Chapter 1
Sustainable Phosphorus Management: A Transdisciplinary Challenge

Roland W. Scholz, Amit H. Roy and Deborah T. Hellums

Abstract This chapter begins with a brief review of the history of phosphorus, followed by a description of the role of phosphorus in food security and technology development. It is then followed by discussions on critical issues related to sustainable phosphorus management, such as phosphorus-related pollution, the innovation potential of phosphate fertilizers and fertilizer production, uneven geographical distribution of phosphate resources, transparency of reserves, economic scarcity, and price volatility of phosphate products. In order to identify the deficiencies in the world's phosphorus flows, we utilize the "not too little–not too much" principle (including the Ecological Paracelsus Principle), which is essential to understanding the issues of pollution, supply security, losses, sinks and efficiency of phosphorus use, and the challenges to closing the phosphorus cycle by recycling and other means. When linking the supply–demand (SD) chain view on phosphorus with a Substance or Material Flux Analysis, the key actors in the

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global phosphorus cycle become evident. It is apparent that sustainable phosphorus management is a very complex issue that requires a global transdisciplinary process to arrive at a consensus solution. This holds true both from an epistemological (i.e., knowledge) perspective as well as from a sustainable management perspective. To gain a complete picture of the current phosphorus cycle, one requires knowledge from a broad spectrum of sciences, ranging from geology, mining, and chemical engineering; soil and plant sciences; and all facets of agricultural and environmental sciences to economics, policy, and behavioral and decision science. As phosphorus flows are bound to specific historical, sociocultural, and geographical issues as well as financial and political interests, the understanding of the complex contextual constraints requires knowledge of related sciences. The need for transdisciplinary processes is equally evident from a sustainable transitioning perspective. In order to identify options, drivers, and barriers to improving phosphorus flows, one requires processes in; capacity building that may be changed and consensus building on the phosphorus use practices that must be changed and maintained, along with recognition of how changes in phosphorus use in the current market may be framed. The latter is illustrated by means of the Global TraPs (Global Transdisciplinary Processes for Sustainable Phosphorus Management) project, a multi-stakeholder initiative including key stakeholders on both sides of the phosphorus SD chain which includes mutual learning between science and society.

Keywords Sustainable phosphorus management · Supply–demand chain analysis · Food security · Environmental impacts

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1 New Perspective on Phosphorus Management

1.1 What's New About This Book?

Many books, theses, and papers have been written from various perspectives on phosphorus. The present book targets *global sustainable phosphorus management*. *Transdisciplinarity*, whose core is *the integration of knowledge between practice and science*, is seen as a means by which a sustainable transition toward global efficiency may be achieved. This is a new concept, and the subject of a comprehensive project, the Global TraPs (Global Transdisciplinary Processes for Sustainable Phosphorus management) project, which was officially launched on 6 February 2011.

This book explains what *sustainable phosphorus management* may mean, why we need transdisciplinarity (as defined in the context of the Global TraPs project) and why phosphorus (P) is so distinctive that it may serve as a learning case for any *global biogeochemical cycle management*. In the case of P, sustainable biogeochemical cycle management includes *pollution prevention, resource conservation, technology development,* and *knowledge generation* in a way that future generations may have efficient access to P. Closing the fertilizer loop from the mining of phosphate rock to its use, at least to some extent, is definitely one means. However, this may only be accomplished if we have a clear view of how losses and sinks of phosphorus are related to the actions of the key stakeholders. Clearly, phosphorus atoms do not disappear from earth. We denote those fractions that have been excluded from the value chain by human action (such as phosphorus in mining waste, sewage, and manure) as losses. This is why we take a supply–demand chain perspective. Here, demand is explicitly mentioned because phosphorus is essential, and human life is inextricably linked to the use of considerable amounts of P, particularly for food production. Chapters 2–6 of this book, like the Global TraPs project itself, are structured to follow the stages of the supply–demand chain, which are *Exploration*, *Mining*, *Processing*, *Use* and *Dissipation and Recycling*. A large share of phosphorus flows is tied to economic transaction. Thus, a chapter *on Trade and Finance*, which addresses critical aspects such as the origins of price peaks, is included in this book.

The conceptual vision is elaborated in the *Closed-Loop Supply–Demand* Chain Management of the *anthropogenic* portion of (CloSD Chain Management) phosphorus flows in this chapter. The concept makes reference to ideas in industrial ecology such as "loop closing" (Lifset and Graedel 2002), or "from cradle to cradle" (McDonough et al. 2003, SI 7), stressing the need for recycling. Special emphasis is given to the economic perspective. This is also indicated by including a demand perspective. As Scholz and Wellmer (2013) point out, phosphorus is a demand-driven market rather than a supply-driven market. There is a steady but—as phosphorus is essential and mineral fertilizers a key element of current food supply security, see Spotlight 1—limitedly adaptable demand function and, compared with other minerals and metals, rather abundant resources. Thus, we face a demand-driven market and must understand how the demand side may be affected by technology, population growth, lifestyles, etc.

Though CloSD Chain Management may be considered a necessary condition of sustainable phosphorus management, it is by no means a sufficient one. Sustainability goes beyond the environmental, economic or technological dimensions and includes *social* (Brundtland 1987) and *equity* (Laws et al. 2004) dimensions. The *social dimension* is certainly the most difficult and challenging, but is of major importance. We can easily illustrate this dimension by reviewing the case of sub-Saharan Africa's smallholder farmers. Most of these smallholders live in countries whose soils have the highest need for fertilizers. *Smallholder farms* in this region constitute 80 % of African agrarian land (IFAD 2011), yet they are the most disadvantaged with respect to soil fertility and other factors (i.e., erosion). As a result, the percentage of undernourished within the African rural population is about 16 % (FAO 2010b). In addition to having a large share of highly weathered soils with low nutrient content, some soils in sub-Saharan Africa tend to bind phosphorus (significantly reducing phosphorus available to plants). Gaining access to P, therefore, is fundamental to improving the productivity and livelihoods of smallholder farmers. As documented in 2009, Africa's soils received on the average (including countries with large-scale agroindustrial plantations) only 2.48 kg P ha^{-1} $year^{-1}$, whereas the soils of Europe and North America, which have higher loads of soil phosphorus from centuries of fertilizer use received 18.7 and 19.12 kg P ha^{-1} $year^{-1}$, respectively, during the same period (FAO 2012b). Thus, African farmers, and many others who do not practice balanced fertilization, are removing a larger portion of one or more nutrients from the soil (through harvested crops) than is being added (through organic amendments and mineral fertilizers) on an annual basis. Clearly, many smallholder farmers in developing countries are neither able to access manufactured fertilizers, nor do they have access to technologies that promote efficient fertilizer use. In many developing countries, providing access to phosphorus and other nutrients is essential to improving food security.

This book, in support of the Global TraPs project mission, states that we must not only learn from the different stakeholders about their knowledge and cultural backgrounds, but we also must learn from history to better understand the role of phosphorus in biotic and abiotic processes. Ultimately, we must use this knowledge to change current use practices. To that end, we ask the reader to review the brief history of phosphorus that follows.

1.2 Learning from Phosphorus History: Light, Fertilizers, and a Conflict of Interest

In ancient times, the planet Venus was referred to as "phosphorus" by the Greeks (Wisniak 2005). As indicated by its etymological meaning (phosphorus: light bearer; from phos "light" [related to phainein, "to show, to bring to light": see phantasm] + phoros "bearer," (OED 2012)]), the earliest interest in phosphorus was as a lighting element. History indicates that in 1669, the alchemist Henning Brand (c.1630–c.1710) "rediscovered" the element and the procedure to generate phosphorus (Krafft 1969), which entailed boiling silver pieces in urine, drying the silver, mixing it with sand (silica), heating the mixture and collecting the resulting yellowish mass in a condenser. This mass caught fire easily when exposed to air (at ambient temperature). He was believed to have discovered a "black" substance, a "Prima material," or "elemental 'fire,'" i.e., "one of the four Aristotelan 'elements,' earth, water, air, and fire" (Krafft 1969). Giants of the history of science such as Gottfried Wilhelm Leibniz (1646–1716)—who wrote the "Historia inventionis phoshori" (1710)—and Christiaan Huygens (1629–1695) were involved in documenting the procedure, which was run with "a full ton of urine" (Leibniz 1710). Through the work of Lavoisier (1743–1794, Lavoisier 1776), phosphorus became the 13th element in the history of the discovery of elements (Emsley 2000a).

Phosphorus was of *commercial interest* from the very beginning. Alchemists rigorously explored the element, and pharmaceutical companies found uses for it soon after its discovery (Richmond et al. 2003). Eben Norton Horsford (1818–1893), chemist working on phosphorus and a scholar of Justus von Liebig and Professor at Harvard of the Application of Science to the Useful Arts, was the inventor of baking powder. He became cofounder of Rumsford Chemical Works and promoted the selling of phosphate acid for medical purposes (Jackson 1892, see Fig. 1). Large-scale match production began in the early nineteenth century (see Fig. 2) and phosphorus bombs became warfare agents.

After Brand's discovery, "for a century, urine was the only source from which phosphorus was attained" (Färber 1921). But in 1769, Carl Wilhelm Scheele (1742–1786) and Johan Gottlieb Gahn (1745–1818) discovered phosphoric acid in animal bone and many other animal parts (Färber 1921; Petroianu 2010). Théodore de Sassure stated in 1804 that, "we had no means to believe that plants can exist without phosphorus" (Färber 1921, p. 11). These statements were later proven by the emerging experimental "Animal and Vegetable Chemistry" (Dumas and Boussingault 1844), which provided insight into the metabolic nature of plant physiology (Liebig 1840) and set the foundation of *nutrient balance*, which suspected that deficiency of phosphorus was the limiting factor in plant growth (Liebig's Law of the Minimum; see Paris 1992).

But farmers knew about phosphorus long before the modern scientific community. Phosphorus has been used in agriculture, even if unknowingly, since prehistoric times. In fact, archeologists use phosphorus as a tracer element for human settlements (Schlezinger and Howes 2000), and fertilizer use can be traced back to at least the third millennium B.C. (Wilkinson 1982). The Inca civilization used guano as fertilizer (de la Vega 1609/1990). Roman agriculture included manures for crops in the first century (Lelle and Gold 1994), and the use of bones as fertilizer was reported by Walter Blithe (1605–1654, Brand 1937).

Without understanding its scientific properties, farmers utilized the phosphorus and other macronutrients in manure, excrements, and bones as fertilizer. Eventually, scientists learned from these ancient practices, and farmers adapted quickly. As an example, desperate farmers were said to have raided Napoleonic battlefields such as Waterloo (1805) and Austerlitz (1815) to collect human bodies for their phosphorus contents [Hillel, 1991; cited in Foster (1999)]. In his book, *Farmers of forty centuries: organic farming in China, Korea and Japan,* Franklin H. King provides us with another example: "Manure of all kinds, human and animal, is religiously saved and applied to the fields in a manner which secures an efficiency far above our own practices" (King 1911/2004). "This was not done directly, but potential fertilizer such as river mud" was often dried and pulverized before being carried back and used on the fields as makeshift fertilizers (p. 8).

In 1804, Alexander von Humboldt (1769–1859) observed that Peruvian fields were fertilized with guano. He took samples to Europe where chemists noticed high levels of nitrogen (N) and phosphorus (von Pier 2006). In the period between 1857 and 1867, about 50,000 metric tons (mt) of guano were imported annually by Europe (Färber 1921). But technological progress opened other options.

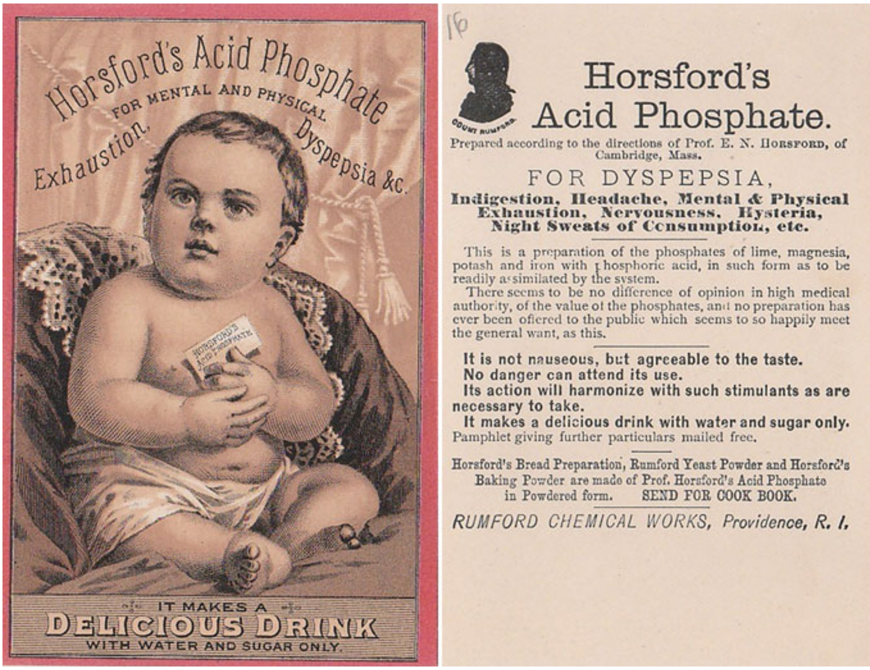

Fig. 1 Phosphate acid was seen as remedies for many diseases (*Source* Hulman & Co)

Fig. 2 Phosphorus may have positive and, in certain forms, negative effects. This picture shows a former employee of the Reliable Match Company of Ashland, Ohio, who died in 1912 due to exposure to *white P*. The disease, which was labeled "phossy jaw," recently reappeared with patients who were treated with *bisphosphonate*, a P-based medicine (Body 2006). Thus, the new term, "bis-phossy jaw," emerged (Hellstein and Marek 2004). Picture taken from the "A last victim," *The Survey* 28, no. 2, 1921 after a reproduction of Moss (1994)

The history of phosphorus fertilizer (organophosphate) invention, and essentially the beginning of the fertilizer industry, was written primarily by three icons of their times, Sir James Murray (1788–1871), Sir John Bennet Lawes (1814–1900), and Baron Justus von Liebig (1803–1873). When referring to experiments in converting "bones to biophosphate of lime as fertilizer, using sulfuric acid," Lawes is noted to have carried out the first field experiments mixing wastes, compost, and manure in 1817. He then experimented with different mixtures of nutrients (Alford and Parkes 1953; Childs 2000). In 1842, trials were carried out to compare the new fertilizer with manure (Childs 2000). Here, superphosphate, a composition of calcium hydrogen phosphate and calcium sulfate was applied. Practically, rock phosphate was treated with sulfuric acid. Lawes bought patents from Murray and Liebig and, in 1843, founded the Rothamsted Experimental Station in an area of the United Kingdom that was extremely deficient in nutrients due to centuries of nutrient-extractive agriculture. In France, Boussignault demonstrated the synergetic effects of P, N, and other minerals. Quickly, the chemical and manure industries developed to fill the growing agricultural need (Daly 1984) to avert famine.

The development of scientific knowledge in the nineteenth century may be considered a history of errors, as even the greatest knowledge of that time was incomplete. This point may be highlighted with the earliest of Liebig's seminal contributions. Initially, Liebig's patented fertilizer proved to be a failure, as it contained no N or potassium (K), and phosphorus was present in an unavailable form. Liebig corrected the latter idea—that soluble forms of phosphorus would be washed away from the soil by rainwater—when he realized that soluble phosphorus was essential for plant growth (Emsley 2000b; Oertli 2008).

Seventy-five years ago, the executive secretary of The US National Fertilizer Association wrote:

> Not so many years ago, the fertilizer industry was largely a waste-products industry. The bone, blood, and tankage of the packaging industry, the fleshings and scraps of the leather industry, the slops of the beet sugar industry and the meal residues of the vegetable oil industry made up the greater part of mixed fertilizer." And he noted that buyers had been "more impressed … by … odor than by chemical composition or guarantee of plant food content. (Brand 1937)

The idea to solubilize phosphorus in bones by sulfuric acid (transforming slow release calcium phosphate to superphosphate) was also transferred to phosphate rock. Single superphosphate, triple superphosphate (monocalcium phosphate), and diammonium phosphate became the pillars of the phosphate industry.

But historically, fertilization has been only one of the uses for P. Boyle discovered in 1680 that when sulfur and phosphorus were rubbed together, they caught fire. It took about 140 years until "Lucifers," the original name for contemporary "strike anywhere" matches (Battista 1947), were invented. Excessive exposure to *White* (also called yellow) phosphorus (P_4O_{10})-containing matches that were produced in some countries caused many diseases such a "phossy jaw," a variant of bone cancer. This particular disease was first diagnosed in Vienna

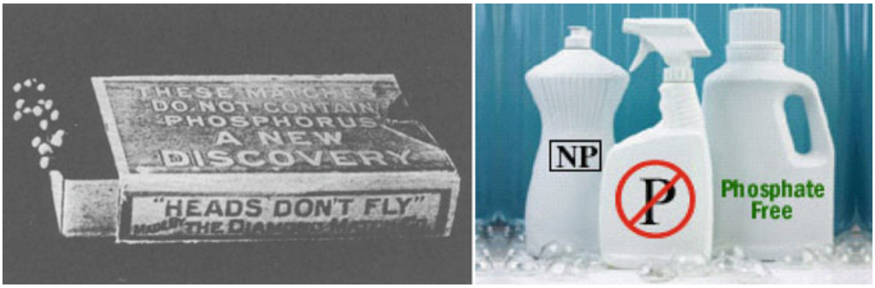

Fig. 3 The Berne Convention of 1906 banned the highly toxic *white phosphorus* from matches. Whereas no biomass may emerge without P, matches without *white phosphorus* and household detergents without phosphorus could be produced to avoid critical collateral impacts (*left* picture taken from Andrews (1910) after a reproduction by Moss (1994), *right* picture after courtesy of the South East Regional Centre for Urban Landcare, Brisbane, Australia)

(Moss 1994), where its P-related etiology was proven (Marx 2008). Young girls who carried matchboxes on their heads became bald (Datta 2005). The import and sale of matches containing white phosphorus were banned by many European countries under the Berne Convention of 1906. "In the United States, nearly all interested parties supported legal abolition, but… no state wanted to be the first to act (for the fear of driving industry from its borders), and the federal government lacked the power to regulate intrastate economic activity …" (Moss 1994). The necessity that global phosphorus management should advocate for international action may be well-learned from this case.

White phosphorus (P_4) is still in use for match production in developing countries and is permitted for contemporary epidemiological studies (González-Andradea et al. 2002). The lethal dose is about 1.0 mg/kg weight in adults (Gossel and Bricker 1994). The critical toxicity of *White* phosphorus can be demonstrated in a new form of "phossy jaw," the "bis-phossy jaw," which is observed in people who are treated with bisphosphonate to combat bone necrosis (about 10 % of the human bone is P, see Fig. 3).

It should be noted that *phosphorus* does not appear in a pure form in nature, but rather, is generally observed in the oxidized form of *phosphate* (PO_4) which becomes *organophosphate* such as DNA if it is bound with organic compounds. This book deals with the chemical element phosphorus, which is denoted as P, though occasionally phosphorus also denotes phosphate in the context of this publication.

2 The Role of Phosphorus in Food Security and Technology Development

"Producing enough food for the world's population in 2050 will be easy." This is the first sentence of a recent Editorial in *Nature* (2010) in a series on world food systems. Given the possible doubling of the food demand in the next 50 years (Tillman et al. 2002), *Nature* undoubtedly makes an extremely optimistic statement. This optimism is linked to what many envision as a second *Green Revolution* and the "sustainable intensification of global agriculture." But under what constraints is this possible? And what role does nutrient management play in general, and phosphorus management in particular, in this vision? The optimistic view has been criticized as far too simplified, or even naïve, due to a singular focus on technology that does not take into account the social dimension, resource dynamics or environmental issues. The authors of this chapter do not believe that the challenge of feeding the world in 2050 will be easy, but it will be possible if a proper system view is taken, which allows us to better understand the demands for phosphorus posed by human systems.

2.1 Increasing Demands for Phosphorus in the Future

Phosphorus is an *essential* element for any living organism, as it cannot be substituted by another element. DNA, the basic building block of life itself, consists of carbon, hydrogen, oxygen, nitrogen, and phosphorus. Phosphorus is also the key component of the "workhorse" molecule, adenosine triphosphate (ATP), which provides the energy to keep cells alive and active. But phosphorus plays many other roles in the body as well; phosphorus is a component of the lipids that make up cell membranes. Phosphorus deficiency is often the *limiting factor* of plant growth (de Vries 1998). Thus, phosphorus is a *critical* element in food security: a shortage of phosphorus in any agrosystem results in low agricultural productivity that, in many cases, may cause undernourishment and, in extreme cases, famine (Ragnarsdottir et al. 2011; Sanchez and Swaminathan 2005). The impetus for the *Green Revolution* that began in the 1940s was a world *population increase* that required an exponential increase in world food supplies. This new age of agriculture relied heavily on mineral fertilizers and other agrotechnological innovations such as new higher-yielding seeds (including the breeding of modern varieties; see Evenson and Gollin 2003), expansion of irrigation systems (with higher groundwater depletion and energy costs), pesticide and herbicide development and application, more efficient agricultural machinery, intensification of crop and grazing land areas, and better means of education.

Today, humankind faces a new challenge as it makes its way into the twenty-first century. The United Nations (2009) projected the population could increase by more than 30 % to 9.2 billion people, by 2050. This estimate reflects more than a tripling of the population in 90 years as there were 3 billion people in 1960. According to latest projections, total population in 2050 may be 9.6 billion (UN 2013). If the population growth trend over the last five decades continues, there may be more than 1 billion undernourished people, considering that 1 billion have been attained in 2009 (FAO 2009). In percentage terms, the number of people starving has declined in the last centuries. A firm projection is difficult as we are witnessing opposing trends, of reduction (e.g., in China or Vietnam) and increase (e.g., India and Pakistan) in the number of undernourished people (Cuesta 2013; Fan et al. 2013). During the next decades, there will be additional demands for phosphorus due to an increased demand for meat and other dietary changes (particularly as emerging nations become more developed). As phosphorus is a cornerstone of food production, world phosphorus management may be challenged in the coming decades.

There were 25 megatons (Mt) phosphorus (corresponding to 191 Mt of phosphate rock [PR]) produced and recorded in the Mineral Commodity Summary of USGS in 2011 worldwide (Jasinski 2012). The importance of the availability of chemical fertilizer for today's world food system may be taken from the following data: in the year 2000, there were 14.2 Mt of phosphorus fertilizer used (given a total production of 18.1 Mt P [calculated from 139 Mt total production of phosphate rock concentrate, according to Jasinski, 2001]) compared with 9.6 Mt of manure produced for crop production. Thus, about 13 kg P ha^{-1} year^{-1} was used on farmland including pastureland (MacDonald et al. 2011a).

On average, each person consumes the equivalent to about 31 kg of phosphate rock per year (Scholz and Wellmer 2013). We may take from Fig. 7 that the average PR demand for a world citizen decreased slightly after the decline of the Soviet Union around 1990 but is currently forecasted to increase. Sustainable phosphorus management seeks to more efficiently use phosphorus and to reduce the relative (kg PR consumed per person annually by means of increasing efficiency) and the absolute consumption (i.e., decreasing the Mts of mineral phosphorus which are inserted into the ecosystems, see Sects. 3.2 and 4.1) per year. Fertilizer is the main segment of phosphorus use (see Fig. 4). But between 10 and 15 % are used for other purposes. In 2011, from a total production of 25 Mt P, the category of food and dark soft drinks accounted for 2 % (0.50 Mt P), while animal feed additives amounted to 7 % (1.74 Mt P). In addition, there is sodium triphosphate (STPP). Most STPP is used for detergents and a broad set of cleaning products. Prud'homme (2010) estimates that phosphorus in STPP amounts to 8 % [4 Mt P_2O_5 year^{-1} out of 49.5 Mt P_2O_5 year^{-1} which would correspond to 1.7 Mt P year^{-1} for STPP out of 21.6 Mt P year^{-1} used as reference in Prud'homme (2010), see Fig. 4]. These 8 % include a wider range of industrial uses of STPP. An estimate of Shinh (2012) of STPP is much smaller estimating about 0.93 Mt P year^{-1} for STPP in 2011. Shinh states that the use of STPP for detergents which historically made up a major share reduced by half between 2007 where he reports a production of 1.23 Mt P year^{-1} (see Sect. 5.2.8) and in 2011. The EU has recently adopted the detergent regulations that call for a ban of phosphorus in laundry detergents as of June 2013 and automatic dishwater detergents beginning in January 2017 (EU 2012b).

Finally, phosphorus is used in other industries such as in lighting or electronics. While the amount of industrial use of phosphorus is limited, it is very beneficial for many technical processes (see Spotlight 8, Gantner et al. 2013). However, in principle, phosphorus could be substituted with other minerals in this instance and in other industrial applications.

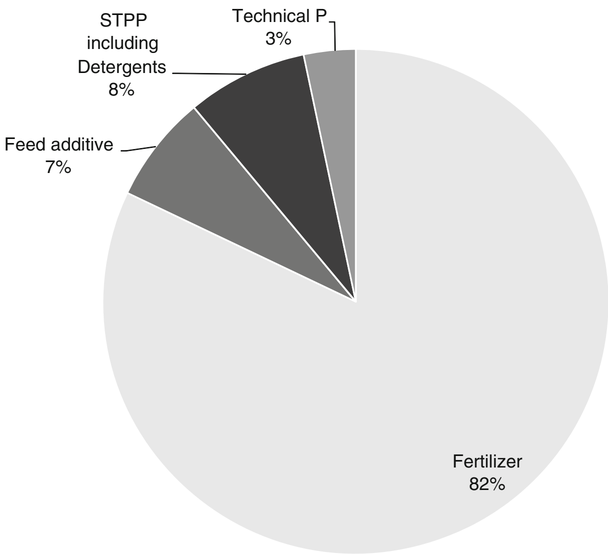

Fig. 4 Shares of phosphate rock (*PR*) use for main purposes according to Prud'homme (2010)

There is an increasing pressure on P availability under *biofuel* demands. Predictions suggest that in 2020, individuals in the developed world will use, on average, 150 kg of maize per person, per year (Rosegrant et al. 2008; FAO 2011). This number may easily demonstrate the trade-off between food and fuel (Jansa et al. 2010). Even using conservative estimates (e.g., assumptions about weight of wet and dry corn), about a quarter of the recommended daily calories (2,000–2,500 calories) of edible vegetable is used for biofuel (Kelly 2012). There are many critical arguments against biofuel, both with respect to bioethanol and biodiesel, because of trade-offs with food (and potential price increase), supplementary land use, etc. (Alexandratos and Bruinsma 2012). From a phosphorus resources management perspective, we have to acknowledge that most of the phosphorus of the plants used for bioethanol and biodiesel production remains in the biofuel co-products (e.g., oilcake and microalgae slurry) may be fed to livestock (Zhang and Caupert 2012) or even processed as organic fertilizer.

2.2 Different Phosphorus Demand Trends in Different Parts of the World

An important lesson to be learned is that we are facing completely different histories, constraints (with respect to soil, crops, etc.), and prospects with respect to phosphorus demand in different regions and countries of the world. A first impression of the different trends may be gained from Fig. 5. We must acknowledge that there are different trends in agricultural phosphorus use per

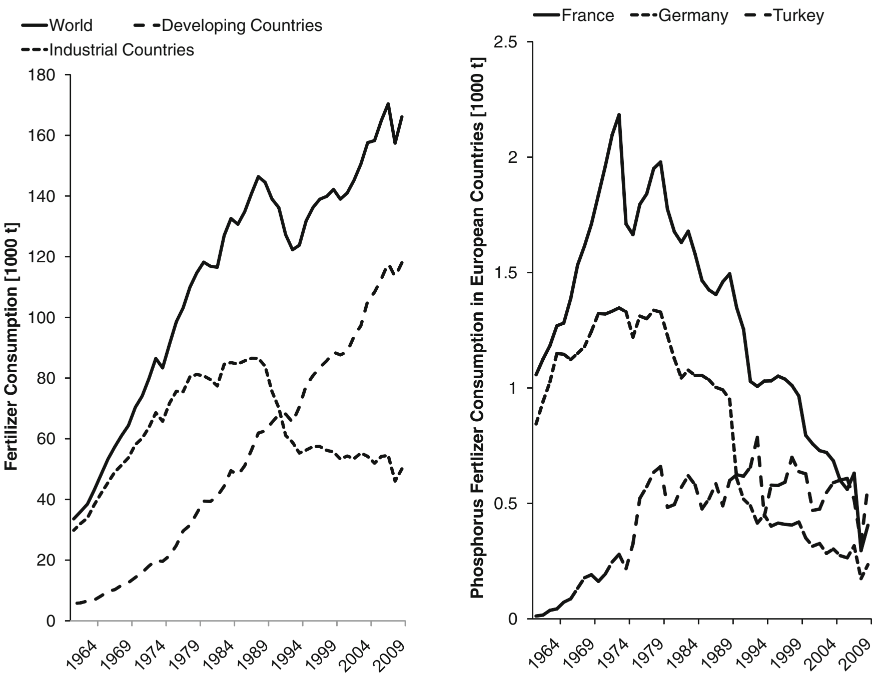

Fig. 5 Fertilizer (*left*) and phosphorus dynamics [*right*, based on (FAO 2010b)] show different trends in different countries

hectare (ha) in many parts of the world. Industrial nations have experienced decreasing demands since the 1980s. This is primarily due to an accumulation of residual phosphorus, which was not taken up by annual crops, but rather, is bound to soil particles and is available for subsequent crops. The decrease is also reflective of the increasing use of livestock manures from concentrated feeding operations. The balanced fertilizer application practice, which has been adopted by farmers in most developed nations, has been one factor which contributed to a moderate reduction in the use of agricultural land. In contrast, many developing countries are increasing demand (Fig. 5 left) for phosphorus though some countries—such as China—are now promoting efficiency and thus may flatten or decrease future demand projections.

An important study (MacDonald et al. 2011a) calculated that 10 % of croplands, mainly in South America (especially Argentina and Paraguay), northern United States, and eastern Europe, had deficits of phosphorus (−3 to −39 kg P/ha) in the year 2000; whereas another 10 % (East Asia cropland, large areas of western and southern Europe, the coastal United States, and southern Brazil) had large surpluses (13–840 kg P/ha). Large surpluses of phosphorus occurred in less than 2 % of cropland in Africa, existing particularly in North Africa or on large plantations that export their crops. MacDonald et al. elaborate that there is a large potential for more efficient use, which may increase world food production (see

Table 1 Cropland area, phosphorus (*P*) input per ha of cropland, P uptake, and average P consumption in two periods, according to Sattari et al. (2012)

	Cropland (10^6 ha)		P input by fertilizer and manure (kg ha^{-1} year^{-1})		P uptake rate (kg ha^{-1} year^{-1})		Average P input (Mt)	
Year(s) region	1965	2007	1965	2007	1965	2007	1965–2007	2008–2050
World	1390	1520	7.6	16.6	3.2	7.6	18.6	29.1
Western Europe	107	94	23.8	17.2	4.9	9.9	2.6	1.2
Eastern Europe	231	199	6.1	4.7	2.6	3.9	2.1	1.0
North America	230	225	8.7	11.4	3.9	8.8	2.5	3.3
Latin America	112	170	4.4	20.8	3.1	8.9	1.6	3.9
Asia	446	541	6.4	27.3	3.5	10.0	7.9	15.5
Africa	173	247	1.9	4.1	1.8	3.1	0.8	3.8
Oceania	41	46	14.8	16.0	1.1	2.5	5.7	7.8

Calculations are based on the mean area of 1965 and 2007, based on a linear extrapolation of area increase/decrease as between 1965 and 2007

Spotlight 1). We will take a closer look at this issue further on, but we can surmise from Fig. 5 and Table 1 that there are varying trends. Overall, we see an increase in nutrient and phosphorus production (see Chap. 5, Fig. 3). We take a more differentiated view of these trends in Sect. 4.3.

In order to understand fertilizer use trends and the pressure for recycling, we must also acknowledge the dramatic change in cropland availability per person. From 1960 to today, there has been a population increase in about 230 % (from 3 to 7 billion). Almost proportionally, there were 217 % more ha of unutilized cropland available in 1960 than today (Pimentel et al. 2010, all data in those paragraphs are taken from this source). Currently, the available cropland per capita differs dramatically across the globe. China has only 0.08 ha of available land per capita. This is reflected in the consumption rates. Whereas US citizens consume 1,481 kg year^{-1} of agricultural products per capita, the Chinese consume only 785 kg year^{-1}. As the United States still has 0.5 ha per capita of available cropland, it may provide large amounts of grain to China and other countries with fewer arable land resources. It is clear that the pressure to overuse fertilizers—and the subsequent pollution and land degradation—is more pronounced in China, Vietnam, and other highly populated, resource-poor countries. More detail on this issue is provided in the Use Node, Chap. 5.

A recent study by Sattari et al. (2012) provides further insight to the different continental trends of phosphorus use. This study utilized data on phosphorus use by different continents from 1965 to 2007 and provided simulations for another 43-year window from 2008 to 2050. This model is based on the dynamic input–output of phosphorus by plants based on a "labile pool" and a "stable pool" (see also Dumas et al. 2011), including fertilizer and manure as input and runoff, erosion and uptake by plants as output. We should also note that Sattari et al. are using as specific definition for use efficiency that is also applied in this chapter. The ratio of nutrient output (in grain) to nutrient input is defined as use efficiency (see Fig. 6d).

