DOI:10.3220/LBF1458735160000

Variable rate application of manure – gain or pain?

Silvia Haneklaus*, Judith Schick*, Sylvia Kratz*, Daniel Rückamp**, and Ewald Schnug*

Abstract

In intensive agricultural livestock production manure prevails regularly as a waste problem rather than an organic fertilizer and valuable source of nutrients. Even if maximum loads will not exceed the upper limit of 170 kg/ha*yr nitrogen (N), its use is not sustainable as phosphorus (P) is applied at rates that outreach crop demand by far. The revision of current practices of manure application is urgently requested in order to close the agricultural P cycle. A solution to the problem offers variable rate (VR) application of manure combined with an upper limit of 22 kg/ha*yr P on soils that are sufficiently supplied with P. Such procedure will limit the quantity of manure that can be utilized on a big livestock unit drastically which makes recycling chains for excess manure mandatory. On-farm experimentation employing precision agriculture tools enable a site-specific application of manure and a targeted P input. The presented study was carried out in different countries of the Baltic Sea Region and demonstrates the problem of P accumulation in soils of livestock farms, addresses the spatial variation of plant available P in soils, identifies applicable factors that influence the mineral composition of manure and provides algorithms for a balanced, variable rate application of manure.

Keywords: *balanced fertilization, marine protection, phosphorus, site-specific nutrient management*

Zusammenfassung

Variable Ausbringung von Gülle – Vorteil oder Strafe?

In der intensiven Landwirtschaft wird Gülle oftmals als Abfallproblem wahrgenommen, denn als organisches Düngemittel und wertvolle Nährstoffquelle erkannt. Selbst bei Einhaltung einer maximalen Obergrenze von 170 kg/ha*a Stickstoff (N) ist diese Nutzung nicht nachhaltig, da Phosphor (P) in Mengen ausgebracht wird, die den Bedarf um ein Vielfaches übersteigen. Es ist jedoch notwendig praxisübliche Verfahren der Gülleausbringung zu revidieren, um den landwirtschaftlichen Phosphatzyklus zu schließen. Die variable Ausbringung von Gülle könnte das Problem lösen, sofern sich die maximalen Ausbringungsmengen an der ausgebrachten Menge an P orientieren und 22 kg/ha*a nicht übersteigen, welche dem mittleren Entzug durch eine Ernte entspricht. Dies hätte zur Folge, dass sich die verwertbare Menge an Gülle insbesondere auf viehhaltenden Großbetrieben drastisch verringert und das Recycling von Gülle zwingend erforderlich macht. Ein betriebseigenes Versuchswesen, welches Precision Agriculture Technologien nutzt, ermöglicht die variable Ausbringung von Gülle und damit die gezielte Applikation von P. Die vorliegende Studie wurde in Anrainerstaaten der Ostsee durchgeführt und zeigt deutlich das Problem der Anreicherung von Phosphat in Böden von Betrieben mit Tierhaltung auf, ermittelt die kleinräumige Variabilität von pflanzenverfügbarem Phosphat im Boden, identifiziert Faktoren, die die mineralische Zusammensetzung von Gülle bestimmen, und stellt Algorithmen für die variable Ausbringung von Gülle mit dem Ziel einer bilanzierten Ausbringung von Nährstoffen bereit.

Schlüsselworte: bilanzierte Düngung, Meeresumweltschutz, Phosphor, variable Düngung

* Julius Kühn-Institut (JKI), Federal Research Institute for Cultivated Plants, Institute for Crop and Soil Science, Bundesallee 50, 38116 Braunschweig, Germany

** Geozentrum Hannover, Federal Institute for Geosciences and Natural Resources, Stilleweg 2, 30655 Hanover, Germany

Contact: silvia.haneklaus@julius-kuehn.de

1 Introduction

The Baltic Sea is one of the most polluted marine bodies in the world. According to the Helsinki Commission (HELCOM), "the Baltic Sea ecosystem has degraded to such an extent that its capacity to deliver goods and services to humans living in the nine coastal states has been hampered". To improve the condition of this unique ecosystem and its valuable resources, sustainability in word and deed must be obligatory for all sectors and at all scales. A transdisciplinary assessment of the significance of P management in the Baltic Sea Region outlines cornerstones for a sustainable use of the resource (Schultz-Zehden et al., 2011). In particular, N and P losses from agriculture, which result in eutrophication, have a strong impact on the highly sensitive ecosystem (Corell, 1998; Schnug et al., 2001; Granstedt et al., 2008). On November 15, 2007 the member states of the Helsinki Convention (HELCOM) for protecting the Baltic Sea decided in Krakow on a Baltic Sea Action Plan for reducing nutrient inputs into the Baltic Sea, which implies among others the distribution of country-wise quota for upper nutrient loads (HELCOM, 2007; Elofsson, 2010; Ahvenharju et al., 2010).

The legal framework for manure application in the countries of the Baltic Sea region is harmonised in directives of the European Union. Most rules for manure application originate from one of the oldest EU environmental programs: the Council Directive of 12 December 1991 concerning the protection of waters against pollution caused by nitrates from agricultural sources (91/676/EEC, "Nitrate Directive"). 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") and 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") influenced guidelines for manure application rules with a view to P losses. As a consequence of the Nitrate Directive, codes of good agricultural practice have been developed and implemented in national guidelines and laws. The oldest framework for the protection of the Baltic Sea and preventive measures onshore is the Convention on the Protection of the Marine Environment of the Baltic Sea Area (Helsinki Convention). 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, 2007). VR application of fertilizers matches the small-scale variation of the nutrient demand of crops in the field whereby rates vary in a continuous mode (Haneklaus and Schnug, 2006). It is intrinsic that such site-specific nutrient management complies with a sustainable input of resources that favors crop growth and minimizes negative impacts on the environment. Algorithms for the continuous VR input of straight and compound mineral fertilizers have been developed (Haneklaus and Schnug, 2006) while those for farmyard manures and slurries are still missing though modern spreading machines automatically control manure application rates (Saeys et al., 2008). Commonly application rates of manure are not based on a documented demand of nutrients, but fully exhaust the maximum legal input. Thus a VR input of manure is likely to be objected by farmers as it demands changes in the production and recycling chain of manure and slurries. Nevertheless a widespread implementation of precision agriculture technologies in agricultural production will have a significant potential for reducing nutrient losses from agriculture because diffuse P losses will be reduced. Alternatively, further legal confinements or the charge of clean-up costs for intensive livestock enterprises may come into force in order to reduce negative environmental impacts of agricultural production.

