SOILS2SEA DELIVERABLE NO. 2.3

BONUS
SCIENCE FOR A BETTER FUTURE OF THE BALTIC SEA REGION

Scenario analyses of spatially differentiated N measures in catchments under future climate and land use

SOILS2SEA

Reducing nutrient loadings from agricultural soils to the Baltic Sea via groundwater and streams

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Scenario analyses of spatially differentiated N measures in catchments under future climate and land use

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SOILS2SEA

Reducing nutrient loadings from agricultural soils to the Baltic Sea via groundwater and streams

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Table of Contents

1. Summary

The Baltic Sea Action Plan and the EU Water Framework Directive requires further reductions in nitrogen (N) loadings to the sea, a large part of which originates from agricultural land. Also, the geology in the catchments influences nitrogen (N) flows and the N reduction processes affecting loading. Measures therefore need to be taken to reduce N loadings. However, future climate change and changes in socioeconomic developments will affect the baseline, on top of which mitigation measures for reducing N loadings need to be taken.

We analysed the effect of a combination of land use and climate scenarios on N leaching from two Baltic Sea catchments: Norsminde in Denmark and Kocinka in Poland. The two catchments vary greatly in time lag of the groundwater flow and the related N retention and reduction processes. For each catchment, the effects on N leaching were analysed with the NLES leaching model, which at Norsminde was linked to a physically-based distributed groundwater model (MIKE SHE). The land use changes were based on three selected future scenarios taken from the Shared Socioeconomic Pathways (SSP), i.e. SSP1 (sustainability), SSP2 (middle of the road) and SSP5 (fossil fueled development). For each SSP quantitative effects were given for changes in land use and agricultural activities, including fertilisation. The agricultural land use was maintained in SSP2 compared to baseline, reduced by 10% in SSP1 and increased by 10% in SSP5. Livestock density was maintained in SSP2, reduced by 50% in SSP2 and increased by 50% in SSP5. The climate change scenarios cover a 20-year period for 2041-2060 compared with the baseline period of 1991-2010, and four different climate model runs were used, based on the RCP8.5 emission scenario. The N leaching estimation with the NLES model was recalibrated for the temperature changes in the climate change scenarios using representative model runs with the dynamic Daisy simulation model.

For Norsminde the mean N leaching from agricultural areas was 54-60 kg N ha^{-1} in the baseline land use and climate, which increased to 71-88 kg N ha^{-1} under projected climate change. Under baseline climate, SSP1 reduced N leaching by 9-10 kg N ha^{-1} and SSP5 increased leaching by 10-11 kg N ha^{-1}. These differences increase under projected climate change due to the higher N leaching level. These effects are moderated at catchment scale by different land use in the different SSPs. The range of N leaching in the catchment compared with baseline therefore ranges from 5% decrease to 23% increase and for N load from the catchment between 6% decrease and 26% increase for SSP1. For SSP2, N leaching is predicted to increase 23%-60% and N load 20%-59%. For SSP5, N leaching increases 63%-113% and N load 52%-106%.

For Kocinka the mean N leaching from agricultural land was 28-34 kg N ha^{-1} in SSP2 under baseline climate, and this increases to 38-52 kg N ha^{-1} under projected climate change. The leaching in SSP1 was reduced by 2-3 kg N ha^{-1} under baseline climate and 3-5 kg N ha^{-1} under future climate. In SSP5 N leaching was increased by 3 kg N ha^{-1} under baseline climate and 4-5 kg N ha^{-1} under projected future climate.

A scenario analysis was conducted for Norsminde to explore how large an agricultural area would be needed for spatially targeted set-aside to meet an N load reduction target of 20% compared to the baseline. For SSP2 this set-aside area is about 850 ha under baseline climate increasing to 1400-2200 ha under future climate conditions. For SSP1 and SPP5 this range is 650-1400 ha and 2150-3000 ha, respectively, under future climate conditions.

2. Background and objectives

The Baltic Sea Action Plan and the EU Water Framework Directive both require substantial additional reductions of nutrient loads (nitrogen, N and phosphorus, P) to the marine environment. The BONUS SOILS2SEA project conducts research on a widely applicable concept for spatially differentiated regulation, exploiting the fact that the removal and retention of nutrients by biogeochemical processes or sedimentation in groundwater and surface water systems shows large spatial variations. By targeting measures towards areas where the local removal is low, spatially differentiated regulation can be much more cost-effective than the traditional uniform regulation. While this approach may have scope under current conditions, it is uncertain how other drivers such as changes in land use and climate will affect N loading from agricultural catchments.

The present deliverable focuses on assessing the impact of land use change and climate changes on N loads to the sea from two groundwater dominated catchments in Denmark and Poland. In addition, the study analyses the potential for targeting measures to reduce the N loading under these changes in land use and climate.

Nutrient loadings from land to the sea are largely determined by human activities, both directly and indirectly. The direct effects occur through the human influences on nutrient loadings 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., 2017). The indirect effects occur through the influence of changes in temperature and precipitation on the water and nutrient cycle (Jeppesen et al., 2011).

The future is by nature uncertain, and this uncertainty can be represented through different scenarios. In this case, a variation of scenarios of future land use and future climate was used in accordance with the methodology developed by IPCC. The variation in land use is represented through three selected Shared Socioeconomic Pathways (SSPs) and the variation in future climate based on different climate model realizations for the Representative Concentration Pathways 8.5 (RCP8.5). The results thus represent a range of possible futures on both land use and climate.

Previous model-based studies have shown higher N leaching from agricultural soils (Doltra et al., 2014; Öztürk et al., 2018) and higher N loadings from agricultural catchments (Teutschbein et al., 2017) under projected climate change. Several 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; Arnheimer et al., 2012; Eriksson et al., 2013). Other studies have considered measures to reduce the nutrients loadings (Wulff et al., 2014), and targeting measures spatially according to variation in groundwater N retention may enhance efficiency of mitigation measures (Hansen et al., 2017; Hashemi et al., 2018).

The objective of the present deliverable report is to describe analyses that quantify the effect of changes in land use and climate on N leaching from agricultural land and the resulting N load to the sea after transformation processes in groundwater and surface waters. The further objective is to analyse how spatially targeted mitigation measures can be used under these changed conditions to lower N loadings to the sea.

3. Case study areas

The study has applied two case study areas, Norsminde in Denmark and Kocinka in Poland, as described below.

3.1 Norsminde

The Norsminde catchment is 101 km^2 and is located on the eastern coast of Jutland (Figure 1). The catchment discharges into the Norsminde Fjord, which is a sensitive water body with respect to nitrogen. The most downstream gauging station in the stream (st. 270035) where total observed N loads are available covers an area of 85 km^2. The Norsminde catchment is located in a glacial landscape from the Weichsel glaciation where the upper geology is dominated by clayey till with smaller units of glacial melt water sand and post-glacial freshwater peat. Due to the clay till soils, the farmland is to a large extent tile drained.

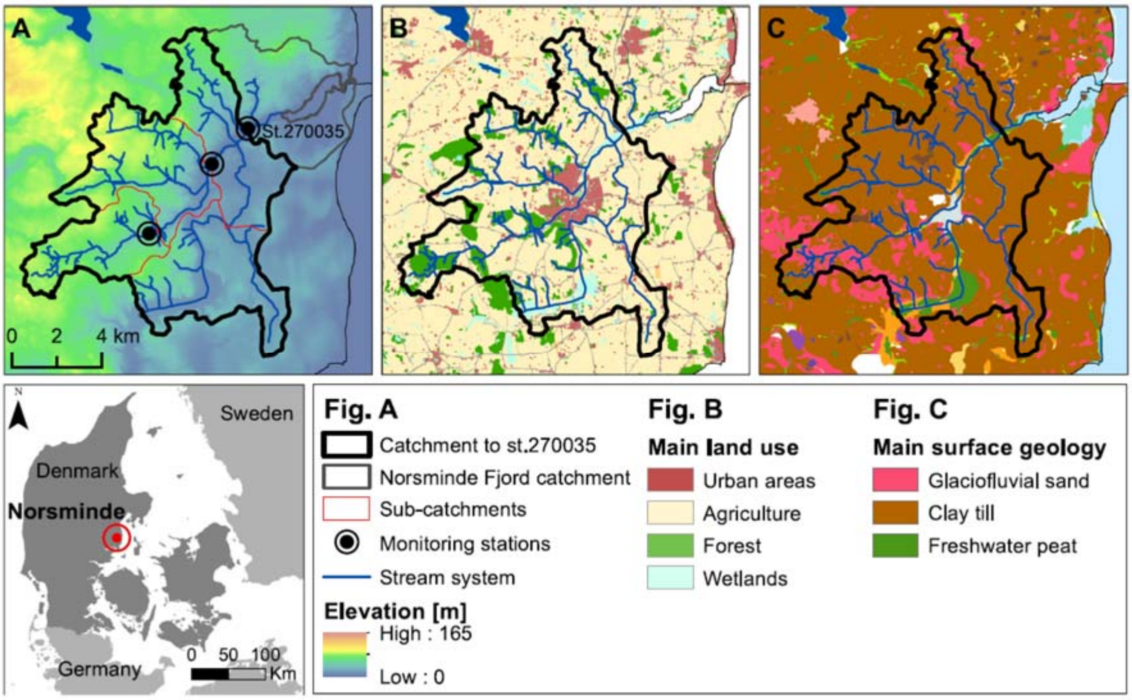

Figure 3.1. Norsminde catchment. A: Elevation, stream system and monitoring stations. B: Land use. C: Surface geology (Hansen et al., 2017).

