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Reducing agricultural nutrient surpluses in a large catchment – Links to livestock density

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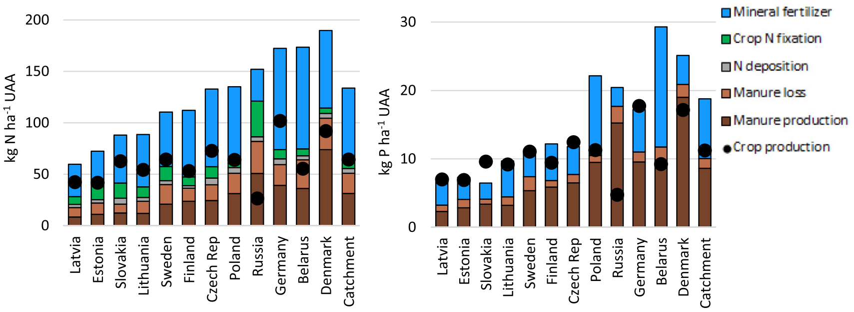
HIGHLIGHTS

- Large agricultural N and P surpluses are often in areas with high livestock density.
- Efficient manure use in crop production reduces dependency on imported fertilizer.
- Opportunity to use soil P reserves to a greater extent.
- Policy instruments can reduce nutrient surpluses and eutrophication risk.

GRAPHICAL ABSTRACT



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ABSTRACT

The separation between crop- and livestock production is an important driver of agricultural nutrient surpluses in many parts of the world. Nutrient surpluses can be symptomatic of poor resource use efficiency and contribute to environmental problems. Thus, it is important not only to identify where surpluses can be reduced, but also the potential policy tools that could facilitate reductions. Here, we explored linkages between livestock production and nutrient flows for the Baltic Sea catchment and discuss management practices and policies that influence the magnitude of nutrient surpluses. We found that the majority of nutrients cycled through the livestock sector and that large nitrogen and phosphorus surpluses often occurred in regions with high livestock density. Imports of mineral fertilizers and feed to the catchment increased overall surpluses, which in turn increased the risk of nutrient losses from agriculture to the aquatic environment. Many things can be done to reduce agricultural nutrient surpluses; an important example is using manure nutrients more efficiently in crop production, thereby reducing the need to import mineral fertilizers. Also, existing soil P reserves could be used to a greater extent, which further emphasizes the need to improve nutrient management practices. The countries around the Baltic Sea used different approaches to manage agricultural nutrient surpluses, and because eight of the coastal countries are members in the European Union (EU), common EU policies play an important role in management. We observed reductions in surpluses between 2000 and 2010 in some countries, which suggested the influence of different approaches to management and policy and that there are opportunities for further improvement.

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However, the separation between crop and livestock production in agriculture appears to be an underlying cause of nutrient surpluses; thus, further research is needed to understand how policy can address these structural issues and increase sustainability in food production.

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1. Introduction

In many parts of the world, some regions are more dominated by livestock production, while others are more focused on crop production. The crop-livestock separation is an important driving force for nutrient imbalances in agriculture (Nesme et al., 2015; Schipanski and Bennett, 2012). Areas focused on crop production often depend on imported mineral fertilizer to a large extent. Areas focused on livestock production import a large proportion of feed for animals (Wang et al., 2018), while the manure usually is applied on fields close to the farm, often in excess of crop needs.

The importance of improved use and handling of manure in order to reduce nutrient surpluses and eutrophication risk has been highlighted in a number of studies (e.g. Buckwell and Nadeu, 2016; Oenema et al., 2007; Tybirk et al., 2013). The benefits of manure to soil fertility and soil structure are well established (e.g. Diacono and Montemurro, 2010; Haynes and Naidu, 1998; Zavattaro et al., 2017). However, it can be challenging to manage manure in a resource-efficient way. Issues include excessive amounts of manure in intensive livestock production areas, its bulkiness and costs of transport, and mismatch of nutrient composition in relation to crop demands (Buckwell and Nadeu, 2016; Kleinman et al., 2012; Toth et al., 2006). There are several ways to process the manure to make it more transportable and easier to handle (Sommer et al., 2013), and the development and evaluation of various manure processing techniques is currently an active research field (e.g. Hanifzadeh et al., 2017; Hou et al., 2018).

There are many reasons for increasing nutrient recycling, improving nutrient use efficiency in agriculture, and reducing nutrient surpluses. Application of mineral fertilizers and/or manure in excess of crop requirements has negative environmental effects such as increased nitrate levels in groundwater (EEA, 2012; Spalding and Exner, 1993), buildup of legacy P sources (Powers et al., 2016) and, ultimately, increased eutrophication risk (Bai et al., 2013; Cameron et al., 2013; Withers et al., 2017). The production of synthetic and mineral fertilizers has local environmental effects and also requires high energy inputs (Mirlean and Roisenberg, 2006; Zhang et al., 2017). Using available nutrients efficiently and buying less mineral fertilizer can be positive for the farm economy (Nordin and Höjgård, 2017); conversely, low nutrient use efficiency suggests ineffective resource use. In a global context, the anthropogenic influence on the biogeochemical cycle of nitrogen (N) and phosphorus (P) is large, with widespread effects on ecosystems and problems of excessive amounts in some parts of the world, while the lack of fertilizer limits food production in other parts of the world (Elser and Bennett, 2011; Steffen et al., 2015). Phosphate rock, which is used to produce mineral P fertilizer, is a finite resource which was added to EU's list of critical raw materials for which both economic importance and supply risk is high (EC, 2014a).

Eutrophication is a severe environmental problem in the Baltic Sea (HELCOM, 2014), as well as in many lakes and rivers in its catchment (EEA, 2012). For decades, human activities have increased the amounts of N and P entering the sea, causing large effects in the ecosystem (e.g., hypoxic zones and changed species composition) (HELCOM, 2017), and affecting the possibilities for humans to use and enjoy the sea (e.g., swimming and fishing). Inputs from point sources such as centralized sewage systems have been reduced to a large extent (Naturvårdsverket, 2014; Swinarski, 1999) but there is still potential for further improvements (ECA, 2016). Diffuse inputs from agriculture have been more challenging to control, and agriculture is currently the single largest source of anthropogenic nutrient inputs to the Baltic Sea, contributing about 40% of total waterborne nitrogen inputs and 30% of total phosphorus inputs (HELCOM, 2018).

Hong et al. (2017) and Hong et al. (2012) calculated regional net anthropogenic inputs of N and P in the Baltic Sea catchment (NANI and NAPI), finding that imported fertilizer and feed are the major components of net nutrient inputs. Strong linear relationships exist between regional net N and P inputs and riverine nutrient fluxes to the Sea; when net N or P inputs to the catchment increases, riverine N or P fluxes also increase. Changes in regional net N and P inputs between year 2000 and 2010 were generally reflected in changes in riverine N and P fluxes to the sea's sub-basins. Thus, reducing imported fertilizer and feed are important steps towards reducing land-based nutrient loads to the sea.

