Silvia Haneklaus, Judith Schick, Ewald Schnug

The Role of Organic P in the Baltic Sea Region – Lessons (to be) Learned

Die Bedeutung organischen Phosphors im Ostseeraum – Lehren, die gezogen werden müssen

Abstract

The Baltic Sea is one of the most eutrophicated marine bodies worldwide. It is essential to develop strategies to close the agricultural P-cycle because only then P fertilization will be sustainable and P losses reduced to an unavoidable minimum. On intact soils that are sufficiently supplied with P in order to achieve the site-specific maximum yield a balanced use of mineral and organic P sources complies with actual plant needs and exclusively replaces P that is removed by harvest products. This is on an average 22 kg/ha* yr P. Algorithms for the variable rate application of mineral and organic fertilizers have been developed and are a suitable tool to match the small-scale spatial variability of plant available soil P with P rates. The milestones of a study carried out in four countries of the Baltic Sea Region are presented. These reveal that on livestock enterprises excessive P rates are applied particularly with pig and poultry manure though the upper quantity of manure equaling 170 kg/ha N is met. This caused P accumulation in soils over time and bears an enhanced risk of P losses by surface run-off and erosion. The result is eutrophication of the Baltic Sea and its water quality in terms of light transmittance has been deteriorating consistently during the past 60 years. Current fertilizer practices on livestock farms and statutory rules in the Baltic Sea Region are not convenient to reduce nutrient discharges to the Baltic Sea in a magnitude that will reduce eutrophication. Based on current data it is estimated that it will take at least 70 years to lower the soil P status from excessive to sufficient if no P is applied. Zero P application where the soil P status is excessive and variable rate application of manure in combination with a strictly demand-driven application of P on sufficiently supplied soils is imperative for a sustainable P use.

Key words: Eutrophication, manure, variable rate fertilization, soil phosphorus status

Zusammenfassung

Die Ostsee eines der am stärksten eutrophierten Meere weltweit. Die Entwicklung von Strategien, die den landwirtschaftlichen P-Kreislauf schließen, ist unverzichtbar, da die P-Düngung nur dann nachhaltig sein kann und P-Verluste auf ein unvermeidbares Minimum reduziert werden. Auf intakten Böden, die ausreichend mit P versorgt sind, um das Ertragspotential am Standort zu realisieren, ist eine P-Zufuhr über mineralische und organische Düngemittel genügend, die P, welches mit dem Erntegut entzogen wird, ersetzt. Dies sind im Mittel 22 kg/ha* a P. Algorithmen für die räumlich variable Ausbringung im Rahmen der Präzisionslandwirtschaft von mineralischen und Wirtschaftdüngern wurden entwickelt, die die optimale Ausbringungsmenge entsprechend der kleinräumigen Variabilität der P-Versorgung im Boden reguliert. Im vorliegenden Beitrag werden die wichtigsten Erkenntnisse einer internationalen Studie in vier Ostseeanrainerstaaten vorgestellt. Diese zeigte, dass insbesondere mit Schweine- und Hühnergülle überproportional viel P ausgebracht wird, auch wenn das obere Limit von 170 kg/ha N eingehalten wird. Hierdurch kam es auf den Böden über die Jahre zur Anreicherung von P,

Affiliation
Julius Kühn-Institut (JKI) – Federal Research Centre for Cultivated Plants, Institute for Crop and Soil Science, Braunschweig, Germany

Correspondence
Dr. Silvia Haneklaus, Julius Kühn-Institut (JKI) – Federal Research Centre for Cultivated Plants, Institute for Crop and Soil Science, Bundesallee 69, 38116 Braunschweig, Germany, phone: +49 531 596 2121, e-mail: silvia.haneklaus@julius-kuehn.de

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was wiederum das Risiko von P-Verlusten über Oberflächenabfluss und Erosion stark erhöht und in direktem Zusammenhang mit dem Problem der Eutrophierung der Ostsee steht. So nahm die Wasserqualität, welche zum Beispiel mittels der Lichtdurchlässigkeit bestimmt wird, in den letzen 60 Jahren kontinuierlich ab. Die derzeitigen gesetzlichen Vorgaben und Praktiken bei der Ausbringung von Wirtschaftsdüngemitteln sind nicht ausreichend, um die Eutrophierung sichtbar zu reduzieren. Neue Studien deuten vielmehr darauf hin, dass es mindestens 70 Jahre dauert bis die P-Versorgung von exzessiv auf ausreichend sinkt sofern kein P ausgebracht wird. Deshalb ist der Verzicht auf die Ausbringung von P auf Böden oder Teilflächen, die exzessiv hohe Gehalte aufweisen zusammen mit einer variablen Düngung, die strikt dem Bedarf folgt, notwendig, um die P-Düngung langfristig nachhaltig zu gestalten.

