



Opportunities to reduce nutrient inputs to the Baltic Sea by improving manure use efficiency in agriculture

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Abstract

While progress has been made in reducing external nutrient inputs to the Baltic Sea, further actions are needed to meet the goals of the Baltic Sea Action Plan (BSAP), especially for the Baltic Proper, Gulf of Finland, and Gulf of Riga sub-basins. We used the net anthropogenic nitrogen and phosphorus inputs (NANI and NAPI, respectively) nutrient accounting approach to construct three scenarios of reduced NANI-NAPI. Reductions assumed 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. We also used the Simple as Necessary Baltic Long Term Large Scale (SANBALTS) model to compare eutrophication conditions for the scenarios to current and BSAP-target conditions. The scenarios suggest that reducing NANI-NAPI by redistributing manure nutrients, together with improving agronomic practices, could meet 54–82% of the N reductions targets (28–43 kt N reduction) and 38–64% P reduction targets (4–6.6 kt P reduction), depending on scenario. SANBALTS output showed that even partial fulfillment of nutrient reduction targets could have ameliorating effects on eutrophication conditions. Meeting BSAP targets will require addressing additional sources, such as sewage. A common approach to apportioning sources to external nutrients loads could enable further assessment of the feasibility of eutrophication management targets.

Keywords Baltic Sea · Eutrophication · NANI · NAPI · Nitrogen · Phosphorus · Manure

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Introduction

Eutrophication is a pervasive and serious environmental problem in the Baltic Sea, which is home to the world's largest hypoxic zones (areas with insufficient oxygen to support aquatic animal life). Over the past 40 years, the maximum seasonal extent of hypoxia has averaged 49,000 km², ranging between 12,000 and 70,000 km² (Conley et al. 2009). The causes and consequences of eutrophication are well documented, and a number of policies have been implemented to reduce external nutrient inputs (Andersen et al. 2017; HELCOM 2017). These policies include the Helsinki Commission (HELCOM) Baltic Sea Action Plan (BSAP), an ambitious program that established nutrient reduction targets to restore the ecological status of the Baltic marine environment by 2021. Additionally, a number of European Union (EU) policies legally require member states—eight of the nine coastal counties—to reduce nutrient inputs to surface waters in order to meet environmental goals (Schumacher 2012).

Since 2000, N and P inputs to the Baltic Sea have decreased by 9 and 14%, respectively (Svendsen et al. 2015b). There has been greater progress in achieving N reductions compared to P and current loads remain about 8 and 47%, respectively, greater than their targets. Due to reductions in coastal sewage effluent inputs and atmospheric N-deposition, agriculture remains the largest source of external nutrients, contributing about half of waterborne loads (HELCOM 2011). The situation in the Baltic Sea region is not unique; nutrients from agriculture contribute to eutrophication in many regions globally (Moss 2008; Withers et al. 2014).

To improve the effectiveness of nutrient abatement efforts, it is important to identify opportunities to reduce loads associated with agriculture. Previous research has found that there is opportunity to use nutrients in livestock manure more efficiently in crop production (Oenema et al. 2007; Buckwell and Nadeu 2016). More specific to the Baltic Sea region, Hong et al. (2017) estimated net anthropogenic N and P inputs (NANI and NAPI, respectively) for the entire region and found that the amount of nutrients in livestock manure could meet a large portion of crop and forage nutrient needs at the country scale. These results suggest that over-fertilization is occurring and that manure is not being used efficiently. Consequently, it could be possible to reduce NANI-NAPI by redistributing manure nutrients and using them in place of imported fertilizers (synthetic, Haber-Bosch-derived fertilizers for N and phosphate rock-derived fertilizers in the case of P). Reductions in NANI-NAPI could, in turn, reduce nutrient loads to the sea because of the strong, positive relationship between NANI-NAPI and river nutrient loads (Hong et al. 2017). Indeed, Bouraoui et al. (2014) reported greater reductions in N loads to the Baltic Sea in modeling scenarios that optimized the reuse of manure as fertilizer compared to

scenarios that improved sewage treatment or changed human diets.

Here, we build on Hong et al. (2017), to estimate potential reductions in nutrient loads to the Baltic Sea by using manure more efficiently in agriculture. While Bouraoui et al. (2014) estimated reductions for the entire sea, we focus on three major sea sub-basins for which further nutrient load reductions are needed to meet BSAP targets: Baltic Proper, Gulf of Finland, and Gulf of Riga (Svendsen et al. 2015a). It is particularly relevant to consider where nutrient reductions are possible because of how the targets were allocated. The BSAP used the “polluter pays” principle to allocate reductions among countries in proportion to their nutrient inputs for the reference period 1997–2003. These country-specific targets did not consider where the most cost-efficient reductions could be implemented or where there was the greatest potential for nutrient reductions (Elofsson 2010). Thus, it is possible that some countries may be unable to meet their target.

To identify areas where reductions from agriculture are possible, we use nutrient use efficiency (NUE) in crop and forage production. NUE is a measure of the conversion of the amount of nutrients in inputs, such as synthetic and mineral fertilizers and manure, to the amount of nutrients in outputs, such as crop harvest (Gerber et al. 2014). NUE is a useful approach to benchmark nutrient management in agriculture. Regions with low NUE are generally associated high nutrient surpluses and have greater risk of nutrient loss via leaching, overland flow, and volatilization to the atmosphere in the case of N (Lassaletta et al. 2014; Sharpley 2016).

We have three objectives in this paper. First, we estimate NUE in crop and forage production for N and P (NUE_N and NUE_P, respectively) at regional and national levels. Second, we construct scenarios to understand the potential to reduce NANI-NAPI and consequently, nutrient inputs to the Baltic Sea by using manure more efficiently (Howarth et al. 2012; Swaney et al. 2012). Lastly, we use a steady-state marine model to understand the effect of reduced nutrient inputs on eutrophication in the Baltic Sea.