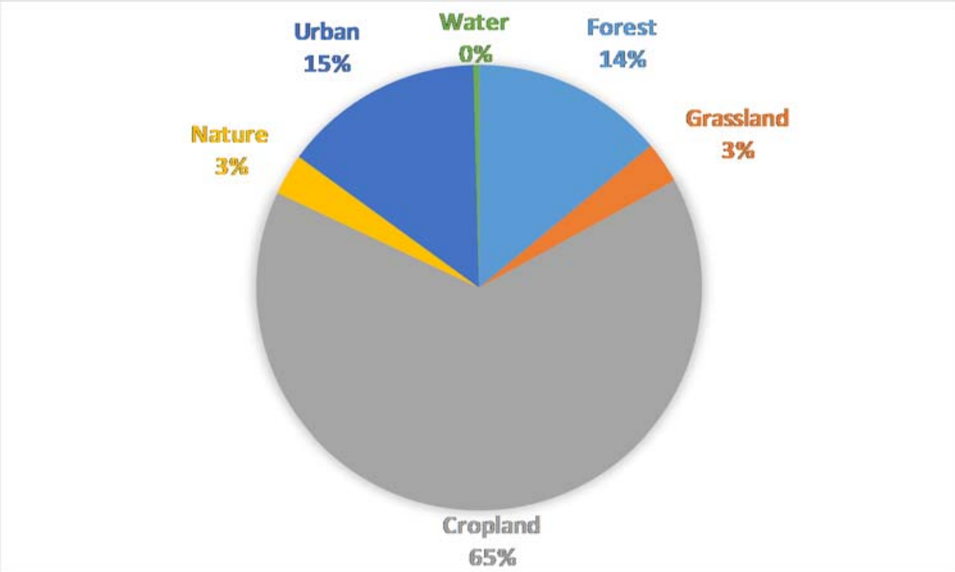

Figure 3.2 Distribution of land use in Norsminde in 2006.

The land use classes (Corine classes) of the Norsminde catchment in 2006 are shown in Figure 3.2. Cropland is the dominating land use class with 65% of the total area. Nature and forest covers 3% and 14%, respectively, and urban areas 15%. Grassland/wetlands and open waters areas (lakes and streams) represent 3% and less than 1%, respectively. In the analysis of nitrate leaching from the catchment the focus is the leaching from the cropland and the grassland. The N leaching from forest, urban area and nature have minor contributions to the total N loading from diffuse sources at catchment scale.

3.1.1 Soils types used in the nitrogen simulation models

The soils used in the analysis were defined in terms of texture, organic matter content and soil chemical and hydrological properties. The soils in the catchment are described in geological terms as clayey till, glacial melt water sand and post-glacial freshwater peat. These soils were redefined into soil profiles representing the top 3 meters of the soil and used as input to the modelling of the water balance and the nitrogen leaching. The soil-profiles are described with three dominating soil horizons: A, B and C. Soil profile data used were taken from a previous study (Børgesen et al., 2013). The soil texture, soil organic matter content and bulk density data for the individual soil horizons (A, B and C) are listed in Table A2 in Appendix A. The distribution of the soil profiles (soil types) within the catchment is presented in soil-maps Figure 3.3A. The soil map is built up as raster grid cells (250m by 250 m). The soil types are dominated by USDA soil texture classes: loamy sand, sandy loam, loamy soils and organic soils. In the Danish soil classification system these soils are described as JB4, JB6, JB7 and JB11. The sandy loam (JB6) and loamy soils (JB7) have high root zone water capacity and good yield potentials. JB4 soils have a higher sand fraction and generally have higher leaching rates and lower crop yield potentials. The organic soils are often affected by a high groundwater table and this has also been included in the soil drainage description of the model.

Most of the soils (JB6 and JB7) in the catchment are artificially drained, typically with tile drain system. As there are no complete digital maps delineating areas with subsurface drainage systems, the soil types used are individual classified as either 1: tile drained, 2: free drainage (no drain system) or 3: high ground water table. Table A2 lists the drainage conditions for the different soils. In the wetland areas (Figure 3.1B) soils are described as organic soils or loamy sandy soils (Figure 3.3A). The drainage conditions of these soils are described by a variating high groundwater table. Organic soils are mainly found near streams and lakes, but these soils only have a minor representation within the catchment.

3.1.2 Cropland description in Norsminde catchment

A simplified approach for setting up farming systems was used, where only two dominating farm types were considered: dairy/cattle farm and a pig/plant farm. There is some variation in cropping systems within these farms, but overall these two farm types are considered a good general description of the agricultural systems in the Norsminde catchment. Table 3.1 summarizes the area and number of livestock units (2011 data) of the two farm types. Figure 3.3B shows the spatial distribution of cropland of the two farm types within the catchment. The majority of farms in the catchment (95%) are classified as pig/plant. Only 5% of the cropland belongs to dairy/cattle.

Table 3.1 Cropland area in rotation in Norsminde catchment classified as dairy and cattle crop rotation and pig and arable crop rotation.

Farm type	Area [ha]	%	Livestock units (LSU)	LSU/ha
Dairy and cattle	283	5	243	0.86
Pig and plant	5736	95	5061	0.88

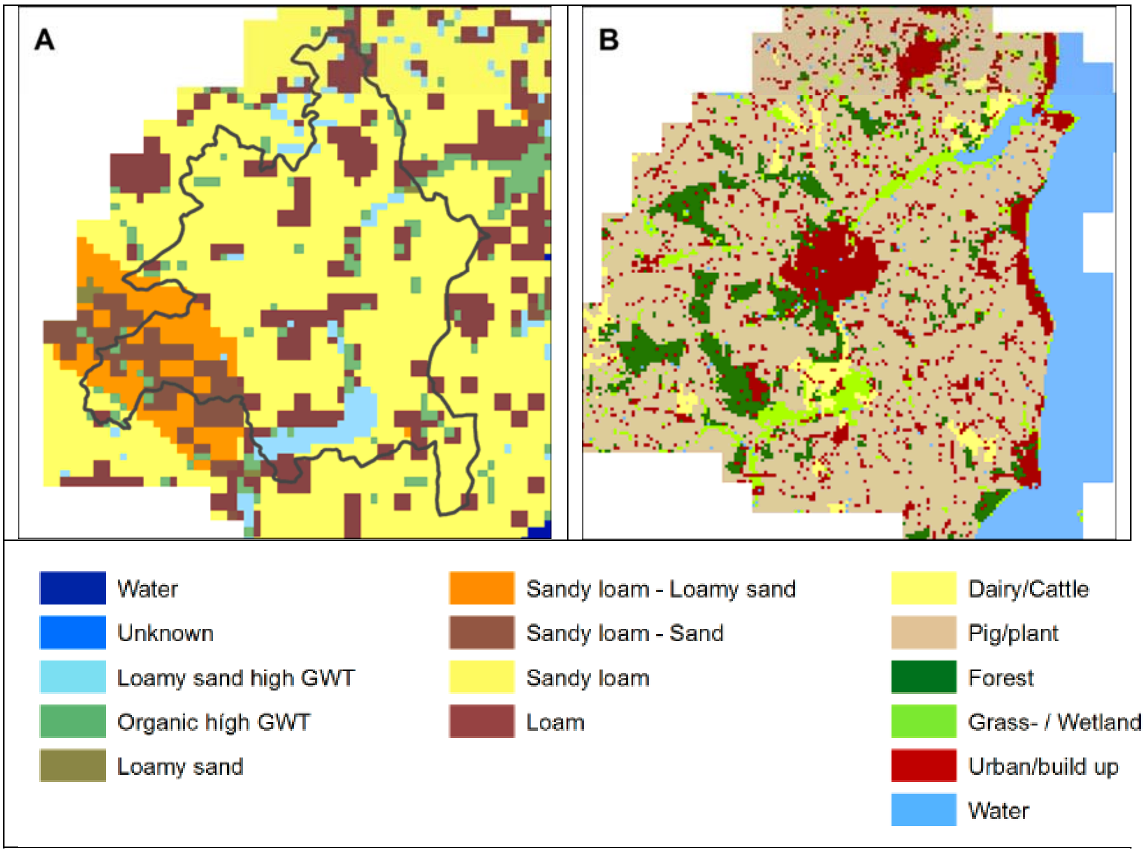

Figure 3.3. Soil types classified after top and sub soils (A) are described in detail in Table A2 of the appendix (Børgesen et al., 2013). Agricultural area are classified into 100 m grid cells representing the different combination of soil type (A) and farm type (B).