Stichwörter: Eutrophierung, Gülle, variable Düngung, Phosphorstatus des Bodens

Introduction

A sufficient phosphorus (P) supply of agricultural crops is essential to maintain crop yields. P that has been removed by agricultural crops with harvest products can be replenished by mineral or organic P-sources. Important is that P is 100% plant available (Schnug and De Kok, 2016). In comparison, where excessive P rates are applied, P accumulates in soils and is prone to be discharged into water bodies. A high livestock density, which is common in conventional agriculture, has been identified as the main originator of P surpluses in soils. The reason behind is that upper manure rates are based on a maximum nitrogen (N) limit of 170 kg/ha N in form of farmyard manure (Nitrate Directive) so that P rates exceed regularly the nutrient demand of an average of 22 kg/ha P (Anonymous, 2004). Extensive data about the elemental composition of different types of farmyard manures and slurries in the Baltic Sea Region are provided by Rückamp et al. (2013) and Haneklaus et al. (2016). It is a well-known fact that a direct link exists between high stocking densities and nutrient losses to aquatic ecosystems (Carpenter et al., 1998; Granstedt et al., 2008; McCrackin et al., 2018; Schnug et al., 2001; Svanbäck et al., 2019). It has been the aim of this analytical report to recapitulate the contribution of agricultural production to eutrophication, particularly of the Baltic Sea, to evaluate the success of previous and current recommendations to tackle the problem, and last but not least to outline a roadmap for truly sustainable fertilizer management.

P-loads Into the Baltic Sea and eutrophication

With view to the Baltic Sea, a semi-enclosed, brackish sea, the sector agriculture is said to be responsible for about 50% of the total diffuse nutrient loads (Kauranne and Kemppainen, 2016). Due to its geological and geographical distinctiveness, the Baltic Sea is extremely sensitive to eutrophication (Larsson et al., 1985). Eutrophication results in algal blooms and murky water, oxygen depletion and a lifeless sea floor (Kauranne and Kemppainen, 2016). Oxygen deficiency in the deep-water was first realized in the 1960's. At that time a link between riverine nutrient loads and increase of anoxic areas in the deep basins of the central Baltic Sea was established (Elmgren, 2001; Voss et al., 2011). The transparency of water, which has been monitored for the Baltic Sea since 1903, is expressed as the Secchi-depth (Aarup, 2002). For the Baltic Proper, a decrease of the Secchi-depth by −0.05 m/yr has been determined from the Second World War until the late 1990's (Sandén and Håkansson, 1996).

The monitoring of P concentrations in the Baltic Sea over a longer time-period showed for the winter season a positive trend for the concentrations in the surface waters of all sub-regions of the Baltic Proper from the late 1950's to the early 1990's. A considerable increase was especially observed between 1969 and 1978; afterwards the concentration strongly fluctuated on a high level but no significant trends were analyzed (HELCOM, 1996). The restoration will presumably take decades (Schindler, 2012). It is important to note that a shift from turbidity to a clear state of water bodies occurs at lower P-concentrations than from clear state to turbidity (Jeppesen et al., 2007).

Table 1 shows the development of P and N inputs into the Baltic Sea before the 20th century when the anthropogenic influence (in form of point nutrient losses) was relatively small in the mid 1980's and in the time period 2010–2012. Larsson et al. (1985) estimated that before the 20th century there were no domestic and industrial P inputs and the river-borne P inputs were approximately 10% of those in 1985. At that time municipal and industrial P point losses peaked. Nowadays, the coastal point sources for P have been successfully reduced by more than 50% compared to the mid 1980's. However, the non-point sources, including the massive nutrient inputs resulting from agricultural actions, are still a major con-

Table 1. Estimated total P inputs (t/yr) into the Baltic Sea before the 20th century, in the 1980 s and in 2010–2012. Sources: before 20th century and 1980s: Larsson et al. (1985); 2010–2012: Svendsen et al. (2015).
Geschätzter P-Eintrag (t/a) in die Ostsee vor Ende des 20ten Jahrhunderts, Ende der 1980er und zwischen 2010–2012. Quellen: vor Ende des 20ten Jahrhunderts und Ende der 1980er: Larsson et al. (1985); 2010–2012: Svendsen et al. (2015).

	Total P input (t/yr)
Before 20th century	9,600
1980s	77,700†
2010–2012	31,883

†Municipal and industrial discharges included

cern as the data for the time period between 2010 and 2012 show (Voss et al., 2011).