Methods

Study area

The drainage basin of the Baltic Sea includes all or part of 14 countries (Fig. 1a in ESM). We do not further discuss the Czech Republic, Norway, Slovakia, or Ukraine, because these countries occupy < 3% of the basin area. We defined sub-national regions using the EU's data collection system (Nomenclature of Territorial Units for Statistics, NUTS2) and oblasts (Russia and Belarus) within the drainage basin of the sea. All countries have multiple sub-national regions,

except for Estonia, Latvia, and Lithuania where the NUTS2 delineation is the same as the entire country.

The Baltic Sea has seven sub-basins: Baltic Proper, (BP) Bothnian Bay, Bothnian Sea, Danish Straits, Gulf of Finland (GF), Gulf of Riga (GR), and Kattegat (Fig. 1b in ESM). Land areas that drain to each sea sub-basin are detailed in Online Resource 1.

Net anthropogenic nitrogen and phosphorus inputs

Our work is based on the NANI-NAPI nutrient accounting approach that is described in detail by Swaney et al. (2012). Briefly, NANI was estimated as the sum of imported inorganic fertilizer, net import or export of N embedded in food and feed, biological N-fixation (BNF) by agricultural plants, and oxidized atmospheric N-deposition. NAPI was estimated as the sum of imported fertilizer, and import or export of P embedded in food and feed, and imported P detergent. Nitrogen and P that were converted to livestock manure represented recycled nutrients, not new sources. As such, manure is not typically calculated under the NANI-NAPI approach; however, Hong et al. (2017) explicitly calculated manure in order to estimate agricultural nutrient surpluses and explore NUE in crop production.

Previous research found strong, linear relationships between NANI and NAPI and riverine fluxes of N and P, respectively, for regions in North America, Europe, and Asia (Howarth et al. 2012). As a result, riverine N and P inputs resulting from human activities can be estimated as the product of NANI and NAPI, respectively, and land-to-sea transfer efficiencies for each sea sub-basin. Transfer efficiency, the proportion of NANI and NAPI exported from land to sea for the Baltic Sea as a whole, was 14 and 4%, respectively, in 2010. Transfer efficiencies did not differ significantly between 2000 and 2010, despite substantial changes in regional NANI and NAPI over the same period (− 40 to + 58 and − 25 to + 19%, respectively, depending on sub-basin) (Hong et al. 2017). These results suggest that we can estimate potential reductions in nutrient loads as product of the reduction in NANI-NAPI and the transfer efficiency; as a result, we held transfer efficiencies constant across scenarios (Online Resource 1).

Nutrient use efficiency in crop and forage production

We estimated NUE for the 5-year periods centered on 2000 and 2010 as

$$NUE_N = Plant_N / (Fert_N + BNF + Dep_N + Man_N) \quad (1)$$

and

$$NUE_P = Plant_P / (Fert_P + Man_P). \quad (2)$$

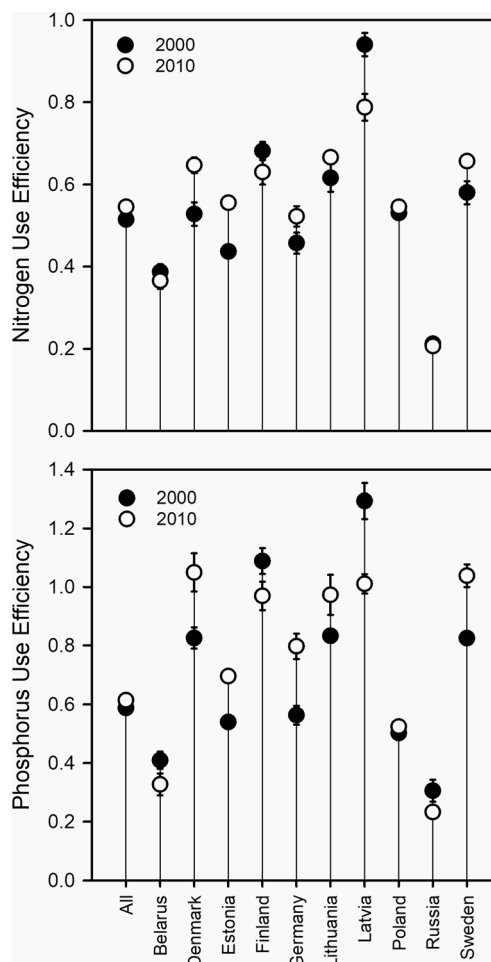


Fig. 1 Comparison of average (+/− standard error) nitrogen (upper panel) and phosphorus (lower panel) use efficiency in crop production for countries (or portions of countries) in the Baltic Sea drainage basin for the 5-year periods centered on 2000 (filled circles) and 2010 (open circles)

Plant_x was nutrients removed in harvested crops and by grazing livestock, Fert_x was imported inorganic fertilizer, and Man_x was livestock manure applied to crops and deposited on grazed areas by livestock, where x was N or P (all in kg per hectare of utilized agricultural area (UAA)). BNF was biological N-fixation by agricultural plants. Dep_N was atmospheric deposition of oxidized-N. Man_x was less than the amount excreted by animals because of leaching and volatilization losses (Online Resource 1).

One can estimate N and P surpluses on agricultural land from these same components as the difference between the denominator and the numerator in Eqs. 1 and 2, respectively (i.e., inputs minus outputs). All components of NUE were obtained from Hong et al. (2017), who used statistical databases for the EU, Russian Federation, and Belarus and published conversion parameters (e.g., nutrient content in excreta of different livestock) for NANI-NAPI calculations (Online Resource 2). We also calculated livestock units from

data provided by Hong et al. (2017) using standard coefficients from Eurostat (2013) to facilitate analysis.