McCrackin et al. (2018) used the NANI NAPI budgeting approach and constructed scenarios of improved nutrient use efficiency, assuming that manure nutrients were redistributed from areas with intense animal production to areas that focus on crop production and would otherwise import synthetic and mineral fertilizers. The basic idea is that if manure nutrients were used more efficiently in crop production and nutrient recycling increased, the need to import mineral fertilizers would decrease and contribute to lower overall nutrient surpluses. Nutrient use efficiency was capped at 0.75 for N and 0.9 for P in the scenarios. The analysis showed that there is substantial potential to improve nutrient use efficiency in the Baltic Sea catchment and that the scenarios could lead to reductions of N and P inputs to the sea.

Calculation of N and P balances in agriculture (i.e. positive or negative surpluses) is a commonly used approach to assess whether nutrients are used efficiently and how nutrient management can be improved (e.g. Blicher-Mathiesen et al., 2014; Buckley et al., 2015; Uwizeye et al., 2016). The balances can be calculated using different approaches and at various scales, from individual fields to the global scale.

While Hong et al. (2017) focused on total net N and P inputs to the catchment related to riverine fluxes to the Sea and analyzed inputs per total land area, and McCrackin et al. (2018) quantified the benefits of increasing manure use efficiency and reducing import of mineral fertilizer with focus on country and sub-sea basin scale, here, we quantify N and P surpluses per agricultural area at sub-country regions and analyze causes of surpluses. Specific aims in this study were to quantify agricultural N and P surpluses, analyze causes of surpluses on a country and sub-country level, examine how the separation of crop- and livestock production affects surpluses, identify ways to reduce surpluses, and discuss and provide examples of relevant policy tools to reduce nutrient surpluses and thus reduce eutrophication risk. This work provides timely and relevant information for assessing and strengthening the HELCOM Baltic Sea Action Plan (BSAP) and the revision of the EU Common Agricultural Policy.

2. Study area

2.1. Agriculture in the Baltic Sea catchment

Most of the agricultural land in the Baltic Sea catchment is located in its southern regions (Fig. 1a), which to some extent reflects the climatic preconditions for agriculture and where most people live. About 40% of the entire agricultural land in the Baltic Sea catchment is located in Poland alone. The proportion of total country area represented by agricultural land varies greatly around the sea. For example, about 7% of Sweden and Finland is agricultural area, while agriculture covers 40%

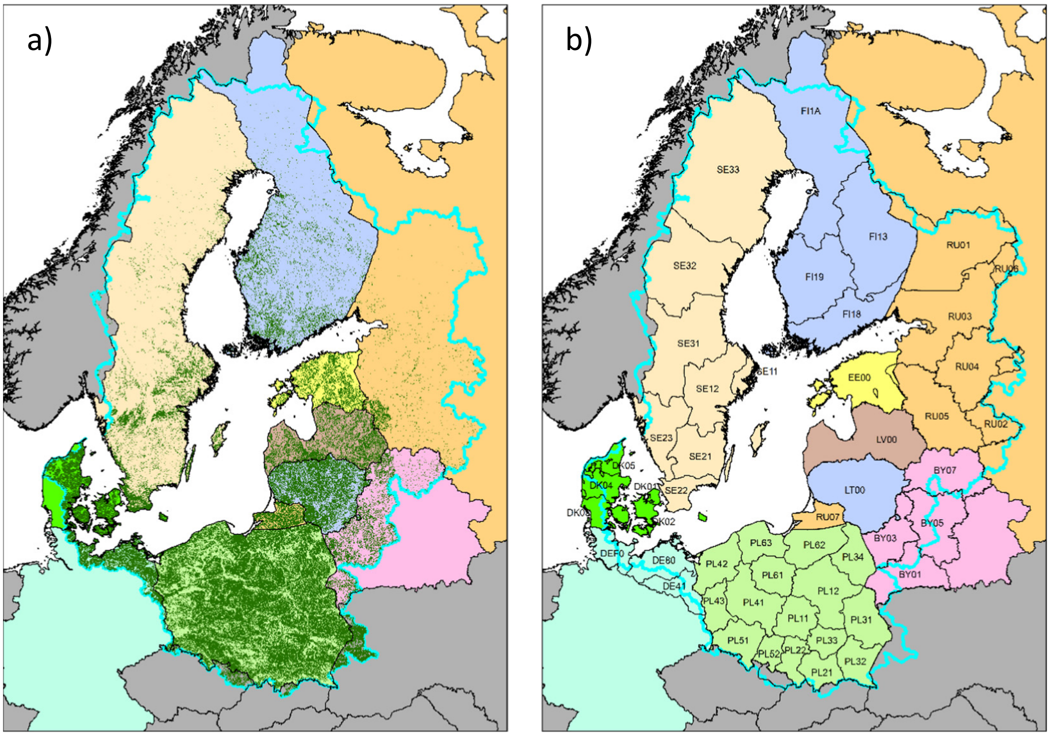

Fig. 1. Maps of the Baltic Sea catchment with the catchment border shown by the blue line. (a) Agricultural land within the catchment is shown as darker green areas on the map (CORINE Agricultural areas for EU countries and Global Land Cover Cultivated and managed areas for non-EU countries). (b) NUTS2 and Oblasts within the Baltic Sea basin (BY Belarus, CZ Czech Republic, DE Germany, DK Denmark, EE Estonia, FI Finland, LT Lithuania, LV Latvia, PL Poland, RU Russia, SE Sweden, SK Slovakia).

of Poland and 60% of Denmark. The number of livestock in relation to agricultural area also varies, with Denmark having the highest livestock density compared to other countries (Table 1).

There is a general trend towards larger and fewer farms in the EU countries within the catchment, and an increasing number of livestock on large farms and fewer on small farms (EuroStat, 2016a, 2016b). Average farm size varies greatly, from about 10 ha in Poland to about 150 ha in the areas of Germany within the catchment (EuroStat, 2016a). There are still many small farms, especially in Poland, but more than 40% of the utilized agricultural area in EU countries in the catchment was found on farms larger than 100 ha (EuroStat, 2016b). In Denmark, Germany, and Sweden, most of livestock were also found on farms larger than 100 ha (year 2013). This is especially pronounced in Denmark, with over 70% of the Danish livestock units (LSU) found on farms larger than 100 ha (EuroStat, 2016b).

Table 1
Utilized agricultural area (UAA), average farm size, livestock density, and numbers of cattle pigs and poultry. Only NUTS2 regions or oblasts within the Baltic Sea catchment are included.

