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Economic policy instruments for sustainable phosphorus management: taking into account climate and biodiversity targets

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Abstract

Background: Phosphorus (P) is a vital and non-substitutable nutrient for agricultural production. However, P is often used inefficiently in European agriculture. To ensure food security while avoiding environmental damage caused by improper fertilization, a sustainable P management is required. Although P-related problems are partly addressed by existing agricultural and environmental legislation, e.g., in the EU, the current regulation lacks sufficient governance effect. In addition, the existing legal framework is strongly characterized by detailed command-and-control provisions and thus suffers from governance problems such as enforcement deficits, rebound and shifting effects. This paper focuses on how these challenges could be addressed by economic instruments. The article highlights not only the impact of the instruments on P management, but also on adjacent environmental areas. We pay particular attention to the governance effects on reaching international binding climate and biodiversity objectives, for which fertilization and agriculture play a major role.

Results: The analysis builds on two economic instruments that ensure compliance with the climate target of the Paris Agreement and the Aichi targets of the Biodiversity Convention: a cap-and-trade scheme for fossil fuels and a cap-and-trade scheme for livestock products. We state that both instruments simultaneously address a large part of P-related problems. Moreover, if the two emissions trading schemes are combined with a livestock-to-land ratio at farm level, only little need for regulatory supplementation relating to P remains. The latter includes in particular a threshold value for contaminants in P-containing fertilizers. Furthermore, we discuss an almost complete phasing-out of fertilizers containing rock phosphate by means of a further certificate trading scheme.

Conclusions: The article shows that a wide variety of problems can be tackled with a few overarching instruments. This is true even for very specific and diverse problems such as those related to P use in agriculture.

Keywords: Phosphorus, Fertilization, Agriculture, Sustainability, Economic instruments, Governance, Climate, Biodiversity, Fossil fuels, Livestock

Background

Phosphorus (P) is vital for plants, animals and humans. However, although the non-substitutable nutritional element secures our food production, P fertilization in European agriculture is often inefficient [1, 2]. While soils in some regions of Europe are showing nutrient deficiencies and thus losing their productive capacity, elsewhere, especially in regions with high livestock density, large amounts of P accumulate in the soil. In these regions, the risk of P discharge and water eutrophication increases, which is illustrated for example by dead zones in the Baltic Sea [3–5]. In addition, fertilizers containing rock phosphate often contain high levels of cadmium (Cd) and uranium (U), posing a further risk to ecosystems and human health [6–8]. Last but not least, the EU is almost entirely dependent on imports of rock

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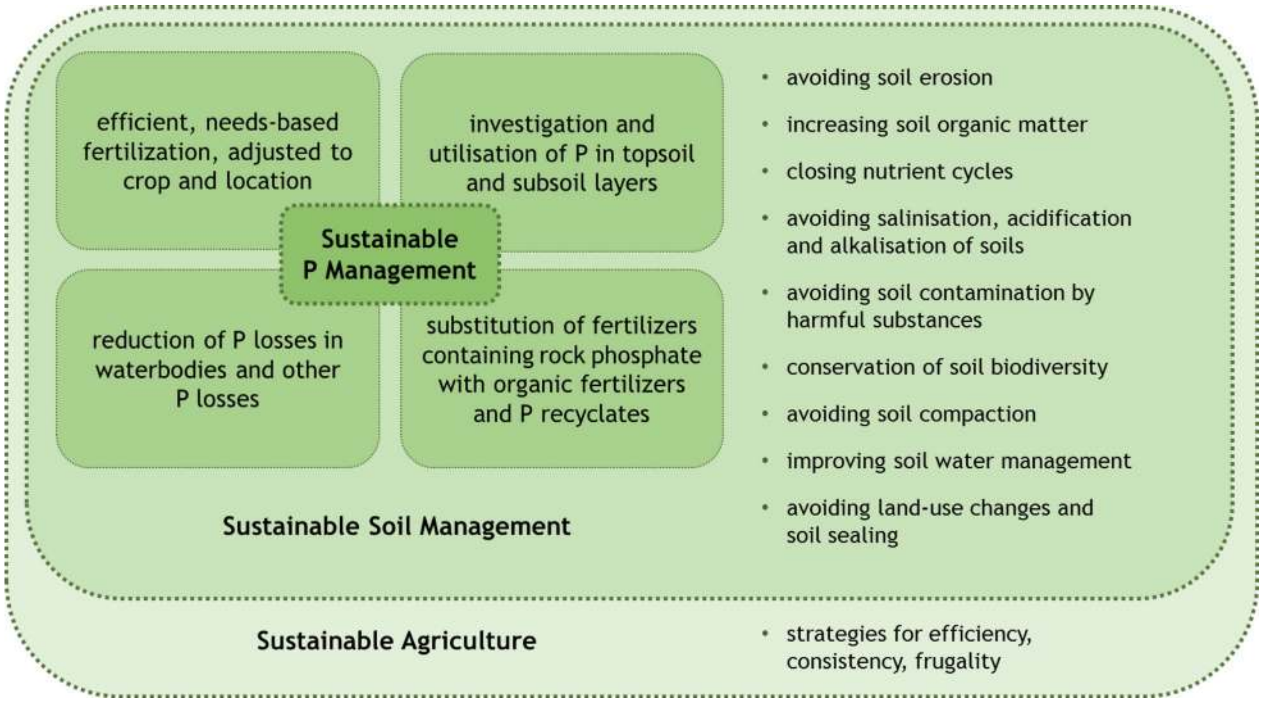

Fig. 1 Sustainable P management as part of sustainable soil management and sustainable agriculture

phosphate or fertilizers derived from it. The finite rock phosphate resources are concentrated in a few, partly politically unstable regions of the world, such as Morocco and Western Sahara [9]. This bears the risk of supply shortages [1, 10], which is why the EU has classified phosphate rock and P as critical raw materials [11–13]. However, rather than recycling P as much as possible, P losses occur along the entire value chain in the EU, and significant amounts of P in wastewater and waste streams remain unused for recovery [14–17].

Better P management is required to secure P supply for European agriculture, to ensure long-term preservation of soil fertility and soil functions, while avoiding environmental damage such as eutrophication of water bodies. At the same time, resources of rock phosphate should be conserved and import dependency on P minimized. To achieve these goals, a needs-based, site-adapted and crop-specific fertilization is necessary in order to avoid P surpluses, taking into account soil characteristics such as soil P contents. Simultaneously, P-mobilizing measures are recommended (see below) [18–20]. Likewise, efficiency in animal feeding can be increased. At the same time, P fertilizers from mining should increasingly be replaced by organic fertilizers and P recyclates that are compatible with circular economy [1, 21–24]. Contamination with Cd and U needs to be eliminated. Furthermore, organic farming and other agro-ecological cropping systems are to be encouraged, while livestock farming and arable farming should be combined more strongly to close P cycles [25].

Terminologically, these measures involve aspects of consistency, efficiency and sufficiency, i.e., the established sustainability strategies [26, 27]. Moreover, sustainable P management is embedded in sustainable soil management [28] as an integral part of sustainable agriculture [25, 26, 29]: reducing soil erosion decreases P losses to the aquatic environment and thus eutrophication [18, 30]. A loosened soil rich in microorganisms contributes to mobilizing existing P contents, for which, among other things, diversified crop rotations are beneficial. Soil microbial activity can furthermore be increased by various P activators such as biochars and by adding organic matter through organic fertilization including compost and green manure [31–36] (for more details on sustainable P management see [25, 37]). Figure 1 illustrates the main aspects of sustainable P management and the larger context.

A major factor influencing P balances at farm, regional and European level is the high and further increasing production of animal derived products (the same applies to nitrogen, N) [16, 38–41]. In particular, the spatial separation of livestock farming and arable farming is disrupting the P cycle: (mineral) P fertilizers have to be brought to regions of fodder cultivation.

