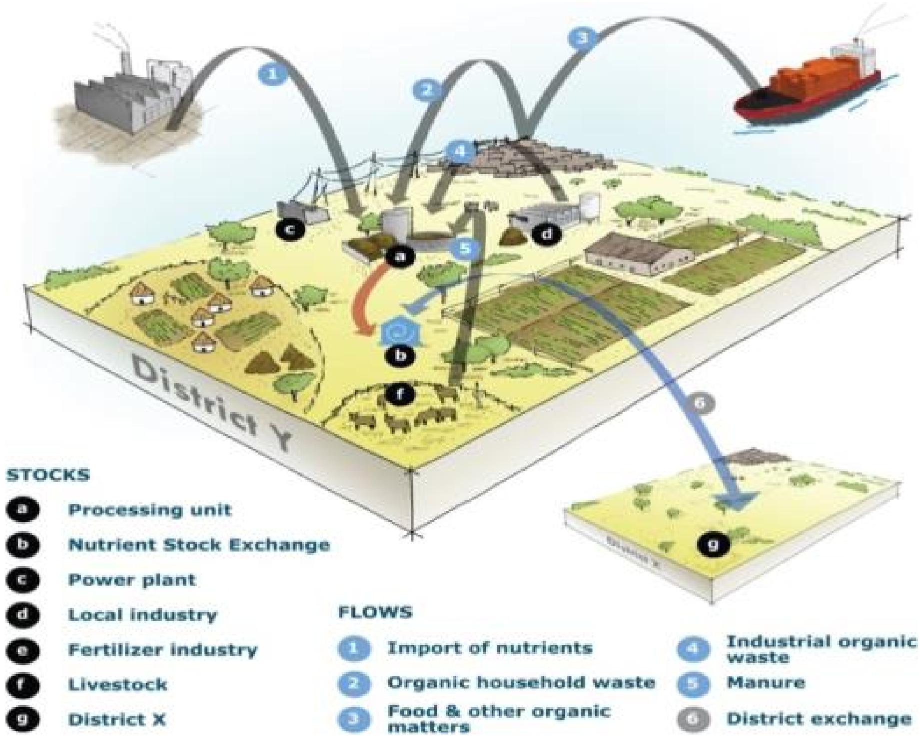
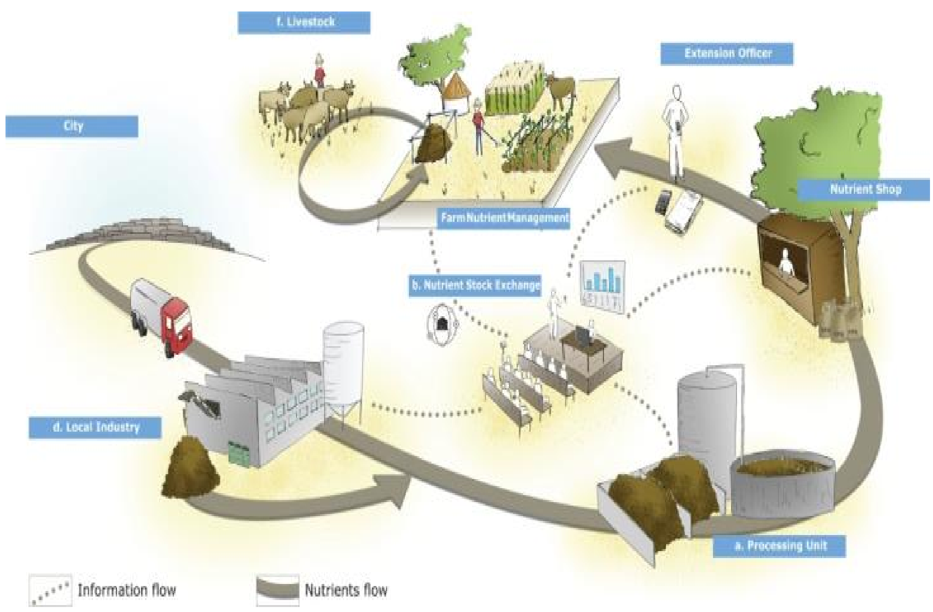
An integrated approach to nutrient availability and use efficiency



Above: Elements of the proposed nutrient cycling mechanisms at the district level. Below: Information and nutrient flows in the proposed nutrient cycling mechanism of the Fertile Ground Initiative.



