Global sustainable phosphorus management: a transdisciplinary venture

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Phosphorus (P) is a key human, animal and plant nutrient and an important ingredient of many non-agricultural products. However, phosphorus is also a critical pollutant and is unequally used and distributed in the world. The Global Transdisciplinary Phosphorus Management (Global TraPs; 2010–2015) project organizes a multi-stakeholder discourse involving key actors at all stages of the supply–demand chain with differing viewpoints, knowledge and concerns to guide and optimize future P use. Focusing on the sustainability of future phosphorus use, Global TraPs will bring together 'practice' (producers, traders, users of phosphorus, sewage-plant operators, recycling companies, public agencies, NGOs etc.) along with those facilitating their efforts (such as policy makers and development organizations) and 'science' (researchers from various disciplines with an interest in phosphorus) to work towards a common aim, expressed in the guiding question of the project: What new knowledge, technologies and policy options are needed to ensure that future phosphorus use is sustainable, improves food security and environmental quality, and provides benefits for the poor?

Keywords: Environmental quality, food security, Global TraPs project, policy options, sustainable P management.

Introduction

TRANSDISCIPLINARITY (Td) (according to the Zurich 2000 definition[1]) is seen as a specific methodology of efficient utilization and a way to relay knowledge from practice and science to the management of complex sustainable transitions. As human activity has approximately tripled Earth's phosphorus input flows, resource phosphorus is in need of global, biogeochemical cycle management to avoid unwanted critical developments on different scales. The Global Transdisciplinary Phosphorus Management (Global TraPs) project explores whether this can be done efficiently using a transdisciplinary process.

Following a Td perspective, the first part of this contribution provides a comprehensive picture of phosphorus from a biogeochemical cycle and substance/flow perspective. This section provides a science-based view of the risks and vulnerabilities linked to poor phosphorus management and resulting in low efficiency of phosphorus use. The second section describes how scientific knowledge can be used in processes Td and how mutual learning about the sustainable transitioning of phosphorus management can take place among key stakeholders on a global scale.

Why phosphorus? essentiality, finiteness and dissipation

Phosphorus (P) is the 13th most abundant element in the Earth's crust[2]. It is a very reactive and dissipative element. As P cannot be fixed in the atmosphere, it is not recycled (on a short-term scale) and primarily as a result of soil erosion is disappearing into the oceans. Phosphorus represents an interesting case of resource management, a key component in the pillar of information (DNA) and energy (ATP) molecules of the cell, and is non-substitutable for all living organisms. Furthermore, no P substitute exists for food production. Phosphate rock (PR) deposits are non-renewable on a human time scale, and high-grade P ores are finite. In nature, P atoms are not disappearing but are transferred from rock formations to other compartments that make them theoretically accessible but presumably at unacceptably high costs that necessitate critical sacrifices.

Phosphorus as a pollutant

Too much phosphorus in the environment causes eutrophication resulting in algal blooms with dead zones and fish kills; 400 such systems with dead zones have been identified thus far[3]. Polluted aquifers also affect the quality of drinking water. In assessing the critical load of phosphorus, we should distinguish between the geogenic and the anthropogenic layers of the phosphorus cycle. A cornerstone of marine life, phosphorus is released by weathering and transported by runoffs and rivers to the sea. We also have freshwater systems such as Alpine lakes that have very low natural phosphorus content and are highly sensitive to additional phosphorus input. Therefore, it is difficult to define standards for aquatic systems with respect to phosphorus loads. According to

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Dutch environmental standards, P concentration of about 0.1 mg Pl^{-1} may be considered critical for eutrophication and ecosystem health[4].

We should note that – given the high-performance extraction of P from wastewater in many developed countries – some studies showed that certain life cycle analysis evaluations of P in detergents (i.e. STTP) provided better results than the main substitute, zeolites[5]. In both seawater and freshwater, too much phosphorus may also be seen as a threat to terrestrial systems. Plant ecologists state that the excessive use of 'P fertilizers is unsustainable and may cause pollution'[6]. One critical issue is that phosphorus has been identified as a cause of biodiversity loss because high phosphorus loads 'favour a few species that would competitively displace many other species from a region'[7,8].

Sedimentary phosphate rock can include loads of heavy metals, toxic elements and other precious elements that induce long-term critical contamination of soils by phosphate fertilizers. With respect to cadmium in phosphate fertilizer, 60 mg Cd/kg P_2O_5 and above are the amounts expected to result in critical long-term soil accumulation[9]. However, the bonding of heavy metals as well as nuclear and other elements with phosphorus also offers the potential of co-mining, given that economic extraction technologies are developed.

(Economic) Scarcity, geographical distribution, and food/phosphorus security

Policymakers and the public have become concerned by a statement that P will become a physically scarce commodity: 'the global reserves may be depleted in 50–100 years' and 'global peak in P production is predicted to occur around 2030'[10]. This statement was based on applying a symmetric Gaussian curve to the production curve of PR. The total area below this curve was equal to the sum of the up-to-date previous PR production plus the 2009 USGS data on world reserves (which was16 Gt PR), referred to as the ultimate recoverable resource (URR). Based on this assumption, a peak in 2030 followed by a rapid decline has been predicted. This method of predicting resources (which does not consider whether there would be a market for the supply at the peak) became popular when M. King Hubbert predicted the peak of the US oil reserves in 1971 with remarkable precision.

