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Nitrate leaching losses from two Baltic Sea catchments under scenarios of changes in land use, land management and climate

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Abstract Pollution with excess nutrients deteriorate the water quality of the Baltic Sea. The effect of combined land use and climate scenarios on nitrate leaching and nitrogen (N) loads to surface waters from two Baltic Sea catchments (Norsminde in Denmark and Kocinka in Poland) was explored using different models; the NLES and Daisy models for nitrate leaching, and MIKE SHE or MODFLOW/MT3DMS for N transport. Three Shared Socioeconomic Pathways (SSP1, SSP2 and SSP5) defined change in land use and agricultural activities. The climate change scenarios covered 2041–2060 compared with 1991–2010 under RCP8.5, applying four different climate models. Increases in predicted N-load from climate change vary from 20 to 60% depending on climate model. SSPs moderate these N-load changes with small changes for SSP1 to large increases for SSP5, with greater increases for Norsminde than Kocinka due to land use differences. This stresses needs for new measures and governing schemes to meet sustainability targets.

Keywords Climate change · Diffuse water pollution · Land management · Land use · Nitate leaching · Nitrogen load

INTRODUCTION

In recent decades, water pollution has been a main concern for societies, since this has direct impacts on biodiversity, ecosystems, human well-being, drinking water quality and food production (Hashemi et al. 2016). Much of the water pollution is related to excessive nutrient loadings of nitrogen (N) and phosphorus. Nutrient loadings from land to the sea are largely determined by human activities. Direct effects occur through the human influences on

nutrients from settlements (in particular through sewage) and through land use affecting diffuse losses of nutrients, e.g. nitrate leaching from agricultural land (Hashemi et al. 2016). Indirect effects occur through the influence of changes in temperature and precipitation on the water and nutrient cycles (Jeppesen et al. 2011). Complex interactions between land use, land management and regional climate change modify hydrology and water quality (Arheimer et al. 2012). In particular, coastal areas and their water bodies are vulnerable to land use transformations, climatic change and nutrient loadings (McGranahan et al. 2007).

The Baltic Sea is among the most heavily polluted marine ecosystems worldwide, due, amongst other reasons, to excessive nutrient loads (Gustafsson et al. 2012; Wulff et al. 2014). This has led to the adoption of the Baltic Sea Action Plan (BSAP), which requires substantial additional reductions in nutrient loads to the marine environment. Although the BSAP has to some extent been successful in reducing nutrient loads to the Baltic Sea, severe problems still remain (Elmgren et al. 2015; Reusch et al. 2018).

While there may be scope through improved and more spatially and temporally targeted implementation of measures within catchments to further reduce nutrients loads, this is being challenged by other drivers influencing land use, land management and climate affecting N-loads (Hashemi et al. 2016). The uncertain future can be represented through scenarios, where the scenario framework of the IPCC is often used for describing possible future land use and climate (Zandersen et al. 2019). A model-based catchment study in Denmark has shown that climate change may lead to enhanced N-loads to the marine ecosystems, but that this may be reduced or enhanced by changes in agricultural land use (Trolle et al. 2019).

Previous model-based scenario studies have shown increased N-leaching from agricultural soils (Doltra et al. 2014) and increased N-loadings from agricultural catchments (Teutschbein et al. 2017) under projected climate change in Scandinavia. Scenarios for future land use and climate in the Baltic Sea basin have projected increased N-loadings to the Baltic Sea (Humborg et al. 2007; Arheimer et al. 2012; Eriksson et al. 2013). A recent study for the Baltic Sea area suggests that socio-economic drivers may be more important for nutrient loads to the Baltic Sea than climate change (Bartosova et al. 2019). However, such assessments may depend on the modelling approaches and the scale and structure of the catchment in study. Also, these interactions between land use and climate change may play out differently depending on farming systems, soils and geology.

In this study, we focus on the impact of land use and climate changes on N-loads to the sea from two groundwater-dominated catchments that vary greatly in groundwater travel times and N-reduction processes. The objective is to quantify the effect of changes in future land use and climate on N-leaching from agricultural land and the resulting N-load from the catchments after transformation processes in groundwater and surface waters.

MATERIALS AND METHODS

Study sites

The study was conducted for two catchments in the Baltic Sea drainage basin, Norsminde in Denmark and Kocinka in Poland (Fig. 1). Norsminde is a 101 km^2 catchment dominated by agriculture (67%, mainly cropland) located on the eastern coast of Jutland. The study was conducted in a sub-catchment of 85 km^2 covering the catchment area to the most downstream monitoring station. Norsminde has a temperate and humid climate with a surface geology dominated by clayey tills. Kocinka is a 260 km^2 catchment also dominated by agriculture (56%) and located in the southern part of Poland (Fig. 1). Kocinka has a temperate climate with a surface geology of sandy and sandy loam soils.

Scenarios

A number of scenarios were developed to analyse the effects of combinations of possible future land use and climate on N-leaching and N-loads. The variation in future land use is represented by three selected Shared Socio-economic Pathways (SSPs) that were developed for the Baltic Sea region by Zandersen et al. (2019) to cover different aspects of future land use changes in agriculture,

management and technologies related to nutrient loadings to the Baltic Sea. The three SSPs used in this study include SSP1 (sustainability), SSP2 (middle of the road) and SSP5 (fossil-fuelled development).