In the Baltic Sea region about 981,000 t of N and 281,000 t of P incur annually in the form of manure (Tybirk et al., 2013). Here, liquid manure or slurry needs to be distinguished from solid manure (Derikx et al., 1997). The first contains 90 to 96 % water, while the latter less than 90 % (Derikx et al., 1997; Popovic, 2012). N can be found favorably in the liquid phase and P in the solid fraction (Popovic, 2012).

This contribution presents the results of a survey carried out in riparian states of the Baltic Sea within the framework of the partly financed the EU project Baltic Manure. Focus has been put on P as mineral phosphate rock reserves are finite so that a sustainable use of P is imperative in order to warrant global food security for future generations (Van Kauwenbergh, 2010). An oversupply with P by manures is not only a waste of this resource, but also linked to an increased risk of P losses by surface run-off and erosion (Lemola et al., 2013). The VR application of manure is an important step towards a targeted input of nutrients. It is the aim of this paper to deliver a strategic concept for a sustainable use of manure whereby special attention is paid to closing the agricultural P cycle. Prerequisites and limitations for a site-specific nutrient management using manure will be outlined and algorithms for their VR application presented.

2 Materials and methods

In total 2632 geo-referenced top soil samples (0 to 30 cm) from Germany, Estonia, Finland and Poland were taken. Sample locations in each country were selected which reflect typical regional differences of soil parameters such as texture, pH and total P-content.

The plant available P content was determined in air-dried top soil samples (0 to 30 cm) which were previously sieved to a particle size of < 2 mm in all samples by employing calcium acetate lactate extraction according to Schüller (1969). In 257 out of these samples soil material was extracted with double lactate according to Riehm (1942), ammonium lactate according to Egnér (1954) and Mehlich-3 according to Mehlich (1984). P was determined colorimetrically in the extracts according to Murphy and Riley (1962). The classification of soil test P data was based on the categories suggested by Kerschberger et al. (1997):

A – strong deficit (≤ 20 mg/kg P),
B – deficit (21 to 44 mg/kg P),

C – optimum (45 to 90 mg/kgP),
D – excess (91 to 150 mg/kg P) and
E – strong excess (≥ 151 mg/kg P).

For geostatistical analysis at least 30 geo-referenced top soil samples were taken along transects at distances of 10 meter. At each sampling point core soil samples were retrieved within a radius of 1 to 2 m and thoroughly mixed in order to assess the small-scale spatial variation of plant available P contents. The traditional mixing of 15 to 30 sample cores per hectare interferes with the variability of soil features and is therefore unsuitable (Haneklaus et al., 1998). Additional samples were taken where topographical differences such as summits, depressions, slopes and plains existed.

Representative samples from liquid and solid manure from cattle, pigs and chicken were sampled in Denmark, Estonia, Finland, Germany, Poland, and Sweden. Generally, manure was taken from storage tanks. In total 138 samples of different origin were analyzed. A detailed description of sampling sites, sampling procedures and supplementary analytical data is given by Rückamp et al. (2013a, b and c).

Algorithms for the calculation of variable manure rates have been calculated exemplary for the German P soil classification and fertilizer recommendation scheme. The algorithms were directed towards a nutrient input (N, P, K) that is balanced within one year using manure and mineral fertilizer products.

For all statistical analyzes SPSS version 17.0 and Microsoft Office EXCEL 2007 were employed. For geostatistical analysis of the plant available P content in soil samples taken along transects at sampling intervals of 10 m variogram models were tested by ArcGIS 10.2 (ESRI, Redlands, USA). The algorithm of ordinary kriging was chosen, because it is suitable for an unknown mean, while it allows trend removal. In most cases a first order trend removal was performed, some sites did not need a trend removal and at sites with no proper linear transect, a second order trend removal was calculated. Model variograms were computed and the one with best results in cross-validation was selected. This means that the "Root-Mean Square Standardised Error" was close to one and the "Mean Standardised Error" close to zero. The "Root Mean-Square Error" should be as low as possible, but also similar to the "Average Standard Error" (ESRI, 2012). For modelling, a lag size of 11 m was chosen which fits to the distance of the sampling plots along transects.

3 Results and discussion

Soil P analyzes in relation to fertilizer form and origin of manure in four countries reveal that the P status was in the surplus range except on sites where cattle manure was applied in Finland (Figure 1). Here, the P supply was in the optimum range of 45 to 90 mg/kg P according to Kerschberger et al. (1997).