From these areas, P is removed with the harvest and transported to regions with animal husbandry, where P from feed is only partially utilized by animals leaving the rest to be excreted. P-containing manure, in turn, often remains in the region of animal husbandry resulting in high soil P levels [3, 4, 38, 42–44]. High livestock numbers (both overall and regionally) not only counteract closed nutrient cycles [39, 45–47], but climate and biodiversity protection as well: approximately 70% of the world's agricultural land, including pastures, is used for producing animal-based food today [48–50]. The FAO assumes that, if consumption trends remain the same, the share of cereals fed to livestock will rise from 30 to 50% in 2050, resulting in land-use changes [48, 51–55] harmful to climate and biodiversity [29, 56–62] (critical on the growth-based FAO forecasts see [39, 63–65]). At the same time, livestock farming is a major emitter of greenhouse gases. Carbon dioxide (CO_2) is produced by humus depletion, for example as a result of land-use changes. Digestive processes of farm animals produce methane (CH_4), and CH_4 and nitrous oxide (N_2O) are released by manure application and storage as well as from soils as a result of N fertilization [29, 57, 66–68]. At last, greenhouse gases in livestock farming and in agriculture as a whole are released as a consequence of using fossil fuels, for instance for transportation, tillage and, above all, the energy-intensive production of N fertilizers using the Haber–Bosch process [57, 69–72].

Some of the emissions from animal husbandry, fertilization and soils are unavoidable. This is true even for vegan diets, but even more so if at least some (pasture) animal husbandry is further pursued, which has benefits for the world's food supply and, to some extent, for biodiversity [73]. This increases the pressure on mitigation measures in other areas as well as on compensation measures such as reforestation, enhancing carbon storage of soils, rewetting of wetlands and the like [74–77].

In consequence, integrated solutions are needed for P-related problems and the associated agricultural challenges. Up to now, on the one hand, the scientific discussion on P has focused mainly on natural scientific issues (see e.g., [1–3, 20, 36]). On the other hand, questions of P governance usually deal with one of the various P problems, for instance Cd contamination or P surpluses (see e.g., [6, 38]). However, if only one of these problems is addressed, further regulation is still required to solve the other problems. A P-surplus tax, for example, would have no impact on resource conservation of phosphate rock or its contamination with Cd and U. Moreover, the specific solutions proposed usually fail to provide a link to overarching, binding environmental goals. This paper aims to fill this gap.

Methods

This article is a contribution to interdisciplinary sustainability research with a focus on governance. It deals with the current issue of P in the context of agriculture. In doing so, it covers detailed questions of fertilization as well as broader issues of a more sustainable, environmentally and climate friendly agricultural sector. In particular, this paper develops the core elements of P governance in such a way that, in addition to P, climate and biodiversity-related challenges of agriculture are taken into account as well. The instruments to be developed are designed to contribute to achieving the binding international environmental targets, i.e., to limit global warming to well below 2 °C and pursuing efforts to limit the temperature increase to 1.5 °C above pre-industrial levels, according to Art. 2(1) Paris Agreement (PA) [78] and to halt biodiversity loss in accordance with Aichi Targets B and C of the Convention on Biological Diversity (CBD) [79]. Both agreements require zero emissions by means of zero fossil fuels in a maximum of two decades and a significant reduction in animal husbandry, thus calling for comprehensive changes in the agricultural sector including P management. Besides, European environmental law, in particular the Nitrates Directive [80] and the Water Framework Directive [81], points in the same direction, i.e., reducing high livestock densities to ensure good water quality [25, 38].

With regard to P, the main points of sustainable P management can be derived from the challenges described above. However, an overarching, binding objective such as a global reduction target for rock phosphate use is lacking to date. In fact, the precise, appropriate sustainability strategy for P is still partly dependent on open normative questions concerning the sustainable use of scarce resources as well as open empirical questions. The large empirical heterogeneity, for instance regarding current soil P contents in different regions and questions of the type of diet to be assumed in the future (whose P intensity varies strongly) make it even more difficult to make assumptions about the most sustainable future strategies for P use. In this respect, further clarification is needed, both politically and scientifically. However, an efficient use of the finite resource phosphate rock as well as better environmental and health protection are plausible—and thus the above-mentioned strategies are—especially since they are directly linked to reduced animal husbandry, which in turn is required to meet climate and biodiversity goals.

Methodically, the article applies a qualitative governance analysis, sometimes called legal impact analysis [72, 76, 82, 83]. It examines the effectiveness of potential or existing governance instruments on the basis of a given objective and takes into account human motivational

Table 1 Assessment criteria for analyzing the impact of economic instruments on phosphorus use

Assessment criterion	Explanation
P efficiency	Promotion of efficient, needs-based, site- and crop-specific fertilization and P-mobilizing management strategies Reduction of P fertilization at highly supplied sites Avoidance of P losses Enhancement of P efficiency in animal feeding
Regional P surpluses	Avoidance of P surpluses at farm and regional level to reduce eutrophication risk
P balances	Balancing of imports and exports of P to and from the EU, focusing on the reduction of dependence on P imports
P fertilizer quality	Reduction of the contaminant levels of imported P fertilizers, particularly of Cd and U
P circular economy	Substitution of fertilizers containing rock phosphate by organic fertilizers and recovered P, in particular promotion of P recycling
Agricultural structures	Promotion of organic farming and further agro-ecological production methods Increased linking of livestock and arable farming Improvement of the condition of soils, water, biodiversity, climate

factors. Behavioral research in various disciplines (sociology, economics, psychology, ethnology, etc.) and methods (experiments, surveys, participant observation, etc.) identified in particular the following driving factors of human behavior: self-interest, values, conceptions of normality, emotional constraints such as convenience, denial and habits, peer pressure, the tendency to make excuses, difficulties in perceiving distant challenges and structural problems such as path dependencies and problems of collective goods [27, 84, 85]. Based on this knowledge of the motivational factors of consumers, producers, entrepreneurs, politicians, etc., and on empirical findings, for example on resource consumption, typical governance problems with respect to sustainability can be identified (see the next section). They limit the effectiveness of policy instruments [72, 76, 82, 83]. Effective instruments should therefore avoid these governance problems. At the same time, the instruments have to be designed in such a way that they achieve the given objectives.

In terms of terminology, a distinction has to be made between effectiveness and normative necessity (e.g., on the basis of obligations under international law) on the one hand and actual feasibility (in terms of having a majority in parliaments and society) of policy instruments on the other hand [27]. Often—if at all—only weak measures (e.g., labeling), which are not sufficient to achieve the given objectives, are easy to implement. In contrast, the introduction of tough but effective measures is frequently hampered by lobbying, especially in the agricultural sector [85–87]. However, our analysis focusses on the effectiveness and necessity of instruments. At the same time, we propose a rather small number of effective instruments with flexibility for the addressees, which are principally better to enforce than a large number of individual, rigid rules.

In order to develop effective policy instruments for P governance, the article firstly summarizes the challenges related to P management, fertilization and agriculture as a whole (see first section). These findings are derived from an interdisciplinary literature review including international scientific literature on environmental and agricultural sciences such as soil sciences, plant nutrition, microbiology, hydrology, etc. Thereupon, a description of the cornerstones of sustainable P management is provided.

Based on the review of literature, the next step of the governance analysis is the identification of relevant legal acts for P governance in the EU. To this end, we used the EUR-Lex database [88] which collects and publishes all official documents of European institutions. Besides, publications form official authorities such as the European Commission are assessed to include relevant political strategies and objectives that are not yet incorporated in legal form. Building on an earlier publication [37], this article shortly summarizes and updates the relevant legal areas of European agricultural and environmental law for P use. In particular, the status quo section draws attention to the deficits of the existing legal framework, which is mostly based on command-and-control law and focusses on details and individual products or processes. In response, we present the advantages of economic instruments to solve quantity-related sustainability problems such as resource overuse. At last, the article proposes improved governance options that avoid governance problems and achieve not only a more sustainable P management but also the environmental targets set by the PA, the CBD, the Nitrates Directive and the Water Framework Directive. The focus is on comprehensive economic instruments. Table 1 summarizes the assessment criteria for analyzing the impact of these instruments on P use besides the overall climate and biodiversity targets. They are directly related to the key aspects of sustainable P management.

