РОЗДІЛ 1

Економіка природокористування і еколого-економічні проблеми

Phosphorus Economics – a Review[*]

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Adding mineral Phosphorus fertilizers to fields has fueled the Green revolution since the early 1960ies. The formerly limited yields could be enhanced by factor 3 or more using the same area but fertilizing the arable land. Ecologists observed that P accumulates in soils and in surface and coastal waters causing environmental disturbances such as eutrophication and oxygen depletion e.g. in the Baltic Sea and the Chesapeake Bay already in the late 1980ies. Environmental and ecological economists saw in these developments a new example for external effects causing social costs that should be avoided. Scientists from various disciplines dealt with the effects to the environment and how these impacts can be mitigated. Whereas the rate of P application to fields stagnates due to over-fertilization in the Europe already in the 1990ies and continues on a lower rate the use of P in other parts of the world still let the demand on P increase by about 1.4 percent annually. Economists observed price spikes in P fertilizers twice in the 60 years history of exploitation of the P rock reserves in the 1970ies and 2008. According to economic theory increasing prices may indicate a beginning shortage of the resource. If P is getting scarce the Green Revolution would end, the yields may drop down and there would not be enough food to the increasing world population and to feed the livestock and dairy stock. In case of scarcity and allocation of the remaining reserves extends the P problem from the environmental to the economic sphere. The paper deals with the importance of P to life, the broken P cycle, the peak P model, the dimension of the P related food problem, the inefficient P use, the uneconomic P fertilization in fields, new P stocks and solutions to avoid food shortage in future due to the predicted P endowment.

Key words: P stocks and flows, peak phosphorus, inefficient P use, uneconomic P fertilization, P pollution, relocation of P stocks by human impact, phosphorus recycling, no P shortage by best agricultural practice, re-closing the P cycle.

УДК 332.3+332.6 *JEL Codes:* Q01, Q24

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1 P and the cycle of life

P is essential for almost all life processes. DNA, RNA, fatty acids, teeth, bones and on the cellular scales the mitochondrial energy system converting ADP into ADP and vice versa, all these processes require or base on the availability of various species of P. Thus, P is not

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[*] *This work was funded by the German Federal Ministry of Education and Research (BMBF) project InnoSoilPhos (No. 031A558) – in the frame of the BonaRes-Program.*

substitutable (e.g., Ashley et al., 2011; Childers et al., 2011; Smil, 2000). Hence, too much P may harm human health (Razzaque, 20114; Huffmann, 2015) or ecosystem resilience.

Ecosystems recycle P and thus sustaining themselves. They accumulate P in stocks that buffer the demand – supply mechanisms within the system maintaining the P flow within the ecosystem parts. The flows of P in ecosystems or their subsystems can be separated into the composition of biomass by primary producers mainly driven by light in photosynthesis, the transfer through the food web and the decomposition of biomass by destruents such as bacteria and fungi. The later process may contribute to an enhancement of the stock quantity but also remobilize P for the plant/algae growth. Some P, however, will not stay within the subsystem itself. The losses are accumulated in downstream systems such as the marine deposits in the oceans or are in part biologically recycled by the coastal marine ecosystems as deposits like guano (Fig. 1).

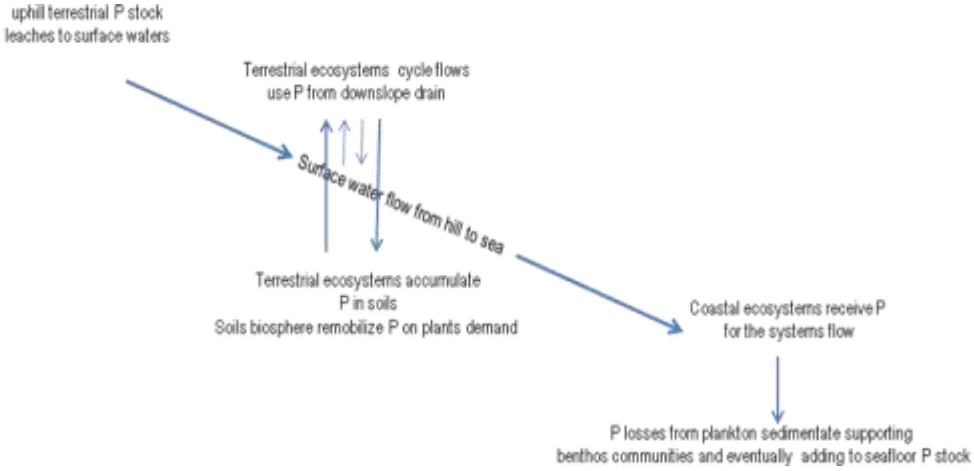

Fig. 1 P cycle – stocks and flows in natural ecosystems

If humans interfere in the natural cycle by taking food from the system, the loss of the inherent P needs to be compensated by recycling or adding P, which promotes the system sustaining its balance and productivity. Therefore, the human impact induces a secondary cycle to the system. The P stock of the soil system permits and sustains the secondary cycle as long as the output is compensated by returning P regionally to the system or the P stock in the soil is not over-exploited (Fig. 2).

Organic fertilizers served as the P source in almost closed farmland cycles until the 1950s, when manure, sewer, teeth and bone meal or other organic wastes delivered P. Smil (2000) estimated the annual supply to 5–10 kg organic P per hectare and the loss along with the grain harvest respectively to 3 kg per hectare and ton before 1950s.

In the stock – flow model given so far the P is total P although the different P-species are of different bioavailability and not all P species are easily available for primary production. The conditions in the soil (e. g. redox potential, % of P-fixing minerals) and soil micro-organisms can convert fixed P compound into plant available P and vice versa (Fig. 3, Kucey et al., 1989; Gholamhoseini et al., 2013; Battini et al., 2014; Kruse et al., 2015).