The climate change scenarios used in this study were based on the IPCC representative concentration pathway RCP8.5 (Moss et al. 2010). The climate change projections were made with Regional Climate Models (RCM) nested within a Global Climate Model (GCM). These climate scenarios were combined with the three SSPs to investigate the effect of climate change on N-leaching and N-load. In reality, not all SSPs are consistent with the RCP8.5 concentration pathway; however, the projections of climate change by 2050s vary less between RCPs than between GCMs. The baseline period was 1991–2010 and future scenarios were developed for 2041–2060.

Socio-economic scenarios

The socio-economic scenarios were defined in terms of agricultural land use, crop management in terms of application of catch crops, livestock production and fertilisation rates. Spatial changes in agricultural land use for each SSP were implemented through predefined transition and allocation rules for the specific land use classes. The SSPs defined the change in agricultural land use, and the changes were applied to current land use by assuming that changes take place along current land cover interfaces (Verburg et al. 2004).

SSP1 describes a world making good progress towards sustainability, with efforts to achieve sustainable development goals. A 10% reduction in agricultural land use with conversion to forest is assumed, together with implementation of current objectives within the EU Water Framework Directive (WFD). SSP2 describes a world, where trends typical of recent decades continue, with some progress towards achieving sustainable development goals. No change in agricultural land use is assumed. SSP5 is a world that stresses conventional development oriented towards economic growth as the solution to social and economic problems through the pursuit of enlightened self-interest. It is assumed that there is a 10% increase in agricultural land use, mostly from current forest.

Cropping systems for both catchments were defined for two farm types (pig/plant and dairy/cattle farm) using information on current farm structure in the two catchments. The crop rotations were defined to reflect the average farm management in relation to cropping sequences and N fertilisation. The frequency of catch crops (CC) in the crop rotations varied between SSPs. In SSP1 CCs were applied to their fullest extent, and in some rotations winter cereals were changed to spring cereals with use of
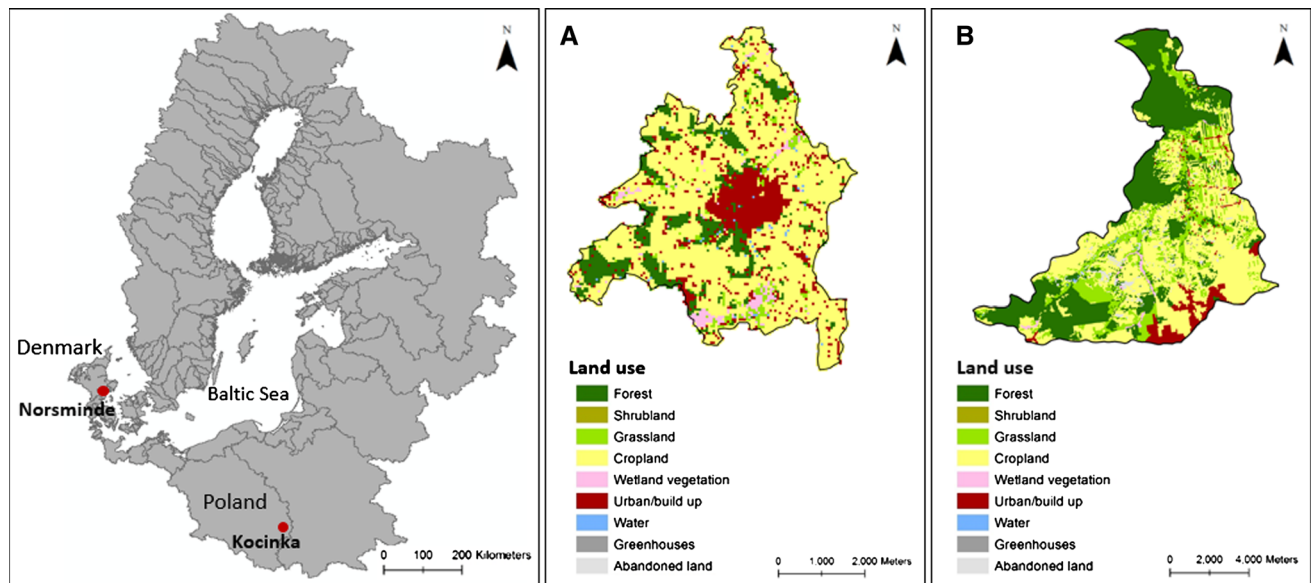
Fig. 1 Location of Norsminde and Kocinka catchments in the Baltic Sea drainage basin, including descriptions of land use for both Norsminde (**a**) and Kocinka (**b**)

CC. No change in CC relative to baseline was implemented for SSP2, and in SSP5 all use of CC was removed.

N fertilisation in the different SSPs covers both mineral fertiliser and manure. The amount of N in manure is given by the livestock production, and the amount of manure applied is also determined by how efficiently the N in manure is used. This is defined through the replacement value of N in manure (N_{rep}). The effective N applied (N_{eff}, kg N ha^{-1}) is calculated from N in mineral fertiliser and manure as:

$$N_{eff} = N_{fer} + N_{rep}N_{man} \qquad (1)$$

where N_{fer} is N in mineral fertiliser (kg N ha^{-1}), and N_{man} is N in manure (kg N ha^{-1}). N_{rep} is set to 0.65 in the baseline situation corresponding to the current value for manure in Denmark (Dalgaard et al. 2014).