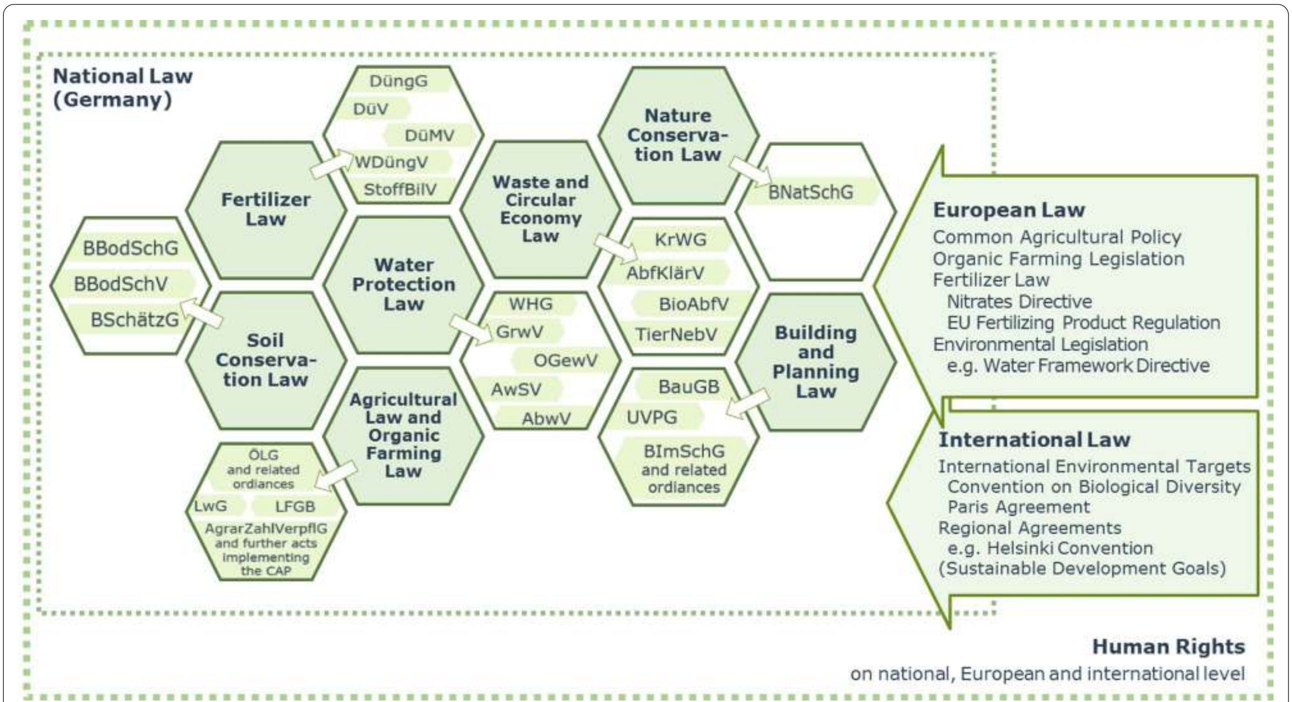

Fig. 2 Relevant legal areas for P management

In particular, we discuss two economic instruments for a more sustainable agriculture, i.e., an emissions trading for fossil fuels and another emissions trading for animal products. Both instruments achieve comprehensive changes in agriculture. They are necessary in order to comply with the globally binding environmental targets. In principle, the parallel application of instruments with overlapping or even counteracting effects is to be avoided for efficiency reasons (see e.g., [89, 90]). This is why we examine to what extent the two overarching instruments solve P-specific problems and which supplementary P-related instruments remain necessary. As a result, an integrated approach to address P-related challenges and to achieve broader environmental goals is proposed.

Status quo of phosphorus governance and shortcomings of command-and-control law

The specific aspects of sustainable P management touch on various legal areas of the EU and the national states. In addition to agricultural law, soil protection law, water protection law, the application- and product-related regulations of fertilizer law and, with regard to P recycling, circular economy law are relevant. The regulation of livestock facilities furthermore includes building and planning law as well as immission control law. Moreover, the law of organic farming contains some regulatory impulses for a more sustainable P management. Figure 2 summarizes the relevant legal areas for P management. The various acts and ordinances in Germany serve as an example for national law, which is influenced by the provisions of EU law, e.g., by the Common Agricultural Policy (CAP). Transnational and international environmental targets as well as obligations arising from human rights constitute the framework.

A detailed analysis of these legal areas revealed a lack of adequate steering effect, although some important starting points for a more sustainable P management are anchored in different parts of the legislation [25, 26, 37, 91, 92]. In particular, high animal density and high animal numbers, which are of particular importance for P-related problems and at the same time counteract climate- and biodiversity targets, are not sufficiently addressed by any of the existing regulations.

One exception is organic farming, which prescribes a link between the number of animals kept and the area in Art. 5 lit. g) and Art. 14(1) lit. d) No. i) Regulation (EC) 834/2007[93].[1] This livestock-to-land ratio takes into account the feed requirement and the amount of manure produced. However, terminological vagueness and the resulting loopholes hamper the effectiveness of organic farming legislation. For example, the legislation lacks a precise definition of 'region' of feed cultivation. Apart from this, a restriction of the livestock numbers

[1] From 1. January 2022, the new Regulation (EU) 2018/848 [94] applies.

in accordance with the climate target remains absent. In addition, only 7.5% of the EU's agricultural land is managed organically to date [95]. Ultimately, organic farming will remain a rather marginal phenomenon even if the target of expanding organic farming to 25% of agricultural land by 2030, as set out in the Farm-to-Fork Strategy published by the EU Commission in May 2020 [96], is achieved. Still, in addition to the livestock-to-land ratio, organic farming contains further starting points for sustainable P management. These encompass the maintenance and enhancement of soil life and natural soil fertility, the minimization of off-farm inputs including low solubility mineral fertilizers (Art. 5 lit. a), b), Art. 4 lit. b) No. iii) Regulation (EC) 834/2007) as well as the prevention of soil erosion and the preservation and increase of soil organic matter (Art. 12(1) lit. a) Regulation (EG) 834/2007). Despite these strong points, it is important to avoid P surpluses on organically cultivated land as well. Likewise, P deficits need to be addressed as they often occur on organic farms without livestock [97]. Nonetheless, organic farming deserves support from a P perspective.

Apart from the subsidies of the CAP, which have faced ongoing criticism for their negative environmental impact [98],[2] the current legal framework is dominated by command-and-control provisions. Command-and-control law is characterized by its orientation towards detailed rules for individual products, processes or facilities. As a result, it shows shortcomings in solving quantity-related sustainability problems (such as the issues of P, N, biodiversity, and climate):

Complex cause–effect relationships such as those between ecosystems and often multi-causal ecological damages characterize the environmental sector and particular the situation of P and soils. It is hard to capture and depict them in detailed regulatory rules (problem of depicting). In addition, rebound effects frequently offset efficiency gains in individual areas. Sectoral or spatial shifting effects allow problems simply being shifted from a regulated to a less regulated area. Besides, the requirements of norms are often show an insufficient level of ambition to effectively implement the overarching objectives—a fact that is usually lost in the plethora of regulatory provisions. At the same time, exceptions and loopholes impair the effectiveness of legal requirements (lack of rigor). Furthermore, enforcement problems frequently occur, especially in the agricultural sector with its large number of individual processes [27, 72, 82].

When dealing with sustainability issues, instruments with a direct or indirect quantity-controlling effect, i.e., economic instruments such as levies and cap-and-trade systems (emissions or certificate trading systems), have the potential to avoid these governance problems. The prerequisite for this is an appropriate design. If the quantity cap or the price is linked to an easily graspable control variable (such as fossil fuels) and if the system is applied sectorally and geographically broad, problems of enforcement and depicting as well as sectoral and spatial shifting effects are unlikely (at the latest through supplementary border adjustments). In addition, the absolute quantity limit excludes rebound effects, at least in the case of caps [25, 27].