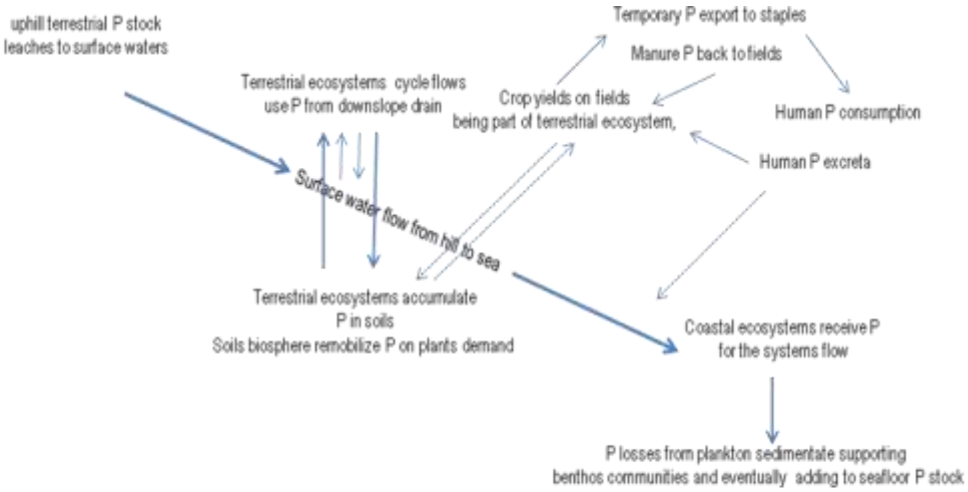

Fig. 2 P cycle – stocks and flows due to the secondary P cycle

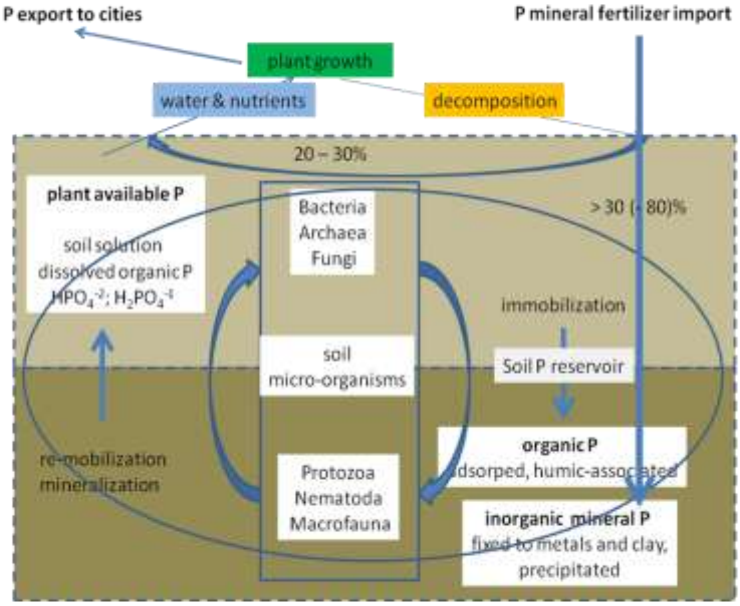

Fig. 3 Storage, release and stock – flow mechanisms in soils

Plant available P is the solved phosphate ion. This implies that P from mineral fertilizers organically bound phosphate as part of organic matter has to be converted into phosphate to support plants growth. That is the “up-stream” path of P. In the down-stream path P is being mineralized or sorbed or precipitated to e.g. Fe-oxides or soil organic matter or being once more used by organisms incorporated in organic P forms. However P can also be “lost” from soil either by harvest of plants or by leaching to ground water or surface erosion of P loaded soil particles.

Moreover, different P species exist in soil, which can be differentiated by their potential bioavailability and/or in more detail by their chemical identity. Wet chemical extraction techniques such as P fractionation by Hedley et al. (1982) differentiate P for example by their solubility in extracts such as labile P (extracted by water and/or anion exchange resin, or $NaHCO_3$), moderate labile P (extracted by NaOH and assumed to be sorbed to Al- and Fe-oxids and soil organic matter) or “not” plant available P (extracted by HCl or H_2SO_2, being interpreted as Ca-bound P). Deeper insights to chemical P species in soil can be provided by spectroscopic techniques such as ^{31}P-NMR, P-XANES, IR spectroscopy or different mass spectroscopic techniques (cf. Kruse et al., 2015).

2 P – a resource of growing interest

The agricultural revolution induced a threefold growth in food production in the developed countries in the last 50 to 75 years. Along with the increasing crop yield the demand of fertilizers (nitrogen, phosphorus and potassium) grew simultaneously. An exponential growth in the demand on P fertilizers was reported mainly in the US, Canada and (Western) Europe from the 1960s to the 1990s (Munson et al., 1959; Smil, 2000; Childers et al., 2011; Jat et al., 2012). Today, only four countries consume 64 percent of the phosphorus fertilizer worldwide: China, India, USA and Brazil and the EU states consume another 10 percent. However, around 80 percent of P is lost along the path from mine to fork to plate. Eventually only about one-fifth of the pure P extracted from phosphate rock is consumed as food (Neset et al., 2012).

Schröder et al. (2010) report an application rate on arable land of 10 to 13 kg P per hectare and year in Asia and Northern America, 6 in Europe, and 2 in Africa. In the 1990s scientists report on an over-supply of P, which is at least accumulated in the soil (Harenz, 1991). Consequently, the demand of P stagnated especially in Europe. As a consequence, the demand of phosphate fertilizers shifted from the developed towards the developing regions such as SE Asia or Africa now (Sanchez et al., 1997; Motsara, 2002; Amanullah, 2011; Jat et al., 2012; Ryan et al., 2012). Thus, the total demand on P fertilizers is still increasing globally at about 1.4 percent per year (Heffer et al., 2014; Zhang et al., 2008).

3 P reserves and resource stocks

There are at least three resource stocks to distinct:

1. A **biological** flow-stock that renews within short times (mainly years and decades).
2. A **magmatic** stock depending on magmatic occasions.
3. A **marine sediment** stock accumulated in geological times.

The **biological** stock is almost ever in flow. It includes all P in living organisms, in decomposition processes, in animal bones or in excreta (manure, sewer or guano). Renewable or "biological" phosphate reserves like guano (P fixed in a biological stock) were always relatively rare compared to the P hunger in the world. It accounts only to 0.3 percent to the worldwide phosphate resources (Killiches, 2013). This amount does not even compare to the huge demand of industrial agriculture nowadays (Heffer et al., 2014).

In the first period of P fertilizer use Nauru guano was the main source for P. Guano is a final product of the marine food web. Algae accumulate P, zooplankton feeds algae, small fish feed on zooplankton, seabird feed fish and lose their excrements on their nesting places, onshore cliffs and islands. The Nauru guano was gone within a mining period of just 50 to 70 years. Nauru was a paradise for sale (Gowdy et al., 2000), provided high quality “clean” organic P fertilizer (Weikard et al., 2009). Today, organic P enters the agricultural cycle by another way, by-passing guano. About 80 percent of the World’s fish production is converted into fish meal feeding livestock (mostly poultry) or fish in aquaculture and thus returning to fields as manure far away from its geographical origin (FAO, 2017).