P speciation in agricultural soils

The plant availability of a nutrient does not only depend on its soil concentration but also on its chemical speciation (Ure and Davidson, 1995). The determination of the speciation of fertilizer P provides an important insight into the interaction of plant nutrients with other soil factors and consequent management practices in contrast to the application of common standard P tests (Gassner et al., 2003). For a balanced nutrient application it is important not only to assess the instantly-plant available P forms in the soil, but also all forms which may potentially become available during the growth period (van Noordwijk et al., 1990). Gassner et al. (2003) investigated environmental factors that may influence the spatial speciation of P in the soil. Ca-phosphates represented the sparingly available P pool (P extracted by *aqua regia* digestion), the absorption capacity of the soil was tightly linked to the reversibly available P pool (P extracted by ammonium acetate + 0.02 m Na_2-EDTA) and the distribution of manure closely related to the organic P pool (calculated as the difference between total and inorganic P). The readily available P pool, however, could not be modeled sufficiently due to its high variance and random distribution. The authors attributed the strong influence of parameters such as mineralization, manure amendment and plant uptake as the causal reason for variation within these P-fractions. The dominating small-scale variability of plant available P was attributed to the high P supply of the fields investigated in their study. On fields with a consistently high P-supply over several years the small-scale variability of plant available P was most pronounced.

P accumulation in agricultural soils

Regularly manure applications, e.g. in the Baltic Sea Region and water catchment areas in the U.S., exceed the nutrient demand of the crops and nutrient flows to aquatic ecosystems are directly linked to stocking densities (Carpenter et al., 1998; Svanbäck et al., 2019). Soils of conventional livestock farms typically exhibit an excessive soil P status. A sampling campaign in 2011 covering 86 agricultural fields in the 4 HELCOM-countries Estonia, Finland, Germany and Poland which followed different production systems (organic vs. conventional) and fertilization practices (mineral vs. organic) underlined the problem of a consistently higher P concentration on soils which received manure for many years (see Fig. 1) (Haneklaus et al., 2016). Where pig slurry and chicken manure had been applied soils showed the highest P content. In comparison the use of solid cattle manure and slurry did not result in P accumulation in soils (Rückamp et al., 2013).

Legal and Intergovernmental Measures to reduce nutrient inputs into the Baltic Sea

Within the Baltic Sea Region, manure application is regulated by one of the oldest EU-environmental programs, the Nitrates Directive (*Council Directive 91/676/EEC of 12 December 1991 concerning the protection of waters against pollution caused by nitrates from agricultural sources*), which „*aims to protect water quality across Europe by preventing nitrates from agricultural sources polluting ground and surface waters and by promoting the use of good farming practices*“ (EC, 1991). In addition, the Directive 2008/1/EC of the European Parliament and of the Council of 15 January 2008 concerning integrated pollution prevention and control (IPPC Directive) as well as the Directive 2000/60/EC of the European Parliament and of the Council establishing a framework for the Community action in the field of water policy (Water Framework Directive) were the basis for the formulation of guidelines for manure application rules with respect to P losses. Based on the regulations and prohibitions of the Nitrate Directive, codes of good agricultural practice (GAP) have been developed and implemented in national guidelines and regulations (Haneklaus et al., 2017). The Marine Strategy Framework Directive (MSFD) comprises a framework for the development of marine strategies designed to achieve a good environmental status in the marine environment (Borja et al., 2010).

P from agricultural sources is (in contrast to N) not regulated by European legislation (Ekardt et al., 2016). The current European as well as the German fertilizer and soil regulations are estimated to be too weak to counteract nutrient pollution resulting from agricultural actions (Ekardt et al., 2016). On the European level, a precautionary concept for environmental issues is largely inexistent and within the field of soil protection, water quality, fertilizers and wastes legislation usually based on orders and prohibitions, a command and control strategy (Haneklaus et al., 2017; Svanbäck et al., 2019). Ekardt et al. (2016) evaluated the chance of a success of such administrative legal system as being only minor since the implementation of an area-wide control system is not feasible. Another risk would be the simple relocation of the problems caused by nutrient surpluses by exporting excess manure to other countries. In fact, it is important to ensure the reduction of P application on a global scale (Ekardt et al., 2016). Since current regulations are lacking concreteness and real enforcement, a global approach for closed agricultural P cycles is seen as the only way to maintain food security, preserve geological P reserves and to reduce losses to water bodies. This can be achieved by implementing GAP codes and enforcement of legal regulations (Ekardt et al., 2016).