Economic instruments are neutral towards the various sustainability strategies. This is because they allow the norm addressees, who are subject to the explicit or implicit price pressure generated by the quantity shortage, to decide whether they choose consistency, efficiency or sufficiency. Hence, in line with the principles of liberal democracies, economic instruments are not only ecologically effective in achieving objectives and avoiding governance problems (if designed in the way described), but they offer more freedom due to the flexibility left to the addressees as well. At the same time, they implement the polluter pays principle and are economically cost effective. However, just as (detailed) command-and-control rules, economic instruments have to be strict in accordance with the objective pursued, i.e., the quantity limit has to be ambitious and the tax rate sufficiently high [25, 27, 104–107].

However, the terminology 'economic instruments versus command-and-control law' is prone to misunderstanding. The main difference between governance instruments is less between 'price' and 'ban' than between quantity and detail control. Eventually, a zero cap could be called a ban. In turn, regulatory bans affect prices. For example, regulatory requirements on contaminant loads can increase the price of fertilizers containing rock phosphate and thus encourage the use of recycled P fertilizers and organic fertilizers. Irrespective of this, economic or quantity-oriented instruments have hardly been applied in fertilization law so far. In some Member States of the EU, they were discussed politically and scientifically, e.g., when Germany faced an infringement procedure [108] because it violated the EU Nitrates Directive. Proposals included, among others, a nitrogen surplus tax [104, 109]. Since the focus of the proposed instruments was clearly on N, we will examine whether economic instruments can provide effective solutions for the problems associated with P use as well.

[2] The CAP is currently undergoing a reform. For the draft regulations for the future CAP after 2021/ 2023 see [99–101]; for a critically review of these see [102, 103].

Results: economic instruments for phosphorus governance and interlinked ecological problems

This section analyzes two economic instruments to achieve binding climate and biodiversity targets: firstly, a reformed EU emissions trading scheme for all fossil fuels in the first trading phase, which phases out fossil fuels in a maximum of two decades [27, 75], and secondly, a separate emissions trading scheme for animal products, which strongly reduces the number of animals [72]. Then, with regard to P, we discuss to what extent these overarching sustainability instruments impact P management (see Table 1) and which additional instruments are required.

Emissions trading for fossil fuels

Not only agricultural production, but a major part of the economy in industrialized countries is based on the use of fossil fuels. They are utilized as fuels in transportation and industry, for electricity and heating, for producing fertilizers, chemicals, plastics, pharmaceuticals, and so on. Fossil fuels permeate almost all areas of life. Accordingly, they offer a sectorally broad and at the same time easily graspable starting point for an integrated solution to various environmental problems [27].

Ideally, a global cap-and-trade scheme for fossil fuels covering all sectors would limit the use of fossil fuels to zero in no more than two decades by progressively lowering the absolute quantity limitation (cap) [27, 75, 110–112] (see [86] for the alternative option of a global price on CO_2). As long as no such global solution can be implemented, EU emissions trading could be turned into to a primary energy-based approach—with a cap aligned with the Paris climate target. Border adjustments could then avoid carbon leakage to countries without similar approaches [27, 113, 114]. This is currently being discussed again at EU level as part of the Green Deal [115–117].

Starting at the first trading level ensures a broad coverage of all CO_2 emissions (and at the same time a reduction of some other greenhouse gas emissions). The price signal generated by the emissions trading scheme can be transferred from primary energy companies to all companies and consumers via electricity, fuel and heat prices, and subsequently via all types of energy-dependent products. Due to the small number of norm addressees, enforcement would be simplified and transaction costs reduced [27].

Since agriculture depends on energy input (see, among others [118]), phasing-out fossil fuels in no more than two decades will pose major challenges for the agricultural sector. Agricultural machinery, which has frequently been energy-inefficient up to now, could be more efficient and powered by renewable energies in the future. Digitalization and technological progress, including precision farming methods, hold further potentials for increasing the efficiency not only of fertilization or the use of further agrochemicals, but with regard to energy use as well [119–121]. Nevertheless, producing renewable energies, i.e., their cultivation or production, operation and, last but not least, their disposal will always require resource consumption and has impacts on ecosystems (see for example [122, 123] on bioenergy and [124] on offshore wind energy). Moreover, the challenge of achieving zero emissions within a maximum of two decades will be too big for a purely technological strategy. For these reasons, reformed emissions trading would probably trigger sufficiency. In other words, efficiency, increased use of renewables (consistency), and sufficiency will all be incentivized by rising energy prices due to the phasing-out of fossil fuels from the market.

Besides, the energy price is considered to be one of the determinants of prices for phosphate rock and P fertilizers (on factors influencing P prices see [17]). For example, the sharp increase (up to 800%) of world market prices for phosphate rock around 2008 is associated with the oil price shock in the same year. Similar developments occurred in 1974/75 [10, 125, 126]. Others argue that this correlation is rather moderate [127]. Still, price increases for fertilizers do affect fertilizer sales. Figures 3 and 4 illustrate the rising prices for one of the most common P fertilizers, triple-superphosphate, around 2008 and the subsequent decline in sales of these fertilizers (measured in terms of the content of phosphorus pentoxide, P_2O_5) in the EU.

Energy consumption of P fertilizers varies depending on the production process and the final product [129]. A large share of phosphate rock is processed by adding sulfuric acid (H_2SO_4) to obtain phosphoric acid (H_3PO_4), which is the raw material for various P fertilizers [130, 131]. This step is an exothermic reaction generating energy that can be used for further processing. In fact, the overall energy balance of modern production processes for triple-superphosphate can even be positive, while older processes consume energy. Besides that, fertilizer transport requires relatively high amounts of energy given the long distances between the deposits of raw materials and the sites of production and use [118, 132, 133]. Moreover, for every ton P_2O_5 in the end product, an average of five tons of (radioactive and toxic) phosphogypsum is produced. Most of it has to be deposited in dumps. This requires a large amount of transport energy [133]. Last but not least, fertilizer application consumes energy, with the amount depending on the field size, the technology used and the application rate [132]. In principle, an increase in the price of fossil fuels is likely to lead

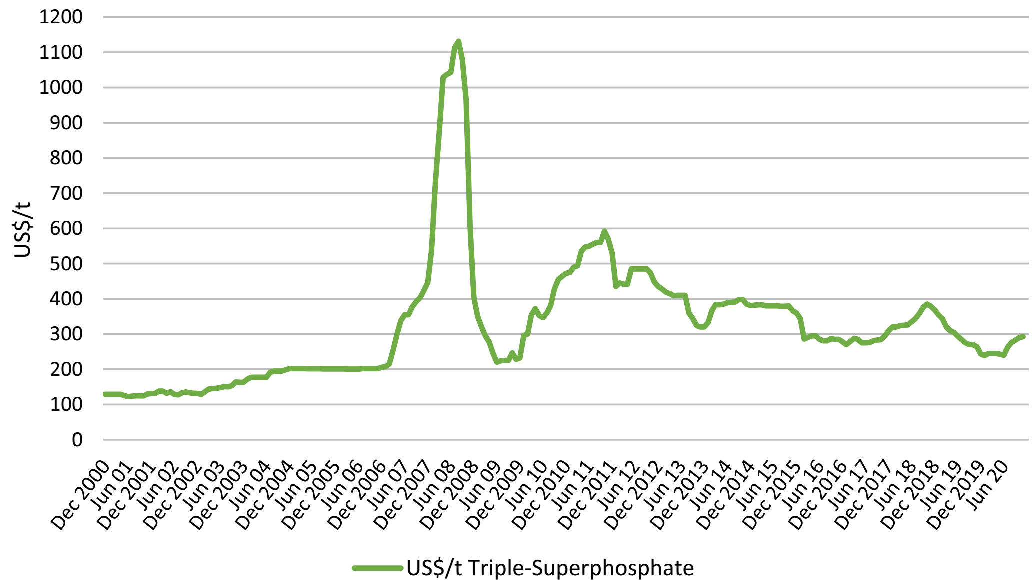

Fig. 3 Price of triple-superphosphate (2000–2020) (own figure based on data of Index Mundi [125])