The two **mineral P** resource stocks are apatite ore of magmatic origin and marine sedimentary phosphate ore. Both result from long-time geochemical and geophysical cycles (Cordell, 2010; Filippelli, 2011; Killiches, 2013). For this reason, the mineral P resources are an almost non-renewable resource, although phosphogenesis takes place in the oceans also on a low rate at present (Filipilli, 2011). Both geological phosphates exist as apatite. Apatite consists of different calcium phosphates accompanied by almost all stable Earth elements. Thus, these resources are not as "clean" as the biological P sources and need to be treated if one wants to avoid spraying those "pollutants" along with P fertilizers on fields. According to Chen et al. (2015) phosphate rock can host 63 elements but the elemental composition of the ores depends on their geological history and varies substantially. Beside P, the most common elements in phosphate rock are Si, Ca, Fe, and Al, with median abundances of 53.3 wt%, 30.0 wt%, 13.6 wt% and 8.0 wt%, respectivel (Chen et al., 2015). However, also some rare and toxic earth elements such as Cd, Sb, Se and U can have a ten times or higher abundance in phosphate rock compared to their natural abundance in earth crust (Chen et al., 2015). This contamination of rock phosphates with toxic elements causes the contamination of the P fertilizers and following the accumulation in soil and food chain.

Generally, ninety percent of the phosphate is of marine-sedimentary origin. The P content in marine sediments is higher than in the magmatic ores as well as the portion of contaminants is (Killiches, 2013). Generally, most of the P was deposited on the sea floor in extensive layers covering thousands of square miles. The extension of the P mines exploration producing P fertilizers mainly and applying it to fields is part of a P shift from mine to field to food and finally back to the ocean. In this way, a "new" geo-cycle for marine sedimentary ore has been started by humans' activity in particular by industrial agriculture measures inducing a steadily increased P run-off to the coastal seas by factor three within the last 50 years (Moss, 1998; Smil, 2000). The second main source of P run-off is untreated and treated wastewater from municipalities in the drainage basins. The eutrophication process induced by additional P loads is well documented especially for the drainage basins of the Chesapeake Bay, the North Sea or the Baltic Sea (e.g., BEACON, 2014; Costanza et al., 1995; Köhn, 1999; Laane et al., 2005; Smil, 2000; Turner et al., 1999). Hence, these huge amounts of P cannot be recycled to human uses today. Their addition to the marine sediment stocks, enhance the recipient systems' entropy and can stress the ecosystem.

As for the new marine sediment stock, the most of the mineral P resources can not contribute to the P reserves still sit in the deep ocean are unavailable for human usage because of lacking technologies and unaffordable prices (Smil, 2000). However, geological processes may up-lift the seafloor phosphate rock above sea level within geological time spans making the resource technical and economical exploitable.

In addition to the problems of its today mine ability, phosphate rock ores are unevenly distributed around the world. Huge phosphate deposits were discovered in Florida (1870s), in Morocco (1910s) and Russia (1930s) and laid the foundation for the rapid post-World War II expansion of the fertilizer industry (Smil, 2002a). The worlds´ known reserves of phosphate rock are located in Western Sahara (Morocco), China, South Africa, the US and Jordan mainly (Fig. 4). These countries host about eighty-five percent of the world mineral P reserves (Schröder et al., 2010). Thus, the supply market of mineral P is an oligopolistic one if one neglects manmade stocks (Fig. 5). Moreover, the resources of the world largest supplier

Morocco are still due to dispute about the Western Sahara political status (Lewis, 2014). Thus, political conflict may interfere in the phosphate rock market too.

The high exploitation rate of mineral P rocks may picture a thread of the world's food security when phosphate rock once is gone. Nowadays, resource economists are aware that the Western Sahara with its mineral P reserves may share the fate of Nauru with its totally exploited biological P stocks (Schröder et al., 2010; Lewis, 2014; Deutschlandfunk, 2016).

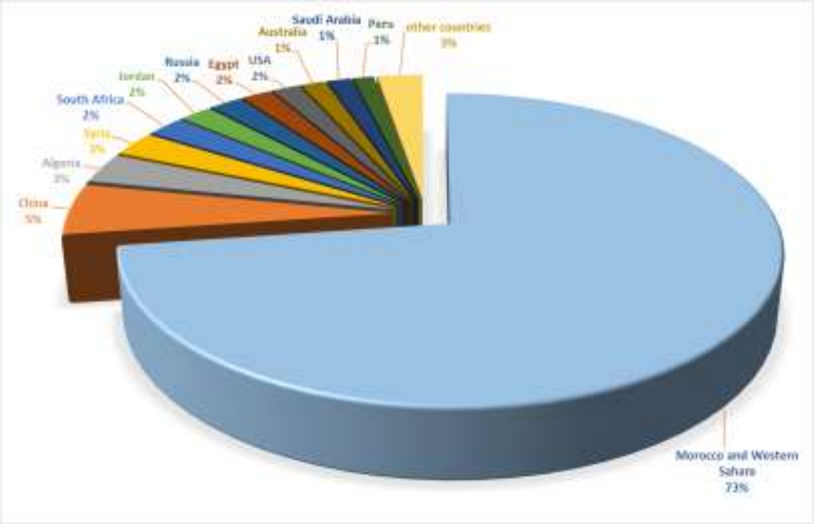

Fig. 4 The distribution of global phosphate reserves,
data were taken from U.S. Geological Survey (2016)

4 The demand on P fertilizers

In natural terrestrial ecosystems, P, as most of the other nutrients, is mainly provided by weathering of original lithogenic material and recycling of organic P from regional dead biomass. Some P can be lost downstream by surface run off and leaching to ground water being at least transported to limnic or marine ecosystems (Kruse et al., 2015). Therefore, the terrestrial ecosystems are more or less stabilized by the balance of again and again recycled nutrients such as P, input from upstream ecosystems and losses to downstream ecosystems (see Fig. 1).

If, along with crops, more P is exported as the system itself and the up- and downstream system can deliver these losses need to be compensated "artificially". As long as the production – consumption – decomposition cycles were local or regional ones, the P simply was returned with human or animal faces or compost. However, the cycles are broken if crop (and animal) exports from farmland to cities exceeded the return of nutrients with food waste and sewage, which creates an open nutrients chain to downstream environments (Fig. 5). This way of P losses grew exponentially since the end of the 19th century. Until then only about 30 percent of the world´s population lived in urban areas. The situation changed in Europe respectively within only 30 to 50 years. At the beginning of the 20th century almost 70 percent of the population had their homes in cities or agglomerations (Bähr, 2007). Such a change induced completely different matter and energy flows and thus, decoupled regional cycles (Cordell et al., 2015b; Thitanuwat et al., 2015; Wu et al., 2015).