In all scenarios, the current fertiliser and manure rates in the catchments are taken as the baseline, and these values are changed in the different scenarios by changing the amount of manure (N_{man}), the N replacement value in manure (N_{rep}) and the amount of effective N (N_{eff}). The mineral fertiliser rate is then subsequently calculated for each scenario using Eq. (1).

N fertilisation schemes were constructed for each of the crop rotation systems using the current recommended N rates for both the baseline and SSP2. The total N application with mineral N was based on the recommended N rates, the preceding crop's effects on N ($N_{precrop}$) and the replacement rate for total N in organic fertilisers. Calculation of the individual mineral N application rates for the different crops (Eq. 2) includes residual N effects of crops and CCs grown in the previous year ($N_{precrop}$). The organic

N applied follows typical practice for applying the organic fertilisers and the recommended N rate:

$$N_{min} = N_{rate} - N_{precrop} - N_{rep}N_{man} \qquad (2)$$

where N_{min} is the rate of mineral N fertiliser applied (kg N ha^{-1}), N_{rate} is the recommended N rate for the specific soil and crop (kg N ha^{-1}) and $N_{precrop}$ is the effective N supply from previous crops (kg N ha^{-1}). Table 1 shows the overall changes in key aspects related to N management used in setting up the N fertilisation schemes under the different scenarios.

For SSP1, there is a 50% reduction in livestock implemented as a 50% reduction in manure N. The N replacement value in manure is increased to $N_{rep} = 0.75$ through implementation of biogas, acidification etc. The effective N amount applied is reduced to 5% below the current level. If this results in $N_{fer} < 0$ then N_{fer} is set to 0. For SSP2,

Table 1 Relative N rate, livestock density and agricultural area compared with the baseline for the various scenarios. The N replacement value using organic N fertilisers instead of mineral N also varies among the SSP scenarios

Covered aspect	Baseline	SSP1	SSP2	SSP5
N rate relative to current (%)	100	95	100	105
Replacement value of N in manure (%)	65	75	70	60
Livestock units per hectare relative to current (%)	100	50	100	150
Agricultural area relative to current (%)	100	90	100	110

livestock and manure production is maintained at current levels. The N replacement value in manure is increased to $N_{rep} = 0.70$. The effective N amount applied is maintained at current level. For SSP5, there is a 50% increase in livestock implemented as a 50% increase in manure N. The N replacement value in manure is decreased to $N_{rep} = 0.60$, since new livestock production facilities will not prioritise reductions in ammonia losses. The effective N amount applied is increased to 5% above current level. If this results in $N_{fer} < 0$ then N_{fer} is set to 0.

Climate change scenarios

Figure 2 shows the baseline climatic conditions of the two study catchments with monthly average temperature and precipitation. Results of four climate models were used (Table 2), all of which are part of the CORDEX database and, based on RCP8.5, are selected to represent the variation in climate model projections of temperature, precipitation, evapotranspiration and discharge in the Baltic Sea drainage basin (Bartosova et al. 2019). Due to climate model limitations and inherent variability in the climate system, the climate model data showed biases when compared to local observed data during a past reference period.
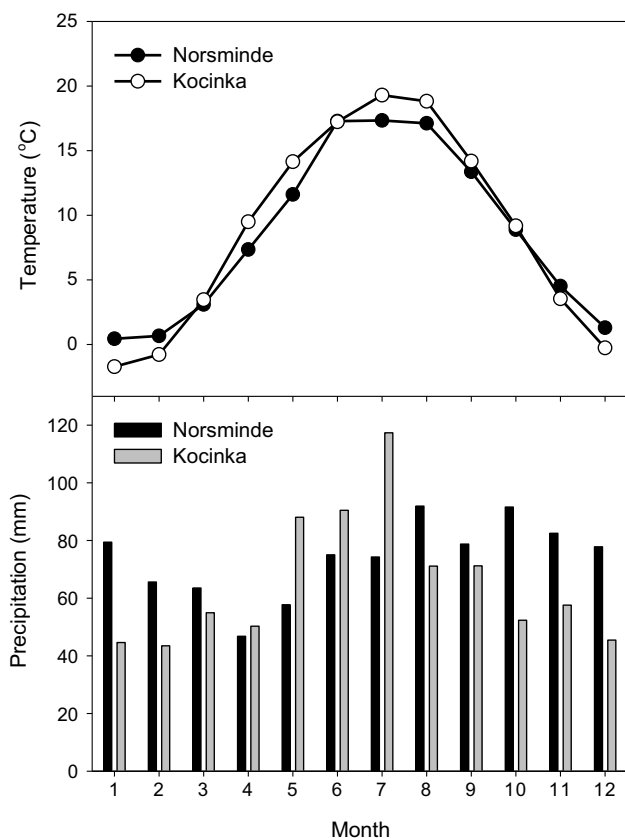
Daily mean temperature, precipitation, wind speed and relative humidity were bias-corrected using the quantile-mapping variant of distribution based scaling (Yang et al. 2010) using observed weather data for the period 1991–2010 for reference. The downscaled climate model data were applied as forcing data to the hydrological models for both the future and baseline periods.