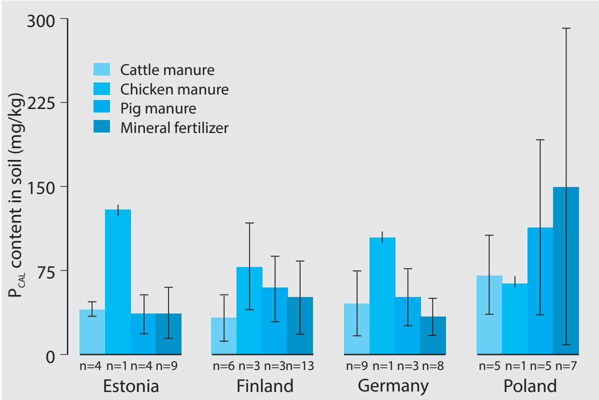

Figure 1
Mean P_{CAL} content in soil samples from different countries in relation to fertilizer form and origin. (Error bars indicate the standard deviation based on the given sample numbers)

The data from soil test P revealed that in 37 % of all samples the P supply was not sufficiently high employing the German classification system (data shown in Shwiekh et al., 2015). If the Swedish or Estonian classification system is applied this value is significantly lower with 9 and 5 %, respectively (Shwiekh et al., 2015). The data showed that in 85 % of all tested samples the Swedish soil analysis and classification system delivered categories denoting a higher P supply by one and two categories when compared to the German system. For Estonia the corresponding share of samples was 38 % (Shwiekh et al., 2015). These findings stress that the continuation of current application practices of manure will further aggravate the problem of undesired nutrient surpluses and discharges to water bodies.

The comparison of the soil P status along transects of neighboring fields showed that the soil P content was regularly higher on livestock farms (Figure 2). Farmers of these fields have been applying either exclusively mineral fertilizers or manure over time.

Grid distances of 30 to 50 meter may be required in order to accurately determine the spatial variation of soil crop features and to produce representative fertilizer application maps (Haneklaus and Schnug, 2006). In the present study samples were taken along transects in order to assess the small-scale variation of the soil P content in different riparian states of the Baltic Sea. Variogram analysis of in total 86 transects in Estonia, Finland, Germany and Poland showed that suitable variograms could be adapted for nearly all fields (Table 1; Figure 3). The range of the model variogram is a measure for the distance up to which samples exhibit a spatial correlation. Ranges of 20 to 30 m, 30.1 to 55 m, 55.1 to 90 m and 90.1 m to 220 m were determined for the studied fields at equal percentages of 25 %. No correlation was found between range and country, fertilizer type or validation errors.

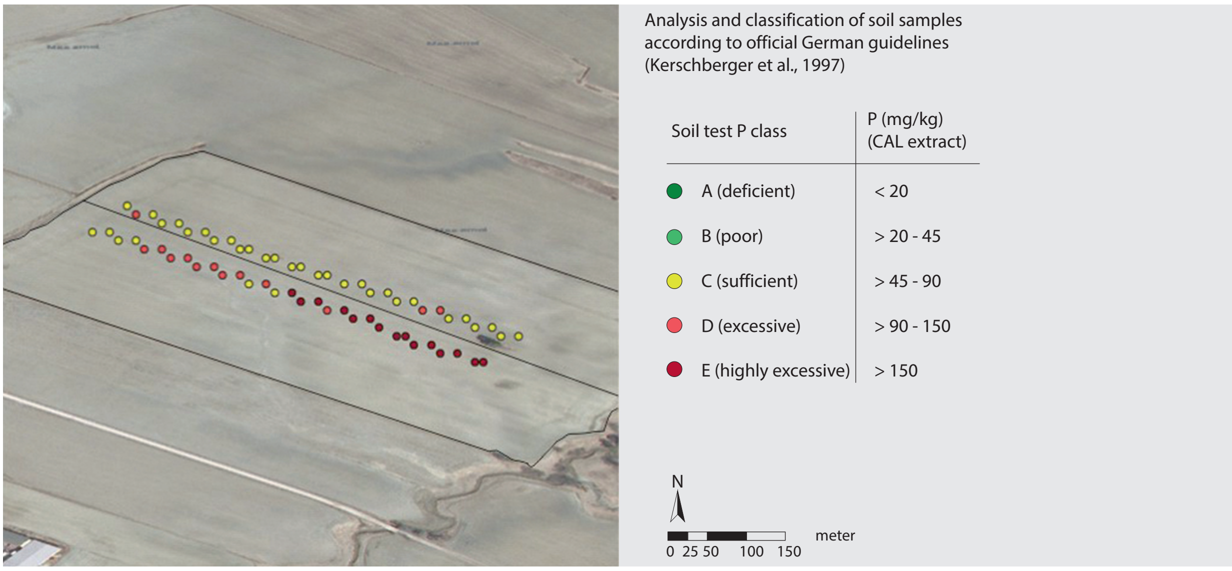

Figure 2
Categorized P content along transects of neighboring fields (the northerly field received exclusively mineral fertilizers and the southerly field exclusively chicken manure as P supply in the past).

Table 1
Examples for results from semi-variogram analysis of plant available P_{CAL} content in soils along transects on arable and live-stock farms in four countries of the Baltic Sea Region.

Farm ID	No of lags	Model Type	Range	Nugget	Partial Sill	Root-Mean-Square Error	Mean Standardized Error	Root-Mean-Square Standardized Error	Average Standard Error
Range: 20 to 30 m									
EE9	10	Stable	22	33	123	9.10	0.01	0.88	10.51
FI10	7	Stable	25	423	1116	33.34	-0.08	1.00	32.86
DE7	12	Exponential	23	258	381	30.45	-0.04	1.12	26.59
PL4	10	Stable	28	87	3314	25.82	-0.03	0.97	28.03
Range: 30.1 to 55 m									
EE11	11	Exponential	50	0	473	17.50	-0.05	1.01	16.51
FI2	11	Circular	48	0	37	3.36	0.02	0.99	3.44
DE1	12	Exponential	57	0	124	7.35	-0.03	0.91	7.78
PL5	10	Spherical	44	314	1733	31.91	0.00	0.95	33.75
Range: 55.1 to 90 m									
EE7	12	Spherical	71	143	1598	23.09	-0.02	0.97	23.89
FI1	11	Stable	68	108	1427	11.82	0.01	0.88	13.90
DE11	11	Gaussian	78	38	95	9.34	-0.08	1.19	7.28
PL10	12	Stable	83	0	28350	69.43	-0.03	0.89	80.68
Range: 90.1 to 220 m									
EE5	15	Circular	142	91	313	14.46	-0.04	1.14	12.13
FI16	17	Spherical	160	6	274	6.48	0.01	0.99	6.24
DE9	12	Stable	132	104	0	11.28	-0.05	1.06	10.61
PL8	15	Stable	135	304	87	18.55	-0.03	1.00	18.57

