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Impacts of changing society and climate on nutrient loading to the Baltic Sea

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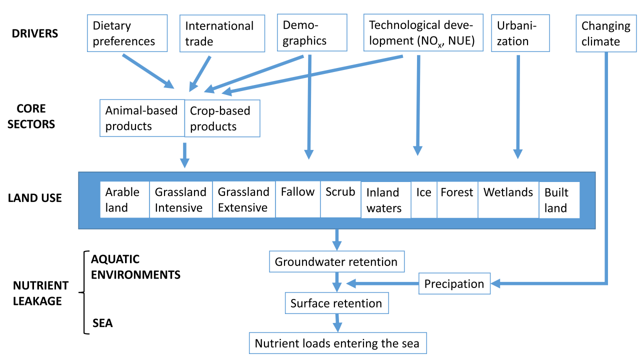
HIGHLIGHTS

- We provide plausible projections for nutrient pollution to the Baltic Sea until 2100.
- Projected overall nutrient loads at 2100 range from 52% to 115% of the initial levels.
- Changing society outweighs climate change in the effects on nutrient loading.
- Projections of nutrient loading are most sensitive to changes in agriculture.
- Combatting eutrophication should focus on reducing phosphorus loads to the Baltic.

GRAPHICAL ABSTRACT



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ABSTRACT

This paper studies the relative importance of societal drivers and changing climate on anthropogenic nutrient inputs to the Baltic Sea. Shared Socioeconomic Pathways and Representative Concentration Pathways are extended at temporal and spatial scales relevant for the most contributing sectors. Extended socioeconomic and climate scenarios are then used as inputs for spatially and temporally detailed models for population and land use change, and their subsequent impact on nutrient loading is computed. According to the model simulations, several factors of varying influence may either increase or decrease total nutrient loads. In general, societal drivers outweigh the impacts of changing climate. Food demand is the most impactful driver, strongly affecting land use and nutrient loads from agricultural lands in the long run. In order to reach the good environmental status of the Baltic Sea, additional nutrient abatement efforts should focus on phosphorus rather than nitrogen. Agriculture is the most important sector to be addressed under the conditions of gradually increasing precipitation in the region and increasing global demand for food.

1. Introduction

Anticipation of future developments of human and natural systems is a challenging, but necessary task for any foresight study and cost-benefit analysis investigating the long-term viability of public

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investment or policy intervention. Uncertainties tend to increase exponentially over time, and pathways become more difficult to justify the longer the time horizon of the analysis (Heal and Milner, 2014). In cost-benefit analysis, the impact of an investment or policy decision is typically weighted against some previous reference point or baseline. The usual, but unsatisfactory, assumption of such baseline or business-as-usual scenarios is that society, the natural system, the level of pollution, or whatever is the studied system, remains unchanged over time. Extending the baseline scenarios to several plausible, but internally consistent and well documented global futures would give better understanding and provide a richer picture of the breadth of possible future challenges and uncertainties associated with the viability of decisions.

The climate research community has developed an architecture of climate scenarios (4 alternative Representative Concentration Pathways, RCPs) and a set of socioeconomic scenarios (5 Shared Socioeconomic Pathways) to be applied in combinations to study climate mitigation and adaptation, as well as other environmental problems that are somehow affected or associated with the changing climate (van Ruijven et al., 2014). Global SSP narratives (O'Neill et al., 2014) provide the reference pathways for the overall societal development. The SSP narratives have been translated as numerical projections of population and urbanization (Samir and Lutz, 2017), economic growth (Dellink et al., 2017), technological development (Leimbach et al., 2017), international trade and dietary preferences (Popp et al., 2017), energy production (Bauer et al., 2017) and emissions of several pollutants (Riahi et al., 2017). Many of the projections created within the climate research community have been collected and made readily available for researchers and practitioners in the SSP Scenario Database of IIASA.[1]

Numerical projections of societal factors, pollutant loads and the climate, extended and downscaled at various spatial and temporal scales, emerged as valuable sources to envision future pathways of resource use in analyses of food security, water availability and environmental quality. Fisher et al. (2005) applied an earlier generation of climate and socioeconomic scenarios to study the long-term prospects of agricultural production globally. Wiebe et al. (2015) studied the global and regional impacts of climate change on agricultural yields, area, prices and trade of agricultural commodities under the RCP/SSP scenario architecture. Booth et al. (2016) developed land use, wastewater effluent, and fertilization scenarios that are consistent with four alternative scenario narratives developed with stakeholder input at the watershed scale for Yahara watershed in Wisconsin. Hofstra and Vermeulen (2016) applied and extended two extreme SSPs (SSP1 and SSP3) to global changes in sanitation, and developed projections for the concentrations of one pathogenic parasite (Crystosporidium) in surface waters at the global scale. van Puijenbroek et al. (2015) also focused on SSP1 and SSP3 and developed scenarios for global nutrient emissions from households and industries.

Our study examines societal and climate change impacts on nutrient pollution in the Baltic Sea region. The Baltic Sea is a large and shallow semi-enclosed body of brackish water in Northern Europe. It is vulnerable to natural and anthropogenic disturbances due to its hydrographical characteristics. The Baltic Sea is sensitive to nutrient inputs being even in preindustrial state susceptible to, e.g., oxygen depletion. Recovery from eutrophication is expected to be slow (e.g., Murray et al., 2019; Saraiva et al., 2019b) due to long residence time of phosphorus, in particular (Gustafsson et al., 2017). Historical nutrient loads and the state of the Baltic Sea have been studied by e.g. Schernewski and Neumann (2005) and Gustafsson et al. (2012). McCrackin et al. (2018) made projections of phosphorus loads showing significant delayed response in the catchment to management actions. Österblom et al. (2013) developed a framework for integrated marine social-ecological scenarios. Huttunen et al. (2015) studied the impacts of changing climate and land use on agricultural nutrient loading from Finnish catchments to the Baltic Sea. Olesen et al. (2019) studied nitrate leaching losses from two Baltic Sea catchments (in Denmark and Poland) for locally extended combinations of Shared Socioeconomic Pathways (SSPs) and climate scenarios (RCPs) and compared the consequences of changed climate, land use and agricultural activities for the period 2041–2060 with recent past (1991–2010). Bartosova et al. (2019) extended the approach to the entire Baltic Sea catchment with E-HYPE, a large-scale hydrological model at a daily time step.