Future scenarios

We constructed scenarios to explore the potential to meet BSAP nutrient reduction targets by reducing the imported synthetic and mineral fertilizer component of NANI-NAPI (HELCOM 2013). Our approach assumed that these reductions were achieved by redistributing manure nutrients within a region, from areas that focus on livestock production, where over-application of nutrients occurs, to areas that focus on crop production, where it is substituted for some of the imported fertilizer. Specialization and spatial separation of crop and livestock production systems can result in over-application of nutrients in regions that have large amounts of manure in relation to arable land (Nesme et al. 2015).

Our approach to estimating potential reductions in NANI-NAPI iteratively increased the minimum NUE for a region (as shown in Fig. 1a in ESM) until certain stopping conditions were met. In concept, regions with low NUE bore greater NANI-NAPI reductions than regions with already high NUE. Through this process, NUE for a region could only increase, not decrease. Starting with the regions with the lowest NUE, we reduced the fertilizer component (thus reducing NANI-NAPI and increasing NUE) until one of three conditions was met: (1) the new regional NUE met a theoretical limit, (2) fertilizer import in a region was reduced to zero (in such cases, crop nutrient needs equal to $Plant_X$ were met by Man_X), or (3) the BSAP reduction target for the sea sub-basin was met. There was no transfer of manure between regions.

We capped regional NUE_N at 0.75, a theoretical limit for Europe that is below the 90% established by the EU Nitrogen Expert Panel (2015), because using manure-N efficiently in crop production in mixed crop-livestock systems is challenging (Zhang et al. 2015).

Identifying a limit for NUE_P was more difficult, because farmers are often advised to apply sufficient P to compensate for the amount removed in crop harvest once a certain level of soil P-availability is established and to apply less than the amount removed in crop harvest if soil P levels are above the recommended range (Jordan-Meille et al. 2012). If soils P levels are very high, crop yields can be maintained even at very low or no P application (Le Noe et al. 2018). It was beyond the capability of our approach to consider existing soil reserves. For simplicity, we assumed that NUE_P does not exceed 0.9, recognizing that some inefficiency is inevitable.

Where regional NUE for 2010 exceeded the theoretical limit, we increased fertilizer imports (and thus, NANI-NAPI and river loads to the sea) for that region until NUE_N of 0.75 or NUE_P of 0.90 was achieved. We made this adjustment in the scenarios in order to acknowledge that NUE above theoretical limits is not sustainable for long periods.

The three scenarios were designed to compare outcomes if reductions in nutrient loads aligned with country-allocated reduction targets (CART) under the BSAP or if reductions were made in regions where there is greater opportunity to improve agronomic practices, as indicated by low NUE:

OptCART: NANI-NAPI reductions were optimized to meet CART, and no country-level reduction exceeded their BSAP commitment.

NoCART: NANI-NAPI reductions were prioritized for regions with low NUE, irrespective of CART. The intent of this scenario was to explore “best-case” nutrient reductions; thus, it was possible that a country could bear greater nutrient reductions than its BSAP commitment.

NoCART-EU: Same as NoCART scenario but for EU countries only. The intent of this scenario was the same as for NoCART, but we excluded Russia and Belarus, because common policy instruments exist to address nutrients from agriculture within the EU. There was no change in NANI-NAPI from year 2010 for Russia and Belarus.

We assumed that reducing nutrient application rates did not affect crop yield. We recognize this to be a simplification, because the fertilizer-yield curve shows that, all things being equal, reducing nutrient application rates reduces crop yield. However, in the low-response segment of the yield curve, crop yield responses to nutrient inputs tend to diminish when nutrient application rates are high, suggesting that reducing “over-application” will have minimal impact on yield.

Historical nutrient budgets have found that for many countries, decreases in N inputs have been accompanied by constant or increasing crop yields (Lassaletta et al. 2014). Such results have been credited to changes in agricultural practices, such as the placement and timing of nutrient application and the use of improved seed varieties (Cassman et al. 2002). For the scenarios, we assumed that reductions in N inputs were accompanied by changes in, for example, how, when, and where nutrients were applied (Kirchmann et al. 2002). In the case of P, a synthesis of field-scale studies found negligible to low yield responses to fertilization on soils with medium or high soil P levels (which is the case for much of the Baltic Sea region per Tóth et al. (2014)) (Valkama et al. 2009).

We only explored land-based nutrient reductions to BP, GF, and GR, because the latest HELCOM assessment found that further nutrient reductions are needed to achieve BSAP targets for these sub-basins, while targets for other sub-basins have been met or nearly met (Svendsen et al. 2015a).

Eutrophication responses to reduced riverine nutrient inputs

We used the Simple as Necessary Baltic Long Term Large Scale (SANBALTS) model to explore the effect of scenarios

of reduced nutrients on eutrophication conditions in the sea in comparison to 1900, 2010, and BSAP-target conditions. This marine model was used to develop nutrient reduction targets for the BSAP in 2007. For the scenarios, we only altered data inputs related to riverine nutrient loads to BP, GF, and GR and held other data inputs constant (Online Resource 3).

SANBALTS simulates steady-state, coupled-N and coupled-P cycles in the seven sub-basins of the sea. The model is driven by external nutrient inputs, biogeochemical fluxes in sub-basins, and transport between sub-basins (<http://apps.nest.su.se/next/>). Wulff et al. (2013) provide the model documentation. Briefly, the rate of N-fixation by phytoplankton depends on the ratio of water-column N/P concentrations and the stoichiometric P surplus. When the N/P ratio is < 7 (mass basis), there is a surplus of P relative to N under to the Redfield ratio, which creates conditions that favor N-fixation. The modeled Secchi depth is based on empirical relationships between mean water clarity and water-column N and P concentrations. Savchuk and Wulff (2009) reported that SANBALTS output compared well with measurement-derived data for a number of ecosystem components, such as sub-basin average nutrient concentrations, Secchi depth, and hypoxic area.