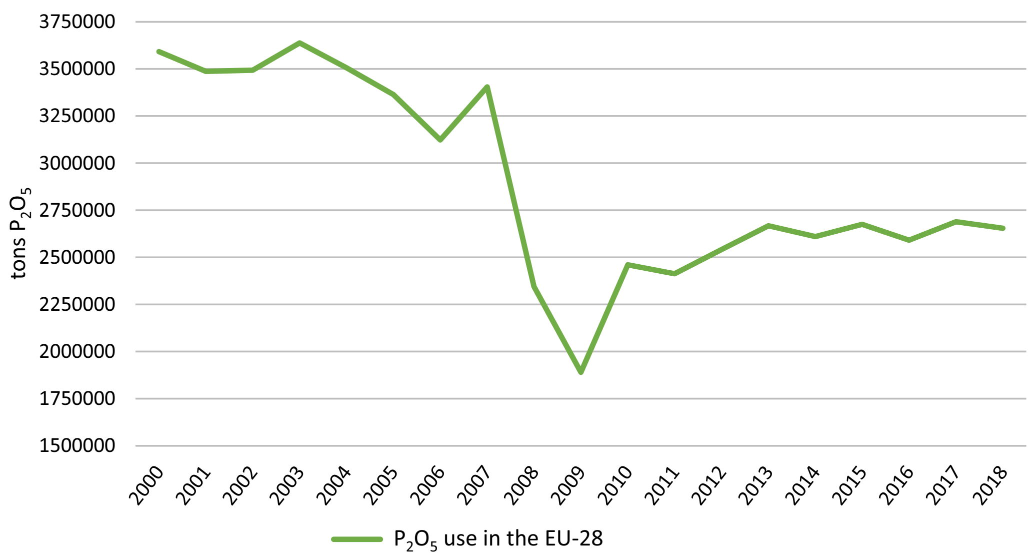

Fig. 4 Agricultural use of P_2O_5 in the EU-28 (2000–2018) (own figure based on data of FAOSTAT [128])

to an increase in the price of fertilizers containing rock phosphate, as mining, processing, transport and application costs rise.

However, compared to the production of N fertilizers, the production of P fertilizers requires significantly less energy. N-fertilizer production with the Haber–Bosch process requires the highest energy input in the agricultural sector. In fact, it accounts for about 1–2% of the global energy demand [69–71, 134]. An absolute quantity limit for fossil fuels would make it almost impossible to produce synthetic N fertilizers to the same extent as today (at least as long as the EU and other countries do not achieve their goal of using fusion energy widely for energy supply [135]). This would have a crucial impact on agricultural practices (especially in interaction with the regulation of animal products presented below). In principle, the hydrogen required for ammonia synthesis could be produced both more efficiently and by using renewable energies. Likewise, the high energy demand of the ammonia synthesis itself could basically be covered by renewables [69–71, 134, 136–138]. Yet, the implementation of the EU's hydrogen strategy [139], which aims at producing green hydrogen to foster decarbonization of the EU's economy, is just getting underway. So far, such processes have been used predominantly in areas where renewable energies are available in large quantities, e.g., hydropower in Norway [136, 138]. In theory, an efficient and marketable process for synthetically produced N fertilizers without using fossil fuels can indeed be part of a sustainable agricultural and fertilization management. But for now, the scarcity of fossil fuels would limit the production of synthetic N fertilizers. This encourages efficient, site- and crop-adapted fertilization as well as a switch to alternative fertilizers such as organic fertilizers and recyclates.

Since a large proportion of mineral fertilizers is sold as mixed fertilizers (e.g., NP fertilizers), a shortage of synthetic N fertilizers would ultimately impact the sale of P fertilizers, too. Nevertheless, in principle, the P demand could be covered by single-nutrient fertilizers as well. However, it is usually necessary to supply both P and N (as well as other nutrients such as potassium) to plants. Thus, it seems likely that more attention will be paid to fertilizer efficiency, while organic fertilizers and recycled products containing P and N will be increasingly used.

In addition, it can be assumed that a reformed emissions trading will trigger an increased use of N-fixing legumes to supply N to plants. Integrating legumes into diversified crop rotations has simultaneously a positive effect on the efficiency of P fertilization. P uptake by crops would be improved and P mobilization in the soil enhanced due to, e.g., a loosened soil, deep rooting and because of the coupling of microbial N and P turnover [31, 33, 140].

Less synthetic N fertilizers and higher prices of fertilizers containing rock phosphate are likely to impede pure crop cultivation, especially pure fodder cultivation. At best, a stronger coupling of animal husbandry and arable farming would be stimulated as the dependence on organic fertilizers increases. Likewise, long transport distances for organic fertilizers are expected to be avoided due to higher energy costs—even where renewable energies are utilized. Yet, where transportation remains necessary, separating organic fertilizers into their liquid and solid components allows for easier transportation. Hence, above all, these developments make the regional use of organic fertilizers relatively more attractive. The same applies to the transport of animal feed and in particular to long distance transportation, for instance from Latin America to the EU. Thus, P imports through feed imports (for example soy) are likely to become less attractive as well. Moreover, rising rock phosphate prices would increase prices for P additives and thus stimulate increased P efficiency in animal feeding.

Furthermore, increased organic fertilization is expected to reduce the amount of imported mineral P fertilizers, especially since they would become more expensive. However, a complete stop of imports of P fertilizers containing rock phosphate would not be achieved unerringly by phasing-out fossil fuels as long as extraction, production, transportation, etc., can be assured by using renewable energies. Neither would such a regulation have any influence on the quality of imported P fertilizers, in particular with regard to their contamination with Cd and U.

In addition to organic fertilization, P recycling would gain a competitive advantage over using mined P fertilizers. P recycling processes with low energy demand are expected to benefit in particular. However, it is crucial to use renewable energy sources for recovery.

Besides, organic farming with its lower use of fossil energy and the renunciation from mineral fertilizers is likely to be favored by phasing-out fossil fuels. Organic farming would result in further benefits for the environment [141–143], among others, due to the livestock-to-land ratio and reduced feed imports.

With respect to livestock, a cap on fossil fuels would achieve price increases (on feed, for example). However, this effect is likely to be insufficient to achieve global environmental targets. Moreover, emissions from animals, especially methane emissions from ruminants, would not be covered by such an emissions trading. In addition, limiting fossil fuels fails to target regionally high livestock densities and, accordingly, nutrient hotspots. Thus, a core problem of P use remains unaddressed. Nor would there be a sufficient impact on further problems of livestock farming, such as land use and thus land-use changes that threaten biodiversity. Consequently, additional regulation of livestock production remains necessary to avoid regional nutrient surpluses, to limit greenhouse gas emissions from livestock production in line with the 1.5 °C target and to mitigate further ecological impacts of livestock farming, including those of extensive feed production.

In addition, phasing-out fossil fuels bears the risk that manure is co-fermented in biogas plants instead of being utilized for fertilization. Likewise, the harvest could increasingly be used to produce energy in biogas plants. This is problematic given the limited availability of fertile soils. To prevent shifting effects from one environmental problem to another, i.e., increased pressure on land due to expanded energy crop cultivation, additional regulation might be required [122, 144]. Table 2 summarizes the effects of a cap-and-trade scheme for fossil fuels (see the end of the next section).

