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Spatially differentiated regulation: Can it save the Baltic Sea from excessive N-loads?

Jens Christian Refsgaard, Anne L. Hansen, Anker L. Højberg, Jørgen E. Olesen, Fatemeh Hashemi, Przemyslaw Wachniew, Anders Wörman, Alena Bartosova, Nico Stelljes, Boris Chubarenko

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Abstract The Baltic Sea Action Plan and the EU Water Framework Directive both require substantial additional reductions of nutrient loads (N and P) to the marine environment. Focusing on nitrogen, we present a widely applicable concept for spatially differentiated regulation, exploiting the large spatial variations in the natural removal of nitrate in groundwater and surface water. By targeting mitigation measures towards areas where nature's own capacity for removal is low, spatially differentiated regulation can be more cost-effective than the traditional uniform regulation. We present a methodology for upscaling local modelling results on targeted measures at field scale to Baltic Sea drainage basin scale. The paper assesses the potential gain and discusses key challenges related to implementation of spatially differentiated regulation, including the need for more scientific knowledge, handling of uncertainties, practical constraints related to agricultural practice and introduction of co-governance regimes.

Keywords Baltic Sea drainage basin · Co-governance · EU Water Framework Directive · N-loads from agriculture · Spatially differentiated regulation

INTRODUCTION

The need to reduce nutrient loads from anthropogenic sources to avoid harmful impacts on groundwater and surface water resources, including eutrophication and hypoxia in aquatic ecosystems, has been widely recognised (Diaz and Rosenberg 2008). The Baltic Sea is among the most heavily degraded marine ecosystems worldwide, due in part to excessive nutrient loads (Reusch et al. 2018). Of the total nutrient loads from land reaching the Baltic Sea, over half of the nitrogen (N) and one-third of phosphorous (P) come from agriculture (Arheimer et al. 2012). This has led to adoption of the Baltic Sea Action Plan with heavy reduction targets for N (13%) and P (41%) (HELCOM 2007, 2013). Although the Baltic Sea Action Plan has been partially successful in reducing nutrient loads to the Baltic Sea, severe problems still remain (Elmgren et al. 2015; Reusch et al. 2018).

Some of the nutrients leaching from the root zone do not reach the marine environment due to a variety of biogeochemical processes, sorption and sedimentation (Wulff et al. 2014; Højberg et al. 2015). These processes are often denoted 'retention' (Wulff et al. 2014). We will in this paper specifically deal with nitrogen and use the term N-reduction, as nitrogen is subject to biogeochemical reduction when transported in anoxic environments, where degradable organic matter, pyrite or other reductants are present.

Many measures have been proposed and applied to reduce nutrient loads from agriculture through actions on land (Dalgaard et al. 2014; Wulff et al. 2014) as well as to remove nutrients by restoration actions in streams (Wortley et al. 2013). The existing action plans typically use measures uniformly across entire countries without considering local variations in N-reduction capacity in soils, groundwater and surface water systems. As N-reduction varies significantly at small scales depending on the hydrogeological and riverine conditions (Hansen et al. 2014b; Højberg et al. 2015), a spatially differentiated approach with measures targeted towards areas where the natural N-reduction is low, will be more cost-effective than the traditional uniform measures (Jacobsen and Hansen 2016). The potential for such new, spatially differentiated approaches accounting for local data and knowledge has not yet been tested (Hashemi et al. 2016).

Evaluating the impacts of field level spatially differentiated measures at the 1.8 million km^2 Baltic Sea drainage basin poses a particular challenge. The model setups typically used at this scale (Donnelly et al. 2013) are not able to simulate small-scale spatially differentiated measures, because (i) the models operate at a much coarser spatial resolution than the measures; (ii) they often do not include small-scale data but instead use aggregated data which can vary in quality and resolution between countries and (iii) they often have simplified process descriptions adequate for the input data complexity but inadequate to simulate specific measures, e.g. for N-reduction in rivers, wetlands and groundwater. Such measures can be simulated by comprehensive and data-demanding small-scale models (Hansen et al. 2017). However, for computational and data access reasons, these models are not operational at the greater Baltic Sea drainage basin scale. Therefore, a method must be applied for upscaling the results from suitable small-scale models to models operating at the Baltic Sea scale. Bronstert et al. (2007) provide one of the very few examples reported in literature of such upscaling based on dynamic combinations of small- and large-scale models.

Design of scheme with spatially differentiated measures requires estimates of water flows and nutrient fluxes at the spatial scale for which it is intended to be applied. Hydrological models providing such estimates are known to have increasing prediction uncertainty the smaller the area is considered (Hansen et al. 2014b; Refsgaard et al. 2016). Another challenge is therefore that while spatially differentiated measures will be most efficient when applied at local scale, they are at the same time faced with the largest uncertainties at local scale. Furthermore, spatial differentiation will affect stakeholders differently. Hence, use of spatial differentiation in a regulatory context may pose new governance challenges.

In this paper, we confine our analyses to N and outline a widely applicable concept for spatial differentiation. The objectives of our paper are (i) to quantify the potential benefits of spatially differentiated measures; (ii) to identify the key scientific challenges related to implementing the concept in practice; and (iii) to assess the policy challenges related to a governance regime based on a spatially differentiated regulation.

MATERIALS AND METHODS

Study area

The Baltic Sea drainage basin covers a land area of around 1.8 Mio. km^2 in Finland, Russia, Estonia, Latvia, Lithuania, Belarus, Poland, Germany, Denmark, Norway and Sweden, as well as small areas in Ukraine, Slovakia and the Czech Republic. The landscapes within the basin are heavily influenced by their glacial or periglacial history. Geologically, the northern parts of the basin belong to the Fennoscandian shield, consisting of silicate bedrock with low geochemical reactivity, low permeability and thin soils. Lakes cover large fractions of the land surface here. The southern parts are geologically more diverse, and non-consolidated Quaternary sediments occur extensively, providing for comprehensive groundwater resources in geochemically reactive aquifer materials. Owing to the cold climate and less-developed soils, land cover in the northern parts is dominated by boreal forests, while agriculture is prevalent on suitable land in the southern parts of the basin (Fig. 1).