Country	UAA (1000 ha)	Average farm size (ha)	Livestock density (LSU/ha)	Cattle (1000 heads)	Pigs (1000 heads)	Poultry (10,000 heads)
Poland	14,410	10	0.64	5890	11,301	13,055
Belarus	3969	nd	0.92	2846	3151	3120
Germany	3645	155	0.75	2186	3196	1818
Sweden	3036	45	0.56	1497	1399	1655
Lithuania	2861	17	0.29	716	765	906
Denmark	2619	67	1.58	1615	12,076	1889
Finland	2282	42	0.51	912	1300	1029
Latvia	1878	23	0.26	413	365	499
Estonia	958	50	0.32	262	379	212
Russia	913	nd	1.17	501	718	3521

All data except average farm size from Hong et al. (2017), year 2013. Average farm size from EuroStat (2016a). LSU = Livestock Units according to Eurostat (2013), nd = no data.

The economic importance of the agricultural sector also varies between the countries. The output of agricultural goods as percentage of the gross domestic product (GDP) in the EU countries in the catchment in year 2016 was highest in Lithuania (5.5%) and lowest in Sweden (1.1%) (Table S1). The agricultural employment as percentage of total employment in year 2016 was highest in Poland (10.5%) and lowest in Germany (1.3%) (Table S1). Farmers' income varies among and within countries in the catchment. Farm net-value-added per full-time person equivalents working on the farm is highest in Denmark and lowest in Latvia, Lithuania, and Poland, out of the EU countries in the catchment (EC, 2016b). For the entire EU-27, a strong relationship exists between the economic size of farm businesses and the average levels of income generated, with higher income for larger farm businesses (Hill and Bradley, 2015).

2.2. Data sources and calculations

Here we use agricultural nutrient surpluses, livestock density, percentage of imported/locally produced feed, and nutrient flows related to production and consumption of food, based on data developed by Hong et al. (2017). We focus on total N and P and refer to them as nutrients for simplicity.

We focus on five-year averages for the years 2008–2012. Hong et al. (2017) used the net anthropogenic N and P inputs accounting approach (NANI-NAPI) that has also been described in detail in Howarth et al. (1996), Howarth et al. (2012), Hong et al. (2012) and Swaney et al. (2012).

Hong et al. (2017) used data from Eurostat for EU countries, national statistics for regions in Russia and Belarus, and published conversion parameters to calculate the components of NANI-NAPI (Supplemental material Section 1 and Tables S2–S4). We also calculated livestock units from data provided by Hong et al. (2017) using standard coefficients from Eurostat (2013) to facilitate analysis. The spatial unit for the data collected is Nomenclature of Territorial Units for Statistics 2 (NUTS2) for EU countries and oblast for Russia and Belarus (Fig. 1b). Oblast and NUTS2 are administrative geographical borders that are used for reporting statistics. Strong, linear relationships between NANI and NAPI and riverine fluxes of N and P have been found in the Baltic Sea catchment (Hong et al., 2017; Hong et al., 2012), as well as for regions in North America and Asia (Howarth et al., 2012; Swaney et al., 2012). For the Baltic Sea as a whole, riverine input of N and P was about 17% of NANI and 5% of NAPI in 2010 (Hong et al., 2017).

We calculated the agricultural N surplus (S_N) and P surplus (S_P) as

$$S_N = \mathrm{Fert}_N + \mathrm{Man}_N + \mathrm{Dep}_N + \mathrm{BNF} - \mathrm{Crop}_N \quad (1)$$

and

$$S_P = \mathrm{Fert}_P + \mathrm{Man}_P - \mathrm{Crop}_P \quad (2)$$

Fert_X was mineral fertilizer N or P, Man_X was manure N or P excretion, Dep_N was oxidized forms of atmospheric N deposition, BNF was biological N fixation by crops, and Crop_X was N or P in harvested crops. These values can be negative (i.e. deficits) and we refer to deficits as negative surpluses. All components used for calculating the surpluses were obtained from Hong et al. (2017). The agricultural surpluses were expressed as kg N or P per ha Utilized Agricultural Area (UAA). The UAA is defined by Eurostat (2017) as total area taken up by arable land, permanent grassland, permanent crops, and kitchen gardens. A majority of the UAA is arable land and permanent grassland. By focusing on agricultural surpluses per UAA (and not e.g. total land area), it is possible to make relevant comparisons between agriculture in different countries and regions, which allows for a better understanding of nutrient use in the agricultural system. However, while scaling by UAA enables a better understanding of agricultural issues, scaling net inputs by total area (e.g. in Hong et al., 2017) may be more useful for assessing the relative contribution of different regions to coastal nutrient loads (Swaney et al., 2018), especially when regions vary considerably in their agricultural area.

We used estimated manure excretion from Hong et al. (2017), which was calculated as numbers of livestock multiplied by excretion rates (Table S3). We follow the approach of Swaney et al. (2018) in our calculation of agricultural N and P surplus and use manure excretion, without accounting for manure losses such as excretion outside livestock housing or during handling of the manure collected in the housing. Most of the manure losses are somewhere in the catchment and have the potential to reach the sea. This is especially true for P which does not have gaseous forms, but to a large extent also for N because a large proportion of manure losses in the form of ammonia volatilization are deposited regionally (Boyer et al., 2002). This approach also eliminates the uncertainties in quantifying the manure losses.

Our approach assumes that all nutrients, including manure N and P, were spread evenly across all the agricultural land within the given NUTS2 or oblast; in reality, this is unlikely. Instead, the manure spreading areas are usually smaller, further increasing the local surpluses in high-intensive livestock production areas.

The amount of N and P in feed within a NUTS2 or oblast is calculated by Hong et al. (2017) based on number and type of livestock. The feed import (or export) is then calculated as the difference between the amount of nutrients needed by livestock and the amount and type of feed crops grown within each NUTS2 or oblast.

We used analysis of covariance (ANCOVA) to test the significance of the relationship between livestock density and N, P surplus at the country level. Tukey's post-hoc test was used for pair-wise comparisons of countries.

Soil P status in agricultural soils was mapped using data from the LUCAS soil survey (Tóth et al., 2013). We used CORINE land cover 2012 (categories 211, 212, 221, 222, 231 and 241) (EEA, 2007; http://land.copernicus.eu/pan-european/corine-land-cover/clc-2012) to choose LUCAS data points on agricultural land in the NUTS2 regions within catchment (i.e. same NUTS2 regions as in Hong et al. (2017)), resulting in about 2400 data points. The median soil P value was calculated for each NUTS2 and mapped in Fig. 2d.