The objective of this study was to develop spatially explicit projections of nutrient loads for several combinations of regionally-extended socioeconomic and climate futures. We developed multiple plausible baseline projections of nitrogen and phosphorus loads for point sources, land use and atmospheric deposition to the Baltic Sea for the period 2010–2100. We extended global (O'Neill et al., 2014) and regional (Zandersen et al., 2019) narratives of societal development for the main polluting sectors and factors relevant for the nutrient emissions from agriculture, wastewater treatment and combustion processes in traffic and production of power and heat. This extends earlier frameworks (Österblom et al., 2013) and computations (e.g. Huttunen et al., 2015; Olesen et al., 2019; Bartosova et al., 2019) into internally consistent sets of long-term projections of nutrient loading to the Baltic Sea.

2. Framework for modelling long-term nutrient emissions

This section presents the elements included in the modelling of nutrient pollution to the Baltic Sea. These elements are further elaborated in Section 3. The process of building long-term projections of nutrient loading consists of four steps. The first step is to inventory the current pollution sources and to identify economic sectors and consumer groups responsible for nitrogen and phosphorus emissions to aquatic environments. In the case of the Baltic Sea, the external loading of nutrients is well monitored and recorded since the 1970s (Voss et al., 2011). The main pathways of nutrients include (i) non-point source nutrient pollution from agricultural land and other land uses (see Section 3.4.2), (ii) point source pollution (in particular from wastewater treatment) (see Section 3.4.1), and (iii) atmospheric deposition (see Section 3.4.3). Non-point source nutrient loading from agricultural and forestland, including the natural background, is the most important source of both nutrients. Atmospheric deposition comes second to nitrogen, while households are the second greatest contributor of phosphorus load. See Table S1 for the initial nutrient loads (year 2010) for the three main pathways.

The second step is to identify anthropogenic and natural drivers that affect production processes and intensity in the polluting sectors. Global socioeconomic drivers such as population growth, urbanization and changes in consumption patterns represent the ultimate drivers of change that determine the demand for different products and services, guide management and investment in infrastructure, and eventually determine the rate of climate change at a global scale. Local and regional drivers along with global trends in consumption determine the intensity and magnitude of the agricultural sector (e.g. numbers of production animals) and other polluting industries, and guide management effort and investment in pollution reduction technologies (Zandersen et al., 2019). In this study, changes in precipitation, land use and technological developments in agriculture were identified as the most important drivers of non-point source nutrient loading. Advancement of wastewater treatment technologies and the spatial distribution of population are the main drivers of point source pollution. Atmospheric deposition of nitrogen is affected by numbers of livestock and manure handling technologies applied in the region and the global technological transitions in fossil-fuel and biofuel combustion processes in the transportation, power generation and heating sectors.

After identifying the pollution sources and drivers, the third step is to prepare projections for the main drivers at spatial and temporal scales relevant for the polluting sectors and natural processes. In this

[1] http://www.iiasa.ac.at/web/home/research/researchPrograms/Energy/Databases.en.html

study, we made use of the IIASA SSP database giving numerical projections for population, urbanization, and economic and technological development, and regionally extended SSP narratives for sectors causing nutrient emissions (Zandersen et al., 2019) (see Section 3.1). Furthermore, we developed and applied models for disaggregating population and land use change at spatial and temporal resolutions relevant for the polluting sectors (see Section 3.2). To incorporate the impacts of changing climate into the nutrient projections, climate scenarios were downscaled for the Baltic Sea catchment area (see Section 3.3).

The fourth, and final, step is to develop and adapt models that use projections of drivers as inputs and produce sectoral projections of nutrient loads. In this study, we developed and applied nutrient load models for agricultural land and other land uses (see Section 3.4.2), treatment of wastewaters from households (see Section 3.4.1), and atmospheric deposition (see Section 3.4.3). The projections of these models are presented in detail in the Results section of this paper.

3. Materials and methods

3.1. Sectoral and regional extension of SSPs

The SSP narratives (O'Neill et al., 2014) and spatially explicit extensions of demography, gross domestic product, and urbanization comprise a consistent and rich package of information to be used as inputs of sectoral models of nutrient emissions, leakage and loading. However, existing literature rarely provides exhaustive datasets to model the future advancement of relevant technologies, changes in demand or stringency of policies. In such cases, a number of additional scenario interpretations are needed. Table S2 shows the extended narratives for parameterizing nutrient loss models from land uses, households and industries, and atmospheric deposition in the Baltic Sea region. The extended narratives specify technological development and diffusion within and across sectors, future demand and investment, and the expected compliance of sectors with the regulations.

3.2. Spatially explicit projection of population

Population is an important driver of both point source loading (determining the amount and geographical distribution of wastewater and the treatment facilities) as well as for the magnitude of agriculture (land area required to feed the population). We developed a downscaling framework for disaggregating national population and urbanization trends at a resolution of 10 × 10 km (see Fig. 1). For each grid cell, the population size was updated at 10-year intervals for the period 2010–2100. A distance-based model distributed periodic changes in the national population in proportion to the weights associated with each grid cell. In the case of increasing national populations according to the specific SSP, higher weights were assigned to the grid cells nearer to urban hotspots. For decreasing national populations, the grid cell-wise decreases were made in proportion to the initial population and distance from hotspots. Such an approach assumes that the current population hotspots are preserved in the future.

The development of national populations of countries within the Baltic Sea catchment area is based on the country-wise demographic projections by Samir and Lutz (2017) for each SSP. The initial (year 2010) urban and rural population by grid cells was obtained from Hasler et al. (2014). Grid cells with more than 40,000 inhabitants for SSP1 and more than 20,000 inhabitants for other SSPs were classified as population hotspots. It was also required that the urbanization rate should be higher than 0.8 and the fraction of urban area (out of the grid cell area) higher than 0.2 for a grid cell to qualify as a population hotspot.

3.3. Downscaling climate scenarios

In this study, we prepared the simulations for two Representative Concentration Pathways: RCP4.5 representing moderate climate change and RCP8.5 representing a high end climate change scenario (Moss et al., 2010) to assess the plausible impacts of climate change on non-point source nutrient loading. We used the results from four alternative General Circulation Models prepared for the period 1976–2098 (see Table S3). These projections were downscaled for the Baltic Sea catchment area by using the regional climate models RCA4, WRF and REMO applied to Europe and parts of the Northeast Atlantic (Donnelly et al., 2017). Finally, the hydrological model E-HYPE (Donnelly et al., 2016) was used to compute the impacts of changing climate, and in particular variations in temporal and spatial distribution of rainfall, on nutrient loads from the contributing drainage areas to the Baltic Sea. Other model inputs and driving data, such as land use and crop distribution, fertilization rates, point source discharges, and atmospheric deposition, were kept unchanged, representing their current values. The non-point source nutrient loads to the Baltic Sea were aggregated by drainage