To improve knowledge of N-reduction processes in surface water and groundwater, we conducted combined field and modelling studies in four small catchments: Norsminde (Denmark), Tullstorp (Sweden), Kocinka (Poland) and Pregolya (Russia/Poland), representing different climatic, geological and socioeconomic conditions (Fig. 1, Table 1). In addition, some of the modelling studies in Denmark used an existing model from the 486 km^2 Odense catchment located in Funen in the middle of Denmark (Karlsson et al. 2016).

The concept of spatial differentiation

Excess nitrate, that has not been taken up by plants, may be leached from the root zone (N-leaching) and transported either via overland flow or near-surface flow paths, including drain pipes, directly to surface waters or flows deeper into the groundwater system. In the upper, oxic part of the groundwater zone, nitrate will act as a conservative tracer, while, when transported into the anoxic zone, it will be biogeochemically reduced to N_2. The extent of nitrate reduction occurring in groundwater depends on the flow paths and the depths of the redox interface separating the oxic and anoxic zones (Postma et al. 1991; Hansen et al. 2014a). After leaving the groundwater zone, nitrate is subject to biogeochemical reduction in the hyporheic zone along the river and in sediments of lakes and rivers (Boano et al. 2014).

Due to heterogeneities in geology and river morphology and due to anthropogenic drainage systems, the extent of N-reduction in groundwater and surface water can exhibit substantial local spatial variations. Figure 2 shows the calculated N-reduction between the root zone and the marine recipient for a farm in the Norsminde catchment. This reveals very large variations in the natural N-reduction, which can be exploited to spatially target mitigation actions. The concept of spatial differentiation is to use knowledge of how natural N-removal differs in each area

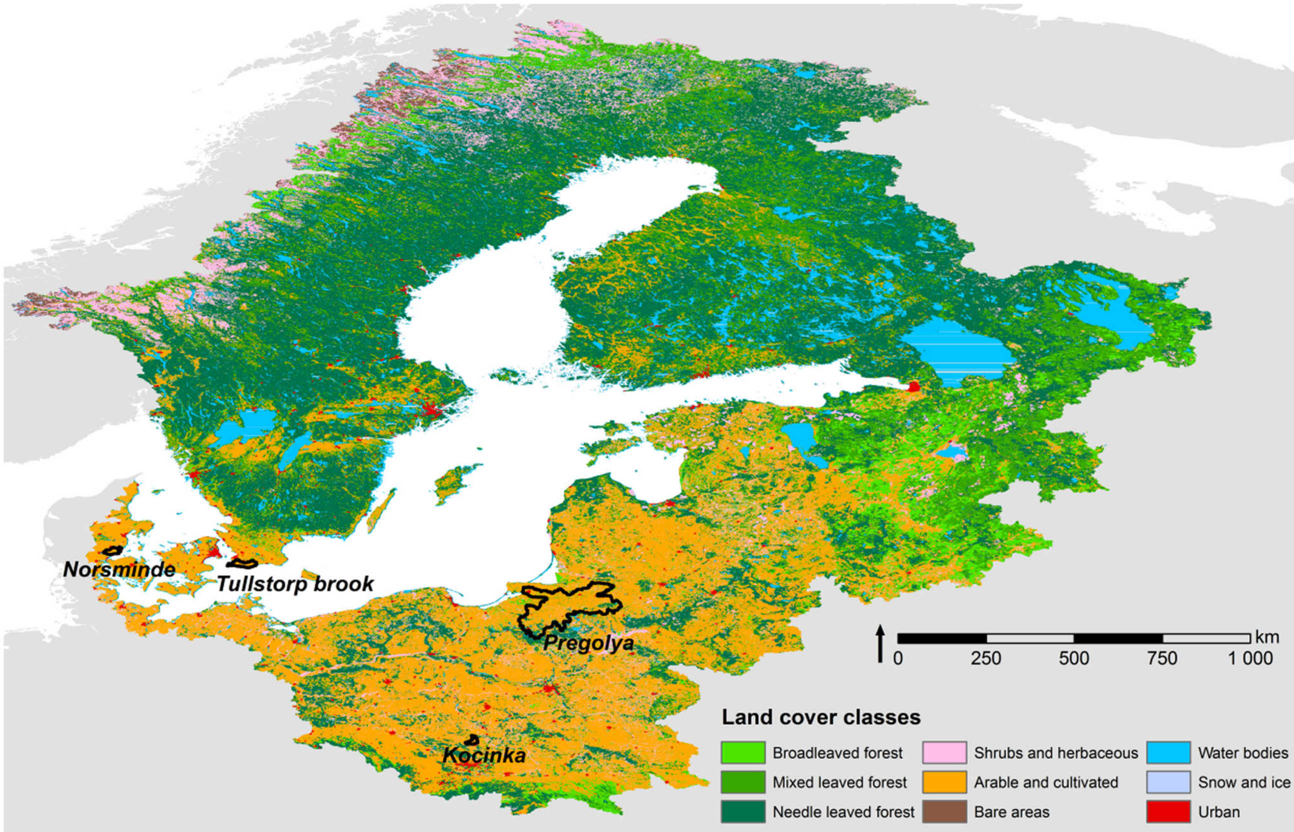

Fig. 1 Land cover classes in the Baltic Sea drainage basin, with case study catchment locations outlined. Simplified classification based on Global Land Cover 2000 data (Bartholomé and Belward 2005)

(Fig. 2) to manage N-loads. It would, for example, be wasted effort, and potentially impose an unnecessary cost burden, to restrict agricultural N management on fields where the natural N-reduction already removes more than 90% of the N-leaching from the root zone. Conversely, it will be much more efficient to locate the mitigation measures on fields with N-reductions which are considerably lower, in the order of 30%.

