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Research article

Identifying phosphorus hot spots: A spatial analysis of the phosphorus balance as a result of manure application☆

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A B S T R A C T

In this paper, we analyze the phosphorus balance as a result of manure application on the parish level for Denmark and investigate its local geographic distribution. For our analysis, we determine phosphorus loads for the five main animal groups and the phosphorus demand of the fifteen major crop categories. Our results show that there is a large variability in the phosphorus balance within Denmark. Due to industry agglomeration statistically significant hot spots appear mainly along the west coast, while cold spots are predominantly present on southern and eastern coasts towards the Baltic Sea. The proximity of oversupply areas to water bodies and other environmentally sensitive areas reinforces the need for further phosphorus regulation. Our findings show the importance of a combined spatially targeted regulation, which allows different levels of phosphorus application depending on local economic and environmental circumstances in combination with subsidizing manure processing technologies in phosphorus hot spots.

1. Introduction

Animal manure is a side product of livestock rearing systems. It is derived from animal feces and urine and is mainly used as organic fertilizer in agriculture. It contains nutrients, such as nitrogen, phosphorus and potassium. Today, the application of manure is regulated on national level, e.g., Dutch Manure and Fertilizer Act (1999) or the Danish Action Plans for the Aquatic Environment (APAEs), as well as international level, e.g., European Nitrates Directive (EEC, 1991), European Water Framework Directive (EU WFD, 2000) and the EU Rural Development Program (EC, 2005). The aim is to control the amount of nutrients entering the field and limit the corresponding run-off to, and pollution of adjacent rivers and other water bodies (Szögi et al., 2015).

Despite thirty years of regulatory effort to reduce nutrient pollution from agriculture, improvements are still needed (Kaspersen et al., 2016). In general, regulation of manure faces three problems. First, it is often applied uniformly on all agricultural land in a country. This means that the level of regulation is not or only very coarsely spatially targeted, which usually ignores the varying capacity of a specific field and crops to uptake nutrients. Second, the regulation regularly focuses on one nutrient, namely nitrogen, thereby often ignoring other nutrients, which are contained in manure and which do not appear in fixed relations (Sharpley et al., 1994; Goetz and Zilberman, 2000). This can potentially divert attention from balancing of other nutrients. Additionally, nutrients in manure appear in ratios in contrast to those required by most crops (Szögi et al., 2015). Third, livestock production today is assumed to be price inelastic in the short run (Feinerman et al., 2004; Smith et al., 2006). Spatial relocation of production facilities in areas with a low animal unit density is accompanied by large capital investments and is, therefore, hardly possible in the short run. Decreasing the number of livestock is unlikely due to fixed capital costs and scale economies. Therefore manure regulation will lead to large compliance cost effects, in particular in regions with a concentrated livestock industry. While, due to the limited flexibility of the industry to alter the use of manure or to reduce manure production, manure output will remain high in

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these areas. High compliance costs will make livestock production unprofitable and may lead to farmers exiting the industry, which will affect the political feasibility of a manure regulation (Smith et al., 2006; Mack and Huber, 2017). These problems can result in a severe imbalance of nutrients on agricultural fields with a significant local oversupply in some areas, whereas others exhibit a nutrients deficit (Bateman et al., 2011). This makes the balance between nutrient inputs to the soil and nutrient removals from the soil critical for sustainable agriculture and appropriate resource use (Goetz and Zilberman, 2000; Kuosmanen and Kuosmanen, 2013; Kuosmanen, 2014).

To illustrate such a case of nutrient imbalance, we show the example of phosphorus application stemming from manure in Danish livestock and crop systems. Denmark is a country, which has a large livestock farming industry and, therefore, a large amount of manure, which has to be applied on agricultural land. In Denmark, manure application is in general regulated by the "Harmony rules".[1] This regulation focuses on the amount of nitrogen in manure. It, therefore, indirectly affects the total phosphorus application rates per hectare (Willems et al., 2016). In particular, the regulation specifies the livestock density on a farm through nitrogen limits of 140–170 kg nitrogen/ha and requires redistribution of excess manure based on written contracts between farmers (Sommer et al., 2013). Today, it is estimated that fields in Denmark have, on average, an oversupply of phosphorus (Sørensen and Møller, 2006; Jacobsen, 2011). Given the pattern of Danish livestock production, with two thirds of all livestock units being located in the southern and southwestern part of Denmark and only 11% in the east of the country (Klinglmair et al., 2015), it is likely that on local level these values are highly heterogeneous. This can have a strong influence on manure management options and local redistribution possibilities, which have to account for the geographical location of the farm, the degree of spatial industry agglomeration, as well as the agricultural land to which manure is applied.