note: country code: EE – Estonia, FI – Finland, DE – Germany, PL - Poland

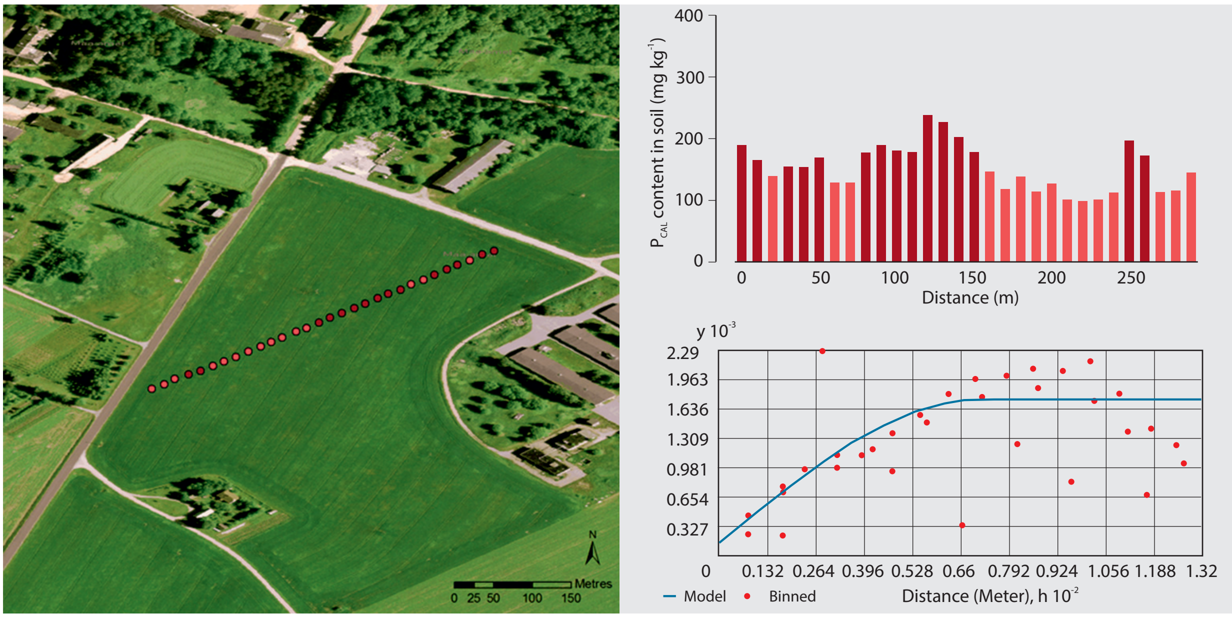

Figure 3
Sampling locations in transect of field EE7 classified (left), variation of plant available P content at sampling points (top right) and semi-variogram where sampling points were binned in groups and the curve reflecting the theoretical semi-variogram (for details see Table 1).

The complete data of variogram analysis on all test sites are provided by Rückamp et al. (2013a). The small-scale variability of the plant available P content in soils was even higher on some fields of the present study than in other investigations in Denmark and Germany where ranges between 60 and 364 m were found before (Haneklaus and Schnug, 2006). In the present study the small-scale variation of the soil P_{CAL} content was so high that sampling distances of <20 meter are required to assess the variability reliably. This information is important if variable fertilizer rates are adjusted to the variation of the plant available soil P content. Different approaches such as directed sampling, self-surveying and identification of monitor pedo cells have been tested to reduce sampling efforts whilst keeping the spatial reference and validity (Haneklaus and Schnug, 2006).

4 Factors influencing the variability of the nutrient content in manure

The nutrient content of manure is highly variable and is related to animal species and weight, feedstuff quality and quantity, housing management, storage time and conditions, and water content (Cordovil et al., 2012). In the first year of application about 35 to 40 % of the total P is plant available (European Commission – Directorate General Environment, 2010). Studies of Eghball et al. (2005) showed that P can be plant available to 100 % in the first year of application. Thus it is fair to assume that the entire P in manure is plant available on a long-term basis which makes it an ideal P source.

In general, cattle manure contains more solids and N so that the N:P ratio is wider than in pig manure. The content of solids and the N:P ratio increases with age of fattening pigs which results from an increasing nutrient uptake during live weight gain. Poulsen (2012) analyzed manure from weaners and fattening pigs and determined 3.36 kg N and 0.99 kg P per ton, and 4.96 kg N and 1.16 kg P per ton, respectively.