Spatial differentiation can be implemented in different ways. One option is to relocate existing agricultural practices according to the N-reduction capacity, so that crops/practices with high N-leaching are moved to areas with high N-reduction and vice versa. Another option is to apply agricultural mitigation measures such as changing crop rotation and applying cover crops on target areas with low natural N-reduction. A third option is to perform engineered restoration actions that enhance nitrogen removal capacity, e.g. constructed wetlands, drain filter solutions, re-meandering of streams, sediment traps or flooding areas alongside the main stream channel.

It is important to note that spatial differentiation is not a measure in itself parallel to existing measures such as norms for fertiliser application, cover crops, engineering restoration. Instead, spatial differentiation is a strategy applied "on top of" other measures to ensure optimal spatial location of the other measures. Our assessments of the effects of spatial differentiation to increase the N-reduction in groundwater have all been performed using Danish standard norms for fertiliser application, where there already are strict requirements for N book-keeping and limits for fertiliser application (Hansen et al. 2017; Hashemi et al. 2018a).

Modelling approaches

Key characteristics of the study areas and the focus of the modelling studies are listed in Table 1. The main objectives of the local case studies were to obtain improved understandings of flow paths, travel times and nutrient processes, enabling more accurate modelling at small spatial scales, and to develop methods for upscaling of the processes for use across the Baltic Sea drainage basin. In the study areas in Denmark (Hansen et al. 2019; Jakobsen et al. unpubl. results), Sweden (Riml et al. unpubl. results) and Poland (Wachniew et al. 2018) comprehensive field studies were combined with detailed, small-scale models, while the focus in the Russian part of the Pregolya catchment was to

Table 1 Characteristics of the five full case studies

Catchment	Norsminde	Tullstorp Brook	Kocinka	Pregolya	Baltic Sea drainage basin
Area	101 km^2	63 km^2	260 km^2	13 700 km^2	1.8 million km^2
(scale)	(hillslope + catchment scale)	(reach + catchment scale)	(catchment scale)	(catchment scale)	(basin scale)
Hydrology	Glacial till, dominated by groundwater and tile drainage	Glacial clays and till, dominated by groundwater and tile drainage	Glacial till and glacio-fluvial sands and gravels underlain by karstic-fractured Jurassic limestones	60% of Pregolya runoff goes into the Vistula Lagoon, and 40% into the Curonian Lagoon. The river plain is flat, salt wedge intrusions	Varied Boreal forests in North, agriculture in south, 8% wetland, lake dominance in large regions 0.34 million km^2 agricultural area of which 0.20 million km^2 is arable land
Agricultural land	75%	85%	54%	56%	
Average farm size	62 ha	50 ha	3 ha	15 ha in Russia and 23 ha in Poland	
Nutrient problem statement	N and P loads from catchment should be reduced by 25–50% in order to a comply with the EU Water Framework Directive and Groundwater Directive	N and P load from the catchment should be reduced by 30 and 52% in order to obtain good ecological status according to EU Water Framework Directive	Increasing use of fertilisers and local point sources.	Diffusion sources dominate. Transboundary basin between Poland and Russia	N and P load for each country around the Baltic Sea should be reduced by amount stipulated in Baltic Sea Action Plan
Focus of study in case area	Flow paths and N-reduction in groundwater, differentiated regulation, land use and climate scenarios, governance and monitoring concepts	Surface water N-reduction, interactions with shallow groundwater, scenario analyses of local measures	Flow paths, travel times and retention in groundwater, interaction with surface water	Water discharge redistribution between the branches going to Curonian and Vistula Lagoon. Estimate of nutrient load from the Russian and Polish territories	Upscaling of improved N-reduction knowledge. Scenarios for changes in climate, anthropogenic impacts and management/governance
Model types used	FEFLOW, MIKE SHE, NLES, DAISY, E-HYPE	COMSOL, Analytical models, E-HYPE	MODFLOW, MT3D, NLES	E-HYPE, FyrisNP	E-HYPE
Stakeholder processes	Develop new governance and monitoring concepts	Develop new governance and monitoring concepts	Develop new governance and monitoring concepts	Transboundary governance and monitoring concepts	Test acceptance of new governance and monitoring concepts

establish a dataset enabling detailed calibration and use of the E-HYPE model for scenario analyses.

We quantified the potential for increasing N-reduction in groundwater by differentiation between fields within catchments. We analysed the benefits of spatial targeting by considering the N-leaching and N-reduction in spatial units corresponding to small fields (1–4 ha) and then relocated the units with largest N-leaching to the units with the largest N-reduction (Hansen et al. 2017). In this way, the natural N-reduction is maximised and the N-load out of the catchment is minimised. The gain from the spatial targeting is then the difference between the N-load resulting from the actual location of the N-leaching and the N-load for the relocated N-leaching. The idea behind this is that the N-leaching is primarily determined by the crop rotation and agricultural practices and is independent of the N-reduction occurring in the groundwater, and hence the N-leaching can be reduced by management actions to relocate agricultural practices.

The pan-European setup (E-HYPE; Donnelly et al. 2016) of the HYPE code (Lindström et al. 2010) was used for simulating flows and nutrient fluxes for the Baltic Sea drainage Basin. E-HYPE uses daily time steps and divides the Baltic Sea drainage basin into 7145 sub-basins with a median size of 215 km^2. An upscaling approach, described in detail by Hansen et al. (2018), was adopted for utilising knowledge from the local catchment models in E-HYPE thus enabling E-HYPE to simulate the effect of spatially differentiated measures.