The assessment of phosphorus levels on agricultural land is done on global, national and regional scale (see, for example, Sheldrick et al., 2002; OECD & Eurostat, 2007; Bateman et al., 2011). For Denmark, phosphorus balance assessments exist on the national and the local level. Sørensen and Møller (2006) and Jacobsen (2011) assess the phosphorus balance on the national level and find that on average Danish national oversupply of phosphorus is in the magnitude of 8–10 kg phosphorus/ha. Klinglmair et al. (2015), assess phosphorus balances for Denmark based on three regions. They find that manure has the largest potential for mineral fertilizer substitution, but availability of manure is highest in areas with lowest demand. Further, they find large differences in manure application and phosphorus demand between the three regions. On the local level, phosphorus budgets exist through farm-gate (Nielsen and Kristensen, 2005), soil surface and soil system approaches Kuosmanen and Kuosmanen (2013). The constructed budgets are usually based on case studies with selected farms (Nielsen and Kristensen, 2005; Spiess, 2011), or for sensitive areas such as lakes, specific catchments or fjords (Kaspersen et al., 2016). Based on those studies the phosphorus balance ranges between 7 and 42 kg phosphorus/ha oversupply in Denmark and depends on the farm type, animal species, size and housing technology (Nielsen and Kristensen, 2005). However, for such detailed studies, a full coverage on a national level is not possible and not intended, even though farm-gate studies are subsidized by the Danish Government to increase the availability of information in the long run (Nielsen and Kristensen, 2005).

Given this context, we address the following research questions in this paper. First, we ask whether phosphorus stemming from animal manure is balanced on a local level for the whole of Denmark. To answer this research question we apply a soil surface approach, which accounts for nutrients entering the soil via manure application and that leave the soil via crop uptake. In a second step, we then ask if, due to the spatial agglomeration of the livestock industry, the phosphorus balance forms significant local patterns, i.e., hot- and cold spots, of phosphorus over- and undersupply, which would lead to large compliance cost effects of manure regulation.

These results are of high environmental and economic relevance as information on nutrient balance hot spots on local level and their pattern in space can improve the economic effectiveness of manure management instruments by combining spatially targeted regulation across the regions with a subsidy scheme for manure processing technologies to dampen the potentially large compliance cost effects (Smith et al., 2006; Kuosmanen and Kuosmanen, 2013; Jacobsen and Hansen, 2016).

2. Method

In this paper, the phosphorus balance is analysed on the parish level, which represents former church administration units and is the smallest census unit in Denmark (Schullehner and Hansen, 2014).[2] The border demarcation of the parishes in Denmark is plotted in Fig. 2. The study covers fifteen crop categories and five animal manure categories. As it is difficult to get data on such a high degree of disaggregation, not all potential phosphorus flows, like compost, sewage sludge, crop residues and mineral fertilizers, are considered. We focus our analysis on animal manure based on following two reasons: Due to its large livestock farming industry, manure is the largest source of non-mineral fertilizer in Denmark. Nielsen and Kristensen (2005) show that compared to the soil type, animal stock per land area has a high impact on the nutrient surplus. Further, manure contains multiple types of nutrients, whereas the focus of the regulation is mainly on nitrogen. This can lead to large imbalances of applied nutrients.

The analysis is performed in the following steps: First, phosphorus supply based on animal manure production is calculated on parish level. Second, the demand for phosphorus depending on the crop type is determined per field and aggregated on the parish level. Third, based on phosphorus supply and demand the phosphorus balance per parish is calculated. And, fourth, a hot spot analysis is performed by employing the Getis Ord Gi* statistical method (Ord and Getis, 1995) to identify statistical significant local patterns of spatial clustering.

2.1. Animal phosphorus supply

Five animal groups, including cattle, pig, poultry, mink and a category "other", which summarises smaller groups of animals like sheep, are the contributors to the phosphorus supply in Denmark. The phosphorus values are calculated for the animal stock, which is published in the central animal register and provides information on the number of animals in statistical animal units per species and per parish. The data is provided by the Danish online GIS service of the Ministry of Environment and Food.[3] The nutrient load is reported in animal units (Table 1), which is based on the Danish

[1] Ministry of Environment and Food in Denmark (2015): Vejledning om Gødsknings-og harmoniregler. Online available under http://www.naturerhverv.dk (26.07.2017).

[2] The average size of a parish in Denmark is around 1280 ha.

[3] Online available under http://jordbrugsanalyser.dk/downloadside/index.html, shape file: "CHRsogn2000Til2015" (09.11.2017).