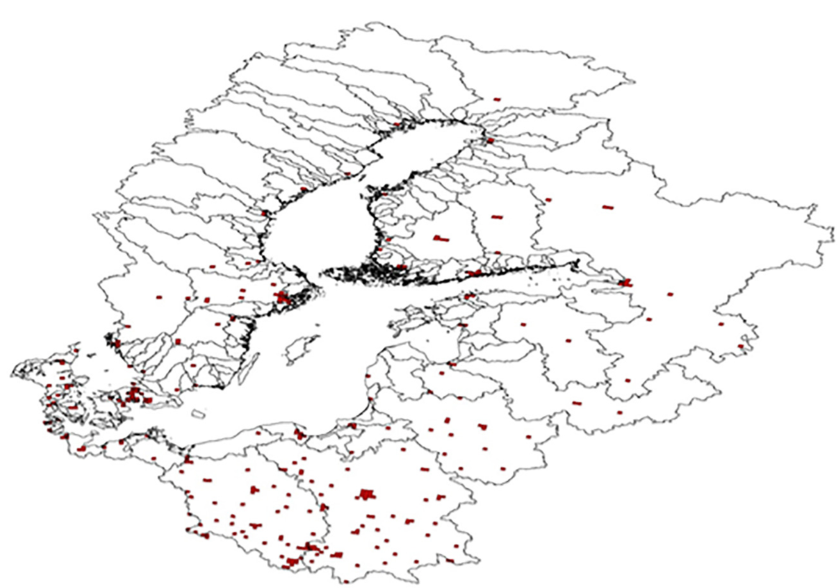

Fig. 1. Grid cells classified as urban hotspots in the 118 Baltic Sea drainage basins. The coastline of the Baltic Sea is shared by Poland, Russia, Lithuania, Latvia, Estonia, Finland, Sweden, Denmark and Germany.

basins at an annual scale for the period 2010–2098, and assuming that the climate variability of the years 2080–2098 remained the same for the two last years of the simulation (years 2099–2100). A change was determined in comparison to a reference time period (2010).

3.4. Projecting of nutrient loads

3.4.1. Household and industrial sources

The projections of nitrogen and phosphorus loading from households, including wastewater treatment, the greatest contributor of point source nutrient loading, were computed for each SSP. The modelling approach accounted for dietary changes and corresponding changes in the nutrient content of household discharges, current and future projections in treatment technology, and surface retention, i.e. processes that capture or remove nutrients on the flow path from source to sea (see Fig. 2). Population size and the dietary preferences are the most important factors that determine the quantity of human waste entering the wastewater treatment plants or ending up untreated in the aquatic environment. Per capita consumption of proteins is the main driver of household discharges of N and P, while non-food sources such as detergents and food residues play smaller role (van Puijenbroek et al., 2015). Income growth, technological development, technology diffusion across countries and environmental preferences are the main factors that drive maintenance and investments in treatment technologies and sanitation.

The municipal wastewater treatment technologies are divided into primary, secondary and tertiary depending on the combination of physical, chemical, and biological treatment processes applied in the plant. The non-connected share of the population includes rural population outside the municipal sewage system and urban population that are connected to municipal wastewater treatment, but whose wastewaters drain untreated to the water bodies. Existing sewage systems and treatment facilities require regular funding to maintain operating infrastructure and to cover the running costs (such as energy, chemicals, labor). Additional investment is needed in case of increases in nutrient loads, updates in treatment category (e.g. from primary or secondary to tertiary treatment) or technology updates within the current treatment category.

Additional investment is also needed in case new facilities are built or new households are connected to the sewage grid or if the existing sewage system is updated by building separate lines for sanitary wastewater and storm waters. Also, any new on-site treatment outside the municipal sewage systems comes with a cost. Wealth has been found to correlate with sophistication of wastewater treatment (WHO, 2014). In addition, sanitation and wastewater treatment exhibit positive economies of scale (Lundin et al., 2000). As a result, densely populated and wealthy areas have the best prospects for acquiring and maintaining sophisticated treatment technology. The narratives and assumptions relevant for alternative SSPs studied are summarized in Table S2 for wastewater treatment. The numerical model and parameters are specified in Supplementary material (Section S4). Developments in industrial and other point source wastes are assumed to develop at similar rate as in the loads of household-driven nutrient loading.

3.4.2. Diffuse loading from land uses

Trajectories of non-point source loads were aggregated by drainage basin by multiplying: i) area of each land use class, ii) root-zone leaching (reflecting change in the inputs of manure, fertilizers and atmospheric deposition), iii) retention factor and iv) impacts of changing temperature and precipitation on nutrient leaching and runoff losses. Land is divided into 10 land use classes. Agricultural land is represented by three classes: arable land and intensively and extensively managed grasslands.

Global socioeconomic development drives land use change, inputs used in crop production and the relative contributions of animal-based and crop-based products (Fig. 3). Changes in dietary preferences (caloric consumption and the proportions of animal/plant based foods), openness of international markets for food and beverages (exports/imports) as well as change in the population globally (aggregate demand) and nationally (domestic food demand) determine the size and structure of the agricultural sector in the region. These factors also determine the relative contributions of manure and inorganic fertilizers applied on arable land and grassland. Nutrient use efficiency (NUE) improvements due to the use of new cultivars and better crop protection reduce the need for inorganic fertilizers. Technological changes may also affect nutrient inputs to the land through indirect pathways (e.g. development of technologies that reduce ammonia emissions from livestock houses and manure storages).

Spatially explicit projections of population and a set of transition rules based on scenario interpretations (Table S2) were used to develop spatially detailed projections of land use for each SSP using a random forest classification approach at a spatial resolution of 300 × 300 m