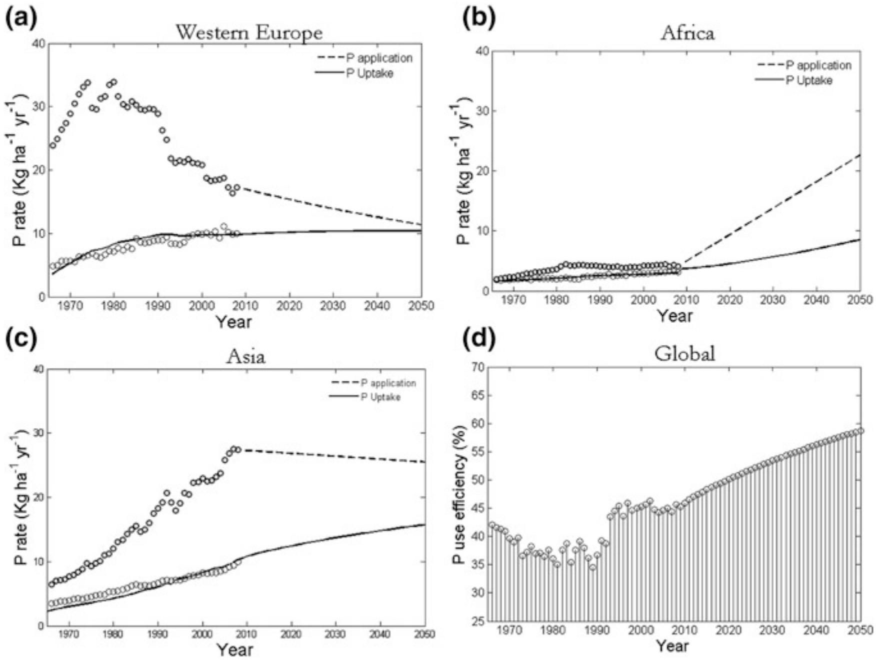

Fig. 6 Potential trends of phosphorus (*P*) application and trends of phosphorus application and uptake in the croplands of **a** western Europe, **b** Africa and **c** Asia (Sattari et al. 2012), **d** presents the P use efficiency [for 1965–2007 based on historical data, figure **d** provided by (for 1965–2007 based on historical data, figure **d** provided by Sattari 2013)]

One message of this chapter is that the phosphorus demand will not decrease, but rather increase in many parts of the world. This assertion is in line with estimations by Dutch researchers (Bouwman et al. 2009, 2012) who provide estimates of the future use of global phosphorus between 26 and 31 Mt P annually in 2050 including mineral fertilizer and manure. Though this model may be considered to contain early, rough estimates, it nevertheless suggests that African countries may quintuple their use of the input "from 4 kg ha^{-1} year^{-1} in 2007 to 23 kg ha^{-1} year^{-1} in 2050" (Sattari et al. 2012). This increase is due to the necessity to build up phosphorus stocks in agricultural soils to increase and sustain productivity in some countries, but in others is related more too balanced fertilization. Figure 6 shows quite well three dynamics of phosphorus use. The western Europe simulations propose a sort of equilibrium of 10 kg ha^{-1} year^{-1}. The Africa graph presents the backlog demand before a level of 10 kg ha^{-1} year^{-1} is attained. And the Asian graph may indicate that overloading of phosphorus in the soils may be close to an end, and that there will be a decreasing demand per ha in the future.

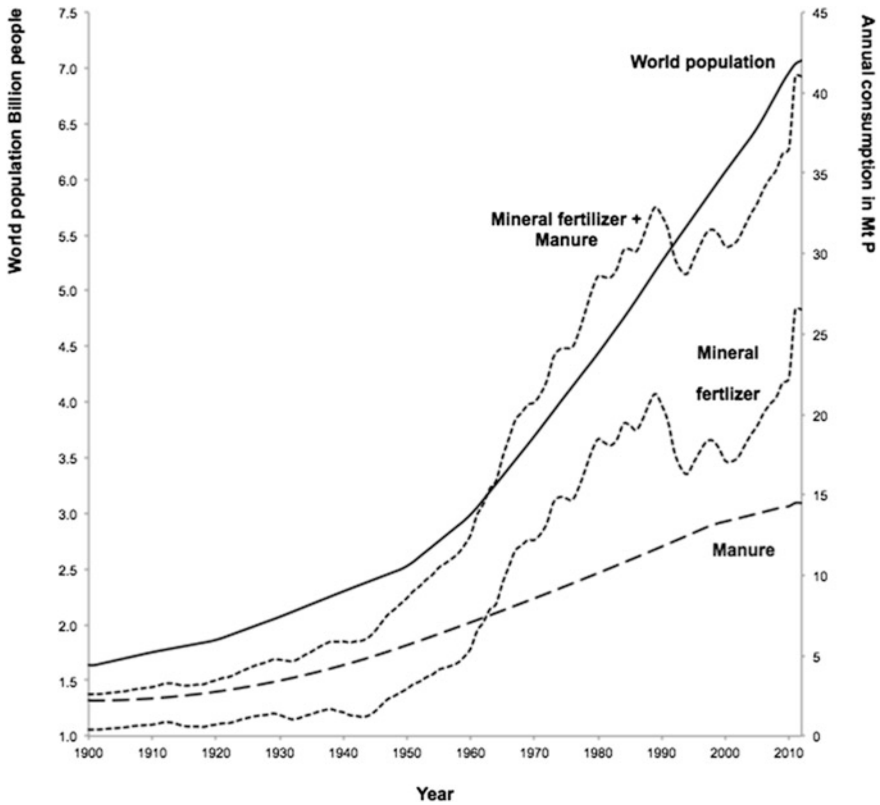

Fig. 7 The evolution of phosphorus fertilizer use, where mineral phosphorus plays an increasingly important key role (phosphorus data—80 to 85 % for fertilizer use—from USGS, presented as moving mean with a 3-year sliding window; rough estimation of manure data based on literature, see Sect. 4.8.2; population data from (USCB 2009); manure data extrapolated from different data on annual manure production, see text)

2.3 Increasing Efficiency: "Save and Grow" for Food Security?

There is no doubt that food security to match the anticipated world population growth is unthinkable without mineral fertilizer. Figure 7 presents the trends in the use of different types of fertilizer and the world population. If we assume that the world population will increase to 9.2 billion people by 2050, we may face different options or scenarios. One is "business as usual," which means that we produce more phosphorus in a "linear fashion," with the same amount of phosphorus required per capita. However, a closer analysis of historical per capita consumption reveals a strong increase leading up to the 1970s followed by a reduction in demand. This demand was due to the increasing efficiency of agriculture in the developed world and other factors (the decline of the demand) at the end. The temporary decline of consumption between 1990 and 2003 due to the decline of the Soviet Union will be dealt with in other sections (see e.g., Fig. 26). The idea of increasing efficiency has been adopted by FAO (2011) in "a policymaker's guide" which—almost exclusively—focuses on agrotechnology. Let us review the potential and limits of such an approach.

Efficiency is an input–output relationship. Phosphate fertilizer use efficiency in the domain of cropland agriculture is simply defined by how much phosphorus of the phosphate fertilizer added to cropland is actually taken up by plants. Here, in the first instance, the uptake of plants is of interest. If we denote the uptake of phosphorus as u, denote the uptake by plants which received phosphorus fertilizer as u_P, denote plants that did not receive phosphate fertilizer as u_o and the input of phosphorus simply as P, we may calculate the *uptake efficiency*: $\mathrm{eff}_u = (u_P - u_0)/P$. There are other forms of efficiency such as "agronomic efficiency," which refers to the yield, where the increase in yield is by phosphorus input, i.e., $\mathrm{eff}_y = (y_P - y_0)/P$ is considered, whereas y_P is the yield with phosphorus, and y_0 is the yield without phosphorus. Sutton et al. (2012) distinguish between nutrient efficiency for food crops, feed crops, and animal uptake, followed by nutrient use efficiency (NUE) of the *food supply* (with follow-up recycling food efficiencies of NUE in sewage and manure recycling). Clearly, as demonstrated in field experiments, the method of measuring the phosphorus use efficiency is in the study of its interaction with the other mineral nutrients (primary and secondary), the availability of hydrogen (H), oxygen (O), carbon (C), and many other factors such as soil texture (see Chap. 7). However, in practice, this has not been properly acknowledged.

Here, we focus different viewpoints on the questions, "how substantial is the NUE (measured by different parameters) for the case of phosphorus? And, how big are the losses?" Answering these questions on a global level is difficult because the regional differences in soils, climates, plants, agricultural technologies, etc. must be considered and integrated. Also, one must distinguish between real losses (e.g., by erosion and losses to the sea) and by temporary "virtual" losses when phosphorus binds with soil particles but becomes plant-available over extended periods of time. Just the difference between estimated soil erosion of 10 t ha^{-1} $year^{-1}$ on cropland in the United States compared with China at 40 t ha^{-1} $year^{-1}$ reveals potentially vast differences. Recent estimates of soil erosion on the African continent indicate an increase by a factor of 30 in the last three decades (Pimentel et al. 2010).

However, we may roughly identify an *optimist* and a *pessimist camp* (Pimentel et al. 2010). The optimists argue that the chemical phosphorus fertilizer in the soil is not lost. Syers et al. (2008)—based on long-term trials, mostly under temperate conditions and with relatively low erosion losses—provide the following pronounced statement:

> The main conclusion of this report is that the efficiency of fertilizer P use is often high (up to 90 percent) when evaluated over an adequate timescale using the balance method. (Syers et al. 2008)

Others, such as Cordell et al. (2011, whose work has been based on a literature review instead of experimental work), suggest an estimate of 8 Mt P associated *erosion losses* from agricultural soil and pastures out of their estimate of 14 Mt P of mineral fertilizer (plus a further 3 Mt P of losses from crop uptake). Even higher estimates are provided by Liu et al., based on the phosphorus balance of topsoil ("plow layer") contents.

> This gives world phosphorus losses at 19.3 MMT P/yr [MMT means that Mt in the nomenclature of this book] from cropland and at 17.2 MMT P/yr from pastures, respectively, … (Liu et al. 2008)

Most presumably, the reality is somewhere between the two purported limits. We must also acknowledge that "natural P," i.e., phosphorus in the soil deposited through weathering processes, is lost from terrestrial systems, not only "mineral and organic fertilizer" phosphorus. Otherwise, there would be no (extensive) life in the sea. A critical point for understanding the difference between the two statements is the time range. Whereas one position takes a static view with a one-year window, the other takes a dynamic life cycle view. From the latter perspective, phosphorus stored in soil is not lost (following some dynamics that may be described by differential equations), as plants may gain access to most of the phosphorus in the soil (Dumas et al. 2011; Sattari et al. 2012). Clearly, it is important to get a proper picture here and distinguish between *temporary losses* (which may be retrieved over a couple of decades and centuries) and *real* losses (which may become accessible for terrestrial plants after millions of years).

> A new global effort is needed to reduce nutrient losses and improve overall nutrient use efficiency in all sectors, simultaneously providing the foundation for a Greener Economy to produce more food and energy while reducing environmental pollution. (Sutton et al. 2012)

We agree that efficiency is an important means in transitioning to sustainable phosphorus flows. But we should acknowledge that, logically, efficiency is neither a necessary nor a sufficient reason for sustainability. Former agrarian societies, such as those based on "slash and burn" agricultural extensification, may have shown low NUE (Escueta and Tapay 2010; Kauffman et al. 1995), but may have lived in a steady and productive societal state for a long period of time. Thus, efficiency is not a prerequisite of sustainability. To the contrary, we might imagine a world population that has managed a very high NUE in its agrosystem, but has become vulnerable due to its disregard for other aspects, such as population growth, biodiversity, or climate change, which has rendered its agrosystem unsustainable. Nevertheless, given the current situation of population growth, dietary change, scarcity of arable land, etc. NUE is an important means to avoid further land degradation, avoid the negative environmental impacts of fertilizer (mineral and organic), and foster food security. Given our current knowledge of the demand and the environmental impacts of the supply of phosphorus and other inorganic fertilizers, increasing efficiency is an absolute requirement.

2.4 Phosphorus and Biofuel

Liquid biofuel for transportation has seen a significant rise in many countries over the last decade. Bioethanol comprises 80 % of liquid biofuels, and almost 90 % is produced in Brazil and the United States, which are also two leaders in world food production (FAO 2008). For fear of running out of fossil oil, biofuel has been regarded as an acceptable alternative:

> Biofuels may contribute to the crucial goals of enhancing energy security, energy diversification, and energy access; improving health from reduced air pollution; and boosting employment and economic growth for rural communities. (UN 2006, p. 29)

In 2008, the world's arable land used for liquid biofuel production was approximately 1 %; that number is expected to increase to 3.8 % by 2030. However, this would only lead the "global share of biofuels in transport demand to increase to 10 %" (FAO 2008, p. 21). Though it does not fundamentally act as a substitution for oil in transportation, biofuel does affect the demand on P, in particular, in corn-based bioethanol production, which in 2010 amounted to 118 Mt (see also Sect. 5.2.9). Scholz (2011b) identifies and discusses the trade-offs of large-scale bioethanol production, and concludes that bioethanol may not be considered a renewable energy because of the additional use of non-renewable rock phosphate fertilizer and additional agricultural land extension. According to the International Fertilizer Industry Association (IFA):

> High crude oil prices provide strong incentives for biofuel production. This also pulls up agricultural commodity prices, which stimulates intensification and higher fertilizer applications. (Heffer and Prud'homme 2011)

It should be noted that the trade-off between competing uses of phosphorus and biofuel in various manners is a salient historical conflict. Cow dung may be used as fertilizer or fuel, and grass may be used as biofuel to feed plow- and carthorses or livestock animals.

2.5 Virtual Phosphorus Flows

By referring to virtual or unintended flows of phosphorus, we denote that these flows are included in the production of goods and commodities in which phosphorus is embodied, but phosphorus is not targeted or officially recognized. Research on material flows in Japan (Matsubae-Yokoyama et al. 2009; Matsubae et al. 2011) revealed that the quantity of phosphorus in iron- and steel-making slag is of the same percentage compared with the phosphorus contained in phosphate rock.

> Importantly, the results show that our society requires twice as much phosphorus ore as the domestic demand for fertilizer production. The phosphates in "eaten" agricultural products were only 12 % of virtual phosphorus ore requirement. (Matsubae et al. 2011)

Clearly, “our society” in the last quote refers to “Japanese society,” which, among others, has a strong car production-related heavy industry. But there are other nations with a large share of industrial metals and other processes which include “non-accounted” phosphorus flows. Thus, “virtual” industrial use is an important part of the anthropogenic phosphorus cycle. In principle, virtual flows represent a sort of secondary feedback loop (Scholz 2011a). As we engage in the production of steel or another commodity, we severely affect the phosphorus cycle. What this means, what impact these phosphorus flows have on the ecosystem or whether the phosphorus may be used as nutrient at some time is an open question. We may also reflect about virtual flows of phosphorus by trade of commodities and their potential multiple impacts.

2.6 Phosphorus and Technology Development

A small share of mined phosphorus (about 3 %) is used for technical non-food purposes (see Spotlight 8, Gantner et al. 2013). *White* phosphorus (P_4) is the most common intermediate for a wide range of P4-containing products. In addition to the use of phosphorus in lighting, there is a wide scope of technological applications, ranging from superconductivity and energy storage (lithium-ion batteries) to warfare implements such as bombs and nerve gas (see Spotlight 8, Gantner et al. 2013), which are based on different forms, or allotropes, of phosphorus such as red or black phosphorus for batteries (Park and Sohn 2007).

3 Critical Issues of Phosphorus Management: Phosphorus as a Case of Biogeochemical Cycle Management

Sections 3 and 4 address the critical aspects of phosphorus flows, including impacts such as pollution, health-related food security issues, scarcity, innovation demands for phosphorus fertilizer, geographical distribution, and price volatility. Section 4 takes a substance flow view, focusing on sinks and losses, for preparing CloSD Chain management. As we noted in Sect. 2.3, phosphorus atoms are not lost from the earth. But they may be removed from the human value chain *temporarily* or *forever*, e.g., through erosion. We elaborate that there are different types of *losses* and *mobilizations* of phosphorus by human activities that may be considered critical.

3.1 What is Critical?

Technological development has changed human life and increased human wealth and health. Most notably, technology has increased human longevity and, therefore, is a direct contributor to population growth. We have determined from Fig. 7

that the tremendous increase in the use of phosphorus, such as the option of using this element in other fields, is highly related to technology development. Humans have become masters of "digesting at the periodic table" (Johnson et al. 2007), and as such, the global biogeochemical cycle of an increasing number of elements is dominated by anthropogenic activities.

The criticality of minerals has been defined by a criticality matrix with dimensions of importance and availability (National Research Council 2008). Graedel et al. (2012) even suggest a methodology of assessing metal criticality when focusing on *environmental implications*, *supply risk,* and *vulnerability to supply restriction* (Erdmann and Graedel 2011). These dimensions are assessed differently depending on the scale, i.e., whether a company-, state-, national-, or global-level view is taken.

In this section, *criticality* of a system is linked to a state of a human system that may become subject to undesired, drastic alteration, or negative change dynamics. This may be related to environmental, social, or economic issues both from a cause and from an impact side. We consider the use or management of phosphorus *critical* if a human system is exposed to threats and the use or deficiency of phosphorus will cause adverse or unwanted impacts which endanger the vitality of a system.

Given the current discussion both in risk research and sustainability science, this brings us straight to the concepts of *vulnerability* and *resilience* (Adger 2006; Aven 2011; Scholz et al. 2012; Holling 1973). From a sustainable phosphorus management perspective, it is not only of interest how *sensitive* a human system is that is *exposed* to certain threats but rather how *fast* or with *what efforts* a system may cope or adapt if a negative event (*threat*) has factually occurred. Threats with respect to phosphorus management may be low agricultural yields due to nutrient deficiency or eutrophication of aquatic systems. Traditionally, *exposure* and *sensitivity* are the core concepts which define *risk*, at least from a human and environmental health perspective (Paustenbach 2002). The inclusion of the adaptive capacity (after being exposed to a known threat) transfers *risk* to *vulnerability* assessment (Metzger et al. 2008; Scholz et al. 2012). A challenge may be to assess for a specific human or environmental system how resilient it is with respect to deficiency or abundance of phosphorus.

Vulnerability may be considered as *specified resilience*. A system is denoted as resilient with respect to (a known) risk, if it has the ability to recover to a (acceptable) vital level in a tolerable time. The vulnerability assessment may open new research perspectives for research. We want to note that this type of research will be shaped by quantitative and qualitative analysis. This holds particularly true if the *general resilience* of a system is targeted. General resilience may be described as the ability to cope with the (still) unknown (threats). The challenge is to establish a kind of (environmental) system limit management capability, e.g., to provide access to needed phosphorus inputs and to avoid harmful doses.

Criticality in the following refers to these ideas. Criticality and vulnerability have been widely synonymic used in adaptation to climate change (Bohle 2001). Another interpretation of criticality goes back to network analysis. We are talking about floats or buffers in resource constraint networks and identify critical paths which may harm the system's performance (Bowers 1995). The idea of indispensability was used for defining criticality of metals in the supply chain of technical systems (Reller et al. 2013). This idea, which looks at resources filters and barrier of supply chains (Krohns et al. 2011; Reller 2011), may become of interest also for phosphorus. In the latter notion, criticality may differ from vulnerability as it is more focusing on sensitivity than vulnerability (Scholz 2011a).

This section looks at critical trends in essential domains such as food security or ecosystem health. We also discuss technology lock-in and market imponderability, both of which are barriers to advancement and which may promote vulnerability. In general, this section is intended to properly identify *critical aspects* that should be addressed in sustainable phosphorus management.

3.2 Phosphorus as a Pollutant

Phosphorus is a highly reactive element and may thus function as a "secondary pollutant." Sedimentary phosphate rock may include heavy metals, toxic elements, and other precious elements. This may induce long-term critical contamination of soils (Nicholson et al. 1994). With respect to cadmium (Cd) in phosphate fertilizer, we find contradictory risk assessments. In Europe, strict regulations on the cadmium concentration in fertilizers are under discussion. Concentrations between 20–60 mg Cd/kg P_2O_5 have been discussed as thresholds (Chemicals Unit of DG Enterprise 2004). Fertilizer concentrations above this domain are expected to result in critical long-term soil accumulation (Nziguheba and Smolders 2008). These conclusions were drawn from a precautionary perspective. This is justified by the short-term irreversibility of heavy metal soil contamination, which cannot be reduced in a short term if big areas show a critical cadmium concentration. There is a wide range of Cd concentration in fertilizers, yet most of the sedimentary phosphate rock shows concentration below 100 mg/kg (Roberts in print). During the processing of phosphate rock with sulfuric acid, e.g., for fertilizer production, much cadmium is deposited in gypsum. A comprehensive human risk assessment is difficult to construct and is not yet sufficiently developed. There is a wide range of Cd concentration in fertilizers depending on its origin of phosphate rock concentrates (Roberts in print). Thus a differentiated view on the phosphate rock and the heavy metal concentrations (i.e., the purity of fertilizer) may become a subject which asks for a comprehensive assessment.

In general, an overabundance of phosphorus in the aquatic environment from all sources will cause eutrophication, algal blooms with "dead zones" (i.e., hypoxic zones) and fish die-off in lakes, rivers, and oceans. Similar pollution of water bodies also affects drinking water quality. Here, for instance, the UK Water Supply Regulation (MacDonald et al. 2011a) defines a maximum value of 2,200 mg P/l. This value, however, must be seen relative to estimations of no-effect levels of human uptake. Here, longer-term studies (6 weeks) showed that dosages up to

3,000 mg/day did not elicit adverse effects (EFSA Panel on Dietic Products Nutrition and Allergies 2005). This reference value is currently under re-evaluation.

We argue that water systems are the most sensitive environmental compartment. Diaz and Rosenberg (2008) identified 400 systems throughout the world with hypoxic zones. When assessing the critical load of phosphorus, we should distinguish between the geogene and the anthropogene. Phosphorus in its natural ecological state is released by weathering and transported by runoff and rivers to the sea, where it is a cornerstone of marine life. On the other hand, there are freshwater systems, such as alpine lakes, which have very low natural phosphorus content; these systems are highly sensitive to additional phosphorus input. Against this background, it is difficult to define standards for aquatic systems with respect to phosphorus loads. According to Dutch environmental thresholds, a concentration of phosphorus below 0.1 mg P l^{-1} is considered critical to stave off eutrophication and protect ecosystem health (van der Molen et al. 2012), but this value depends on hydrological and other factors.

Eutrophication, due to perpetual algal blooms, became a problem for the Great Lakes of North America in the 1950s. The blooming algae prevented the sunlight from reaching the lakes' deeper domains. As the algae died, the microbes responsible for the breakdown of decay on the lake bottoms began using the oxygen dissolved in the lakes' water. The lakes became green and malodorous, and an alarming fish die-off occured. At the height of the issue, research was engaged to discover the genesis and impacts of this phenomenon.

Synthetic phosphate products, and in particular, sodium tripolyphosphate (STPP), had been added to detergents on a large commercial scale since 1948. From the 1940s to the 1970s, raw wastewater effluent increased from 3 to 11 mg l^{-1} (Litke 1999). STPP has the property to bind magnesium and calcium ions, and thus the ability to increase the effectiveness of detergents. Environmental chemists provided clear evidence that phosphorus from all sources was a major source of eutrophication (Stumm and Stumm-Zollinger 1972). And detergents contributed significantly. In 1983 and in the United States alone, 2 Mt phosphorus was annually used for detergents.

The scientific community made the first real effort to understand the eutrophication process and problem (Knud-Hansen 1994). Regression models were applied to the contamination of the lakes (Vollenweider 1970). After 1977, with the introduction of the US Environmental Protection Agency's (EPA's) "Detergent Phosphate Ban," several US States and European countries banned phosphorus-containing detergents. Following the ban, the industry voluntarily offered laundry detergents free of phosphate. However, phosphate-containing dishwashing powders remained, as no economic substitute could provide the same performance and satisfy consumer demands. The effect of STPP in detergents is due to its ability to bind minerals and metals and does thus "enable cleaning components of the detergent to act" (Global Phosphate Forum 2012).

From their very inception, the role of detergents in eutrophication has been disputed. For one camp of detractors, detergents seemed "the devil in disguise, and the less we had to do with it the better" (Emsley 2000b, p. 270). Others provided loose calculations such as: "if detergents make 30 % of the total phosphorus of domestic wastewater and the wastewater discharge represents only 25 % of the phosphorus load to the lake, a ban would provide a reduction in only 7.5 %" (Lee and Jones 1986). If we were to introduce (full) phosphorus precipitation or biological extraction in the sewage plants, phosphorus would be an ideal additive to detergent, in particular as zeolite. Zeolites, the primary substitute for STPP, perform better, based on a cradle to grave-based life cycle analysis (LCA) for sites with very advanced wastewater treatment plants (such as those in Scandinavian countries). The LCA recorded roughly the same environmental performance in the UK, which features relatively simple sewage cleaning systems (Köhler 2006). Compared with human excreta, the contribution of phosphorus-based detergents was, and continue to be (in those places where STPP-based products are still used), relatively low. Thus, whether a phosphorus ban on detergents is effective seems to be site-specific. For developing countries, in which only a minor part of the domestic population is connected to sophisticated wastewater treatment plants, a release of detergent phosphorus seems to be instantly feasible and operationally eco-efficient, as it may provide some environmental effect, but with low costs (Scholz and Wiek 2005).

A lesson learned from history is that water pollution is a complex issue that depends on a variety of historical and situational factors. The role of phosphate is certainly important and must be viewed in relation to other eco-toxicants that eliminate natural zooplankton that in turn consume the algae.

3.3 Human Health and Phosphorus Food Additives

Phosphorus is present in almost any food, though a few products, such as industrially processed sugar, do not contain phosphorus. As outlined in Spotlight 6 (Elser 2013), both a deficiency and excess of phosphate in food may cause health issues. In that light, phosphorus-based food additives deserve a special review. Disodium phosphate (DSP) and STPP are used to improve the texture of ham and other meats, and phosphate is used to avoid weight losses in humans. DSP and sodium aluminum phosphate are used in producing processed cheese and to process milk. Trisodium phosphate "is considered too risky to be used in general cleaning products, but it is still used to remove food-poisoning germs from raw chicken" (Emsley 2000b, p. 264). Bacteria such as salmonella on surface fat of the carcass are washed away with a trisodium phosphate solution. This procedure was patented and received approval from the US Food and Drug Administration (FDA) in 1992 (Emsley 2000b).

Regarding phosphate additives in general, and STPP in particular, the critical question is how sensitive the human health system may be. The chemist Emsley provides a relaxed view:

> Even when the food additive is STPP, which is the commonly used dishwater and laundry detergent component, it is deemed safe because the body is plentifully equipped with phosphatase enzymes that can break down this complex phosphate into simple phosphate. (2000b)

According to our current knowledge, the use of phosphate suggests that the human metabolic systems are fairly well equipped and robust with respect to the processing of phosphate and phosphate-based acids, at least for most forms in medium doses. In what domains there are limits, and where and whether we may identify more "concealed effects," is yet to be determined. Such has been the case with phthalates, whose (estrogen) health impacts have been identified, but whose real effect is still elusive (Halden 2010)—even after more than two decades of intense research.

The daily uptake of phosphorus between countries widely differs and depends on the diet. European countries show mean dietary intakes of 1,000–1,500 mg P/day (EFSA Panel on Dietic Products Nutrition and Allergies 2005). The recommended intake for adults between 19 and 65 years is 700 mg P/day, the highest recommended value is for adolescents between 10 and 19 years and is 1,250 mg P/day (DACH 2008). Given normal health conditions, there is no evidence for negative health impacts by normal Western diet (Schnee et al. 2013).

3.4 Innovation Potential of Fertilizers

We describe the early history of chemical phosphorus fertilizers in Sect. 1.2. The big gray box of Fig. 21 presents the main wet processes for producing fertilizer, e.g., single superphosphate (SSP), nitrophosphate (NP), monoammonium phosphate (MAP), diammonium phosphate (DAP), triple super phosphate (TSP), the common NPK fertilizers, and others. These wet processes are acid based and are linked to high amounts of waste, energy use, and water consumption. In its basic sense, the wet process is more than 100 years old (see Chap. 6, Herrmann et al. 2013).

Perhaps, because phosphorus fertilizer may be considered a low-cost commodity, technological processing has not yet attained high efficiency with respect to waste and to purity. Zhang et al. (2008) consider the amount of gypsum and other waste such as phosphate slag as one key environmental indicator for improving phosphorus fertilizers. There are about 5–7 mt of phosphogypsum produced for each mt of sulfuric acid-based wet-process phosphate fertilizer via the sulfuric acid route. "There are currently about 1 billion tons of phosphogypsum stacked in 25 stacks in Florida (22 are in central Florida) and about 30 million new tons are generated each year." Phosphogypsum includes high percentages of calcium and sulfur, e.g., 26 % CA and 20 % S in the case of Richard Bay, South Africa, production line. We should note that there are alterative routes of phosphorus fertilizer production via the nitrophosphate route (SSP, which was once the most commonly used fertilizer) that do not generate any gypsum (IPNI 2013).

The amelioration and valorization of gypsum for use in the construction of buildings and roads and for agricultural purposes is another challenge that requires innovation (Hilton and Dawson 2012). However, the market is limited as there is an abundance of flue gas desulfurization gypsum as by-products from coal power plants (FIPR 2013). Another interesting aspect is that some phosphate rocks contain relatively high amounts of uranium and heavy metals (Schnug et al. 1996). Here, the long-term accumulation in the soil and potential toxicity of the food chain is one consideration, but recovery/recycling of these metals presents an ancillary opportunity. This toxicity concern is primarily linked to cadmium, as has been mentioned in Sect. 3.2. Under what constraints what cadmium concentrations in fertilizers may cause adverse health effects is assessed with deterministic risk assessment methods (Woltering 2004). There is no evidence that cadmium in fertilizers may cause health risk in the near future.

Most phosphorus fertilizer is from phosphate rock of sedimentary origin. "The average cadmium content in European fertilizers is 138 mg/kg phosphorus" (Finnish Environment Institute 2000, p. ii). Given the data about cadmium in rock phosphate from different mines in the worked used for fertilizers reported by Roberts (in print), these concentrations seem to be surprisingly high (Chemicals Unit of DG Enterprise 2004). A large share of the phosphorus fertilizers used in Finland, for instance, are from the igneous form of phosphate rock and has a cadmium concentration from 1 to 5 mg/kg P (Finnish Environment Institute 2000).

Given that phosphatic uranium could cover the current rate of uranium consumption for some centuries (Schnug et al. 1996; Hilton and Dawson 2012), the option of mining and meaningfully using this uranium and other heavy metals is a key challenge in sustainable resource management. The above aspects refer to the first stages of the phosphorus supply chain. From a chemical engineering aspect, we may clearly identify the potential for the extraction of heavy metals and uranium by efficient means. Whether this may become economically feasible depends on the accessibility from conventional uranium deposits. In this scenario, however, a sophisticated assessment of the long-term application of fertilizer related to different crops is missing.

If we look at the aspect of use, we can see three or four further opportunities for the innovation of fertilizer. The *first* is the improvement of the "compounds" contained in organic and inorganic fertilizer. Compounds, on one hand, are heavy metals, radionuclides, and pathogens associated with manures and sewage-based products. Here, the economic extraction of heavy metals or radionuclides from phosphate rock with high concentration may be considered an innovation. On the other hand (VFRC 2012), there is an emerging deficiency of micronutrients such as zinc (Zn), manganese (Mn), iron (Fe), sulfur (S), and even boron (B), a situation that may require much more sophisticated fertilizers in the future.

Second, the challenge will not only be the site-specific optimization of the currently available phosphorus. Rather, we see that the relationship among soil–plant/species–fertilizer should be viewed from a prospective, *dynamic perspective* (Zhang et al. 2002, see Fig. 8). At the least, large-scale farming should anticipate

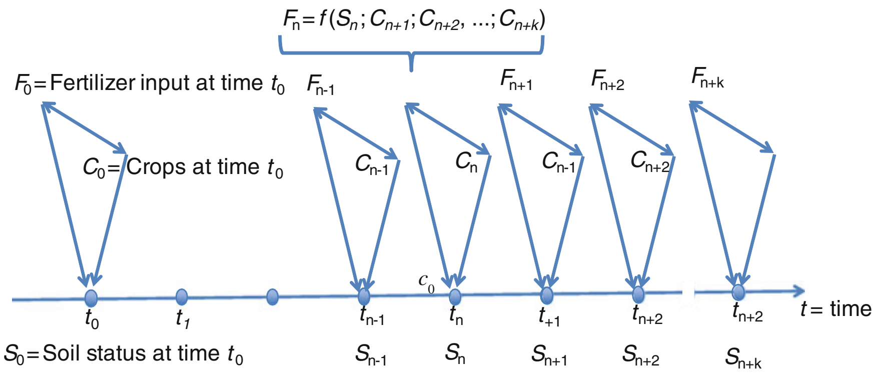

Fig. 8 Dynamic precision crop rotation asks that at any time t_0 the decision of what amount and type of fertilizer should be added does not only depend on the soil status S_0 and the specific crops C_0 but also depends on the prospective crop grown at that time C_{n+1}, …, C_{n+k}

prospective cropping and available phosphorus, and thus, apply prospective balancing. But this problem may require a biotech solution. When water-soluble phosphate fertilizers are added to the soil, a significant portion not taken up by the plant is converted to less plant-available forms that may or may not become available again in the near term. These less soluble forms result from the pH-dependent reactions of phosphate with iron (Fe^{3+}), aluminum (Al^{3+}), calcium (Ca^{2+}) and magnesium (Mg^{2+}) ions that are present in the soil. Some plants, however, possess biological properties (including enzymes) that allow them to utilize phosphorus from these less soluble forms. This capability opens up other opportunities for technological innovations to either produce new fertilizers that are responsive to the soil and plant enzymes or to transfer this capability to other plant species.

Third, we may consider *seed coating and pelleting* as another form of innovation. This idea originated in the 1940s and is common in sugar beet (Vogelsang 1950) and cotton, but may be applicable to other crops (Fig. 9). The advantage is that the fertilizer is optimally placed in the rhizosphere. The pellets may be processed to include fungicides, pesticides, or micronutrients, if necessary. Naturally, we must carefully reflect under what constraints of farming such technologies make sense. Clearly, the coating in itself is not sufficient to improve plant growth. But here, the coating is a concept that has the opportunity to improve efficiency. With respect to nitrogen, the coating may also have positive effects from a use-efficiency perspective. We should mention that in general, the coating of the seed usually only contributes a minor, but important start-up fertilization of the root zone.

To ensure that one has a complete picture of P, one must recognize that though many phosphorus fertilizers are water soluble, phosphorus in the soil is virtually immobile. The leaching of phosphorus to groundwater is not a common occurrence and thus not a major issue (Hesketh and Brookes 2000). Losses are primarily related to erosion of soil particulate matter containing P.

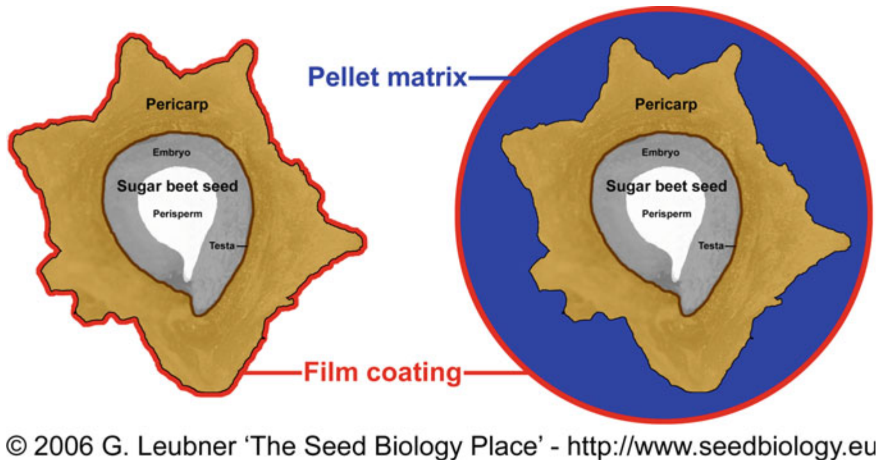

Fig. 9 The coating of the sugar beet seedling is successfully applied (figure taken from Leubner 2013)

Fourth, the amelioration of organic fertilizers from different types of manure, from compost or peat to sewage may require low and high technologies. Here, not only soil-biological knowledge and plant-biological knowledge are required, but also the understanding of comprehensive transdisciplinary processes, including the collaboration of key stakeholders from a given region to assess whether the technology is "sociotechnologically robust." In particular, this may hold true for "smart" manure management.