Modelling water and N flows

Modelling N-leaching

Annual N-leaching from agricultural land for both the Norsminde and Kocinka catchments under current and future climatic conditions were calculated using the NLES (version 4) model. For non-agricultural lands, standard values for N-leaching from different land uses were used. NLES is an empirical regression-based model that estimates N-leaching from information on N application in fertiliser and manure, cropping sequence, catch crops, soil type and drainage (Kristensen et al. 2008). This model was calibrated on N-leaching measurements from Denmark. Since climate and soils of the Kocinka catchment are rather similar to those in Denmark and no measurements of N-leaching were available for Kocinka, the calibrated model parameters for NLES were directly transferred to the Kocinka catchment. This model was chosen, because it allows estimation of N-leaching from practical cropping systems with simple input data.

The Daisy model (Abrahamsen and Hansen, 2000) was used to calculate the monthly percolation from the root zone, which is a required input to NLES. The water balance was simulated for all crops within the cropping system for 20 years of weather data for both 1991–2010 and 2041–2060. These simulations were done for the selected cropping systems and the dominant soil types in the two catchments.

Daisy was also used to bias-correct the NLES predicted N-leaching for the future climate scenarios. The Daisy crop

Fig. 2 Monthly average baseline temperature and precipitation in Norsminde and Kocinka catchments for 1991–2010

Table 2 Climate models and average correction factors for adjusting NLES nitrate leaching levels for cropland and grassland used in simulations for Norsminde and Kocinka catchments

Climate model	GCM	RCM	Correction factor	
			Norsminde	Kocinka
CM1	MPI-ESM-LR	CCLM	1.44	1.30
CM2	CM5A-MR	WRF-JPSL	1.24	1.03
CM3	CNRM-CM5	RCA4	1.08	1.09
CM4	CanESM2	RCA4	1.17	1.08

parameters were adapted for future climatic conditions and atmospheric CO_2 concentration using the method described in Børgesen and Olesen (2011). The Daisy model was run for baseline and future climate conditions and the relative change in N-leaching was used to correct the annual N-leaching calculated with NLES:

$$\text{N-leaching}_{future} = \text{NLES}_{future} * \text{Correction} \qquad (3)$$

$$\text{Correction} = \frac{\text{Daisy}_{future}}{\text{Daisy}_{base}} * \frac{\text{NLES4}_{base}}{\text{NLES4}_{future}} \qquad (4)$$

where Daisy and NLES4 are N-leaching calculated with the Daisy and NLES models, respectively, and future and base refer to average values for the future and baseline periods, respectively. The correction factors were developed for the typical crop rotations in the respective catchments, and average values were calculated for these rotations, including grassland. Table 2 shows the correction factors of the four climate models for both Norsminde and Kocinka catchments.

The N-leaching was calculated with NLES for all agricultural areas in the catchments at 1 ha grid scale (100 × 100 m). Each grid cell is described by one dominating land use. For both cropland and grassland, average results of all crops within the given soil and rotation system combination were used. For other land use classes, a standard value of annual N-leaching of 2 kg N ha^{-1} was used (Christensen et al. 1990).

Due to the high inter-annual variation in nitrate leaching caused by varying weather conditions, the mean result of 20 years of simulations from NLES was used in the following catchment scale modelling.

Simulating N-transport and reduction

The transport and transformations of N in the catchments were calculated using different models for the two different catchments. For Norsminde, the MIKE SHE model was used, whereas the MT3DMS was used for Kocinka. These models were chosen since they had previously been applied on the respective catchments and therefore the necessary geological information and calibrations were already available. These two models thus fitted the available data and previous experiences for the respective catchments.

N-transport and reduction in Norsminde MIKE SHE is a distributed physically-based hydrological model, and here the setup from He et al. (2015) and Hansen et al. (2014) was used. The N-transport and N-reduction were simulated applying particle tracking using spatially distributed daily N-input from NLES. Annual NLES N-leaching was downscaled to daily leaching using simulated average seasonal percolation profiles from DAISY. The

groundwater N-reduction was simulated assuming instantaneous reduction at the redox interface, which defines the transition from oxic to anaerobic conditions in the groundwater (Hansen et al. 2014). The location of the redox interface was distributed following the spatial pattern in groundwater recharge (Hansen et al. 2014).

The N-reduction in the stream system (as a percentage of N transported to the stream) was assumed to be constant over time and defined as a function of the stream length. The N-transport was calibrated by adjusting the location of the redox interface (Hansen et al. 2014) and the stream N-reduction was adjusted until the simulated N-transport to the stream monitoring station matched the observed N-transport for the period 2000–2007 reaching the assumed split between groundwater and surface water N-reduction. For the future scenarios the location of the redox interface was assumed unchanged, and the N-reduction in surface waters was assumed unchanged in all scenarios.

N-transport and reduction in Kocinka Modelling of nitrate migration in the Kocinka catchment was performed by MODFLOW and MT3DMS (Zheng and Wang 1999), which is a modular 3-D transport model that simulates advective–dispersive and reactive transport of dissolved solutes in groundwater. N-load was provided to the model as concentration in infiltrating water calculated from the estimated N-leaching in nitrate divided by effective infiltration.