The crop distribution of the two farm types are presented in Figure 3.4. For the pig/plant farm the dominating crops are winter cereals (dominated by winter wheat) with 65% of the total cropland. Of the agricultural area, 12% is grown with spring cereals and 8% with rapeseed (winter oilseed rape). Other crops include grain legumes, horticultural crops, christmas trees, fruit trees, which represent 9%.

For the dairy and cattle farms, roughage crops include cereals harvested for whole-crop silage or for grain at maturity, silage maize and grass in rotation. Cereal crops in the form of winter cereals (winter wheat) have the highest share (35%). Spring cereals (13%) have the same share in the dairy/cattle cropping system as in the pig/plant farms.

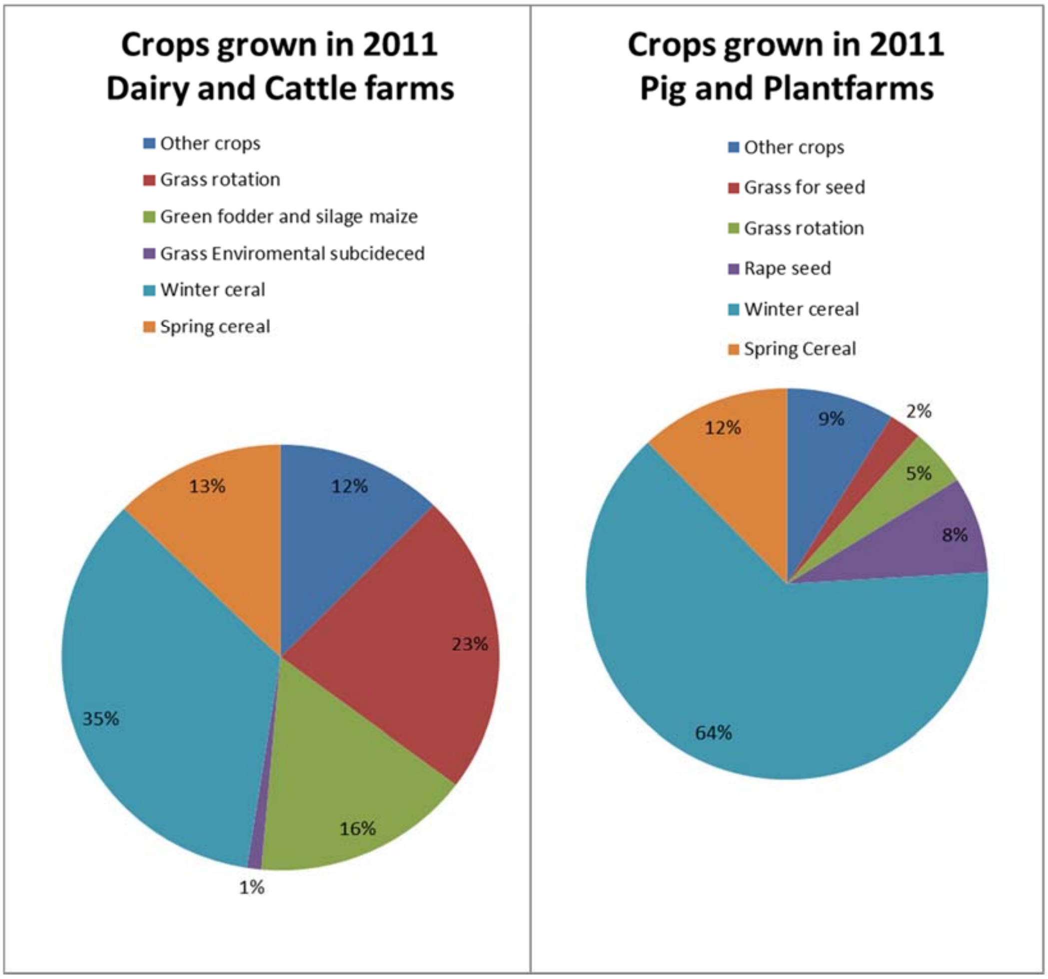

Figure 3.4 Distribution of crops grown on the two farm types in Norsminde catchment in 2011.

3.2 Kocinka

The Kocinka catchment (surface area of 260 km^2) is located in the southern part of Poland in the Oder river catchment Figure 3.5D. The 40.2 km long Kocinka river discharges to the Liswarta river. The catchment is covered by 1-33 m thick Quaternary deposits of fluvioglacial and aeolian origin – underlain by Upper Jurassic limestones (Figure 3.5C). The Jurassic strata contain one of the largest groundwater bodies in Poland, the Major Groundwater Basin 326 (MGWB-326). The topography is slightly undulating with elevations varying between 185 to 329 m a.s.l. The climate is temperate with an average annual precipitation of 600-700 mm yr^{-1} and average air temperatures between 7.5 to 8 °C. The catchment is mostly agricultural (grassland and cropland representing 19 and 37%, respectively, of the land use within the catchment (Figure 3.6). Forest areas cover 36%, with pine forests dominating in the south-western and northwestern part of the catchment. Urban areas cover 5% of the area. Wetland vegetation, water and greenhouses all represent less than 1%. Abandoned land is dominated by previous agricultural land and represents 2% of the total catchment. The dominating land use in the catchment area is agriculture and grasslands (total 56%).