We used SANBALTS-derived estimates for water-column concentrations of TN and TP (both in $\mu\text{mol L}^{-1}$) and Secchi depth (m) as response variables for the scenarios. We also used the size of the hypoxic area (km^2) for the BP; this is the only sub-basin for which SANBALTS estimates hypoxia, because most hypoxic areas are located there.

Results

Patterns of nutrient use efficiency

Average NUE increased for both N and P between 2000 and 2010, with most countries showing improvement (Fig. 1). Germany and Denmark had the greatest increases in NUE_N (> 0.18) due to decreases in the four input components (manure for only Denmark) that were accompanied by increased crop harvest and grazing. Increases in NUE_P were greatest for Germany, Finland, and Sweden, > 0.20 between 2000 and 2010. These improvements were associated with decreased fertilizer imports and manure inputs (except for Germany) and increased crop harvest and grazing. NUE for Estonia and Latvia decreased between years due to increases in fertilizer imports and decreases in crop harvest and grazing.

There was generally a gradient of NUE across the drainage basin, with greater efficiencies in western areas compared to eastern areas (Fig. 2a, b). Regions of Belarus and Russia had the lowest NUE among all regions, reflecting relatively low crop production and relatively high synthetic and mineral fertilizer imports and/or manure production. Regional NUE

tended to decrease with increasing livestock unit density and, hence, manure application (Online Resource 2).

Scenarios of reduced nutrient inputs to the sea

We assessed the potential to make progress towards nutrient reduction targets for three sub-basins of the Baltic Sea. The OptCART scenario achieved 67, 40, and 1% of the N-reduction targets and 51, 4, and 30% of the P-reduction targets for BP, GF, and GR, respectively (Fig. 3, Online Resource 4). The results suggest that Belarus, Estonia, Finland, Germany, and Poland could potentially meet 90% of more of their N reduction targets. Only Belarus came within 90% of its P reduction target, although a few other countries made progress towards theirs.

In the OptCART scenario, NUE_N increased by 0.08 and 0.12 for Lithuania and Estonia, respectively (to the limit of 0.75), increased by 0.07 for Finland, and increased by 0.04 or less for the remaining countries. There was no opportunity to improve NUE_N for Latvia because year 2010 NUE_N exceeded 0.75. Country-scale increases in NUE_P were 0.02 for Belarus and Russia, 0.07 for Finland, and 0.17 for Poland. The resulting efficiencies were 0.35, 0.26, 0.90, and 0.69 for Belarus, Russia, Finland, and Poland, respectively. We found no opportunity for improved NUE_P for a number of countries; year 2010 NUE_P exceeded 0.90 for the Baltic States and regions of Germany, Denmark, and Sweden (Methods, Online Resource 5).

Generally, nutrient reductions were greater under NoCART compared to the other scenarios. As we defined this scenario, a country could bear larger nutrient reductions than required under the BSAP. Indeed, this was the case for Finland (N only) and Poland. As a result, total load reductions to the three sub-basins were 52 and 70% larger for N and P, respectively, under NoCART compared to OptCART.

There were relatively small differences in eutrophication responses between scenarios and sub-basins (Fig. 4, Online Resource 3). Eutrophication conditions improved the most for NoCART-levels of nutrient inputs, followed by NoCART-EU and OptCART. Across all scenarios and eutrophication responses, GF and GR generally showed more improvement than BP. The only response variable that met its BSAP target was TN concentration in GF under all scenarios; otherwise, there was generally progress towards targets for the other responses.

The scenarios achieved 40–80% of the gap between 2010 and BSAP conditions for TN for BP and GR (depending on scenario), although this gap was smaller to begin with compared to other response variables. The scenarios achieved 50% of the gap between 2010 and BSAP target TP concentrations, with the exception of BP under OptCART, which remained unchanged from 2010. For Secchi depth, the scenarios achieved 9–27, 12–24, and 33–50% of the gap between