Mineral fertilizers compensated the losses due to the decoupling of regional cycles starting in the 1950s and 1960s. Predominantly, the nutrient imports to farmland were generally higher than the P exports with the crop to the cities (Zhang et al., 2008; van Dijk et al., 2016). Additionally, animal farming was and is often concentrated in some regions whereas arable farming is concentrated in another. The decoupling of regional cycles is the main reason for

1. a steadily growing hunger for mineral fertilizers from P mining,
2. the "new" P stocks accumulating in landfills, that hardly can be recycled for economic reasons today,
3. P stocks in manure from livestock staples too far from farmland, where it can be applied as organic fertilizer and
4. the P flows to the downstream environments (e.g. coastal zones).

Zhang et al. (2014) demonstrate the dimension of the economic problem in agricultural P use. Whereas the mineral P input increased by factor of 20 over the last 50 years in China the crop yield grew by a factor of 3.8 only. Thus, the P efficiency in the agricultural production system along the food chain is as low as 7 percent. They estimate the losses to the environment to 20 kg P ha^{-1} year^{-1}. The authors conclude that P demand could be reduced by one third without harming crop yields. Their conclusions are in line with those in Europe and Northern America where the overall P input decreased by more than 20 percent starting in the 1990ies due to better management practices and environmental regulations (Smil, 2000; Schröder et al., 2010).

However, the public as well as the scientific dispute suppose P as a scarce resource that need to be added to field to fight the hunger in the world (Cordell et al., 2009, 2015a). Today, the agricultural demand on P fertilizers is greater than the biological renewal rate, thus, it is supposed that the high consumption rate can only be met by mining and converting the mineral and non-renewable phosphate rock into P fertilizers. The global annual production of phosphate rock almost doubled from 1970 to 2010 (Prud'homme, 2010). The demand on phosphorus still increases by about 1.4 percent annually (Heffer et al., 2014).

The application of inorganic phosphorus as fertilizer is still seen of paramount importance in agricultural industry. More than 90 percent of the globally mined phosphate rocks are used in the agrarian sector. 82 percent fertilize farmland and 9 percent add to animal feed. Phosphorus is considered indispensable for food and feed production sustaining food security (Shakhramanyan et al., 2012).

In addition, the feed production demands more land and thus P than the production for human (vegetarian) food (WRI, 1994). The livestock – around the world is too high that arable land may support them in a sustainable manner. In addition, P shortage in feed may harm substantially livestock health, especially during the lactation period in dairy (Grünberg et al., 2015). Moreover, special crops such as soya or oil plants demand even higher application rates of P fertilizer. The transition from oil and coal based energy production towards bio-energy caused another pressure on P demand (Schröder et al., 2010).

5 The supply of P in the ecosystem and by fertilizers

Originally, P as well as other nutrients is supplied for primary producers/organisms by weathering of the lithogenic material during pedogenis. Some of the resulting P in soil solution can directly be used by organisms, some may be sorbed (again) by soil minerals and soil organic matter and some may be leached to ground water or transported by surface run off downstream (Kruse et al., 2015). Some of the temporarily fixed P can be mobilized again for plant growth by plant roots, (symbiotic) fungi and bacteria as studies on crop plants demonstrated (Palomo et al., 2006; Richardson et al., 2009; Hunter et al., 2014; Battani et al., 2014). Thus, terrestrial ecosystems organisms form P stocks in soil and these P stocks in soils nourish the ecosystems organisms when P is scarce, which at least retards P draining to the sea. Different studies tried to estimate annual P loss from differentially used soils. Because P losses from soil is affected by for example hill slope, precipitation, soil type, soil texture, P-saturation and vegetation cover and P loss occurs predominantly by surface run off but also by sub surface leaching of solved and colloidal P, difficulties exist to estimate real P loss from soils. Generally, erosion of lithogenic or pedogenic material and therefore leaching of P will be higher in regions with higher hill slope (especially mountains) compared to low lands and also higher from areas without vegetation cover compared to those with dense vegetation.

In low lands McColl et al. (1977) for example detected an annual total P (TP) loss of 71 to 201 g ha^{-1} y^{-1} from different forests and of 293 g ha^{-1} y^{-1} from fertilized hill pasture by run off. Similarly, Verheyen et al. (2015) detected a P loss of 80 to 280 g dissolved reactive P (DRP) ha^{-1} y^{-1} from arable and pasture soils and 14 to 22 g DRP ha^{-1} y^{-1} from forest soils. Therefore, they detected an up to 11-fold higher DRP loss from arable and pasture soil compared to forest soils. This fact pointed to the predominant influence of vegetation cover and P saturation of the soil. Assessing TP concentrations in arable soil of around 400 mg per kg soil in a depth of 0…30 cm (Zimmer et al., 2016) and an average soil density of 1.6 g cm^{-3}, a P stock of around 1,920 kg TP can be assumed in 1 ha of arable soil (only in a depth of 0…30 cm). McColl et al. (1977) estimated a loss of around 300 g TP ha^{-1} y^{-1}. This figure confirms a loss of only 0.016 % of the TP stock in the upper soil levels (0…30 cm) lost to water bodies by run-off. However, this low amounts in relation to the soil TP stock can have disastrous effects on water bodies.

For example, TP concentrations in streams and drain water from arable soils vary from 0.036 and 0.044 mg l^{-1} (Tiemeyeret al., 2009) to 0.4 mg TP l^{-1} (Gentry et al., 2007). Therefore, the quality of water from arable fields can be classified mostly as ‘moderately polluted’ according to the water quality class II according to LAWA (1998). For a general orientation, concentrations of 0.05 mg TP l^{-1} reflect the shift from a „very good ecological status“ to a „good ecological status“ and 0.1 mg TP l^{-1} that from a „good ecological status“ to a „moderate ecological status“ in lowland rivers according to LAWA (2007). Therefore, TP concentrations >0.1 mg TP l^{-1} can generally be assumed as anthropogenically increased eutrophication of water bodies. This is especially true if the N:P ratio exceed 16:1 because the N concentration is normally much higher than the P concentration and therefore algal growth is restricted by P (Redfield, 1958).