Scholz and Wellmer[11] showed that the Hubbert curve approach might not be applicable for predicting the world's resources of P reserves. We will present three arguments here.

The world P reserves are not static

Resources and parts of the geopotential may become reserves by new (less costly) technologies of mining (including underground mining), new data on exploration etc. We speak about the feedback control cycle as a regulator of mineral supply security[12] (Figure 1). For instance, USGS's 2009 data on P reserves of 16 Gt PR increased to 71 Gt PR in its 2011 data. Given the 2011 production data of 191 Mt PR, about 2 Gt PR will be consumed in 10 years. Thus, there is no reason why we should reach peak phosphorus in 20 years, if approximately 4 Gt PR of the 67 Gt PR that the USGS[13] has documented would be depleted. Similarly, we might question why we should run out of P in 100 years if 20 of the known 67 Gt PR will be mined (given that approximately 200–250 Mt PR would be used annually). This also holds true for the USGS data, which mix PR ore and phosphate concentrate. If the USGS P reserves data are adjusted and accounted in marketable phosphate concentrate (PR-M) with about 30% P_2O_5 as reserves, we will face a decline to 58.5–67 Gt PR-M[14].

Geological data on resources have been ignored

Currently, the 'static lifetime' of P-reserves, which is defined as the ratio between identified resources and annual consumption, is on the magnitude of 300 years[13]. This variable can be perceived as a rough, early-warning indicator but not as an estimation of future phosphorus availability. However, resources might become reserves in the future if they can be accessed at feasible costs; this could be the case for the phosphorus of the Western Phosphate Field (WPF) in the US. Since 1904, 70 mines have operated in the WPF. Of these, 49 were underground operations, but they have been shut down due to high costs. Here, some reserves became resources. Conversely, the WPF is presumably the largest phosphate-ore body on Earth. The WPF was explored intensively in the 1970s, as the US government was interested in uranium resources, and the data on P resources may be considered a byproduct. Nevertheless, we can identify 825 Gt PR ore with an average concentration of 24.6% P_2O_5 (ref. 15). However, only 29% (i.e. 239 Gt PR) is located above 5000 feet (which has been the approximate depth of the current deepest coal mining in Germany). Here, the potential for future technology development (i.e. higher extraction efficiency for underground mining and technology for deeper mining in the mid-term future) suggests that this ore body alone might provide an annual supply of a magnitude of 200 Mt for a timespan on the magnitude of 1000 years. In this case, we have to consider that the WPF ore is of interest only after 300 years, when all the current reserves have been consumed. We should also note here that a PR price increase, ceteris paribus, is not an event that would endanger the average world citizen. The annual production of PR of 200 Mt marketable PR concentrate amounts to US$ 20–40 billion per year. This is less than 1% of the annual global energy costs[14]. The world would not collapse as a result of a 10-fold price increase for PR. To

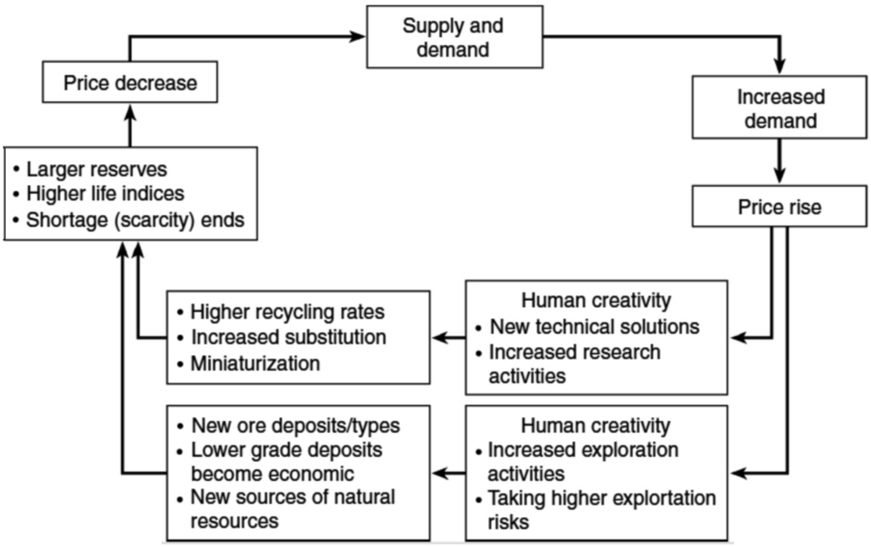

Figure 1. Feedback control system of mineral resource management[36], which functions in unbiased markets if costs remain feasible.

express this in other terms, the feedback–control cycle would not reach a price limit, although many small-scale farming operations could suffer severe economic setbacks as a result of such a price increase.