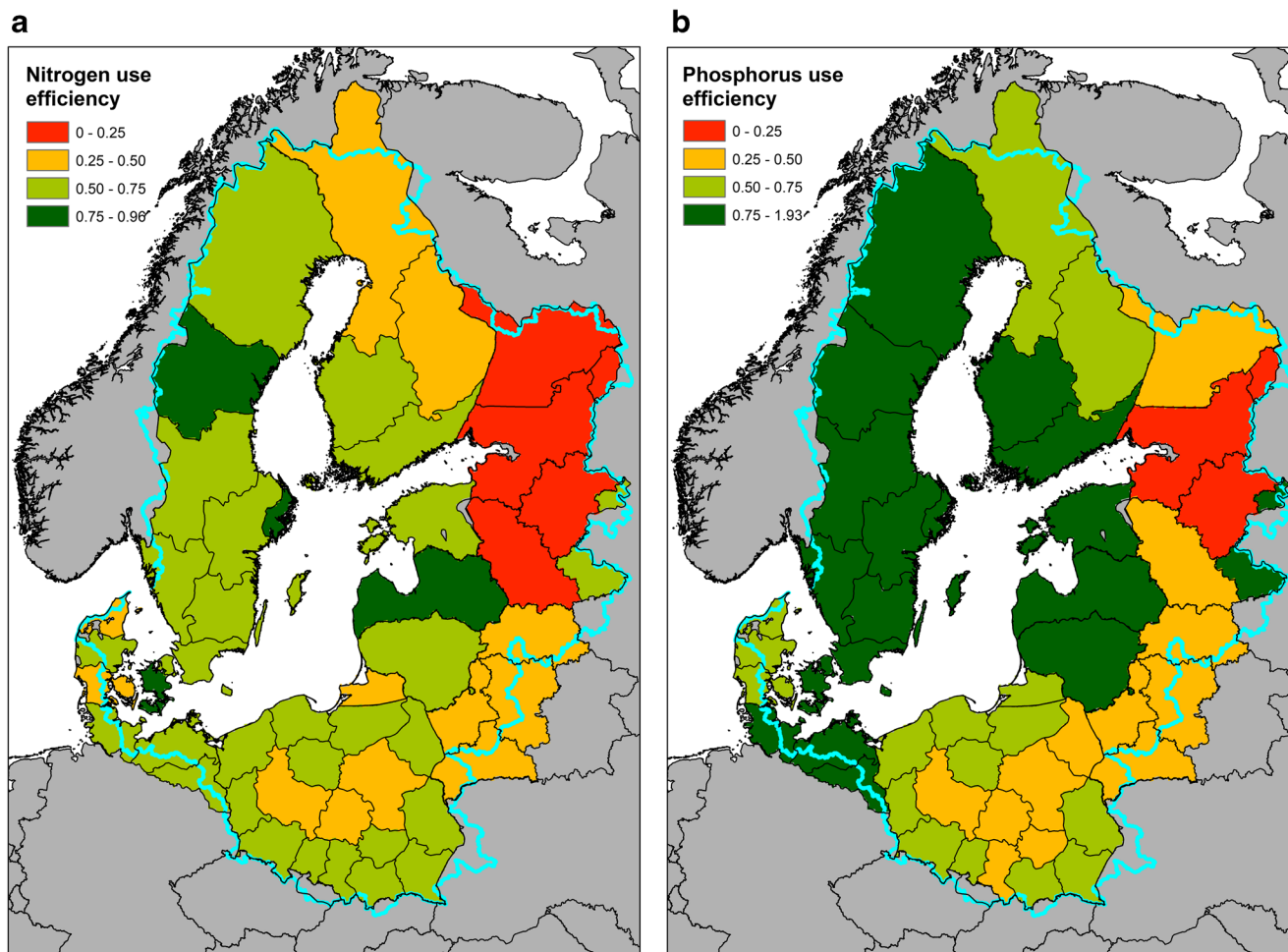


Fig. 2 Average regional nitrogen (**a**) and phosphorus (**b**) use efficiency in crop production for the 5-year period centered on 2010. Blue line denotes delineation of land areas that drain to sea sub-basins

2010 and BSAP conditions for BP, GF, and GR, respectively, depending on scenario. Lastly, the areal extent of the BP hypoxic zone decreased by 3700 km² (12%) for OptCART and by about 6000 km² (20%) for both NoCART and NoCART-EU; these reductions closed about 40 and 60%, respectively, of the gap between 2010 and BSAP conditions.

Discussion

Nutrient use efficiency in crop production has improved substantially in Europe in the past decades, and the Baltic Sea region is no exception (Buckwell and Nadeu 2016). For the EU-27, NUE_N in crop production averages 53%, ranging between 45 and 76%, depending on country (Leip et al. 2011); NUE_P averages about 70% and ranges between 17 and 140% among EU countries (van Dijk et al. 2015). Our NUE estimates for EU countries in the Baltic Sea drainage basin fell within the range of values reported elsewhere (Online Resource 6); however, we found no other published

studies to which we could compare results for Russia and Belarus.

The usage of nutrients in crop and forage production will never be perfectly efficient due to unavoidable losses during manure handling and application to fields, as well as to other factors such as weather and soil conditions. However, in the Baltic Sea region, 55 and 61% of the N and P, respectively, are converted to harvested crops or removed by grazing animals (Fig. 1), suggesting that improvement is possible. The scenarios found potential for further progress towards nutrient reduction targets by using manure more efficiently in agriculture. This is important, because the targets were based on what is needed to achieve a sea “unaffected by eutrophication,” not on reductions that were feasible. Scenario NoCART showed an opportunity for larger reductions than OptCART if certain countries were to reduce beyond their BSAP responsibilities (Fig. 3, Online Resource 4). Lastly, scenario NoCART-EU found that there is potential for EU countries to make additional nutrient reductions (beyond NoCART) to partially compensate in the event of no further reductions from Russia and Belarus.