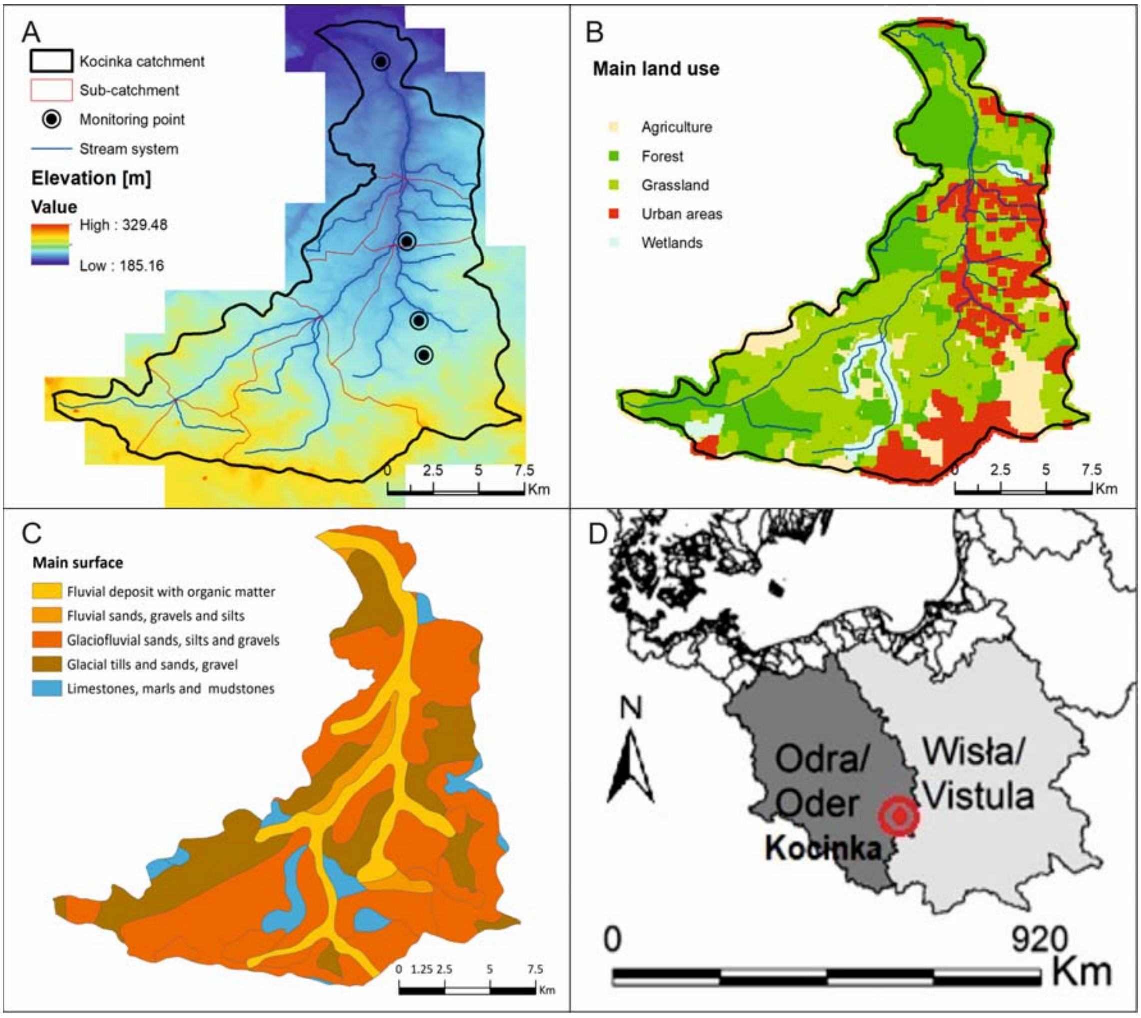

Figure 3.5. Kocinka catchment. A: Elevation, stream system and monitoring stations. B: Land use. C: Surface geology.

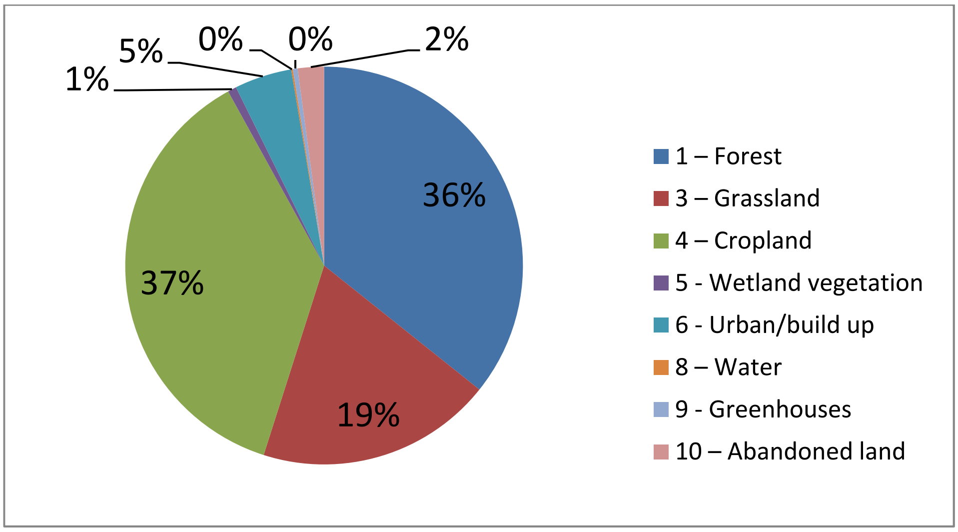

Figure 3.6 Land use classes and distribution in the Kocinka catchment.

Land use data was obtained from Corine Land Cover 2006 (CLC 2006) and supplemented by information on wetland vegetation in the catchment area (vector thematic maps from the Institute of Land Reclamation and Grasslands in Falenty (IMUZ)) and high-resolution digital aerial photography (Central Documentation Center of Geodesy and Cartography (CODGiK)). The cropland and the grassland areas were classified into seven classes of cropping systems: CRP1..CRP7 described in section 4.2.1 (Figure 3.7B).

3.2.1 Soil types and groundwater in the Kocinka catchment

The soil types in the Kocinka catchment are dominated by three main soil texture classes: sandy soils, sandy loams and organic soils (Figure 3.7C). Cropland is the dominating land use class on the sandy and loamy soil types. Permanent grassland is most often found on the organic soils, but also wetland vegetation or forests are found here. In the river valley, organic soils are associated with a shallow groundwater level.

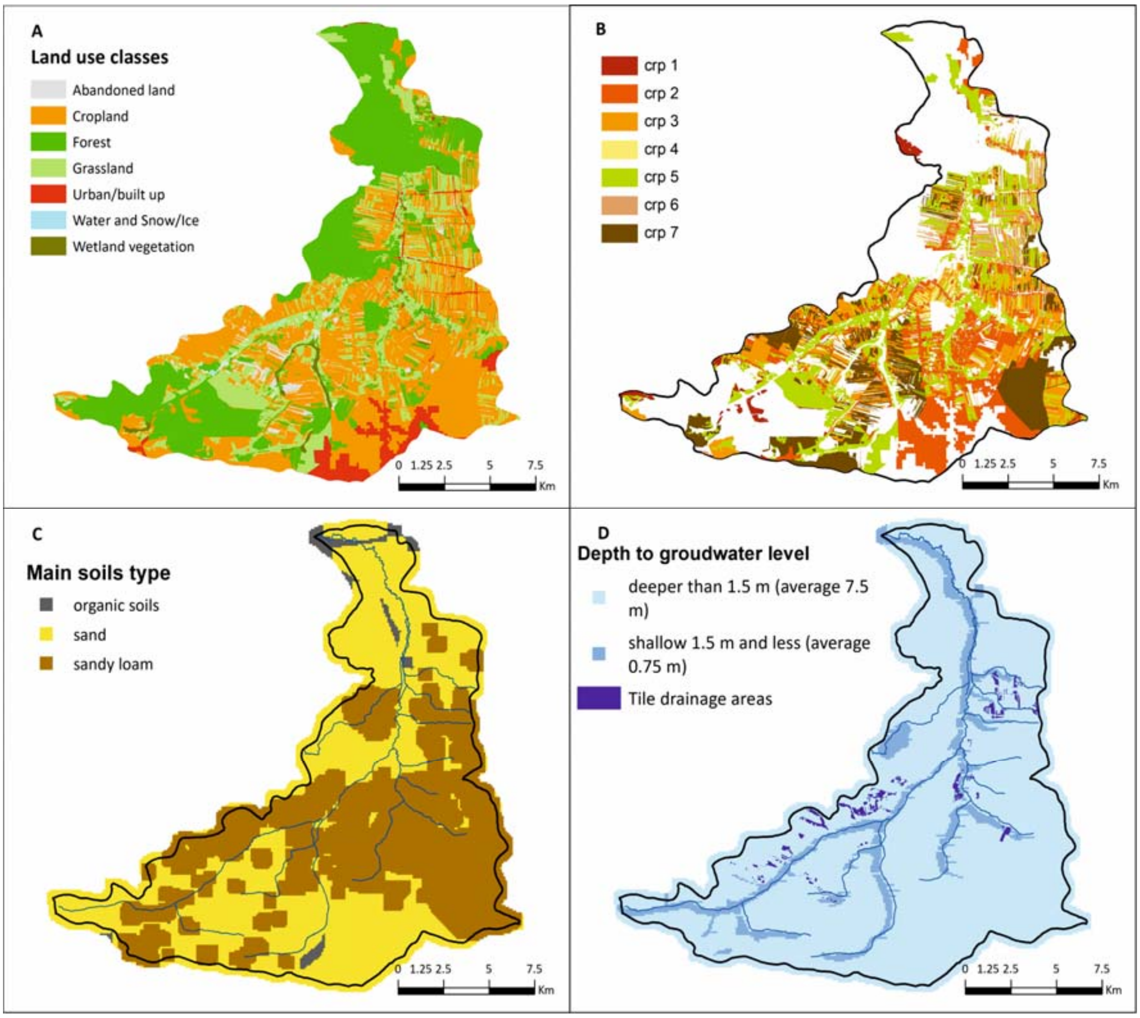

Figure 3.7. Kocinka catchment: A. Land use classes. B. Crop rotation systems (description in text), blank area occupied by classes other than crops and grassland. C. Main soil types. D. Main depth to groundwater level classes and tile drainage area.

Other important aspects in relation to water and N flows at catchment level is the depth to the groundwater and the drainage system. In the Kocinka catchment two categories of depth to the groundwater were distinguished in the modelling:

- Shallow, with the groundwater at ≤1.5 m depth, with an average depth of 0.75 m
- Deep, with the groundwater at >1.5 m depth, with the average depth of 5 m.

Areas with shallow groundwater occur only in rivers valleys and are associated with wetland vegetation and grassland. Cropland is seldom found on the soils with high groundwater levels.