The world's phosphate-rock market is a demand market but not a supply market

The Hubbert curve may have some validity for predicting reserves from a certain mine ore limited area (such as the US oil fields or the Guano of Nauru[16]) given that any amount offered is consumed by the market. However, this is not the case; reserves that may deliver 58.5–64 Mt PR-M have been identified[14], and there will be no arbitrary increase in demand (for instance, we may exclude a quintupling of the current annual P use). With more-efficient agricultural methods, better recycling, future exploration etc. any agricultural model would predict that we are likely to have PR for many centuries. Therefore, we can conclude that the Hubbert curve is the wrong mathematical model to use in this regard, as it may be applied only under specific constraints and thus may not properly model the dynamics of supply, given changing demands for the next century and beyond. The Hubbert curve, however, might work for some supply markets where all that is offered will be bought by the market. We should note that the previous Hubbert curve application[10] used the USGS data on reserves as an estimate of the URR (which means that, with a reserve estimate of 16 Gt PR in 2009, zero success in further exploration was assumed). If the Hubbert curve is based solely on the curve fitting the historic production data (without an estimate of URR), then the method provides a severe underestimation of the reserves by a factor of 10 (of the 58.5 to 64 Mt PR-M documented by USGS in 2014)[11,14].

Recently, concerns have emerged about the high clustering of (documented) reserves in a few countries, in particular, Morocco. As mentioned above, a recent calculation by Scholz and Wellmer[14] showed that the USGS estimate of the Morocco reserves is given as marketable phosphate-rock concentrate, whereas many other countries' data are given as PR ore. Thus, the share of Morocco's reserves is between 78% and 85%. However, we should acknowledge that other countries have roughly doubled their resources from 10 Gt to 20 Gt PR ore or concentrate within the last five years (providing a static lifetime of about 45 years, in a worst-case calculation, without taking into account Morocco's reserves). We are facing similar situations with other essential minerals or metals. Canada and Russia, have 81% of the global potash reserves. Furthermore, for assessing geopolitical risk not the reserves but usually the production (Morocco produces about 13% of the global rock phosphate) are essential for assessing the risk of geopolitical distribution (Figure 2).

Figure 2 includes a common estimate of geopolitical risks, i.e. the Herfindahl–Hirschman Index (which is a geographical concentration index that does not consider the lifetime, i.e. abundance versus physical shortage) and the Worldwide Governance Index, which evaluates, among other factors, political stability, absence of violence/terrorism, and regulatory quality[17]. Clearly, there is an opportunity here to consider a thought experiment about what the case might be if Syria rather than Morocco had these reserves; doing so can help us to see that mitigating the risk of supply by diversification (e.g. via recycling), stocks etc. can help to mitigate the geopolitical risk.

Inefficient mining, processing and use

Given that P is a pollutant and that human activity has tripled the world phosphorus flows[18], the prevailing

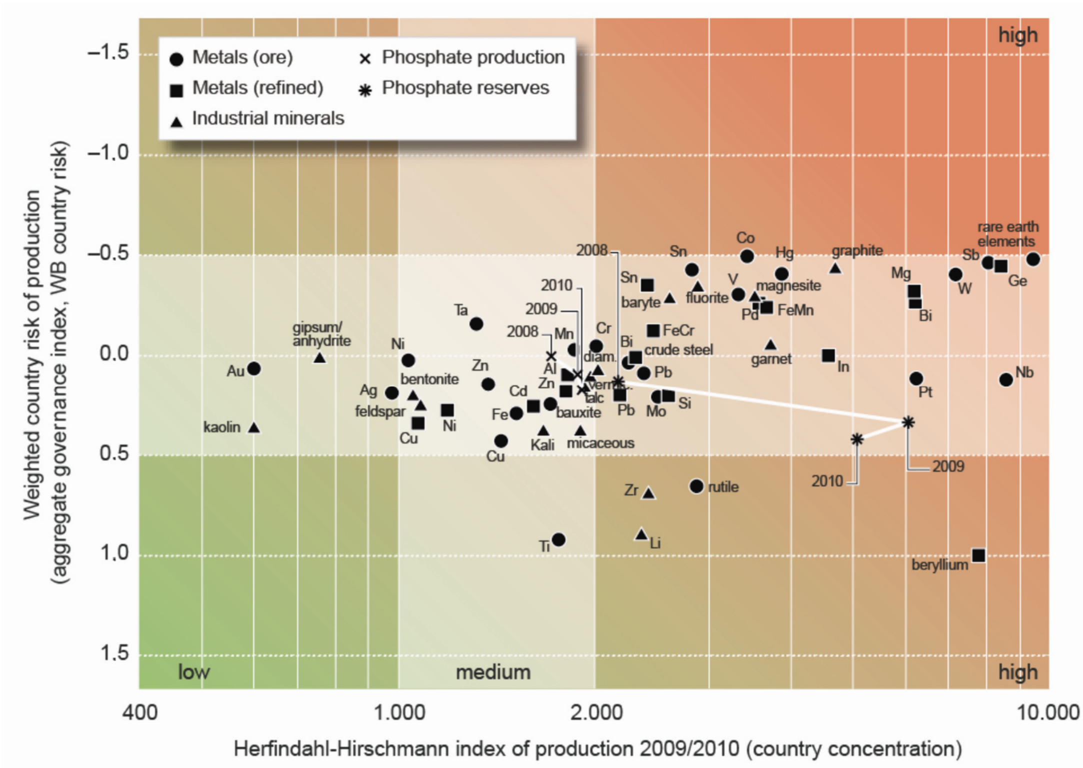

Figure 2. Supply risks of metals and minerals measured by the HHI index (*x*-axis) and the Weighted World Governance Index (WWGI, *y*-axis) for production and for phosphate production and phosphate reserves[11], based on USGS data.