The water content of manure makes it expensive to transport over long distances. At the same time, the mixture of solids and water impairs flow properties so that solids may block the manure spreading machine. Segregation causes stratification of manure with different nutrient compositions at the top and the bottom of the tank. Though solids sink to the bottom, the nutrient content is not necessarily higher at the bottom. Pig manure stored in lagoons showed in the top layer a content of solids of only 0.4 % while it was 8 times higher when the manure was stored in concrete containers (Campbell et al., 1997; Lovanh et al., 2009). Seasonal trends of manure composition have been reported, too. DeRouchey et al. (2002) found higher N and P concentrations in June than October (1.6 versus 1.2 kg/t N; 0.29 versus 0.13 kg/t P). DeRouchey et al. (2002) attributed such seasonal changes to climatic differences such as higher temperatures and evaporation rates and less precipitation, resulting in a higher number of microorganisms. Impact factors on the variation of the mineral composition of manure are summarised in Figure 4.

The interfarm coefficient of variation for P_{CAL} in manure was 35 % and 45 % with means of 0.5 and 1.6 kg/t P in cattle and pig manure, respectively. These results are comparable to those of Dupont et al. (1984). The results reveal that sedimentation in the manure tank or reservoir yields the strongest variation in the P content, followed by age and feeding regime. In comparison other factors such as breeds,

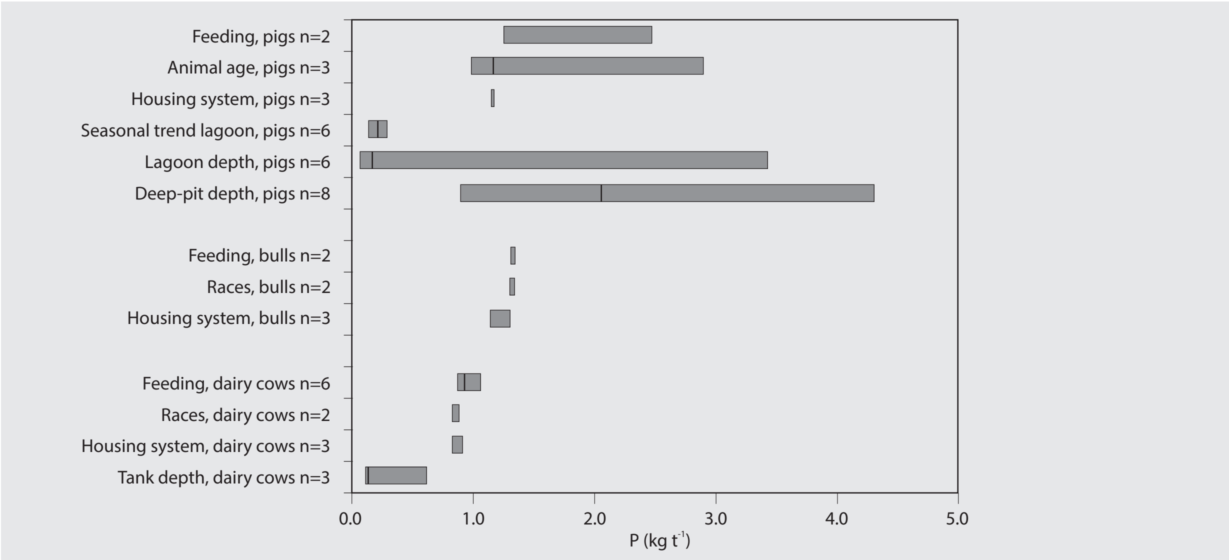

Figure 4
Range of P_{CAL} contents in manure in relation to animal species, breed, age, season, housing system and storage depth (Boxes indicate minimum, maximum values and median if more than two values were available) data summarise own results plus references from literature (for details see Rückamp et al., 2013c)).

housing system and season seem to be of minor relevance (Figure 4). Thus it may be concluded that apart from constant production factors on a farm such as animal species, feeding regime and breeding duration an efficient homogenization of manure is a major prerequisite for the VR input in order to assess reliable nutrient input data (Derikx et al., 1997). Such assumptions are strengthened by studies of Conn et al. (2007) who showed that the mineral composition of manure was consistent over time on individual farms while the variation between farms proved to be high. Another contribution to overcome the problem of inhomogeneity is a solid/liquid separation as N can be found in the liquid and P in the solid fraction (Popovic, 2012). Such procedure yields a product with a higher P content which in return increases maximum profitable transport distances (Knudsen and Schnug, 2016).

5 Algorithms for variable rate (VR) fertilization of manure

According to the EU Nitrate Directive the maximum permitted load of manure for fertilizer purposes is based on the N content and must not exceed 170 kg/ha N. It is 140 kg/ha N in nitrate vulnerable zones in Estonia and in Denmark for pig manure. Noteworthy is that in Sweden not more than 22 kg/ha P must be applied with manure. This amount of P corresponds with the mean P off-take by harvest products. Any additional supply with mineral fertilizers is not regulated. Denmark is the only country where the nutrient flow is controlled on farms and balances are calculated for each farm separately on a crop rotation basis (Knudsen and Schnug, 2016).

The rationale for a sustainable use of P in manure is simple. Only if upper manure application rates are based on the P off-take by harvest products on soils which are sufficiently supplied with P it can be expected that diffuse P losses to water bodies decrease. A basic rule of balanced fertilization is that the nutrient input matches the demand in order to avoid equally surpluses and undersupply. Here, the problem arises that many soils of livestock farms are already overloaded with P (see Figure 1). A mandatory limitation of the P input to 22 kg/ha P as practised in Sweden implies that alternative ways for the utilization of manure are required, livestock densities have to be reduced, or the acreage where manure is applied is extended (Powers and van Horn, 2001). With 22 kg/ha P, on an average 141, 88 and 77 kg/ha N would be applied with cattle, pig and poultry manure, respectively. In contrast, maximum application rates of manure equalling 170 kg/ha N (as commonly practised) exceed the mean P off-take of agricultural crops with harvest products by 95 % to >120 % if pig and poultry manure is used. If cattle manure is applied the surplus is minor with approximately 2 %.