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 fertilisers and organic manures with other aspects of agronomic management (seed, crop protection, soil and water management).

Fertile Grounds Initiative

The Fertile Grounds Initiative (FGI) aims 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. he 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.

Eight components

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 fertiliser products.
3. **Brokerage**: nutrients in natural resources and fertiliser products are given a value and a commercial agreement is arranged between suppliers and clients.
4. **Site-specific fertiliser 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.

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Manure as low-hanging fruit

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.

Manure recycling

Recycling of manure as a soil amendment/fertiliser 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).

Other benefits

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.

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How to promote sustainable phosphorus fertilisation

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.

Target soil P content

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 (see below).**

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.

(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

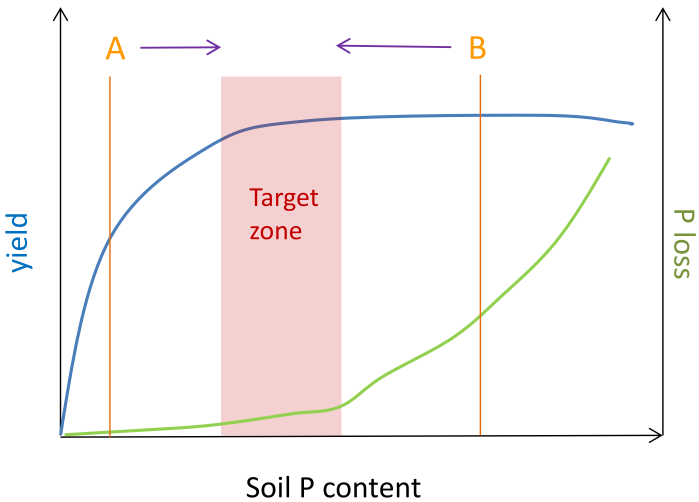

Figure 1. Yield and P loss evolutions at increasing soil P content, with an optimal agro-environmental target zone

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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Agenda

- 10-12 September, Basel, Switzerland, P-REX summer school (students, researchers, young professionals): **Implementation of P-Recovery from Wastewater - Why and How?** *www.p-rex.eu*
- 11 September 2014, Leeds, England **Resource Recovery in the Water Industry** *www.aquaenviro.co.uk*
- 17 September, Kobyli na Morave, Czech Republic **P-REX Regional Workshop** *www.p-rex.eu*
- 23-24 September, Warsaw, Poland **Greener agriculture for a bluer Baltic Sea** *http://www.balticcompass.org/_blog/gabbs/post/a-greener-agriculture-for-a-bluer-baltic-sea-stakeholder-conference-2014*
- 7-8 Oct., Manchester, UK, **8th European Waste Water Conference**. Including: wastewater as a resource, nutrient factory. *www.ewwmconference.com*
- 4-5 December, Florence, Italy: 1st International **Conference on Sustainable P Chemistry** *www.susphos.eu/ICSPC*
- 6-8 December 2014, Lisbon, Portugal **Nutriplanta2014** *www.congressos.abreu.pt/Nutriplanta2014*
- 5-6 March 2015, Berlin: 2nd **European Sustainable Phosphorus Conference** *www.phosphorusplatform.org*
- 23-25 Mar 2015, Tampa, Florida: **Phosphates 2015** (CRU) *www.phosphatesconference.com*
- 4-8 May 2015, Morocco: **SYMPHOS** (dates to be confirmed) *www.symphos.com*

Nutrient Platforms

Europe: ***www.phosphorusplatform.org***

Netherlands: ***www.nutrientplatform.org***

Flanders (Belgium): ***http://www.vlakwa.be/nutrientenplatform/***

Germany: ***www.deutsche-phosphor-plattform.de***

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