3. Results and discussion

3.1. Nutrient surpluses varied across the catchment

Regional agricultural N and P surpluses varied greatly across the Baltic Sea catchment (Fig. 2a and b). Denmark, and regions in Poland, Russia, and Belarus had especially high surpluses. The components of the N and P surpluses are shown in Fig. 3. Manure and mineral fertilizer constituted various proportions of the inputs of N and P to agricultural land across the catchment, with Denmark and Russia having a large proportion of inputs as manure. The amount of P in manure compared to the amount of P in harvested crops (at a national level or part of country within catchment) varied from about 30% in Estonia, Latvia and Lithuania, to over 100% in Belarus, Russia and Denmark. Even though this is a coarse country-scale estimate, it shows that these countries (or part of country within the Baltic Sea catchment) would have had a P surplus even if mineral P fertilizers were completely omitted.

It is worth noting that crop yields are relatively low on average in the Russian parts of the catchment (Fig. 3), and in addition to the large amounts of manure and mineral fertilizer used, this is a contributing factor to the large N and P surpluses. Poor maintenance of agricultural drainage systems may be one important reason for low yields (Surovtsev et al., 2009). The data for EU countries comes from one data source (Eurostat), while national statistics were used for Russia and Belarus (Hong et al., 2017) and this may add some uncertainty to the comparison between the EU countries and Russia and Belarus.

3.2. Livestock density and feed imports contribute to nutrient surpluses

There were often large agricultural N and P surpluses in areas with high livestock densities, for example in Denmark and parts of Poland, Russia and Belarus (Fig. 2). In regions with high livestock density, a large proportion of feed is imported to the region (because agricultural land is needed to produce feed), and the resulting manure is often applied on nearby fields, leading to nutrient application in excess of crop demand. In this way, feed imports (together with fertilizer imports) lead to N and P surpluses and the accumulation of nutrients in regions that focused on livestock production. Indeed, we found that regions with high livestock density often imported a large proportion of the feed (out of total feed needed for livestock) (Figs. 2c and S2), which is consistent with previous literature related to the separation of crop and livestock production (Le Noe et al., 2017; Nesme et al., 2015; Schipanski and Bennett, 2012; Swaney et al., 2018). At the same time, surpluses were often low (or negative) in regions focused on crop production, but the production in these regions relies to a greater extent on imported mineral fertilizer and high levels of soil P arising from previous management practices. For example, in NUTS2 region DE41 Brandenburg–Nordost, average livestock density was less than 0.5 LSU ha^{-1}, average N in crop harvest greater than 85 kg ha^{-1}, and P surplus was negative.

The N and P surplus has been shown to increase with increasing livestock density in studies at continental, national and regional scale, especially at livestock densities above 2 LSU ha^{-1} (Liu et al., 2017; Nesme et al., 2015; Wang et al., 2018). For the Baltic Sea catchment, we also see that the N and P surpluses are related to the livestock density (Fig. 4; Table S5), but with livestock densities typically lower than what is often found in e.g. the Netherlands and China (Liu et al., 2017; Wang et al., 2018). There are some interesting differences between countries in the catchment (Fig. 4; Table S6) that may be due to differences in management and policy. For example, the Danish NUTS2 regions had lower nutrient surpluses than several other countries at the same level of livestock density (Fig. 4). Denmark has high livestock

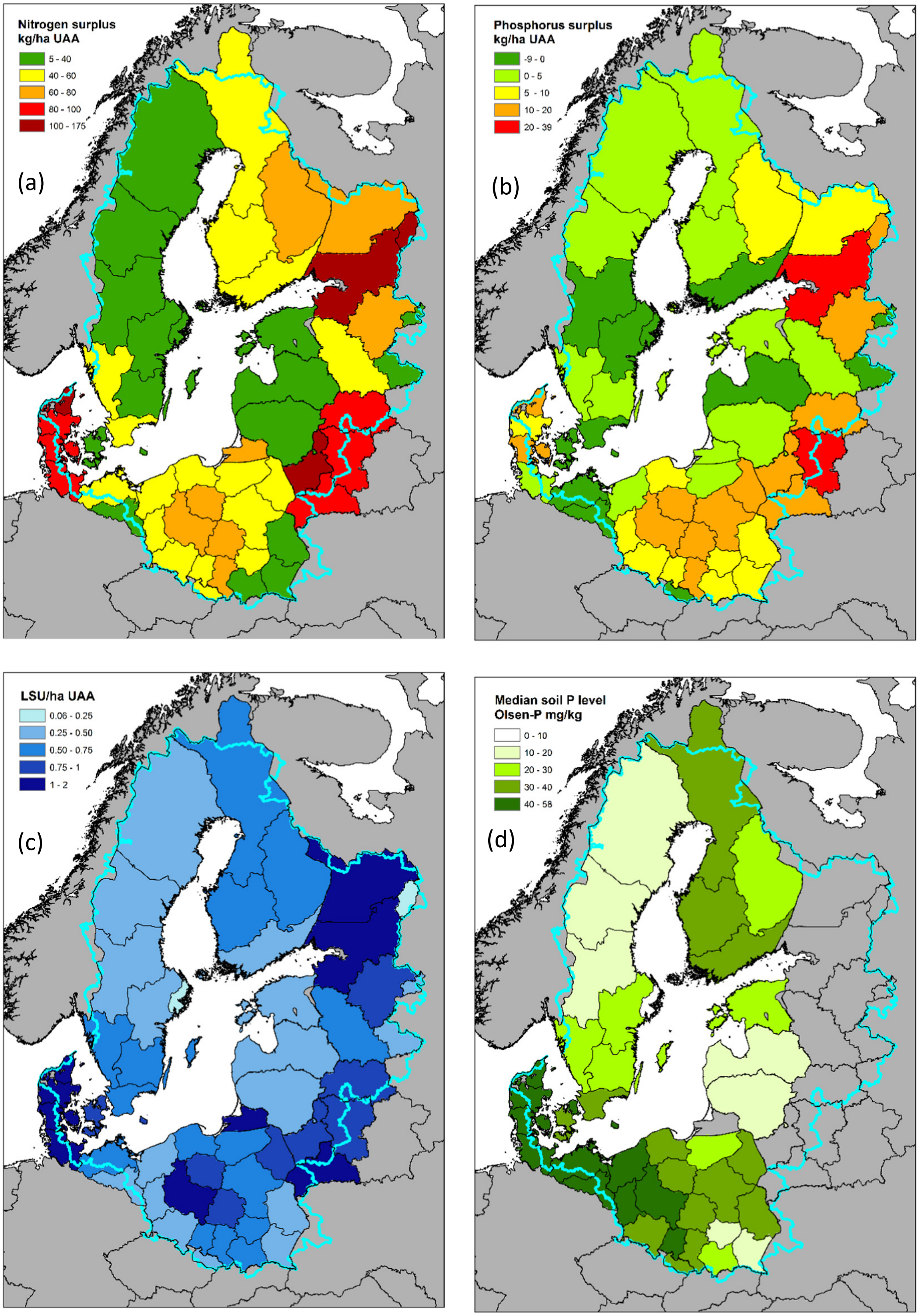

Fig. 2. (a) Nitrogen and (b) phosphorus surplus on agricultural lands in the Baltic Sea catchment. The location and extent of agricultural land is shown in Fig. 1a. The N surplus is calculated as the sum of manure N excretion, fertilizer N, oxidized forms of atmospheric N deposition, and biological N fixation in legumes minus N in harvested crops, expressed as kg N per ha utilized agricultural area. Same calculation for P except without atmospheric deposition and biological fixation. (c) Livestock density in the Baltic Sea catchment, i.e. livestock units (LSU) per ha utilized agricultural area (UAA). (d) Median topsoil P concentration on agricultural area. Soil P data from Tóth et al. (2013) and other data are averages for the period 2008–2012 from Hong et al. (2017).