Table 2 Impact of emissions trading for fossil fuels and emissions trading for animal products on P management

Assessment criteria	Emissions trading for fossil fuels	Emissions trading for animal products	Legend
P efficiency	+	∞	
Regional P surpluses	o	o	+ Positive effect
P balances	+	+	− Negative effect
P fertilizer quality	o	o	o No effect
P circular economy	+	−	∞ Partial or conditional effect
Agricultural structures	+	∞	

Emissions trading for livestock products

Agriculture is highly relevant to climate change, accounting for around 18% of global greenhouse gas emissions and 10% of European greenhouse gas emissions. The livestock sector, including the storage and spreading of manure, is responsible for more than 60% of these emissions [41, 77, 137, 145] (according to the European Commission even 70% [96]). At the same time, livestock farming is a major driver of land-use changes for feed production, while feed cultivation is often based on high P (and N) fertilizer and pesticide use in monoculture. In consequence, biodiversity is harmed. In fact, the livestock sector is estimated to contribute around three quarters of the biodiversity loss caused by agriculture [24, 41, 146]. Simultaneously, as described above, livestock production is central for P because it is responsible for regional P surpluses.

In order to achieve zero emissions in one to two decades, avoidable emissions in the agricultural sector have to be eliminated entirely. Avoidable emissions include CO_2 emissions from (transport) energy use as well as fertilizer production. They would be addressed by primary energy emissions trading. Other emissions would have to be reduced as much as possible, especially CH_4 and N_2O from animal husbandry, soils and fertilization. Any remaining emissions need to be compensated for by carbon sequestration, for example through afforestation or by increasing carbon storage of agricultural soils [76, 77, 110–112, 147, 148]. The United Nations Framework Convention on Climate Change, which is the foundation of the Paris Agreement, even points to agriculture as a greenhouse gas sink (Art. 4 Abs. 1 lit. d) UNFCCC [149]).

Given the climate impact of animal husbandry, the 1.5 °C target of the PA implies an emission cap for greenhouse gas emissions from livestock [72]. With regard to the biodiversity conservation targets of the CBD, a measurable control parameter that could be used for an economic instrument is lacking. Yet, a strong reduction in animal numbers would automatically have a positive impact on biodiversity. This is because fewer animals require less feed with correspondingly less land use (changes), pesticide use, etc. Thus, a separate biodiversity regulation is not necessarily needed.

Both taxes and cap-and-trade schemes for livestock farming or agriculture as a whole have proven to be administratively complex, simply because a large number of farms and climate-relevant individual activities is involved. In contrast, the number of processing companies, i.e., slaughterhouses and dairies, and in case of eggs first buyers, is lower and would be easier to manage. Consequently, a promising approach is a product-based emissions trading. Based on standardized emission values per animal and per kilogram (kg) of product, this approach keeps transaction costs relatively low compared to other strategies (see [71], partly similar as well [67, 150]).

To enhance accuracy, rather than using EU-wide (or even global) emission values, regionally or nationally differentiated emission values per animal product can be used. Standardized calculation methods are provided by IPCC guidelines [151, 152]. Moreover, these calculation approaches can be adjusted to different production methods [67, 72, 151, 152]. The allowances to be distributed to processing companies or first buyers would then have to be reduced gradually in line with the 1.5 °C limit. This would strongly reduce livestock farming in total. Within the livestock sector, shifting effects from emission-intensive cattle farming to chicken and pig farming are likely to occur [72, 150]. However, since emissions trading for fossil fuels increases the price of feed imports, especially for soy imports, chicken and pig farming would become less attractive as well. Shifting effects to other countries could in turn be avoided by border adjustments.

While large reductions in livestock numbers would significantly contribute to achieving climate and biodiversity goals and avoiding other environmental problems such as air and soil pollution (see, among others [41]), impacts on P-related problems are mixed: declining livestock numbers would result in lower feed demand, reducing import dependence on P in the form of feed and feed additives. In addition, lower fodder cultivation would require less P. However, with drastically reduced animal numbers, less P from organic fertilizers would be available. Therefore, mineral fertilizers may increasingly be used.[3] This could impede the substitution of fertilizers containing rock phosphate. Furthermore, apart from potential efficiency gains triggered by the reduced amount of manure, there would be no sufficient incentive to increase P fertilization efficiency or P feeding efficiency. Moreover, emissions trading of livestock products will have no effect on the Cd and U contamination of P fertilizers. In particular, despite an absolute reduction in the number of animals, emissions trading for animal products would not preclude regionally high livestock densities and thus nutrient surpluses. The trading component distributes emission allowances without considering local conditions. Thus, neither a targeted effect on closing nutrient cycles at farm and/ or regional level nor a stronger linking of animal husbandry and arable farming is achieved. Likewise, organic farming is not expected to benefit from emissions trading for animal products. Although emissions per area and per animal are lower in organic livestock farming, emissions per product unit often exceed the values of conventional farming due to lower yields. However, emission amounts vary widely, and organically managed soils regularly show advantages in terms of carbon storage and long-term yield stability, even in times of climate change risks [142, 154–157].

Overall, a higher price for CO_{2e} for emission- and resource-intensive, animal-based food induced by emissions trading for animal products would stimulate changes in consumption behavior towards a much more climate- and biodiversity-friendly, more plant-based, and at the same time less P-intensive diet [146, 158]. Simultaneously, higher food prices also incentivize the reduction of food waste and thus P losses [82, 158]. However, the dual emissions trading system requires further regulation with regard to P. This is discussed below. Beforehand, Table 2 summarizes the effects of the cap-and-trade scheme for animal products on P management as well as the effects of the cap-and-trade scheme for fossil fuels as described in the previous section.

Discussion: phosphorus-specific need for supplementation

We proposed a primary energy emissions trading system and an emissions trading system for animal products. A combination of these instruments not only contributes to the achievement of the climate and biodiversity objectives of the PA and CBD as well as to the protection of further environmental compartments, but even positively affects a number of the P-related problems. In particular, price increases for fertilizers containing rock phosphate will stimulate efficiency efforts and an increased use of organic and recycled fertilizers. P imports through feed imports will become less attractive as transport costs rise, especially since declining animal numbers will reduce feed demand and thus the amount of P required for feed cultivation. However, the problem of regional nutrient hotspots due to high livestock densities remains unsolved. This can be addressed relatively easily by a livestock-to-land ratio (see the next subsection). Furthermore, the proposed combination of instruments neither addresses the criticality of rock phosphate or rock phosphate-containing fertilizers nor their contamination with Cd and U. And while emissions trading for fossil fuels raises the price of P fertilizers containing rock phosphate and thus reduces their competitiveness compared to organic fertilizers, emissions trading for animal products lowers the amount of organic fertilizers available. This increases the pressure on P recyclates. They would then have to cover most of the P demand. At the same time, P recyclates would have to be produced using renewable energy. However, several questions arise, which, as mentioned above, are partly dependent on missing empirical findings and the normative P target, which has not been fully clarified. These questions can thus only be answered for certain scenarios or under the assumption of certain prerequisites (see the subsection after next).

Avoiding regional phosphorus surpluses by a livestock-to-land ratio

As explained above, land-related livestock production is so far only legally binding for organic farming Art. 5 lit. g) of Regulation (EC) No. 834/2007 in conjunction with Art. 14 (1) lit. d) No. i) of Regulation (EC) No. 834/2007 stipulates that feed for livestock has to be obtained primarily from the holding where the animals are kept or from other organic farms in the same region.[4] In turn, the manure produced by livestock can then be spread on the farm's own land or in the region. The maximum application limit for N from farm manure, i.e., 170 kg/ha (hectare) according to Annex III No. 2 Nitrates Directive, is equivalent to about two livestock units (LSU) per hectare of agricultural land. These values may vary by region and methodology and depend on how much N a LSU excretes [160, 161]. This application limit applies for conventional farms, too. However, legislation does not exclude the sale of excess manure and the purchase or leasing of land with

[3] This is also true for synthetic N fertilizers. On nutrient deficits due to reduced animal farming, see [153].