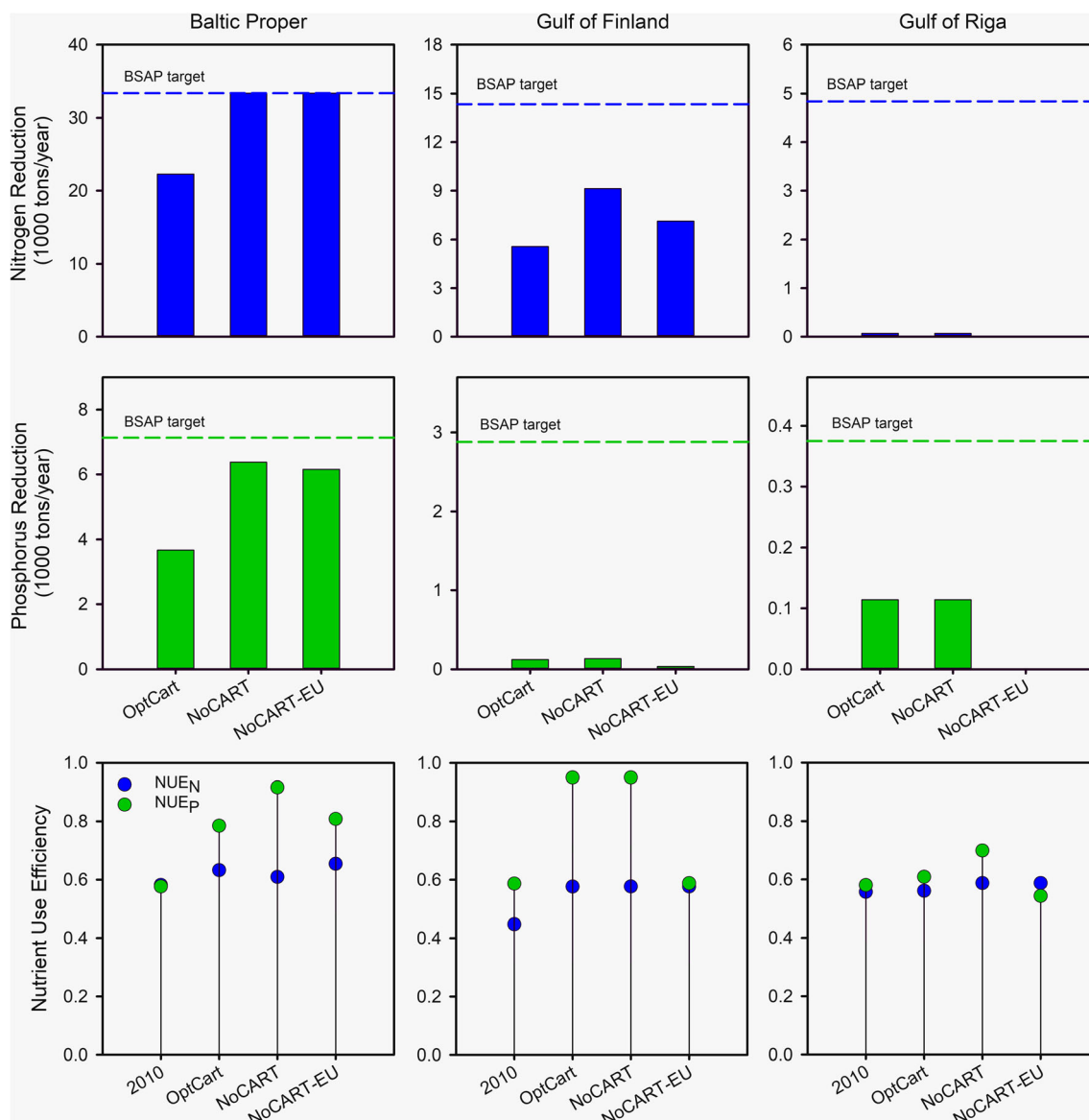


Fig. 3 Bars are external nutrient reductions achieved (in 1000 t nitrogen (blue) or phosphorus (green) per year) under the scenarios (top and middle panels). Dashed lines are targets under the Baltic Sea Action

Plan (BSAP). Points are NUE that correspond to nutrient reductions for the scenarios (lower panels). NUE for 2010 is included for comparison

Our estimates of potential nutrient reductions did not always align with country-reported source apportionment (HELCOM 2011). For example, scenario NoCART found potential reductions of 33.4 kt N to BP (Fig. 3). This is less than the 90 kt N attributed to agriculture for this sub-basin (Table 1), lending support to our estimate. In contrast, scenario NoCART found potential reductions of 9 kt N to GF, but here, only 6.9 kt N was attributed to agriculture; this suggests that the reductions we identified are not feasible. We note that agricultural sources could be classified elsewhere, because not all countries explicitly attribute nutrient loads to agriculture. For example, Russia and Latvia reported no agricultural sources, but included > 100 kt N with “other diffuse” sources for GF. If other diffuse includes agriculture, then our estimated

reductions could be possible. Caution should be used in interpreting country-reported source apportionment in Table 1, because methods were not harmonized among countries. A consistent approach to estimating source apportionment for the entire drainage basin is needed to better reconcile the potential nutrient reductions that we identified with country-reported sources. Such an analysis could also be used to assess the overall feasibility of achieving nutrient reductions identified in the BSAP.

Implications for nutrient management

Across regions, NUE tended to decrease with increasing livestock density, suggesting that manure could be better used in