For the agricultural areas, N-leaching was calculated for the past (1950–1975 and 1976–1990) based on statistical data. Data for N-leaching reaching back to the 1950s were included due to long time (several decades) of nitrate migration delay in the unsaturated (vadose) zone (Fig. 3). Organic fertilisation was estimated from province livestock numbers (Michalczyk et al. 2018). N-leaching was estimated assuming that 15% of applied N is leached. The initial nitrate concentration for 1950 was assumed to be 5 mg NO_3 L^{-1}. For baseline and future periods leaching was estimated from NLES. There is a long transport time in the catchment implemented as a lag-time, which is the sum of the travel time of water through the unsaturated zone (MRT) and the travel time associated with movement of water between the recharge and discharge areas. The mean value of the total lag-time of nitrate for the Kocinka catchment is in the order of 40–50 years.

The N-loads from agriculture and wastewater were assigned to each model cell in the input to MT3DMS. The N-loads were applied directly to the aquifer through the recharge concentration module for each 1-ha model grid cell. In MT3DMS N-load was applied at the groundwater table (saturated zone). The lag-time of nitrate in the unsaturated zone was assessed on the basis of MRT of water in this zone, calculated for each grid from the
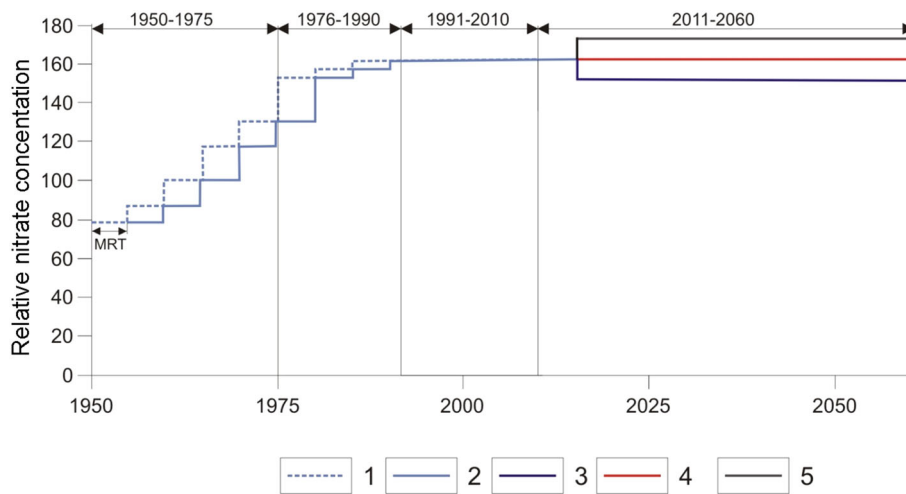
Fig. 3 Schematic diagram of N (as nitrate) input function for the MT3DMS model cell (100 × 100 m) with agricultural land use for historical periods (1950–1975 and 1976–1990), baseline (1991–2010) and future (2011–2060) periods. Explanations: 1: N-leaching below root zone for historical and baseline periods; 2: input function with incorporating lag-time in unsaturated zone assessed as Mean Residence Time (MRT); 3–5: input functions for future periods, 3: SSP1; 4: SSP2; 5: SSP5. The values shown are to be considered relative to the actual site conditions

Table 3 Changes in temperature, precipitation, reference evapotranspiration and percolation of water out of the root zone calculated using the Daisy model for future climatic conditions (2041–2060) compared to baseline (1991–2010)

Climate model	Temperature (°C)		Precipitation (mm year^{-1})		Evapotranspiration (mm year^{-1})		Percolation (mm year^{-1})	
	Norsminde	Kocinka	Norsminde	Kocinka	Norsminde	Kocinka	Norsminde	Kocinka
CM1	1.4	1.5	3	− 74	21	43	77	12
CM2	1.0	1.3	108	123	− 8	− 16	150	143
CM3	1.3	1.6	124	113	− 10	− 26	156	147
CM4	1.8	2.1	23	18	− 4	11	40	38

Groundwater Vulnerability Map of Poland (Witczak et al. 2014). The denitrification is described in MT3DMS by the first-order kinetic rate constants, with half-lives of 5.3 years for the Quaternary aquifer and 47.5 days for the Jurassic aquifer. No denitrification was assumed in the unsaturated zone (Michalczyk et al. 2018).

RESULTS

Water balance

Table 3 shows the estimated future changes in water balance components (precipitation, reference evapotranspiration and percolation out of the root zone) compared to the baseline. The temperature increases were slightly higher for Kocinka than for Norsminde, with the greatest temperature increase for CM4 and the lowest for CM2. Changes in average rainfall varied between climate models, but with similar values for the two catchments. CM2 and CM3 showed increases in rainfall, whereas there was little change in rainfall for CM1 and CM4. There were

smaller changes in reference evapotranspiration, but all climate models resulted in increased average percolation with the highest increases for CM2 and CM3.

Nitrate leaching

The effects of land use and climate change on N-leaching were generally smallest for SSP1 and highest for SSP5 (Fig. 4). For Norsminde the mean baseline N-leaching from agricultural areas and the entire catchment were 57 kg N ha^{-1} and 38 kg N ha^{-1}, respectively, versus for 31 kg N ha^{-1} and 21 kg N ha^{-1} for Kocinka. The relative changes in N-leaching from agriculture were overall at similar levels for the two catchments with the smallest increase for SSP1 and highest for SSP5. The greater extent of arable farming in Norsminde compared with Koncika resulted in greater relative changes in N-leaching at catchment scale between SSP1 and SSP5 at Norsminde than at Kocinka.