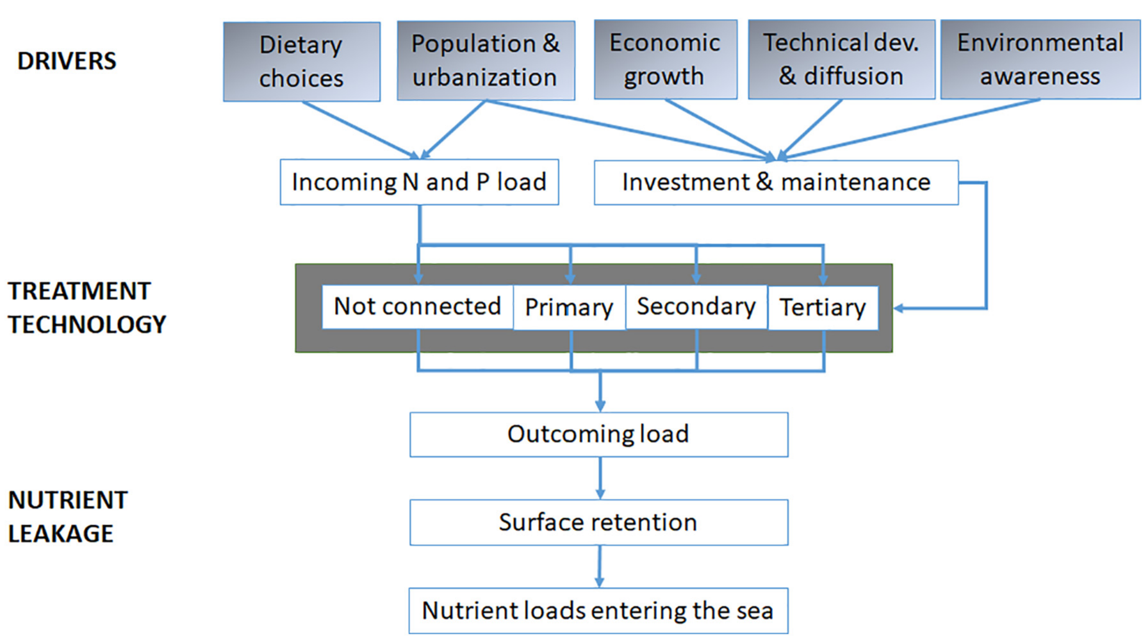

Fig. 2. Drivers of water-borne nutrient pollution from households.

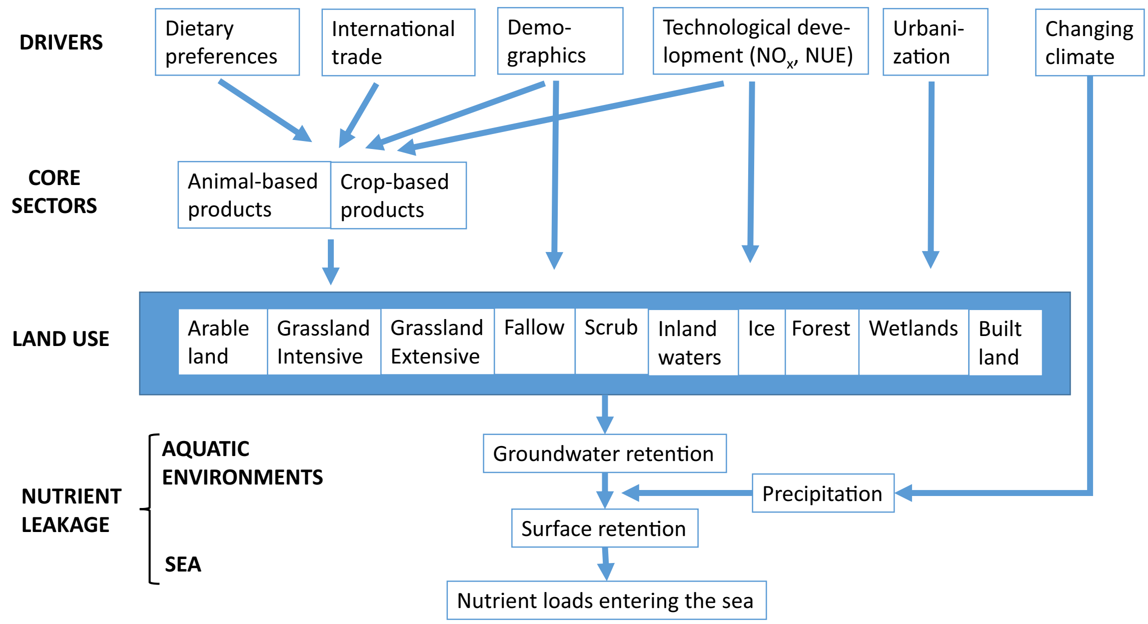

Fig. 3. Drivers and processes of diffuse nutrient loading.

(see Bartosova et al., 2018 for details). At each time step, the urban area was first increased or decreased according to population change assuming the current population density in the urban area remains constant. The expansion or contraction of urban areas was simulated in two steps: first, by associating land use change randomly for those neighboring areas that are suitable for conversion, including agricultural land, grassland and bare land, and second, allowing agricultural or forestland areas to iteratively expand to those pixels adjacent to these two land uses. The initial division of land use and input use by 118 drainage basins were obtained from Hasler et al. (2014). Section S5 explains the computation of non-point source nutrient pollution in detail.

3.4.3. Atmospheric deposition

Atmospheric deposition of N consists of nitrogen oxides (NO_x) and ammonia (NH_3). Nitrogen oxides originate mostly from combustion processes associated with energy production, industry and transportation in the countries sharing the Baltic Sea coastline, but also from Central Europe. Ammonia deposition is predominantly of local or regional origin and it mainly originates from agriculture and animal husbandry. Ammonia is lost from slurry and manure during storage, handling and during spreading to the fields. Atmospheric deposition of phosphorus is driven by natural processes, including dust that can be transported over long distances, and its contribution is generally small.

The initial deposition of nitrogen oxides, ammonia and phosphorus on sea areas was obtained from HELCOM (2015), and on land areas from Hasler et al. (2014). The long-term projections of nitrogen oxides deposition are averages for the OECD countries and are based on the outcomes of several integrated assessment models[2] available at IIASA SSP database. All the projections show a clear declining trend in nitrogen oxide emissions and deposition regardless of the climate scenario. The change in livestock projected for each SSP by year 2010 (S2) was linearly distributed at a decadal scale. Atmospheric deposition of phosphorus was assumed to remain constant over time.

[2] Projections from Image, AIM/CGE, GCAM4, GLOBIOM, REMIND-MAGPIE and WITCH-GLOBIOM models. Projections developed for RCP6.0 climate scenario were used for RCP8.5 because of the lack of IAM results for the high-end climate scenario.

4. Results

4.1. Trends in nutrient loading and the relative importance of different drivers

According to the simulations, several factors of varying influence may either increase or decrease total nutrient loading. Increasing precipitation due to climate change increases nutrient leaching from agricultural soils, forests and other land uses. According to our approximations, changing climate alone would increase nutrient loads per area by 28–36% for the high-end climate scenario (RCP8.5) and 7–20% for moderate climate change (RCP4.5) by the end of the current century. Socioeconomic factors may have either positive or negative impacts on loads, and the overall trend can be either increasing or decreasing. The combined nutrient loads from all sources and scenarios projected for 2100, including both climate impacts and direct impacts of socioeconomic factors, range between 52% and 115% of the initial loading.

Fig. 4 shows the proportions of different nutrient sources over the current century for several combinations of global climate and socioeconomic futures. One common feature in all studied combinations of climate and socioeconomic scenarios is the declining rate of atmospheric deposition of NO_x and point source emissions. The most important driver for such development is the anticipated technological progress in the end-of-the-pipe treatment technologies of industrial pollution. For all scenarios the share of the population under tertiary treatment clearly increases due to urbanization and transition of population to areas that are readily connected to the sewage systems and municipal wastewater treatment (see Fig. 5).