Therefore, if higher P loads are transported to lakes and the sea by rivers it stimulates primary producers in the littoral zone of the rivers and of the lakes and the oceans as well. This increase in primary producers supports the whole food web and add biomass and as well as P to the limnic and marine sediments. From a short-term point of view, these limnic and marine sediments act as final sink for P. In sediment fixed P, mostly as organic or Fe sorbed P, can be reactivated to water soluble and “algal” available phosphate if anaerobe zones occur within the water column/sediment (e.g., Mort et al., 2010; Rydin et al., 2011; März et al., 2008). Such anaerobe events can result in reductive dissolution of P and a repeated P recycling from the sediment into the water column (e.g., Mort et al., 2010; Rydin et al., 2011; März et al., 2008). Gustafson et al. (2012) demonstrated in long-term studies in the Baltic Sea that within anaerobic periods the Redfield ratio of C:N:P may drift substantially towards a fivefold higher turnover rate of biological production due to the P effect than the Redfield ratio predicts.

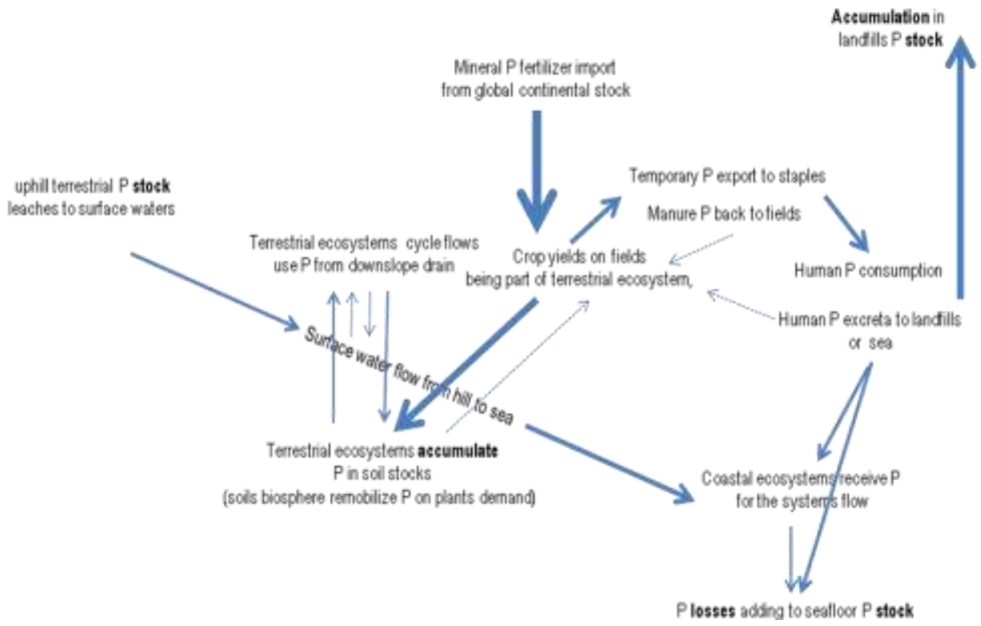

Fig. 5 The broken P cycle, enhanced flows and P stock relocations

Humans firstly interacted directly with soils during Neolithic revolution starting around 12,000 to 10,000 years before present when societies shifted from forager to producer societies with domestification of plants and animals in different regions of the world (e.g., Butzer, 1976; Barker, 2009; Bocquet-Appel, 2011). For centuries soils were cultivated/fertilized e.g by swidden farming, aboriculture, wetland cultivation (Fedick and Ford, 1990), usage of alluvial soils in floodplains which are regularly flooded with fertile sediments (Butzer, 1976), by life stock manure (Cunfer and Krausmann, 2009; Hughes, 1992), by domestic waste (Bakels, 1997), by plagging of manure enriched grass sods etc. (Conry, 1971; Davidson and Simpson, 1984), and by e.g. seaweed input in coastal areas (Davidson and Simpson, 1984; Acksel et al., submitted). These ways of fertilization were characterised more or less by a regional character and therefore a regional nutrient especially P cycle. After the second world war, especially the western agriculture was intensified (so called green revolution) and shifted therefore from an extensive regional use of “organic” phosphorus to a global “cycle” defined by anthropogenic mined rock phosphate (e.g., Ringvale et al., 2014).

In the meantime the business as usual mineral P imports mined from the World’s reserves (Fig. 4) will still feed the market and the fear of economists that one day the P reserves are gone (Cordell, 2010). Moreover, the P “problem” will further worsen, since

1. the phosphorus content in the phosphate rock is decreasing (Smil, 2000; Zhang et al., 2008),
2. the costs for exploration, mining and processing per ton phosphorus fertilizers and the amount of waste of the fertilizers processing are exploding (Zhang et al., 2008),
3. the number and amount of contaminants in the rock and in the finished fertilizer is increasing (Chen et al., 2015),

4. the loads of unwanted substances such as cadmium and uranium to the environment (and consequently to feed and food) grow (Knolle, 2008; Schnug et al., 2014).

To summarize, although the P demand is still increasing due to political will, neglecting scientific and technological, e.g. recycling, knowledge as well as using arable landscapes for unwanted wastes (P wastes from uranium enrichment) respectively better and sustainable options and management practices the costs for an ecosystem renewal grow unattainably. The "cooperation" with the ecosystems capabilities especially the soil biosphere may prevent the system against the collapse. This conclusion, however, includes a regional recycling of the P taken from the fields by harvest and transferred to the urban centers.

There are only some occasions in the World that still need a further supply of plant available P at present (Jat et al., 2012). In the most other regions the demand on P can be met by applying better P and soil management as well as in changing consumption modes (Smil, 2002b, 2014; Syers et al., 2011; Neset et al., 2012).

6 Peak phosphorus?

Most of the P reserves are unevenly distributed around the world and therefore form oligopols on the supply side of the market. Only a handful (in some cases state owned) suppliers may override the market, dictate prices or shorten quantities. The situation makes the prices for P very volatile as seen between 1974-5 (peak prices were above 1.800 $/t) and in 2008, when prices jumped of 800 to 900 percent (peak prices 1.200 $/t). The market price for P at mine is about 200 $/t on average and almost constant during the last decades (farm gate prices are higher and depend from many other aspects). The 2008 price shock called economists to study P markets and to assess how long P still can be used (Cordell et al., 2009, 2011; Heckenmüller et al., 2014; Schröder et al., 2010).

Since P prices are very volatile and oil crops require considerably high amounts of the fertilizer to achieve and sustain high yields this impact can be seen reasonable for the price spike in the early 2000ies (e.g., Smil, 2000). Clift et al. (2012) assumed that policy induced the price jump in the phosphorus market. The political target to substitute as much as possible fossil fuel by biological ones for climate change reasons may have caused that market players speculated on increasing phosphorus demands. The more the first price jump in P in 1974-75 occurred always simultaneously between the two oil price shocks. The oil market shows very similar economic properties (Heckenmüller et al., 2014).