Information about localization of tile drainage systems are based on maps in 1:5000 scale from Silesian Board of Land Reclamation and Water Facilities in Katowice – Local Department in Częstochowa (ŚZMiUW). The correctness of these maps was verified in the field. Only 347 hectares of cropland and grassland are drained, representing only 3% of their total area. This fraction was considered negligible in the modelling of water and N flows in the catchment (Figure 3.7D).

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4. Scenarios of land use change and climate change

The variation in future land use is represented through three selected Shared Socio-economic Pathways (SSPs), SSPs are used in the climate research community to explore uncertainty in mitigation, adaptation and impacts associated with alternative climate and socio-economic futures and can be viewed as boundary conditions that provide the framing for more complex assumptions for regions and/or sectors. They are quantitative and qualitative narratives of possible socio-economic futures up to the end of the century. These SSPs were developed for the Baltic Sea region by Zandersen et al. (2018) to cover aspects also related to nutrient loadings to the Baltic Sea. The three SSPs used here include SSP1, SSP2 and SSP5.

The N fertilisation in the different scenarios cover both mineral fertiliser and manure. The effective N (N_{eff}, kg N/ha) is calculated as a weighted value 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), N_{man} is N in manure (kg N/ha), and N_{rep} is replacement value of N in manure. N_{rep} is set to 0.65 in the baseline situation corresponding to the current value for other types of 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 by changing the amount of manure (N_{man}), the N replacement value in manure (N_{rep}) and the amount of N effectively applied (N_{eff}). Based on these changes, the mineral fertiliser rate is calculated for each scenario.

SSP1 (sustainability) describes a world making relatively good progress towards sustainability, with sustained efforts to achieve development goals, while reducing resource intensity and fossil fuel dependency. For the Baltic Region it is assumed that there is a 10% reduction in agricultural land use and most of this is converted to forest. In agriculture, management plans to achieve goals of the EU Water Framework Directive (WFD) and all other plans are fully implemented. Consumption trends towards less demand for meat. This scenario involves a 50% reduction in meat consumption in the Baltic Sea Region, and this is implemented as a 50% reduction in manure N, i.e. N_{man} is reduced by 50%. The N replacement value in manure is increased to N_{rep} = 0.75 through implementation of biogas, acidification and other measures to reduce emissions and increase manure value. The effective N amount applied is reduced to 5 % below current level. If this results in $N_{fer} < 0$ then N_{fer} is set to 0. For further reducing N leaching losses, this scenario applies catch crops as far as possible in the rotations.

SSP2 (middle of the road) describes a world, where trends typical of recent decades continue, with some progress towards achieving development goals, reductions in resource and energy intensity at historic rates, and slowly decreasing fossil fuel dependency. For the Baltic

Region there is no change in agricultural land use. Trends in agriculture are towards larger farms, more intensive farming, industrialized and more effective agriculture. Management plans for reducing nutrient loadings from agriculture (WFD) are only partly implemented. 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.

SSP5 (fossil-fuelled development) 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. For the Baltic Region it is assumed that there is a 10% increase in agricultural land use and most of this is taken from forest. The increasing agricultural land use is associated with a higher livestock production within a global market. There will be less regulations of agricultural nutrient loadings, but improvements in production technologies. This scenario involves a 50% increase in meat consumption in the Baltic Sea Region, and this is implemented as a 50 % increase in manure N, i.e. N_{man} is increased by 50%. The N replacement value in manure is decreased to N_{rep} = 0.60, since new livestock production facilities will not prioritize 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.

4.1 Land use in Norsminde

4.1.1 Cropping data and cropping systems for Norsminde catchment

Cropping systems were defined for the crops grown on fields of the two farm types (Figure 3.4) based on farm data (NaturErhvervsstyrelsen, 2011). For the scenario analysis the crop rotation setups for the baseline were modified for the different land uses in the SSP scenarios (SSP1, SSP2 and SSP5). The crop rotations were set up to represent current dominating crops grown on the two farm types. The rotations also reflect the average farming management in relation to cropping sequences and N fertilization. The reduced number of cropping systems limits the single crop frequency and thereby only the dominating crops within the farm types are represented. The rotations for dairy/cattle farms have 5 crops, and thus each crop represents 20% of the cropping area (Table 4.1). The pig/plant cropping systems have 10 crops in the rotations, and one crop thus represent 10% of the cropping area. Therefore, crops representing less than 10% of the cropping area were not included in the analysis.

In the model simulations, the cropping systems for the pig/plant farm (crops P1- P10) are split up into two five-year crop rotation systems CR1 and CR2. The CR1 crop rotation consists of the crops P1 -P5, and CR2 of the crops P6-P10. The mean results for N leaching of the two cropping systems (CR1 and CR2, i.e. P1-P10) was used for the pig/plant farm type. The dairy/cattle rotation only consists of one, five year cropping system (D1 to D5). Therefore, the average of these five crops represents the results for the dairy and cattle farm type. This simplification means that the mean results for the baseline period cannot directly be compared to simulations in other studies that have applied actual cropping sequences. For grassland a permanent grass rotation with low N input was used for both the grass and wetland land use categories.

Table 4.1 Crop systems for the different scenarios (Baseline, SSP1, SSP2 and SSP5) used in the simulations for Norsminde.

Farm type	Baseline	SSP1	SSP2	SSP5
Pig/plant				
P1	W. Rape	W. Rape	W. Rape	W. Rape
P2	W.Wheat	W.Wheat	W.Wheat	W.Wheat
P3	W.Wheat	W.Wheat	W.Wheat	W.Wheat
P4	W.Wheat	W.Wheat^{CC}	W.Wheat	W.Wheat
P5	W.barley	S. Barley	W.barley	W. Barley
P6	S.Barley/ley	S.Barley/ley	S.Barley/ley	S.Barley/ley
P7	Seed grass	Seed grass	Seed grass	Seed grass
P8	W.Wheat	S.Barley	W.wheat	W.wheat
P9	W.Wheat	W.Wheat	W.Wheat	W.Wheat
P10	W.Wheat^{CC}	W.Wheat^{CC}	W.Wheat^{CC}	W.Wheat
Perm. grass	Perm grass	Perm grass	Perm grass	Perm grass
Dairy/cattle				
D1	W.Wheat	W.Wheat^{CC}	W.Wheat	Maize
D2	Maize^{CC}	Maize^{CC}	Maize^{CC}	Maize
D3	S.Barley/ley	S.Barley/ley	S.Barley/ley	S.Barley/ley
D4	Grass-clover	Grass-clover	Grass-clover	Grass-clover
D5	S.Barley	S.Barley	S.Barley	Grass-clover

CC: Catch Crop

4.1.2 Nitrogen fertilization strategies

For each of the crop rotation systems a N fertilisation scheme was constructed. The N rates for the baseline and SSP2 are the recommended N rates from 2016 (NaturErhvervsstyrelsen, 2016). The total N application with mineral N is based on the recommended N rates, the precrop effects on N ($N_{precrop}$) and the replacement rate for total N in organic fertilisers (slurry/manure). The calculation of the individual mineral N application rates for the different crops follows eqn. 2. In this calculation the N effect of the crop grown in the previous year ($N_{precrop}$) is included. High precrop N rate corrections are obtained from grass-clover with 95 kg N ha^{-1} and 23 kg N ha^{-1} for winter rape. The precrop effects for catch crops is set to 17 kg N ha^{-1}. The amount of organic N applied with slurry on the fields was balanced with the mean production of organic N on the two farm types. The strategy follows mean practice for applying the organic fertilizers and the recommended N rate:

$$Mineral_N = N\_rate_{soil} - N_{precrop} - Replacement * organic\_N \quad (2)$$

where $Mineral_N$ is the rate of mineral N fertilizer applied (kg N ha^{-1}), N_rate_{soil} is the recommended N rate for the specific soil and crop (kg N ha^{-1}), $N_{precrop}$ is the effective N supply from previous crops (kg N ha^{-1}), and *organic_N* is the total N applied in manures and other organic fertilizers.

4.1.3 Scenarios of N fertilization in Norsminde

Table 4.2 shows the overall changes in the key parameters (recommended N rate, replacement rate of N in manure, and amount of N in organic fertilizers) used in setting up the N fertilization schemes representing for the different scenarios. For the baseline and SSP2, the N rates are based on 2016 recommendations (NaturErhversstyrelsen, 2016). For SSP1 the N rates are reduced with 5% and for the SSP5 the N rates are increased with 5%. In the baseline scenario the replacement percentage using slurry and manure is set to 65%. This is changed to 75% for SSP1, and for SSP2 the replacement percentage is 70% and decreases in SSP5 to 60%. As the different scenarios have different N rates, different cropping systems and different replacement percentages are used in setting up the fertilization scheme. Table A2 in Appendix A shows the N fertilization rates and applied amount of N with mineral and organic N fertilizations for the individual crops. Figure 4.1 shows the average N rates, mineral N application rates and manure N application rates for the different scenarios.