The aggregate loads from point sources decrease over time for all SSPs, although partly for different reasons. Under SSP1 and SSP2 the population size in the Baltic Sea area remains at about the current level. The decline in nutrient loading is caused by a fast transition to tertiary treatment, increasing investment in on-site treatment and extending sewer networks in rural areas. Under SSP3, technological development is much slower, and the reduction in point source loading is a consequence of a markedly reduced population in the area. In contrast, under SSP5, the total population increases, but the aggregate loads decrease due to high investment in wastewater treatment in urban areas.

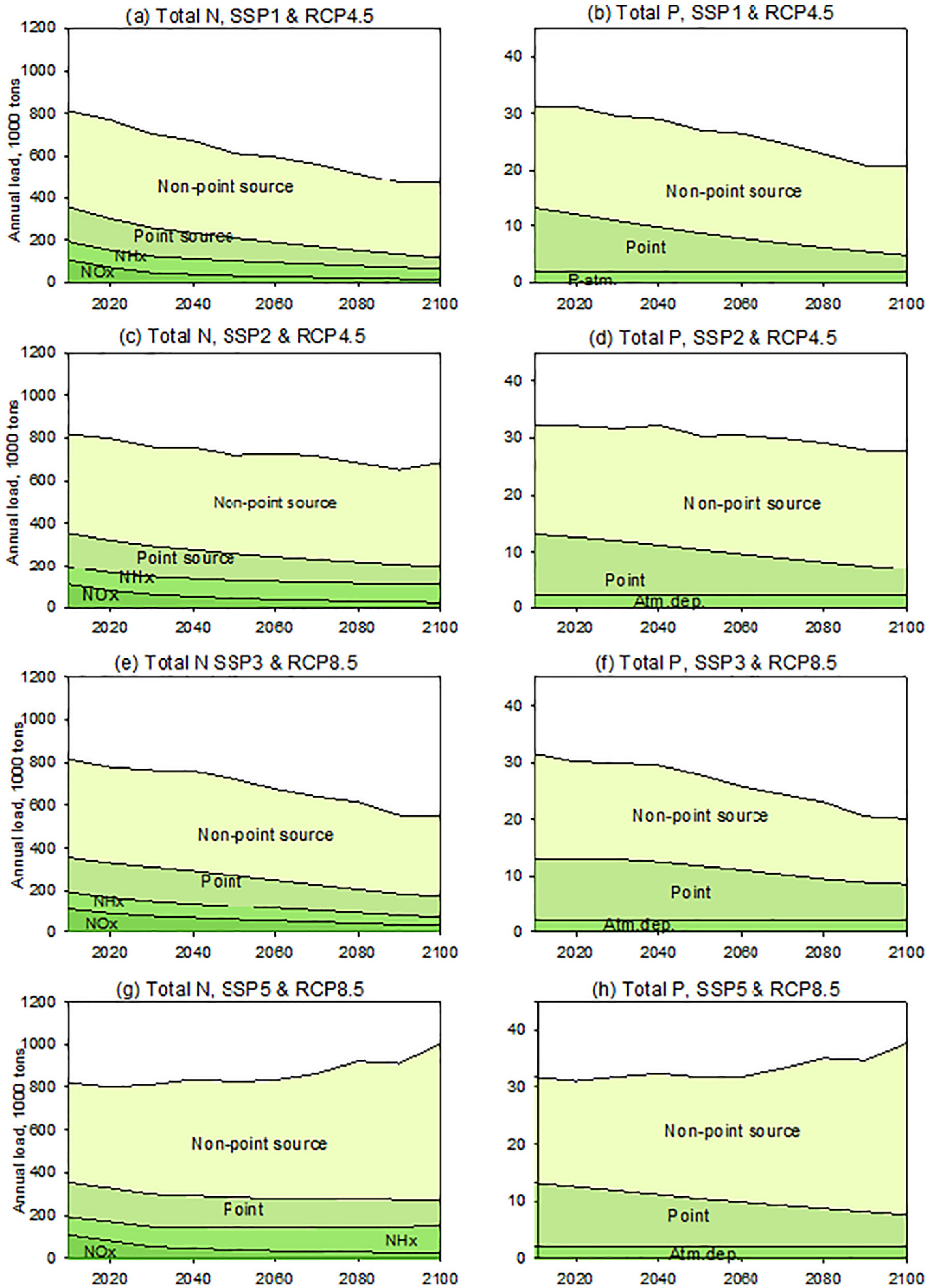

Fig. 4. Projected nitrogen and phosphorus inputs to the Baltic Sea as non-point source loading, point source loading and atmospheric deposition for selected combinations of climate and socioeconomic scenarios.

Long-term trends in non-point source loading are even more sensitive to societal changes. Under SSP1, the changes in the dietary preferences result in a lower demand for meat and dairy products, which lead to gradual reduction in the agricultural land. Circular agro-food systems become more common and resource-saving technologies, such as precision fertilization, are adopted widely. As a result, the nutrient loads will reduce 64–72% by the end of the century. Under SSP2, dietary preferences as well as the size of agricultural sector will remain about the same, while nutrient use efficiency is improved due to technological development. The non-point source loads slightly increase due to increased precipitation.