For maximum utilization of manure variable rates should follow the spatial variability of the plant available P content in soils as an indicator for the P demand of crops. The corresponding algorithms can be developed easily, for example on basis of national recommendation schemes. The following contemplation will, however, reveal impressively that this might not be a commendable approach in all member states of the Baltic Sea Region when a sustainable P use is the overall target. The problem is that not only threshold values for evaluating the soil P status proved to be not congruent in the countries that were studied, but recommended fertilizer rates deviated highly (see above). In other words, a farmer sending his soil samples to laboratories in Germany and Sweden for instance will receive a different assessment of the soil test P classification which may deviate by up to two classes. In addition to the diverging assessment of the soil P status the recommended fertilizer rates may deviate by up to 28 % for grain crops and 37 % for sugar beet if the P supply was rated optimum in both countries (Henriksson, 2007; Landwirtschaftskammer Niedersachsen, 2011). In the worst case, three and four times higher application rates to sugar beet and cereals may be advised to German farmers. These findings stress the urgent need for a harmonization of analytical methods, interpretation and recommendation procedures in the EU countries. Alternatively, on-farm experimentation employing precision agriculture technologies delivers truly site-specific threshold values and response curves to nutrient input which can be translated into VR manure application maps (Haneklaus and Schnug, 2006). The latter aspect is of key relevance on livestock farms with a view to balancing the soil P level (see Figure 1).

On livestock farms with feed supplementation of Cu and Zn the risk of their accumulation in soils is existent and should be monitored together with yield data in order to avoid yield reductions. A balanced input of N, P, K, Cu and Zn by pig manure is only possible if rates will not exceed the Cu off-take by harvest products as Cu is the nutrient that is enriched strongest (Kratz and Schnug, 2006; Schnug et al., 2006). If Cu and Zn are amended at rates which equal the off-take, only 8 % and 24 % of the maximum permitted manure rates equalling 170 kg/ha N could be applied which is actually no practical option. Here, extraction procedures for Cu and Zn from raw manure are required (Popovic, 2012).

The ideal P supply is given when rates equal the off-take and the P source is fully plant available because only then P utilization is 100 % on a long-term basis (Schnug and DeKok, 2016). Djodijic et al. (2005) came to the same conclusion as a result of a long-term field experiment in Sweden. In case of manure P is fully plant available (Hansen, 2006). Here, recycled P fertilizer products and rock phosphates have to be evaluated critically as a significant amount of P will not take place in the soil P cycle and thus will not contribute to the P nutrition of agricultural crops (Schick, 2010).

The following conditions were defined for adopting general algorithms for VR application of manure (Table 2): 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 is analyzed prior to fertilization to follow up any changes in livestock management, and the minimum N demand is 170 kg/ha N.

Ideally, manure is applied at rates which match the lowest N, P or K demand and respective deficits of N, P and/or K are balanced either by mineral fertilizers within one year (Table 2), or by manure together with mineral fertilizers in subsequent years on a crop rotation basis. The spatial variation of the P and K off-take can be established easily by yield maps if the technology is available (Haneklaus and Schnug, 2006). With respect to N, annual rates need to match the spatial variation of the crop demand. A suitable approach to assess the site-specific N demand is for example by adjusting rates to the spatial variation of the clay and organic matter content (Haneklaus and Schnug, 2006).

It has been mentioned above that a P-based manure application will limit its utilization on livestock farms. However, it is not only P, but a balanced input of K may further decrease the manure quantity applied, particularly in case of cattle and pig manure (Table 2). As a rule of thumb cereal grains and oilseed rape remove about 40 kg/ha, sugar beets 100 kg/ha and intensive grassland 120 kg/ha K (Hydro Agri Dülmen, 1993). Thus a balanced K management is only feasible in sugar beet/cereal crop rotations where straw is harvested and constrictedly on intensive grassland (Table 2).

Table 2
Algorithms for variable rate (VR) application of manure targeting a balanced input of N, P and K.

Variable P rates as manure (kg/ha)					Mineral fertilizer rate (kg/ha)		
Cattle manure (N:P = 6.4:1 and P:K = 1:6.4)							
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)	N	P	K
A, B[2]	Y = -0.880X + 61.4	X > 41	≤ 170	≤ 177[3]	$N_{VR}=N_{demand}-N_{manure}$	$P_{VR}= P_{demand}-P_{manure}$, if X ≤ 41	
C	22 or [3]$VR_{off\text{-}take}$		141	147[3]			
Pig manure (N:P = 4:1 and P:K = 1:3.9)							
A, B[2]	Y = -0.880X + 61.4	X > 21.5	≤ 170	≤ 1424	$N_{VR}=N_{demand}-N_{manure}$	$P_{VR}= P_{demand}-P_{manure}$, if X ≤ 21.5	$K_{VR}=K_{demand}-K_{manure}$ or [5]$VR_{off\text{-}take}$ if ≤ K_{VR}
C	22 or [3]$VR_{off\text{-}take}$		88	73			
Poultry manure (N:P = 3.5:1 and P:K = 1:1.5)							
A, B[2]	Y = -0.880X + 61.4	X < 45	< 77	≤ 32	$N_{VR}=N_{demand}-N_{manure}$	$P_{VR}= P_{demand}-P_{manure}$, if X ≤ 45	$K_{VR}=K_{demand}-K_{manure}$ or [5]$VR_{off\text{-}take}$ if ≤ K_{VR}
C	22 or [3]$VR_{off\text{-}take}$		77	32			

notes: [1]for details see Figure 2; [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:

$$\sum_{i=1}^{n} K_{rates}(yr_1 + yr2 + \cdots + yr_n) = \sum_{i=1}^{n} K_{offtake}(yr_1 + yr2 + \cdots + yr_n)$$

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.