Table 4.2. Relative N rate, livestock density and agricultural area compared with the baseline for the various scenarios. The N replacement rate using organic N fertilizers instead of mineral N also varies among the SSP scenarios.

	Baseline	SSP1	SSP2	SSP5
N rate relative to 2016 recommendations (%)	100	95	100	105
Replacement rate of N in manure (%)	65	75	70	60
Livestock units per hectare relative to 2011 (%)	100	50	100	150
Agricultural area relative to 2011 (%)	100	90	100	110

In SSP1 the pig/plant cropping system is changed by introducing one additional year with catch crop (after P4). This means that 20% of the autumn/winter crops cover of a pig and plant farm is grown with catch crops. This was only possible by changing a winter cereal to a spring cereal, i.e. crop P5 (winter cereal) was replaced with a spring cereal. For the pig/plant cropping system crop P8 (winter wheat) was replaced with spring barley to avoid ploughing the seed grass (P7) in the autumn, which can lead to high N leaching losses. The catch crop also includes a higher total precrop effect for the cropping system and leads to a lower N fertilization with mineral N.

The main crops for the dairy/cattle cropping system were unchanged in SSP1, but one additional year with catch crop (D1) was included in the cropping system. The total area of catch crops is increased from 20% to 40% for the dairy/cattle cropping system.

The N fertilization rates in SSP1 were reduced by 5% compared with the baseline and the amount of organic fertiliser was reduced by 50% due to the lower number of livestock units per hectare (Table 4.2). The overall effects of these changes was that the mineral N application increased with 1 kg N ha^{-1} for pig and plant farms and increased with 11 kg N ha^{-1} for the dairy and cattle cropping system (Figure 4.1). This was a combined effect of more catch crops, reduced N rates, replacing winter cereals with spring cereals with lower recommended N rates, and 50% reduction in organic N fertilizers.

In SSP2 the crop rotation and the N rate was unchanged compared to the baseline. Here the replacement rate of N in manure was increased with 5% to 70%. This reduced the mineral N application with app. 3 kg N ha^{-1} for both cropping systems (Figure 4.1).

In SSP5, the replacement rate for N in manure was decreased with 5% to 60%. The recommended N rates were increased with 5% and all catch crops were removed from the crop rotations. The dairy/cattle farm type intensified their number of livestock per hectare meaning that the green fodder production had to follow the need for feed for the cattle. By replacing the cereals (D1 and D5) with maize and grass-clover, respectively, the feed production increased with the number of livestock units. This also affected the mean N rates as grass-clover has a higher N requirement than spring barley (crop D5). Having no catch crops also increased the required mineral N fertilizer rate as the precrop effects of catch crops were removed. In SSP5, a 50% increase in the animal production is assumed. This results in an increased N application rates of organic fertilizers from 88 kg N ha^{-1} (baseline and SSP2) to 132 kg N ha^{-1}. The mineral N rate decreased from 125 kg N ha^{-1} (SSP2) to 116 kg N ha^{-1}. This is a combined effect of change in crop N rates, changes in cropping system and an increase in manure.

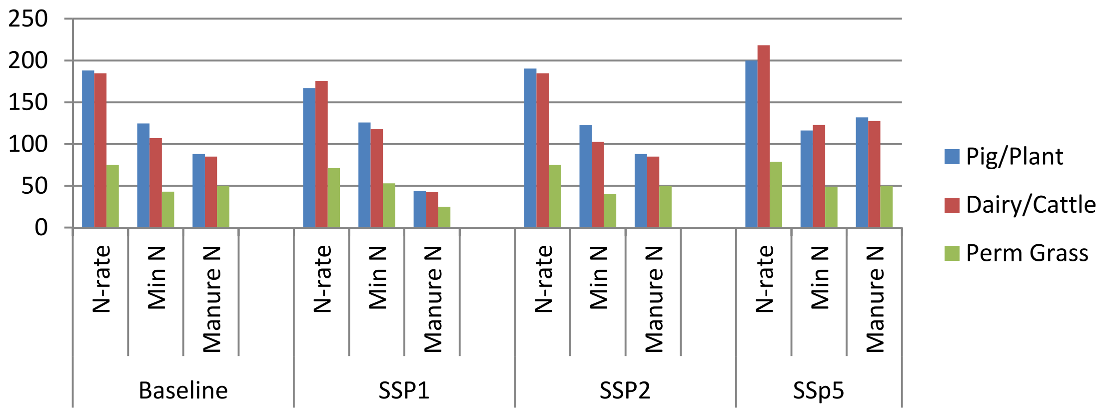


Figure 4.1. Recommended N rate (N-rate), Mineral N applied (Min N) and Manure N applied in the simulations for all scenarios (kg N ha^{-1}). Actual used N fertilizations rates on single crops level are listed in Table A1 of Appendix A.

4.1.4 **Spatial changes in land use in Norsminde**

The different land use scenarios for each of the SSP's were created using a simple methodology that is based on (i) determining land use changes for each SSP and (ii) using predefined transition and allocation rules for the specific land use classes (Table 4.3). The land use change is made for the catchment (Figure 4.2) and a buffer area around the catchment. In total, the area for land use change included more than 150 km^2, whereas the catchment, where the model simulations are conducted, only includes 85 km^2. This means that the transition of land use in the catchment (85 km^2) does not exactly follow the relative changes for the large area (150 km^2). The decision of including the buffer area compared with only the catchment was to make the transition more flexible and realistic in relation to especially increasing the forest area and the changes in grassland proportion. Also many farmers have areas inside and outside the catchment, which also affects the land use changes.

Table 4.3. Land use demand and transition and allocation rules for the different SSPs

SSP	Land use demand	Transition rules	Allocation rules
SSP1	10% reduction in agricultural land	50% to grassland	Proximity to stream
		50% to forest	Proximity to forest
SSP2	No change	-	-
SSP5	10% increase in agricultural land	From grassland and forest	Proximity to agricultural land

The land requirements of the different land use types are defined by the actual area of the different land use types that are usually allocated by considering a wide range of local and more regional factors that can influence the suitability of a location for a specific land use type (Kim et al., 2014). Among these, neighborhood relationships to land-uses are regarded as important land-use change factors. This follows Tobler's first law of geography, which, translated to land use, implies that land uses are spatially related and that nearby land uses have a stronger relation than land uses at a greater distance. Therefore, the close surroundings of a raster cell are more subject to land use changes than more remote surroundings. This notion has been confirmed by numeral studies focusing on the empirical analysis of neighborhood characteristics of a considered location (e.g. Verburg et al., 2004; Liao et al., 2016). Therefore, to simplify the land use change model used in this study, only the distance matrix calculated for each land use class to the rest of raster cells was considered as driving factor for land use change. Once the distance matrix was generated, the predefined transition and allocation rules for each land use class were applied to the adjacent raster cells at a specific land use class until the land use demands for each of the SSPs are met.

Figure 4.3 shows the relative changes in land use obtained for the 85 km^2 catchment. The rules of transition decreased the cropland with 12% in SSP1 and increased the cropland with 15% in SSP5. The cropland within the catchment is 5509 ha in 2011 (Table 4.4) and reduces to 4842 ha in SSP1 and increases to 6321 ha in SSP5.

Table 4.4 Land use classes (ha) in the catchment for the different scenarios in Norsminde

	Baseline	SSP1	SSP2	SSP5
Forest	1162	1555	1162	565
Grassland	289	563	289	74
Cropland	5509	4842	5509	6321
Urban	223	223	223	223
Nature	1295	1295	1295	1295
Water	50	50	50	50

As the forest area is 1162 ha in the baseline (2011) and the grassland is 289 the relative changes (Figure 4.3) in forest area are lower compared to grassland.