The oldest framework for a targeted protection of the Baltic Sea is the Convention on the Protection of the Marine Environment of the Baltic Sea Area (Helsinki Convention). After acknowledging that the eutrophication of the Baltic Sea has been accelerating and being a man-made problem, Denmark, Sweden, Finland, the

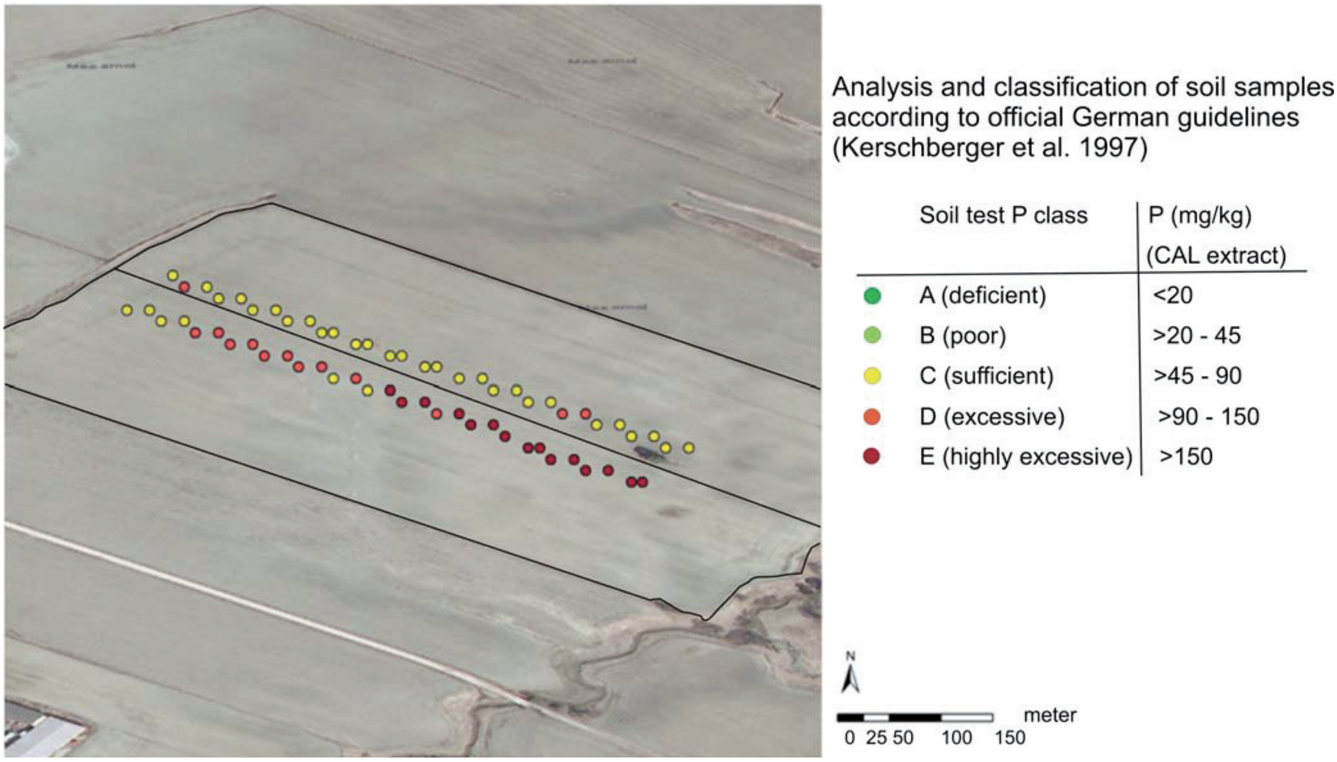

Fig. 1. Classification of P_{CAL} content along transects of neighboring fields. The northerly field received exclusively mineral fertilizers and the southerly field exclusively chicken manure as P supply in the past; extracted from Haneklaus et al., 2016.
Klassifizierung der P_{CAL} Gehalte entlang zweier Transekte in benachbarten Feldern. Das nördliche Feld erhielt ausschließlich Mineraldünger und das südliche Feld ausschließlich Hühnergülle als P-Quelle in der Vergangenheit; Daten extrahiert aus Haneklaus et al. 2016.

Soviet Union, Poland and West and East Germany formed the Helsinki Convention in 1974 with the aim to solve the ecological problems of the Baltic Sea. After the breakdown of the Eastern Bloc, nine riparian states (Denmark, Estonia, Finland, Germany, Latvia, Lithuania, Poland, Russia and Sweden) agreed on an updated convention in 1992, which was called into life in 2000. Based on this convention, the Helsinki Commission „*the governing body of the Convention on the Protection of the Marine Environment of the Baltic Sea Area which comprises the water-body and the seabed including their living resources and other forms of marine life*“ was formed (Voss et al., 2011; HELCOM, 2008). Referring to the HELCOM Recommendation 28 E/4 of the amended Annex III of the Helsinki Convention it is advised to apply measures with view to Best Environmental Practice (BEP) and Best Available Technology (BAT) to reduce the pollution from agricultural activities (HELCOM, 2008).

One major program established by HELCOM is the *Baltic Sea Action Plan* (BSAP), which aims to restore the good ecological status of the Baltic Sea by 2021. To achieve this status, maximum allowable inputs (MAI) for water- and airborne P have been determined and ratified during the HELCOM Ministerial Meeting in Copenhagen in 2007 (Table 2 and HELCOM, 2007). The BSAP will be updated and reconducted in 2021 (Anonymous, 2020).