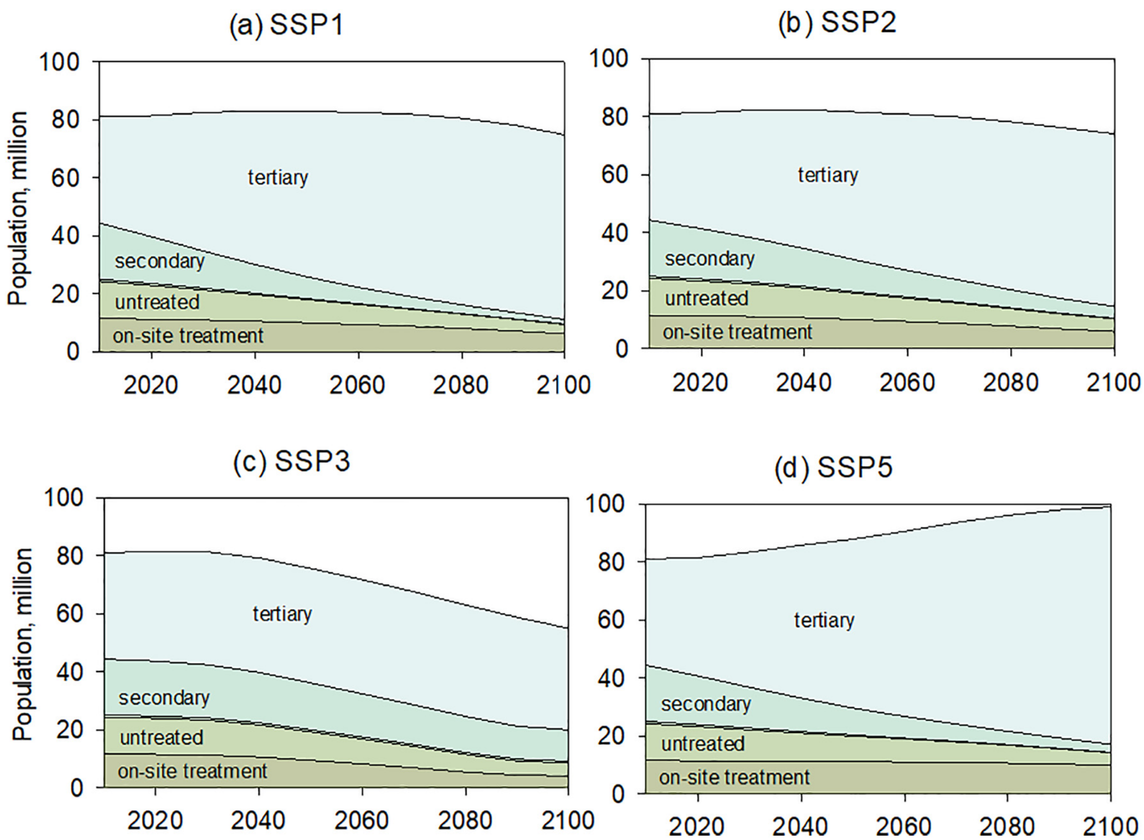

Fig. 5. Development of population under different wastewater treatment categories.

Under SSP3, the agricultural sector shrinks in particular in the southern catchments of the Baltic Sea, where agricultural land use dominates, due to reduced international trade in agricultural products and a shrinking population in the region. Despite low technological progress, the non-point loads would be reduced by 30–50% at the end of the century. SSP5 shows increasing relative competitiveness of the Baltic Sea region in the global markets for agricultural products. As a result of increased agricultural land, production animals and input uses, the nutrient load would grow by about 50% for both N and P by 2100.

4.2. Changes in nutrient loading to different Baltic Sea sub-basins

Fig. 6 shows the relative changes in projected nutrient loading over the 21st century for the seven sub-basins of the Baltic Sea: Kattegat, Danish Straits, Baltic Proper, Bay of Riga, Gulf of Finland, Bothnian Sea and Bothnian Bay. For scenarios with reduced overall loading (SSP1, SSP2 and SSP3), the relative reductions are highest for those sub-basins that currently suffer the most from eutrophication. These include Baltic Proper, Gulf of Finland, Gulf of Riga and the

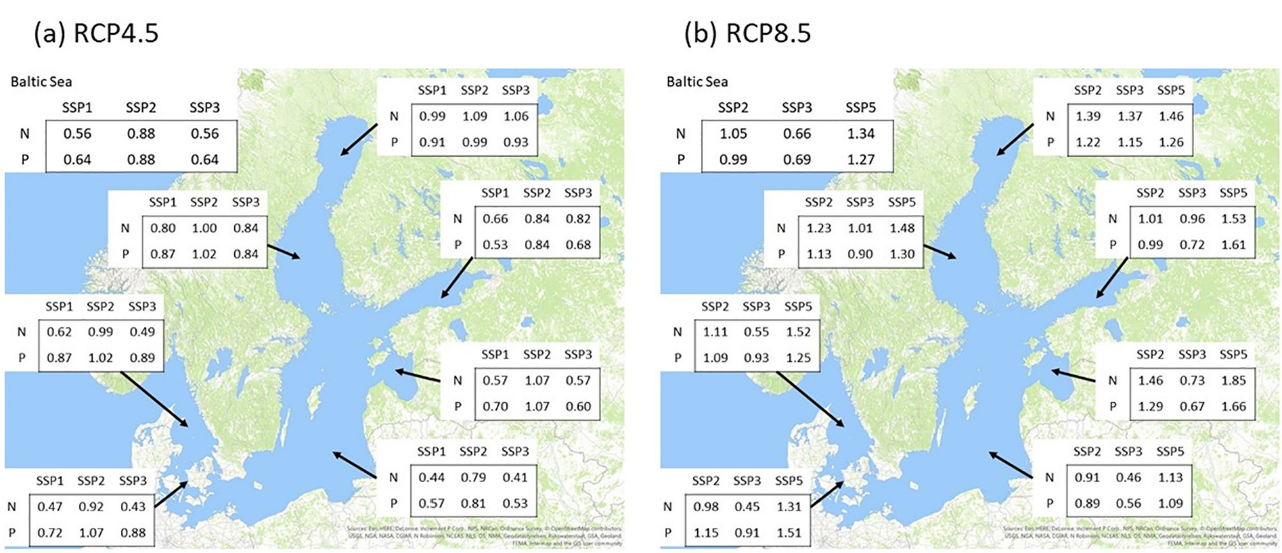

Fig. 6. External loading of N and P to the Baltic Sea by 2100 as proportion of current loading for RCP 4.5 (a) and RCP 8.5 (b).

Danish Straits that all receive waters from densely-populated catchments. There are several reasons for this. Firstly, the potential for technology updates in point source nutrient loading are highest in catchments of the Baltic States, Russia and Poland that drain to the Baltic Proper, Gulf of Finland and Gulf of Riga. Secondly, under SSP1, the decline in the demand for animal products affects most the agriculturally dominated catchments in the southern Baltic Sea. Thirdly, under SSP3, the decline in population size (and associated load to wastewater treatment facilities) is particularly strong in the Baltic States that drain to the Baltic proper and Gulf of Riga. Under SSP5, the nutrient loads increase fastest for smaller sub-basins and for northern sub-basins of the Baltic Sea. Expansion of agricultural area is greatest in those regions that are currently dominated by forest and have small population size.

4.3. Use of load projections for planning future mitigation effort

Nutrient load trajectories that show the consequences of alternative global development can be used as a baseline when planning the need for additional mitigation effort. Fig. 7 shows the inter-annual variability in simulated nutrient loads under current conditions (2010−2030) and towards the end of the century (2080–2100) under two deviating socioeconomic and climate futures and in comparison to the target loads as specified in the HELCOM Baltic Sea Action Plan (HELCOM, 2007). Current phosphorus loads are clearly higher (+40%) than the current target loads, while total nitrogen loads are slightly above (+5%) the threshold. Under the low-end nutrient load scenario (SSP1 & RCP4.5), nitrogen loads would decrease below the maximum allowed levels due to a change in lifestyle and a move towards strong and coordinated environmental regulations. Phosphorus loads would also gradually decrease over time and achieve the target level by the end of the century. However, reaching the phosphorus targets earlier would require substantial additional mitigation effort. In contrast, with high-end nutrient load scenario (SSP5 & RCP8.5) both N and P loads will tend to increase. In such a global future, the nutrient mitigation challenge would increase over time.