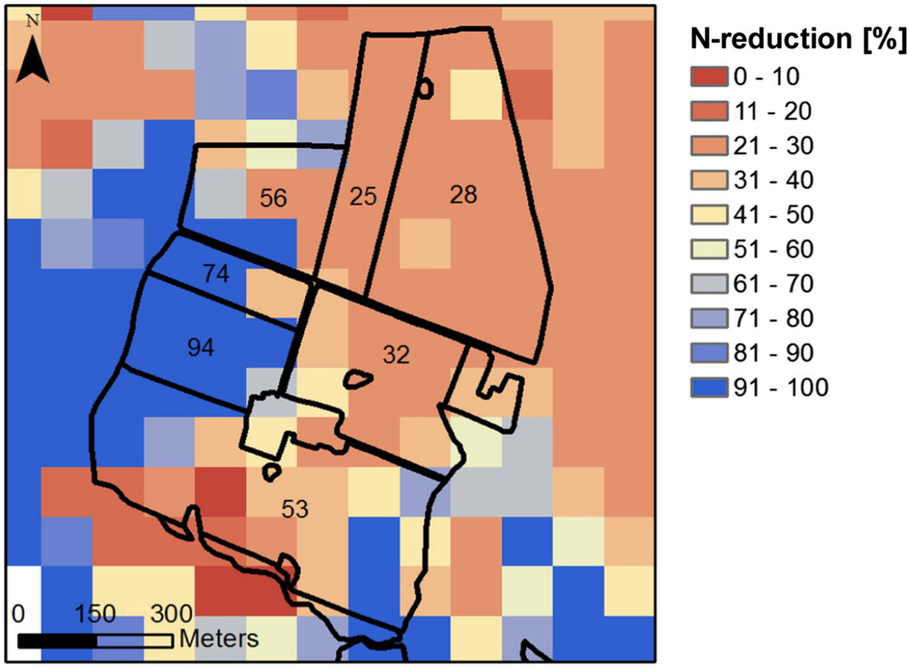

Fig. 2 N-reduction map with a 100-m resolution for a part of the Norsminde catchment with numbers displaying the average N-reduction across the fields (black lines) belonging to a specific farm (Jacobsen and Hansen 2016)

Water policy and governance

A broad range of policy instruments for a new governance regime based on a spatially differentiated strategy were analysed with focus on how to incentivise and regulate agriculture under such a regime (Stelljes et al. 2017a). The instruments were evaluated via two workshops and interviews with local stakeholders in each of the case areas in Denmark, Sweden and Poland, followed by workshops with regional stakeholders in Germany, Sweden and a transboundary workshop in Poland/Russia. The case study areas have different histories and degrees of agricultural regulation, as well as very large differences in stakeholder awareness about the nutrient problem. Parallel to the workshops and the work on the policy options, ethnographic studies were undertaken to understand the culture-induced knowledge and perceptions of the different stakeholder groups (Stelljes et al. 2017b).

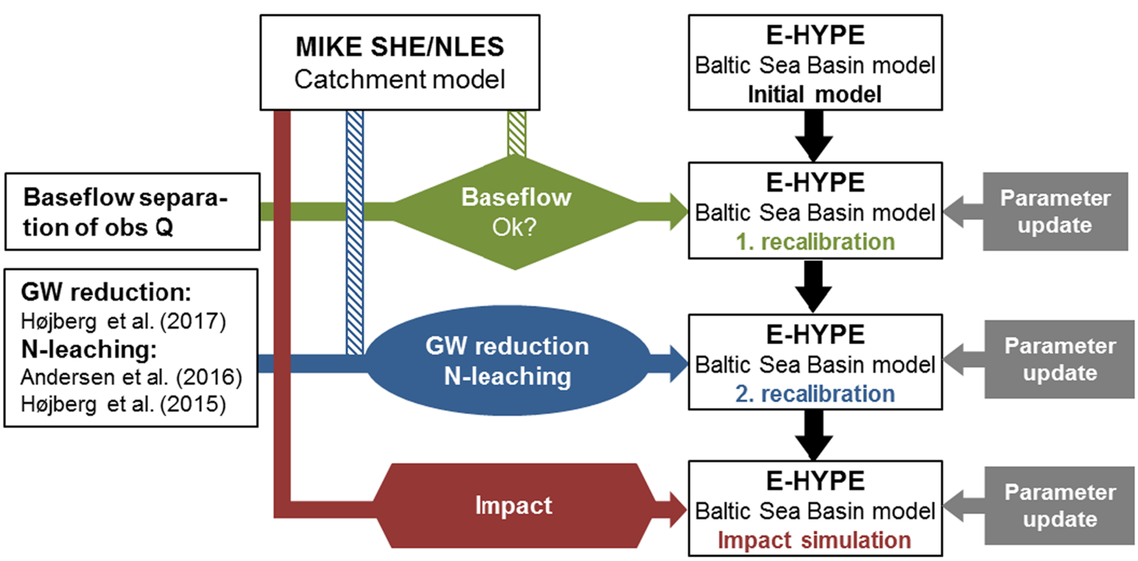

Fig. 3 The upscaling methodology for simulation of increased N-reduction in groundwater at the Baltic Sea drainage basin scale by spatially targeting of crops within catchments (Hansen et al. 2018)

RESULTS

Upscaling approach

The upscaling approach developed for learning E-HYPE to simulate the changes in N-reduction in groundwater by spatially targeting of measures is illustrated in Fig. 3. As a first step, the model structures and process equations of the local scale models (MIKE SHE + NLES) and the Baltic Sea drainage basin scale model (E-HYPE) were compared. This resulted in a consistency check of the baseflow fractions of the two models (successful) and a minor revision of the HYPE model structure to provide a better representation of deep aquifers and denitrification at individual soil layers (Bartosova et al. 2018).