Table 1. Summary of IFA[34] and IFDC[35] recording of losses of phosphorus from different activities (per million tonnes phosphorus)

	IFA (reference year 2009/2010)		IFDC (reference year 2009, 156 PR Mt production recorded by USGS)	
Losses	Operated (Mt P)	Losses (Mt P)	Operated (Mt P)	Losses (Mt P)
Mining	30.5 (25 recorded)	5.5 (18%)	36.5	3.5 (9.5%)
Beneficiation	25	4 (16%)	33.4	10.0 (30.2%)
Processing	20.8	2 (10%)	18.8	(10–15%)
Fertilizer applied	17.8	–	10.9	–
Total losses	–	11.5 (38%)	–	10.9 (40%)

inefficiency of phosphorus use is a critical issue (Table 1). In order to understand this, we take a supply–demand-chain perspective (Figure 3) and distinguish three ‘phases’.

Phase 1 is the industrial stage, from mining via beneficiation to processing of fertilizer mostly by wet processes or the production of yellow phosphorus (for industrial and technical uses) by thermal processes.

Phase 2 is the complex use phase. In this article, we focus on the agricultural use (accounting for more than 90% of phosphorus use) including (synthetic) fertilizer use, feed additives found in different types of animal manure fractions and manure management, phosphorus runoff losses and flows, food waste between farm and table, i.e. post-harvest handling and storage, followed by critical food-use practices (in industrial processing, distribution/trading and cooking), particularly food littering or losses; and insufficient recycling of human excreta. However, we subsume also the unintended ‘virtual flows’ of phosphorus, for instance in heavy industry, under this phase.

Phase 3 is the dissipation and recycling phase and includes waste and sewage management. The losses at the mining and beneficiation stages are absolutely critical; for instance, 5–7 tonnes of phosphor gypsum are produced from one tonne of diammonium phosphate (DAP) fertilizer. Thus, the demand for technological innovation, just in fertilizer production with respect to process and by-products, is huge. At least 40% of the phosphorus mobilized in mining and processing is lost, in the sense that it is excluded from the value chain.

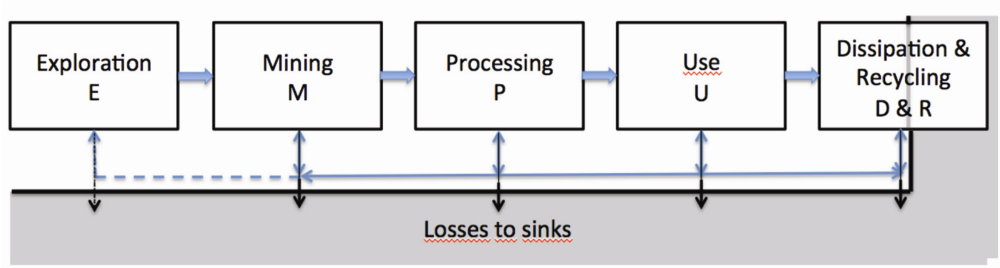

Figure 3. Supply–demand chain.

Looking at P from a biogeochemical cycle-management perspective, virtual P flows of phosphorus, for example, in heavy industry, should also be considered. Matsubae and colleagues[19] provided an illuminating analysis of Japanese P flows showing that P flows in steel-making and other industries account for 137 Kt phosphorus, compared to 285 Kt in fertilizers and 163 Kt in food and feed. Some slag, resulting for instance from steel production, shows about the same concentration as igneous PR[20,21]. Thus, we may consider that sustainable biogeochemical substance-flow management in the case of phosphorus requires going far beyond agricultural use.

If we consider efficiency in Phase 2, we might gain a similar picture[22]. Much insight can be gained simply by answering the question, 'How much phosphorus is mobilized to produce the food we consume?' If we take a simple functional perspective, phosphorus uptake is the 'target variable'. Based on human uptake/excretion of 1.2 g P each day, we get an annual uptake of a little more than 3 Mt P for the global population. Compared to this, we have an input of the magnitude of 15 Mt P in fertilizers, 10 Mt P in manure[23]. This is supplemented by an high uptake of P from pastures including naturally weathered P (which partly reappears in the manure[24]), about 1 Mt P from feed additives, 1 Mt from food waste, 1 Mt from human excreta, plus 1.5 Mt estimated input from weathering and from some other sources such as fertilization by slurry. Thus, we are mobilizing annually a magnitude of 40 Mt P for a human uptake of 3 Mt P in food. A recent analysis of the 15 EU countries provided some more-favourable data, with a phosphorus consumption of 4.7 kg P per year per consumer, of which 1.2 kg P are consumed and only 0.77 are recycled[25].