3.5 Geographical Distribution of Phosphorus Reserves and Resources

The availability and accessibility of phosphorus supply may be endangered by geopolitical risks. A common method of assessing the risks that a country may not be able to deliver (phosphorus) minerals is through the Worldwide Governance Index (WWGI) (Kaufmann et al. 2009). In WWGI calculations, political stability is a critical aspect. A second dimension that is usually considered is the global *supply concentration*, which is measured by the Herfindahl–Hirschmann Index (HHI) (Scholz and Wellmer 2013; Graedel et al. 2012). The first important question when applying the WWGI and HHI is whether the reserves, the beneficiation sites, and the fertilizer production sites are integrated. Figure 10 presents the two aforementioned indices for metals and minerals. As a rule of thumb, values outside of the medium domain are considered risky.

We may take from Fig. 10 that *phosphate production* is in the non-critical domain (within the medium). The *reserves* show a critical tendency in the WWGI

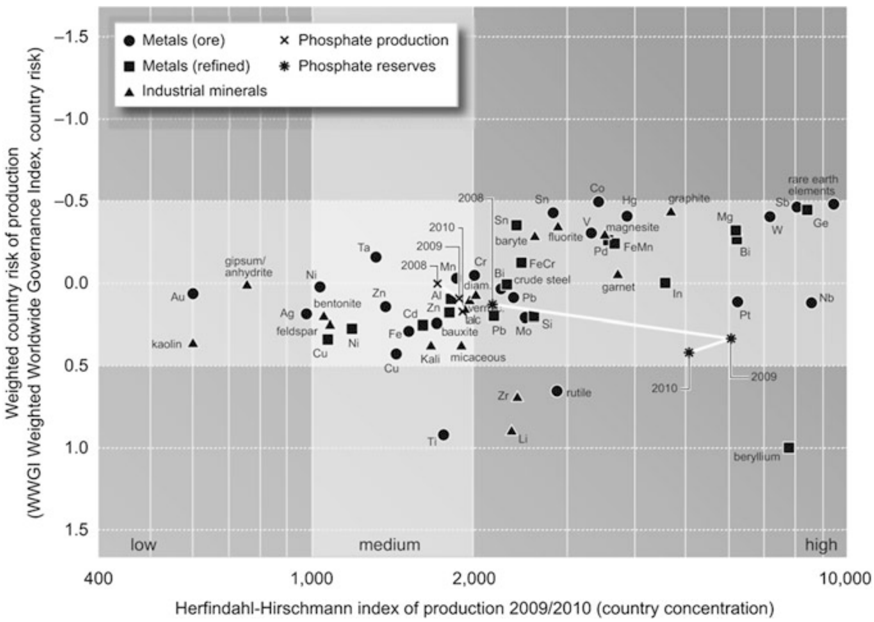

Fig. 10 Linkage of the Herfindahl-Hirschmann Index (HHI) (figure according to Deutsche-Rohstoffagentur/BGR 2011, present version taken from Scholz and Wellmer 2013, p. 15) with the Weighted World Governance Index (WWGI, data from Jasinski 2009, 2010, 2011a, 2012; Kaufmann et al. 2011) for production. "*" Presents the HHI for phosphorus reserves

due to increasing political instabilities in many *countries* in North Africa and the Near East, which began in late 2010. The strong increase in the reserve-based concentration index is due to the increase in the Moroccan data from 5,700 Mt of PR in 2008 to 50,000 Mt in 2011.

We should also note that the essential element potash shows a high concentration with respect to reserves. Here, two countries, Canada and Russia, have a combined 81 % of the documented potash reserves, where Morocco and China represent 80 % of phosphorus reserves (USGS 2012).

Does the HHI index properly represent the *supply* concentration in the case of phosphorus? Does the graphical increase in the HHI with respect to phosphate *reserves* really mean that the world is facing increased supply vulnerability? As we will show, this is not necessarily the case. Let us look at the data. Before 2009, Morocco had only 33 % of the 16 Gt of PR world resources (USGS 2010). In 2011, it had 70 %, or 50 Gt of the 71 Gt of PR world resources. The HHI suggests "increasing geographical concentration," and an increasing dependency on Morocco. Upon further inspection, one may argue that the dependence on Morocco has decreased, because the non-Morocco reserves increased from 11 Gt of PR before 2009 to 21 Gt of PR after 2011. If we roughly calculate with a (current) annual demand of about 0.2 Gt of PR annually, one may argue that the static lifetime without Morocco has increased from 50 to 100 years (which is roughly the 2010 static lifetime of titanium). We should take from this that the HHI index of reserves does not represent the demand-related abundance/scarcity of the commodity and, despite the large reserves in Morocco, there are sufficient options to avoid a dependence on one major provider—even if recycling options are not taken into account.

3.6 Phosphorus Scarcity: Physical or Economic?

Historically, concerns have emerged repeatedly regarding the potential scarcity of phosphorus. US President Franklin D. Roosevelt addressed fundamental aspects of sustainable phosphorus management in his Message to Congress on Phosphates for Soil Fertility, May 20, 1938[1]:

> The necessity for wider use of phosphates and the conservation of our supplies of phosphates for future generations is, therefore, a matter of great public concern. We cannot place our agriculture upon a permanent basis unless we give it heed.
>
> I cannot overemphasize the importance of phosphorus, not only to agriculture and soil conservation, but also to the physical health and economic security of the people of the Nation. Many of our soil types are deficient in phosphorus, thus causing low yields and poor quality of crops and pastures …
>
> Recent estimates indicate that the removal of phosphorus from the soils of the United States by harvested crops, grazing, erosion, and leaching, greatly exceeds the addition of phosphorus to the soil through the means of fertilizers, animal manures and bedding, rainfall, irrigation and seeds …
>
> It appears that even with a complete control of erosion, which obviously is impossible, a high level of productivity will not be maintained unless phosphorus is returned to the soil at a greater rate than is being done at present …
>
> Therefore, the question of continuous and adequate supplies of phosphate rock directly concerns the national welfare …
>
> It is, therefore, high time for the Nation to adopt a national policy for the production and conservation of phosphates for the benefit of this and coming generations. (Roosevelt 1938)

We can see from this passage how the basic principles of phosphorus management had already been keenly identified by the 1930s. The prevalence of concern over phosphorus can be illustrated by Aldous Huxley, who used the absence of phosphorus recycling as an example of technological entrapments in his very serious 1928 novel, *Point Counter Point*:

> "With your intensive agriculture," he went on, "you're simply draining the soil of phosphorus. More than half of one percent a year. Going clean out of circulation. And then the way you throw away hundreds of thousands of tons of phosphorus pentoxide in your sewage! Pouring it into the sea. And you call that progress. Your modern sewage systems …" (quoted according to Ulrich 2011)

[1] We wish to thank Andrea E. Ulrich for hints in the historic sourcing.

The physical scarcity, the finiteness of rock phosphate reserves, and the dissipation of phosphorus have been recently brought to the fore again by Cordell et al. (2009):

> However, modern agriculture is dependent on phosphorus derived from phosphate rock, which is a non-renewable resource and current global reserves may be depleted in 50–100 years. While phosphorus demand is projected to increase, the expected global peak in phosphorus production is predicted to occur around 2030. (p. 292)

Though this statement has been frequently cited, this alarmist statement does not adequately describe the scarcity issue. As Scholz and Wellmer (2013) conclude, the Cordell et al. analysis is (a) applying an inappropriate mathematical model; (b) ignoring basic geological data; and (c) ignoring the dynamics of resources and reserves which are given in a demand-driven market. In the case of phosphorus, scarcity is an *economic* issue. *Ceteris paribus*, there are enough resources that may become reserves within feasible production cost ranges for phosphate rock for at least some centuries before a purported "peak" in resources occurs. Extraordinarily, high phosphorus prices, production peaks, or the volatility of prices (see Chap. 9, Figs. 3 and 5) are not due to physical scarcity, but rather, due to other reasons such as bubbles in the financial markets, imbalances of supply and demand, unfruitful prospecting efforts in the mining industry, geopolitical effects and many other factors (see Chaps. 2 and 7).

The mathematical model applied by Cordell et al. (2009) is the Hubbert curve fitting (Hubbert 1956; Brandt 2010). This model assumes that for a finite deposit, production may be described as a bell-shaped curve (logistic curve, Gaussian curve, etc.). The curve has been very successfully applied for predicting the "Peak Oil" in US production, though the actual curve more closely resembles a log-normal curve than a normal curve. We acknowledge that the Hubbert curve may show high validity dynamics for US oil production (if we exclude unconventional forms of oil production such as oil shale production). But, as the paper with the indicative title "Peak Nothing" (Rustad 2012) indicates, for most minerals, and even for oil, we are facing different dynamics, including multiple peaks, plateaus, and other issues:

> Although many resources have exhibited logistic behavior in the past, many now show exponential or superexponential growth. (Rustad 2012)

As Scholz and Wellmer (2013) elaborate, Hubbert curve modeling may be applied for limited resources with a supply market structure. Thus, in cases such as nineteenth century guano production or current US oil production, you may assume that (annual) production increases due to increasing exploration, expertise, technology, equipment, etc. until a certain peak is attained. Then, in a second phase, the production declines as the mined resource becomes more difficult to access due to location, decreasing ore grade and other issues. Supply-driven markets show no saturation and—in principle—take everything that is available. This is definitely not the case for phosphorus. If we refer to the recorded reserves by the US Geological Survey (USGS) of 71 Gt P and the annual demand of

200 Mt P year^{-1} (=0.2 Gt P), then look at the data for fertilizer demand, it is easy to see that the market may be saturated for a good length of time.

Cordell et al. (2009) simply take USGS data from 2009, which was 16 Gt P, add the former cumulative production to this value (thus figuring what Hubbert modelers call the Ultimate Recoverable Resource [URR]), and fit a Gaussian curve to past annual production data applying least square technique. Based on this formula, "Peak 2030" and "depleted in 50–100 years" are inferred. However, the documented reserves increased; in 2012, they were 71 Gt P. Cordell et al. (2011, April 4) then revised their 2009 calculations using (USGS 2010) data of 60 Gt P, which resulted in a peak around 2070. It should be noted that usual Hubbert curve modeling does not refer to an estimated URR. Some authors (Déry and Anderson 2007; Ward 2008) provide applications without referring to the URR, which Cordell et al. simply assess by adding the formerly mined (cumulative) phosphate rock with the USGS data.

We also know that some reserves of the USGS survey are underestimated, and large reserves from other countries such as Saudi Arabia, USA, Peru, Kazakhstan (Evans 2012) or the largest reserves in Europe, i.e., Estonia, have not been comprehensively assessed to date though resources of more than 250 Mt P have been already identified in surface rock just for this country of the Baltic Basin (Äikäs 1989).

An estimate without a URR is provided in a paper by Dery and Anderson (2007). This application suggests a URR of 8–9 Gt P, of which, about 6.3 Gt have already been mined. Similar extraordinary underestimation is also reported in a paper by Ward (2008). Here, the application of the Hubbert provided an estimate of 11 % of the mined or known reserves. It should be noted that these papers are mostly published in unreviewed journals.

But the physical scarcity judgments also ignore geological data. There is geological evidence that many current PR resources may become reserves. If one considers the history of exploration of the Western Phosphate Field (WPF) in the United States (Jasinski et al. 2004; Moyle and Piper 2004), or other related literature (such as Volume 8, *Handbook of Exploration and Environmental Geochemistry* (Hein 2004), one can assume that as the price of PR increases, a large portion of these occurrences (along with others) currently classified as resources may become reserves. Since 1904, 70 mines have operated in the WPF; 49 conducted underground mining and stopped when cheaper surface mines began operation or increased production. This illustrates the dynamic boundary between reserves and resources (Jasinski et al. 2004). For example, a price increase by a factor of 2 to 4, accompanied by an improvement in technologies, may make phosphate rock from a discontinued mine more economically viable for a very long time. This point in particular holds true, as phosphorus is a low-cost commodity. Currently, each person consumes about 31 kg of PR per year, with a price of about US $6 per year (Scholz and Wellmer 2013). Given this price level, there is a great deal of flexibility if we simply look at "average global" consumption. However, we should acknowledge that some farmers, and in particular smallholder farmers, are highly sensitive to fertilizer prices. Nevertheless, we may conclude that scarcity with respect to phosphorus, for the foreseeable future, will be an economic issue, though—from a very long time perspective—physical scarcity of mineable ores may emerge.

3.7 Inefficient Use

Efficiency has become a key term in resource management. Simply stated, "efficiency" targets an increase in the input–output relationship. One critical point is that efficiency relates to specific systems (e.g., an individual, company, society, or a world scale) and to a certain time frame. What may be efficient in an accounting cycle may be inefficient from a company life cycle or a societal or ecosystem perspective. How "inefficient use" is defined must be specified case by case. From the chosen system theoretical view on sustainability, "an ongoing inquiry on system limit management in the frame of intra- and intergenerational justice" (Laws et al. 2004), it is clear that a global long-term perspective should include the economic and social perspectives. However, acknowledging the multi-level nature of human-environment systems (Scholz 2011a), it is clear that efficiency must be viewed from many perspectives, from the consumer via smallholder and industrial farmers to high-tech companies, and from mining companies to geological services, to mention a few. All of them are challenged in the systems scale, but single-scale efficiency must be reflected in a contextualized larger scale. In some cases, this may require the framing of phosphorus management, e.g., by national or international rules or (environmental) laws.

We reveal in Sect. 2.3 that efficiency is neither a necessary nor sufficient condition of sustainable transitioning. However, given the challenges of twenty-first century human development, it is clear that sustainable phosphorus management on a global scale is not meaningful without efficiency along all steps of the supply chain, i.e., exploring, mining, processing, use and dissipation and recycling. Exploration should be efficient in the sense that we must reflect on how much manpower and money we have to invest in the assessment of reserves, given current knowledge and future demands. It should be acknowledged that efficiency is not absolute. Rather, it is relative to technologies and context, and also to the options of improving efficiency in other domains. Here, we speak about cross-sectional efficiency, or operational (eco)efficiency (Scholz and Wiek 2005). In practice, this means that the improvement of efficiency at one stage of the phosphorus supply–demand chain (how much improvement does one get for how much investment) must be considered relative to other stages and other elements, for instance, nitrogen.

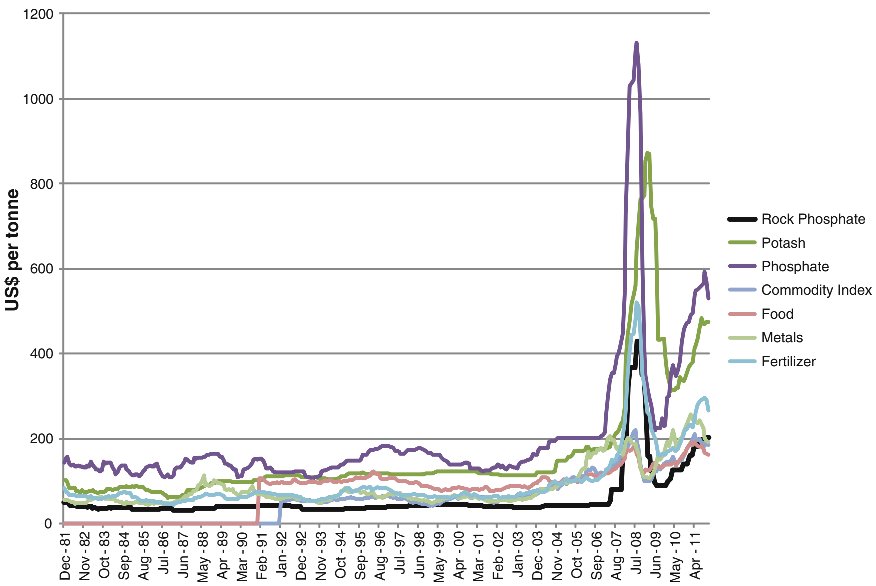

Fig. 11 Price dynamics for rock phosphate, food, commodity index, etc. in US$ per metric ton (graph with the courtesy of Olaf Weber)

3.8 Price Volatility

Price volatility of fertilizer has remained high since 2007/2008. This has strongly affected farmer access to fertilizers, particularly the smallholders in less-developed countries. This is one of the main conclusions in the analysis of Weber et al. (2013), featured in Chap. 7 of this book. In the 2007 peak, prices were closely linked to those of other commodity markets (see Chap. 7, Fig. 5). It is clear that *energy prices* affect phosphorus fertilizer production, in particular those related to nitrogen such as DAP and MAP, and transportation. The level of energy intensity can be traced back to different crops (Mitchell 2008) and has lingering effects on transportation. Figure 11 presents grain, nitrogen, and PR prices over the last five decades. One may observe that there is a step-like increase after the 1973 oil crises, with fairly constant price-level increases over the following three decades. However, around 2002, there is a sharper increase, culminating in a historic peak in 2008. We should acknowledge, however, that econometric analysis reveals that fertilizers experienced much higher (standardized) annualized volatility in 1974 than in 2008 (see Weber et al. 2013). It is important to note that both volatile periods have been linked to world food crises.

In an analysis of the 2008 price peak, specific effects are identified. US fertilizer production declined 42 % between 2000 and 2008 and production capacity could not be quickly adapted. In 2008, dramatic price increases were due to supply–demand imbalances, weather-related crop failures, high energy prices, biofuel mandates, and numerous trade barriers. For example, China, which exported about 3 Mt of urea in 2011 (YARA 2013), imposed an export tariff of 185 % (CNCIC 2008) which contributed to low exports. As a result, world demand could not be met by available supply, affecting global fertilizer price stability. The 2007/2008 food crises may be seen as converging events resulting from this trend.

Given that the demand for food raises crop and livestock prices is a common market effect, the purchase of fertilizer became more attractive, thus increasing fertilizer prices as a result of higher demand.

Often, the argument is made that commodity speculation led by the global financial sector affected the sharp rise in food prices.

> The dramatic rise and fall of world food prices in 2007–2008 was largely a result of speculative activity in global commodity markets, enabled by financial deregulation measures in the United States and elsewhere. (Ghosh 2010)

There is some intuitive evidence to this theory. Speculation in physical markets may be defined as financial activities that are not related to "fundamental" production and commercial activities. Following the collapses of the technology "bubble" and the US housing market, financial investors expectedly shifted to far less risky investments, including commodities. And, as market speculators tend to follow the most active, high-volume trading, it seems plausible that speculation had a hand in the 2007–2008 price spikes. However, this theory cannot be proven by econometric analysis for all commodities (Wright 2011).

Taking an alternative view, we note that according to standard economic theory (Ghosh 2010), speculation—in unbiased markets—can stabilize market prices. This may seem counterintuitive, but it does meet economic theory:

> … the existence of a derivative market increases in the long term the level of inventory. Indeed, suppose a commercial hedger (for its physical stock) needs a counterpart to hedge it, and there is no hedger accepting the risk (counter position) business… In the opposite, a liquid derivative market will ensure the hedger to find a counterpart, which can be a commercial trade or a speculator… A liquid derivative market leads to larger stock, which in turn lowers the volatility, as it can act as a buffer to mitigate supply (or demand) shocks. Speculators help to increase the liquidity of the market. (Ott 2012)

Thus, there may be both positive and negative effects that financial agents pose in the management of fertilizer price risks. The assertion that speculation had an affect on the 2007/08 commodity price peak could be proven (Sanders and Irwin 2010). Kenkel (2012) points out that there are two main strategies to becoming less exposed to price peaks: *diversification* (e.g., by not being solely dependent on chemical fertilizers), and *hedging* (e.g., buying fertilizer earlier and allowing another party to take the risks inherent in future price volatility), referred to loosely as "insurance." Kenkel estimates that the price volatility of fertilizers represents two-thirds of the price volatility of crop-related commodities.

4 What is Wrong with the World's Phosphorus Flows?

This section is devoted to the review of global phosphorus flows, with a focus on identifying the characteristics that may be viewed as *critical from a* general *sustainability perspective*. We subscribe to a general definition of sustainability, which refers to *sustainable development* as an *ongoing inquiry on system limit management in the frame of intra- and intergenerational justice* (Laws et al. 2004). The phrase "ongoing inquiry" reflects that we do not know exactly what is and is not sustainable, and that we must continue to explore the question. *In order to avoid the negative aspects*—in the context of this book—we must be critical in identifying ways of utilizing phosphorus that may induce unacceptable risk or vulnerability with respect to famines, environmental degradation, economic crises, etc.

One of the other aspects is "intra- and intergenerational justice." This aspect of phosphorus management refers to the "needs component" of the Brundtland (1987) definition. In the European discussion on sustainability, this has been called "sustainability as a regulating idea" (Minsch et al. 1998). We are aware that this includes a normative component. But goals such as "providing access to phosphorus to the poor" or "human beings far into the future should have access to phosphorus" ask for a reference point, which is provided by the idea of intragenerational and intergenerational justice, which are included in the presented definition of sustainability. We should note that this section also lays the foundation for the use and a critical view on the Global Material Flow Analysis, which is presented in the following chapter.

Contrary to other essential elements such as carbon, hydrogen, oxygen, or nitrogen, phosphorus does not freely circulate between the earth's spheres. Phosphorus may not be fixed to the atmosphere, as only a marginal amount of phosphorus (about 0.3 Mt P is in the air at any given time) goes into the atmosphere, mainly as dust and sea spray. Given the scale of human development, there is no noteworthy natural recycling to match human need, as the formation of sedimentary rock phosphate and its uplift to accessible mines took tens or even hundreds of millions of years. About 13 Mt of P year^{-1} are released from rocks through natural weathering each year with an additional human-induced input of up to 5 Mt P year^{-1} (Carpenter and Bennett 2011) to the soil system. Similar amounts pass into rivers, lakes, and seas and are deposited as sediments (Emsley 2000b). Ruttenberg (2003) provides an estimate of 20 Mt year^{-1} of phosphorus as a flux from rocks and sediments to the soil by weathering and erosion, causing soil accumulations. However, there is also the opposite flow by lithification and "deep burial," with a "fuzzy" estimate of 9.3–19.5 Mt year^{-1}, indicating that the Emsley estimate may be a reasonable one (for more details, see Sect. 4.6).

Through the natural cycle, phosphorus moves from the land into rivers and the seas. In addition to natural erosion, phosphorus is formed through the decomposition of dead organic material or by the formation of insoluble calcium phosphate that sinks to the seabed as sediment. Fish-eating birds provide some minor recycling from the sea back to the land. Their droppings have built guano deposits on some islands and coasts that represent about 1 % of world reserves.

However, one should acknowledge that, as Smil (2000) stated, there is a "paucity," or lack, of knowledge, as many estimates refer to amounts first published in the 1970s. The inconsistency of some estimates can be illustrated by the estimate of erosion and runoff, considered to be 18–22 Mt P year^{-1} for particulate and 2–3 Mt P of dissolved phosphorus (Smil 2000). This estimate does not align with the Emsley estimate. The Liu et al. estimate (presented in Sect. 2.3) of 36 Mt P year^{-1} from pastures and cropland is even more divergent and shows how critically the existing data should reviewed.

In the following, based on the uncertainty of the data, there will be variances between years, measuring techniques, modeling assumptions, extrapolations, etc. This inconsistency will be a "steady companion." Here we may expect, in many fields, a typical *factor 2 uncertainty* (Fresenius et al. 1995) of quantitative estimations of concentrations in systems which are well known in the specific, but whose extrapolation is linked to uncertainty. For instance, the uncertainties of the estimates of the amount of phosphorus mined each year are certainly below factor 2. Naturally, some data are much more precise, such as data on fertilizer production. And for some data, we may have multiple datasets or sophisticated statistical methods of assessing uncertainty, which may result in much higher accuracy and robustness. But given multiple environmental and economic variability, we must be aware that regional and global data are subject to multiple transformations.

4.1 The Dose Matters: The Ecological Paracelsus Principle

It is difficult to precisely define what is wrong with the phosphorus flows, or to "put it in a nutshell." However, there is no doubt that—independent of the scale of system—we may find a "not too much" principle, expressed by the medieval alchemist Paracelsus (1493–1541) in the following terms: "All things are poison, and nothing is without poison; only the dose permits something not to be poisonous." Paracelsus, who lived during the Renaissance, was a deterministic thinker, rather than a probabilistic one. Thus, he supposed that there is a "threshold" for each living system, beyond which, the exposure to any (chemical) element is negative or toxic. In simple terms, this means that "the dose matters." From an ecological/human health perspective, this means that we may identify for living systems concentrations that are too high for positive performance. This concept aligns with the balanced nutrient supply that any living system should have. Thus, we assume—simply and deterministically—that there is a level of uptake or access $\bar{P}_{\text{crit}}$, beyond which the phosphorus use is considered critical, or negative. In addition, we can construct an ecological Paracelsus principle that

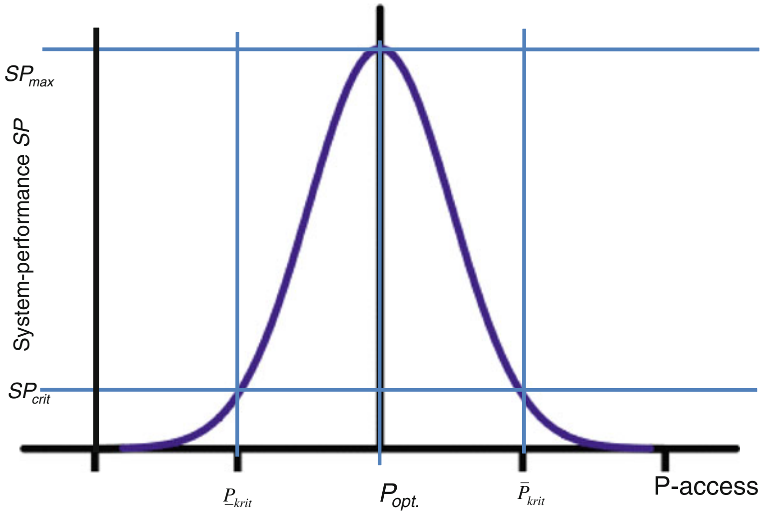

Fig. 12 Illustration of the "not too little–not too much" principle. Phosphorus (P) access (x-axis) with lower ($\underline{P}_{\text{krit}}$) and upper ($\bar{P}_{\text{krit}}$) critical "thresholds," optimal phosphorus use P_{opt} and y-axis with critical (SP_{crit}) and maximal (SP_{max}) system performance level

defines that which makes the use of phosphorus sustainable. Here, "critical" may refer to an ecological or an economic dimension, or both. Likewise, we have critical intake or access $\underline{P}_{\text{crit}}$, under which, the performance may be considered economically or environmentally critical. And there may be an application P_{opt} that is considered optimal. Figure 12 presents the case that we may measure the performance of the system with a one-dimensional parameter SP.

We may speak of an ecological Paracelsus principle, which defines what represents the sustainable use of phosphorus. The uncertainties of the estimates of the amount of phosphorus mined each year are certainly below a factor of 2.

We should acknowledge that from an evolutionary perspective, the tripling of the flows of an essential element such as phosphorus in less than 100 years is considered to be a dramatic and rapid change to the ecosystem grid. Diaz and Rosenberg (2008) conclude that industrialized primary production and the increase in fertilization after the 1940s, and in particular after the 1960s, led to widespread hypoxia. More than 400 "hypoxic zones" with more than 245,000 km^2 have emerged. However, outside of increased nutrient overflow, hypoxia can be caused by a number of other factors, including water stratification due to saline or temperature gradients that prevent mixing of oxygen-rich surface waters with oxygen-poor waters at greater depths. The weight of evidence indicates that in pre-industrialized times, coastal and offshore ecosystems seldom became hypoxic, except in the occasional natural upwelling of cold, nutrient-rich ocean water (Diaz and Rosenberg 2008).

In addition to sea and freshwater systems, an overabundance of phosphorus may also be seen as a threat to terrestrial systems. If we look at biodiversity, we come to more critical judgments on the extraordinary increase in phosphorus flows. Plant ecologists state that, "the use of P fertilizers is unsustainable and may cause pollution" (Hammond et al. 2004). One critical issue is that phosphorus is seen as a cause of the loss of biodiversity, as high phosphorus loads "favor a few species that would competitively displace many other species from a region" (Tilman and Lehman 2001). Or to express this in other terms, "enhanced phosphorus is more likely to be the cause of species loss than nitrogen enrichment" (Venterink 2011). But further evidence is needed to determine under what constraints this may occur (Molina et al. 2009).

Given our current knowledge, the groundwater concentration of phosphorus is not a critical issue if we exclude highly sandy soils. This is obviously due to the very high absorption capacity of soil, which functions as an effective buffer (Smil 2000).

4.2 Finiteness: Securing Long-Term Provision of a Public Good

Though phosphorus is ubiquitous, high-grade igneous and sedimentary PR seams (or layers) are limited. Nevertheless, we may define resource availability as "a sustainable phosphorus cycle if—in the long run—the economically mineable (primary and secondary) reserves of phosphorus increase higher than the losses to sinks (i.e., dissipation), which are not economically mineable" (Scholz and Wellmer 2013).

The dissipative nature of phosphorus is a long-term threat for the sufficient supply of the mineral. In the natural biogeochemical cycle, most of the weathered phosphorus ends its migration into the sea, with only minor amounts returning to the land as guano. The phosphorus reserves that are currently mined cannot infinitely provide high-grade ore phosphate rock.

Though we currently operate with a static lifetime of about 400 years, and we have identified reserves that may be mined at feasible costs over a few thousand years, it seems conceivable that there will be a time for humans in which the mining of phosphorus in conventional form might not be possible. One may argue that one could extract phosphorus from sea water, as the ocean shows a large reservoir of 93,000 Mt P (Scholz and Wellmer 2013). A rough estimate (based on an average concentration of phosphorus in seawater) shows the extraction of phosphorus from seawater not to be a realistic option. The 191 Mt of PR that are recorded by the USGS (2012) per year correspond roughly to 25 Mt P $year^{-1}$. Considering that the volume of the world's oceans is about 1.4×10^{21} l and recognizing that the concentration of phosphorus in seawater varies strongly (depending on oxygen and carbon content), a rough estimation of the amount of seawater required to extract that amount of phosphorus is $4.2 \times 10^{5}\ km^{3}$ (4.2×10^{17} l). This represents about 0.03 % of the ocean's volume.

From an environmental systems perspective, we are facing different timescales within various human systems. With respect to phosphorus, *individuals* are tasked with trying to ensure consumption of nutritious foods with the appropriate dietary amount of phosphorus on a daily basis. This situation is different for farmers, fertilizer producers and other service providers who may maintain stocks, forcing them to consider longer time frames of several months to a year. If one considers the phosphate rock mining companies, the perspective is much longer, from a 50- to 100-year time frame, similar to the planning horizon of coal mines, hydropower plants or urban sewage or water utilities. An additional consideration is that a large share of current world food production is dependent on chemical or mineral fertilizers (see Roy et al. 2013, Spotlight 1), and that—depending on the soil type (Dumas et al. 2011)—there will be a large reduction in the yield without mineral fertilizer use. Naturally, one may think about organic farming or small-scale farming where one seeks out local produce, but here (as previously seen in the small-scale renewable energy sector), the global community is ultimately dependent on large-scale operations with longer planning horizons. In the case of phosphorus, change on a large scale, e.g., for the recycling of phosphorus from sewage and manure, not only requires a long-term planning horizon but technological and economically robust innovations.

4.3 *Different Phosphorus Input and Balances in Various Parts of the World*

From a global and regional viewpoint, phosphorus use has a unique history and will have an equally unique future. Amounts of indigenous soil phosphorus, patterns of consumption, levels of crop production and the resulting nutrient balances vary greatly by regions and countries of the world. In developing the regional trends presented below, data were drawn from different statistical sources; in cases of non-availability of complete phosphorus data, occasionally nitrogen/phosphorus/potassium (NPK) data are reported to build a more comprehensive picture.

Figure 13 presents global and regional fertilizer consumption. We see how sharply eastern European (East Europe) fertilizer consumption declined after the collapse of the Soviet Union, and how sharply Asian consumption has increased since the 1970s.

If we look at phosphorus fertilizer consumption, Table 1 provides insight into the regional differences. With near certainty, world demand will be considerably higher than today when we consider the sum of manure and mineral fertilizers. One reason is the continued increase in meat production/consumption per capita. Meat production is remarkably inefficient on both energy and nutrient scales.

However, future trends in phosphorus application differ in different regions of the world. Sattari et al. (2012) predict an increase in total phosphorus consumption by a factor of 2 in Latin America and Asia by 2050, and a quintupling of the

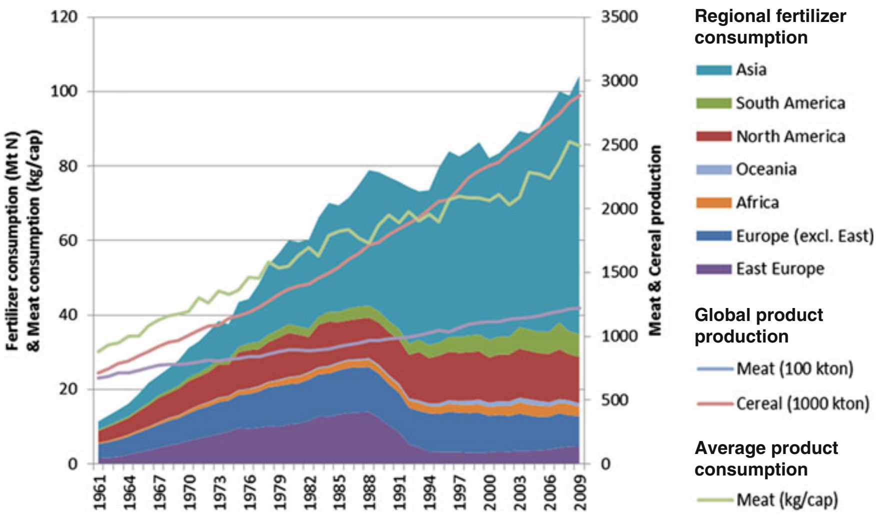

Fig. 13 Trends in total fertilizer consumption, distinguishing different world regions (sum of N, P, and K expressed as N, P_2O_5, and K_2O; Sutton et al. 2013; based on (Davidson 2012; Sattari et al. 2012) and trends of world cereal and meat production (*Source* Our Nutrient World, Sutton et al. 2013)

demand in Africa compared with 1965 consumption rates within a past and future 42-year window. Conversely, the consumption in Europe is expected to decrease by a factor of 2, whereas North America and Oceania are projected to modestly increase consumption.