Cordell et al. (2009) introduced the peak P concept illustrating the shortage of the P reserves. Their model bases on the presently known stock, today's exploitation rates and expectations on future demand growth. They estimated that the global peak for P mining and fertilizer production is likely to occur as early as 2033. They defined the term "peak phosphorus" a point at which the production of P from phosphate rock reaches its maximum due to the decreasing availability rock deposits, the declining P content of the rock, assuming a steadily high or growing demand on the resource.

Cordell et al. (2009) used the a Hubbert styled resource model to assess the longevity of the resource assuming that P might be behave similar to the oil resources (Hubbert, 1979). Cordell et al. (2011, 2015a) corrected their estimates, according to their calculations, peak P may occur some years later – in 2070 or after 2300. If the demand of a non-substitutable, essential and non-renewable resource clearly is larger than its supply in the long run we are faced with a phenomenon economists call a "cake eating problem" (Hotelling, 1931).

The cake – P – can be eaten up only once. By the end the resource, the cake, is gone completely. Those models such as the cake eating one may illustrate the scarcity of a resource using prices as indicators for an economic scarcity. The simple economic theory truth is, “The higher the price of a (normal) good the more scarce the resource is”.

Hence, economic scarcity concept does not only include the physical shortness of a resource but also is it worth or economically feasible and viable to continue extracting P from the rock. The part worth to exploit forms the presently known reserve. However, one may influence the rate of consumption from the reserve stock by various political or economic measures. Whereas new P rock locations might be detected worth to be exploited other models show that various strategies and technologies may reduce the consumption rate, thus the remaining reserves last longer. Moreover, P is a waste of nuclear power industry or mining of rare Earth elements, it is recyclable (Drangert, 2012) and the exploitation of the P reserves and their translocation formed new stocks in arable soils. The new soil stocks may prevent under certain circumstances P fertilization at all.

Giraud (2011) argued for some reason that a Hubbert-style analysis, the tool used by Cordell et al. (various papers), depend on a set of specific conditions that are not apply to P. He argued that there are two important qualitative differences between P and carbon-based fossil fuels: (1) P is in principle recoverable after use but (2) P is not substitutable by any other resource because it is an essential element for almost all life-forms (quoted in Clift et al., 2012). Vaccari et al. (2011) show that a Hubbert analysis cannot be used in this case since there is no substitute for P.

In general, there is no substitute for P as long as we assume that P is a clean and pure product. In the context that P is used as a fertilizer, P is not such a good. P fertilizers are “polluted” by many other elements in some cases P fertilizers are wastes from other industries (Chen et al., 2015). Moreover, P rock mining causes unconceivable piles of waste at a rate of 1 (P fertilizer) to ten (P waste) and larger. These piles still contain P but the remains are that toxic that they are not permitted to other uses than waste (Smil, 2000; Zhang et al., 2008). The peak P dispute neglects that the relocation of P from mine to dumpsites and to soil stocks offer new reserves.

In addition, there are enormous losses along the mining, processing and application line that can be avoided. Therefore, “peak P” rather is a concept to draw attention and awareness on this resource than P a finite physical resource is (Smil, 2002a; Scholz et al., 2013). If P is handled efficiently it will last forever (Drangert, 2012).

More dynamic models contradict at least in part the peak P model and shift the awareness of the P scarcity discussion to other important aspects of the issue. Scholz et al. (2013) show in their analysis that the P resources are underestimated, that many aspects a Hubbert analysis requires are not fulfilled in the case of P (such as innovations, various markets, many stakeholders etc.) and that the reserve stocks in P are rather high compared to other resources.

However, the peak P dispute made economists and politicians aware of a resource and its un-efficient use and losses to the environment discussed for long by natural science according to negative impacts to the environment (see for instance Costanza et al., 1995; Köhn, 1999; Turner et al., 1999). The peak P dispute opened the floor for transdisciplinary research along the broken P cycle and the P chain from mine to fork (and human health) and back to the oceans. Almost 90 percent of P is lost along the application line to the environment (Clift et al., 2012). There are no or only little economic incentives to change this chain into a close cycle for a sustainable use of P (Molinos-Senante et al., 2011).

7 Balancing demand and supply of P

Ott et al. (2012) found the annual net per capita P use was 4.7 kg, of which only 1.2 kg reached the consumer, only about one quarter. After use there was little recycling (0.77 kg P/ca/year) in the EU-15. According to their calculations large fractions of the surplus P accumulated in agricultural soils (2.9 kg P/ca/year) were sequestrated in landfills (1.4 kg P/ca/year) and were emitted to the hydrosphere (0.55 kg P/ca/year). That means, more than half of P imports is accumulated in soils and one eighth is discharged indirect or direct to surface waters. In other words, three quarters of the P import does not provide any economic benefit but,

1. is accumulated in stocks that may support crop growth in future if the stock can re-mobilized from the soil by the soil biosphere,
2. forms stocks in landfills that maybe never ever can be recycled, or
3. enhance eutrophication of surface waters and will be once add to marine sediment P stock unavailable for economic use.

Van Dijk (2016) provided another mass balance calculation for P in the EU countries using 2005 data. Their results show that the mineral P fertilizer import still is necessary if the mode of production will not be changed also in Europe. They calculated the inputs – outputs and losses of P within the farm gate to fork chain based on national statistics in the EU-27. In summary, about 50 percent of the P inputs are lost along the P chain. The main part of losses is added to the P stock in arable soils – about 40 percent in 2005. Another huge part of P ends on landfills or in surface waters after human consumption. Thus, two third of the P imports are whether lost or add to soil stocks that one may use by alternative land use practices or through recycling.