The assessment of these losses and their environmental, economic, and social impacts (e.g. by soil degradation) is a significant societal and scientific challenge. This is especially true in regard to runoffs and soil erosion, both requiring monitoring and assessment, in central European regions. Globally, runoff and erosion from cropland account for an annual loss of about 10 Mt P[24], compared to the approximately 15 Mt annual phosphorus input from synthetic fertilizers.

How much phosphorus is released into aquatic environments, contributing to eutrophication, depends on various factors? An interesting question to consider is what share of phosphorus effluent is coming from point sources (e.g. industry, households and wastewater treatment (WWT) plants) and what share is coming from diffuse sources (e.g. agriculture, atmosphere). Figure 4 presents the results for different European countries on a hectare level.

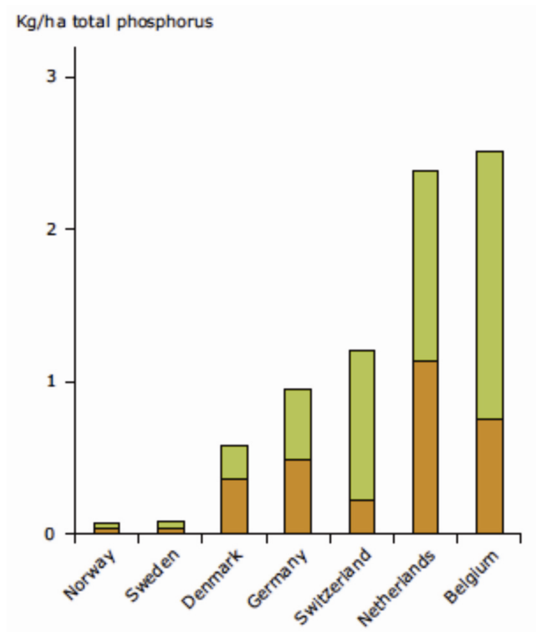

Figure 4. Source-apportioned annual load of phosphorus in large river catchments[37], lower-stack 'diffuse', and higher-stack 'point' source emissions.

We should note that the global use of phosphates in *detergents and cleaners* as well as toothpastes, etc., decreased from 1.2 to 0.8 Mt P between 2007 and 2012 (ref. 26). However, the situation in regard to such data is not transparent. While several large detergent producers are going to (widely) withdraw P from laundry detergents generally[27], we suspect that P in detergents might be critical in developing countries and megacities without sewage systems that extract phosphorus from wastewater.

From an anthropogenic phosphorus-flow perspective, the type of diet, i.e. how much meat is consumed, is a critical issue affecting phosphorus flow. Estimates for the urban transition in China, which has been linked to dietary changes, note that the 300 million people migrating to cities has caused an increase of about 10% more phosphorus use for China. Thus, we can expect a growing use of phosphorus by 5–10% due to lifestyle changes. In addition, the increasing demand of biofuels for vehicles may be subsumed under lifestyle changes and cause an increase in P demand – ceteris paribus – of 3–5% (ref. 24).

Food is wasted after agricultural production, and the amount of waste is estimated to be 15–95 kg per year per capita in Europe compared to low-waste regions such as Sub-Saharan Africa and South/Southeast Asia with 6–11 kg (ref. 28). The main reasons for food losses in the 'southern regions' are the difficult climatic conditions and the lack of cooling, storage, packaging, transporting and processing technologies. Additionally, there are many reasons for food losses related to the food industry, to retail markets, and to consumers, who, especially in northern regions, tend to consume only close-to-perfect goods and thus waste edible food, demonstrate careless purchase planning, and are more likely to be able to afford to waste food dollars. Therefore, industrial and retail food management requires a closer analysis, as approximately 1 Mt P that could be used as animal feed or composted is estimated to be wasted in these regions.

Besides food (and other solid waste which is not considered here), wastewater and manure treatment are key issues in sustainable phosphorus management. On a global scale, we are facing two dislocation processes. Global urbanization with new WWT structures has significantly reduced the agricultural reuse of human excreta. In addition, the industrialization of agriculture with large-scale poultry, hog and beef production sites has hampered the use of manure. On a global scale, the amount of recycled P from manure is difficult to access, as we are facing heterogeneous and sometimes rapidly changing practices.

In EU15 countries, 0.174 Mt P of 0.248 Mt P influent are found in sewage sludge (70% efficacy[25]), with an efficiency of 85% for industrial wastewater. However, the efficacy worldwide is certainly lower. On the European level, 49% of sewage sludge is applied to agricultural and forestry uses, 11% is incinerated, 20% is composted, and 20% is disposed of in landfills[29]. Finally, struvite production (i.e. extracting phosphorus by crystallization from the aqueous phase of human excreta and sludge) may be an interesting solution, as it works well as a fertilizer and the extraction of P from the sludge supports the sludge drying process and is thus economically favourable. Several of the described options of P recycling have strengths and flaws. Direct recycling (e.g. to the fields) is criticized due to public health and environmental concerns. In Europe, a thermal, incinerator-based track might be identified for P recycling and struvites and similar products. In considering different recycling technologies, a comprehensive evaluation that acknowledges both the economic and the multiple environmental aspects has been lacking.