Table 1 also informs on how the estimation of the average *phosphorus nutrient use efficiency* (phosphorus NUE) changed across the last four decades. Here, we learn that the annual "phosphorus plant uptake ratio" to "phosphorus soil input" increased in Western Europe; this means that the "one-year P nutrient efficiency accounting" dramatically increased. In 1965, the crops in Western Europe extracted 4.9 kg P ha^{-1} $year^{-1}$ given an input of 23.8 kg ha^{-1} $year^{-1}$. In 2007, the extraction was 9.9 kg P ha^{-1} $year^{-1}$ given an input of 17.2 kg P ha^{-1} $year^{-1}$. Thus, the *nutrient efficiency for phosphorus* in Western Europe increased from *phosphorus NUE* = 21 % to *phosphorus NUE* = 58 %, although the fertilizer input increased from 1.9 to 4.1 kg P ha^{-1} $year^{-1}$. Annual fertilizer P input in Western Europe decreased over the time period by 6.6 kg P/ha $year^{-1}$. The phosphorus use efficiency in Africa was *phosphorus NUE* = 95 % in 1967, which means that the balance was slightly negative. In 2007, Africa experienced a *phosphorus NUE* = 76 %, which indicates that P efficiency decreased in Africa.

MacDonald et al. (2011a) provide a profound analysis of phosphorus imbalances, referring to data for the year 2000. The authors state that cereal crops accounted for more than half of phosphorus removal from soils. Further, in 29 % of global cropland areas, there were phosphorus deficits; in 71 % of the areas, there were phosphorus surpluses. The large surpluses, with a mean value of

26 kg ha^{-1} year^{-1}, are found in East Asia, areas of Western and Eastern Europe, and North America, whereas the most widespread deficits may be found in South America, particularly in Argentina and Paraguay. An important issue for global sustainable phosphorus will be proper management of all streams of phosphorus flows: the natural streams, those from mineral fertilizer, and those from sewage and manure. On a global level, manure is important and has been included in most simulation studies. According to MacDonald et al., manure application shows high variability:

> Manure P alone, exclusively of P fertilizer, exceeded crop use only in 11 % of croplands globally, particularly in areas with high livestock densities but relatively limited cropland areas … or in regions with relatively low P fertilizer applications and low P surpluses (e. g., across central Africa). (MacDonald et al. 2011a)

In order to understand the differential use of phosphorus fertilizer, we present Fig. 14. The *y*-axis is a double logarithmic scale of phosphorus NUE expressed in kg P per hectare per year (kg ha^{-1} year^{-1}). A value of 10 means that there is a surplus of 10 kg P per hectare each year; a value of -10 indicates a loss at the same rate. The data are attained by a large-scale simulation (MacDonald et al. 2011a; Potter et al. 2010) for fertilized areas with certain exclusions (i.e., excluding non-cultivated grassland). The uncertainty appears here, as in other data, due to the definition of fertilized cropland for spatial units of 50 $\times$ 50 km (which underlies the simulation) and due to the varying quality of national statistical data. Further, the calculations do not include natural system-based losses or gains of phosphorus through runoff or flooding. Thus, the robustness of these simulations is not definite.

We see that—Europe notwithstanding—there are positive phosphorus balances, indicating that (depending on assumptions of phosphorus loss in crop residues (MacDonald et al. 2011b), we may have an annual surplus of about 12 Mt P on a global scale. What happens with this surplus will be discussed hereafter. Note that many data of the simulation refer to the year 2000 and, thus, may not completely coincide with Table 1 or Fig. 14 data.

Often, to illustrate the intensity of mineral fertilizer use, we present the mean annual input of mineral NPK fertilizer in different countries for the years 2007–2009 on arable land in the 2007–2009 window according to the World Bank (The World Bank 2012) records, which are denoted as NPK fertilizer input. All unreferenced data in Sect. 4.3 refer to this source. To complement the efficiency discussion by absolute values, Fig. 15 presents the cereal yield per hectare for the different regions.

Asia, China, and India: We observe in Fig. 14 that Asia occupies the upper two quartiles (the upper 50 % of the Asian grid areas), showing a high P balance surplus. This indicates the extraordinarily high phosphorus consumption in parts of Asia, and in urban horticulture in particular. China holds about 20 % of the world population, yet since consumes since 2006 about 40 % of world nitrogen fertilizers (Gong et al. 2011). And the numbers for phosphorus fertilizers should be similar. On the other hand, we see from the outliers (the lower 5 % of the box-and-

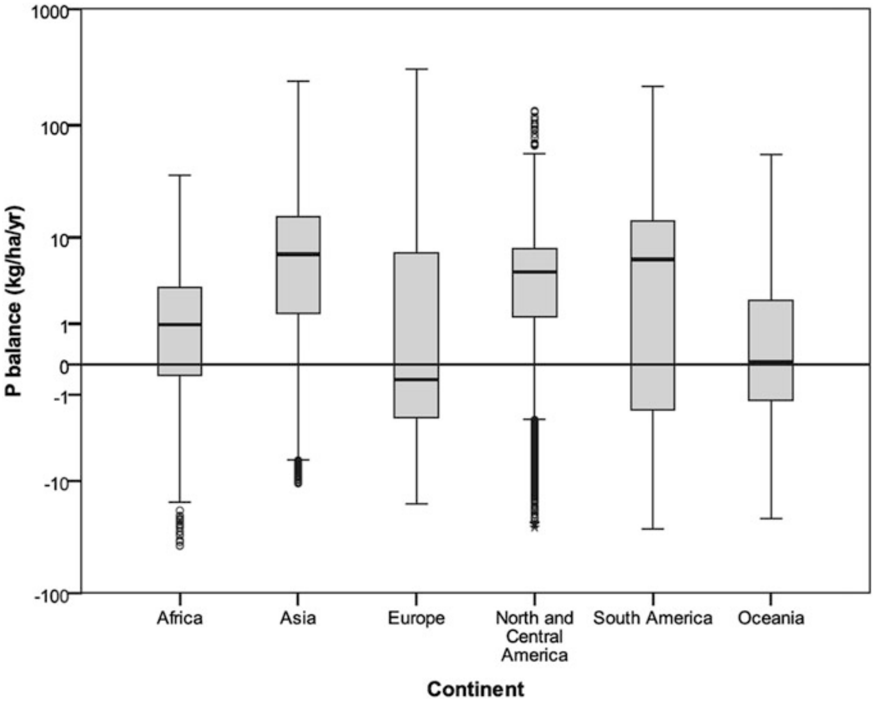

Fig. 14 *Box*-and-*whiskers plot* showing median grid-cell P balances (for all grid cells with >5 % cropland area). Note the logarithmic scale on the *y*-axis. Russia is included in the Europe grouping (MacDonald et al. 2011b)

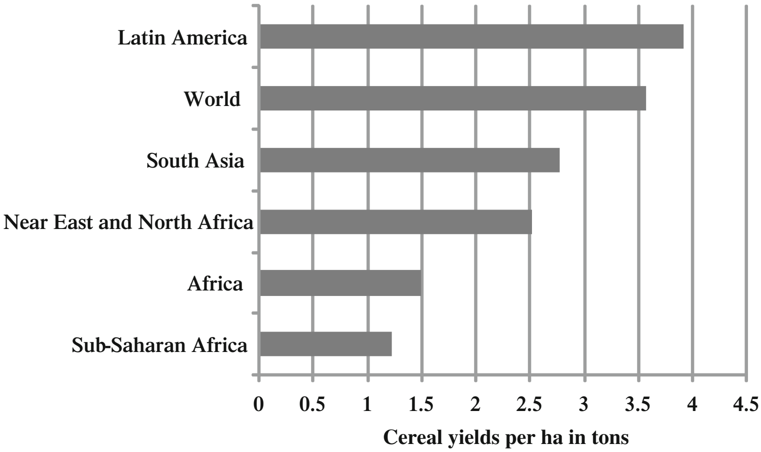

Fig. 15 Cereal yields per hectare by region for 2011/2012 (VFRC 2012, based on FAO data)

whiskers box) that there are also cropland regions with high losses, for instance in northwest Vietnam, which show severe nutrient depletion (Vu et al. 2012). The NPK inputs in China (482 kg ha^{-1}) and Vietnam (354 kg ha^{-1}) are among the highest in the world.

China is not only the largest phosphorus user, but also the largest producer. Here, Zhang et al. (2008) point to another flaw that has been linked to the rapid growth of phosphorus mining in China:

> P resource use efficiency decreased from a mean of 71 % before 1995 to 39 % in 2003, i.e., from every 10 kg P in rock material, only 3.9 kg P was used to produce fertilizer, 5.6 kg of the residues were discarded at the mining site, and 0.5 kg was manufacturing waste. (Zhang et al. 2008)

We should remember that the Asian statistics also include India, which represents another 17 % of the world population. Though the statistics do not distinguish between mineral fertilizer, manure, and sewage-based phosphorus flows, there are indications of overfertilization in other areas of Asia, including India; the average NPK fertilizer input in India is 154 kg ha^{-1}. A recent study (Pathak et al. 2010) indicates that the majority of the Indian states have a positive phosphorus balance, and that manure represents 78 % of the phosphorus input (Tirado and Allsopp 2012). This is in sharp contrast to the situation in China, where 80 % of the phosphorus inputs are from mineral fertilizers (Ma et al. 2011). The high application rates in Chinese agriculture have had negative impacts on a large share of inland lakes, which have been exposed to eutrophication (Tirado and Allsopp 2012). India and China, combined, account for 37 % of the world population and, thus, Asia is by far the largest and most critical region in the pursuit of sustainable phosphorus management.

Africa: Despite having some of the most nutrient-depleted soils, Africa has the lowest fertilizer input per ha of all regions measured and, importantly, with 3.1 kg P ha^{-1} $year^{-1}$, represents, by far, the lowest crop removal of all regions. Consequently, we find very low cereal yields in Africa (see Fig. 15). This is less than one-third of the removal rate in Asia or Europe, illustrating the difficult situation faced by the continent's smallholder farmers. Given that Africa is faced with highly weathered, nutrient-poor tropical soils in many regions, we begin to understand how important improvements can be from a sustainability perspective.

If we look at the regional balance of mineral phosphorus fertilizer flows based on data from 2000–2005, Cordell et al. (2009) suggest that there are 5.39 Mt P $year^{-1}$ of fertilizers exported from Africa to other countries, but only 0.38 Mt of the mineral fertilizers are used domestically. Here, we may further reflect that there is a substantial difference in fertilizer use between exported crops and subsidized crops. Whereas exported crops (e.g., from Egypt) are grown on highly fertilized soil, subsistence agriculture elsewhere engages in little or no mineral fertilizer use. Further exasperating the situation is the fact that the limited phosphorus that does exist in these soils is being exported from the continent in the form of agricultural production; this should be considered a critical situation. This resource deficit, which is often believed to be "a typical African phenomenon" (Mehlum et al. 2006), may be illustrated by a review of general NPK use across a number of African countries. Though Africa does have phosphorus mines and fertilizer companies, the use of NPK fertilizer is low, for instance, 2 kg ha^{-1} in Uganda, 4 kg ha^{-1} in Angola, 10 kg ha^{-1} in Algeria, 17 kg ha^{-1} in Ethiopia, 34 kg ha^{-1} in Kenya, and 51 kg ha^{-1} in South Africa. Conversely, Egypt has been known to apply and as much as 574 kg ha^{-1} in some areas.

We suggest that the low input of phosphorus is a matter of social equity that most African smallholder farmers tend to face, speaking to the question of fertilizer access. Further, given that the benefits of phosphorus application are not immediately evident (as with nitrogen) and that they provide multi-year benefits, low land ownership in Africa may be seen as another reason for the low phosphorus input. In other words, if farmers do not own the lands that they cultivate, they are less likely to invest in plant health and sustainable soil quality.

South America shows the greatest heterogeneity, or diversity, indicated by the middle box and the spread of the whiskers (i.e., the 5 and 95 % percentile). South America faces negative P balances in many parts of Argentina, and positive balances on large-scale plantations in Brazil and other countries. This is very likely related to NPK fertilizer input, which is 40 kg ha^{-1} in Argentina, 158 kg ha^{-1} in Brazil, and as high as 566 kg ha^{-1} in Chile (which explains the upper whisker boundary of South America). These rates correspond with the high cereal yields (see Fig. 15) that are found in the mostly large-scale farming operations of South America.

Europe: Eastern Europe and Western Europe are not separated in Fig. 14, but they do offer different pictures. Whereas Central Europe and Southern Europe show high surpluses, often as much as 10 kg ha^{-1} $year^{-1}$, large areas of eastern Europe present negative balances. Here, spatial statistics reveal that—given comparable sizes—the yield and phosphorus recovery in eastern Europe is only 38 % of that of western Europe.

The tremendous differences between the western and eastern European countries may be observed when looking at the range of NPK fertilizer consumption in eastern Europe (15 kg ha^{-1} $year^{-1}$ in the Russian Federation, 21 kg ha^{-1} $year^{-1}$ in Armenia, 48 kg ha^{-1} $year^{-1}$ in Romania, 84 kg ha^{-1} $year^{-1}$ in Albania, 128 kg ha^{-1} $year^{-1}$ in Bulgaria, and 385 kg ha^{-1} $year^{-1}$ in Croatia) and western Europe (84 kg ha^{-1} $year^{-1}$ in Sweden, 121 kg ha^{-1} $year^{-1}$ in Finland, 169 kg ha^{-1} $year^{-1}$ in France, 188 kg ha^{-1} $year^{-1}$ in Germany and 428 kg ha^{-1} $year^{-1}$ in Ireland).

Australia and Oceania: This region shows a very balanced picture. As we review the NPK fertilizer data, we see that the Philippines (134 kg ha^{-1} $year^{-1}$) and Indonesia (154 kg ha^{-1} $year^{-1}$) are in the midfield, while Malaysia, which has large palm oil plantations, is at the high end (574 kg ha^{-1} $year^{-1}$). Conversely, Australia shows low use of NPK fertilizer inputs (40 kg ha^{-1} $year^{-1}$) on cropland.

North and Central America: In the United States, one may find areas with large phosphorus surpluses, such as in coastal areas, yet negative balances are pervasive in the northern portions of the country. The NPK fertilizer use in the United States averages 113 kg ha^{-1}. However, the level of fertilizer consumption may differ on smaller regional scales, and socioeconomic and political impacts may affect phosphorus use. This may be observed when comparing two Meso-American countries. Nicaragua, for example, uses only 28 kg ha^{-1} NPK fertilizer, while the neighboring Costa Rica, with an NPK fertilizer input of 775 kg ha^{-1}, is ranked third among all countries (if we discard certain extremes, such as Iceland or Qatar).

We should also note that the crop mix may affect the above statistics as we have crops with low- and high-fertilizer-consuming plants.

4.4 Do We Have Low or High Nutrient Efficiency?

Sections 2.3 and 4.3 explore the question of phosphorus use efficiency. In review, phosphorus and potassium fertilizers are much less mobile than nitrogen fertilizer. Thus, the key factor for assessing nutrient efficiency is whether we frame the question in the context of annual or multi-year balancing. Once phosphorus is bound to soil particles, it does not simply disappear or forever become plant unavailable, yet it is in danger of being lost to runoff and erosion. Here, best agricultural management practices are required (Kroger et al. 2012; Sharpley et al. 2004).

We believe that multi-year balancing is not considered in many studies assessing (mineral) fertilizer phosphorus nutrient efficiency. Thus, one may find that unrealistically high losses for fertilizer inputs are reported (Cordell et al. 2009, 2011). Others believe that, given the use of best practices and proper environmental constraints, phosphorus nutrient efficiency may well be as high as 90 % (Syers et al. 2008). We expand on this question in the following section.

4.5 "Losses" and "Sinks" of Phosphorus from a Supply–Demand Chain Perspective

As the terms "sinks" and "losses" are pivotal in the analysis and construction of the MFA-Chart, which is a key representation for identifying means of sustainable phosphorus management, we will define the notion of sustainability in these terms. A definition of losses is also necessary, as phosphorus atoms do not disappear from the earth, but simply take on new inaccessible forms. A loss denotes the "harm or privation resulting from losing or being separated from something …" (Webster's 2002a). In defining sustainability, a loss may mean that phosphorus reserves become excluded from the current and future value chain, for example, due to economically motivated action. As it is impossible to predict which parts of the geopotential of phosphorus may be mined in, say, the next 1,000 years (for example, whether we begin to extract it from sea water), we rather take a present-

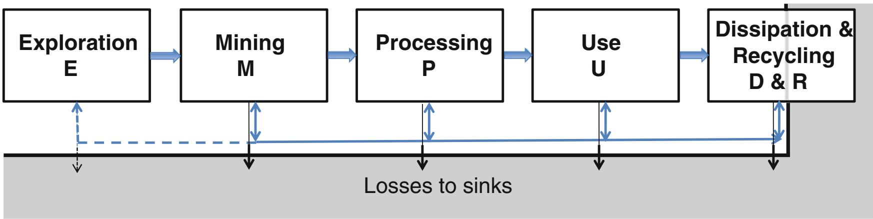

Fig. 16 The five stages of the supply–demand chain

day perspective and, thus, a precautionary view, which does not speculate about currently undeveloped future technologies. But "sink" also includes an evaluative connotation, denoting not only "a pit for the deposit of waste or sewage," but also "a place where vice, corruption or evil collects or gathers" (Webster's 2002b). The latter definition brings to light that, as phosphorus is removed from the economic value chain, the action may cause negative impacts that must be considered in a comprehensive sustainability assessment.

Harms from losses or sinks are, thus, always relative to a particular actor's interests. With respect to the supply–demand chain, we distinguish five stages: *Exploration*, *Mining*, *Processing*, *Use* and *Dissipation* and *Recycling* (see Fig. 16). The major information and material flows move from left to right. From a functional perspective, primary demand is represented in the *Use* stage (phosphorus use for agriculture or technology). The figure presents multiple interactions, such as the emergence of urban mining of municipal waste disposals. The losses or gains from information with respect to recycling are represented by dotted lines.

Identifying and managing uneconomical or unsustainable losses of phosphorus along the supply chain is a prerequisite of sustainable phosphorus management. But we face (at least) two types of losses. One type of loss (within the phosphorus industry) moves along the industrial value chain and includes mining, beneficiation, and downstream processes of producing fertilizer, phosphoric acids for feed additives or yellow phosphorus (P_4). The other loss is linked to phosphorus use, and includes losses from soil, crops, livestock, and industrial flows. These losses may be due to different key actors and the technologies they employ. We include these key actors from 'a Global transdisciplinary roadmap' perspective,[2] which decisively includes the key stakeholders in order to properly design Global Transdisciplinary feedback.

We separate industrial and agrofood losses, as they are of different natures. But even though we deal with them separately, they share common statements about

[2] Here, we may refer to (*individual*) consumers, (*groups* such as) households, companies and diverse non-governmental organizations (NGOs) from sectors such as environment, development etc. (as examples of *organizations*), nations (as the major form of *societies*), *super-national organizations* (such as the EU), and the human species (as the *supreme entity* from which the intragenerational and long-term aspect of social responsibility may be defined).

tremendous "losses" in recent publications. That which has been nicely elaborated for China also holds true on a global scale:

> P losses must be reduced in both the agricultural production sector and the industrial manufacturing process. (Zhang et al. 2008, p. 132)

As a starter (and in order to prepare the reader for the previously mentioned factor two uncertainty), we confront the critical reader with two views, both of which speak to the magnitude of the different types of "losses."

> IFDC estimates that between 30 and 50 % of the P_2O_5 equivalents in the mined ore is unrecovered and is contained in waste ponds and piles. (VFRC 2012)

It is interesting that we find the same magnitude of losses in the agro-use phase (the following text refers to 2008 production; Cordell et al. and Greenpeace estimates).

> … the livestock system loses about 45 % of the phosphorus entering the livestock system itself (which makes 7 Mt P/yr input of 15.6 Mt P/yr to livestock) … and this represents 29 % loss of the phosphorus entering the agriculture system overall. (Tirado and Allsopp 2012)

The latter data hypothesize an input of a total of 51.1 Mt P year^{-1} (which is 15.1 Mt P^{-1} year^{-1} higher than the above estimate (Liu et al. 2008) which excludes animal feed and results in a tremendous annual "loss" of 21 Mt P year^{-1}). We will discover which of these loss statements may be reasonably considered and which may not.

4.5.1 Phosphorus "Losses" from Industrial Phosphorus Processing

In this section, we look at the losses in the exploration and mining processes. As outlined in Spotlight 4, much of what are referred to as "losses" may neither be physical losses (e.g., by irreversible dissipation which makes phosphorus inaccessible for the foreseeable future) or losses from a business perspective (e.g., by not implementing state-of-the-art mining management principles). And what may be considered a loss today may be viewed a gain in the future. The phosphates that are not mined, but are left on the mines (e.g., by incomplete excavation or by supposed low grades) will be referred to as "ore residues." Please note that in this book, the phrase "ore residues" does not include the potentially risky beneficiation residues or tailings, only the phosphorus that is not processed from the ore.

We should also note that this section (as most parts of this book) deals with 191 Mt PR, *which makes* 25 Mt P *as recorded by USGS* (2012) *for the year 2011*. This 25 Mt P entered processing. One question addressed in the Exploration and Mining sections is how phosphate rock (phosphorus) has been moved or affected (e.g., by separating it from a large ore layer) before processing.

Exploration: We begin with the resources, which we may consider portions of the ore residues that are economically mineable but are not included in the reserves. The largest "losses" are attributable to mine planning, mainly in the decision regarding what parts of the deposits are to be mined and which are to remain untouched. The main factors here are the technological and economic conditions at the time—identified in the feasibility study used to determine the cutoff grade of the ore. Even in the future, the ores beyond this point may rarely be suitable for subsequent extraction because they are most likely located at the margins of the deposit or at considerable depth (Kippenberger 2001). In this context, we may talk about losses due to exploration limits. To the best knowledge of the authors, there are no publications that provide an assessment of this type of "loss" due to the limits of exploration of phosphorus mines.

Estimates of geopotential of phosphorus span some millions of gigatons (Smil 2000). But a comprehensive survey on reserves and resources is missing. There may be various reasons for this; some nations with presumably high phosphorus reserves, such Estonia, may not yet have surveyed and documented possible resources for various reasons. In recent years, USGS (2010) reassessed Morocco's reserves following a report of IFDC (van Kauwenbergh 2010) which updated already existing resources to reserves from 5.7 to 50 Gt PR [which seems to still be considered a conservative estimation (Terrab 2013; quoted from personal communication)]. In similar fashion, Iraq submitted information documenting 5.8 Gt PR to the USGS in 2011 (USGS 2012). But this number was lowered to 0.46 Gt PR in their 2013 reporting (USGS 2013b). The fact that about 90 % of the Iraqi reserves was downgraded and not included in 2013 recording (USGS 2013b) was due to an inaccurate use of the Russian categorization of reserves in the reserves assessment (Al-Bassam et al. 2012), rather than the common US classification (Jasinski 2013). Thus, 5.3 Gt PR were downgraded to resources as phosphate rock production seems to be more expensive (in mining) than the documented reserves at USGS. The ambiguous situation of exactly classifying reserves is also illuminated by the most recent statement of the Geological Survey of Iraq which states "The phosphate rock resources of Iraq are estimated at 9.5 billion metric tons" (Benni 2013). Here, it seems unclear what definition is taken.

Further, given the lengthy static lifetime of at least 350 years for economical phosphorus extraction, currently "… no company nor institution has the interest or the means to invest in exploration which does not contribute to their business plan. In general, companies only spend money at the high risk of exploration if they can bring the deposits quickly into production" (Scholz and Wellmer 2013). We may infer from this that there may be many unidentified reserves in the geopotential. We should note that speculation on what deposits may be economically extracted and processed under current and assumed future market conditions is a core business aspect of mining companies.

Mining: Mining is a multi-step economic and physical activity. Planning includes designing and constructing the mine, mining technology, infrastructure (particularly energy and water supply), extraction, and handling of the ore prior to beneficiation (UNEP and IFA 2001). As described in Spotlight 4, we must distinguish between the *mining ratio*, which describes the percentage of the ore that is excavated and the percentage left in the site (touched or untouched), and the low-

Table 2 IFA and IFDC recording of "ore residues" (for a definition of "ore residues" see text) based on the USGS (2012) with linear extrapolation (assuming the same ore grade in the processed phosphorus and the ore residues)

	IFA		IFDC	
	Operated (Mt P)	"Ore residues" (Mt P and %)	Operated (Mt P)	"Ore residues" (Mt P and %)
Mining	36.3	5.8 (18 %)	39.6	3.8 (9.5 %)
Beneficiation	30.5	5.5 (16 %)	35.8	11.8 (30.2 %)
Processed P	25		25	

grade ore which is put aside before primary beneficiation. The mining ratio does not refer to the overburden, but rather the rock or to the ore (this is sometimes not unambiguously clear in literature) that has been assigned to the ore.

Mining ratios have been assessed by IFA (Prud'homme 2010). Many mining companies obviously have reported very low losses in mining, with mining ratios well above 90 %, whereas others perform poorly, with rates of recovery as low as 45 %. *The global weighted average of the mining ratio is assessed to be* 82 % (Prud'homme 2010), *thus* 18 % *of the phosphate ore is not excavated.*

The IFDC data (VFRC 2012, p. 12) differ slightly from the IFA data. When using data from the year 2009,[3] IFDC estimates a loss of 9.5 % from 560 Mt ore rock extracted with 1,700 Mt overburden. Of the total of 36.5 Mt P year^{-1}, about 3.5 Mt P year^{-1}, which makes 9.5 %, remains unrecovered. This is roughly half of the IFA estimate (see Table 2).

Given the percentage of loss, one could estimate the total amount of phosphate rock and phosphates that have been affected in the mining process. This, however, would require one to know the amount that enters beneficiation which is currently unknown. We only know the amount (24.8–25.7 Mt P included in phosphate rock granulate) that enters processing or that is used for direct application as fertilizer based on the USGS (2012) and 2013 data. We use 25 Mt P as a rounded-up value of the USGS (2012) data in the following. We may provide estimates of the total amount of phosphate rock after the amount put to beneficiation has been assessed (refer to the formulas in the following sections).

We should note that the reported estimates are below those of Kippenberger (2001) from the German Geological Survey who reports non-used phosphate ores of 36 %. Compared with some other minerals such as aluminum (13 %) or iron (23 %), this is in the higher end of the range (Wagner 1999). The 25 Mt P year^{-1} for 2011 recorded by USGS (2012) include phosphates after primary beneficiation. Based on this, the estimates of a virtually mined amount of phosphate rock provide a broad range of *v*irtually *m*ined phosphate rock (PR_{vm}) that may be transferred to virtually mined phosphorus P_{vm}. We should also note that Kippenberg estimates refer to *tons of ore*. The degree of ore material that is left in the mines (e.g., the

[3] USGS reports mine production of 158 Mt in 2009; (Löffler 2013).

below cut-off material) compared with the ore that is processed is unknown. We may assume that the ores not sent for processing are of lower quality. Thus, the "losses" may be overestimated in terms of phosphorus.

(*Primary*) *Beneficiation* is most often conducted at the minesite, which results in a higher phosphorus concentration—in particular for igneous phosphate rocks, which have very low phosphorus content. The rock phosphate is subjected to a multi-step process that includes crushing, grinding and flotation, acid washing, magnetic metal extraction, dewatering, and drying. For primary processing recovery, IFA (Prud'homme 2010) presents a statistical analysis including 93 % of world production. These data are attained from private companies and, thus, are not generally available to the public. IFA provides an estimate of 84 % of primary processing recovery. This would calculate to an additional loss at the mining stage of 5.5 Mt P or 16 %.

These data allow for a rough extrapolation of the amount of phosphorus (by means of simplification, we work with phosphorus and not phosphate rock).

(*) $25 \text{ Mt P} = (25 \text{ Mt P } 0.84^{-1})\ 0.82^{-1} = 36.3 \text{ Mt P}$

(*) $36.3 \text{ Mt P } (1.0\text{–}0.18)\ (1.00\text{–}0.16) = 25 \text{ Mt P}$

(***) $36.3 \text{ Mt P} - 5.5 \text{ Mt P} - 5.8 \text{ Mt P} = 25 \text{ Mt P}$

This means—if we take the IFA data—that roughly 5.5 Mt P (in phosphate ores) are left at the mines in the process of excavation and 5.8 Mt P is put aside during beneficiation. Thus, about 11 Mt P in ore fractions is put aside. The degree of these fractions is not known. We may assume that they are certainly of lower degrees, but the IFA data refer to P_2O_5 which may be transferred to P. Naturally, one may assume that the concentration of the set-aside from which no phosphorus is recovered and which left on the mines or put to waste deposals is of lower concentration and may not economically processed. This would mean that this part is not lost (from the value chain). Thus, we lower the above estimates and assume that only 50–80 % of the above 11.3 Mt P may be considered as losses. *Thus, a realistic estimation of the lower boundary, referring to the IFA data and based on the above assumptions, may provide an (conservative) estimate of 2.7–4.4 Mt P residues from mining and 2.9–4.6 Mt P from beneficiation.*

The IFDC (VFRC 2012, p. 12) data for beneficiation again differ from the IFA survey and provide a much more unfavorable picture. Of the 38.6 Mt P year^{-1} (contained in P_2O_5 concentrate) which is beneficiated, 30 % are classified as unrecovered by beneficiation (see Table 2).

We presented different estimates of IFA and IFDC in Table 2. There are similarities, but also large differences, which may be due to differences in the definitions of system boundaries (e.g., what is overburden and what is ore in mine spoils), the definition of system elements (what are "other" or "industrial" uses), accessible data, and the author's decision on what information the data are derived, etc. Both surveys are reports by industrial or nonprofit organizations and have not been independently evaluated, as is the case with scientific papers.

Both IFDC (about 31 % if 36.3 Mt P is taken as a reference) and IFA (39 % if 39.3 % is taken as a reference) suggest a total of 35 % ore residues or non-recovered phosphate rock. This means that only two-thirds of the rock phosphate ore becomes a marketable product.

In the following, we use the IFA data for the amount of phosphorus that is affected by mining and beneficiation (i.e., a loss of phosphate rock of 31 %). And we use adjusted estimates (which assume a lower grade for the ore residues of between 50 and 80 %) for the crop residues or losses, or 2.7–4.4 Mt P unrecovered phosphorus in mining and 2.9–4.6 Mt P unrecovered in beneficiation.

Finally, the USGS and the IFA numbers differ as IFA does not include the official China phosphate rock production data (Prud'homme 2013). Thus IFA has smaller data, which may affect, for instance, some estimates in Fig. 21.

Non-processed fertilizer: We should note that according to Prud'homme (2010) in 2007, about 1.9 Mt P_2O_5 was used as direct fertilizer. If we adjust this number linearly to compare directly to 2011 data (USGS 2011), we get an estimate of 1.1 Mt P that was directly used in 2011 as fertilizer without entering wet or thermal processing. If we include the difference between the USGS and the IFA data, we may face even (slightly) higher values here. The thermal route is all dedicated to industrial uses.

Processing: Providing reliable data on phosphorus losses in this node of the supply chain is critical because no comprehensive survey has been performed and the expert estimations often prove to be inconsistent.

Prud'homme (2010) reports that in 2007, 51.7 Mt of P_2O_5 (which makes 22.6 Mt P) was shipped to or processed at plants linked to mines. Here, almost 4 % was directly used, about 5 % was thermally processed (mostly for P_4 production) and the bulk of the remaining 91 % was subject to chemical wet processing, primarily for fertilizer production (see Fig. 17).

According to a mid-term 2011 estimate by IFA (Heffer and Prud'homme 2011), 18.1 Mt P was used for fertilizer. IFDC (VFRC 2012) estimates for 2009 that about 18 % went for uses other than fertilizers (see Fig. 4) including feed and food additives, detergents and technically and industrially used P, including some used as additives (as a strengthening agent) of steel.

If we simply extract 18 % from the 25 Mt P and the 1.1 Mt P for direct use, we get 18.4 Mt P, which become subject to fertilizer processing. The challenge is now to assess how much phosphorus is lost in fertilizer processing.

This estimate is below the IFDC (VFRC 2012a) estimate of 10–15 % that is not recovered in the wet processing of fertilizer which provides 1.8–2.7 Mt P. IFDC estimates that 4–9 Mt P_2O_5 (i.e., 1.7–3.9 Mt P) is lost in stacks or ocean disposals from fertilizer processing in 2009.

We may also look at the survey performed by Villalba et al. (2008) that focuses on the 2004 production streams. This study well distinguishes between fertilizer and non-fertilizer, and wet and thermal phosphoric processing. For wet phosphoric processing, clearly phosphogypsum is identified as a major environmental issue. Villalba et al. (2008) suggest that a range of 2–12 % is lost. The wide span refers to the different properties of the phosphate rock, processing technology, etc.

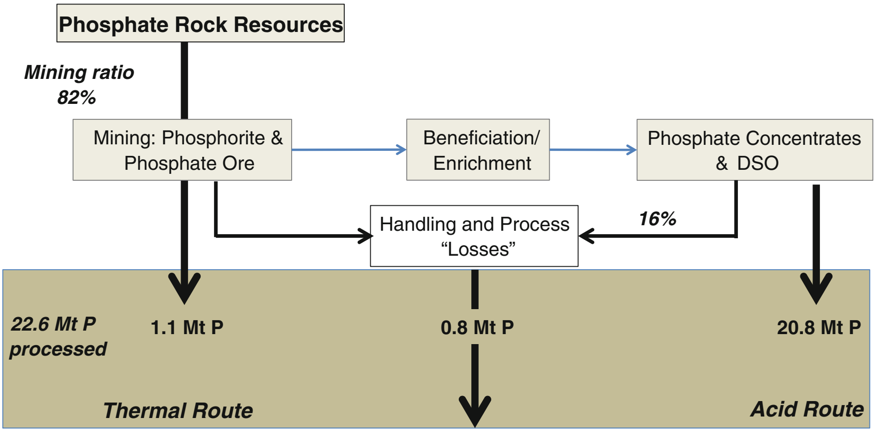

Fig. 17 Mining, beneficiation, and routes taken as described in 2007 data (Prud'homme 2010)

> We see that a precise estimate is beyond our capabilities. However, including the non-fertilizer route, a loss range of 2–3 Mt may be seen as a moderate, conservative estimate. Thus, the amount of phosphorus in fertilizers in 2011 was around 16 Mt P.

Virtual flows: Before we deal with agricultural use, we briefly touch on non-chemical industry virtual phosphorus flows. Here, we mean phosphorus that is bonded with mineral resources such as iron, coal, or limestone. In heavy industry, phosphorus causes impurity. Also, in steel production, phosphorus has two faces and—depending on the quality of the steel—is sometimes added and sometimes subtracted and goes to the slag.

Matsubae et al. (2011) provide an interesting analysis on the amount of real (phosphate ore) and virtual phosphorus which is imported (Matsubae et al. 2011). For Japan, virtual phosphorus flows take a large share. Matsubae et al. (2011) state that the consumed agricultural products in Japan make only 12 % of virtual phosphorus consumption. This number is certainly specific to Japan, which has a high proportion of car and metal-based industries. But these data may suggest that the magnitude of the virtual flows may well be of the magnitude of the phosphorus in the food uptake (Jeong et al. 2009). We do not deal with the virtual flows, which may define a new research domain, in detail in this chapter.