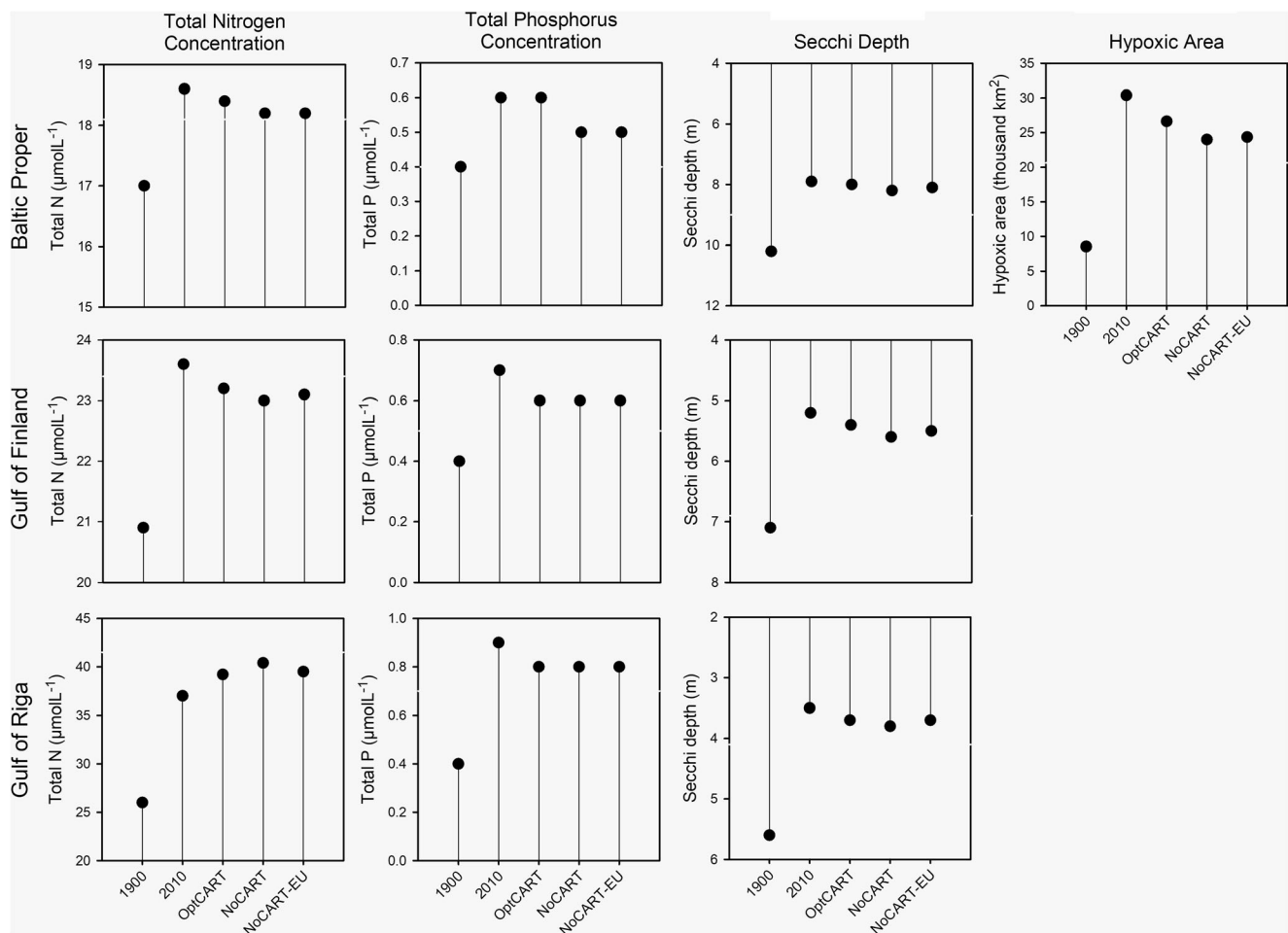


Fig. 4 Points are SANBALTS model output for the Baltic Proper (top panels), Gulf of Finland (middle panels), and Gulf of Riga (bottom panels) for different scenarios of external nutrient loads. See “Methods”

for scenario descriptions. Red dashed lines are SANBALTS model output using nutrient input targets from the Baltic Sea Action Plan (BSAP). Note that y-axis scales differ among sea sub-basins

crop and forage production (Online Resource 2). Indeed, this is a problem in many areas globally; a number of studies have reported that manure nutrients are not recycled efficiently (Liu et al. 2017; Wang et al. 2017). Our scenarios assume that synthetic and mineral fertilizer imports are reduced by shifting manure nutrients from animal-dense areas to areas that focus on crop production and would otherwise need to import fertilizers. This redistribution could be facilitated in several ways, for instance, through limits on the amount of nutrients that can be applied, the creation of markets for manure nutrients, and better integration of crop and livestock production.

Denmark provides an example of how “command and control” policies can influence the distribution of manure. The Danish implementation of the Nitrates Directive limits the amount of pig manure-N that can be applied to arable land. Because less than half of Danish pig farms have enough land to comply with these limits, farms must own or rent additional land or enter into manure contracts to have other farms take the excess manure (Willems et al. 2016). This requirement and other policies are credited with reducing the agricultural N

surplus by more than 40% in the past 30 years (Dalgaard et al. 2012).

Creating and promoting markets for manure-based fertilizers could also increase manure use efficiency. For example, establishing common quality standards could allow recycled nutrients to be “productized,” which could extend sales opportunities across country borders and increase farmer trust and willingness to buy manure-based fertilizers over traditional synthetic and mineral fertilizers (Buckwell and Nadeu 2016). In addition, subsidizing manure transportation and processing costs could enable markets by making manure-based fertilizers more cost competitive.

Lastly, more efficient manure usage could also be achieved by reducing the degree of specialization and spatial separation of crop and livestock production systems (Oenema et al. 2007). Research suggests there is potential to reduce nutrient losses to the environment if regions were to shift from specialized to mixed crop-livestock production, thus, reducing the distances between crop and livestock production (Nesme et al. 2015; Garnier et al. 2016). Changing the structure of

Table 1 Country-reported source apportionment for waterborne loads to the Baltic Sea for 2006 (HELCOM 2011). These data are provided for context in interpreting nutrient reductions under scenario conditions in Fig. 4. However, data should be interpreted with caution because the time period differs from that in our analysis (2010) and the countries used different methods to estimate source apportionment. Estonia, Latvia, and Russia apportioned no loads to agricultural sources for any sub-basin or nutrient; these data could be included in the Unknown-Other Diffuse category

Sub-basin	Source apportionment (tons nitrogen)					Stormwater-Sewage-Industry	Transboundary ^a	Background
	Agriculture	Atmospheric deposition	Unknown-Other Diffuse	Aquaculture	Stormwater-Sewage-Industry			
Baltic Proper	99,811	7905	7147	94	56,022	20,493	29,272	
Gulf of Finland	6864	2899	112,756 ^b	75	14,313		8409	
Gulf of Riga			21,283 ^c	51	2527	26,212	5644	
Sub-basin	Source apportionment (tons phosphorus)					Stormwater-Sewage-Industry	Transboundary ^a	Background
	Agriculture	Atmospheric deposition	Unknown-Other Diffuse	Aquaculture	Stormwater-Sewage-Industry			
Baltic Proper	5882	196	101	8	3990	1068	1526	
Gulf of Finland	310	35	3621 ^b	7	1293		182	
Gulf of Riga			722 ^c	7	351	1334	188	