densities relative to other countries in the Baltic Sea catchment (Table 1), especially regions on Jutland, i.e. DK03 Syddanmark, DK04 Midtjylland and DK05 Nordjylland. For the past several decades, policies in Denmark focused on using manure nutrients more efficiently and reducing primarily N-application (Dalgaard et al., 2014) (also see Section 3.5.1).Despite focusing on N, and only recently having more incentives directly related to P surpluses, policies and changes in nutrient management seem to have reduced P surpluses as well.

Poland and Belarus (oblasts within the catchment) often had higher P surplus than other countries with the same livestock density (Fig. 4; Table S6), indicating that there is potential for improvements. McCrackin et al. (2018) also found relatively low nutrient use efficiency

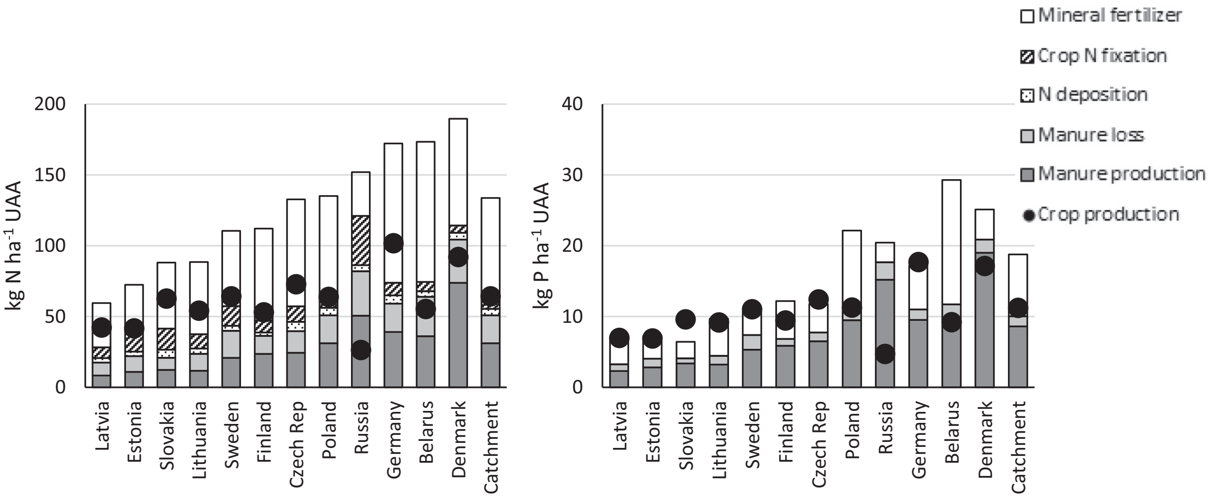

Fig. 3. The bars show the input of N and P in mineral fertilizer, biological N fixation by crops, oxidized N deposition, estimated manure losses and manure production (i.e. manure excretion minus losses). The points show the output of N and P in harvested crops. Data is expressed as kg N or P per utilized agricultural area and presented per country or part of country (only NUTS2 regions or Oblasts within the Baltic Sea catchment are included).

in regions in Russia, Belarus and Poland, and that improved nutrient use efficiency in these areas is important for reducing nutrient inputs to the Gulf of Finland and Baltic Proper. Substantial nutrient reductions in these sub-basins are needed to meet goals in the BSAP, especially for P (HELCOM, 2015) (map of sub-basins in Fig. S1). The N and P surpluses at the national level (or the part of country within the catchment) have decreased in most of the EU countries when averages for five-year periods centered on year 2000 and 2010 are compared, except that there was little change in surpluses in Poland and Estonia and some increases in Latvia (Table S7). The N and P surpluses in Russia and Belarus increased between the two periods (Table S7), which is due to both increasing inputs of fertilizer and/or manure and a decrease in agricultural area.

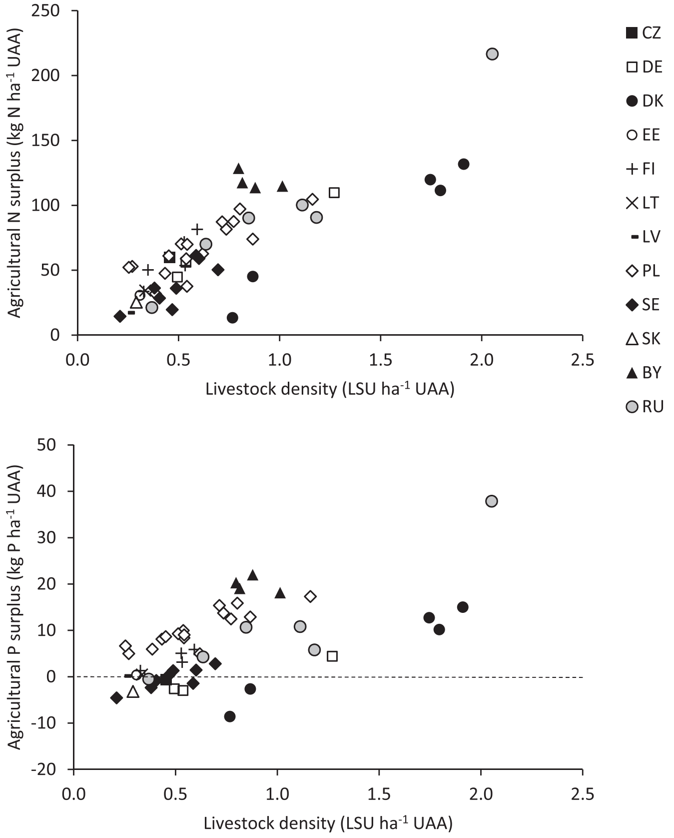

Fig. 4. Livestock density (livestock units per hectare utilized agricultural area) plotted against agricultural N and P surplus. Names of countries abbreviated as: CZ = Czech Republic; DE = Germany; DK = Denmark; EE = Estonia; LT = Lithuania; LV = Latvia; FI = Finland; PL = Poland; SE = Sweden; SK = Slovakia; BY = Belarus; RU = Russia.