4.5.2 Phosphorus Losses from Agricultural Use

The use system is an overly complex, multilayered, partially interconnected system. It includes arable and livestock farming and forestry of very different types. A specific challenge is that the phosphorus flows in the agricultural system sometimes are in a rapid state of change due to changes in the demand/diet side or due to events such as the mad cow disease outbreak that changed the processing of animal bones and carcasses in some countries. In the following, we aim to adjust all data to be representative of the year 2011.

A specific challenge in assessing use system losses is to distinguish between the natural biogeochemical flows, i.e., the flows from weathering, runoff, and erosion, and those from anthropogenic impacts. As we live in the anthroprocene (Crutzen 2002), our current geological epoch, we are experiencing a rapidly changing world in which the phosphorus flows may not be explained without human impacts.

In cropping (grains, vegetables, and fruit) and in terrestrial and aquatic livestock farming, we distinguish between natural/organic and synthetic/processed (e.g., beneficiated) phosphorus. The organic form has two cycles. One is land-based, between soil and terrestrial fauna and flora. Zoomass (10 % of which is anthropomass) is not relevant here, as it makes only 1 % of phytomass (and thus, we may exclude fish-eating terrestrial animals). The other cycle is water-based; phosphorus circulates between sediments and aquatic biota (Chapin et al. 2009). Terrestrial phosphorus is moved to aquatic environments by erosion of soil particles and surface water runoff. This is a natural cycling that nourishes aquatic life. Human activity, in particular plowing and overgrazing by livestock, may change the cycle dramatically. Whereas the cycling of phosphorus may repeat 100 times in a natural biotic environment before it is transported via rivers to the sea system, intensive cropping and grazing without best management practices may reduce the cycling to just a few times. Thus, the anthropogenic regional and global change (e.g., climate change effects on runoff) may affect the speed by which phosphorus is removed from terrestrial systems. From a human-environment systems (HES) perspective, the rate at which phosphorus is lost depends on the functionality of the land use. Natural land use losses are much less than losses associated with grazing land and cropland.

If we consider losses from crop production, we are interested in how much applied phosphorus is taken up by the crop, recognizing that some of the applied phosphorus is lost by erosion, runoff, or leaching (possible on sandy soils), while much is converted to less soluble forms in the soil. Naturally, both the organic and the mineral fertilizer inputs must be considered. While there is more or less reliable data on phosphorus fertilizer use, the recording of organic inputs such as manure, slurry, peat, seaweed, leaves, compost, human excreta, irrigation is not a common subject of statistical surveys. Consequently, estimates of manure or organic fertilizer are more difficult to obtain, though better standards have been developed (Wang et al. 2011). We find similar uncertainties in the diverse system of animal production with respect to household waste, crop residues, etc.

4.6 Runoff and Erosion

Surface runoff and erosion cause two large sets of losses of phosphorus in agriculture. Runoff occurs if the soil is saturated or cannot absorb rain or melting ice. Erosion includes soil and nutrient removal by wind and water. As much of the phosphorus runoff is of particulate phosphorus that is bound to soil particles, the two processes overlap. Wind combined with droughts may become a major source of erosion. Both runoff and erosion depend on the geographical setting (e.g., soil type, slope) of the cropland and grassland agrotechnology (e.g., tilling technologies, drainages) and intensity of use, e.g., overgrazing (Haygarth and Jarvis 1999; Sharpley et al. 2003). Both runoff and erosion of soil and fertilizer are most vulnerable to "incidental losses" (Haygarth and Jarvis 1999), i.e., discrete events such as heavy rains or storms. These *event-specific losses* surprisingly have "received relatively little study" (Hart et al. 2004) though they make up a major share of phosphorus losses.

> … event-specific losses often make the dominant contribution (50–98 %) to P in runoffs from field plots … (Hart et al. 2004)

We must also be aware that climate change increases the vulnerability of cropland and grassland by extreme event-caused erosion (Nearing et al. 2004).

We illuminate the difficulties in providing reliable estimations with the case of wind erosion. For instance, Liu et al. (2008) refer to Schlesinger (1991) who provided an estimate of 4.6 Mt P year^{-1} of atmospheric phosphorus deposition (with a mean residence time of about 80 h). But this does not tell us about the wind erosion transfer to oceans. Ruttenberg states that "atmospheric deposition is relatively unimportant" (Ruttenberg 2003). In his phosphorus flow model, 4.3 Mt P year^{-1} is transferred from land to the atmosphere and 3.1 Mt P year^{-1} return to soil, which would provide an estimated loss of 1.2 Mt P year^{-1} by wind erosion to the sea.

With respect to erosion, we may also look at the data provided by Graham and Duce (1979), which, however, was developed in a time when world phosphorus mining was about 13 Mt P year^{-1}. Graham and Duce estimate that the atmospheric burden is 0.28 Mt P year^{-1} (corresponding to a lifetime of 80 days and a wind erosion of 1.2 Mt P year^{-1}). In their balance, 1.4 Mt P year^{-1} is moved from the continent to the sea and 3.2 Mt P year^{-1} is transferred to other soil. But there are some flows back to the land (0.33 Mt P year^{-1}) from seawater; a net balance of 1.0 Mt P year^{-1} is the result. But here, we must acknowledge that "50 % of this transport is due to the flux of dust from the Sahara desert to the North Atlantic at 15° and 25° N" (Graham and Duce 1979).

Another important flow affecting erosion and runoff is the annual input by weathering. Carpenter and Bennett (2011) distinguish between a natural, non-anthropogenic weathering of 10–15 Mt P year^{-1} (which may differ between interglacial and warm stages) and human-induced weathering of around 5 Mt P year^{-1}. This brings the weathering input to 15–20 Mt P year^{-1}.

The transfer from soil to the water system is a very critical one. Smil provided an estimate of erosion and runoff of 18–22 Mt P year^{-1} for particulate and 2–3 Mt P of dissolved P (Smil 2000). Ruttenberg (2003) is very close to this, estimating 18.3–20.2 Mt P year^{-1} for particulate and 1.0–1.8 Mt P year^{-1} for dissolved P. These data have been challenged by Hart et al., who refer to studies that conclude that runoff from organic (poultry) fertilizer included 67 % dissolved phosphorus, and runoff from mineral fertilizer was more than 95 % phosphorus. Because of the chemical dynamics of phosphorus, this data may not be transferred to the phosphorus transported in rivers. Here, the phosphorus transported in global river sediments to the ocean (Beusen et al. 2005) amounts to 9 Mt P year^{-1}. We suggest that the Liu et al. estimate of 36 Mt P year^{-1} of runoff and erosion from pastures and cropland seems to be too high and will not be referred to in the following. We follow Carpenter and Bennett (2011) with an estimate of 22 Mt P year^{-1} for the losses of phosphorus from soil sea via freshwater.

According to a rough balance, in 2002, USGS accounted for 17.4 Mt P year^{-1} after beneficiation and about 10–15 Mt P year^{-1} input resulting from manure. This totals 25–30 Mt from anthropogenic sources compared with 22 Mt P year^{-1} from weathering. This provides considerable stock building in terrestrial systems.

Of course, we are interested in how much is lost from the 12 % of cultivated land and the 22 % of grassland (Leff et al. 2004). The review of Hart et al. (2004) illuminates the difficulties in providing a reliable estimate. This starts with difficulties in distinguishing between particulate phosphorus and dissolved phosphorus, as phosphorus has specific physicochemical characteristics:

> Phosphorus can occur in a continuum of sized down to near-molecular dimensions, and thus the definition of particulate and dissolved forms of P is rather arbitrary, defined by analytical convenience … (Hart et al. 2004)

The surveys on phosphorus losses differ by scale, soil type, slope, weather conditions, tillage and drainage systems, crops, and types of fertilizer. Thus, it is not surprising that the conclusion is that these runoffs are highly site-specific. Hart et al. review 29 studies on phosphorus losses from different land uses related to fertilizer applications. The losses vary from 0.03 to 42 % with a mean of 17 %. But the studies by no means can be considered representative. The difference between estimates of soil erosion of 10 t ha^{-1} year^{-1} on US cropland compared with China at 40 t ha^{-1} year^{-1} (Pimentel et al. 2010) shows the large variance. Cordell et al. (2011) provide an estimate of 8 Mt P of *erosion losses* from agricultural soils and pastures. Again, it seems clear that the Liu et al. (2008) estimation of 19.3 Mt P year^{-1} from cropland and 17.2 Mt P year^{-1} from pastures seems to be an overestimation.

When providing an assessment of the losses, we face uncertainties and a lack of understanding. Given an input of 16 Mt P year^{-1} in 2011 from mineral P, between 15 and 20 Mt P year^{-1} from manure, sewage, crop residues, dry collection system etc. we may assume that around 35 Mt P year^{-1} is put to soil.

Rockström et al. provide (without considering the losses) this estimate:

> Some 20 million tonnes of phosphorus is mined every year and around 8.5 million–9.5 million tonnes of it finds its way into the oceans. (Rockström et al. 2009)

Transferred to 25 Mt P year^{-1} of mined phosphorus in 2011, this provides between 10 and 12 Mt P year^{-1} that is transferred from mined phosphate to the sea. If we wish to provide an estimate for the total inflow to oceans, we may refer to the Carpenter and Bennett (2011) and assume that most of the weathering input of 15–20 Mt will be transferred to the ocean. Thus in 2011, an estimate of 25–30 Mt P year^{-1} may be a reasonable estimate for the phosphorus input to the sea, more than double the non-anthropogenic input.

4.7 Changing Lifestyles Increase Anthropogenic Phosphorus Flows

Economic growth in China, India, and many other countries of the world is directly linked to a change in dietary habits, including an increase in the consumption of meat, fish, and dairy. "World meat production is projected to double by 2050, most of which is expected in developing countries" (FAO 2012a). The impact of this dietary change on phosphorus consumption may be inferred from the data currently available. Measured in calories, 1 kg of meat includes 1,500 calories, whereas, 1 kg of cereals provides about 3,000 calories. Moreover, it takes 3 kg of grain to produce 1 kg of meat, even if we assume that part of the feed is taken from rangeland and organic waste (Nellemann et al. 2009). This translates to a factor 6 increase in nutrient efficiency for food uptake if you refer to energy.

Today, we find the following data for cereal production:

> Of the 2.4 billion tonnes of cereals currently produced, roughly 1.1 billion tonnes are destined for food use, around 800 million tonnes (35 percent of world consumption) are used as animal feed, and the remaining 500 million tonnes are diverted to industrial usage, seed, or wasted. (FAO 2012b)

For 2050, UNEP assumes that "at least 1.45 billion t [Mt] cereals are used as animal feed" (Nellemann et al. 2009). This means that—all things being equal and taking the uncertainties of the numbers into account—several hundred (around 600–750) Mt of cereals must be produced in addition to the current consumption. Assuming a population growth by 23 % through 2050 (and the factor 2 calorie efficiency differences between cereal and meat), this would mean that just about 10 % (i.e., 235 Mt) more cereals as UNEP assumed must be produced annually to account for dietary change to more meat production.

The latter estimate is very much in line with an estimate by Hu (2011), FAO (2012b) on the impacts of the migration of Chinese farmers into cities and townships (75 % in 2050 compared with 47 % in 2010). Given that 300 million rural persons move to cities, Hu estimates an increase in phosphorus demand by about 20 % (0.36 Mt P year^{-1}) due to diet change, and a further 10 % increase (0.18 Mt P year^{-1}) due to sewage loss and increased biofuel consumption. Given the current wastewater treatment technology in China, urban lifestyle change, for instance, is linked to the recycling of sewage at 30 % compared with 94 % which was the recycling rate related to traditional sewerage treatment. Naturally, these are rough estimates under certain assumptions. But this reveals that dietary and lifestyle changes may induce additional phosphorus use and provides some information about the magnitude of the increase.

Fig. 18 There are historic trade-offs to the use of dung as fertilizer or fuel (picture taken in Tibet, R. W. Scholz)

4.8 Insufficient Phosphorus Recycling from Manure and Crop Residues

Possibilities exist for improvements in some anthropogenic flows of phosphorus related to agricultural food production, i.e., through the reclamation of phosphorus in *manure*, *crop residues* and *sewage*. All three flows are central from a soil management perspective and, thus, are significant factors in future food production. All three flows must be viewed from a historical, sociotechnological perspective and, thus, viewed in the context of the evolution of human-environment systems. This holds true in particular since gatherers and hunters are nearly extinct and the world has faced almost simultaneous agrotechnology developments across our agrarian, industrial, and post-industrial societies. As a result, history shows how new trade-offs have emerged (see Fig. 18).

4.8.1 Learning from History

Sustainable farming requires sophisticated amelioration and fertilization of the soil. About 7,000 years ago, Asian Neolithic farmers learned to improve soil fertility of otherwise non-arable land by dunging the cropland with the excreta of grazing cattle, sheep, and goats (McNeill and Winiwarter 2004; Bellwood 2005). Though livestock manure may improve soil quality by increasing organic matter or expanding the water-holding capabilities of soils, it does not possess the optimal composition of nutrients for maximum crop production in a given field. Various types of composting performed by early agrosocieties are known to have improved the efficacy of manure.

Fig. 19 A flotilla of manure boats on Soochow creek, Shanghai, prepare to transport excreta to cultivated fields (taken from King 1911, p. 195)

Another important step of *dislocation* has been linked to urbanization. About 5,000 years ago, when the first cities emerged (Benevolo 1980), nutrients were drawn from the fields to the cities. The importance of human excrement for soil fertilization may be observed in a 1649 decree in Tokyo that banned toilets that emptied into canals or creeks (Smil 2004). Here, we may have met an early trade-off inherent in manure recycling, which is that the Tokyo decree may have improved the ecosystem health in canals, but may have increased the risk to human health, as manure may contain a variety of pathogens. The latter rebound effect, in particular, holds true if, for example, the cycling system for human sewage is too short, and the product is applied directly to vegetable fields while pathogens still remain.

Clearly, the specialization and industrialization of agriculture may have been a significant factor in the reduced use of manure as a crop fertilizer. If large-scale swine or cattle production became clustered, transportation costs may have become a barrier for the economical application of manure to cropland. And in times of increasing rural residential settlement, odor became another factor preventing widespread manure, and sewage use.

With respect to sewage, the anthropologist, King (1911/2004), reported how sophisticated the amelioration of sewage had become in highly populated areas such as the Hankow-Wuchang-Hanyang area in China, where 1.8 million people lived in a radius of four miles (see Fig. 19). Here, history shows that utilizing manure and sewage requires treatment before reuse and transportation.

Finally, if reviewing the history of crop residues, three distinct stages and loss mechanisms emerge. The first is between *soil and farm*, where the widespread burning of straw and stalks resulted in losses of nitrogen, phosphorus, and other nutrients (which has implications for long-term nutrient management and climate change). The second may be between *farm and table*, and the third is *after-table* losses.

4.8.2 Phosphorus Recycling from Manure

While manure represents a major portion of inefficiently used and wasted phosphorus, providing reliable data on a global scale remains difficult. Cordell et al. (2009) provide a figure which suggests that the current share of manure being used for fertilization amounts to about 3 Mt P year^{-1}. A recent thorough analysis of MacDonald et al. (2011a) estimated the agricultural input of manure to be 9.6 Mt P year^{-1}, or 40 % of total manure phosphorus excreted by livestock in 2000. But the lack of data outside of those cited indicate the uncertainty and bias that may be tied to data on manure.

Nevertheless, the practice of manure recycling differs from country to country, and even within regions of a single country. The practice may also differ among cropping systems. Sattari et al. (2012, SI p.1) provides an estimate of 15–24 Mt P year^{-1} for annual manure production. This study points to the different uses of manure in industrialized countries, where about half is supposedly used for grassland and half for cropland.

The comprehensive report *Lifestock's long shadow* (FAO LEAD 2006) deliberates on many scales the need and potential for better nutrient management. For instance, a cow excretes 18–20 times a much phosphorus load as a human (Novotny et al. 1989). And the energetic potential of manure as well as the pollution potential may be seen by the estimate that "Methane released from animal manure may total up to 18 tonnes per year" (FAO LEAD 2006, p. 113).

In developing countries, 95 % of the available manure is assumed to be applied on cropland (Sattari et al. 2012, SI p.1). This assumption may be questioned as manure is competing with other uses such as fuel (see Fig. 18). A very high estimate of 24.3 Mt P year^{-1} is provided by Potter et al. (2010) while other studies provide estimates of 21.1 Mt P year^{-1} (Sheldrick and Lingard 2004).

In order to provide a more comprehensive picture on the potential, but also the limits of phosphorus use, the most available and widely elaborated statistics from the United States are reviewed (Ruddy et al. 2006; MacDonald et al. 2009; EPA 2012). If we look at the total phosphorus nutrient input on the land surface in 1997, 50.4 % of total farmland phosphorus input was mineral fertilizer, 48.5 % was manure phosphorus, and 1.1 % mineral fertilizer was applied to non-farmland. These figures, compared with the MacDonald et al. (2009) report cited below, suggest that significant amounts of phosphorus from manure production remain on the grazing land, are contained in lagoons, were incinerated or ended up in streams and rivers from surface water runoff. There were high farm-fertilizer inputs in the upper Midwest areas, along the east coast and in irrigated areas of the west. A 2007 estimate of animal manure provides a phosphorus total of 2.04 Mt P year^{-1} just in the United States, which is higher than the 1.72 Mt P year^{-1} in 1997 and the 1.62 Mt P year^{-1} in 1987.

Given animal manure production increases—nearly 50 % of total phosphorus input to the land was contained in manure and "Manure was spread as fertilizer on 15.8 million acres" (D, see MacDonald et al. 2009)—the increasing need to recycle nutrients and manage waste is clear. Maize (the largest single crop accounting for 25 % of the total acreage in the United States) accounted for over half of acreage fertilized with manure (9.1 million acres), with hay and grasses accounting for 4.2 million acres and soybeans accounting for slightly less than 1 million acres. Maize being a major beneficiary of manure is due to a number of beef feedlots and swine operations in the Midwest located close to large maize farms.

Due to high transportation costs, manure markets tend to be highly localized. And obviously its value as fertilizer is not unanimously acknowledged, as about 60 % of swine and broiler manure that is not used on the farm is given away for free in the United States. Finally, the odor associated with manure spread on croplands is offensive to nearby neighbors and peri-urban areas, creating friction and complaints about air quality and elevating health concerns as a result of recent food contamination occurrences.

The 2007 USDA ERS estimate of 2 Mt P year^{-1} of 2012 (Frear 2012) allows for a first rough estimate about the magnitude of phosphorus in livestock production. The world population is 22 times larger than the population in the United States, which is known as the world's leading meat-producing country. However, meat production and protein consumption from livestock is rapidly changing in most parts of the world. Between 1967 and 2007, the production (per person) of pig meet increased by 152 % and poultry meat by 369 %, whereas beef and buffalo meat decreased slightly to 93 %. If we acknowledge that the world population has more than doubled, one may see that manure has become more important. Even acknowledging that the phosphorus contents of manure depends on feed, species (see Table 5), and many other factors, we may suppose that the 9.6 Mt P year^{-1} of MacDonald et al. (2011a) for the global phosphorus in manure is assuming that there are more than four times as much phosphorus in animal manure in the United States (with a large share of beef with relatively low phosphorus content) than for the average world citizen. Given that the world protein consumption is increasingly shifting to livestock-based dietary demands, the global phosphorus in manure tends to have 10–15 Mt P year^{-1} and more rather than below 10 Mt P year^{-1}.

In Europe and other developed countries, the application of manure developed a negative image due to the odor and human health concerns, despite advanced environmental regulations in most developed countries. The regulations focus on preventing direct application of manure to salad or other directly consumable products without extensive processing. Regardless of the current situation, the nutrient content of and the possibilities for nutrient recycling from manure must be assessed. Proper strategies for improving manure quality in combination with crop residues, other waste, or mineral fertilizers are possibilities. While the potential of nutrient recovery from manure is not assessed on a global scale, it appears that in developed countries, a large share is used in incineration (e.g., in the cement industry), or dumped in waste fields. With the recent growth in the renewable energy sector, manure has become of interest as feedstock for energy production. The major processes to be distinguished are (a) the thermal combustion path, and (b) biological anaerobic digestion.

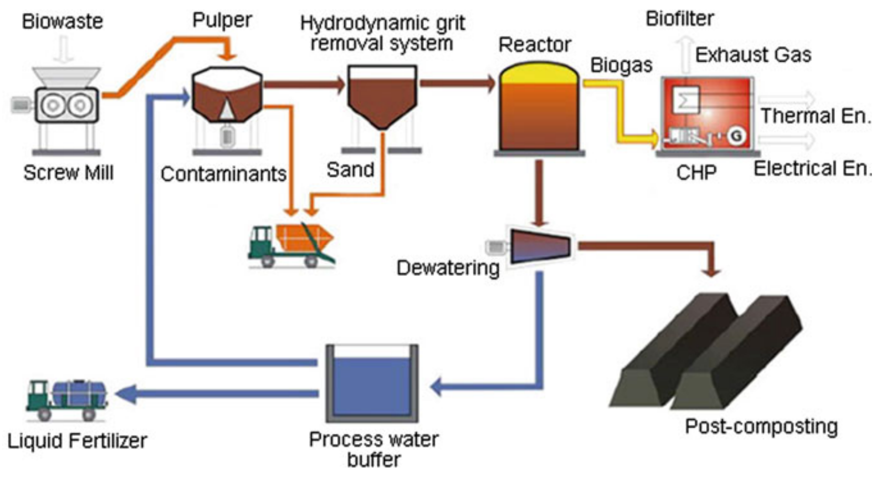

Fig. 20 The process schematic of the anaerobic digestion of biowaste (BTA International 2013)

Combustion will burn most nitrogen, but the ash residues retain the phosphorus and potash. The challenge here is to process the nutrients in the ash in a way that they become plant-available. The interest in manure as fuel is evident (see Fig. 18), as the heating value of horse manure, for instance, is on the same level as wood, with about 20 MJ kg^{-1} dry matter (Edström et al. 2011).

Anaerobic digestion (see Fig. 20) has the advantage that the nutrients N, P, and K are (mostly) retained, and both the effluent of the digestion process and the solid biowaste may be processed and used after energy production. The operation of an anaerobic digester requires technical knowledge, but is applicable at different scales, e.g., from the farm or on a municipal/community scale.

4.8.3 Phosphorus Recycling from Crop Residues

> Crop residues incorporate more than half of the world's agricultural phytomass … Consequently, it would not be inappropriate to define agriculture as an endeavor producing mostly inedible phytomass … [But] No nation keeps statistics on the production of crop residues. (Smil 1999)

The role of *crop residues* in agricultural systems prior to biofuels was primarily seen as a contributor to maintenance of the soil structure and soil organic matter content. The management of residues is central to conservation and no-till practices common in intensified agriculture. In other parts of the world, crop residues are extremely important sources of fuel and fodder. We may also need to acknowledge that the classifications of crop residues and plant-based animal feed are "fuzzy."

Table 3 Phosphorus contents in different animal and crop products (Lamprecht et al. 2011, most data refer to Swiss or German reference values)

Product	Phosphorus content (%)
Bone shred (CH, FS)	9.0–11.0
Bone meal (CH, FS)	7.7
Meat meal (CH, FS)	5.1
Fresh bones (CH, FS)	3.0
Sewage sludge (DS)	2.5
Animal waste from meat processing (CH 2002, FS)	1.1
Soy beans, dried seeds (91.5 % DS)	0.650
Cheese: Tilsit cheese (FS)	0.500
Cereals: feed wheat, grains, FS (87 % DS)	0.380
Compost (DS)	0.301
Beef, FS (24.7 % DS)	0.237
Pork, lean meat without fat (FS)	0.204
Waste (Weinfelden and St. Gallen, DS, 2003; water content 22 %)	0.092
Cow milk, raw (FS)	0.092
Potatoes, raw, freshly harvested (FS)	0.050
Vegetables, Swiss production, 1998 (FS)	0.039
Cola drinks (FS)	0.014
Apple, unpeeled, raw (FS)	0.010

DS dry substance, *FS* fresh substance, *CH* Values from Switzerland

Crop residues gained additional attention with the advent of biofuel production. Smil's initial estimate of 3.75 Gt (Smil 1999) was affirmed by independent bioenergy researchers who estimate that residuals for cereal crops are between 2.80 and 3.76 Gt for 27 food crops (Lal 2005). However, in terms of phosphorus content, cereals and residuals differ significantly. For instance, soybean contains about twice the phosphorus found in cereal (wheat grain), and 15–20 times more than potatoes (see Table 3).

The estimates in Table 4 also reveal the potential of phosphorus recycling from crop residues. According to Smil (1999), the potential of phosphorus in annual crop residues is about 4 Mt P and is thus a significant share of the 14 Mt P of phosphorus in organic fertilizers, which is about the same magnitude as the roughly 16 Mt P of mineral phosphorus fertilizers that were used around the year 2000 (USGS 2000).

The burning of crop residues is higher (around 25 %) in developing countries than in the developed world, primarily due to slash/burn agriculture, pest control and the use of residues as fuel for cooking. Slash and burn agriculture to bring forested land into production or to prepare land set-aside (or fallow) for cropping is most critical from a nitrogen conservation and greenhouse gas perspective. We note here that there is an impending trade-off with bioethanol use (Kim and Dale 2004), which would require a differentiated assessment (see Sect. 5.2.9).

Table 4 Estimates of macronutrient content in crops, crop residues, and inorganic fertilizer in terms of MT year^{-1} (taken from Smil 1999)

Outputs and inputs	Nitrogen	Phosphorus	Potassium
Crop residues	25	4	40
Harvested crops	50	10	20
Total crops phytomass	75	14	60
Inorganic fertilizer	80	14	19

Table 5 Average N, P, and K content of different types of manure in % of dry matter from different livestock (Schnug et al. 2011)

Manure source	Nitrogen	Phosphorus	Potassium
Cow slurry	9.7	0.8	5.9
Cow manure	2.8	0.9	2.6
Swine slurry	8.7	2.4	6.3
Swine manure	3	2.8	4.6
Poultry manure	4.7	4.7	2.6

4.9 Phosphorus Recycling from Animal Carcass and By-products

The part of the animal carcass (e.g., meat, bowels, blood, bones, skin, hooves, feathers) that is used for food, feed, composting, anaerobic digestion, or other purposes differs among cultures and times. In developed countries, carcass waste may cover a considerable amount of the phosphorus cycle. For instance, in Switzerland, there are about 7,000 t P year^{-1} in sewage compared with 2,800 t P year^{-1} in by-products from meat processing, animal and pet carcasses (Lamprecht et al. 2011). Further, there are 3,500 t P year^{-1} in waste and separate collection. Due to the high concentration of phosphorus in bones, in Switzerland about 50 % of the phosphorus was in livestock carcass and by-products of meat processing (Lamprecht et al. 2011).

The animal carcass-related flows are higher concentrations and provide a very good option for recycling. The losses on a global scale are difficult to quantify but deserve increasing attention from a sustainable phosphorus management perspective—though severe trade-offs with health protection must be acknowledged (Scholz 2011a; Sharrock et al. 2009).

4.10 Phosphorus Recycling from Sewage

Although there is a wide range of recycling options along all nodes of the supply–demand chain (see Fig. 16), the popular focus today is very much on sewage sludge (also referred to as “sludge,” “compost,” or “biosolids”). Options for recycling from sewage, manure, and solid industrial waste are addressed comprehensively in Chap. 6 of this book (Smith 1995). As this is the case, a brief illustration is presented which shows that there is no panacea for recycling sewage, and that the technological options may be site-dependent and will have a historic tendency to change.

Natural sewage recycling has become the object of environmental concerns due to the pervasiveness of toxic elements and compounds and their potential negative effects on humans, livestock, and ecosystem health—including soil fertility (Davis 1996). The dry weight of sewage sludge after multiple (primary, secondary and even tertiary) treatments in the EU is still 90 g per person per day (Scholz et al. 1990). If one looks at the current streams of sewage use, three main streams for recovering nutrients may be roughly and ideally identified along with one stream centered on the use of manure for energy.

Stream one is the recycling of human excreta and manure to the nutrient chain in a *direct or moderately processed way*. This is certainly the most natural and historically common stream and may include waste treatment processes such as drying, fermentation, and other composting-type processes. Here, it is noteworthy that even historic sewage recycling in Japan or Korea did not use direct application, but rather, treated the sewage to mitigate certain unwanted effects. Sewage fields, in which high concentrations of sewage were applied to soils, were dependent on the hope that soil microorganisms would remove associated toxicants that could endanger human health—the effects of which were measured in residential gardens where waste disposal biomonitoring took place (Polprasert 2007). But the issue of reuse (in the sense of organic reuse) may function properly if the wastewater is properly treated (Quazi and Islam 2008); this treatment is also common and considered to be effective in aquaculture and the potential to detect struvite. This has already been stated by Ulex (1845).

Stream two is the recovery of phosphorus *by crystallization from sewage water*. Struvite is produced by adding magnesium and ammonium to phosphorus. The mineral, which also forms naturally—a fact that was first scientifically documented in 1845 (Johnston and Richards 2003)—is, in general, a low-pollutant fertilizer. It may be produced in a water-soluble form with high plant availability (Baur 2010), it is available on a commercial scale (Chen et al. 2012) and it can be economically attractive in various sociocultural contexts (Kabbe 2013; Herrmann 2012, September, 4). Struvite processing is of interest from an operational wastewater treatment point of view. When applied it may provide process stability (avoidance of incrustation and abrasion) for sewage plants, reducing maintenance costs, lower sludge disposal costs by less sludge production, and less chemicals consumption (e.g., polymers for flocculation). Lower energy consumption and incomes by selling struvite are further positive components,

Stream three is fertilizer produced from *mono-incinerator-based sewage sludge*. A challenge here is to economically extract and process phosphorus in a plant-available form for a variety of soil types. Sewage sludge ash contains high amounts of either iron or aluminum and is, thus, not a material appropriate under traditional P fertilizer processing methods. Nevertheless, some thermal and perhaps wet processes may be developed to extract phosphorus from ash (van Otterdijk and Meybeck 2011).

The *fourth stream* is using the sludge as an *energy source* that is partially involved in stream three. Here, the recycling of phosphorus has not yet been sufficiently investigated.

In principle, there is a sustainability competition among the four described streams of sewage recycling though streams 2 and 3 do not directly compete because the catching of dissolved phosphorus in the aqueous phase may reduce the amount of particulate phosphorus extracted. To determine which operation is environmentally and economically viable is very much dependent on local conditions and constraints.

4.11 Food Waste

Simply stated, large amounts of food are wasted after agricultural production. The food waste is estimated to be 95–115 kg annually per capita in Europe compared with low-waste regions such as Sub-Saharan Africa at 6 kg per capita per year and South/Southeast Asia at 11 kg per capita per year (van Otterdijk and Meybeck 2011).

The primary reasons for food losses in the developing countries are multiple inefficiencies and underdeveloped infrastructure in storage- and transportation-related, given difficult climatic conditions and a lack of temperature control, proper storage, packaging, unpaved roads, and processing technologies. In the developed world, food losses occur at food industry, retailer, and consumer levels. Consumers in the developed countries tend to consume only goods perfect in appearance and, thus, waste perfectly edible food. They also do not plan their purchases carefully, in part because most are more readily able to afford the food waste. The industrial and retailer management of food requires closer analysis to identify both causes and effects. Nonetheless, there is believed to be about 1 Mt P that is wasted annually through food loss in the developed countries, which might have been diverted to use as animal feed, composted or avoided altogether. The total estimate is that "one-third of food produced for human consumption is lost or wasted globally, which amounts to about 1.3 billion tons." (Scholz and Wellmer 2013, SI 7).

4.12 How May We Define Sustainable Phosphorus Use?

Food security and supply security With today's agrosystem and food demand, food security means avoiding the scarcity of phosphorus. Taking an anthropogenic perspective, one must consider a time range that is relevant for *human individuals* and the *human species*. Since the human body requires food and phosphorus, scarcity must be avoided on a daily and an evolutionary timescale of the magnitude of 100,000 years. Accordingly, with the specific dissipative nature of phosphorus, in our (geological) age, a large amount is estimated to dissipate (from surface waters and rivers to the sea) just from agricultural systems. This phosphorus is not easily accessible, as the sedimentation of phosphorus from seawater occurs over an extremely long period. While extraction of phosphorus from seawater is technically possible, the required scale of mining is neither technically or economically feasible (MacDonald et al. 2011a). Thus, from a precautionary and socially responsible view, the currently known phosphorus reserves and resources must be optimally managed to provide for food security and to prevent phosphorus scarcity in the long term.

Efficiency If we consider *efficiency*, much insight may be gained from simply answering the question, "how much phosphorus is mobilized to produce the food which we consume?" If we take a (simple) functional perspective, phosphorus uptake is the "target variable." Based on human uptake/excretion of 1.4 g P per day, we get an annual uptake of 3.4 Mt P for the current global population. Compared with this, we have an input on the magnitude of 15 Mt P in mineral fertilizers annually, and—with a very low estimate—at least 10 Mt P in manure (Liu et al. 2008). These numbers are supplemented by phosphorus that enters the agrosystem due to weathering. Liu et al. (2008) provide an estimate of 17 Mt P from pastures, which is partly accounted for in manure. Then, we account for 1 Mt P from feed additives, and about 1 Mt from food waste as well as 1 Mt from human excreta. Further, we must incorporate the input from weathering (which is also accounted for in the pasture based phosphorus input) and some other sources such as fertilization by slurry. This amounts *to a magnitude of 40–50 Mt, which we are mobilizing for a human uptake of 3 Mt P in food.* Naturally, the annual input from fertilizer and geogenic phosphorus is lower, but remains around 30 Mt P.

In a recent analysis organized by the European Union (EU), 15 nations provided slightly more friendly data, stating a phosphorus consumption average of 4.7 kg P annually per consumer, of which 1.2 kg P are consumed and only 0.77 recycled (Dumas et al. 2011).

Avoiding pollution When defining sustainability with respect to *environmental quality*, referring to the essence of the Brundtland definition (Rockström et al. 2009), the risk or vulnerability of fulfilling human needs in relation to available ecosystem functions is the reference. Here, we must ponder in what ways the pollution of aquatic systems and the potential overload of phosphorus by fertilizer may become critical, and what *environmental responsibility* should be taken.

Finally, we mention again the stark differences in P fertilizer use between developing countries and the developed world. This is directly related to extreme differences in agricultural yields, which subsequently may cause a critical state in the food supplies of many developing countries, with large shares of crop systems dependent on soils that require the highest input of P fertilizers.

5 CLoSD Chain Management

5.1 The Vision of Closing Anthropogenic Material Flows

We know that humans will eventually triple the phosphorus flows. And phosphorus may become a pollutant.