A difficult situation also exists with respect to manure; in the US, for instance, only 5% of the cropland is fertilized with manure[30], but it is also noted that 48.5% of US phosphorus fertilizer is derived from manure, which suggests an intense grassland application. A challenge for future research and phosphorus management is that the percentages of the macronutrients nitrogen, phosphorus, and potassium differ between cow, swine, and poultry slurry/manure and require not only (costly) transportation but also sophisticated processing in order to meet the demands of the soil and crops. Both sewage and manure have attracted attention for energy production. Here, anaerobic digestion appears to be superior to incineration, as the remaining biowaste seems easy to use.

What is transdisciplinarity?

Td[1] may be considered a third mode of conducting scientific research that complements disciplinarity and interdisciplinarity, whereas, interdisciplinarity refers to the integration of concepts and methods from different disciplines. Td integrates, additionally, different epistemics (i.e. ways of knowing) from science as theory and its practical application by stakeholders. Td starts from the assumption that scientists and practitioners have expertise in different kinds of knowledge, and both sides may benefit from a mutual learning process. Thus, the co-leadership of scientists and practitioners, based on an equal footing at all levels of the project activities (i.e. the umbrella project, the nodes and the case studies), is needed to ensure that the interests and capacities of theory and practice are equally acknowledged.

Td processes target the generation of knowledge for a sustainable transition of complex, societally relevant, real-world problems. Td processes include joint problem definition, problem representation, and preparations for sustainable transitions by practitioners and scientists. The beginning of this paper, for example, may be considered an interdisciplinary review of anthropogenic phosphorus fluxes along the supply–demand chain which has been constructed in a Td process[22]. The identification of the key actors responsible for the flows may lead to an actor-based material-flow analysis[31] that may become a key element of the multi-stakeholder discourse (Figure 5). In Td processes, the stakeholders are not only identified but also incorporated in the process of problem definition (represented by the guiding question in the first paragraph, which came out of the second Global TraPs workshop, http://www.globaltraps.ch/).

In general, Td processes provide improved understanding of the problem and robust orientation towards policy options or business decisions for practitioners. Td processes serve in capacity building for all participants and facilitate consensus development, for instance, about which options for changing the most important flows should be explored. In Td processes, participants benefit

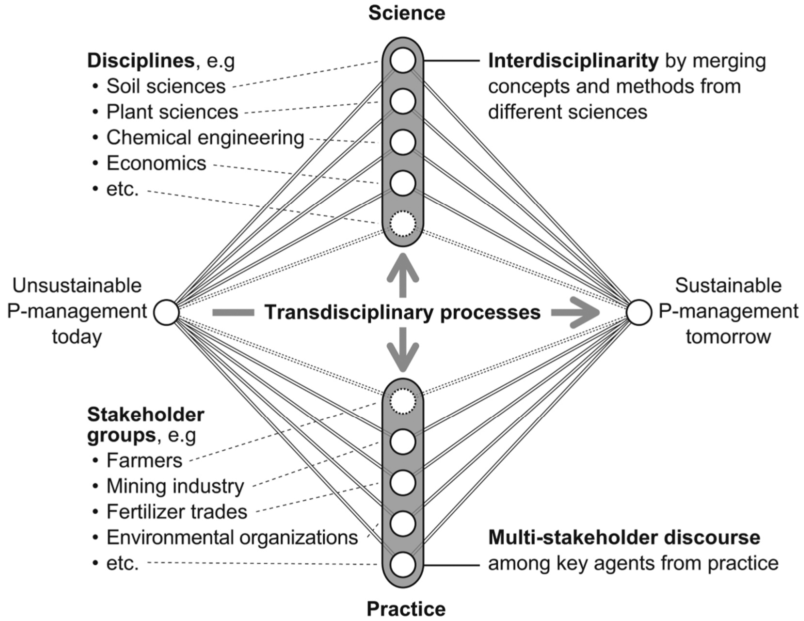

Figure 5. Illustration of transdisciplinary processes (see ref. 38, p. 120).

by gaining in-depth insights into the dynamics of complex systems and the mechanisms of sustainable transitions. The mutual learning between science and practice is the basic principle of a Td process. Scientists and practitioners work on an equal footing, and co-leadership of the Td project is a key property. In principle, we distinguish among three types of agents:

- A legitimate decision-maker from a practice orientation.
- A representative from a university or public science institution.
- People concerned about the problem to be considered or about the decision made by legitimate decision-makers.

All agents remain in their roles and positions. This holds true, in particular, for scientists, whose task is to provide a problem representation that is as close to reality as possible, which may be utilized by all key actors, independent of their interests and values. Td processes run for a limited timespan (the Global TraPs project was planned for the period from 2011 to 2015, but was terminated at the end of 2014 as there had been not sufficient funding for the last two years; the UNEP–GPNM positively voted on a proposal to provide a more permanent structure to the Td process launched by Global TraPS). In order to allow for learning, a Td process has to provide a protected discourse arena that allows for thought experiments and unproven ideas. As key actors from industry and business are participating in the Global TraPs, special care must be taken to consider only issues of a precompetitive nature[32].