The data for the average annual P inputs between 2010 and 2012 indicate that currently > 30% more P enters the Baltic Sea than permitted according to the MAI. This strongly underlines the urgent need to implement efficient methods to reduce the discharge of P into the Baltic Sea. One promising technology could be variable rate application (VRA) of manure operating in a continuous mode which matches the small-scale variation of the nutrient demand of crops in the field with fertilizer rates (Haneklaus and Schnug, 2006). It is intrinsic that the implementation of such a site-specific nutrient management will result in a sustainable use of resources that ensures optimum crop growth and reduces the negative impacts on the environment in form of excessive nutrient inputs (Haneklaus et al., 2016). In contrast, uniform application rates of manure are not based on the real nutrient demand, but are rather oriented on the maximum legal input. It can be assumed, that VRA of manure will be objected by farmers since it requires changes in the production and recycling chain of manure (Haneklaus et al., 2016).

Next a strategic concept will be delivered which contributes to the sustainable use of manure with special attention to a closed agricultural P cycle. Prerequisites and limitations for a site-specific nutrient management using manure will be outlined and algorithms for their VR application presented.

Table 2. Maximum allowable annual inputs (MAI) and actual inputs (annual average of 2010–2012) of P into to Baltic Sea sub-basins (Svendsen et al., 2015).
Maximale jährliche P-Frachten und aktuelle P-Frachten in die Unterbecken der Ostsee (Svendsen et al., 2015).

	MAI	Actual inputs
	P (t/yr)	
Bothnian Bay	2 675	2 824
Bothnian Sea	**2 773**	**2 527**
Baltic Proper	7 360	14 651
Gulf of Finland	3 600	6 478
Gulf of Riga	2 020	2 341
Danish Straits	**1 601**	**1 514**
Kattegat	**1 687**	**1 546**
∑ Baltic Sea	21 716	31 883

Bold letters=MAI met; regular letters = MAI not met with inputs increasing

Variable rate application of manure

Factors influencing the variability of the nutrient content in manure

The nutrient composition of manure is heterogeneous and depends on several parameters such as animal species, feedstuff quality and quantity, housing regime, time and condition of storing and water content (Cordovil et al., 2012). Haneklaus et al. (2016) reported of an interfarm coefficient of variation for plant available P concentrations (P_{CAL}) in manures of 35% and 45% with means of 0.5 kg P/t for cattle and 1.6 kg P/t for pig manure, which is in accordance with the results of Dupont et al. (1984). Sedimentation in the storage facility has the strongest influence on the P content followed by the factors animal age and feeding regime. In contrast, parameters such as breed, housing system and season seem to have only a minor influence (Haneklaus et al., 2016). Consequently, not only constant production factors on a farm (e.g. animal species, feeding regime, etc.) but also an efficient homogenization of manure is important to assess reliable nutrient input data for the realization of an accurate VRA of manure (Derikx et al., 1997). This is underlined by Conn et al. (2007), who reported a consistent mineral composition of manure over time on individual farms, while the variation between farms was high. Yet another approved option in the federal state of North Rhine-Westfalia is the use of certified NIRS sensors in order to assess the P content of slurry in real time (Ehnts, 2019). The farmers are obliged to file the nutrient and dry matter content of slurry, the type of slurry, sensor type and calibration model as well as application rates (Ehnts, 2019).

It is estimated that about 35–40% of the total P in manure is plant available (European Commission – Directorate General Environment, 2010). However, investigations of Eghball et al. (2005) indicate that even up to 100% may be plant available within the first year of the application. Consequently, it can be assumed that the entire manure P is plant-available on a long-term basis (Haneklaus et al., 2016; Hansen, 2006).

Algorithms for a balanced VRA of manure

The load of manure for fertilizer purposes is regulated by the EU Nitrate Directive and restricted to 170 kg/ha N. In nitrate vulnerable zones in Denmark and Estonia the corresponding value is 140 kg/ha N for pig manure. In Sweden, the legal application of manure takes the P load into account which may not exceed of 22 kg/ha P (Anonymous, 2004); this value corresponds with the average removal of P by crops (Haneklaus et al., 2016). A deficit of all regulations is that an additional P-supply with mineral fertilizers is not regulated.