^a Nutrient inputs from Belarus are included in the Transboundary category. No additional source apportionment information is available

^b Nitrogen amount includes 105,000 from Russia and 7500 from Estonia. Phosphorus amount includes 3200 from Russia and 400 from Estonia

^c Nitrogen amount includes 17,000 from Latvia and 4000 from Estonia. Phosphorus amount includes 660 from Latvia and 60 from Estonia

agriculture, along with the establishment of limits on fertilizer application rates and the creation of markets for manure nutrients, will require substantial capital investment and changes in agricultural policy and practices. Such changes could be challenging to implement in the absence of strong political will.

There are few published studies that discuss how NUE could be improved in Russia and Belarus. HELCOM has engaged farmers and government authorities around St. Petersburg and Kaliningrad to foster discussions aimed at improving manure handling and fertilization practices. Pilot projects found the potential for 30–50% reductions in nutrient losses from agriculture (HELCOM 2012); however, a study found that subsidies for inorganic fertilizers and low profitability of farms are major barriers to improved manure management (Lindgren 2013). There are also efforts to build competence in organic farming practices in Belarus through knowledge sharing (Granstedt 2012). Continued international cooperation and investment could further reduce agricultural nutrient losses from Russia and Belarus.

There are other opportunities to reduce nutrient losses from agriculture that we cannot capture with our modeling approach. For example, best management practices such as buffer strips, cover crops, and sedimentation ponds could increase nutrient retention and reduce land-to-water transfer efficiencies (Salomon and Sundberg 2012). Improved outreach could also be important in areas where farmer awareness of nutrient management practices is low (Drangert et al. 2017). In addition, because we estimated NUE at coarse spatial scales, we could not identify local “hot spots” within regions. Thus, targeted measures in areas with particularly large nutrient surpluses or that are prone to nutrient loss could be beneficial. Lastly, we do not take into account accumulated soil nutrients. Large areas of arable land in the Baltic Sea drainage basin have high or very high P supply (Tóth et al. 2014) and it may be possible to reduce P inputs to these areas without reducing yields (Valkama et al. 2009). Indeed, we found that NUE_P for 2010 exceeded one for regions of Denmark, Germany, and Sweden, which could indicate that actions are being taken to utilize legacy pools in these countries.

Meeting BSAP targets will require reductions in sewage and urban-related inputs, which are the second largest source of nutrients after agriculture (Table 1). The potential for reducing inputs from sewage varies between countries, with N- and P-removal efficiencies in centralized waste treatment systems varying from >90% in Denmark to <70% in Estonia and Latvia (Hautakangas et al. 2014). A recent assessment found that most EU member states in the Baltic Sea region had not fully met their obligations under the Urban Wastewater Directive for specified levels of N- and P-removal efficiency (ECA 2016). Meeting these requirements could reduce wastewater nutrient sources to the sea. However, even stronger action is needed to meet environmental goals and HELCOM has

recommended more stringent standards for nutrient removal than the EU directive (HELCOM 2007).

Nutrient reductions and eutrophication conditions

Even if BSAP targets are not achieved, the SANBALTS model output showed that reduced nutrient inputs to the Baltic Sea could improve eutrophication conditions. Generally, the scenarios reduced TN and TP concentrations and the extent of hypoxia and increased Secchi depth compared to current conditions. Increased water transparency could improve recreational experiences and opportunities (Rönnbäck et al. 2007). Reductions in the size of the hypoxic zone could improve conditions for benthic fauna and increase the reproductive success of cod (Limburg et al. 2011).

Despite substantial reductions in external nutrient inputs since the 1980s, the sea as a whole remains eutrophic (HELCOM 2017); however, there are signs of improvement in a few areas (Andersen et al. 2017). The lack of more robust responses is due to lag times resulting from long water residence times and internal recycling of P. We note that our modeling approach assumes no lags, either in the responses of land-based nutrient loads to changes in agronomic practices or in responses of eutrophication conditions to reduced land-based loads. In practice, it could take years to decades for the sea to respond to changes in agricultural nutrient management practices.

Under the scenarios, greater progress was made in reducing nutrient inputs to BP compared to GF and GR; however, eutrophication conditions did not improve as much for BP as for GF and GR. This somewhat counterintuitive result is due to circulation patterns assumed in SANBALTS; the BP receives more nutrients from GF and GR than it transfers to them (Savchuk 2005), which dampens the responses of reduced inputs of land-based nutrients to BP. In other words, eutrophication conditions in each sea sub-basins not only depend on direct external nutrient loads but also on conditions in adjacent sub-basins.

Conclusion

Here, we estimated the NUE in crop and forage production, which we used to identify opportunities to reduce nutrient loads from agriculture to the Baltic Proper, Gulf of Finland, and Gulf of Riga. There was evidence that manure is not being used efficiently because NUE generally decreased with increasing density of livestock. By redistributing manure nutrients from areas where over-fertilization is likely occurring to crop-producing areas that rely on imported synthetic and mineral fertilizers, there is potential to riverine nutrient loads. However, such actions will likely require substantial changes in agricultural practices. A harmonized method for

apportioning nutrient sources is needed to assess the feasibility of reductions identified in our scenarios, as well as to identify reductions from other sources, such as sewage. Even if nutrient reduction targets are not fully met, further reductions of land-based nutrient loads could improve eutrophication conditions.

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