3.3. Opportunity to use soil P reserves to a greater extent

When manure or P fertilizer is applied to agricultural land in excess of crop demand, much of the P accumulates in soils. If repeated over many years, the soil P level can rise well above the agronomic optimum, where there is a greater risk of P losses to the aquatic environment and further application does not increase yields (Bai et al., 2013; Valkama et al., 2009). In other words, soil P levels in agricultural soils reflect the P fertilization history to a large extent and not necessarily current P surplus. Correspondingly, we found that the median soil P concentration in agricultural land (per NUTS 2 region) from Tóth et al. (2013) was not explained by the agricultural P surplus for 2008–2012 from Hong et al. (2017) ($R^2 = 0.13$, not shown). This finding suggests that there are some areas where existing soil P content is considered in fertilization, or that there are areas where current build-up of soil P is not as large as earlier. On soils with high P levels, it is desirable to use existing soil P as much as possible, i.e. to have negative P surpluses (Rowe et al., 2016; Sattari et al., 2012). For example, in Finland about half of agricultural soils have such high soil P levels that P fertilization is unlikely to increase yields (Ylivainio et al., 2014). Also, current manure P content in Finland would be enough to meet plant P requirements, with no need for mineral P fertilizer, if manure could be spread to areas with actual need for P (Ylivainio et al., 2014).

From the standpoint of resource efficiency, P management resulting in high P surpluses on soils with high P levels is wasteful. Also, once soil P reaches excessive levels it can take decades to lower soil P levels to the agronomic optimum, and to lower P losses (Fiorellino et al., 2017; Svanbäck et al., 2015). We identified NUTS2 regions where both soil P levels and P surpluses were particularly high (Fig. 2b and d), and where the P surplus therefore need to be reduced substantially. These were the Danish NUTS2 regions DK03 Syddanmark and DK05 Nordjylland and the Polish NUTS2 regions PL41 Wielkopolskie and PL61 Kujawsko-Pomorskie. These four NUTS2 regions were also among the top-ten within the catchment with the highest livestock density.

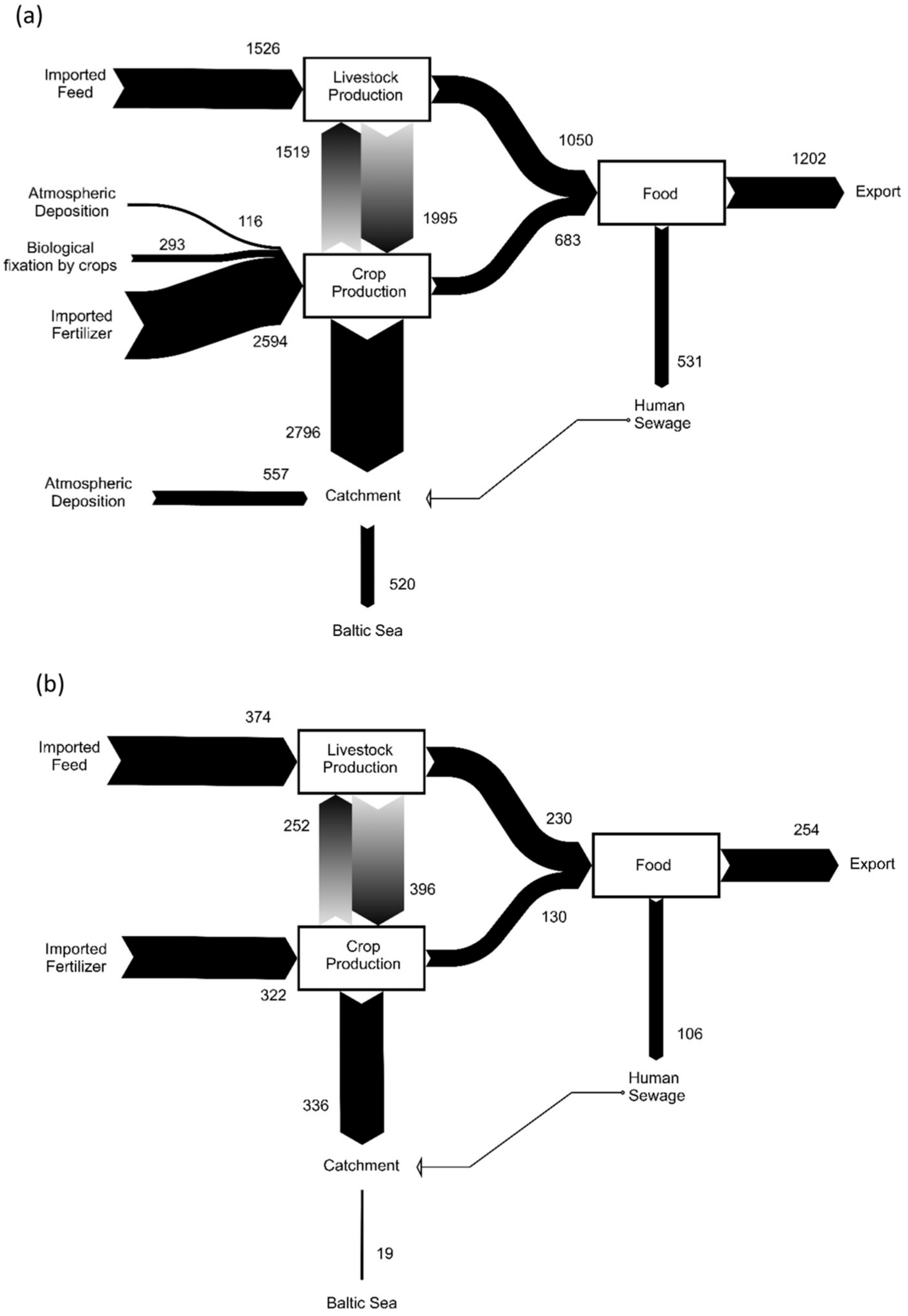

Fig. 5. Magnitude of (a) nitrogen and (b) phosphorus net flows in the food production and consumption system in the Baltic Sea catchment. (Unit: 1000 tons N or P.)

3.4. Nutrient flows connected to production of food and sewage

Nitrogen and P are imported primarily as mineral fertilizer and feed, while the region is a net exporter of food products (Fig. 5). Imported mineral fertilizers are used in crop production and over 65% of crops grown in the catchment are used to feed livestock, together with the imported feed (Fig. 5). Livestock in the Baltic Sea catchment excrete 1.8 million tons of N and 0.37 million tons of P in manure annually, which is more than three times as much as in excreta from humans (Hong et al., 2017). Decades of imports have led to the accumulation of nutrients, for example as buildup of soil P levels and losses to lakes and rivers. On agricultural land over the entire catchment, only about 60% of P and 50% of N in mineral fertilizer, manure, atmospheric N deposition, and biological N fixation are converted to harvested crops (Fig. 5). Agricultural systems will never be perfectly efficient because of unavoidable nutrient losses, but in the Baltic Sea region, there is room for improvement. Scenario analysis suggests that redistributing manure nutrients within NUTS2-regions/oblasts and reducing over-fertilization could reduce annual fertilizer imports by 165–252 thousand tons N and 70–120 thousand tons P (McCrackin et al., 2018).