An adjustment of upper manure rates to the actual P off-take by crops on soils, which are sufficiently supplied with P can significantly contribute to a decrease of diffuse P-losses to water bodies and is mandatory for a sustainable use of P in manure (Haneklaus et al., 2016). To ensure such a balanced fertilization, the nutrient input has to match the actual crop demand in order to avoid both, nutrient surpluses or an undersupply. Thus, the first step to reduce P losses will be to set P rates to zero where the soil P status is higher than in the sufficiency range. A mandatory restriction of the P input to 22 kg/ha P following the example set by Sweden is appropriate on soils that are sufficiently supplied with P. Such approach requires the alternative utilization of excess manure, the reduction of the livestock density or an extended area where manure is applied (Powers and van Horn, 2001). Innovative, environmentally friendly ways of the use and processing of animal manures are summarized by Malomo et al. (2018).

A manure application restricted to 22 kg/ha P would lead to the average N addition of 141 (cattle), 88 (pig) or 77 (poultry) kg N/ha (Haneklaus et al., 2016). In comparison, maximum application rates adjusted to a maximum of 170 kg N/ha (as commonly practiced) would exceed the average P-off-take by the crop by 95% to > 120% (corresponding to 21 – > 26 kg/ha P) if pig and poultry manure are applied. In case of cattle manure the surplus is significantly lower with approximately 2% (corresponding with 0.4 kg/ha P) (Haneklaus et al., 2016).

To ensure an optimum utilization of manure, variable rates must consider the spatial variability of plant available P in the soils, which is an indicator for the P supply of the crops (Haneklaus et al., 2016). Interesting in this context is a study on the comparison and inter-calibration of soil P tests (STP) applied in different Baltic Sea countries, which revealed that the standard procedures that are used to determine and to interpret the available P content in agricultural soils differ widely and as a result, the assessment of the P supply of agricultural soils may yield strongly deviating results (Shwiekh al., 2015). Thus, recommended fertilizer rates may deviate highly among the different countries (Haneklaus et al., 2016). Similar findings were made by Tóth et al. (2014), who compared the P fertilizer recommendation systems in the UK and Hungary with distinct disparities in the advised fertilizer doses. These findings underline the urgent need to define standard analytical methods and harmonize the interpretation of the results and recommendations among the EU-countries. As an alternative, the collection of on-farm data by applying precision agriculture technologies will deliver actual site-specific threshold values and response curves to the nutrient input. These data can be translated into maps for the VRA of manure which is of key relevance on livestock farms to reach a balanced soil P-level (Haneklaus and Schnug, 2006; Haneklaus et al., 2016).

Cu and Zn are usually used as feed supplements on livestock farms. Accordingly, these elements enter the soil via manure fertilization. Therefore, the soil concentration of these metals should be monitored together with yield data to avoid yield losses (Haneklaus et al., 2016). To ensure a balanced input of N, P, K, Cu and Zn by pig manure, the application rates must not exceed the Cu off-take by the crop since Cu is the nutrient that is enriched strongest (Kratz and Schnug, 2006; Schnug et al., 2006). Cu and Zn rates that are adjusted to the off-take by the crop would lead to only 8% and 24% of the maximum permitted manure rates (corresponding to 170 kg N/ha) (Haneklaus et al., 2016). A solution to the problem could be the extraction of both elements from manure (Popovic, 2012).

An ideal P supply of the soil is obtained when the P-rate equals the off-take by the crop and the P source is fully plant available (Haneklaus et al., 2016). This statement is confirmed by the results of a long-term field experiment conducted in Sweden (Djodjic et al., 2005). For P in manure it can be assumed that it is fully plant available (Hansen, 2006), while P sources such as rock phosphates or recycling fertilizers have to be critically evaluated since P is only partially plant-available irrespective of the time scale. These non-available P species rather accumulate in the soil and are prone to leaching or erosion into water bodies (Schick, 2010). The fate of different P forms discharged to water bodies and their contribution to eutrophication is summarized by Reynolds and Davies (2001) with special view to point and non-point P losses.

For the development of general algorithms for VRA of manure, Haneklaus et al. (2016) defined the following conditions (Table 3):

- no manure is applied if the soil P status exceeds the sufficiency range
- the N:P:K ratio in manure is constant
- the N, P, and K content in manure is analyzed before the application to follow up changes in the livestock management
- the minimum N demand of the crop is 170 kg/ha

Ideally, the application rates for manure match the lowest N, P or K demand and the emerging deficits of N, P and or K are either balanced by mineral fertilizers within one year (Table 3) or by manure in combination with mineral fertilizers in subsequent years on a crop rotation basis (Haneklaus et al., 2016). The spatial variation of the P and K off-take can be determined easily by using yield maps if the technology is available (Haneklaus and Schnug, 2006). The annual N rates, however, must match the spatial variation of the crop demand. One suitable approach to determine the site-specific demand for N can be the adjustment of the rate to the spatial variation of clay and organic matter content (Haneklaus and Schnug, 2006).