How was the Global TraPs project organized?

The Global TraPs project was organized on three levels (Figure 6). Level 1 is called the 'Umbrella Project' and is provided by the project leaders, who take responsibility for the overall project. Strategic decisions were made by the Steering Committee, which had, as do all levels and subprojects within the overall project, equal representation by practitioners and scientists. The project leaders and managers were supported by the Knowledge Integration Unit (KIU). This group provided methods for Td discourses, as well as the representation, evaluation and transitioning of complex structures.

Level 2 is the node level and corresponds to the five nodes of the supply–demand chain shown in Figure 3. Additionally, a Trade and Finance Node exemplifies a cross-cutting issue, since financial actors play important roles across all nodes, from financing mines and fertilizer plants to microfinance mechanisms for small-scale farmers to venture capital for new recycling technologies in microfinance. There were also Td coordinators who facilitate the collaboration between science and practice and the overall knowledge integration.

Approximately, 200 people representing the theoretical and practical institutions were affiliated with the project and the nodes. As is typical for any Td project, the first phase of the Global TraPs Project, which involved joint problem definition, was time consuming; but this was accomplished during the second workshop by defining the critical questions. These questions served to identify knowledge gaps, environmental impacts, social equity, technology options, policy means, etc. Each of the six Nodal groups authored a chapter of the book *Sustainable*

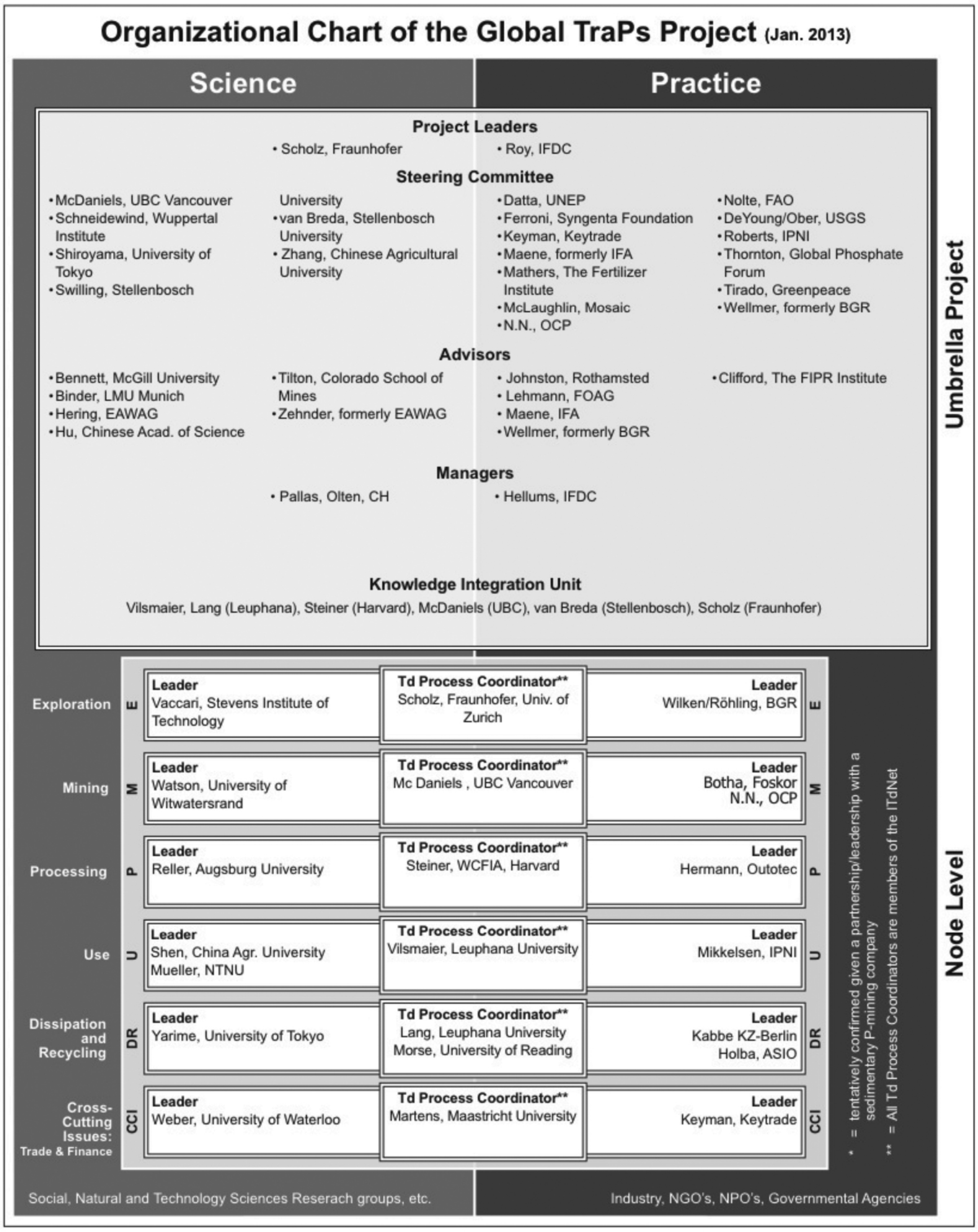

Figure 6. Organizational chart of the Global TraPs project (http://www.globaltraps.ch/tl_files/bilder/about/OrgChart_2013_01_26.pdf).