In consequence, one may reduce the demand on mineral P fertilizers by some 40 – 60 percent without harming crop yields if

1. plants may assimilate almost all the supplied P (plant available P) due to improved fertilizer formulations and application schemes (Bridger et al., 1962; Valente et al., 1982; Helyar, 1998; Burns et al., 2002; Römer, 2006; Meyer et al., 2014; Suriyagoda et al., 2014; Hasler et al., 2015),
2. losses to the soil P stock are reduced and the P soil matrix can be re-mobilised for plant production by soil microbes (Kucey et al., 1989; Wang et al., 2008; Battini et al., 2014; Bahri-Esfahani et al., 2014; Kaur et al., 2015),
3. animal production will be restricted to an extent that the region may support the livestock, that means: reducing also feed production substantially, balancing the regional ecological balance and the regional consumption of dairy and meat, allowing for an economic short distance transportation manure return to fields as organic fertilizer (Bolan et al., 2004; Dolman et al., 2014; Machovina et al., 2015; Petrovic et al., 2015),
4. P losses to the environment are avoided (De Wit et al., 1999; Laane et al., 2005; Innes, 2013; Carliell-Marquet et al., 2014),
5. leaks within the P transformation chain within the society are closed, thus P remains within a regional input – output cycle (Withers et al., 2015),
6. wastes containing P are recycled and cleaned from pollutants not adding longer to the "new" P stocks on landfills (Ashley et al., 2011; Drangert, 2012),
7. the overall societal efficiency will be improved (Li et al., 2014; Allievi et al., 2015; Cordell, 2015 b; Metson et al., 2015).

A reduction of two thirds of mineral P fertilizers annually would cause costs savings for the fertilizers purchase but also for the mitigation costs P leakage causes to the environment and will reduce the inputs of pollutants coming along with P fertilizers to fields and the groundwater. Let us assume that farmers may spend the same budget as now for buying P fertilizers but applying only one third of improved and cleaned P from accompanying pollutants such as cadmium, uranium and other the environmental costs will diminish further. Moreover, since the quoted calculations based on an annual flow data for P input but

1. P fertilizers applications have been already reduced in the last twenty years in Europe,
2. the “old” P stocks in the soils remain, and
3. a lower application rate of only plant available and clean P from re-cycling the stocks may be balanced efficiently.

Further, one may assume that the soil stocks may support high crop yields for long if immobile stocks accumulated in the last decades in soil are remobilised by “living” soils. Kucey et al. (1989) and other showed that the microbial biosphere in the soil provides crop plants with the “right” amount and the “right” quality of P thus serves the system on demand. In summary, the knowledge, the bio-technology at competitive prices for an improved P management are already at hand (Baum et al., 2013, own market desk search for endomycorrhizal bacteria and fungi and application reports). Best agricultural management practices also include to apply as much as (in small amounts) and as often as (according to the growth phases of the crop plant) phosphorus as the plants can take-up as being part of precision farming (Helyar, 1998; Iho et al., 2012; Maine et al., 2007). The old thinking “if you apply more, you will harvest more” needed to rethink, since after an optimum of fertilization yields decrease after passing a species specific threshold of optimum (Jiao et al., 2014; Nyborg et al., 1999). Thus, reducing the oversupply may be beneficial to the crop yield, farmers’ budget and the environment (Buckley et al., 2013). However, Scholz et al. (2015 a, b) doubt that institutional settings assuring those strategies can be introduced in near future.

8 Summary – a better P economy

The Green Revolution induced an ever increasing demand on P fertilizers. The crop yield did not increase simultaneously to the input of P fertilizers. The main part of the mineral P is accumulated in the soils or after human consumption in sewage and landfills or is directly discharged to water bodies. Consequently, these losses formed “new” stocks and caused huge economic deficiencies. Therefore, the economically best P strategy is to minimize or to stop the mineral fertilization. This strategy includes:

1. a substantial reduction of the import of P fertilizers may it be from apatite mines or from nuclear enrichment wastes,
2. an activation of the “new” P soil stocks from 50 years of accumulation nourishing crops in the coming years,
3. the mitigation of external effects to the environment by avoiding the losses to soil and surface waters, and
4. the closing of regional “clean” P fertilizer cycles.

The strategy is almost neutral if not socially beneficial in costs if the external costs of the business as usual are accounted in the balance sheet. If those costs would be included in the P fertilizer price to apply the polluter pays principle, no farmer would afford those prices. P fertilization would stop immediately since P fertilization goes along with polluting the environment with toxic elements and compounds. These compounds really harm food security, drinking water and human health. Thus, P fertilization is a matter of P fertilizers cleanness also not limited on quantitative aspects.

In conclusion, the expected shortage of P harming humans' food security due to an extinction of P reserves in the world may happen if and only if humans will follow the inefficient and uneconomic paths of P use they went the last sixty years.

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Manuscript received 22 February 2017

«Фосфорна» економіка – огляд

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Майже для всіх процесів життєдіяльності фосфор має важливе значення. ДНК, РНК, жирні кислоти, зуби, кістки, мітохондріальна енергетична система перетворення АДФ (аденозин-5′-дифосфат) на клітинному рівні – всі ці процеси потребують або базуються на використанні різних сполук фосфору. Таким чином, його неможливо замінити. З іншого боку, занадто велика кількість фосфору може завдати шкоди здоров'ю людини або стійкості екосистем.

У природних екосистемах фосфор, як і більшість інших поживних речовин, в основному утворюється в результаті природних процесів формування органічних сполук фосфору із біомаси. Частина фосфору змивається поверхневими стоками та, проникаючи в ґрунтові води, потрапляє в озера або морські екосистем. Таким чином, екосистеми більш-менш збалансовані завдяки

постійним процесам формування поживних речовин, таких як фосфор. Фосфорний баланс у екосистемах підтримується завдяки постійній циркуляції води.

Якщо запаси фосфору не поповнювати, утворюється його дефіцит, і тоді втрати потрібно компенсувати штучно. Раніше цикли виробництва, споживання і накопичення відходів мали здебільшого локальний або регіональний характер. Фосфорні сполуки утворювались із залишків тварин або компосту. Цикли змінюються, якщо обсяги постачання сільськогосподарських культур (тварин) у міста перевищують обсяги формування поживних речовин з харчових відходів та стічних вод. Відтак в середовищах, що розташовані в низинах річок, поживних речовин не вистачає. Таким чином, втрати фосфорних сполук зростали в геометричній прогресії з кінця XIX ст. У ті часи тільки близько 30 % населення планети проживало у містах. У Європі ситуація змінювалася впродовж 30–50 років. На початку XX ст. уже майже 70 % населення проживало у містах. Така зміна викликала зовсім інший характер формуванням потоків матерії й енергії, відтак змінилися й регіональні цикли.

Використання мінеральних добрив компенсувало збитки від втрат фосфору в регіональних циклах, починаючи з 1950–60-х років. Як правило, використання добрив для збагачення сільськогосподарських угідь перевищувало обсяги природного рівня формування фосфору.