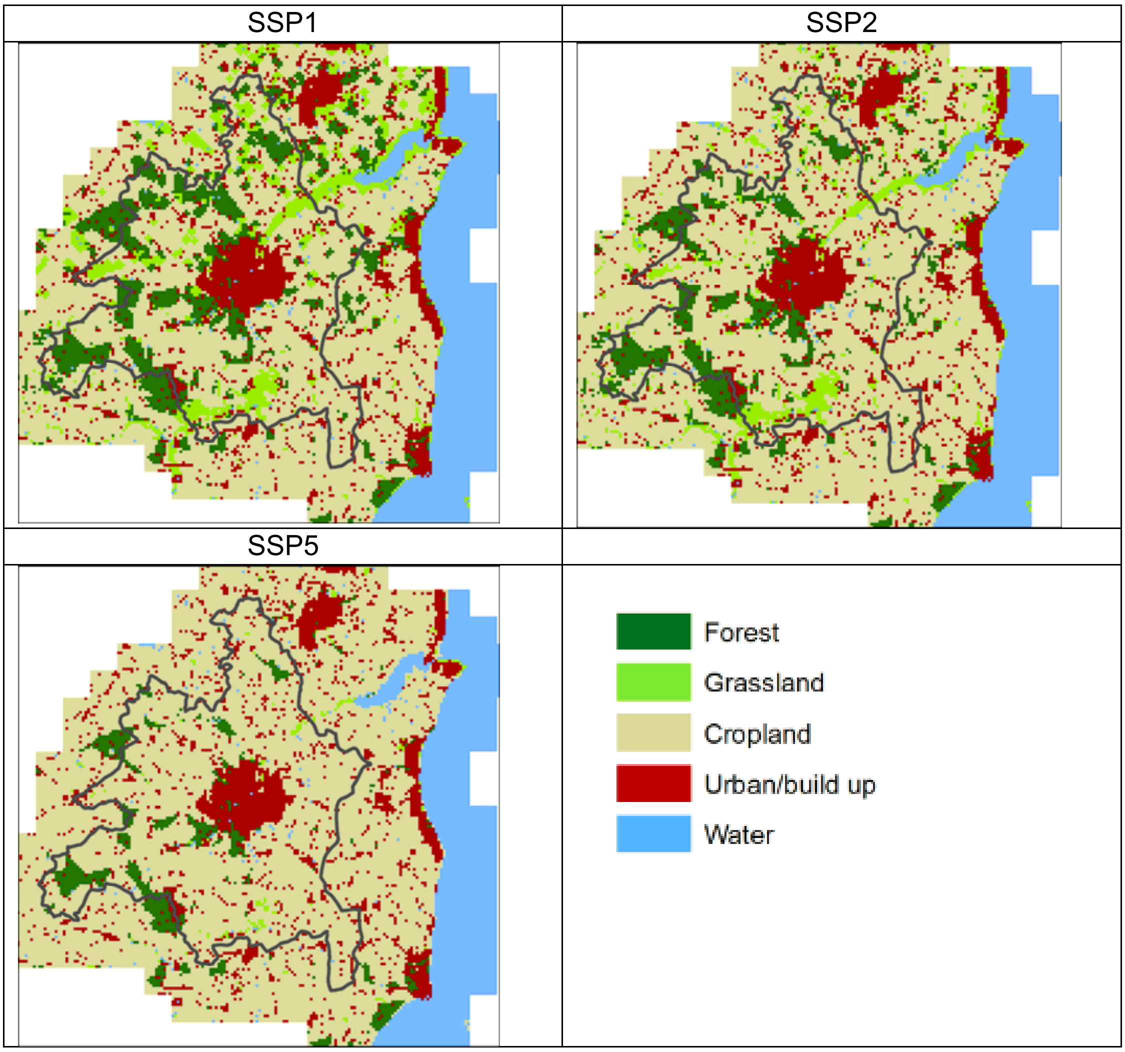
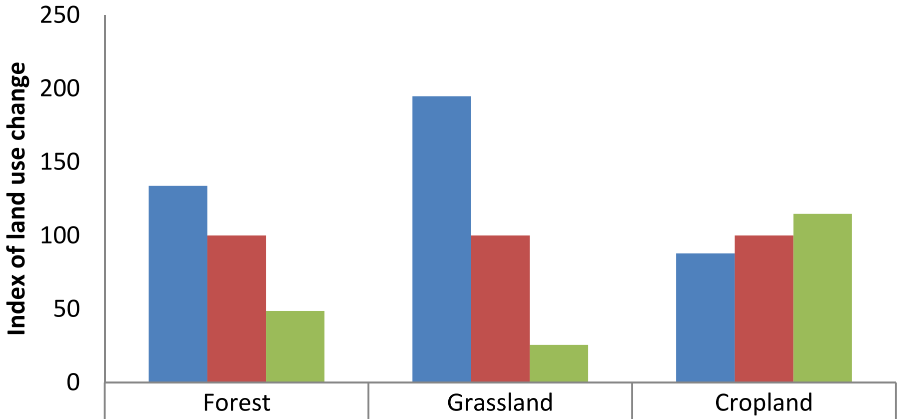


Figure 4.2. Land use maps under the different SSPs for Norsminde catchment.



	Forest	Grassland	Cropland
SSP1	134	195	88
SSp2	100	100	100
SSP5	49	26	115

Figure 4.3 Relative change in land use in the SSP scenarios for Norsminde within the Corine land use classes: Forest, Grassland and cropland compared with the baseline.

4.2 Land use in Kocinka

The scenarios for the Kocinka catchment aimed at addressing three important factors:

- Changes in agricultural area as affected by changing socio-economic conditions (SSPs)
- Changes in agricultural fertilization practices in changing socio-economic conditions
- The effects of climate change on N leaching.

The baseline period was defined as 1990-2010 and the future scenarios were developed for 2040-2060 (Table 4.5). The two periods differed in number of livestock and the production of organic fertilizers and expected use of mineral fertilizers. Changes in the area of arable land, grasslands and forest are included in the scenarios. Data on cropping systems, fertilisation level in the catchment were based on data from the Statistical Office (GUS).

Table 4.5 Main data on land use and fertilisation in Kocinka catchment in past, present and future periods. The future periods are illustrated for SSP1.

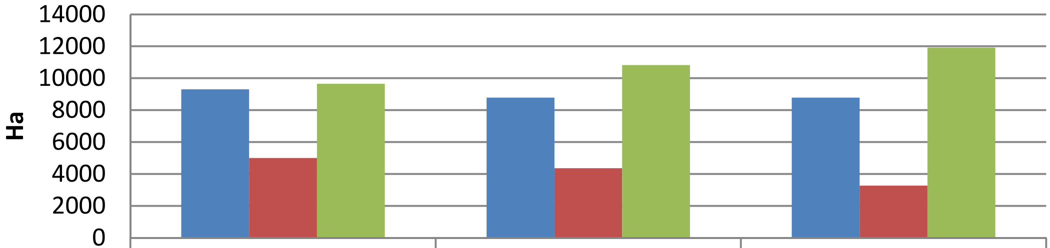
		Baseline 1990-2010	SSP1 2040-2060
Forests	% of catchment area	34%	36%
Agricultural area: arable land		42%	37%
Agricultural area: grasslands and pastures		17%	19%
Cattle	number	787	394
Pigs		5823	2912
Sheep		443	222
Poultry		25766	12883
Yearly production N from livestock manure	kg N	99988	49994
Yearly average organic N (manure) fertilization	$kg\ N\ ha^{-1}$ of agricultural area	17.4 [1]	13.6 [1]
Yearly average mineral N fertilization		93.3	76.0

[1]The value includes the purchase (Import) of organic fertilizers from outside the catchment area

The spatial differentiation of land use change in the SSP scenarios (SSP1, SSP2 and SSP5) were based on the baseline data pattern of land use and crop rotation systems (Figure 4.4).

For SSP1 cropland area decreases by app. 10%. Cropland on most soils is converted to grasslands and forests, if located adjacent to these land use classes, resulting in 542 ha increase of forests and 541 ha increase of grasslands. Forest and grassland areas were extended to areas occupied previously by cropland in crop rotation system CRP3 on sandy soils (sand). Crops in CRP3 are mainly cereals intended for livestock feed. This reduction of feed crops area is a result of the reduction of animal stock.

For SSP5 the cropland area increases by 10%. Croplands with CRP3 were expanded by conversion of 541 ha of grasslands on sandy loam soils. Croplands with CRP4 were expanded by converting 85 ha of the remaining grasslands on sandy loam soils and 455 ha of grassland on sandy soils. Croplands with crop rotation systems CRP3 and CRP4 were expanded to areas occupied by grasslands on sandy loam soils and sandy soils. The feed crops of CRP3 and CRP4 increased as a result of the increasing animal stock.



	SSP1	SSP2	SSP5
Forest	9306	8780	8780
Grassland	5003	4361	3265
Cropland	9655	10820	11916

Figure 4.4. Land use (ha) used in the three scenarios for Kocinka. Land use in SSP2 is the same as in baseline and represents current land use.