> At the planetary scale, the additional amounts of nitrogen and phosphorus activated by humans are now so large that they significantly perturb the global cycles of these two important elements. (Carpenter and Bennett 2011)

Rockström et al. define ten times the natural cycle as *planetary boundaries*. But as the global use of phosphorus is uneven, the environmental impacts are uneven. Thus, we must reflect that phosphorus is spatially not evenly distributed. Ecosystems that are of different scales—including marine systems—may be highly vulnerable with respect to phosphorus impacts. We argue that the "average planetary boundary" may be a questionable concept for many pollutants such a phosphorus. For assessing the planetary boundary of phosphorus load rather a regionalized view seems adequate that assesses unwanted environmental impacts in aquatic and other ecosystems, perhaps from a pattern of contaminated area perspective.

Carpenter and Bennett elaborate that we must distinguish between planetary boundaries of (average) seawater and freshwater and that:

> … planetary boundaries for eutrophication of freshwaters by P have already been surpassed. (Udo de Haes et al. 1997)

A different perspective is provided from a resources management perspective. High ore phosphate rock reserves are finite, non-renewable on the human scale and phosphorus use shows a very low efficiency that should be increased. Thus, it seems desirable if not necessary to close the anthropogenic fertilizer loop. A first focus in a sustainable transitioning would be the reduction in losses of phosphorus by dissipation in the supply–demand chain. The vision here would be the closing of the anthropogenic material flows, or—to express it in other terms—to approach the issue with *Closed Supply-Demand Chain* (CloSD Chain) management of anthropogenic phosphorus.

The Material Flow Analysis (MFA) is a simple, easily understandable method that may help to represent the main losses, sinks, obsolete stock building and options for increasing efficiency by changing consumption, technology development, and recycling. This chapter provides a blueprint for this effort on a global scale.

MFA is a quantitative accounting tool for representing the flows and stocks of materials and energy. Its starting point is mass balances of inputs by extraction, etc. We organize the MFA according to the supply chain (see Fig. 16). We should note that this chapter focuses on the chemical element phosphorus. We also talk about substance flow analysis (SFA) (Brunner and Rechberger 2003), whereas MFA focuses on goods (Binder et al. 2004). As the presented MFA includes (some non-quantified) information about the chemical processes underlying fertilizer and food production, we continue to use the term MFA.

A challenge in the research of MFA is to move *from flows to actors* (Matsubae et al. 2011). As the first step, we organize the MFA along the supply–demand chain and thus may identify key stakeholder groups who may take responsibility in *Closed Supply-Demand Chain* (CloSD Chain) management.

Key Message

MFA may serve as a tool to identify key stakeholders along the supply–demand chain for *Closed Supply-Demand Chain* (CloSD Chain) management.

5.2 A Blueprint of Global Phosphorus Flows

5.2.1 System Boundaries

Figure 21 is the pillar of this section. The bold-lined box represents the *system boundary* of the "supply–demand chain system." The *Bedrock phosphate* and the *Atmosphere* (considered as a constant pool) are external systems. Reserves are partly external and become internal if they become economically accounted values in the supply–demand chain.

The shaded bottom box, *Losses to sinks*, includes (currently) uneconomic stocks in "bedrock" (e.g., the stock "Losses of mining," bottom left), *Sediments*, *Landfills & cesspit*, *Ash dumps*, etc. In principle, the S-D chain system should also include the virtual flows, which are presented as a bottom flow. As these are not addressed in this chapter, they are represented separately. The presented MFA is called a *Blueprint of the Global Phosphorus Material Flows*, as it only provides an initial rough outline, which asks for elaboration and validation of many data.

A classical MFA includes *stocks*, *processes*, and *flows*. The *boxes* present the *stocks and (inner) processes*. The *arrows* represent the *flows* that are linked to material metabolisms. We present the non-quantified flows, as the changes and innovation in fertilizer processing and products (goods) are considered an important issue. Most data are linearly transformed to the 2011 (USGS 2012) input data (referenced to the 25 Mt year^{-1}) if survey data are available for certain processes or flows for 2011. For this reason, among many others (years with extreme weather conditions affecting runoff or erosion, such as different classifications of national statistics, uncertain estimates), one is only allowed to consider the many data as rough estimates within factor 2 precision.

The reader who critically examines the data of Fig. 21 will face some general problems with the consistency of the data of the global phosphorus flows. For instance, the main (top down) reference for the amount of global phosphorus flows are 25 Mt P which enter the processing stage. This is referring to the USGS data for 2011 that have been published in the USGS (2012) Mineral Commodity Summaries (191 Mt PR = 24.8 Mt P year^{-1}). The data in the USGS 2013 report for 2011 differ from that of those published in 2012 and suggests 25.7 Mt P year^{-1}. There are many causes for this inconsistency including the fiscal year in some countries (and thus the basic statistic recording) does not end on December 31 but on March 31. The diverting time frames spoil the coherence of most annual global statistics referring to economic data. Further, in general, there are also competing sources from different statistics with different types of classification system, e.g., what is considered manure may differ from country to country. Many statistics are officially published by various governmental authorities due to different interests. And these interest and thus also statistics may differ from those of market research institutes (which may correct "mis"-classifications). Also, tax declaration may serve as a distractor, e.g., if fertilizer-related use receives special treatment. Thus, it may seem that the principle of mass conservation seems to be violated, e.g., if we look at the input (i.e., 25 Mt PR) or the sum of outputs of processing.

The *virtual flows* at the bottom of Fig. 21 include the phosphate bonded to iron in metals; iron may build an important part of the anthropogenic flows (FAO 2010a). Here, research has just begun (see Sect. 4.5.1).

All figures are Mt if we consider stocks, or Mt P year^{-1} if we consider flows. The latter are presented without units. For most of the figures, there is at least one reference cited as upper quotes. These may be found in literature. The non-referenced figures are derived and discussed in 4.

Key Messages

The system boundaries include the economically accounted flows of goods with respect to phosphorus.

Some data are of high uncertainty and only allow for a factor 2 certainty.

5.2.2 System Inputs

The *system boundaries* (inside the box) are the operations along the phosphorus supply–demand chain and the waste-recycling activities.

The first natural *input* in this system is that from the weathering of rocks to the soil system. There are three main input processes: (a) *natural weathering*; (b) *human-induced weathering*; and (c) *mining*. We have discussed (a) and (b) in Sect. 4.5. Here, soil surface management and climate change are important factors.

We may also look at natural (via seabirds) and anthropogenic (via fisheries) biotic terrestrial inputs. The fishery is relevant. In 2009, 145 Mt of fish were caught; 118 Mt used for food and the remainder for feed (Ruttenberg 2003). About 55 Mt of fish are from fish farms (whose input–output relationship is not represented). The phosphorus concentration of fish is about 0.25 %, which translates to an input of 0.36 Mt P year^{-1}, which is compatible with the 0.31 Mt P year^{-1} suggested by (Ruttenberg 2003). We work with 0.34 Mt P year^{-1}, of which 0.24 is part of food and the rest (not explicitly presented) is part of feed. By means of simplicity, we do not include these flows in Fig. 21.

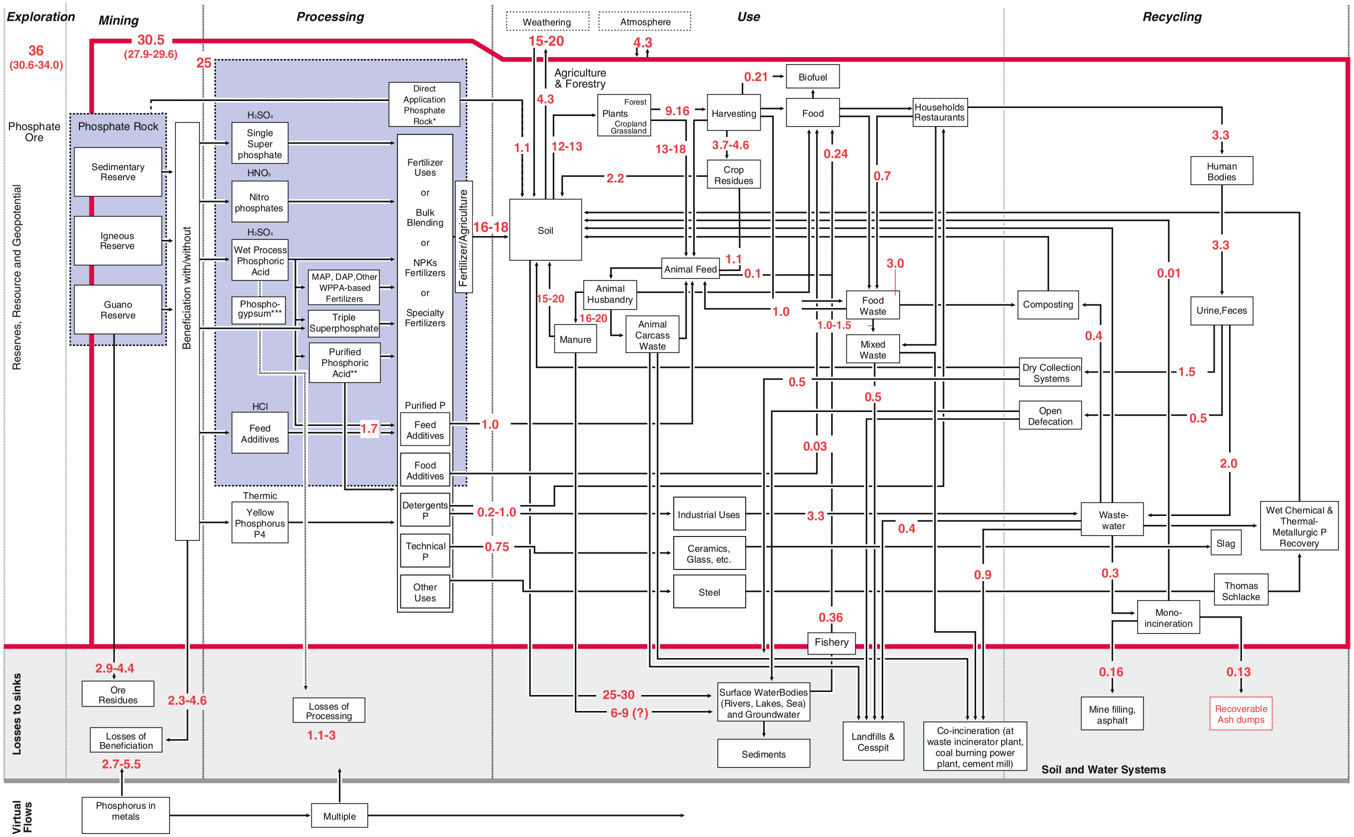

Fig. 21 A blueprint of global phosphorus flows 2011 (USGS 2012) along the steps of the supply-demand chain (non-incorporating virtual flows) referring to an equivalent of 25 Mt P year^{-1} (Fig. 21 is electronically accessible by http://dx.doi.org/10.1007/978-94-007-7250-2_1)

In addition, the *atmosphere* may be mentioned here. Geologists assume a constant pool of only about 0.28 Mt P. The "residence time" is asserted to be only 80 h; thus, a considerable amount of 4.3 Mt P year^{-1} may be assumed to be linked to the annual land (soil) to atmosphere flux (Cunfer 2004). These geological data are—in general—not linked to specific contemporary human activities such as the huge erosions in the Dust Bowl of the United States (USGS 2012) or in other parts of the world.

Mining (c) transferred about 25 Mt P year^{-1} in 2011 (Heffer and Prud'homme 2011) to processing. Of this total, 1.1 Mt P year^{-1} was directly applied to soil after or without differentiated beneficiation, and about 16 Mt P year^{-1} was applied as mineral fertilizer. Thus, 17–18 Mt P year^{-1} (Villalba et al. 2008) of mineral fertilizers entered the soil.

In Sect. 4.5.1, we provide a rough estimate that 2.9–4.4 Mt P of ore phosphorus is left in the mines for various reasons. Whether or which parts of this may be considered a loss in what time frame is difficult to assess. We may assume, however, that much of this may not be assigned to the currently economically mineable phosphates, as otherwise it would not be understandable as to why it would not be excavated.

We may argue similarly for the 2.3–4.6 Mt P from ore phosphate that has been put aside after excavation in primary beneficiation.

We do not provide numbers for the different chemical process engineering pathways. But Villalba et al. (2008) provide some estimates about the share that different tracks may take. Here, we start with the rough estimate that wet-processed ammonium phosphate (MAP, DAP) makes around 47 %. Nitric or nitrophosphate may amount to 28 %. Single superphosphate provides 19 %. The remainder of about 6 % is taken by triple superphosphate. In all the data, the reader should acknowledge the uncertainty and fuzziness that are caused by various reasons—e.g., that countries follow different fiscal years of accounting data or that a multitude of chemical process chains and different types of phosphate rock are linked to one and the same box.

Key Messages

- There are varying changing phosphorus inputs to the (terrestrial) food and non-food supply–demand chain system including *natural* (10–15 Mt P year^{-1}) and *anthropogenic weathering* (up to 5 Mt P year^{-1}) *mining* (more than 30–34 Mt P year^{-1}), *fishery* (0.36 Mt P year^{-1}), in which about 4.3 Mt P year^{-1} is *transported through the atmosphere*.

5.2.3 The Crop–Forest System

With respect to the crop systems, we are interested in: (1) how much phosphorus is taken up by cultivated crops; (2) how great is the phosphorus use efficiency (NUE), and in particular how much phosphorus is taken up by the plant from the applied

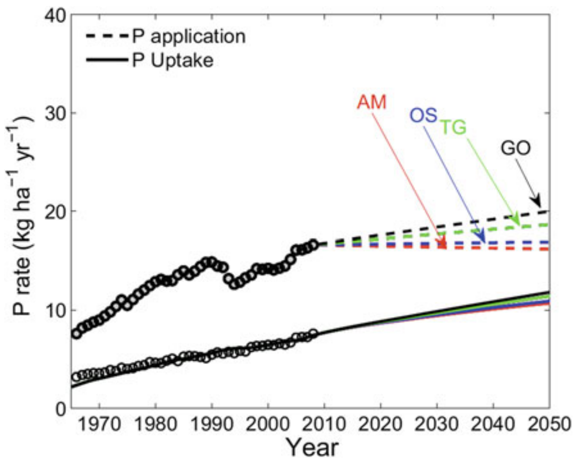

Fig. 22 Annual application of mineral fertilizer and manure per hectare (kg P ha year^{-1}) between 1965 and 2007 and phosphorus uptake in cropland and simulation for future phosphorus uptake for the MEA scenarios [Sattari et al. (2012); *AM* Adapting Mosaic, *OS* Order by Strength, *TG* Techno garden, *GO* Global Orchestration, see (MacDonald et al. 2009; Smith et al. 2008)]

mineral and organic (in particular the manure) fertilizers; (3) what role do crop residues play; and (4) how much is leached or lithified (i.e., transferred to the stable, not to the plant bioavailable pool) in the sense that it will not be available to plants in the foreseeable future.

Also, managed forests receive fertilizers (Tanner et al. 1992), and fertilizers have a tremendous effect on trunk growth (The World Bank 2012). Despite this fact, there is no data available on the global inputs to forest systems other than the inputs to palm oil crops and similar plantation operations. Thus, this part of biomass management is not included here, though it may well be of the magnitude of 1 Mt P year^{-1} and above, given that the average consumption of NPK fertilizer in Malaysia is 770 kg NPK ha^{-1} (Frossard et al. 2000; Dumas et al. 2011; The World Bank 2012).

With respect to the phosphorus uptake (1) of crops, we face a difficult task because of the heterogeneous soil conditions (Liu et al. 2008). In addition, literature provides diverging estimates. Liu et al. (2012) provide an estimate of annual crop uptake in 2005 of 12.7 Mt P year^{-1}. Figure 6 identifies the average world phosphorus nutrient use efficiency (NUE) on a per-hectare basis. According to Sattari et al. (Sims et al. 1998), the total uptake of phosphorus in crops in 2007 was 11.6 Mt P year^{-1}. Thus, given that food production has increased, we work with an estimate of 12–13 Mt P year^{-1} uptake in 2011.

The Sattari et al. (2012) paper also provides insight into (2). The phosphorus nutrient efficiency (P-NUE) increased between 1965 and 2012 only slightly, from 42 to 46 % (see Fig. 22). However, the input from natural and anthropogenic weathering is not included here. Nevertheless, this long-term, equilibrium-like efficiency term allows one to check some input and output data.

A crop uptake of 13 Mt P year^{-1} and an efficiency of 46 % provide an input of 28.3 Mt P year^{-1} and a loss of phosphorus from cropland of 15.3 Mt P year^{-1}. This loss may be assigned to runoff and erosion, transfer to the stable, non-bioavailable pool of the topsoil or leached to the subsoil. This would also imply that about half of the total phosphorus runoff and erosion of 25–30 Mt P year^{-1} that stems from the 10.3 % of the earth's surface grassland erosion is not included in the 15.3 Mt P year^{-1}.

The crop residues (3) play an important part, as the question is how much of the crop may be eaten. Here, we estimate that roughly 50 % of the crop is not removed from the fields (see Sect. 5.2.5). We should note that the current trend of breeding and plant modification to increase the edible part of the plant may cause a rebound effect with respect to fertilizer needs.

Finally, (4) the leaching of phosphorus or the losses in drainage has not been studied for a lengthy period. However, there are losses in sandy or high organic matter soils, or soils with high phosphorus fertilizer overshoot (Oenema et al. 2005). There is also an in–out aspect to groundwater, but it is much lower and less critical with respect to human hazards than that of nitrogen (Alcamo et al. 2006).

Key Messages

- There is a crop uptake of 12–13 Mt P year^{-1}.

- We are facing a long-term global plant nutrient efficiency of about 45 % with losses by erosion, runoff, leaching, crop residues (which are partially reused), etc. of 15.3 Mt P year^{-1}.

5.2.4 Animal Production

Given that animal bones contain up to 10 % phosphorus concentration, a great deal is accumulated in animals (see Table 3). But the phosphorus content in animals depends on feed and differs among species. Poultry manure has about five times more phosphorus in dry matter than cow manure.

We only focus on annual flows in this section. Based on the comprehensive discussion in Sect. 4.8.2, we assume that about 15–20 Mt P year^{-1} of manure is produced and used as a soil amendment.

There are many value-laden controversies regarding manure that touch on energy issues (e.g., for transporting manure, producing organic fertilizers), soil quality, health issues, etc. (Schipanski and Bennett 2012). Thus, it is impossible to provide a reliable estimate of non-soil manure use.

The estimate of phosphorus in livestock feed may be estimated by the output, i.e., the amount of phosphorus in excreta/manure plus the livestock products including meat, milk, eggs, etc. Phosphorus in livestock products is difficult to access due to the high variance of phosphorus content in numerous animal feeds. According to an estimate of 12 countries by Schipanski and Bennet (USGS 2000), about 6 % of the phosphorus in manure becomes animal products. This would provide an estimate of 0.9–1.2 Mt P year^{-1} as animal product. The waste of animal carcasses and the wasted by-products of meat processing are difficult to assess on a global scale, but are increasing in industrial nations (see Sect. 4.9).

Key Messages

- There are about 16–21 Mt P year^{-1} in animal feed from grassland, feed additives and other animal feed.
- There are increasing losses due to animal carcass waste and by-products of meat processing in developing countries.

5.2.5 From the Farm to the Table

In 1999, Smil provided an estimate of food residues of 3.75 Gt, including about 4 Mt P year^{-1}. From 1991 to 2011, the world population increased by 17 %, from 6 to 7 billion, and the fertilizer increased by 35 %. This may be roughly estimated from the total amount of phosphate rock production if we assume that the share of fertilizer in total phosphate consumption did not change over years. The phosphate rock production increased from 145 Mt PR year^{-1} in 1998 (Liu et al. 2008) to 191 Mt PR year^{-1} in 2011. We thus may roughly estimate that crop residues increased by 10–20 %, and we take 4.6 Mt P year^{-1} as a rough estimate for the phosphorus content of the crop residues. We add (Kim and Dale 2005) that 50 % of crop residue is not removed from fields. We may assume that some of the residues that are used as animal feed will end in manure, but we also acknowledge that some portion is burnt.

A critical issue is the trade-off with energy production. Here, the perspective is changing. Rather than calories, we refer to joules: "The functional unit is defined as 1 ha of arable land producing biomass for biofuels to compare the environmental performance of the different cropping systems" (Kim and Dale 2004). And crop waste becomes the status of alternative energy. The high expectations from the energy domain are characterized by the following statement:

> There are about 73 Tg of dry wasted crops in the world that could potentially produce 49.1 GL year^{-1} of bioethanol. (Mihelcic et al. 2011)

Key Messages

- In a time of transition to alternative energy, crop residues have become a hot topic for the energy market. The rebound effects of this option for agriculture must be pointed out.
- The phosphorus balance of biofuel production requires special attention as the recycling streams of the different types of biofuel are not yet well assessed.
- Crop residues and waste of food products in retailing also requires special attention.

5.2.6 After the Table

The *daily intake of phosphorus per person* differs among diets and shows extraordinary variances depending on age, weight, gender, nation, etc. Thus, the uptake in the Democratic Republic of Congo is estimated to be 490 mg P d^{-1} compared with 2,000 mg P d^{-1} in Israel (Walther and Schmid 2008)—or consumer groups in Switzerland, for example, who tend to eat processed food with phosphates as additives, may show an intake of 0.35 g P d^{-1} (Liu et al. 2008; Mihelcic et al. 2011).

We assume an average intake of 1,250 mg P d^{-1}, which makes about 3.4 Mt P $year^{-1}$ (Mihelcic et al. 2011).

If we follow the mass balance for the human population after intake, some 0.05 Mt P $year^{-1}$ (1–2 %) accumulates in the body, but a larger share is excreted by urine and a smaller share via feces. This greatly depends on the digestibility of the food in the diet. Estimates in Sweden assume 68 % in urine, yet those for China reflect only 20–60 %. Often, a rough 50:50 split is assumed for a global estimate (2010).

If we take a simplified look at the flows in the world, we distinguish between *Open Defecation*, *Dry Collection Systems*, which are prevalent in rural areas, and different types of centralized, connected *wastewater treatment treatments*, which are dominant in urban systems.

According to the WHO and UNICEF (UN 2011), about 15 % of the world population represents open defecation, which makes about 0.5 Mt P $year^{-1}$.

The UN statistics on *population connected to wastewater collection* systems is incomplete and varies greatly among countries. There are percentages below 5 % for countries such as Yemen, Maldives, and Kenya. China is recorded with 32 %, Brazil with 26 % and Croatia with 27 %. And some European countries such as Belarus, Germany, or the United Kingdom rate above 95 % (Ott and Rechberger 2012). There are many countries without data, such as India and the United States. And the unweighted average of 101 recorded countries comes to 50.1 %, which provides an estimate—including an average loss of collection of 10 % or more—of about 35 % connected to wastewater treatment systems. This provides an estimate of 1.2 Mt P $year^{-1}$ treated in various types of wastewater treatment (WWT) plants.

Naturally, the performance of sludge extraction differs greatly among these systems. Estimating the current recycling and recycling potential from different types of WWT plants, septic tanks, cesspits, pit drainage, or other systems is difficult. Estimates for the EU 15 countries, which show very high standards of sanitation and make 5 % of the world population, show that 79 % of the population is connected with WWT plants and that about 70 % of the phosphorus of the influent is contained in the sludge, which would provide a 55 % extraction of phosphorus by WWT in the countries with the highest standards of WWT systems (van Otterdijk and Meybeck 2011). This includes households, not including the losses of wastewater by leakage before reaching the WWT plant, which represent about 5–10 % in the EU 15 sample.

Fig. 23 Urine separation and separated dry collection and processing are used by the Guatemalan Mopan Mayas in the region of Peten (*Photo* R.W. Scholz)

Finally, we define a category called *dry collection systems* that includes 1.6–1.9 Mt P year^{-1}, with different types of cesspits, septic tanks, and decentralized management of excreta. There are a large number of culturally driven management systems. As urine is known to include far fewer pathogens and less organic content, urine separation is common and was so even in some ancient cultures (see Fig. 23). The nutrients in urine are directly applied. The feces is processed and composted separately and is assigned to the dry collection path. We work with the rough estimate that two-thirds, i.e., between 1.1 and 1.3 Mt P year^{-1}, of the phosphorus on that track is reused.

Finally, we take a brief look here at the extraction of phosphorus in wastewater treatment plants (see Chap. 6 of this book). There are, in principle, three ways of utilizing treated wastewater. The most common is the direct reuse of the sludge in agriculture, which is represented by the *Composting* box of Fig. 23. The second is the incineration of ash, which became popular in various developed countries such as Japan or many European countries. The third is the extraction of phosphorus by biological or chemical precipitation. We do not discuss the different option of chemical or thermal recycling in this section (see Sect. 4.9), but we do provide an estimate of 0.2–0.3 Mt P year^{-1} that is treated, with about half in asphalt and cement, half ends in dumps and a minor part already used in agriculture.

The food waste by consumers (including restaurants) at the end of the supply chain has been estimated to amount to 1 Mt P year^{-1} in the developed countries (1–1.5 billion people waste 100 kg food waste per year including 0.06–1 % phosphorus). Conversely, the food loss of the 5.5 billion people in the South is estimated to be 10 kg per person, with lower phosphorus concentrations and with a lower phosphate content (perhaps of 0.3 % P kg^{-1} food waste is of marginal magnitude of 0.25 Mt P $year^{-1}$ (Emsley 2000b).

Key Messages

- Related to the total anthropogenically caused flows, sewage is a relatively small fraction of about 3.3 Mt P $year^{-1}$.
- The amount of phosphorus in sewage differs by factor 2 and depends on the diet.
- Phosphorus recycling has to be adapted to the wastewater system.
- The recycling of sewage on a global level is on a very low scale. There are different options for phosphorus recycling, all of which have strengths and flaws. There are examples of economically beneficial recycling procedures.
- The recycling of sewage may become a paradigm and an object of demonstration in how CloSD-Loop Management may look.

5.2.7 Industrial Use

We will distinguish among a wide range of technical uses (including military use) and virtual flows of phosphorus in heavy industry.

The technical part makes about 0.7 Mt P $year^{-1}$ and is based on white phosphorus. "The enigma of phosphorus lies in chemistry" (Webster's 1913). It shows specific chemical characteristics such as the clustering (e.g., P4) or affinity to oxygen. But it is a key element at the boundary between organic and inorganic chemistry and thus may have a huge potential for technological application.

The virtual flows (see Sects. 2.5 and 4.5.1) may have a large potential for resource management. The amount of phosphorus that is included in many mineral and metal processing may become of interest in the future. Thomas slag may be viewed as an historic issue:

> A by-product from the manufacture of steel by the basic process is used as a fertilizer. It is rich in lime and contains 14 to 20 percentage of phosphoric acid. Called also Thomas slag. (Babenko 2012)

But the issue remains of interest (Wetzel 1983). With Thomas slag, as with other ashes and wastes, we are seeking proper technologies that allow one to economically extract the valuable, i.e., economically scarce, materials.

Key Messages

- About 0.7 Mt P $year^{-1}$ is used for a wide range of technical processes.
- The flows of phosphorus in heavy industry and exploration of technology options should become a subject of research.

5.2.8 Detergents

The amount of phosphorus used in laundry and dishwater detergents varies historically and regionally. During the 1980s, in the United States, 2 Mt year^{-1} phosphorus was used for detergents (Wetzel 1983). The detergent industry "was reluctant for quite a long time to look for and tried to minimize its (i.e., phosphorus) role in eutrophication process" (Knud-Hansen 1994). A conflict trade-off emerged between aquatic pollution of STPP, in particular for regions with low profile sewage treatment without phosphorus extraction and the higher toxicity of alternatives (see Sect. 3.2). After the phosphate bans in a few states in the US States in the midst of the 1980s, the share of phosphorus in detergents by weight decreased in the United States and other developed countries. There had been a worldwide discussion at that time and seven nations out of the EU-25 banned detergents from laundry detergents. Other countries relied on the voluntary action of industry. This has been insufficient, to resolve eutrophication problems, for instance in particular in the Baltic Sea and the Danube River (EU 2012a). These cases may also be taken as an example for the necessity of high performance wastewater treatment plants with phosphorus extraction. Factually, in 2007, only 66 % of the detergents of EU-25 were classified as "phosphate free." "Where STPP is used as a builder in household detergents it contributes to up to 50 % of soluble (bioavailable) phosphorus in municipal wastewater…" (EU 2002). Thus a EU regulation (EU 2012b) will set limits for the total phosphorus content in both laundry and dishwater consumer detergents. One should note that the above data are under discussion, also as detergent formulation and phosphorus use in detergent is subject to change in Europe as in other countries of the world.

A reliable estimate of the amount of phosphate use in detergents is difficult. One reason is the high volatility of production in the STPP market. Other reasons are that industry data are not public because it is subject to anti-trust and commercial disclosure restrictions and the only information available are therefore (heterogeneous) estimates. These estimates are provided by marketing studies or industry experts and some customs data which only covers some cross-frontier tonnages.

In the past, the share of STPP in detergents and cleaners was much larger than its use in drinking water, water treatment, metal treatment, food and beverages fire safety, phytochemicals, chemical industry, ceramics etc. This may have changed in the last years (Shinh 2012). Shinh reports that the amount of P in detergents and cleaners has decreased in the last years from about 0.41 Mt P in 2006 to 0.19 Mt P in 2011 worldwide. However, we should acknowledge that China became a key market player in STPP. According to Chinese customs-based market reports in 2011, China exported 0.31 Mt STPP which includes about 0.08 Mt P (Zheng 2013). The total elemental P production (also including a minor share of non-detergent use) in China in 2011 is supposed to be between 0.7 and 0.8 Mt P (Schipper July 9, 2013). This suggests that the Shinh estimate seems too low and rather a lower bound estimation.

A differentiated analysis of regional STPP demand based on twelve business areas resulted in an estimate of 0.71 Mt P year^{-1} in 2011 just for detergents and cleaners (Mew 2013). How much the STPP production may have decreased may be taken from the Global Phosphate Forum homepage, the industry association of companies which are manufacturing phosphates for detergents. At one time, the "World detergent phosphate production is estimated to be 4.7 million tonnes STPP per year" (GPF 2013). But the recent estimate indicates production of only "1.0–1.7 million tonnes/year (as STPP)" (GPF 2013). In terms of phosphorus consumption, this would mean a decrease from 1.19 Mt P year^{-1} to 0.25–0.43 Mt P year^{-1}. The data presented in Sect. 2.1 of 1.7 Mt P for total STPP production in Fig. 4 (Prud'homme 2010) would—linearly extrapolated—provide around 2 Mt P year^{-1} for the year 2011 but keeps unspecified how much phosphorus much is used for detergents and how much for other purposes. Therefore, we are receiving a picture that goes beyond the factor 2 uncertainty in the estimation of phosphorus in detergents. This may ask for clarification, also given that a significant amount of detergents are used in megacities of the developing world where they may cause pollution of waterbodies.

Key Message and Data

It is difficult to reliably access the amount of phosphorus in detergents. There is evidence that it has decreased significantly from far above 2 Mt year^{-1} to around or even below 1 Mt year^{-1} worldwide. But the number of produced tons is highly volatile, most data are not public and the published data show high inconsistency. The uncertainty here may go even beyond the proposed factor 2 uncertainty. Thus, based on the presented literature, we assume that in 2011 the amount of phosphorus in detergents may be between 0.2 and 1.0 Mt P year^{-1}.

5.2.9 Biofuel

Utilizing biofuel and mastery of fire 250,000 years ago played a key role in human evolution and wood has been. But the generation of biofuel is shifting from wood to crops. Since 1900, the share of crops in total human biomass extraction increased from 21 to 35 %. This is countered by declines of wood from 15 to 11 % (Alexandratos and Bruinsma 2012). Thus biofuel now sometimes is named agrofuel. The extensive and increasing use of bioethanol and biodiesel is a factor of agricultural land expansion (Heffer 2013). And there is exceptional high demand on fertilizer, for instance for oil plantations, which may be seen from the fact that in—for instance in the year 2008—Malaysia used 1036 kg fertilizer per hectare of arable land and palm oil plantation are a major consumer (The World Bank 2012).

The biofuel feed stocks are expected to increase. According to a 2011 IFA estimate, biofuel feedstocks received 0.21 Mt P year^{-1} (Heffer 2013). This makes around 3.0 % of world phosphorus fertilizer applications. We should note that but most of the phosphorus found in the feedstocks ended up in oilcakes and slurry which is recycled and thus not lost. Thus, the net impact (after deduction of the phosphorus ending up in co-products) would be much smaller, below 1 % (Heffer 2013).

Key Messages

About 0.5 Mt P year^{-1} was used for biofuel. Due to the high recycling of bioethanol and biofuel by-products (for feeding and livestock), there are few losses and it reduces demand on feed grain and oilseed, and the annual net impact of biofuel on the increase in phosphorus consumption is smaller.

5.3 Actor-Based MFA for Changing Flows

This book aspires to contribute to sustainable phosphorus management and thus seeks to go beyond a mere description of the phosphorus flows from a material flow or resource science perspective. Despite this, most parts of Chaps. 4 and 5 remain in line with classical technology or natural science-based descriptions of flows of phosphorus. This is certainly due to the manifoldness, diversity, scale-dependency and complexity of phosphorus flows. Following the principle that we must *start with a thorough understanding of how the environment works* (Scholz 2011a; Scholz and Binder 2004), the MFA is a simple tool which also may serve from joint problem representation among scientists and practitioners in transdisciplinary processes.

But most flows are affected by human actors. Thus, we must shift our attention from "flows to actors." This means that we must link the material flows with human actions and decisions. This brings us to the modeling of coupled human-environment systems—what may be understood as the cutting edge of complexity research. As phosphorus has been and is an important public good which becomes a commodity, much of the flows may be understood from a supply–demand chain perspective, which focuses the drivers of transactions and material metabolisms and both incorporates and goes beyond pure value chain thinking (see Sect. 5.4).

A first step in developing a comprehensive theory of coupled human-environment systems (Binder et al. 2004) is to integrate material flux analysis with agent analysis (Merton 1938). This means that we must identify each stock, process and flows, the key actors and key persons concerned, and in particular their drivers and the constraints of their behavior. This is a challenging task. We may easily see when looking at Fig. 22 that this may be easy if we look at the mining and beneficiation node. Here, mining companies, their technology providers, and the phosphate processing industry may be identified. But already, when differentiating between private and government-owned companies in different political and economic systems (free market vs. centrally planned economy), we may learn that just looking at "unspecified" actors is insufficient.

What decisions an individual or a company makes depends on the *societal framing*, which is primarily given by the economic system (e.g., free market vs. planning society), the political and legal system, the culture and the available knowledge (USGS 2013a). We may also consider whether a state-owned mining company is seen as an institution, which is conceived as a special organization established by the state to guarantee the reproduction of society; institutions such as traffic or water departments are established to guarantee that certain public services or goods become available. Here, mining companies, just as utilities, are at the interface of companies and institutions. The USGS is a typical representation of an institution and follows six goals which "emphasize the critical role of the USGS in providing long-term research, monitoring, and assessments for the Nation and the world and describe measures that must be undertaken to ensure geologic expertise and knowledge for the future" (Cordell et al. 2011).