Only a small proportion of nutrients reaches the Baltic Sea (Fig. 5), about 14% and 4% of net N and P inputs to the catchment, respectively (Hong et al., 2017), but the inputs to the sea have a large environmental impact (HELCOM, 2017). The inputs of “new” N and P to the agricultural system, i.e. import of mineral fertilizers and feed (in contrast to “recycled” manure sources), need to be reduced to reduce the amount of nutrients that cycle, accumulate, and potentially leak to the environment.

3.5. Reducing nutrient surpluses

Nutrient surpluses in agriculture can be reduced in several ways. In crop production, it comes down to fertilizing according to crop demand, accounting for existing soil P levels, minimizing losses, and recycling nutrients more efficiently. Knowledge about expected crop yields and soil P levels is needed to do this, as well as good fertilizer application practices and manure handling. Increased yields through measures other than N and P application can also reduce nutrient surpluses and increase nutrient use efficiency at the farm level (Nordin and Höjgård, 2017). Over-application of N and P, especially with mineral fertilizer, is an unnecessary cost for the farmer and can be reduced by better-informed nutrient management. However, it is clearly more challenging to reduce nutrient surpluses in regions focused on livestock production, where feed import is large. In areas (or on farms) where the amount of N and P in manure exceeds crop demands there are options to reduce nutrient surpluses, including:

- Eliminate over-application of mineral fertilizers.
- Match livestock feed rations to their nutritional requirements (Arriaga et al., 2009; Dourmad and Jondreville, 2007; Pomar et al., 2009), i.e. avoiding overfeeding, thereby reducing feed import and N and P in manure. Improve livestock nutrient utilization, for example by using phytase in feed for monogastrics (Adeola and Cowieson, 2011).
- Reduce the number of livestock, to reduce feed imports and manure production.
- Use manure more efficiently to reduce the need to import mineral fertilizer. Adequate manure storage, timing of application, application technique and amount are essential for good nutrient management on livestock farms.
- Increase yields through measures such as improving soil structure, drainage, and changes in crop types or varieties, etc.
- Transport manure or manure products to other regions that need crop nutrients. Many techniques exist for processing the manure and making a product which is more easily transported, and in some cases more similar to commercial mineral fertilizer (Flotats et al., 2011; Hanifzadeh et al., 2017; Hjorth et al., 2010). The choice of technique depends on factors such as local conditions at the livestock farm, how far the manure product needs to be transported, and handling requirements for the transported manure product.

3.5.1. Examples of incentives for reduced nutrient surpluses

EU policy plays an important role in water management and agriculture in the Baltic Sea catchment, as eight of the nine coastal countries are EU-members. The main objective of EU water policy is to ensure access to good quality water in sufficient quantity for all Europeans and to ensure the good status of all water bodies across Europe. The Water Framework Directive (WFD) (EC, 2000) and the Marine Strategy Framework Directive (MSFD) (EC, 2008) have targets and programs of measures that affect agriculture, but do not in themselves finance these measures.

The Nitrates Directive has the objective of reducing water pollution caused or induced by nitrates from agricultural sources and preventing further such pollution (EC, 1991). Measures include limiting application rates of manure N, limiting periods when N can be applied, conditions for application (not on frozen soil, water saturated soils, steep slopes, close to water bodies etc.) and techniques for application. The maximum manure application rate of 170 kg N ha^{-1} year^{-1} applies to all countries while the other measures may vary. However, Denmark has farms with exemptions from the maximum 170 kg N ha^{-1} year^{-1}, so called derogation farms, where up to 230 kg N ha^{-1} year^{-1} is allowed (EC, 2017). At these farms, measures (such as catch crops, crop rotations with high N uptake and long growing season) should be taken so that the objectives of the directive are still attained.

The Common Agricultural Policy (CAP) within EU contains both funding and legislation. Objectives of CAP include viable food production, sustainable management of natural resources and climate action (EC, 2013). A majority of the total EU CAP budget is spent on direct payments (Tropea, 2017), which can be seen as income support based on the area that a farmer manages. The CAP supports voluntary agri-environmental measures through the rural development programs (RDP's) and these measures vary between countries.

The integration of EU's water policy objectives into the CAP have only been partially successful, due to a mismatch between the ambition of the policy objectives and the ability of the instruments used to effect change (ECA, 2014). It is argued that the direct payments generally increase environmental pressure; by subsidizing land use and the associated production, the direct payments are not capable of controlling environmentally damaging emissions, which is also in conflict with broad CAP objectives (Brady et al., 2017). To receive direct payments and/or certain rural development funds, farmers must meet certain environmental obligations, so called cross-compliance and greening. For example, greening includes measures for crop diversification and maintenance of environmentally sensitive grasslands. The effects of greening seem to be very limited as it has not led to any large changes in management and practices (ECA, 2017; Hart, 2015); a redesign of this payment could result in greater environmental benefits from the CAP (Buckwell et al., 2017).

The current EU fertilizer regulation does not include fertilizer products made from recycled nutrients, such as manure (EC, 2003) and a new fertilizer regulation has been proposed within the EU's circular economy package that would include fertilizer products made from recycled nutrients (EC, 2016a). This would help to create a market for secondary raw materials by establishing common quality standards, but other policy incentives are also needed to make manure, or fertilizer products made from manure, more cost-competitive with synthetic and mineral fertilizers. Farmer acceptance of recycled nutrients is a key issue, and an understanding of the end-user requirements and the fertilizer market is needed to increase the adoption of organic waste processing technologies and the production of new types of bio-based fertilizers on a large scale (eip-agri, 2017).

Limiting N and/or P application rates, requiring specific nutrient use efficiency for manure, or regulating N and P application based on nutrient balances, would likely spur the development and application of manure processing and transportation in areas with excess manure.

The countries in the Baltic Sea catchment have different approaches to incentivizing nutrient management. For example, some countries (e.g. Denmark) use more mandatory regulations ("command and control") regarding e.g. fertilization rates, while others (e.g. Finland and Sweden) have fewer mandatory regulations, but focus more on voluntary measures and subsidies (Table 2). In the most recent RDP's (years 2014–2020), there are examples of support for improved nutrient management (EC, 2014b). Several countries support measures that reduce the transport of nutrients from the field or in the landscape, such as winter cover crops, buffer zones and wetland areas. The Finnish subsidy specifies maximum allowed application rates of N and P to different types of crops (FMAF, 2014). The Finnish RDP also includes specific support for more efficient use of manure, with subsidies for the extra cost of spreading manure purchased from other farms (to increase interaction between crop and livestock farms). Polish farmers in nitrate-vulnerable zones, as well as Latvian and Swedish farmers, can apply for support for handling techniques/equipment for collection and storage of manure (LMA, 2014; PMARD, 2014; SBA, 2014).