The changes in N-leaching from agricultural land under future SSPs varied considerably between climate models (Fig. 5). For SSP1 there was little change in N-leaching for Norsminde (− 5 to 23%), but an increase for Kocinka (10
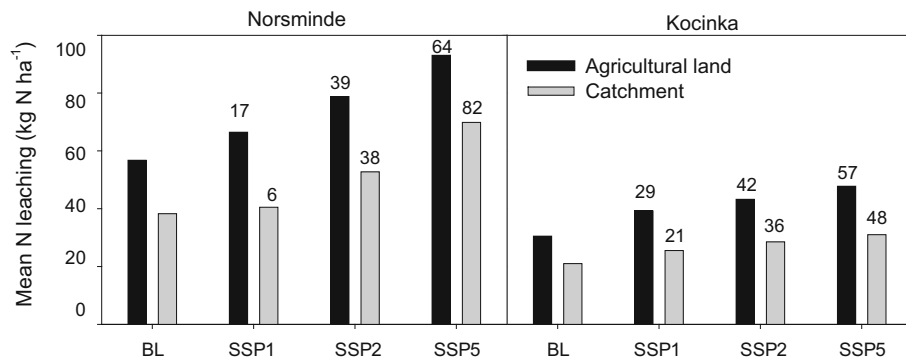
Fig. 4 Effects of climate change and socio-economic scenarios on nitrate leaching from agricultural land and total N-leaching for the entire catchment area for Norsminde and Kocinka catchments. Results for SSPs are shown for future climate and BL for the baseline climate and land use. All results are shown as average of four climate models. The numbers indicate changes (%) relative to BL

to 30%). For SSP2 the changes in N-leaching was at similar levels for the two catchments, but vary considerably between climate models. The N-leaching from agricultural areas under SSP5 increased at Norsminde (63 to 113%) and at Kocinka (29 to 61%). In all cases, CM1 gave the highest increase in N-leaching and CM4 the lowest.

N-load

The four climate models project different changes in N-load from the two catchments (Fig. 6). All climate models project an increase in N-load for both catchments, when only looking at the climate effect (Fig. 6a, b). The variations in N-load among climate models are similar for the two catchments, but with larger variations at Norsminde compared to Kocinka. Compared with SSP2, N-load is reduced in SSP1 and increased considerably in SSP5 (Fig. 6b, c). There appears to be an interaction between SSPs and climate models such that N-load varies more among climate models in SSP5 than in SSP1. For Norsminde, the changes in N-leaching and N-loads are dissimilar between CM3 and CM4 (compare Figs. 5 and 6),

because the N-reduction in groundwater is 13% lower in CM3 compared to CM4 (data not shown).

DISCUSSION

Modelling methodology

Results under changes in land use and climate depend strongly on the choice of future conditions as represented by SSPs and climate models. The climate models were selected to represent a range of future climatic conditions in the Baltic Sea drainage basin. In reality, the greenhouse gas emissions may follow a lower emission pathway than RCP8.5, but this will have relatively little impact on the climatic conditions by 2050. We included only three out of a total of five SSPs developed for the Baltic Sea area (Zandersen et al. 2019). However, these SSPs span the full range of possible land use changes, i.e. from reduction to increase in agricultural land use and intensity of land management. The choice of change in land use and intensity of agricultural management in these scenarios are
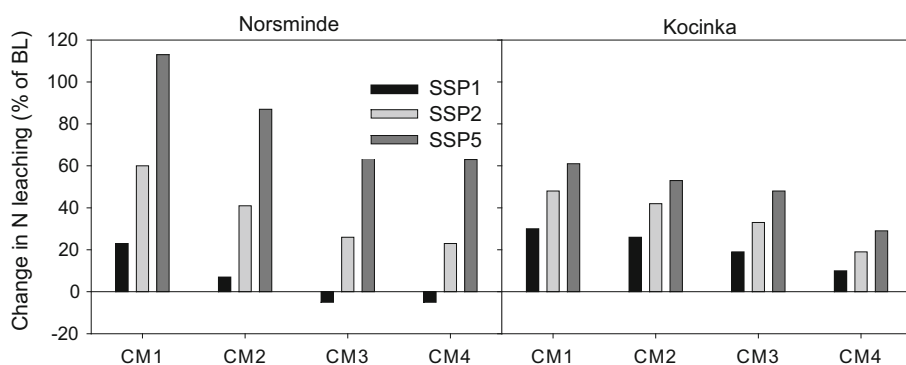