Following these basic rules that ensure a balanced N, P and K input it is evident that the recycling of manure is compulsory in order handle incoming quantities of manure.

6 Conclusions

On big livestock enterprises the disposal rather than the utilization of nutrients in manure is of prime interest. The result is regularly an accumulation of P in soils (Figure 1 and 2) which increases the risk of nutrient losses by surface run-off and erosion. The data of the cross-national investigation stress the need for a harmonization of methods, interpretation routines and fertilizer recommendations. Here, on-farm experimentation employing precision agriculture technologies delivers reliable critical nutrient values for soils and plants. A promising approach for a demand driven P application of manure is to address the small-scale variation of plant available P in soils (Table 1) and match it with variable rates of manure (Table 2). The results of the study show that algorithms for VR application of manure can be established easily, but need to be adjusted to individual feeding and housing conditions (Table 2). As a result on livestock farms housing pigs and chicken the total amount of manure that can be distributed will decrease drastically as regularly only rates which equal the off-take by harvest products would be supplied. Consequently a recycling chain for manure is required to utilize the organic fertilizer. Answering the initial question a P-based VR application of manure conveys a lot of gain for a truly sustainable P use and reduces environmental burdens from nutrient losses to water bodies which will outweigh the pain associated with the implementation of innovative technologies.

Acknowledgements

This study was carried out in the Baltic Manure project which was partly financed by the European Union European Region Development Fund.

References

Ahvenharju S, Halonen M, Rinne P (2010) Analysis of the status of implementation of the Baltic Sea Action Plan for WWF [online]. To be found at <http://wwf.fi/mediabank/1073.pdf> [quoted 03.03.2016]

Campbell AJ, MacLeod JA, Stewart C (1997) Nutrient characterization of stored liquid hog manure. Can Agric Eng 39(1):43–48

Conn KL, Topp E, Lazarovits G (2007) Factors influencing the concentration of volatile fatty acids, ammonia, and other nutrients in stored liquid pig manure. J Environ Qual 36:440-444

Cordovil CMdS, Basanta R, Pires SO, Ferreira L, Kiladze K (2012) Application of fresh and treated pig slurries and a novel organic-mineral fertilizer in maize crop. Comm Soil Sci Plant Anal 43(16):2126–2141

Correll DL (1998) The role of phosphorus in the eutrophication of receiving waters : a review. J Environ Qual 27:261-266

Derikx PJL, Ogink NWM, Hoeksma P (1997) Comparison of sampling methods for animal manure. Neth J Agric Sci 45:65-79

DeRouchey JM, Goodband RD, Nelssen JL, Tokach MD, Dritz SS, Murphy JP (2002) Nutrient composition of Kansas swine lagoons and hoop barn manure. J Anim Sci 80(8):2051–2061

Djodjijic F, Bergstrom L, Grant C (2005) Phosphorus management in balanced agricultural systems. Soil Use Manage 21:94-101

Dupont J, Dionee J-L, Gagné R (1984) Le fumier dans le bassin de la rivière St. Francois : composition chimique, quantités produites, utilisation. Ottawa : Direction générale de la recherché, Agriculture Canada, Techn Bull 1984–5F, 85 p

Eghball B, Wienhold BJ, Woodbury BL, Eigenberg RA (2005) Plant availability of phosphorus in swine slurry and cattle feedlot manure [online]. To be found at <http://digitalcommons.unl.edu/cgi/viewcontent.cgi?article=2191&context=usdaarsfacpub> [quoted 03.03.2016]

Egnér H (1954) Neue Beiträge zur chemischen Bodenuntersuchung unter besonderer Berücksichtigung der Laktatmethode. Landwirtsch Forsch SH 6:28-32

Elofsson K (2010) The costs of meeting the environmental objectives for the Baltic Sea : a review of the literature. Ambio 39(1):49-58

ESRI (2012) Geostatistical Analyst. The ArcGIS Resource Center [online]. To be found at <http://resources.arcgis.com/en/help/main/10.1/> [quoted 01.03.2016]

European Commission – Directorate General Environment (ed) (2010). Study on variation of manure nitrogen efficiency throughout Europe. Annex 1: Examine the current applicable manure-N efficiency rates in the EU 27 by studying literature and contacting research centres / competent administrations in the MS [online]. To be found at <http://ec.europa.eu/environment/water/water-nitrates/pdf/Annex_1_Man_N_Effic.pdf> [quoted 01.03.2016]

Granstedt A, Schneider T, Seuri P, Thomsson O (2008) Ecological recycling agriculture to reduce nutrient pollution to the Baltic Sea. Biol Agriculture Horticult 26:279-207

Haneklaus S, Vanoverstraeten M, Schnug E (1998) Spatial variability of soil fertility parameters and its impact on the application of precision agriculture to sugar beet. Asp Appl Biol 52:95-100

Haneklaus S, Schnug E (2006) Site specific nutrient management – objectives, current status and future research needs. In: Srinivasan A (ed) Handbook of precision agriculture : principles and applications. New York : Food Products Pr, pp 91-151

Hansen DJ (2006) Manure as a nutrient source [online]. To be found at <http://extension.psu.edu/plants/nutrient-management/educational/nutrient-management-general/mid-atlantic-nutrient-management-handbook> [quoted 01.03.2016]

HELCOM (2007) HELCOM Baltic Sea Action Plan : adopted on 15 November in Krakow, Poland by the HELCOM Ministerial Meeting. Helsinki : Helsinki Commission, 103 p

Henriksson A (2007) Actions against phosphorus losses from agriculture in the countries surrounding the Baltic Sea. Uppsala : Sveriges lantbruksuniv, SLU Rapport Mat 21