Secondly, additional data at Baltic Sea drainage basin scale consistent with the local scale models were utilised. This included discharge data for baseflow separation, information on nitrate leaching at national and Baltic Sea drainage basin scales and a map of N-reduction in groundwater (Højberg et al. 2017). With these new data in place, it turned out that there was no need to recalibrate E-HYPE for baseflow fraction, but some recalibration was undertaken to ensure a reasonable split of the N-reduction between surface water and groundwater. Next, the local scale models were used to generate a generic relationship expressing the relative increase in N-reduction in groundwater achievable by spatial targeting of crop locations as a function of the percentage of arable land within the catchment (Fig. 4). To reproduce this relationship in E-HYPE, the denitrification rate in the groundwater zone was changed as a function of the average N-leaching and the soil moisture content in the deepest soil layers in E-HYPE (Hansen et al. 2018). The ability of this upscaling relationship to reproduce the curve in Fig. 4 in E-HYPE was successful (Bartosova et al. 2018) after introducing some limits to the maximum change in the denitrification parameter value (Fig. 5). The upscaling relationship was subsequently applied to predict the impact of spatial differentiation across the Baltic Sea drainage basin.

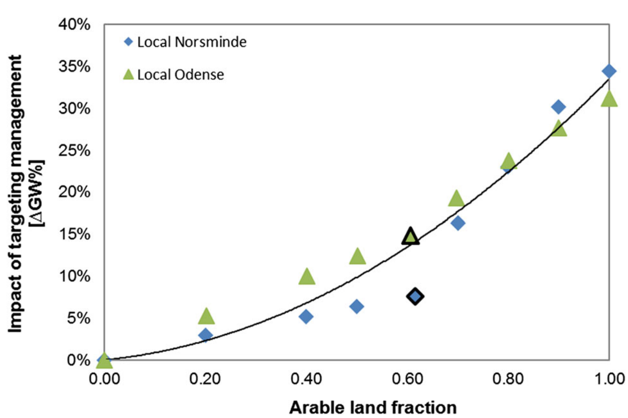

Fig. 4 The impact of spatially targeting of agricultural practices (ΔGW%—increase in groundwater reduction percentage) in two Danish catchments (Norsminde and Odense) as a function of arable land fraction (Hansen et al. 2018). The points marked with thick black lines correspond to the actual arable land fractions in the two study areas

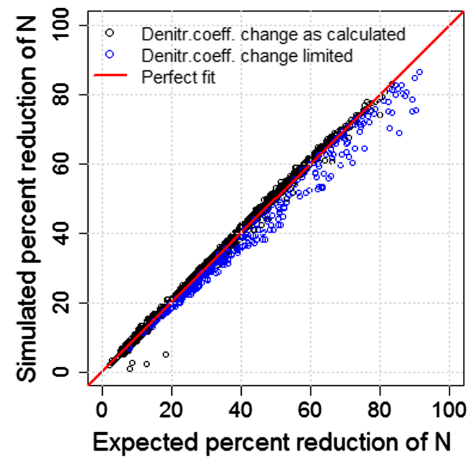

Fig. 5 Comparison of the expected N-reduction in groundwater based on the relation in Fig. 4 and N-reduction in groundwater simulated with E-HYPE. Each circle represents one catchment in the Baltic Sea drainage basin (Bartosova et al. 2018)

Potential benefit: differentiation within catchments of N-reduction in groundwater

The E-HYPE calculated potential for decreasing N-loads by implementing spatial differentiation through changing the location of agricultural land use and management and thus increasing the N-reduction in groundwater is shown in Fig. 6. The results show a substantial variation across the Baltic Sea drainage basin with the largest decrease in groundwater-dominated agricultural areas in Denmark, Germany and Poland, while no decrease in N-load is possible in the most northern areas, where there is limited groundwater and/or no agriculture. For the entire Baltic Sea, the N-load using this specific remediation measure can potentially be lowered by 5%, while Denmark is the country with the largest potential (20%).

While the potential gain shown in Fig. 6 is considerable in some of the regions, where the pressures from intensive agriculture are highest, a number of constraining factors will make the full potential unachievable in practice. Some of these constraints have been analysed for two Danish catchments (Norsminde and Odense) with summary results shown in Table 2 (Hansen et al. 2017; Hashemi et al. 2018a).

As shown in Table 2, the potential decrease in N-load (upper limit) achievable by using N-reduction maps at finest possible scale (100/200 m grids), assuming the maps