We will not delve further into the subject here, but only point out that it is very helpful to work with the concept of a hierarchy of human systems. Scholz (2011a) distinguished among the *individual*, *group*, *organization* (e.g., companies and NGOs), *institutions*, *societies* (the primary subdivision of human society, which is currently given by nations), *supra-national institutions* (such as the EU) and the *human species*. Each of these human systems has generic drivers (goals, motives, preference functions), and there are specific social sciences that may define how these systems function. Psychology may explain how individuals (consumers) function, business science explains how companies work, or administration science may illuminate rationales of administrations.

Two issues are important if we wish to apply the hierarchical view on the phosphorus MFA. One is that the hierarchical levels interact such as each human system interacts with its natural and social environment. The second is that we must distinguish between the specific and the generic. All companies have the primary goal to thrive in the market and generate profit. But how this may be done depends on the mission of the company. Likewise, people may follow different motives and values (explained by psychology), or societies may pursue different national goals (explained among others by political philosophy). A challenge of the future work of Global TraPs will be to utilize this knowledge in transdisciplinary processes.

5.4 Supply–Demand Analysis for Improving Technologies

Each market and technology innovation has a *push* (supply) and a *pull* (demand) functions. When we aspire to *CloSD-Loop phosphorus management*, we must identify incentives, means, etc. in the current trend of increased use, what losses may be averted and how more efficient use may lead to that reduction, and we must identify efficient recycling and better environmental performance.

Before we deal with supply–demand chain analysis, let us clarify how the different methods are related. *Actor-based MFA* is a method to represents the global phosphorus management system. *The SD chain analysis* is a means of "faceting" the phosphorus management system. Such faceting is necessary to cope with the complexity of the system (Scholz and Tietje 2002). And such complexity is a challenge in the case of global phosphorus management. Thus, we utilize MFA and SD analysis as the method for structuring, faceting, and representing the case.

The CLoSD-Loop management of phosphorus takes the role of a goal and a vision. And both MFA and SD analysis function as specific tools that are used in the global transdisciplinary process.

The SD analysis may help to understand and to identify the specific pushes and pulls for the different human actors identified in Sect. 5.4. SD analysis goes beyond value chain analysis. Supply analysis is a core concept of Operations Research and may be used for sustainably transitioning the phosphorus chain.

> Supply Chain Management [is the] design, planning, execution, control, and monitoring of supply chain activities with the objective of creating net value, building a competitive infrastructure, leveraging worldwide logistics, synchronizing supply with demand and measuring performance globally.

SD dynamics takes a global view and embeds options for recovery and reuse of phosphorus in an economic frame, which is part of the goal system of any human actor. We use SD instead of supply analysis to emphasize that the interaction of the human systems makes the market. Against the background of this book, there are five aspects of SD that are central to global phosphorus management.

1. *Supply security of phosphorus*. This key for food security requires the monitoring of changing demand (we require 17–21 Mt P year^{-1} in the next decades), securing worldwide infrastructure logistics from a geopolitical view, and synchronizing supply and demand dynamics that follow different timescales. Due to the relative abundance and the relatively low costs, the demand side may provide the requested amount of mineral fertilizer in the next decades. As announced Morocco is planning to increase its annual phosphate rock production from 30 to 55 Mt PR year^{-1} by 2018 (Jasinski 2011b) and also increase its fertilizer production (Jasinski 2011b). A challenging question here is how regulatory processes and conducive policies to support a viable and sustainable mining industry may be fostered.
2. *Framing markets for increasing efficiency and inducing recycling*. We have identified a set of losses and residues that may require better use (if external or future costs are incorporated). Here, political framing that promotes the development of technologies for recycling or efficient use is essential. The EU (Kanton Zürich 2007) statement "to make use of best practice in the field of resource efficiency …, for example phosphorus, with a view to achieving virtually 100 % reuse by 2020 and optimizing their use and recycling;… should receive direct funding from the EU" may be seen as one example. Likewise, the activities of the Canton Zürich (as an example for an activity of a highly developed country) to recycle phosphorus from 100 % of all sewage reflects back to a governmental decree (Kraljic 1983).
3. *Coping with turbulence in the phosphorus market*. Anticipating and preparing for as well as mitigating financial market turbulence or national political imponderabilities requires sophisticated planning, purchasing, and fallback planning (Binder et al. 2004) including options such as stock building and other means.
4. *Mitigating collateral negative impacts of (current) phosphorus use.* The environmental impacts, the finiteness of phosphate reserves, and the differential

access to phosphorus (political instability due to undersupply) may cause unwanted feedbacks. Sustainable phosphorus management requires meaningful management here.

5. *Changing systems*. Sustainable phosphorus management will require fundamental changes along all parts of the SD chain. Mining and beneficiation may become more (eco-)efficient, more efficient fertilizers may be produced, industrial use of phosphorus may become more efficient, farming systems may use the right or new types of fertilizers in a meaningful way, and recycling may work at the tailings of mining, gypsum, manure, crop residues, food waste, sewage, etc. These changes may induce an evolution of technology and sustainable phosphorus use.

6 The Global TraPs Project: Goals, Methodology, Organization, and Products

This section introduces and defines the terms *transdisciplinarity* and *transdisciplinary processes* and explains, in greater detail, the Global TraPs project.

6.1 What is Transdisciplinarity?

Transdisciplinarity may be conceived as a third mode of science, complementing *disciplinarity*, and *interdisciplinarity*. Whereas interdisciplinarity is defined as the integration of concepts and methods from different disciplines, transdisciplinarity additionally integrates different epistemics (i.e., ways of knowing) from science/theory and practice/stakeholders. Transdisciplinarity begins with the assumption that scientists and practitioners are experts in different aspects of knowledge, where both sides may benefit from a mutual learning process. Thus, co-leadership between science and practice, based on equal footing on all levels of the project (i.e., the umbrella project, the nodes and the case studies), is required to assure that the interests and capacities of theory and practice are equally acknowledged. Spotlight 2 describes in detail the principles of transdisciplinarity.

Transdisciplinary processes (td-processes) target the generation of knowledge for the sustainable transition of complex, societally relevant real-world problems. Td-processes include: (1) joint problem definition; (2) joint problem representation; and (3) joint preparation for sustainable transitions (see Scholz 2000). Section 1 of this book, for instance, may be considered an interdisciplinary review of the anthropogenic phosphorus fluxes along the supply–demand chain. The identification of the key actors that are responsible for the flows may lead to an actor-based Material Flow Analysis (Eilittä 2011; Scholz et al. 2013), which may become a key element of the multi-stakeholder discourse (see Spotlight 2,

Fig. 29). This approach links key actors/stakeholders to the flows of the MFA and thus opens a management perspective.

In transdisciplinary processes, the stakeholders are not only identified but are incorporated into the process of problem definition. A pivotal part of any transdisciplinary process is the formulation and consenting of the *guiding question*. This was a major outcome of the second Global TraPs workshop (see Table 6):

> Guiding question of the Global TraPs 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?* (http://www.globaltraps.ch/)

In general, *transdisciplinary processes provide an improved problem understanding and robust orientations on policy options or business decisions for the practitioners*. Transdisciplinary processes serve for capacity building of all participants and facilitate consensus formation, for instance, about what the most important flows may be, and which options for changing them should be explored. In transdisciplinary processes, scientists benefit by obtaining in-depth insight into the dynamics of complex systems and mechanisms of sustainable transitions. The mutual learning between science and practice is the basic principle of a transdisciplinary process. Scientists and practitioners work on equal footing; the co-leadership of the transdisciplinary project is a key property. In principle, we distinguish among three types of agents: (a) a legitimized decision-maker from practice; (b) a representative from a university or public science institution; and (c) those concerned with or affected by the problem addressed or by the decision made by the legitimized decision-maker.

The dynamics of an ideal transdisciplinary process are presented in Fig. 24. Here, a legitimized decision-maker and members of the science community decide to collaborate about, for instance, sustainable phosphorus use (see Fig. 24) and incorporate stakeholders. In the case of the Global TraPs project, the project was initiated by researchers from ETH Zürich with IFDC assuming co-leadership on behalf of practice (Scholz 2011a).

In a follow-up step, key stakeholders were identified and joined the Global TraPs project (key stakeholder groups may be seen in Fig. 24), which was planned as a five-year project. The core phase of the Global TraPs project was planned for that same five years (from 2011 to 2015). This phase is expected to end by providing what we refer to as "socially robust orientations" on sustainable phosphorus use. As a result, it is expected that science will be enriched in its understanding of sustainable phosphorus management and IFDC and other decision-makers will have attained the capacities to improve sustainable decisions on phosphorus use.

By *socially robust knowledge* (often referred to as sociotechnologically robust knowledge), we refer to orientations on sustainable phosphorus use which: (1) meet science's state-of-the-art knowledge; (2) are based on the integration of knowledge and values from practice; (3) receive acceptance from the practitioners; and (4) acknowledge not only the uncertainties but also the unknowns of scientific knowledge (1996). As the reader may agree upon review of this book,

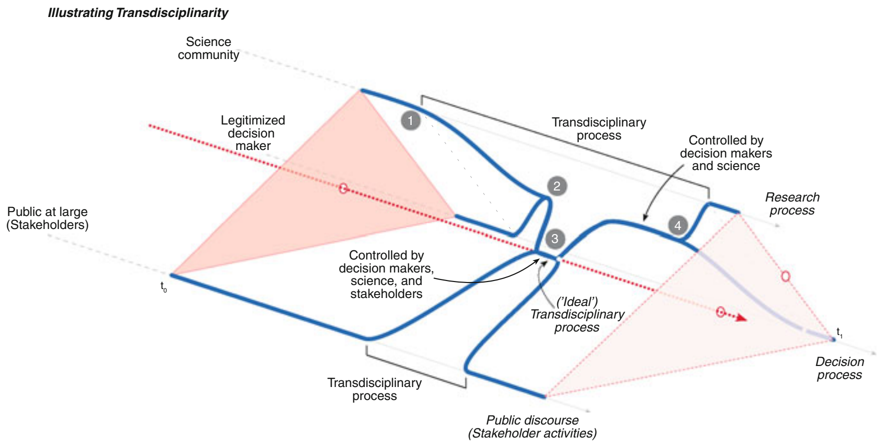

Fig. 24 The dynamics of an ideal transdisciplinary project (Scholz 2011a, p. 375)

acknowledging the unknown is important with respect to the many aspects of sustainable phosphorus management. For example, we do not have exact knowledge of world reserves, nor do we know the exact technologies that may evolve for efficient mining complexity. Also, we do not yet know the most efficient methods of processing manure or recycling sewage.

The following definition refers to the discourse theory (Habermas 1996) postulated by the German sociologist Jürgen Habermas (Regh 1996):

> According to Habermas, conflict resolution on the basis of reasoned agreement involves at least three idealizing assumptions: members must assume they mean the same thing by the same words and expressions; they must consider themselves as rationally accountable; and they must suppose that, when they do arrive at a mutually acceptable resolution, the supporting arguments sufficiently justify a (defeasible) confidence that any claims to truth, justice, and so forth that underlie their consensus will not subsequently prove false or mistaken. (Scholz et al. 2006)

Naturally, we must acknowledge that this is an idealized notion that refers to a European model of discourse and democracy. The history of more than twenty years of transdisciplinary projects (Scholz 2011a), as a means of sustainability learning, has shown that transdisciplinary processes are possible in many cultures, but not all, and that certain constraints must be fulfilled on the side of the participants.

Collaboration in a transdisciplinary project requires *certain rules*. A crucial issue is that all agents remain in their roles and positions. This holds true in particular for scientists who are tasked 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.

In order to allow for learning, a td-process must provide a "*protected discourse arena*," which allows for thought experiments and "unproven ideas." As there are key actors from industry and business participating in the Global TraPs, special care is taken that only issues of precompetitive character are addressed (Scholz et al. 2013).

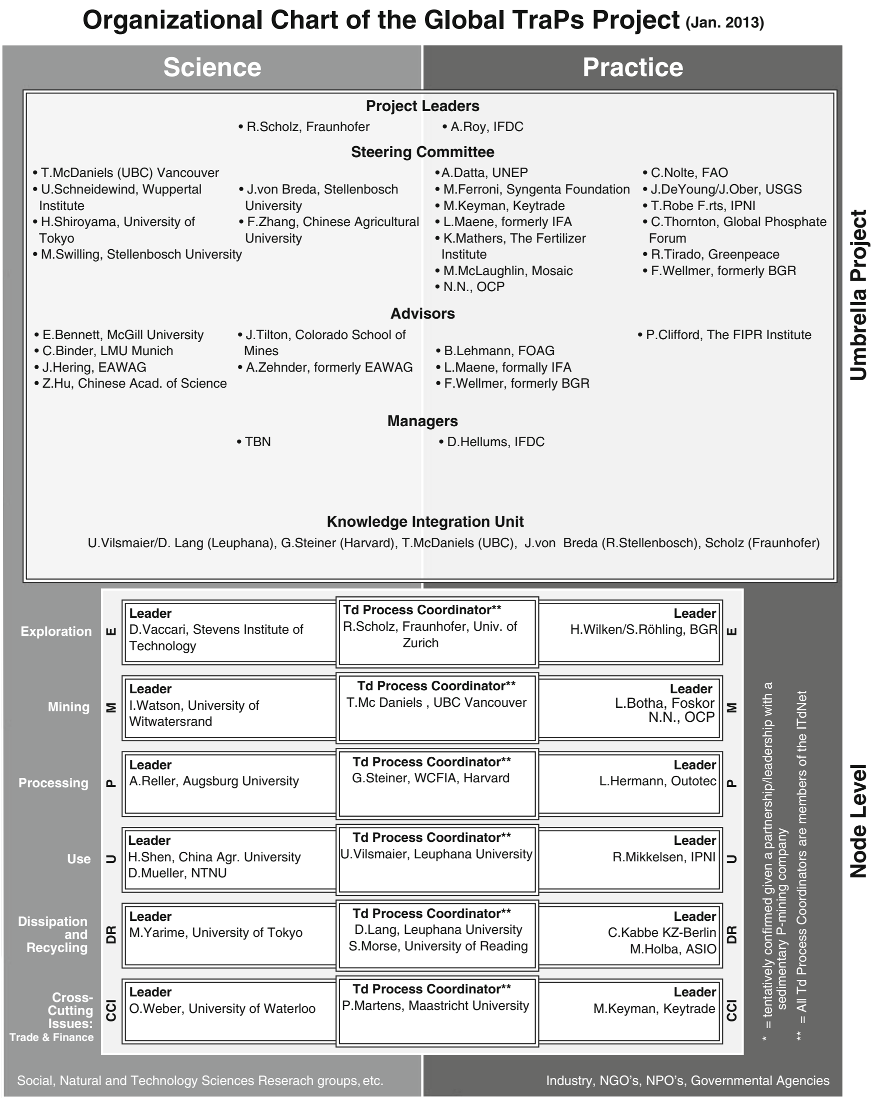

Fig. 25 Organizational chart of the global TraPs project (Jan 2013)

6.2 How is the Global TraPs Project Organized?

The Global TraPs project is organized on three levels (see Fig. 25). Level 1 is referred to as the "Umbrella Project," which is determined by the Project Leaders who take responsibility for the overall project. The strategic decisions are made by the Steering Committee, which shows equal representation—such as in all levels

Table 6 Key events and focus-guiding themes of the seven key meetings of Global TraPs[1] to be determined)

Event	Date	Location	Focus/guiding theme
1st Workshop	February 6, 2011	Muscle Shoals, AL/ Phoenix AZ	Building partnership and co-leadership
2nd Workshop	April 31–May 1 m 2011	Zürich, Switzerland	Consenting the guiding question
3rd Workshop	August 19–30, 2011	Zürich, Switzerland	Identifying critical questions
4th Workshop	March 15–16, 2012	El Jadida, Morocco	Defining Cases–setting priorities
1st World Conference	June 18–21, 2013	Beijing, China	Learning from case studies—exploring policy options
Workshop	Fall 2014	Latin America	Looking for new paradigms—understanding the soil and agrotechnology system (tentative title)
2nd World Conference	Fall 2015	TBD	Orientations for industry, research, governments, and the public at large

and subprojects of the project—from members of practice and science. The project leaders and managers are supported by the Knowledge Integration Group (KIG), which provides methods for transdisciplinary discourse, as well as the representation, evaluation, and transitioning of complex structures.

Level 2 is represented by *Nodes*, which correspond to the five nodes of the supply–demand chain in Fig. 16. Additionally, there is a Trade & Finance Node—as an example of a cross-cutting issue—as financial actors play an important role along all nodes, from the financing of mines and fertilizer plants to micro-finance mechanisms for smallholder farmers and the venture capital for new recycling technologies. There are transdisciplinarity coordinators who facilitate the collaboration between science and practice and overall knowledge integration.

There are approximately 200 professionals from both theory and practice institutions who are affiliated with the project and its nodes. As is typical for a transdisciplinary project, the first phase of the Global TraPs project, i.e., joint problem representation, is a time-consuming issue. The guiding question was determined in the 2nd Workshop by means of defining the critical questions. These questions served to identify knowledge gaps, environmental impacts, social equity, technology options, policy means, etc. Each of the six node groups authored a chapter of the book, *Sustainable Phosphorus Management: a Transdisciplinary Roadmap* (Scholz and Wellmer 2013).

The discussion on peak phosphate theory and the validity of data from Moroccan mines were disputed topics in the first two workshops. With the assistance of key experts from industry, science, and public institutions such as USGS and IFDC, a comprehensive view on geological data, resource economics, mathematical modeling, price dynamics, etc. was developed. In addition, some mining companies provided insight to the methods they use to access reserves and resources. This revealed (in particular, for two large mines) that the data recorded by USGS may be rather conservative estimates. A comprehensive scientific paper emerged from these activities (Scholz and Tietje 2002).

Based on the portfolio of critical questions, a set of approximately 15 case studies were identified, and many are currently in progress. One cluster of Global TraPs members—including representatives of the University of Freiberg, BGR Hannover and USGS, Washington—is addressing procedures that may improve the homogeneity of the data provided by the mining companies to the Mineral Commodity Survey (see also Fig. 27). Another case study, in the case of Manila Bay and Laguna, surveys the hypothesis that phosphorus may be environmentally uncritical in the case of high technology WWTP (Knud-Hansen 1994), which is also valid for megacities in the developing world. Also included in this study is a partnership among key stakeholders, ranging from Greenpeace to detergent producers, that is being sought, just as on other levels of the Global TraPs project. Naturally, in each of these case studies, the principles of transdisciplinarity will be strictly applied. Finally, we mention that questions of social equity (some linked to the socioeconomic divide between developing and developed countries) are an important issue in Global TraPs as well. The project, Smallholder Farmers Access to Phosphorus ([SMAP], financed by Syngenta Foundation), began in January 2013 with two case studies in Vietnam and Kenya. This project focuses on smallholder farmer access to (avoiding underuse) and proper use of phosphorus.

The follow-up steps of the Global TraPs project may be reviewed in Table 6.

6.3 *Knowledge Integration and Mutual Learning as Components of the Global TraPs Project*

Transdisciplinarity—as a new way of engaging in and utilizing science—requires defined methods. This holds true, in particular, for knowledge integration (i.e., capacity building) and for consensus building, two main functions of transdisciplinary processes. Transdisciplinary processes must establish five types of knowledge integration (see Spotlight 2). Here, we highlight different types of knowledge integration that are utilized within the Global TraPs project.

1. *Interdisciplinarity*: integrating knowledge from the natural, engineering, and social sciences. If we wish to improve farmers' use of phosphorus, knowledge of plant nutrition must be combined with agrotechnological knowledge and knowledge about the willingness or the preparedness of farmers to utilize the technology. From a method perspective, Formative Scenario Analysis (FSA), Quantitative System Analysis (SA), or System Dynamics (SD) genuinely establish interdisciplinarity (Scholz 1987; Kahneman 2011).
2. *Integrated systems analysis*: From a sustainable transitioning perspective, different aspects of phosphorus use are interrelated. Here, the definition of the system boundaries is an important prerequisite, as looking at the whole of a

system also requires defining the endogenous and exogenous variables. Besides FSA, SA, or SD in particular, methods of evaluation must consider the holistic perspective taken in sustainability.

3. *Integrating different modes of thought*: The key to transdisciplinarity is that the different modes of thought, knowing, and epistemics are related. Here, the experiential knowledge on the side of practitioners must be integrated with the analytic knowledge of science, which is linked to academic rigor (Scholz and Stauffacher 2007).
4. *Integrating interests and worldviews from different stakeholders*: What you see, what you like, and what you prefer depends on your perspective and interests. This suggests that a transdisciplinary process must acknowledge the different (partial) knowledge of the participants and the different preferences. Usually, there is a conflict of interest related to any sustainable transformation. If for instance, the phosphorus content in manure is reduced, this affects the interest of the inorganic phosphorus feed additives industry. There are methods of "analytic mediation," which may measure consent and dissent of the stakeholders (Godeman 2008; Scholz 2011a).
5. *Relating different cultures*: The most challenging issue in transdisciplinarity is the relating of different cultures (Scholz 2011a, b), which may also be referred to as worldviews or cosmologies. We conceive *culture* as the total pattern of human behavior and action embodied in values, thought, religion, language, and learning transmitted as institutional knowledge to succeeding generations. The way fertilizer is used and agriculture is practiced differs among cultures. The same holds true for the corporate responsibility that companies may take with respect to the environment. These issues must be acknowledged within the Global TraPs project.

6.4 *Mutual Learning Sessions and Dialogue Sessions as Instruments of Transdisciplinary Processes*

In this section, *Mutual Learning Sessions* (MLS) and *Dialogue Sessions* (DS) are seen as methods or techniques under which *capacity building* and *consensus formation* among key stakeholders may be developed for sustainable transitioning of phosphorus use. When entering a learning process for proper knowledge integration, scientists from different disciplines and practitioners (ranging from phosphorus traders to members of environmental NGOs) should *acknowledge the otherness of the other* and must *meet on equal footing* (Thompson Klein et al. 2001).

6.4.1 Why does Sustainable Phosphorus Management Require Transdisciplinary Processes that Include MLS and DS?

Sustainably transforming the P cycle is a remarkably challenging task. The phosphorus cycle is complex in its natural and anthropogenic matrix on local, regional, and global levels. Today, we face an overly complex, rapidly changing, anthropogenic-shaped system of material flows and agricultural food and technological transformations related to phosphates. These transformations involve the many activities, needs, interests, cultural settings, and other aspects of various agents. Both the deficiency and abundance of phosphorus may have negative effects on humans, as well as agro- and ecosystems.

We argue that the complexity and multidimensionality of sustainable transitioning on different scales require the *integration of knowledge* (epistemics), insights, and interests of all key stakeholders involved in the P supply–demand chain. The MLS and DS should help to: (1) sufficiently understand the (dynamics of the) P cycle; (2) identify and appraise critical or negative aspects of current phosphorus use; and (3) properly identify, develop and establish options and policy means for changing/closing the (anthropogenic) nutrient loop. Here, a *transdisciplinary multi-stakeholder* approach is required to provide *interperspectivity* on different scales.

There are three prerequisites, which have been agreed upon by all participants of the Global TraPs project.

First, the exchange of ideas and knowledge integration takes place in a "protected discourse arena." All participants are expected to bring their own personal ideas. None will be allowed to cite or make reference to that which has been stated or distributed during the discourse without explicit agreement of those who have provided the information. Second, all discourse issues, including day-to-day politicization or policies related to programs of political parties, are excluded. Third, all discussions run in a precompetitive setting.

Knowledge integration and mutual learning are key elements of transdisciplinary processes. Transdisciplinary processes serve four functions: (a) *capacity building* of and among all key stakeholders (e.g., regarding how sustainable phosphorus management could be conducted both on a small and a large scale); (b) *consensus building* (e.g., what may be priority fields of action and which issues could be postponed); (c) *mediation* (which includes reflecting on the negative effects that may result for certain stakeholders caused by a change in the practice of phosphorus use); and (d) *legitimization* of practical solutions that are socially robust and have been developed in extended multi-stakeholder discourses, making them more likely to find stronger political support and behavioral acceptance.

The two types of sessions, MLS and DS, were first employed at the Zürich 2000 conference on *Transdisciplinarity: Joint problem solving among science, technology, and society* (Scholz and Tietje 2002). The First Global TraPs World Conference in Beijing (June 2013) utilized both forms of discourse in order to develop a jointly shared view on how the current options and obstacles of sustainable phosphorus management should be addressed.

6.4.2 Mutual Learning Sessions

The basic concept of this type of session—as an element of the transdisciplinary process—is that different stakeholders/key agents jointly deliberate on how to approach a complex, real-world case of (un-) sustainable phosphorus management. The MLS at the First Global TraPs World Conference offered a full day of discourse among key stakeholders on a complex real-world case that represents/embodies a challenging problem/barrier to sustainable phosphorous management. In terms of the theory of science, the type of problem dealt with in mutual learning sessions is referred to as an *ill-defined* (or *wickedly-defined*) *problem*. Such problems typically neither encompass a straightforward solution, nor is it clear whether technical, social, or economic barriers are the most important to be overcome.

Ideally, MLS aspire to merge *experiential wisdom* from practitioners with *academic rigor* from scientists. This means, in particular, that practitioners and farmers meet on equal footing. Practitioners may be key agents from the case or decision-makers or actors who have experience with similar cases.

The First Global TraPs World Conference dealt with cases from the Beijing area with settings and innovation in Chinese agriculture phosphorus or fertilizer management. Participants of these MLS had a direct case encounter by visiting sites in the vicinity of the conference location. There were also opportunities to directly interact with case agents.

6.4.3 Dialogue Sessions

DS offer a protected discourse arena for difficult, contested, and sometimes taboo topics. Dialogue sessions (DS) will primarily explore and discuss policy strategies. In general, a DS session begins with triangulation. This means that contested issues will be portrayed/described from different disciplines or perspectives/interests. Usually, a dialogue session includes a mixture of triangulated input lectures which open a controversial space of hypotheses and propositions. Based on this input, additional propositions may be provided, which are moderated in group discussions. DS may structure the problem space.

6.5 Transdisciplinary Case Studies

A case "is unique; one among others … and always related to something general. Cases are empirical units, theoretical constructs, and subject to evaluation, because scientific and practical interests are tied to them" (Müller 2002). According to this

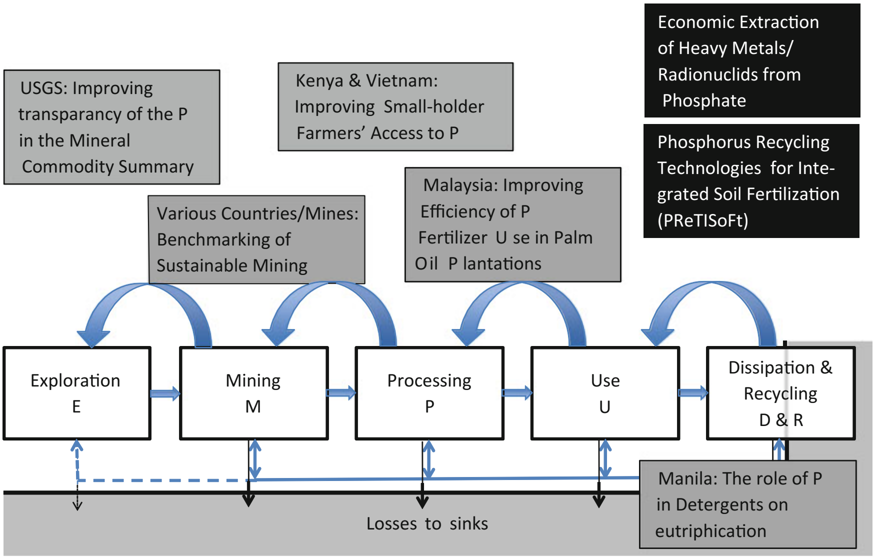

Fig. 26 Some of the planned and realized case studies (*gray-shaded boxes*) and topics for case study research (*black boxes*) of the Global TraPs project

statement, phosphorus issues may stand as a case for phosphorus, just as the Global TraPs project may stand as a case for transdisciplinary processes.

But case studies in the Global TraPs project function as the means of answering the identified critical questions and thus are tools for learning. For each of the nodes, critical questions have been identified and transdisciplinary case studies have been launched and are in progress. Exemplary case studies are listed in Fig. 26. The characteristics of transdisciplinarity (such as co-leadership), as they are stated in Table 7, are addressed in each of these studies. Thus, USGS (Director John H. deYoung) and Prof. Jens Gutzmer (University of Freiberg) are the practice and science leaders of the *Transparency of USGS Data* case study, which examines how the mining companies report reserves and how systems may be harmonized.

7 The Challenge of Increasing Efficiency, Avoiding Environmental Pollution, and Providing Accessibility

Phosphorus is essential for food security and is an important element for many industrial, medical, and technological processes. Due to its importance, humans have almost *tripled the phosphorus flows*, including the virtual anthropogenic phosphorus flows in heavy industry.

Table 7 Principles of mutual learning sessions

Protected discourse arena	All participants agree that nothing that is stated may be communicated without explicit agreement of the person who has made the statement. This promotes learning and allows for thought experiments
Pre-competitive issues	Many issues that are addressed are of economic interest. MLS and transdisciplinary processes include industry-to-industry and industry-to-science dialogues that deal with the early stages of development in which competitors may collaborate in a pre-competitive process of mutual learning or research partnership
Co-leadership	A legitimized decision-maker and (independent) scientist(s) build a partnership. They take co-leadership, which includes responsibility and accountability of the *orientations* developed in the project
Joint problem definition and representation	Joint problem definition asks that the case agents present the problems they are facing, and that scientists adapt their interests to the real case setting. MLS should ratify a (case-related) specific guiding question that is of generic interest, and which answer is of interest for sustainable transitioning. As practice and sciences (such as different disciplines in science) use different languages, a joint representation of the case and its problems is an important issue. Here, graphical representation is an important and common tool
Differentiation of roles	Acknowledging different roles means that the otherness of the interest, perspectivity and role (functionality) of the different actors are acknowledged. If the differentiation of roles (e.g., among fertilizer producers, traders and farmers) is acknowledged, it is possible to identify behavioral changes that affect such issues as the efficiency and environmental impacts related to a specific role. This is a prerequisite of actor-based MFA
Acknowledging constraints	The efficacy and efficiency of learning and the generation of knowledge depend on the time, motivation (money), prerequisites (what knowledge do the participants have), intensity of preparation and many other aspects of the process and the participants (e.g., their diversity). Given that MLS are limited in time, as much time as possible should be spent in preparation
Orientations instead of recommendations	The development of (socially robust) orientations is a goal of the MLS. Here, insight into causal chain logics ("if you do A, then Z is more likely than for you to do B") may lead to an identification of the "do-s & don'ts." We also use the term "orientation" to avoid a doctrinaire flavor that may be linked to (lists of) recommendations

The first two years of the Global TraPs project provided what we refer to as *robust* orientations *on sustainable phosphorus management*. Recognizing phosphorus' crucial role in food production, Global TraPs summarizes the weaknesses in global phosphorus flows when we focus on three aspects: efficiency, pollution, and social responsibility. This chapter focuses on phosphorus use. Naturally phosphorus flows in agriculture are interlinked with other (essential) nutrients. Here, one future task will be to elaborate in what way the use of phosphorus is interconnected with those of other nutrients, in particular nitrogen (Sutton et al. 2013) and what role phosphorus plays in the nexus with energy, or water and the flows of other materials or chemical elements.

7.1 *Efficiency as an Indicator of Unsustainable Phosphorus Use*

Currently, phosphorus use shows extraordinarily low use efficiency across the entirety of the supply–demand chain. If we just look at before processing, about 30–50 % of phosphate rock assigned to mine ore is not used and that much of it is excluded from value chain before processing. Given a conservative estimate that means that from around 36 Mt PR which may become subject of mining 25 Mt PR enters the processing or direct application stage. Please note that all these figures are fuzzy. There is uncertainty in the data (e.g., runoffs depend on whether) and knowledge (for instance the losses in processing are rather based on expert judgments than on empirical data). But, of course, also classification (e.g., what is included in the reserves and what not) may differ between the deposits.[4]

The apparently low efficiency may also be illustrated by another input–output relationship. There is an input on the magnitude of 20–22 Mt P from mining for food production. Only a little more than 3 Mt P are eaten. These numbers become even less favorable if the non-used phosphorus in mining and primary beneficiation/processing to concentrate ore and the use of geogenic, weathered phosphorus is included. With a rule of thumb calculation (referring to the flows of Fig. 21), we may see 30–50 % of unrecovered phosphate from deposits before processing. Here, we should acknowledge that just the mining ratios that were surveyed show a high range between 95 % for many mines and 50 % for some. A moderate estimate of the extracted and not used phosphate rock during extraction and beneficiation increased the 25 Mt P annually used in 2011 according to 36 USGS data up to 36 Mt P year^{-1} (see Sect. 4.5.1). What are factual losses before beneficiation asks for a closer look and may be considered as a knowledge gap such as the ore grades of the phosphate in operating mines.

If we account the anthropogenic flows, we also have to take a look at the increased weathering of phosphorus. Here, estimates go up to 5 Mt P year^{-1} which may be partly promoted by agriculture (see Sect. 4.6). Also in this place, a more substantiated estimate is missing. There are certainly losses in livestock and

[4] One option of representing the uncertainty is by probability distributions. The figures presented may be considered as means of—partly empirically and partly subjectively reasoned—probability distributions. Thus, as the distributions are not independent, the additivity for the means must not be given.

manure management that may amount to the magnitude of 15 Mt P year^{-1} (see Sect. 4.6). In order to reflect on double accounting, this includes phosphorus feed additives and of course also mineral fertilizer inputs.

Of course, we also have to account for the stock building of phosphorus in soil by fertilization which is judged to have a magnitude of presumably 2–3 Mt P year^{-1} or even more (see Sect. 4.2). A coarse figuring may amount to 50 Mt P year^{-1} that may become conceivably subject of CLoSD (Closed-Loop Supply–Demand Chain) phosphorus management. What is considered as loss and what definitions of efficiency may be used to improve the sustainability of the supply chain is a matter of future discussion and research.

When reflecting on whether efficiency is meaningful concept, we further should acknowledge the data from the regional statistics. For instance, Africa shows the highest efficiency but the lowest yield. This certainly asks for properly combining efficacy and efficiency and may illustrate that efficiency is neither a necessary nor sufficient condition for sustainability, but rather a useful means.

We also have to question how efficiency may be improved. There seems to be poor efficiency in processing, recycling, and the general use of phosphorus, at least in the nutrient chain. We have identified unnecessary sinks along all steps of the supply chain. It is obvious that increasing the efficiency of phosphorus use not only offers multiple business and technology options but also may contribute to the sustainable use of this non-substitutable element of life, in particular from an environmental and long-term supply security perspective. We conclude that a multi-stakeholder discourse including industry-to-industry and industry-to-science dialogues among all key stakeholders also may help to set priorities for avoiding unwanted losses of phosphorus.