[4] By taking the feed requirement into account, the livestock-to-land ratio achieves a stronger effect than, for instance, phosphate trading, as introduced in the Netherlands in 2017. The Dutch trading system for phosphate rights for dairy cattle limits the amount of manure and thus encourages land-based farming in the dairy cattle sector [159].

no manure actually applied. As such, these evasive measures impede a limitation of livestock density or herd size [162] and need to be legally restricted. To this end, it may be helpful to record the exact amount of fertilizers actually applied per unit area using a material flow balance. Likewise, other loopholes would have to be closed, for example by introducing a legal definition of the 'region' in which feedstuffs have to be cultivated and manure applied, i.e., the distance between livestock facility and cultivated/fertilized land.

In addition, both the N ceiling of 170 kg/ha and the maximum livestock density of two LSU/ha do not take into account site-specific characteristics such as soil type and regional climate. For example, a lower livestock density could be recommended for sandy, permeable sites, while sites with clay-rich soils might allow more animals (see on different (fertilization) requirements of different sites [163, 164]). Thus, a site-adapted maximum stocking rate for livestock is useful, even though this requires additional administrative efforts. Furthermore, any resulting differences in the level playing field, even within a single country, would have to be mitigated by adjusting agricultural subsidies accordingly.

Agricultural subsidies could incentivize a livestock-to-land ratio by excluding livestock farming that produces independently of the area from support under the CAP. Yet, it would be even more effective to anchor the livestock-to-land ratio in law, for which not only agricultural law but also planning and building law are suitable. The latter could enable municipalities to limit the growth of intensive animal husbandry facilities to, e.g., two LSU/ha or less. Animal husbandry not tied to land area would then no longer be permissible.

A livestock-to-land ratio for all farms in a country or in the EU not only reduces livestock density per hectare, but ultimately implies an absolute limitation of animal husbandry. The permitted number of animals would depend on the agricultural land available. As described above, a further reduction in total livestock numbers in line with the Paris climate target is achievable by emissions trading for livestock products. In turn, a livestock-to-land ratio for all farms would furthermore reduce regional P surpluses as a result of high livestock densities and thus reduce the risk of water eutrophication. Moreover, it would lower the use of purchased feed and thus the import of P. At the same time, limited feed import would minimize threats to soils, waters and biodiversity that are shifted abroad.

Instead, (catch crop) cultivation of native fodder including legume cultivation would be strengthened. In order to integrate fodder cultivation into diversified crop rotations, accompanying support measures and regulatory restrictions may be necessary, for example to avoid grassland conversion as a result of increased land use for fodder production. Diversified crop rotations and increased fertilization with organic fertilizers would stimulate P mobilization and lower the risk of erosion, which would positively affect P use efficiency. Moreover, linking livestock farming and arable farming more closely is in line with the principles of circular economy, since the supply of nutrients to the plants is largely covered by the organic material from livestock farming.

Organic livestock farms and further farms already practicing land-related livestock farming would generally benefit from such a regulation. They would not be subjects to a conversion obligation. Farms that produce fodder without keeping own livestock could be included in the circular economy. How far away these farms may be from the livestock farms, depends on the design of the livestock-to-land ratio. In contrast, pure arable farms would not be affected by the regulation. They would probably continue to use fertilizers containing rock phosphate unless P recyclates are promoted. Hence, a need for further regulation remains, especially with regard to the use of fertilizers containing rock phosphate and their contamination with pollutants.

Regulating contamination of fertilizers containing rock phosphate and/or phasing them out

In principle, contamination of fertilizers containing rock phosphate with heavy metals, in particular Cd and U, could be addressed relatively easy by threshold values under regulatory law. However, it was not possible to implement an ambitious threshold value for Cd in the EU's new fertilizing product regulation [165] from 2019 (for the draft regulation with stricter limit threshold values see [166]). As a result, an opportunity to improve the competitive position of P recyclates, which are usually less contaminated, was wasted. For U, the limit setting was entirely omitted.

An alternative to threshold values are taxes on contaminant levels in fertilizers (see for the Swedish Cd tax [44, 104, 167, 168]). However, the command-and-control approach is more suitable to avoid short-term health hazards and to offer an easily enforceable regulation. Ultimately, both instruments would create market advantages for low-pollution fertilizers, including recycled and organic fertilizers, and would stimulate decadmization processes and uranium separation. Besides, regardless of the choice of instrument, it is important that P recyclates and organic fertilizers are subject to strict quality and hygiene requirements, too.

One question that remains open is whether the use of fertilizers containing rock phosphate, which are not contaminated or only slightly contaminated with heavy metals, is desired at all. This is, as mentioned at the beginning, a normative question on how to deal with a scarce resource. Current estimates suggest that there are 69 million tons of P reserves with a static lifetime of more than 300 years [9, 169, 170]. Moreover, phosphate rock deposits are distributed unevenly around the world, which raises questions of distributive justice. P is a vital element that needs to be available to all people—globally and permanently—in sufficient quantities. This is the only way to guarantee the right to food. While Art. 11 International Covenant on Economic, Social and Cultural Rights (ICESCR) [171] explicitly enshrines the right to food, Art. 2, 3 and 6 Charter of Fundamental Rights of the European Union (CFR) [172] and Art. 2 and 5 European Convention on Human Rights (ECHR) [173] imply sustainability-related rights such as access to food, water, clean air, a stable climate and intact ecosystems (on fundamental rights and the discussion on a right to a minimum subsistence level see [27]).

In principle, however, P can be provided from organic fertilizers and recycled fertilizers as well, implying that the right to food can theoretically be fulfilled without access to fertilizers containing rock phosphate. Consequently, the foremost question is whether sufficient and safe food can be produced even if P fertilizers derived from mining are completely taken from the market.

This raises a number of questions. Firstly, we need to know the P demand of the (global, European or national) agricultural sector and whether this P demand can be fully met by recycled fertilizers and by limited amounts of organic fertilizers. Assumptions about the necessity of rock phosphate-containing fertilizers in the future and the potential for their complete substitution may vary, as P demand in agriculture depends on various factors: to begin with, the P need of areas is determined by existing soil P contents and the ability to mobilize these contents in the soil. Both depend on soil characteristics, which differ by region and its natural conditions, as well as by historical and current management practices. For example, soils rich in iron and aluminum (hydr)oxide strongly absorb P and make P mobilization more difficult [23, 174–176], whereas soils with a large pool of organic matter benefit the dissolution and mineralization of P. Catch crops and diversified crop rotations, as explained in the first section, promote P mobilization and can lower the P demand of subsequent crops. In addition, P demand is crop-dependent. Besides, there are further ways to increase P fertilization efficiency and P uptake efficiency, including precision fertilization and the use of P activators [31, 33–35, 97, 140, 177].

In contrast, climate change-induced extreme weather events such as droughts can increase P demand. Likewise, heavy precipitation after long periods of drought may trigger erosion and thus higher P losses into waterbodies. As a result, the P demand of concerned areas rises in the following period [1, 3, 30, 178]. In addition, P from different fertilizers is available to plants within different time periods. For instance, unlike P from mineral fertilizers, P from organic fertilizers is only available in the long term. Hence, short-term P availability to plants is not necessarily assured. P availability of recycled fertilizers, in turn, varies and therefore represents a further uncertainty factor for future forecasts [21, 179]. In sum, these examples demonstrate that it is almost impossible to accurately quantify P demand for the future, especially on a global scale with diverse soils, crops, cultivation methods, etc.

Still, some studies estimate the amount of organic fertilizers and P recyclates to cover the current P demand of agriculture at European and national level. The outcomes of the studies vary, especially since all calculations are based on a number of partly diverging basic assumptions about the required amount of plant and animal food, feed or crops for energetic and material utilization and about possible saving potentials.