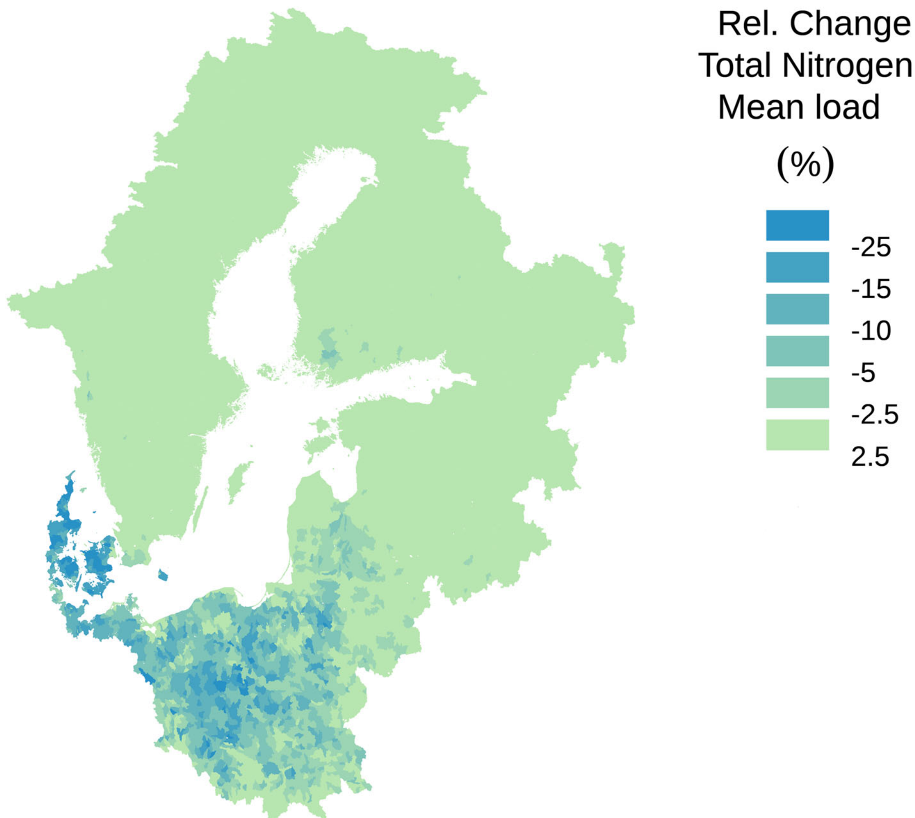

Fig. 6 Potential for decreasing the nitrogen load to the Baltic Sea by increasing the N-reduction in groundwater through spatial targeting of crops (Bartosova et al. 2018)

Table 2 Decrease in N-loads obtained from relocation of crops for different assumptions on management constraints, N-reduction map resolution and uncertainties. All numbers are shown as percentage decrease in N-loads compared to business as usual N-load

Constraint	Resolution of N-reduction map	Norsminde (%)	Odense (%)
None = Full potential	Norsminde: 100 m—Odense: 200 m	8.0	26
Crop relocation only within soil type	Norsminde: 100 m—Odense: 200 m	7.7	22
Crop relocation only within farm boundary	Norsminde: 100 m—Odense: 200 m	5.0	17
Coarse resolution of N-reduction map	500 m	6.2	Not analysed
	1000 m	5.6	Not analysed
	Catchment	0	Not analysed
Geological uncertainty in N-reduction map	100 m	6.1–7.4	Not analysed

to be correct and imposing no agricultural management constraint, is 8% in Norsminde and 26% in Odense. The large difference between the two catchments is mainly due to differences in farming structures leading to a larger variation in N-leaching in Odense. Table 2 also shows the effects of practical agricultural management constraints. If crops cannot be relocated from one soil type to another, the efficiency of differentiated regulation drops marginally in Norsminde (from 8.0 to 7.7%), where one soil type covers most of the catchment, while the decrease in Odense having a wider diversity of soil types is larger (from 26 to 22%). If relocation of crops is not allowed over the entire catchment, but only within individual farms, the efficiency drops significantly, from 8.0 to 5.0% in Norsminde and from 26 to 17% in Odense.

The importance of using high-resolution N-reduction maps is also clear from Table 2. For Norsminde, the gain drops from 8.0% (100 m maps) to 6.2% (500 m maps) and 5.6% (1000 m maps), while there is no gain left if the N-reduction is assumed constant throughout the catchment (uniform regulation).

The N-reduction maps are uncertain (Hansen et al. 2014b). This implies that the decisions on cropping relocations will not be optimal and hence the real gain will be less than the potential gain. The importance of this is illustrated in Table 2 for Norsminde by a decrease in the gain from 8.0% to somewhere between 6.1 and 7.4%. These numbers only consider geological uncertainty that

Hansen et al. (2014b) assessed to be the largest source of uncertainty. The 6.1% corresponds to the worst case using a single N-reduction map among 10 different, equally plausible maps, while the 7.4% comes from a robust estimation of an N-reduction map based on the mean of the ensemble of 10 maps.

DISCUSSION

Potential benefit for the Baltic Sea: the big picture

Spatially differentiated strategies for lowering N-loads can be applied at different spatial scales. Our analysis, which has been confined to spatial differentiation between fields within catchments, suggests that the increased N-reduction in groundwater can potentially lead to a 5% decrease in total N-load from the Baltic Sea drainage basin. Considering larger spatial scales, Jacobsen and Hansen (2016) analysed differentiation between 23 catchments in Denmark concluding that spatial differentiation could lead to a lowering of the mitigation costs associated with achieving a particular N-load reduction target by about 25% as compared to uniform regulation. At the finer spatial scales (differentiation within fields), there is potential for reducing N-leaching through precision agriculture, but Berntsen et al. (2006) assessed this potential to likely be less than 5%.

In addition, restoration of natural wetlands and introduction of stream remediation measures targeting increased N-reduction in surface water systems have a substantial potential in most areas. Applying a new theoretical framework, Riml et al. (unpubl. results) assessed that optimal location of stream remediation measures in all small Swedish streams might lead to a decrease in N-load of about 20%, while Bartosova et al. (2018), using the E-HYPE arrived at an estimate of only around 1%.

Our scientific contribution has been to provide a consolidated estimate for the potential reduction in N-load arising from differentiation between fields within catchments. Considering literature on differentiation between catchments and precision agriculture, and notwithstanding the large uncertainty regarding the effects of stream remediation measures, the total potential for using spatial differentiation strategies to decrease N-loads from agricultural areas to the Baltic Sea in a cost-effective manner appears large. As very limited experience exists with implementation of spatially differentiated strategies, there are a number of scientific and governance challenges that need to be addressed before the potential gain can be achieved in practice.

Scientific challenges

N-reduction maps

N-reduction maps used for applying spatially differentiated regulation must be reasonably accurate and detailed. Errors in these maps will lead to non-optimal location of measures (Table 2). N-reduction maps have traditionally been estimated by combining measured nutrient fluxes at river gauging stations with model calculated nutrient leaching from the root zone within the catchments upstream from the stations. This limits the spatial resolution of these maps to the catchment sizes defined by the river gauging station network, i.e. often several thousand km^2 as in Wulff et al. (2014). To derive N-reduction maps with finer spatial resolution, such as shown in Fig. 2, high-resolution modelling tools that can exploit local data such as topography, soil types, land use and geology are required.