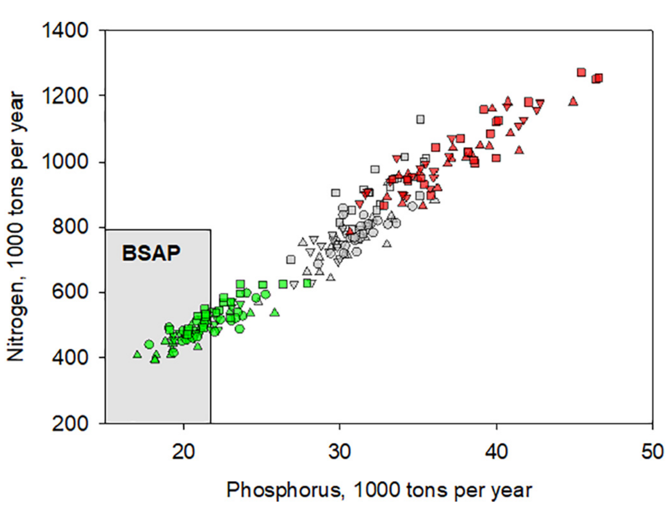

Fig. 7. Simulated annual loads of nitrogen and phosphorus to the Baltic Sea under current conditions (grey symbols, 2010–2030) and by the end of the century (2080–2100) for two extreme combinations of climate and socioeconomic scenarios: SSP1 & RCP4.5 (green symbols), and SSP5 & RCP8.5 (red symbols). The shaded area in the figure shows the target area of total loading as specified in the Baltic Sea Action Plan (BSAP). Different shapes denote the outcomes from four alternative climate models.

5. Discussion

5.1. Interpretations

We explored the combined impacts of societal developments and climate change on nutrient loading to the Baltic Sea. The simulations show that a multitude of factors with varying and opposing influences may either increase or decrease overall nutrient loads (see Section 4.1). There is an enormous difference between the consequences of two extreme scenarios featuring sustainability (SSP1) and a fossil fuel dependent future with high economic growth (SSP5) (see Fig. 4). On the other hand, two distinct global futures featuring sustainable development (SSP1) and regional rivalry (SSP3) may both lead to declining overall loads, although they differ fundamentally with respect to the challenges of mitigating and adapting to climate change. Here, a global socioeconomic setting (SSP3) which is challenging for solving global problems, may be amenable to reaching regional environmental targets, such as sustaining the environmental status of the Baltic Sea. The reduced nutrient load is a consequence of reduced global trade under the SSP3 future, with a declining agricultural sector and food industry in the region that is currently a large exporter of animal products.

The simulation results reveal several issues that need to be addressed further. For example, for all combinations of climate and socioeconomic scenarios studied here, the share of non-point source nutrient pollution increases over time (see Fig. 4). The point source loading as well as atmospheric deposition will decline, due to technological progress in treating industrial pollution. However, agricultural load to the Baltic Sea is heavily dependent on the extent of exports from the Baltic region to the global food market. This calls for additional follow-up of the developments and trends in global food demand and supply, population growth, dietary preferences and consumption patterns. Such information can be used to prepare long-term plans for adaptation, emergency planning and nutrient management in agriculture over decadal and longer time spans.

The spread of plausible global futures, for both climate and socioeconomic futures, and their regional consequences are worth considering when designing or updating international agreements or international environmental legislation (such as the EU Marine Strategy Framework Directive) or when revising the long-term targets for water protection. For example, the pathways of nutrient loading can be compared against the current, internationally agreed targets for upper levels of nutrient pollution to the Baltic Sea to evaluate the implementation gap and the need for additional nutrient abatement efforts (see Section 4.3 and Fig. 7). Our simulations suggest that the nutrient reduction targets of the Baltic Sea Action Plan could under some cases be reached solely as a result of societal developments (SSP1 scenario combined with medium climate change), although at a much slower pace than required. On the contrary, extreme socioeconomic and climatic conditions (SSP5 combined with high end climate scenario RCP8.5) would lead to substantial and increasing challenges to meet the nutrient load targets and reaching the good ecological status of the sea.

Multiple baseline projections of pollutant loads that are consistent with plausible climate change and socioeconomic developments can be used in gap analyses, cost-efficiency analyses and cost-benefit analyses of additional water protection efforts and policies. Several earlier studies (Turner et al., 1999; Elofsson, 2010; Hasler et al., 2014; Ahlvik et al., 2014) assessed the costs of nutrient abatement to meet the internationally set targets in the Baltic Sea by evaluating the future abatement challenges against previous reference points. Such comparisons overestimate the costs of additional policy efforts if the societal trends would tend to reduce loading or underestimate the costs in case the societal trends would increase pollution. Extending the cost-benefit analysis and assessments for several plausible baseline projections reflecting alternative global futures would provide a more robust basis for evaluating economic feasibility and adequacy of planned new policies and public investments in water protection. Furthermore, with spatially detailed projections, the policies and investments can be targeted to anticipate the areas under increasing pressure (see Fig. 6).

The approach and modelling framework presented here is transferable to other regions and partly to other environmental problems. However, we note that the particular combination of tools is case-specific and depends on the availability of models and data. The characteristics of the drainage basin, pollution load and the drivers of pollution as well as the characteristics of the ecosystem studied also affect the choice of relevant models to be integrated and applied. As an example of potential extensions, the projections of nutrient loads can be used as input to biogeochemical models to better understand their consequences on the long-term dynamics and healthy state of the aquatic ecosystem (see e.g. Saraiva et al., 2019a).

5.2. Comparison with other studies

Our simulations suggest that the direct impacts of global socioeconomic developments outweigh the impacts of changing climate on nutrient pollution. Changing climate alone will increase nutrient leaching by 7–36% from agricultural land and other land uses by the end of the century. However, the overall nutrient loads, including all sources and including both climate impacts and direct impacts of socioeconomic factors, range between 52% and 115% of the initial loading. For most cases, socioeconomic drivers (such as new and improved technologies) reduce nutrient loads. On the other hand, one should note that the chosen global SSP scenarios, and the interpretations made with respect to future changes in land use, consumption patterns, and other drivers represent extreme cases. Such choice was deliberately made as the aim of the study was to explore plausible future ranges of baseline nutrient pollution for the purposes of assessing future mitigation need. Our results on the impacts of changing climate factors on nutrient loads are in line with projections for riverine inputs of nutrients to the Baltic Sea computed by Bartosova et al. (2019) and the projections by Huttunen et al. (2015) prepared for Finnish agricultural lands. The projections prepared by Olesen et al. (2019) for two case study catchment areas in Denmark and Poland show somewhat higher increase in nitrogen loading (+20–60% increase by mid-century for a high-end RCP8.5 climate scenario).