Sweden regulates livestock density based on P application rate, requiring that there is enough agricultural area for spreading manure so that the maximum manure application rate is 22 kg P ha^{-1} year^{-1}, averaged over five years for the entire spreading area (SBA, 2012). This requirement limits the amount of manure produced on a farm in relation to spreading area and enforces the connection between livestock production and crop production. Together with legislation on manure

Table 2
Examples of incentives for improved nutrient management and reduced nutrient balances in EU countries in the Baltic Sea catchment.

Objective	Command and control	Subsidies	Tax
Limiting fertilizer input	• Regulate N fertilizer rate (DK) (EPA, 2017) • Regulate maximum surplus (DE) (BMJV, 2017)	• Limited fertilizer rate as requirement to get RDP subsidy (FI) (FMAF, 2014)	• Fertilizer tax (earlier in FI and SE) (Anon, 1992; SFS, 1984)
Calculating nutrient balance at farm and/or field level	• DK, DE (BMJV, 2017; EPA, 2017)	• SE through farm advisory service (Greppa, 2011; SBA, 2014)	
Improved feeding			• Tax on mineral P in feed (DK) (DMT, 2016)
Nutrient management practices and techniques	• Closed periods for manure application • Manure application techniques • Manure storage capacity and construction (Applicable in EU countries through implementation of the Nitrates Directive)	• Manure storage construction (PL, LT, SE) (LMA, 2014; PMARD, 2014; SBA, 2014) • Equipment for good manure application (FI, Schleswig-Holstein, Mecklenburg-Vorpommern) (Anon, 2014a, 2014b; FMAF, 2014)	
Livestock density	• Requiring enough manure spreading area so that a certain manure P application rate is not exceeded (SE) (SBA, 2012)		
Crop livestock reconnection		• Connecting crop farms and livestock farms for manure exchange (FI) (FMAF, 2014)	

storage, it functions as a basis for good manure nutrient management (Aronsson and Johnson, 2017).

In Denmark, there is intensive and export-oriented livestock production which has led to relatively large N and P surpluses. Nitrate pollution of groundwater and negative impacts from agriculture on vulnerable freshwater and marine environments have been addressed through several different action plans since 1985 (Dalgaard et al., 2014). Much focus has been on N and detailed regulation (EPA, 2017) that obliges farmers to have proper manure storage and to consider manure and fertilizer as valuable resources. This focus has significantly reduced N surplus, increased N use efficiency, and reduced N losses from agriculture (Dalgaard et al., 2014; Pilgaard Vinther and Olsen, 2017). The measures have generally been mandatory, applicable to all farmers and without compensation. However, Danish N and P surpluses are still relatively high (Fig. 2a and b) and further action is needed, especially to comply with the WFD. More recently, Danish policy has focused more on targeted measures, and increasing attention on P (Christel and Olsen, 2017; EPA, 2017).

Polish agriculture is quite heterogeneous in terms of farm size and level of specialization and intensity. While there are many small farms currently, farm structure is changing towards fewer and larger farms (EuroStat, 2016a). The Polish RDP supports land consolidation, with the aim to merge agricultural land and to reduce the number of small, scattered plots that make up the farm, and thereby increase the average farm size (PMARD, 2014). Kopinski and Jurga (2016) found that Polish agriculture is experiencing deepening regional differentiation of agriculture intensity, expressed as mineral P fertilizer consumption. They also found large differences in P surplus between NUTS2 regions in Poland, with PL41 Wielkopolskie as an example of a region with high P surplus, high soil P status, and an increasing trend in animal production. Farm-level P surpluses varied widely in a study of 25 farms each in the Polish NUTS2 regions PL 12 Mazowieckie and PL 63 Pomorskie, with a negative P surplus on 31% of all farms (Ulén et al., 2016). Mean P surplus was highest for pig farms and lowest for mixed farms and this was also the case for mean soil P concentration. Farm-gate balances indicated increasing P level for many farms with the highest soil P concentrations and depletion for farms with low livestock density. Based on these farm-gate nutrient balances, manure should be exported from pig farms to arable and small mixed farms in order to reduce overall surplus in the area (Ulén et al., 2016).

In Russia, farmers can get government support to purchase mineral fertilizer (Lindgren, 2013), which is a negative incentive for efficient nutrient use. During the Soviet era, investments were made to increase livestock production in these Russian regions, but equivalent investments were not made in manure storage and equipment for efficient utilization of manure (Lindgren, 2013; Surovtsev et al., 2009). Implementing environmental policy and addressing environmental issues currently seem to be low priorities in Russia (Lindgren, 2013; OECD, 2006).

4. Conclusions

In this study, we quantified N and P surpluses on agricultural lands in the Baltic Sea catchment and showed that nutrient surpluses are connected to livestock density. Regions with high livestock density often imported a large proportion of the feed (out of total feed needed for livestock). However, management practices appear to affect how large surpluses are at a certain livestock density, with varying surpluses across the catchment also for regions with similar livestock density. The surpluses have been reduced between years 2000 and 2010 in Denmark, Finland, Germany, and Sweden, which suggests that improved agricultural nutrient management has had an effect in these areas. There is room for further improvements in the catchment, especially in Russia, Belarus and Poland. Although substantial reductions in surpluses have been made in Denmark through regulation and technical improvements, surpluses are still relatively high due to high livestock density.

To lower the overall N and P surplus in the Baltic Sea catchment, imports of mineral fertilizer and feed need to be reduced. To accomplish this, over-application of N and P to crops and over-feeding of livestock animals needs to cease, and nutrient recycling needs to increase. The spatial separation between crop and livestock production is an important driver for nutrient surpluses. Manure is often used inefficiently in livestock-dense regions that import large quantities of feed, while regions focused on crop production are more dependent on mineral fertilizers. The recirculation of N and P needs to increase, either by moving manure in different forms to partially substitute for mineral fertilizers in regions focused on crop production, or by moving livestock or reducing livestock numbers to accomplish a better balance between crop and livestock production.

There are many policies that can improve agricultural nutrient management further within the current agricultural structures. For example, farm advisory services can increase farmer knowledge about nutrient management. Adequate manure storage and application techniques are critical prerequisites of efficient use of manure and investments may be needed. Regulations can limit the amount of P that can be applied and consider existing soil P reserves. Lastly, support for processing and trade of manure-based fertilizers can reduce nutrient imbalances between crop and livestock farms.

However, given that the separation of crop and livestock production is an underlying cause of nutrient surpluses, further analysis is needed to identify how policy can best address these structural issues to reduce nutrient surpluses and increase sustainability in food production.

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Appendix A. Supplementary data

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