Hydro Agri Dülmen (1993) Faustzahlen für Landwirtschaft und Gartenbau. Münster : Landwirtschafts-Verl, 618 p

Kerschberger M, Hege U, Jungk A (1997) Phosphordüngung nach Bodenuntersuchung und Pflanzenbedarf [online]. To be found at <http://www.vdlufa.de/joomla/Dokumente/Standpunkte/0-4-phosphor.pdf> [quoted 03.03.2016]

Knudsen L, Schnug E (2016) Utilization of phosphorus at farm level in Denmark. In: Schnug E, DeKok LJ (eds) Phosphorus : 100% Zero. Heidelberg : Springer (in press)

Kratz S, Schnug E (2006) Vergleichende Bewertung der Nähr- und Schadstoffgehalte von Düngemitteln und Klärschlämmen. Siedlungswasser Siedlungsabfallwirtsch NRW 3:357-361

Landwirtschaftskammer Niedersachsen (2011) Richtwerte für die Düngung in Niedersachsen [online]. To be found at <http://www.lufanordwest.de/data/documents/Downloads/IFB/duengeempfehlunghauptnaehrstoffe.pdf> [quoted 03.03.2016]

Lemola R, Uusitalo R, Sarvi M, Ylivainio K, Turtola E (2013) Plant requirement and zero balance : soil P development under two P input scenarios in Finland [online]. To be found at <http://www.balticmanure.eu/download/Reports/plant_requirement_web.pdf> [quoted 03.03.2016]

Lovanh N, Loughrin JH, Cook K, Rothrock M, Sistani K (2009) The effect of stratification and seasonal variability on the profile of an anaerobic swine waste treatment lagoon. Biores Technol 100(15):3706–3712

Mehlich A (1984) Mehlich 3 soil extractant : a modification of the Mehlich 2 extractant. Comm Soil Sci Plant Anal 15:1409-1416

Murphy J, Riley JP (1962) A modified single solution method for the determination of phosphate in natural waters. Anal Chim Acta 27:31-36

Popovic O (2012) Pig slurry separation and storage : effects on P, Cu and Zn distribution between separation fractions and particle size classes. Frederiksberg : Univ Copenhagen

Poulsen HD (2012) Normtal for husdyrgødning [online]. To be found at <http://anis.au.dk/fileadmin/DJF/Anis/Normtal_2012_august_ny_2012.pdf> [quoted 03.03.2016]

Powers WJ, van Horn HH (2001) Nutritional implications for manure management planning. Appl Eng Agric 17:27-39

Riehm H (1942) Bestimmung der laktatlöslichen Phosphorsäure in karbonathaltigen Böden. Phosphorsäure 1:167-178

Rückamp D, Schick J, Haneklaus S, Schnug E (2013a) Geochemical atlas on agricultural soils and manures in the Baltic Sea Region [online]. To be found at <http://www.balticmanure.eu/download/Reports/geochemical_atlas_web.pdf> [quoted 03.03.2016]

Rückamp D, Schick J, Haneklaus S, Schnug E (2013b) Final report of WP4 "Standardisation of manure types with focus on phosphorus" [online]. To be found at <http://www.balticmanure.eu/download/Reports/report_on_p_status_final_web.pdf> [quoted 01.03.2016]

Rückamp D, Schick J, Haneklaus S, Schnug E (2013c) Algorithms for variable-rate application of manure [online]. To be found at <http://www.balticmanure.eu/download/Reports/algorithms_for_variablerate_application_web.pdf> [quoted 01.03.2016]

Saeys W, Deblander J, Ramon H, Anthonis J (2008) High-performance flow control for site-specific application of liquid manure. Biosyst Eng 99(1):22–34

Schick J (2010) Untersuchungen zu P-Düngewirkung und Schwermetallgehalten thermochemisch behandelter Klärschlammaschen. Braunschweig : Univ, 179 p

Schnug E, Sparovek R, Storck W, Jering A, Volkgenannt U (2001) The HELCOM Working Group on Agriculture (WGA). Landbauforsch Völkenrode 51(1/2):5-9

Schnug E, Haneklaus S, Kratz S, Fan X (2006) Aspects of phosphorus fertilisation in organic farming. Asp Appl Biol 79:277-28

Schnug E, DeKok LJ (2016) Phosphorus: 100% Zero. Heidelberg : Springer (in press)

Schüller H (1969) Die CAL-Methode, eine neue Methode zur Bestimmung des pflanzenverfügbaren Phosphates in Böden. Z Pflanzenernähr Bodenkd 123:48–63

Schultz-Zehden A, Delsa L, Torres C, Relotius R (eds) (2011) Sustainable agriculture in the Baltic Sea Region in times of peak phosphorus and global change. Berlin : Sustainable Projects, 66p, Baltic 21 Ser 4

Shwiekh R, Schick J, Kratz S, Schnug E (2015) Comparative investigation and inter-calibration of different soil P tests. Journal Kulturpflanzen 67:61-72

Tybirk K, Luostarinen S, Hamelin L, Rhode L, Haneklaus S, Poulsen HD, Jensen ALS (2013) Sustainable manure management in the Baltic Sea Region : results, cases and project recommendations ; Balitc manure report [online]. To be found at <http://findresearcher.sdu.dk:8080/portal/en/publications/sustainable-manure-management-in-the-baltic-sea-region--results-cases-and-project-recommendations%2814728a8f-651a-4edf-b318-8c6aabdbd3f3%29.html> [quoted 03.03.2016]

Van Kauwenbergh SJ(2010) World phosphate rock reserves and resources [online]. To be found at <http://pdf.usaid.gov/pdf_docs/Pnadw835.PDF> [quoted 01.03.2016]