7.2 Avoiding Pollution from Phosphorus

Phosphorus is a basic nutrient required for plant and animal life, but following the rule that *the dose matters*, phosphorus overuse may lead to pollution, while underuse contributes to land degradation. There is irrefutable evidence that excessive amounts of phosphorus can adversely shift freshwater and marine ecosystems due to algae blooms, eutrophication, hypoxia, or anoxia in freshwater systems and the world's oceans. The collective anthropogenic input by agriculture, sewage, industry, detergents, etc. will require thorough monitoring and assessment in many areas around the globe. This monitoring may start with regional or national phosphorus balances. But these large-scale views must be supplemented with impact assessments of anthropogenic phosphorus flows on the small-scale, local environment. In relation to underuse, large areas of land in sub-Saharan Africa are being depleted of nutrients (including phosphorus) resulting in decreasing soil fertility and productivity and culminating in land degradation. In turn, land degradation is intricately linked to food insecurity and poverty. Figure 27 shows that this is possible. The Lake Constance is the third largest

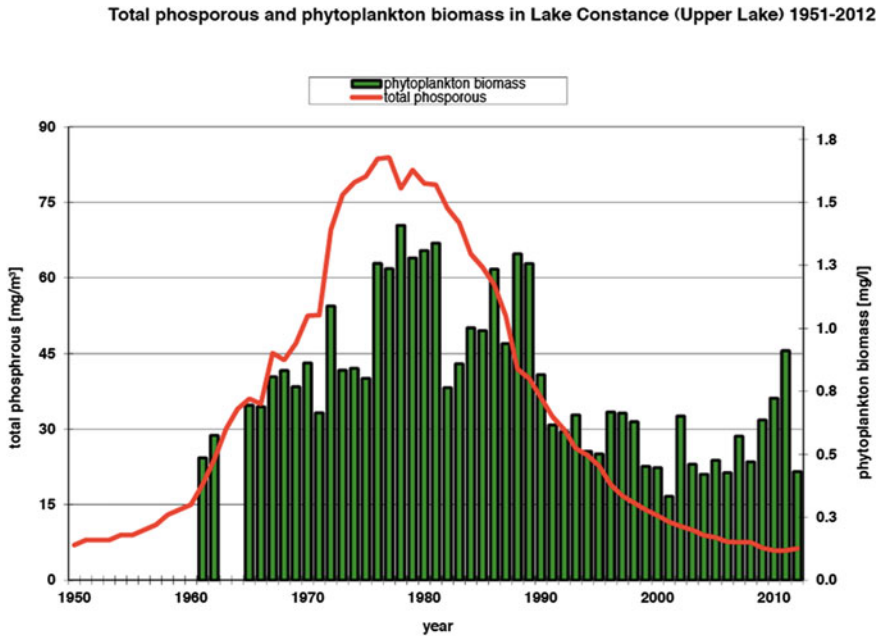

Fig. 27 Development of phosphorus and algal biomass concentration in Lake Constance (There is no clear explanation for the 2011–2012 peak of biomass, changes in the phytoplankton could be observed. By what these changes are caused in under investigation) (Föllmi 1996)

freshwater lake in Europe. Naturally, the lake is phosphorus limited, was heavily polluted by phosphorus, and showed a maximum of 87 μg/l (LUBW 2013; Müller 2002). Due to a joined action of Austrian, German, and Swiss policies for balanced fertilization, phosphorus extraction in sewage plants, limiting phosphorus content in laundry detergents, etc. the phosphorus content declined to 13 μg/l (Fig. 27). The case shows that aquatic systems may be protected if concerted action is taken.

Phosphorus deposits, whether igneous or sedimentary, share space with a number of other elements. Due to its evolution, sedimentary phosphate is linked with critical contaminants such as cadmium, thorium, and uranium. Thus, phosphorus use may become, through possible elemental contamination of compounded elements, potentially hazardous. There are concerns that these compounded elements, if errantly included in fertilizer manufacturing processes, may cause long-term contamination of soils. Here, it is clear that a long-term perspective must be taken, and that the issue of irreversibility of potentially large-scale contamination or high costs of remediation requires thorough research and the development of technologies to economically separate the contaminants from the mineral. As these compounded elements may also be viewed from a co-mining of other elements perspective, there may be multiple incentives for developing such technologies.

A third consideration is currently based on theoretical arguments. We are living in the anthropocene, an age in which most geological and ecological processes are affected by anthropocentric activity. We have learned from sulfur (i.e., acid rain), chlorine, and bromide compounds (i.e., the hole in the ozone) and from human carbon emissions (i.e., emissions-related climate change) that the human impact on biogeochemical cycles can cause unwanted secondary feedback loops that can be irreversible in the short and medium term. There is evidence that—in geological and evolutionary terms—the abrupt tripling of phosphorus flows may cause severe and imponderable changes in the resilience of the world's ecosystem, biodiversity, soil fertility, and other—perhaps not yet identified—areas of impact.

> It is clear from the above, that phosphorus is beneficial to the biosphere in many ways; however, examples from the present and the geological past also show that phosphorus may be deleterious to large parts of the biosphere when released and applied above natural threshold levels. Through the excessive use of phosphorus, an intricate network of feedback mechanisms comes into play, a play that may evolve into a drama, if we look at the present-day anthropogenic release rates of phosphorus and the already visible impact on ecosystems. (Emsley 2000b)

The speed of the change rate of the global phosphorus flows is the rationale of the concern. And there are contradicting hypotheses whether this is critical (Rockström et al. 2009; Carpenter and Bennett 2011). Here, science and society are challenged to develop the knowledge that allows for proper anticipation of the unintended consequences of increased phosphorus flows:

> The overuse of phosphorus contributed to environmental damage because this simply took the brake off this limiting factor in certain vulnerable locales. (Emsley 2000b, p. 301).

7.3 Securing Access to Phosphorus

Phosphorus is essential for food production. Thus, sufficient access to phosphorus is vital for any society to survive, and ultimately thrive. As has been the case for pollution, we look at this issue on different scales.

Undernourishment is rampant, and securing basic food supplies is a global issue. There are about one billion undernourished people in the world. And many of them are *smallholder farmers*, whose soils are extremely deficient in nutrients and often particularly in phosphorus, requiring fertilizer to supplement the deficiency. However, most smallholders do not have the financial means to buy fertilizers, nor have knowledge of their proper use. But beyond this fact, there are a number of other social equity issues. We argue that these issues require suitable policies on both the global and local level. And we argue that these policy means should be elaborated through a transdisciplinary discourse that includes key stakeholders along the supply–demand chain.

The issue of access offers an interesting perspective, as phosphorus may be conceived as a human right; it belongs in the domain of public goods that humans require to survive—simply because they *are* human. Against this backdrop, sustainable phosphorus management is a valuable tool for the *public good*. But we should note that this holds for all essential elements and phosphorus seems to be rather with the use of white phosphorus as a weapon (Mojabi et al. 2010), an issue that has not been not focused in the chapter.

Another level can be defined if the scale was to be *access to phosphorus on a nation level*. As other critical or essential elements, phosphorus is unevenly deposited throughout the world. Although 1,600 phosphorus mines are currently identified (Jasinski 2010), the large, commercially viable, high-grade ore reserves are located in only a handful of countries. Here, the geopolitical dimension is to be considered. However, we wish to note that not only are the recorded reserves important, but so too are the functionality of mines, efficiency of fertilizer production plants, etc. Further, the diversification of, and access to, phosphorus may be increased by recycling and other means such as buffer stocks. Many developed countries may benefit from intense (over) fertilization over some decades which has provided a level of phosphorus stocks that may allow for nutrient-efficient high-yield agriculture. A critical question which asks for further research (Dumas et al. 2011) is how much nutrient inputs soils with poor nutrients or soils which have just recently have become agricultural land (such as tropical forest soils) must receive that they provide high yield with high efficiency.

It is clear, when investigating geological data that there is no forthcoming physical scarcity with respect to phosphate rock in the short- or mid-term future. The *scarcity* of phosphorus is primarily an *economic issue*. Though phosphate rock is finite, we will have access to future phosphorus reserves, albeit for a higher (but feasible) processing cost. The prospective long-term use of phosphorus, however, requires the precautious use of phosphate reserves. Thus, given that one billion people of the world are undernourished, the short-term social dimension of sustainability, i.e., intragenerational equity, is an issue. This has been expressed by one tenet of the Global TraPs project "providing access to phosphorus for the poor."

Finally, we must reflect on the long-term supply security of phosphorus for food production. The domestication of species and sedentary farming began around 7,000 years ago; systematic phosphorus fertilization dates back 500 years, and the chemical processing of fertilizers about 150 years. No one may predict the kind of agrotechnology that will be employed 1,000 years from now. But we may confidently predict that humans will continue to require phosphorus, and that phosphate rock would remain a vital source. The issue is not availability—phosphorus atoms do not disappear, they simply take another form. But due to its dissipative characteristics, phosphorus may get lost and we have to reflect how it may disseminate along the value chain and become the subject of recycling. The issue is (economic) accessibility of phosphorus on different scales of space and time. Thus, social responsibility, as it has been defined, must dictate and provide sufficient access for future civilizations.

7.4 A Transdisciplinary Roadmap Toward a Demand-Based Peak Phosphorus

Against the aforementioned conclusions, the current increase in phosphorus in mineral fertilizer is critical. Figure 28 showed the historical trajectories. There was a demand peak following the dissolution of the Soviet Union. But there seems to be an even more pronounced increase 10 years after, indicating that there seem to be many parts of the world where inefficient use is taking place. The use in these areas dominates the reduction in Europe, North America, and some parts of South America, where phosphorus use stabilized or peaked from the demand side because soil phosphorus nutrient capital and improved nutrient use management practices have built up over time. Given the current knowledge in the Global TraPs project, recycling technologies and smarter agrotechnology may offset or equalize any increased demand in some parts of the world such as Sub-Saharan Africa associated with a transition to intensive agriculture. Thus, sustainable phosphorus management may work toward a demand peak on a global scale, but may face different trends in different parts of the world.

What form that sustainable phosphorus management will take is the subject of the Global TraPs project. There are practice representatives from far more than 100 key stakeholders along the supply–demand chain, including industry, trade, finance, farmer organizations, NGOs, international organizations, and scientists from a broad range of disciplines involved. Global TraPs focuses on phosphorus on a global scale. The knowledge gained in this book is and will be related with that developed by other initiatives on sustainable nutrient use such as GPNM (Global Partnership of Nutrient Management) and with other national or international multi-stakeholder or governmental initiatives related to sustainable phosphorus use and management such as the PCPRJ (The Promotion Council of Phosphors Recycling of Japan) or EPP (European Phosphorus Platform), just to mention a few. The present book focuses global transdisciplinary processes. Chapters 2–5 present pathways on a roadmap that points to transitioning to sustainable phosphorus use. As is typical in constructing a new map of a complex terrain, one may not find all roads recorded. And, of course, some highways are missing that, once identified, may facilitate quicker access to solutions, and the implementation of more desirable methods of phosphorus use. Despite these unknowns, we are confident that the present volume, which includes presentations of 52 practitioners and researchers, will serve as a reference for the better understanding and promotion of sustainable phosphorus use.

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Appendix: Spotlight 1

Fertilizers Change(d) the World

Amit H. Roy, Deborah T. Hellums, Roland W. Scholz, and Clyde Beaver

Due to significant advances in agriculture and medicine in the last century, both food production and global population have increased dramatically. The last 3 years have seen particularly significant benchmarks, with Africa reaching one billion people in 2009 and the world population reaching seven billion in 2011. Looking to the future, FAO (High Level Expert Forum, 2009) and other experts have agreed that the population is likely to surpass nine billion by 2050.

The question that remains in the face of that prediction is whether food production can keep pace with population growth to provide food security for all. More effective use of agricultural inputs—improved seeds, crop protection products and chemical and organic fertilizers can tip the scales in that production goal (Mueller et al. 2012).

The argument that chemical fertilizers have dramatically increased cereal production over the last 50 years seems to be irrefutable. Also acknowledged is that these fertilizers help save the lives of over 3.5 billion people who otherwise would starve given lower agricultural production (Smil 1999; Wolfe 2001; Hager 2008). In 1961—effectively the dawn of modern fertilizer use—global cereal production stood at 877 Mt. By 2010, annual cereal production had increased to 2.4 Gt (FAOSTAT/IFDC data 2012).

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This 174 % increase over the past half century was clearly not serendipitous. From 1970 through 2011, global nitrogen, phosphorus and potassium (NPK) mineral fertilizer consumption increased by 154 %, from 69 Mt to 175 Mt—a strikingly clear correlation between increased production and broader use of NPK fertilizers (FAOSTAT/IFDC data 2012). Perhaps the greatest evidence for the effectiveness of fertilizer in intensifying food production can be found in South Asia, where progressive use of fertilizer on roughly the same area of land over the past 50 years has produced a 165 % increase in output (FAOSTAT/IFDC data 2012). While there are numerous examples of excessive and inefficient fertilizer use (typically above recommended rates of application) resulting in negative environmental impacts, the larger issue is that low productivity (in large part due to underuse of fertilizers) is resulting in millions of people suffering with malnutrition. Over the same period, Africa, which is plagued by inherently nutrient-deficient soils and the lack of fertilizer use (averaging only 8 kg input of NPK fertilizer per hectare [Abuja Declaration 2006]), experienced production increases of only 60 %—and not through crop intensification utilizing modern agro-inputs, but by extending the area of land cultivated while almost irreparably mining the soils of their remaining nutrients (FAOSTAT/IFDC data 2012).

Among the primary nutrients, phosphorus deficiency in the world's soils stands out as a major constraint to food crop production in low-input systems such as those in the sub-humid and semi-arid regions of sub-Saharan Africa. Large areas of the developing world's soils are chronically deficient in phosphorus; legumes, a key to low-input agriculture because of their capability to produce plant available nitrogen through biological nitrogen fixation (BFN), are particularly sensitive to phosphorus deficiency (Parish 1993). Unless phosphorus fertilizers are used in these areas, even the best-managed nutrient recycling system will not achieve the minimum soil phosphorus levels required for good yields.

However, the judicious use of our mineral and chemical nutrient resources alone will not allay future agricultural production concerns. In fact, fertilizers alone will not solve the 2050 dilemma. A more balanced approach to agricultural production that focuses on soil nutrient-supplying capacity, while simultaneously maintaining or improving overall soil quality must rise to the top of production agendas. *Integrated soil fertility management* (ISFM), which includes the combined use of organic and inorganic (commercial fertilizers) nutrient inputs and soil amendments, can lead to sustainable nutrient management. This nutrient management approach along with improved germplasm and water management must become the production norm of the future in order to conserve soil and water resources, build soil fertility and improve water quality.

Even with widespread adoption of production techniques utilizing ISFM, demand for fertilizers will remain high in the coming years, but could also remain out of reach for many. In 2010, according to FAO (FAOSTAT 2012), global consumption of the major phosphate fertilizers (P_2O_5) was 45.4 Mt (equivalent to 19.8 Mt on a mineral P fertilizer basis), with the least developed countries, as a group, consuming only 1.5 % of that annual total. Clearly, a focused effort is required by all stakeholders to increase the production, availability and responsible use of phosphorus to advance global food security, particularly in the developing world. According to Sattari et al. (2012), mineral P demand by 2050 may range from 14.6 to 28 Mt annually—a range derived based on the anticipated combination of residual soil P, the supplementary use of manure and P recycling efforts. While this range considers the regional variations in historical P use and current soil P status, the anticipated global consumption of mineral P fertilizers in 2050 is projected to be 20.8 Mt, slightly more than current consumption rates. This estimate was derived based on the assumption that farmers worldwide will be applying best agricultural technologies and management practices.

In the same run-up to 2050, global NPK demand is estimated to be 223.1 Mt in 2030 and 324 Mt in 2050, and thus an increase of fertilizer use by 27 to 85 % (Drescher et al. 2011). This and similar estimates are based on current agricultural practices and may reflect the massive food production requirements at mid-century. However, this projected fertilizer requirement is likely to continue to be revised downward with the advent of more efficient fertilizer technologies and the widespread adoption of nutrient-supplying and resource-conserving approaches such as ISFM.

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Appendix: Spotlight 2

A Novice's Guide to Transdisciplinarity

Roland W. Scholz and Quang Bao Le

Transdisciplinarity (td) is a key term of the Global TraPs project. All activities of the project on all three levels of the project are transdisciplinary processes: the 'Umbrella project', the Nodes of the P supply chain including the Trade and Finance Node, as well as the case studies which are launched to better define or to close the knowledge gaps on sustainably P management. In this brief, we (1) provide a brief definition of td, (2) outline one of the twenty-five td case studies that have been successfully conducted at ETH NSSI since 1993; and (3) provide a "model" for a brief description of a planned td case study in Vietnam.

What is Transdisciplinarity

Transdisciplinarity is a third mode of doing science complementing **disciplinarity** and **interdisciplinarity**. It was developed during the last two decades in Europe and is now well accepted in the European academic community.

Whereas **interdisciplinarity** means the integration of concepts and methods from different **disciplines**, **td** integrates additionally different epistemics (i. e., ways of knowing) from science/theory and practice/stakeholders. Td starts from the assumption that scientists and practitioners are experts of different kinds of knowledge where both sides may benefit from a mutual learning process. Thus, co-leadership among science and practice based on equal footing on all levels of the project (i. e., the umbrella project, the nodes and the case studies) are needed to assure that the interests and capacities of theory and practice are equally acknowledged.

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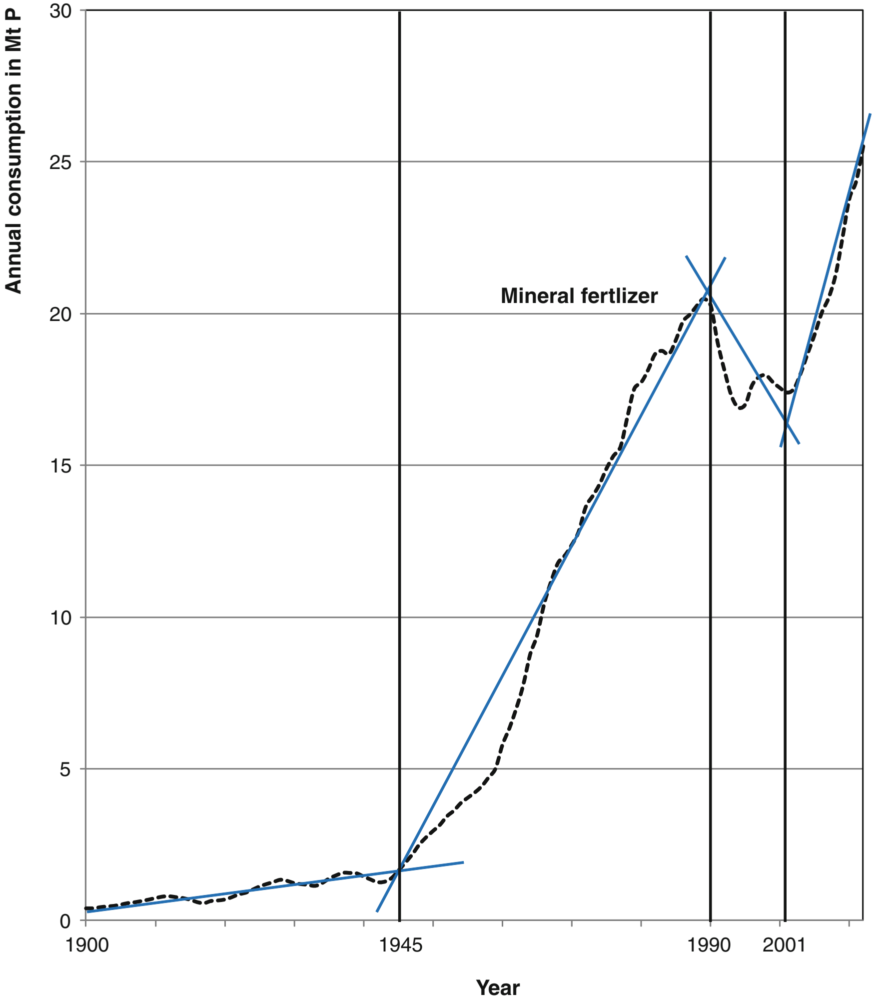

Fig. 28 Different trends of phosphorus use in different periods (x-axis: Mt P, data from USGS Mineral Commodity Summaries; the graph is generated by unweighted moving average statistics to smooth annual fluctuations using a five-year time window)

Transdisciplinary processes (td-processes) target the generation of knowledge for a sustainable transition of complex, societally relevant real-world problems.

Td-processes include joint (1) problem definition, (2) problem representation and (3) preparation for sustainable transitions (see Scholz 2000). In general, td-processes provide an improved problem understanding and robust orientations on policy options or business decisions for the practitioners. Experts from science and practice benefit by getting in-depth insight into the dynamics of complex systems and mechanisms of sustainable transitions.

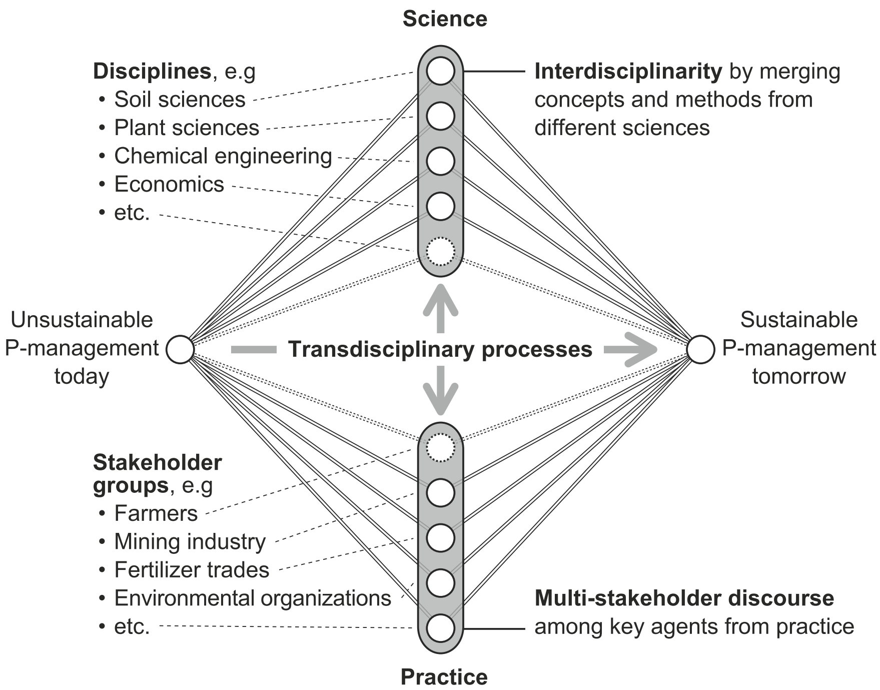

Fig. 29 Disciplines, interdisciplinarity, multi-stakeholder discourses, and transdisciplinarity

A Successful Example: "Sustainable Future of Traditional Industries" in a Rural Pre-Alpine Area

Building partnership[5]: Both, the president Hans Altherr of the small pre-alpine Swiss state Appenzell Ausserrhoden (AR), and ETH professor Roland W. Scholz, were interested in understanding mechanisms of sustaining traditional industries in rural regions. Jointly, they decided to run a transdisciplinary case study and to take *co-leadership* on equal footing for a td-process.

1. **Joint problem definition**: Key representatives (e. g., presidents of industry associations and unions as well as representatives of the communities) formed the steering board. A challenge was to negotiate and define the **guiding question**. It reads: ***What are the prerequisites for a sustainable regional economy meeting environmental and***

[5] Please note that this step also should include a thorough actor analysis identifying "legitimized decision makers" who may become co-leaders of the case study and of the stakeholders who should be involved in the case study.

socioeconomic needs? Further, three industries, i. e., textile, dairy and sawmilling industry, were selected for in-depth understanding of key mechanisms of sustainable transitions. In addition a Knowledge Integration Group was built to identify communalities and specificities of the three industries.

2. **Preparing for sustainable transitions**: By means of a scientific method (i. e., formative scenario analysis), for each industry a *set of different business strategies* (including state, community, and multi-stakeholder activities) were constructed. These strategies were evaluated by the different stakeholder groups to gain insights into dissent and consent within and between them. Scientists analyzed these evaluations, compared them to a "data-based multi-criteria sustainability assessment," and discussed the results with key stakeholders and further interested people. For each industry meaningful business options as well as related latent conflicts (between companies, economic and environmental impacts) were identified. Based on this, a process of mutual understanding was moderated so that consensus could be formed on many issues. The Knowledge Integration Group integrated these results and—together with the head officials of AR—identified potential policy options for the state. The results were published in a book targeting practitioners at regional and national level (Scholz et al. 2003).
3. **Outcomes and follow-ups**: The knowledge generated in the process was used by the practitioners involved in their daily business and policy decisions. Based on the AR-study, the Swiss textile industry launched a study to utilize the favorite strategy from the td-process for new business models (Scholz and Kaufmann 2003). Various concrete projects such as a new wastewater treatment plant for the textile industry, new cooperatives for the dairy industry and (cantonal) forest management followed the study. The study allowed for robust scientific publications on sustainable regional wood flows (Binder et al. 2004), business strategies of traditional industries (Scholz and Stauffacher 2007) or the methodology of transdisciplinary case studies (Scholz et al. 2006)

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Appendix: Spotlight 3

The Yen Chau—Hiep Hoa Case Study: Avoiding P Fertilizer Overuse and Underuse in Vietnamese Smallholder Systems

An Example of How a Transdisciplinary Case Study in the Use Node May be Developed

Quang B. Le and Roland W. Scholz

The problem

Globally, unsustainable P fertilizer management challenges for farmers fall primarily into two P use regimes. The first regime is representative of farmers engaged in intensified production to meet the global demand for food. These farmers often apply P fertilizer at higher than recommended rates in order to reduce risks that could limit production. However, if they fail to utilize best soil management practices significant P losses can result from surface water run-off and soil erosion. Included in this group are smallholder farmers engaged in intensified agricultural production of cereals, fruits and vegetables, who often produce two to three crops per year on the same land area. This overuse scenario often occurs in peri- urban agriculture where the smallholder farmers have good access to local traders and markets.

The second regime is characterized by subsistence smallholder farmers who may or may not have access to fertilizers, but cannot afford the inputs.

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Here P fertilizer is underused, leading to nutrient mining and soil degradation which exacerbates poverty. In both cases, viable options for economically and environmentally efficient P resource use and recycling in smallholder agro-ecosystems require special attention. Vietnam's smallholder systems in the Red River Delta (fertilizer-overuse, market-oriented) and in the Northwest Mountain Region (fertilizer-underuse, subsistence) will be used as example cases for contrasting two P use regimes.

1. *Building partnership and Td organization*

Science-practice co-leaders from the Province's People Committees in Son La and Bac Giang provinces, and researchers from science (ETH, University of Zürich etc.) are interested in understanding mechanisms of sustaining traditional industries in rural regions. Jointly, they will decide to run a Td case study and to take *co-leadership* on equal footing for a td-process. The co-leaders preside over the steering group.

Project groups—Reference groups: The scientific work will take place in project groups spanning the case facets (see session Case Faceting below). The project groups are counterbalanced on the case side with the "so-called" reference groups, which are the committees of stakeholders relevant for the respective case facet (Stauffacher et al. 2008). The reference group regularly meets their corresponding project group to discuss the results and subsequent steps of the work.

Steering group: The group consists of representatives of the scientific disciplines involved in the study topic (e. g., soil and crop scientists, environmental chemists, human-environment system scientists), as well as the representatives of the two provinces. During the problem definition process, representatives of a few (2–3) selected districts/communes will join the steering group. As the study progresses, the steering group will identify additional participants who should be involved in each phase of the project based on the nature of the work (Stauffacher et al. 2008). For this, it seems meaningful/necessary that both locations, i. e., Yen Chau and Hiep Hoa about 12–16 farmers make commitment to be involved in the study and the mutual learning process. These farmers will be key members of the reference groups.

2. *Joint problem definition*

The steering group members (which include the main stakeholder groups) will negotiate and define guiding question, goal and the case areas (system boundaries).

Guiding questions: As a result of science-practice discussion, examples of possible guiding questions could be:

Project year 2013:

What are science-based and society-relevant strategies for P resource use that help improve soil fertility, food productivity and profitability for Vietnamese smallholders of two contrasting P use regimes? What options/

pathways/means are available for the transition of current smallholders' P use to a sustainable use of P?

Goal: Based on these questions, the goal of the case study can be defined so as to provide (strategic) orientations for future development of smallholders regarding P use.

Case definition: The case study should allow to better understand "overuse" and "underuse" of P under certain constraints. The case's characteristics and contextual factors should allow some generalization for other cases (we are investigating cases for something of general interest). Based on reviewing the existing classification of world farming systems (Dixon et al. 2001), the global pattern of agronomic P balance (MacDonald et al. 2011), and national patterns of climate, soil, demography and land uses, the steering group—presumably interacting with regional case stakeholders—identifies case areas in the Hiep Hoa and Yen Chau districts. Characteristics of these areas are in Table 8. Based on extensive farm survey across the selected areas, a limited number of farms (about 6–8 farms/site) representing major farm types will be selected for further considerations.

Case faceting: The goal of faceting is the formulation of a research concept, which is written by the scientists in collaboration with practitioners. Together with the stakeholders, the involved scientists create a general model of smallholder farming system in the two districts with a focus on P use, which allow the application of relevant disciplinary fields and their theories. In order to reduce the complexity and to better analyze the farming practices a 'faceting' of the case should be done. Facets (which have to be discussed) could be: 'Crop-Livestock Production including P fertilizer use and flows', 'Household Decision', and 'Policy, Finance and Market'. Consequently, three corresponding project groups should be formed. For each case facet, P-use related scientific tasks (subprojects) will be identified. In the presented case, there may be an additional project group which focuses on integrating/synthesizing the results from the subprojects, i. e. the so-called "Integrated Assessment" group. It is expected that the case faceting will jointly identify a couple (common) disciplinary sub-tasks with particularly disciplinary foci, such as:

Crop-livestock production, P fertilizer use and flows

- Current state of P use and cycle in the study of smallholder systems,
- problems in P fertilizer use, P-cycle management with respect to sustaining soil fertility and crop/livestock production,
- potential alternatives for P use technology/practice and (on-farm) recycling
- household decisions,
- social-policy, economic, ecological factors that affect farmers' decision about nutrient use and management,

Table 8 Regional settings of the two study areas

Aspect	Hiep Hoa district (P fertilizer overuse)	Yen Chau district (P fertilizer underuse)
World regional farming system/climate zone (Dixon et al. 2001)	Lowland rice-based farming system in Eastern Asian tropical monsoon climate	Highland extensive mixed farming system in Eastern Asian tropical monsoon climate
	About 71 million ha, mainly located in flood-plains of South and Central East China, Korean peninsula and Southeast Asia	About 8 million ha, mainly located in mountains of Southeast Asia
Cultivation area	28.5 thousand ha	201 thousand ha
Agricultural population	216 thousand people (95 % of total population) (2008)	65 thousand people (95 % of total population) (2009)
Main soil (FAO-UNESCO) and land form	Plinthic Acrisols	Ferrasols, Acrisols
	River floodplain	Complex mountain
Key components of smallholder farming system	Crop: Paddy rice (80 % of total crop area), maize, beans, vegetables. Livestock: pig (high density), poultry, cattle. Aquaculture: fish ponds	Crop: Maize (70–60 %), paddy and upland rice, cassava, beans, vegetable, fruit trees. Livestock: pig, cattle (open raising, extensive care). Aquaculture: fish ponds
General livelihood strategy	Market-oriented. Both crop and livestock productions are important sources of cash income. Vegetable is increasingly grown to meet the increasing market demand	Subsistence. Maize, rice and cassava are important food crop. No/weak market links for some marketable crop (maize and fruits)
Existing fertilizer use and nutrient management	Intensive uses of inorganic fertilizers, combined with some manures. Nutrient loop between crop-livestock-fish in some households. About 80 % of animal manure is discharged to the environment	Compound NPK, urea and K fertilizers are used only for a very small share of cropland. Almost no P fertilizer for hillside crops. Manure is seldom used. Nutrient recycling or soil conservation practice is hardly observed
Prevalence of food insecurity and poverty	Medium	Very high (poverty hotspot in Vietnam)
Key problems	(1) lost yield if no or less use of fertilizer, (2) low fertilizer use efficiency, (3) high livelihood vulnerability to increase in fertilizer cost, (4) water pollution	(1) degraded soil and declining crop yield, (2) very low household income, (3) knowledge, cultural and labor constraints for nutrient recycling practices, (4) lack of access to fertilizer and food market, financial services

- interferences between farmer's decision-making and other important human agents at higher levels (e. g., provincial department of agriculture and rural development, rural credit agencies, traders).

Policy, finance and market

- Constraints in policy (e. g., subsidy), finance institution (e. g., rural loans/ credit institution) and market (e. g., prices of farming inputs and outputs) with respect to smallholder's P uses,
- potential alternatives for improving these factors.

Integrated Assessment

- Integrated Assessment including conceptual and parameterized system model that integrates the above-mentioned facets,
- scenarios of soil fertility, food productivity & profitability versus P use strategies, evaluation of trade-offs.

3. *Joint problem representation*

System analysis: A special challenge of the td-process is to collaborate with the decision makers and the stakeholders in a way that the system model and what is focused can be understood by all key (practice) case agents. The system model should represent the smallholder agro-ecosystem in a way that all can understand the dynamics of soil fertility and food production in response to changes in P use and other related drivers (e. g., fertilizer subsidies, market prices). The system model will serve as a basis for the construction of case scenarios in the next steps. Moreover, the joint system model construction will result in a shared representation of the constructed case study. This shared constructive aspect should greatly enhance the mutual learning process.

Scenario construction: For each case area, through Td workshops, stakeholders will jointly identify a set of different alternative P use strategies that they would like to evaluate. By means of either the computerized system model or a scientific participatory method so-called "formative scenarios analysis" (Scholz and Tietje 2002), future scenarios of identified outcome variables corresponding to the alternative strategies will be constructed. The scenarios will also be presented in a verbal or visual form that can be understood by the stakeholders and all case agents involved.

4. *Assessment and preparing for sustainable transitions*

The above-mentioned strategies will be evaluated by referring to scientific data to gain insights into trade-offs, e. g., between costs and benefits or environmental impacts and economical cost driven by the alternative strategies. Further and complementary to that, participatory multi-criteria assessment (Scholz and Tietje 2002) will be used. Different stakeholder groups will evaluate the different scenarios. This will serve to identify tradeoffs between the stakeholder groups and between different aspects of p-use that may be improved. For each meaningful scenario, tradeoffs (between social, economic and environmental impacts; between different preference systems of stakeholder groups) will be identified. Based on this, a process of mutual understanding will be moderated and consensus can potentially be formed on many issues.

5. *Outcomes and follow-ups*

In the final Td workshops, stakeholders will discuss how the knowledge generated in the process should be used for different societal processes, such as farming practices, policy decisions, sustainability learning in higher education systems, framing of follow-up research activities. As one important follow-up, written products will be prepared both for practice partners (e. g. practice manuals, policy briefs) and scientists (articles in academic journals).

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