Сьогодні попит сільського господарства на фосфорні добрива більший, аніж природний рівень його відновлення. Таким чином, передбачається, що проблему забезпечення високого рівня споживання можна вирішити тільки шляхом видобутку й перероблення невідновлювальних мінеральних і фосфатних порід у фосфорні добрива. Глобальний річний обсяг виробництва фосфоритів збільшився майже в два рази у період із 1970 по 2010 рік.

«Зелена» революція спричинила постійно зростаючий попит на фосфорні добрива. Підвищений рівень використання фосфорних добрив, на жаль, не сприяє збільшенню врожайності. Фосфор у значних обсягах накопичується у ґрунтах, потрапляє у стічні води, на сміттєві звалища або безпосередньо у відкриті водойми. У результаті виникають значні економічні проблеми.

Таким чином, кращою економічною стратегією є зведення до мінімуму або припинення використання мінеральних фосфорних добрив, що включає:

1) істотне скорочення обсягів виробництва фосфорних добрив з апатитових руд або з ядерних відходів;

2) використання «нових» природних запасів фосфору, що утворились в результаті розпаду сільськогосподарських культур за останні 50 років;

3) зменшення зовнішніх впливів на навколишнє середовище, рівня забруднення поверхневих вод і втрат ґрунту;

4) закриття регіональних «чистих» циклів виробництва фосфорних добрив.

Така стратегія є оптимальною і може принести певні соціальні ефекти. Якщо б витрати, пов'язані з формуванням екстернальних ефектів, включались у ціну фосфорних добрив, і при цьому застосовувався принцип «забруднювач платить», то їх би просто не купували. Використання фосфорних добрив було б негайно припинено, оскільки їх використання нерозривно пов'язують із забрудненням навколишнього середовища токсичними елементами і сполуками. Використання цих сполук, дійсно, завдає шкоди продовольчій безпеці, погіршує якість питної води і шкодить здоров'ю людини. Таким чином, використання фосфорних добрив – це питання еколого-економічної безпеки.

Ключові слова: запаси і потоки фосфору, фосфорний пік, неефективне використання фосфору, внесення фосфорних добрив, фосфорне забруднення, вплив фосфорних запасів на людину, рециркуляція фосфору, закриття фосфорного циклу.

Mechanism of Economic Regulation, 2017, No 1, 6–28
ISSN 1726-8699 (print)

«Фосфорная» экономика – обзор

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Почти для всех процессов жизнедеятельности фосфор имеет важное значение. ДНК, РНК, жирные кислоты, зубы, кости, митохондриальная энергетическая система преобразования АДФ (аденозин-5′-дифосфат) на клеточном уровне – все эти процессы требуют или базируются на использовании различных соединений фосфора. Таким образом, его невозможно заменить. С другой стороны, слишком большое количество фосфора может нанести вред здоровью человека или устойчивости экосистем.

В природных экосистемах фосфор, как и большинство других питательных веществ, в основном образуется в результате естественных процессов формирования органических соединений фосфора из биомассы. Часть фосфора смывается поверхностными стоками и, проникая в грунтовые воды, попадает в озера или морские экосистемы. Таким образом, экосистемы более или менее сбалансированы благодаря постоянным процессам формирования питательных веществ, таких как фосфор. Фосфорный баланс в экосистемах поддерживается благодаря постоянной циркуляции воды.

Если запасы фосфора не пополнять, образуется его дефицит, и тогда потери нужно компенсировать искусственно. Ранее циклы производства, потребления и накопления отходов имели преимущественно локальный или региональный характер. Фосфорные соединения образовывались из остатков животных или компоста. Циклы меняются, если объемы поставок сельскохозяйственных культур (животных) в города превышают объемы формирования питательных веществ из пищевых отходов и сточных вод. Поэтому в средах, расположенных в низовьях рек, питательных веществ не хватает. Таким образом, потери фосфорных соединений росли в геометрической прогрессии с конца XIX в. В те времена только около 30 % населения планеты проживало в городах. В Европе ситуация менялась в течение 30–50 лет. В начале XX в. уже почти 70 % населения проживало в городах. Такое изменение вызвало совсем другой характер формированием потоков материи и энергии, поэтому изменились и региональные циклы.

Использование минеральных удобрений компенсировало ущерб от потерь фосфора в региональных циклах, начиная с 1950–60-х годов. Как правило, использование удобрений для удобрения сельскохозяйственных угодий превышало объемы природного уровня формирования фосфора.

Сегодня спрос сельского хозяйства на фосфорные удобрения больше, чем естественный уровень его восстановления. Таким образом, предполагается, что проблема обеспечения высокого уровня потребления можно решить только путем добычи и переработки невозобновляемых минеральных и фосфатных пород в фосфорные удобрения. Глобальный годовой объем производства фосфоритов увеличился почти в два раза в период с 1970 по 2010 год.

«Зеленая» революция вызвала постоянно растущий спрос на фосфорные удобрения. Повышенный уровень использования фосфорных удобрений, к сожалению, не способствует увеличению урожайности. Фосфор в больших объемах накапливается в почвах, попадает в сточные воды, на мусорные свалки или непосредственно в открытые водоемы. В результате возникают значительные экономические проблемы.

Таким образом, лучшей экономической стратегией является сведение к минимуму или прекращения использования минеральных фосфорных удобрений, включающей:

1) существенное сокращение объемов производства фосфорных удобрений из апатитовых руд или из ядерных отходов;

2) использование «новых» природных запасов фосфора, образовавшихся в результате распада сельскохозяйственных культур за последние 50 лет;

3) снижение внешних воздействий на окружающую среду, уровня загрязнения поверхностных вод и потерь почвы;

4) закрытие региональных «чистых» циклов производства фосфорных удобрений.

Такая стратегия является оптимальной и может принести определенные социальные эффекты. Если бы расходы, связанные с формированием экстернальных эффектов, включались в цену фосфорных удобрений, и при этом применялся принцип «загрязнитель платит», то их бы просто не покупали. Использование фосфорных удобрений было бы немедленно прекращено, поскольку их использование неразрывно связывают с загрязнением окружающей среды токсичными элементами и соединениями. Использование этих соединений, действительно, наносит ущерб продовольственной безопасности, ухудшает качество питьевой воды и вредит здоровью человека. Таким образом, использование фосфорных удобрений – это вопрос эколого-экономической безопасности.

Ключевые слова: запасы и потоки фосфора, фосфорный пик, неэффективное использование фосфора, внесение фосфорных удобрений, фосфорное загрязнение, влияние фосфорных запасов на человека, рециркуляция фосфора, закрытие фосфорного цикла.

JEL Codes: Q01, Q24 Figures: *5;* References: *126*

Language of the article: English