Booth et al. (2016) developed methods for translating scenario narratives as numerical long-term projections of nutrient pollution and demonstrated their model at watershed level in Wisconsin, USA. Even though their case study area is much smaller (Yahara watershed is less than 0.1% of the area of the Baltic Sea catchment), their approach is comparable to ours. Both studies address multiple drivers (including socioeconomic drivers such as changes in the values and population) compared to most studies that address only one or few drivers at a time (cf. March et al., 2012). Despite the difference in spatial scale, most elements included in the modelling are similar, including transition rules for population and land use change, leakage of land-applied nutrients, and description of wastewater treatment technology. Due to the smaller case study area and higher spatiotemporal resolution of the climate and land use change, Booth et al. (2016) managed to better account for climate extremes and hotspot areas requiring specific attention.

Many scenario studies, including Booth et al. (2016), use a participatory approach and stakeholders to develop scenario narratives, while we relied on regional extensions of well-established global scenario narratives (Zandersen et al., 2019). Both approaches have their pros and cons. One advantage of stakeholder developed narratives is that they are easier to connect with regional development and local conditions. On the other hand, scenario narratives developed directly for one specific watershed may be difficult to associate with national and global developments. When extending global scenarios (such as the SSP framework) it is easier to maintain consistency across storylines and numerical projections developed at different spatial scales. Another advantage of using well-established global scenarios as the reference is that the numerical results are comparable with extensive literature that makes use of the same set of assumptions. Moreover, rich descriptions of pathways for economic development, population change, land use, and urbanization consistent with general scenario narratives makes it possible to align the studies with other studies of local and regional management problems. For example, we were able to use information about economic and technological development as drivers of land use change and investment in wastewater treatment technology.

5.3. Uncertainties and limitations

In defining the scenarios, some of the assumptions are treated as exogenous, while uncertainty in the remaining parameters and processes serve as a basis for sensitivity analyses. We repeated the simulations for several climate model outcomes, and thus accounted for some of the uncertainties associated with adequacy of the models to describe spatial distribution of climate resources. However, we acknowledge the omission of several other uncertainties. One important issue worth noting when interpreting the results is that there is space for multiple interpretations of SSP narratives. With more alternative interpretations, the range of nutrient load projections reflecting plausible outcomes would be much wider than is documented here. Another important reservation is that while SSP narratives and the associated literature provide a rich description of plausible economic, social and demographic development, they do not provide exhaustive data for describing all important processes relevant for nutrient loading. The remaining modelling elements and parameters need to be established from various additional sources, so it may be challenging to construct internally consistent data sets. Likewise, it is difficult to assess how realistic the model results are under future societal and climate conditions on which there is no prior experience. There are no data available on the nutrient loads under alternative societal futures (or corresponding past conditions) against which the model outcomes could be meaningfully compared with, calibrated and validated.

Likewise, some of the process descriptions (biophysical or socioeconomic processes) relevant for estimating pollutant loading are based on more solid research knowledge than others. As an example, processes that drive nitrogen leaching from agricultural land and other land uses are better understood than the processes affecting leaching and runoff of phosphorus. This results in more reliable estimates of nitrogen leakage from soils than phosphorus leakage. On the other hand, the technologies that remove phosphorus from wastewater are more effective and more robust to disturbances than those for removal of nitrogen, so effluent phosphorus load from wastewaters can be predicted more reliably than effluent nitrogen load.

Finally, it is worth noting that our scenarios do not account for leaps in technology, major innovations or any sudden negative developments due to the collapse of man-made or natural buffer mechanisms. For example, conventional toilets are the primary contributor to point source nutrient pollution. The increasing scarcity of clean water will provide the impetus to develop dry closets and waste recycling techniques that are superior to the current waste management which uses flowing water as a transporter of wastes. In a similar manner, technological breakthroughs in biotechnology to produce artificial meat cost-efficiently on an industrial scale would revolutionize the food industry, and reduce land area needed for agriculture. Development of such new technologies would dramatically reduce nutrient pollution to aquatic ecosystems.

6. Conclusions

Food-related nitrogen and phosphorus emissions (originating from food production or treatment of the wastes of food consumption) represent more than two thirds of the current loading to the Baltic Sea, and their share increased for all scenarios studied. Point source pollution and atmospheric deposition of nitrogen have been declining due to advances in treatment technologies and urbanization. Domestic agricultural sectors will largely determine the future challenge to combat eutrophication and to reach a good ecological status in the Baltic Sea. In order to successfully reach the environmental goals, agro-environmental policies and mitigation efforts should be carefully adjusted to counteract any negative trends in nutrient pollution and will need to anticipate developments in the domestic food demand, exports of agricultural products, and dietary preferences of the consumers. Improved effectiveness of fertilizer management and recycling of manure and human waste to substitute for fertilizer are promising areas of development. A new level of policy coherence is needed: policies that aim to improve water quality need to be proactive, adaptive and integrated with other policy areas (health, industry, consumer policies) to ensure that regional drivers of change actually are aligned with the ecological limits of our environment.

CRediT authorship contribution statement

Sampo Pihlainen: Conceptualization, Methodology, Formal analysis, Writing - original draft. **Marianne Zandersen:** Conceptualization, Methodology, Formal analysis, Writing - original draft. **Kari Hyytiäinen:** Conceptualization, Methodology, Formal analysis, Writing - original draft, Supervision. **Hans Estrup Andersen:** Formal analysis, Resources, Writing - review & editing. **Alena Bartosova:** Formal analysis, Resources, Writing - review & editing. **Bo Gustafsson:** Conceptualization, Resources, Writing - review & editing. **Mohamed Jabloun:** Methodology, Formal analysis, Resources, Writing - original draft. **Michelle McCrackin:** Methodology, Resources, Writing - review & editing. **H.E. Markus Meier:** Methodology, Resources, Writing - review & editing. **Jørgen E. Olesen:** Methodology, Resources, Writing - review & editing. **Sofia Saraiva:** Formal analysis, Software, Writing - review & editing. **Dennis Swaney:** Methodology, Writing - review & editing. **Hans Thodsen:** Resources, Software.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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