As mentioned earlier, a P-based manure application will limit its utilization on livestock farms and a balanced addition of K may further reduce the amount of manure applied, in particular with view to cattle and pig manure. Oilseed rape removes about 40, sugar beets 100 and intensive grassland 120 kg K/ha* yr (Anonymous, 1993). Thus, a balanced K fertilization regime is only feasible in a sugar beet/cereal crop rotation where straw is harvested and constricted on intensive grassland (Table 2). When these basic rules are implemented, a balanced input of N, P and K is ensured but it is also evident that the further processing or recycling of excess manure is obligatory to cope with the accumulating quantities of manure which cannot be applied to agricultural land (Haneklaus et al., 2016). One solution is the mechanical separation of excess slurry into a P-rich solid and an N-rich liquid phase. That way, the liquid phase can be used nearby (on-farm) and the solid P phase can be transported those to areas with dominating crop production and a high P-demand. In addition, the solid fraction may be incinerated or used for biogas production for the generation of energy (Cocolo et al., 2012; Hjorth et al., 2010).

An operative plan to tackle with P surpluses in the BSR

To successfully implement VRA of manure and to reduce nutrient losses to water bodies, a 5-point plan has been suggested by Haneklaus et al. (2017):

Table 3. Algorithms for variable rate (VR) application of manure targeting a balanced input of N, P and K (extracted from Haneklaus et al., 2017).
Algorithmen zur räumlich variable Ausbringung von Wirtschaftsdüngern mit dem Ziel einer bilanzierten Zufuhr an N, P und K (extrahiert aus Haneklaus et al., 2017).

Cattle manure (N:P = 6.4:1 and P:K = 1:6.4)				
	Variable P rate as manure (kg/ha)			
Soil test P class[1]	P rate (kg/ha)	If soil test P (mg/kg)	then N rate (kg/ha)	then K rate (kg/ha)
A, B[2]	Y = −0.880X + 61.4	X > 41	≤ 170	≤ 177[3]
C	22 or [3]$VR_{off\text{-}take}$		141	147[3]
	Variable, mineral P fertilizer rate (kg/ha)		*N rate*	*K rate*
	$P_{VR} = P_{demand} - P_{manure}$, if X ≤ 41		$N_{VR} = N_{demand} - N_{manure}$	–
Pig manure (N:P = 4:1 and P:K = 1:3.9)				
	Variable P rate as manure (kg/ha)			
	P rate (kg/ha)	If soil test P (mg/kg)	then N rate (kg/ha)	then K rate (kg/ha)
A, B[2]	Y = −0.880X + 61.4	X > 21.5	≤ 170	≤ 142[4]
C	22 or [3]$VR_{off\text{-}take}$		88	73
	Variable, mineral P fertilizer rate (kg/ha) N rate			*K rate*
	$P_{VR} = P_{demand} - P_{manure}$, if X ≤ 21.5		$N_{VR} = N_{demand} - N_{manure}$	$K_{VR} = K_{demand} - K_{manure}$ or [5]$VR_{off\text{-}take}$ if ≤ K_{VR}
Poultry manure (N:P = 3.5:1 and P:K = 1:1.5)				
	Variable P rate as manure (kg/ha)			
	P rate (kg/ha)	If soil test P (mg/kg)	then N rate (kg/ha)	then K rate (kg/ha)
A, B[2]	Y = −0.880X + 61.4	X < 45	< 77	≤ 32
C	22 or [3]$VR_{off\text{-}take}$		77	32
	Variable, mineral P fertilizer rate (kg/ha)		*N rate*	*K rate*
	$P_{VR} = P_{demand} - P_{manure}$, if X ≤ 45		$N_{VR} = N_{demand} - N_{manure}$	$K_{VR} = K_{demand} - K_{manure}$ or [5]$VR_{off\text{-}take}$ if ≤ K_{VR}

notes: [1]for details see Figure 1; [2]1.5 and 2-fold P rate in soil test class A and B; [3]geo-coded nutrient off-take data from yield mapping; [4]K input needs to be balanced:

$$\sum_{i=1}^{n} K_{rates}(yr_1 + yr_2 + \ldots + yr_n) = \sum_{i=1}^{n} K_{off-take}(yr_1 + yr_2 + \ldots + yr_n)$$

with view to the N:P and P:K ratios in manure in case of cattle manure this is only possible if the K demand is accordingly high as for instance in sugar beet/cereals crop rotations if straw is removed and on high yielding intensive grassland; from case to case manure rates need to follow K supply; [5]rate equals difference of summated K off-take by crop rotation.