Fig. 5 Mean change in N-leaching from agricultural land under different scenarios and climate model predictions of future climatic conditions compared to baseline
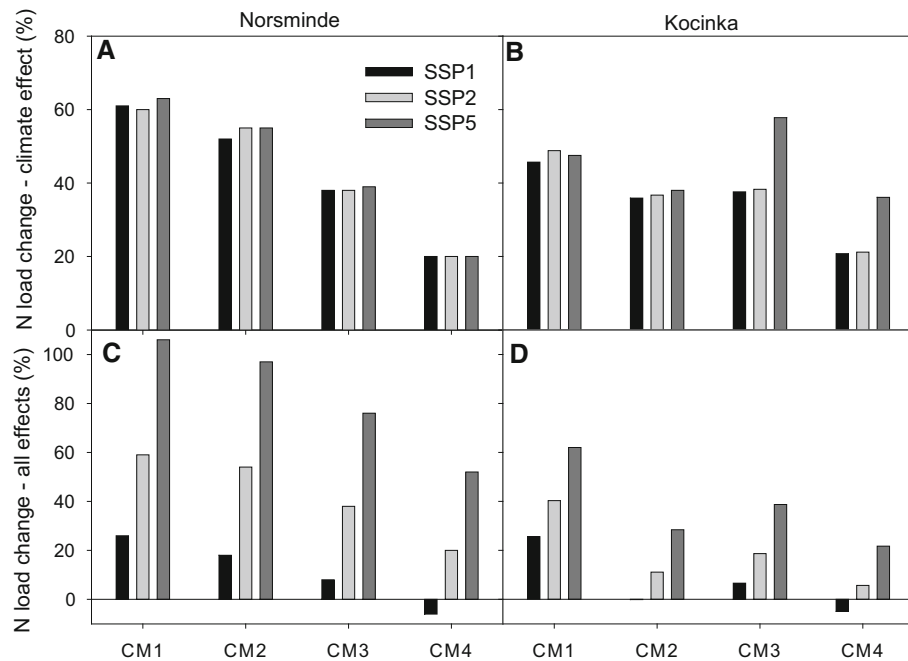
Fig. 6 Relative catchment N-load changes for future (2041–2060) **a**, **b**: compared to similar SSP for baseline climate (1991–2010) (i.e. only climate effect), and **c**, **d**: compared to baseline climate (1991–2010) and land use (i.e. both climate and land use effects)

to some extent subjective, although they align with the overall storylines of the SSPs.

We applied the empirical NLES model for estimating N-leaching, since this model is founded on actual measurements and provides a simple methodology for incorporating effects of changes in agricultural management. However, NLES does not include all relevant climate effects, only the effect of percolation on N-leaching. Therefore, we used the dynamic Daisy model to derive correction factors for each catchment and climate model to scale the N-leaching from NLES to the future climatic conditions. This approach assumes that the setup of Daisy well covers the factors affecting N-leaching in the future. Öztürk et al. (2018) compared N-leaching of a winter wheat monoculture for different fertilisation rates in Denmark using three different models: Daisy, FASSET and SWAT. All these dynamic models simulated higher N-leaching under climate change compared to baseline climate; however, the increases were higher for FASSET and SWAT than for Daisy.

The use of scaling method for adjusting the NLES results to future conditions involves some simplifications. The Daisy simulation model takes into account a number of processes that are related to N-leaching in a direct and indirect way. In particular, the net N mineralization is affected by temperature change, giving a higher net N mineralization, which will influence crop N uptake, especially for SSP1 where the N fertilisation is restricted. For SSP5 the effect on N-leaching will be higher due to a

higher N fertilisation level. In addition, N-leaching is affected by how climate change affects crop yield, where higher temperatures will shorten the growing season of most annual crops, resulting in lower N uptake and thus enhanced risk of N-leaching (Olesen et al. 2007; Børgesen and Olesen 2011).

The modelling of water and N flows in the MIKE SHE model for Norsminde involved several assumptions. The depth to the redox interface was assumed unchanged in the future, which is believed to be reasonable, since the migration rate of the redox interface is on the millimetre scale per year (Hansen et al. 2014). We further assumed the surface water N-reduction to be unchanged in future, which may not be realistic if the N-reduction in surface water depends on temperature. However, surface water N-reduction was implemented as a function of stream length (i.e. transport time), and this made it impossible to estimate change in surface water N-reduction as a function of climate, where reduction rate in surface waters varies with stream temperature. However, for Norminde the reduction in the surface water is small in all cases due to the short stream length.

The modelling of water and N flows with MODFLOW and MT3DMS for Kocinka depended considerably on assumption of transport times and denitrification rates in different geological formations. The modelling setup involved setting best estimates of lag-times and denitrification rates. It would be of considerable interest to explore consequences of scenario uncertainties in these parameters

on N-loads; however, this was not possible in the current study. Due to the long lag-times, the approach for Koncika needed to consider long-term changes in agricultural N use, for which only sparse data were available. Better information on historical N use and N losses should be made available for future studies in such catchments, because of legacy effects on N-leaching and N-loads.

Climate effects on N-leaching

The simulated effects of climate change show an increase in N-leaching from agricultural land of 17% to 64% for Norsminde and 29% to 57% for Kocinka, showing a large variation among climate models in the projected impact on N-leaching. There are only few studies that have explored the effect of climate change on nitrate leaching from cropping systems, where conditions beyond monocultures have been studied. Doltra et al. (2014) used the FASSET simulation model to explore effects of climate change on N-leaching from arable cropping systems under climate change in Denmark. For the future time slice 2040–2060 they found that N-leaching increased by 38% to 70% for arable cropping systems, and these changes were unaffected by whether the cropping systems included catch crops or not. These values are slightly above the ones found in our study, which aligns with the greater leaching changes with climate change simulated for the FASSET compared with Daisy model (Öztürk et al. 2018). The higher N-leaching under climate change is affected by changes in temperature affecting soil organic N mineralisation as well as the percolation of water. It is likely an effect of interactions between processes, since there is no obvious relationship between changes in temperature and rainfall between climate models (Table 3) and change in N-leaching (Fig. 5).