Another challenge is that N-reduction maps are dynamic. The N-reduction in the surface water pathway is for instance a function of the remediation measures implemented in a particular river network and may hence change over time. Also, changes in climatic conditions such as the amount and intensity of rainfall may affect the flow pathways and thus the amount of N-reduction. Furthermore, the response of groundwater systems to nutrient loads is for some places affected by water residence times in the order of years or decades (Wachniew et al. 2018).

More local data: decreasing uncertainty

A significant part of the potential gain from spatial differentiation lies in exploiting the variability in N-reduction within catchments, i.e. at scales where we usually have limited data. We know that prediction uncertainties based on the existing data can often be so large at field scale that this in practice makes spatially differentiated regulation non-feasible. We also know that the uncertainties in estimating N-reduction in groundwater can typically be significantly decreased by using more data (Hansen et al. 2014b). However, data collection with traditional sampling schemes is expensive. Hence, there is a need to link uncertainty assessments and the extent to which more and better data will decrease uncertainties to support decisions on investments in collecting new or additional data. Hashemi et al. (2018b) showed that information on the uncertainty of N-reduction at fine spatial scale can be used to optimise spatial targeting and thus increase cost-effectiveness.

Upscaling

All models are scale dependent, and a model that is parameterised and calibrated to make predictions at a particular scale does often not have predictive capabilities at smaller scales (Refsgaard et al. 1999). To adequately analyse impacts of small-scale spatially differentiated measures at the Baltic Sea drainage basin scale, it is therefore required to combine small-scale and large-scale models.

Although large-scale models generally rely more on calibration than small-scale models, E-HYPE has relatively little data available for calibration, typically only discharges and nutrient concentrations measured at river gauging stations. While this allows calibration of the N-reduction at scales corresponding to the sub-basins upstream of the gauging stations, it also leads to equifinality (Beven 2006) in the sense that many combinations of parameter values with different splits between N-reduction in surface water and in groundwater can provide the same overall N-reduction. As illustrated in Fig. 3, we therefore add additional basin-wide datasets (baseflow separation of discharge, maps for N-reduction in groundwater, maps for N-leaching) as proxy observational data for recalibrations of E-HYPE. Furthermore, we used simulation results from small-scale models to develop an upscaling relationship enabling E-HYPE now to simulate the impact of spatially differentiated measures implemented in terms of increased N-reduction in groundwater. This in reality implies constraining E-HYPE to reproduce results comparable with those from detailed small-scale models. In this way, we expect that the equifinality level in E-HYPE will be reduced such that it will, to a greater extent, simulate the “right answers for the right reasons”. This improves the confidence in model predictions, when E-HYPE is used in scenario analyses to assess impacts of future changes in climate, land use and agricultural practice.

In constraining E-Hype in this way to reduce equifinality, we use so-called dynamic upscaling (Bronstert et al. 2007). A critical assumption here is that our small-scale models, with their more advanced process descriptions and ability to utilise more of the existing system data, have sufficient predictability, and that our case studies have sufficient representativeness to allow model outputs to be used for constraining E-HYPE in other parts of the Baltic Sea drainage basin.

Governance challenges

Uncertainty and spatial scales

Results from modelling studies in the Norsminde catchment suggest that the level of uncertainty inherent in the N-reduction maps can be very high (Hansen et al. 2014b). Figure 7 shows that the uncertainty regarding N-reduction is very large at 100 m (1 ha) resolution, but the uncertainty decreases considerably if the N-reduction results are aggregated to larger spatial scales. To exploit the full potential of spatial differentiation, N-reduction maps with a fine spatial resolution (1–25 ha) are necessary. The potential gain decreases as the spatial scale of the N-reduction becomes coarser, and uncertainty and gain thereby counteract (Hansen et al. 2017).

Before these uncertainty assessments were made, the Danish government had the intention to use N-reduction maps at field scale as a basis for government regulation. However, the level of uncertainty shown in Fig. 7 was so high that it scared both key stakeholders and government authorities from using them in a regulatory context. For this reason, the Danish government currently uses N-reduction maps at around 1500 km^2 resolution in regulation, while 15 km^2 resolution is used for prioritising voluntary N-mitigation measures. While the coarse scale maps have a lower level of uncertainty, their use also removes most of the economic and environmental gains from a spatial differentiation.

The fact that N-reduction maps with fine spatial resolution are required to exploit the potential benefits of spatial differentiation, but that the uncertainties on maps with such fine resolution are so large that they appear to prevent authorities from using them with the existing governance regimes, is a major challenge. If on one hand, when centralised top-down regulation is used, imposing (tough) restrictions, farmers will question the basis for the regulation, and hence a very high certainty is required and the authority will carry the responsibility for that uncertainty. If on the other hand, when more bottom-up/co-governance is used in a management context, i.e. to inform how to reduce the load in the best way possible, then a higher uncertainty can be accepted. And farmers are used to living with their own decisions, taken under uncertainty, e.g. related to weather and market conditions. However, this bottom-up process may be seen from the authorities as imposing a potential lack of control.

Governance regimes

A key governance challenge of spatially differentiated regulation is that different farmers, even neighbours, will have different N-reduction on their land areas (see Fig. 2). Hence, if measures such as fertilisation norms are made dependent on the small-scale N-reduction maps, then farmers will have different allowable fertilisation rates, and the respective advantages/disadvantages will very quickly be capitalised via land prices. Results from our workshops suggest that for this to be acceptable to farmers some kind