1) The EU is advised to adopt a law which determines limits for the use of mineral and organic P in agriculture. On those soils which are sufficiently supplied, P rates must match the mean off-take of 22 kg/ha P by crops. On those soils, which display excessively high P contents, no P is applied until the P status is in the sufficiency range.
2) It has to be obligatory for livestock farmers to prove the whereabouts of the accumulated manure.
3) The implementation of Precision Agriculture technologies for on-farm experimentation (e.g. geo-coded sampling, deduction of critical nutrient values in soils and plants, creation of response curves, monitoring of crop productivity) as well as the adjustment of algorithms for the VRA of mineral and organic fertilizers must become mandatory and will be, in return, acknowledged as a greening component according to EU-policy (Anonymous, 2017) in order to compensate

investments and ongoing expenses. The socio-economic benefit for the implementation of a truly site-specific VR-fertilization is an improved water quality on the long run.

4) Farm-gate balances must be established by using agricultural GIS-systems on the pedon-scale representing the smallest operational unit, which is homogenous with view to those soil factors influencing the nutrient balance (Schumann et al., 1997, Haneklaus and Schnug, 2006).
5) Official advisory services for farmers with view to fertilizer planning and data management, including the preparation of farm-gate balance statements must be extended.

Impact of VRA of manure on the P-status in agricultural soils of the Baltic Sea Region

There is a linear relationship between the dissolved P content in soils and the amount of P lost to surface waters; even more P is transported in particulate form (Carpenter et al., 1998; Sims et al., 2000). In a long-term field experiment with sugarcane on Mauritius Mardamootoo et al. (2013) showed that an excessive P input increased the P losses to surface waters. Though the research was carried out in a mild tropical maritime region, similar findings can be assumed in the Baltic Sea region.

A decrease of the P content on soils can be expected if organic and mineral P fertilizer rates are lower than the P off-take by harvest products. The suggested reduction of P rates based on the amount of residual P added previously by mineral and organic fertilization would, however, involve a too longsome process (Rowe et al., 2016). According to McCrackin et al. (2017) it will take years to obtain a measurable effect of reduced fertilizer input on the P status since the P stock of the complete catchment area in the BSR is estimated to be sufficient for approximately two decades of crop production. Since the maximum allowable annual P discharges into the Baltic Sea are regularly exceeded, there is an urgent need for breakthrough measures. A stringent P fertilizer regime which implies a zero P rate if the soil P status is in the excessive range is indispensible and even if implemented it will still need more than 70 years to reach the sufficiency range as a simple calculation shows. Zicker at al. (2018) conducted two long-term field experiments in northern and southern Germany. In the P control treatment without any P amendments the soil P status decreased from originally 44 to 17 mg/kg P_{CAL} and 42 to 29 mg/kg P_{DL} in 37 and 19 years, respectively (Zicker et al., 2018). Assuming a median P content of 120 mg/kg P_{CAL} in the excessive range (Kerschberger et al., 1997), this would imply a time period of 74 years with zero P application in order to lower the P level to a P content of 68 mg/kg P_{CAL}, which is the median value of the sufficiency range. In the field experiment in northern Germany the corresponding time period for critical P_{DL} values was 70 years. What do these time figures mean for the problem of eutrophication of the Baltic Sea? The reduction of P is the key for lakes and estuaries to recover from eutrophication, a process which is known to take decades (Schindler, 2012). The time span may be shorter with < 1 year, or distinctly longer than a century (McCrackin et al., 2017). At this point it seems reasonable to assume that in case of the Baltic Sea recovery completeness is achieved in a similar space of time as the reduction period for the soil P status and run-off is linked to the initial soil P status and intensity of manure application (Tomer et al., 2016; Tiemeyer et al., 2009). As a result of the meta-analysis McCrackin and co-workers (2017) proposed that a zero nutrient input will not accelerate recovery from eutrophication compared to a reduced nutrient input as the recovery completeness takes 13 years in the first case and 16 years in the latter case. Here, it is suggested that VRA of mineral and organic fertilizers will contribute not only to harmonization of the mineral nutrition of crop plants, but will also reduce nutrient losses to water bodies as algorithms have been developed which take soil, crop, topography and climatic conditions into account thus directing nutrient fluxes and controlling nutrient pools (Haneklaus and Schnug, 2006).

Conclusion

The Baltic Sea is a water body, which suffers from severe eutrophication induced by massive N and P inputs. In particular, the application of manure based on the maximum input limit of 170 kg/ha N yields P rates in case of pig and poultry manure that are manifold higher than the crop demand. The consequences are P accumulation in soils and P losses into water-bodies by surface run-off and erosion. One approach to reduce nutrient surpluses in agricultural soils and to reduce diffuse nutrient losses is the implementation of a truly balanced P application employing Precision Agriculture technologies. Then P rates are adjusted to the actual plant requirement and follow the small-scale spatial variation of plant-available P in soils. Algorithms for the VRA of mineral and organic fertilizers have been developed and can easily be implemented on farms. For livestock farms this will imply that the better part of the manure needs to be salvaged elsewhere.

Conflicts of interest

The authors declare no conflicts of interest.

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