Jabloun et al. (2015) used a statistical approach to explore the effect of variation in temperature and precipitation on N-leaching. Precipitation was the factor that was most influential over N-leaching, but increasing temperature was also found to enhance N-leaching from both spring barley and winter wheat with about 12% for a 1 °C temperature increase. For the climate change scenarios applied in the current study, the temperature changes were in the order of 1.0–2.1°C, which according to the study of Jabloun et al. (2015) would mean increased N-leaching of 12 to 25%. This effect, caused by higher temperature should be compared with the correction factors for NLES derived from comparing Daisy and NLES simulations (Table 2) ranging from 8 to 44%, which is slightly greater than the range suggested by Jabloun et al. (2015).

The responses of N-leaching to climate change are highly dependent on the local conditions (climate, soils, cropping systems), and effects will therefore vary greatly across Europe (Olesen et al. 2007; Jeppesen et al. 2011). Blanke et al. (2017) used the LPJ-GUESS model to assess the effect of climate change on N-leaching for different future time slices and different sites in Europe, showing lower N-leaching for the Boreal region (corresponding to northern parts of the Baltic Sea) with climate change and increased N-leaching for the Atlantic North region (corresponding to southern parts of the Baltic Sea drainage basin). Consequently, responses will likely vary between different countries in the Baltic Sea area, but other studies corroborate our results of higher N-leaching under climate change.

Combined socio-economic and climate effects on N-loads

Both socio-economic changes and climate change are important in determining N-leaching and subsequent N-loads to the sea. For the Norsminde catchment, modelling showed that reduction of nitrate in groundwater was affected by the climate models. The groundwater reduction was lower for climate scenarios that involved a wetter climate, since water retention time was reduced (Refsgaard et al. 2019). Therefore, increased precipitation will lead to higher N-loads to the sea in two ways: (1) by enhancing N-leaching from the root zone, and (2) by reducing the groundwater retention, resulting in a higher proportion of leached N flowing to the sea. The Kocinka catchment is dominated by a karstic geology with long residence time but no nitrate reduction in the groundwater. Therefore, changes in rainfall in Kocinka may change the retention time in groundwater, but not the amount of N reduced in groundwater.

Land use has little effect on runoff and groundwater retention (e.g. Molina-Navarro et al. 2018). The main effects of land use change are therefore on the loss of nutrients (in this case N). This is illustrated by the changes in N-leaching from agricultural land that is highly affected by the intensity of land management, including fertilisation and efficiency of use of N in manure. At the catchment scale, the proportion of land in agriculture is also a vital aspect to consider.

Our results show that in terms of N-loads, variations among SSPs impact N-loads at similar magnitude as variations among climate models. This variation was greater at Norsminde than at Kocinka for effects of both SSP and climate models, reflecting that current land use and biophysical conditions affect responses to changes in both socio-economic and climate conditions. The N-loads for the sustainability scenario (SSP1) showed N-loads under projected climate change that was close to those obtained for the baseline land use under the current climate. Since there is currently a considerable requirement to reduce

N-loadings to the Baltic Sea, not even SSP1 will be sufficient to meet targets under future climate. Therefore, new cropping systems, management methods and technologies should be implemented to achieve required N-load reductions. Such technologies would likely include increased use of crops with long growing seasons and thus high N uptake as well as enhanced use of catch crops to reduce N-leaching (Hashemi et al. 2018).

Comparison with Baltic Sea scale results

An analysis using the same set of socio-economic and climate change scenarios were applied for the entire Baltic Sea basin using the HYPE model (Bartosova et al. 2019). The results of the HYPE model showed only small climate change effects on N-leaching and N-loads to the Baltic Sea. This contrasts with the increased N-leaching simulated with the Daisy and NLES models reported here. Therefore, results were extracted for the Norsminde catchment from the Baltic HYPE model scenario analyses showing an average reduction of 3% in total N-loads from Norsminde as consequence of climate change (data not shown). The variation in N-leaching among climate models in the HYPE simulations were linked to variations in crop N yield. This contrasts with the estimated increases of N-loads in the current study of 20–60% as well as those obtained in a recent catchment study in Denmark using another set of catchment models (Trolle et al. 2019). These large differences among studies may have several causes, and the structure of the different models is likely one of them. Such contrasting results warrant further studies to better and more reliably quantify the projected changes and their drivers.

CONCLUSIONS

We evaluated effects of changes in land use and climate on N-leaching and N-loads from two catchments in the Baltic Sea basin. Since both catchments were dominated by agricultural land use, changes in agricultural land use and management as well as climate effects on N cycling in the agricultural systems had considerable effects on N-leaching losses and consequent N-loads. Variations among socio-economic scenarios impacted N-loads at similar magnitude as variations among climate models. Thus, a sustainability scenario gave N-loads under the projected climate changes that were close to those obtained under baseline conditions. Since there is currently a considerable requirement to reduce N-loadings to the Baltic Sea, not even the conceived sustainability scenario will be sufficient to meet targets under projected future climate, stressing the need for new measures and governing schemes need to meet N-load reduction targets. The results show considerable effects of climate change on N-leaching, which contrasts some other studies, emphasising the need for further studies to clarify impacts of climate change on N-leaching losses.

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