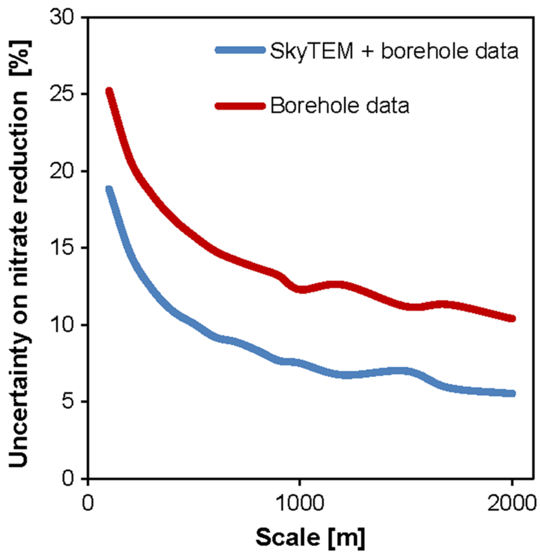

Fig. 7 Uncertainty surrounding the nitrate reduction due to geological uncertainty assessed using two ensembles of each 10 geologies: one based on borehole data alone, and the other using borehole data supplemented with data from airborne geophysics (SkyTEM). The graphs show the uncertainty regarding the percentage of nitrate leached from the root zone that is reduced in groundwater before reaching the coast. The basic calculations are performed using computational grids of 100 m × 100 m (1 ha). The scale (*x*-axis) is the length scale over which the results are aggregated before the uncertainty (standard deviation) is calculated. 500 m corresponds to an aggregation of 25 cells of 100 m × 100 m (25 ha). (Hansen et al. 2014b)

of compensational payments will be required. This issue is further complicated by the considerable uncertainty on the small-scale N-reduction maps implying that additional data may cause significant modifications to the maps.

One way to obtain more local data and at the same time get ownership among farmers is to empower farmers to collect data from their own fields and let these data become part of the overall decision basis. Such citizen data collection approaches require new affordable data collection techniques.

The findings from stakeholder workshops and ethnographic studies in Poland, Sweden and Denmark (Stelljes et al. 2017b) showed that the most promising application of spatial differentiation can be expected within a co-governance approach, where a large amount of responsibility is shifted to local farmers or to catchment councils. While the responsibility would not include the definition of the abatement targets, it would include the responsibility for fulfilling commitments under those targets. This includes designing and implementing mitigation measures (placing of wetlands, change of land use, etc.), collaboration among the farmers within the catchment, as well as internal monitoring of measures and loadings. Trust, along with a repetition of the situation (same people and activities) and the reputation of others' past actions, is crucial to the success of such collective action.

The present governance practice in the Russian Federation can be characterised as a centralised approach. This allows spatially differentiated regulation by setting abatement targets at the level of administrative units (Domnin et al. 2015) based on the quota of nutrient load reduction resulting from area-apportioning in the Baltic Sea Action Plan (HELCOM 2013). Hence, exploiting the full potential of spatially differentiated regulation by targeting measures at finer spatial scales than administrative units and co-governance appears infeasible under the Russian Federation's present governance approach.

CONCLUSION

As the need for reduction in nutrient loading from agriculture to marine environments continues, and in many countries the cheapest remediation measures have already been utilised, the requirement for designing innovative, cost-effective nutrient reduction measures increases. Spatial differentiation targeting mitigation measures at areas with low natural N-reduction in groundwater and surface water holds a significant potential to be cost-effective compared to the traditional strategy of applying measures uniformly across a particular catchment or throughout an entire country. We have quantified the potential gain from increasing the N-reduction in groundwater by differentiation of agricultural practices between fields in catchments to be substantial for agriculturally intensive, groundwater-dominated areas in Denmark, Germany and Poland. Considering also other possibilities for spatial differentiation such as differentiation between catchments, precision agriculture and targeted remediation measures in streams and wetlands, the total potential for spatially differentiated strategies appears to be large. However, several scientific and governance challenges remain to be solved before these can be fully implemented.

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AUTHOR BIOGRAPHIES

Jens Christian Refsgaard (✉) is a Professor at Geological Survey of Denmark and Greenland, Denmark.
Address: Geological Survey of Denmark and Greenland, Copenhagen, Denmark.
e-mail: jcr@geus.dk

Anne L. Hansen is a Postdoc at Geological Survey of Denmark and Greenland, Denmark.
Address: LandboSyd, Aabenraa, Denmark.
e-mail: alh@landbosyd.dk

Anker L. Højberg is a Senior Researcher at Geological Survey of Denmark and Greenland, Denmark.
Address: Geological Survey of Denmark and Greenland, Copenhagen, Denmark.
e-mail: alh@geus.dk

Jørgen E. Olesen is a Professor at Aarhus University, Department of Agroecology, Tjele, Denmark.
Address: Department of Agroecology, Aarhus University, Tjele, Denmark.
e-mail: jeo@agro.au.dk

Fatemeh Hashemi is a Ph.D. student at Aarhus University, Department of Agroecology, Tjele, Denmark.
Address: Department of Bioscience, Aarhus University, Silkeborg, Denmark.
e-mail: fh@bios.au.dk

Przemyslaw Wachniew is a Professor at University of Science and Technology, Krakow, Poland.
Address: AGH University of Science and Technology, Krakow, Poland.
e-mail: wachniew@agh.edu.pl

Anders Wörman is a Professor at Royal Institute of Technology, Stockholm, Sweden.
Address: Royal Institute of Technology, Stockholm, Sweden.
e-mail: worman@kth.se

Alena Bartosova is a Senior Researcher at Swedish Meteorological and Hydrological Institute, Norrköping, Sweden.
Address: Swedish Meteorological and Hydrological Institute, Norrköping, Sweden.
e-mail: alena.bartosova@smhi.se

Nico Stelljes is a Fellow at Ecologic Institute, Berlin, Germany.
Address: Ecologic Institute, Berlin, Germany.
e-mail: nico.stelljes@ecologic.eu

Boris Chubarenko is the Head of Laboratory for Coastal Systems Study at Shirshov Institute of Oceanology, Russian Academy of Sciences, Moscow, Russia.
Address: Shirshov Institute of Oceanology, Russian Academy of Sciences, Moscow, Russia.
e-mail: chuboris@mail.ru