Phosphorus Management: A Transdisciplinary Roadmap[33].

The discussion on peak phosphorus and the validity of the data on Morocco's mines were disputed topics in the first two workshops. With the help of key experts from industry, science, and public institutions, such as the USGS, it was possible to take a comprehensive view of geological data, resource economics, mathematical modelling, price dynamics, etc. Furthermore, several mining companies as well as the USGS provided insights into how they had arrived at figures related to reserves and resources. This revealed (for two large companies) that the data recorded by the USGS might represent somewhat conservative estimates. Two comprehensive scientific papers emerged from these activities and provided a suggestion that the USGS data should be reported in marketable phosphate concentrate (PR-M) and not as a mixture of PR-M and phosphate ore (PR-Ore)[11,14].

Based on the portfolio of critical questions, a set of 12 case studies were identified. Six of them are currently being initiated. One cluster of Global TraPs members including representatives of the Technical University of Freiberg, BGR Hannover, and the USGS Washington worked on procedures that may improve the homogeneity

Table 2. Key events and focus-guiding themes of the seven key meetings of the Global TraPs Project and Fraunhofer IGB follow-up workshop

Event	Date	Location	Focus-guiding theme
1st workshop	5–6 February 2011	Muscle Shoals/Phoenix AZ/USA	Building partnership and co-leadership
2nd workshop	3 April–1 May 2011	ETH Zurich, Switzerland	Consenting the guiding question
3rd workshop	29–30 August 2011	ETH Zurich, Switzerland	Identifying critical questions
4th workshop	12–16 May 2012	El Jadida, Morocco	Defining case studies
Beijing World Conference	18–21 June 2013	Chinese Agricultural University, Beijing, China	Learning from case studies – exploring policy options
Fraunhofer follow-up workshop	29 October 2014	Fraunhofer IGB	Author workshop for a special issue on losses and efficiency in phosphorus management

of the data provided by mining companies to the Mineral Commodity Survey. Another project surveyed the case of Manila Bay and the Manila Laguna. Here, the hypothesis is tested that phosphorus detergents may still be environmentally critical for megacities in the developing world as in such locations no or only low profile WWTPs are available. Also in this project, partnerships among key stakeholders ranging from Greenpeace to detergent producers are aspired too, such as in the other levels of the Global TraPs project. Naturally, in each of these case studies, the principles of Td were strictly applied. Finally, we should mention that questions of social equity (some of them linked to the North–South factor) were important aspects of the Global TraPs project as well. The project Smallholder Farmers' Access to Phosphorus (SMAP, financed by the Syngenta Foundation) was started in January 2013 with two case studies in Vietnam and Kenya.

The follow-up steps of the Global TraPs project may be seen in Table 2. The Global TraPs provided a comprehensive system analysis which was jointly elaborated by 50 people, among them 18 practitioners©. Besides the case studies, seven theses have been written by master's students. Further, on the Beijing 2013 World Conference, one-day workshops on critical questions, eight mutual learning sessions (MLS) including 125 people, i.e. 67 scientists and 58 practitioners were supervised and documented by 12 European and 10 Chinese master's and Ph D students.

Conclusions

- Phosphorus is an essential (non-substitutable) element for global food security, and its access demands strategic resource management.
- The biogeochemical phosphorus cycle has been dramatically altered in a very short period and requires monitoring of unexpected rebound effects (such as eutrophication and changes in biodiversity, soil fertility, human health, etc.) in particular, as phosphorus is/may become a pollutant.
- The eutrophication and hypoxia of dead zones by phosphorus emissions is a critical issue.
- Although there is sufficient evidence against a physical shortage in this century and the foreseeable future, there are many reasons why phosphorus scarcity may emerge (in some regions of the world) because of economic, geopolitical, and/or other reasons.
- The supply–demand-chain approach, combined with a substance- or material-flow analysis (MFA) is a suitable approach for coping with the complexity of the phosphorus cycle in particular, as it allows the identification of key actors who affect and may alter the current flows (this identification may become part of a Td process).
- Perhaps because phosphorus is a low-cost commodity, there is low efficiency of phosphorus use in many steps of the supply–demand chain.
- The low efficiency of phosphorus use, the contamination of phosphate rock with heavy metals and radionuclides, as well as the potential of co-mining of these elements, urgently demands technological innovations, e.g. for extracting/co-mining of special minerals or metals; half of all uranium resources, for instance, are thought to be in phosphate mines.
- A North–South asymmetry of phosphorus use and phosphorus flows exists and deserves special attention from a food security and social equity perspective.
- The biogeochemical P cycle, rock phosphate mining, P processing, and P trade are global. Thus, sustainable phosphorus management demands concerted global actions.
- The Global TraPs project[21] demonstrated that a wide variety of practitioners are willing to actively join processes of authentic mutual learning on sustainable phosphorus management and that the understanding of complexity as well as the access to certain data may be done well when involving the key stakeholders of the supply–demand chain.

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