Jedelhauser/Binder assume the dispensability of the import of P into the European Member States as a result of a more sustainable P management including the use of recovered P [16]. In line with this, Schoumans et al. state that the European P cycle can be closed completely and that water quality in Europe can be improved if imported mineral P fertilizers are replaced by organic fertilizers and P recyclates [1]. Taking Germany as an example, a 2016 study of the Federal Ministry of Agriculture indicates that a large part of the nutrient requirements of German agriculture is currently already covered by organic fertilizers and organic residues, in particular by manure and digestates [180]. However, the availability of manure and residues differs regionally. This complicates a complete coverage of German agriculture's nutrient demand by these substances [180, 181] (with regard to Europe see [40]). Kratz et al., in turn, calculate the potential of organic and organic-mineral P fertilization in Germany (2014). According to their estimates, the P potential of various secondary raw materials, in particular manure, sewage sludge, meat bone meal or its ashes, and compost, is around 431,000–667,000 tons of P. Thus, the demand of 326,000–458,000 tons of P could be completely covered by consistent nutrient recycling [179].

In principle, the studies indicate a great potential for substituting fertilizers containing rock phosphate. Likewise, there are a number of technical possibilities for P recycling, especially from sewage sludge. However, some of the processes are not yet ready for the market or have not yet become established on the market [21, 133]. This increases the importance of organic fertilization.

With regard to the use of manure, such studies assume the current animal population and thus the currently available quantities of manure. Given climate and biodiversity targets require a strong reduction in animal numbers, the question arises to what extent it is possible to abandon fertilizers containing rock phosphate while less manure is available without having to expect yield losses. In addition, rising rock phosphate prices and thus rising prices for P feed additives are likely to induce efficiency measures in animal feeding. As a consequence, animals could excrete less P. In that case, even more manure would be needed to meet the nutrient requirements of plants. Concurrently, as described above, the P demand for the cultivation of feed and for P additives is expected to decrease due to reduced animal numbers, which should at least partially compensate for this. Furthermore, as prices for rock phosphate rise due to emissions trading for fossil fuels, P recyclates are placed in a better competitive position, which cushions the declining supply of manure. Moreover, an additional instrument to promote the use of recycled fertilizers (e.g., subsidies) would be conceivable to make these recyclates available on the market more quickly and at lower costs.

The question whether to use fertilizers containing rock phosphate may have to be answered differently depending on the region. Taking the EU's target of becoming (more) independent of imports of rock phosphate as a guideline [13], both a timeframe and appropriate instruments for this purpose have to be defined. In principle, a phase out of rock phosphate or fertilizers containing rock phosphate can be achieved both by means of a ban under command-and-control law and by economic instruments. A certificate trading system that gradually reduces the amount of available rock phosphate to zero is particularly suitable for this purpose. Since rock phosphate deposits are almost exclusively concentrated in regions outside of Europe (except for some deposits in Finland) [9], it seems plausible that certificate trading at the EU level with corresponding border adjustments would gradually reduce not rock phosphate mining but the sales of fertilizers containing rock phosphate in the EU.

To this end, the target of the recently announced Farm-to-Fork Strategy of the EU could serve as a guideline. The target calls for a 20% reduction in fertilizer consumption by 2030 in order to reduce nutrient surpluses [96]. While it includes all fertilizers, a reduction target of 20% could be set specifically for fertilizers containing rock phosphate for each future decade. In other words, the target would be a 40% reduction by 2040, a 60% reduction by 2050, and an 80% reduction by 2060. In 50 years, in 2070, no more fertilizers containing rock phosphate would be placed on the domestic market.

(Strict) exceptions to ensure short-term P supply to plants when nutrient supply cannot be guaranteed otherwise should be granted. This might be necessary, for instance, because of difficult weather conditions in combination with long-term solubility of P in manure or some recycled products. However, in view of the great potential for substituting rock phosphate, the range of possible efficiency measures in fertilization, and the reduced demand for P for animal feed, the goal of (almost) complete recycling of P is definitely worth striving for. Key are efficiency, the extensive recovery of P from wastewater and waste streams, and the minimization of losses, among other things through farming practices that protect the soil and reduce its vulnerability to erosion (see the first section and Fig. 1). Besides, all of this complies with the water quality objectives, for example from the EU Nitrates Directive and the Water Framework Directive.

Cd and U contamination would no longer be an issue if fertilizers containing rock phosphate were completely removed from the market. In contrast, a threshold value for contaminants would be required during the transitional period and in case of exemption regulations as described above to ensure that risks to health and the environment are averted. This becomes even more important if a complete phase out of the use of rock phosphate is not envisaged. Global rock phosphate resources would then have to be depleted in a controlled manner in the long term, taking into account the most equitable global distribution. Nonetheless, even in that case, increased recycling is advisable in order to conserve limited resources and to enable their access to as many future generations as possible.

Besides European solutions, national or global approaches are conceivable. These P governance approaches will require balancing transnationality and regionality. They depend on, among others, various open questions including: what exactly is the normative target for P? What is the state of the soil and, in particular, the P supply of the soils of different regions and natural areas? How soils are cultivated? How much P for which quantity of both animal-based and vegetarian food are necessarily required? These questions demand not only subject-specific, but above all interdisciplinary research on P and fertilization as well as sustainable agriculture that is in line with climate and biodiversity goals.

Conclusions

Leaving a large part of governance to comprehensive instruments such as emissions trading for fossil fuels, emissions trading for livestock products, and a livestock-to-land ratio solves a number of—not only agriculture-related—problems for climate, biodiversity, air, soils, and water, while contributing significantly to the reduction of P-related problems. The only remaining regulation addresses the contamination of P fertilizers as well as the conservation of limited rock phosphate resources. For the former, threshold values for Cd and U levels of fertilizers containing rock phosphate and further P fertilizers are useful. The extent to which a complete abandonment of fertilizers containing rock phosphate is possible and advisable was discussed with attention being drawn to associated uncertainties and the need for further research. In principle, a further certificate trading system could gradually reduce the quantity of rock phosphate-containing fertilizers placed on the (European) market to zero. Consequently, mined P fertilizers are fully substituted by P fertilizers that are compatible with the concept of circular economy (e.g., recyclates). Exceptions are conceivable to a limited extent to ensure the (short-term) P supply of plants.

Our article has shown that, under certain conditions, a wide variety of problems could be addressed effectively by a few overarching instruments. This is true even though P-related issues themselves are very extensive and diverse, not to mention further challenges in agriculture. In all of this, comprehensive, economic instruments promise not only lower administrative and monitoring efforts and thus better enforcement, but also enhanced flexibility and cost-effectiveness for addressees. In addition, rebound and shifting effects are easier to avoid by well-designed economic instruments compared to sectoral, small-scale approaches aiming at single products or processes. Nevertheless, there is still a need for specific additions by command-and-control law, for example when not flexibility is desired but a targeted defense against hazards, e.g., in the case of heavy metal contamination of fertilizers.

Overall, it is highly useful to develop not only specific solutions for individual problems, but comprehensive governance concepts, especially in the agricultural sector. In doing so, problems are not shifted from one area to the next. This article illustrates that this even applies to very specific subjects such as P-related problems.

Abbreviations

Art.: Article; CAP: Common Agricultural Policy; CBD: Convention on Biological Diversity; Cd: Cadmium; CFR: Charter of Fundamental Rights of the European Union; CH_4: Methane; CO_2: Carbon dioxide; CO_{2e}: Carbon dioxide equivalents; ECHR: European Convention on Human Rights; H_2SO_4: Sulfuric acid; H_3PO_4: Phosphoric acid; ha: Hectare; ICESCR: International Covenant on Economic, Social and Cultural Rights; IPCC: Intergovernmental on Climate Change; kg: Kilogram; LSU: Livestock unit; N: Nitrogen; N_2O: Nitrous oxide; P: Phosphorus; PA: Paris Agreement; P_2O_5: Phosphorus pentoxide; U: Uranium.

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Authors' contributions

The text was written by B.G. and critically reviewed and supplemented by F.E. The underlying concepts on targets, strategies, methodology, motivational problems, governance problems and economic instruments were mainly developed by F.E. All authors read and approved the final manuscript.

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