4.2.1 **Cropping systems and nitrogen fertilization schemes**

Within the cropland and permanent grassland (Figure 3.7A) seven different crop rotation systems (CRP) were constructed. CRP5, 6 and 7 were simulated using only one crop. The allocation of the different CRPs was mapped by combining data from soil and agricultural maps in the 1:20,000 and 1: 5,000 scales (obtained from Commune Offices), aerial photographs (CODGiK), information about municipalities acquired from the Statistical Office (GUS 2015) and surveys conducted among farmers. The crop rotations systems defined for the catchment are:
CRP1: summer wheat - summer barley - winter rye - winter rye - winter wheat
CRP2: winter barley - winter barley - summer barley - winter triticale
CRP3: winter triticale – winter rye - winter triticale - summer oat – summer oat
CRP4: summer oat – summer oat - summer maize – summer barley – winter barley
CRP5: permanent grassland
CRP6: potatoes
CRP7: sugar beets as representative of root and leaf vegetables.

Figure 3.7B shows the allocation of different crop rotations. In Table A3 of Appendix A the different crop rotation systems and the N fertilizer use of the different scenarios SSP1, SSP2 and SSP5 are listed. The change in N fertilization follows the rules of table 4.6. The increase in organic nitrogen from livestock production is much higher than assumed for Norsminde – due to the general low level of the baseline.

Table 4.6. Relative N rate, livestock density and agricultural area compared with the baseline for the various scenarios. The N replacement rate using organic N fertilizers instead of mineral N also varies among the SSP scenarios.

	Baseline	SSP1	SSP2	SSP5
N rate relative to 2016 recommendations (%)	100	95	100	105
Replacement rate of N in manure (%)	65	75	70	60
Livestock units per hectare relative to 2011 (%)	100	50	100	350
Agricultural area relative to 2011 (%)	100	90	100	110

4.3 Climate change scenarios

The employed climate change scenarios provide the required meteorological variables for a possible climate future. They are meant to be combined with the SSP scenarios and various N mitigation scenarios. As such, the choice of the climate change scenarios does not reflect the uncertainty in the available climate change scenarios, but rather tries to answer the question of how much climate change potentially could contribute to changes in N load.

Four regional climate projections were used (see Table 4.7), all of which are part of the CORDEX database. They consist of an assumed evolution of the greenhouse gas concentrations as described by a representative concentration pathway (RCP), a global circulation model (GCM) and a nested regional climate model (RCM), which dynamically downscales the GCM data to a higher spatial resolution of about 0.44 deg. Note that all climate projections are based on the same RCP 8.5. This is the RCP with the highest greenhouse gas concentration at the end of the 21st century within the currently available RCPs (Moss et al., 2010). Thus, the ensemble does not represent the full uncertainty in currently available climate scenarios, but should rather be considered as projections representing the upper end of the range of climate projections of various climate variables. Four different climate models were selected to represent the variation in climate model projections of temperature and precipitation (Table 4.7).

Table 4.7. Elements of the climate change projections used for the climate scenarios.

Climate model	Representative concentration pathway	GCM	RCM
CM1	RCP8.5	MPI-ESM-LR	CCLM
CM2	RCP8.5	CM5A-MR	WRF-JPSL
CM3	RCP8.5	CNRM-CM5	RCA4
CM4	RCP8.5	CanESM2	RCA4

Due to climate model limitations and inherent variability in the climate system, the climate model data show biases when compared to local observed data during a past reference period. Bias-correction of climate models was therefore applied to partly remove those biases. We chose a bias-correction by quantile-mapping (Qmap) and distribution based scaling (DBS) (e.g. Maraun et al., 2010). In quantile-mapping, the quantiles of the scenario data are mapped to the same quantiles of the reference data. After quantile-mapping, the quantile distribution of the bias-corrected scenario data closely follows the one of the reference data.

However, the bias-correction does not specifically correct the temporal sequence of events (for e.g. dry-spell lengths). Also, bias-correction in general is able to bring the climate model data closer to local data, but it also adds an additional uncertainty to the whole modelling chain from the choice of the bias-correction method. Quantile-mapping is a non-linear bias-correction method and can potentially modify the climate change signal.

The set of variables to which bias-correction has been applied as well as the quantile-mapping methods used are listed in Table 4.8. All variables are available as output data of the regional climate models with the exception of the reference evapotranspiration for which we applied a preprocessing as described in Seaby et al. (2013). Each bias-correction method requires reference data. We used local observations or derived data provided by each partner as reference data and the reference period was set to 1991-2010. The biases typically show seasonally varying patterns. In general, we represented the seasonality in the biases by using separate correction parameters for each calendar month, except for temperature variables for which we applied a moving window plus a harmonic smoothing of the annual cycle.

Table 4.8. Summary of bias-corrected variables for the two case study basins

Variable	Norsminde	Kocinka	Bias correction method
Daily mean temperature	Yes		DBS (Yang et al., 2010)
Daily maximum temperature		Yes	DBS (Yang et al., 2010)
Daily minimum temperature		Yes	DBS (Yang et al., 2010)
Daily precipitation	Yes	Yes	DBS (Yang et al., 2010)
Daily relative humidity		Yes	DBS (Yang et al., 2015)
Daily wind speed		Yes	DBS (Yang et al., 2015)
Daily shortwave radiation	Yes	Yes	Qmap (Gudmundsson et al., 2012)
Daily ref. evapotranspiration	Yes		Qmap (Gudmundsson et al., 2012)

At the study catchments, the seasonal average climate change signals between the scenario period 2036-2065 and the reference period 1981-2010 show a considerable spread between the four different scenarios (Tables 4.9 and 4.10). In the Norsminde catchment, the seasonal mean changes of daily mean temperature are projected to be in the range of 0.9 to 2.8 °C. Precipitation changes show a seasonal pattern with clearly increasing precipitation during winter (DJF) and spring (MAM), and a somewhat lower projected increase or even decrease in summer (JJA) and autumn (SON). At Kocinka, daily minimum (Tmin) and maximum (Tmax) temperature were analysed as those parameters were required by the models applied in the different analyses. The magnitudes of the Tmin and Tmax changes are roughly similar, with a slightly larger ensemble range for the Tmax changes mainly in JJA and SON. The seasonal pattern of precipitation changes also shows a clear increase in DJF and MAM and a smaller increase or even decrease in JJA and SON.

A comparison of the results between the original climate model data (columns indicated by header O in Tables 4.9 and 4.10) and the bias-corrected data (headers labelled by C) indicate that the bias-correction method slightly modifies the climate change signal. In most cases, the bias-correction intensifies the climate change signal. A modification of the climate change signal by the bias-correction method is a characteristic of a non-linear bias-correction method such as quantile mapping. It implies that the bias of the climate model varies with increasing or decreasing variable values (i.e., bias for larger temperatures is different than for smaller temperatures). Such variable value-dependent biases have been documented in the literature (e.g., Boberg and Christensen, 2012).

Table 4.9. Seasonal average changes for daily mean temperature (T) and precipitation (P) at Norsminde between scenario period 2036-2065 and reference period 1981-2010. The indicated ranges are minimum to maximum ranges of the four climate scenarios. Both the results for the original RCM data (O) and bias-corrected data (C) are given.

		DJF		MAM	
	Station/Point	O	C	O	C
T [deg C]	Norsminde	1.3-2.2	1.3-2.5	0.9-1.7	0.9-1.7
P [%]	Norsminde	3.3-12.7	7.3-17.3	-3.1-15.8	1.1-24.8
		JJA		SON	
		O	C	O	C
T [deg C]	Norsminde	1.0-2.2	1.1-2.8	1.0-2.3	1.2-2.8
P [%]	Norsminde	-10.2-17.3	-11.1-21.2	-4.3-9.4	-4.2-14.0

Table 4.10. Seasonal average changes for daily minimum temperature (Tmin), daily maximum temperature (Tmax) and precipitation (P) at the case study site Kocinka between scenario period 2036-2065 and reference period 1981-2010. The indicated ranges are minimum to maximum ranges of the four climate scenarios. Both the results for the original RCM data (O) and bias-corrected data (C) are given.

		DJF		MAM	
	Station/Point	O	C	O	C
Tmin [deg C]	Kocinka	1.3-3.4	1.4-3.3	1.0-1.8	1.0-1.7
Tmax [deg C]	Kocinka	1.1-2.8	1.4-3.3	0.7-1.5	0.8-1.6
P [%]	Kocinka	9.1-18.0	12.9-25.6	10.8-15.1	16.2-27.1
		JJA		SON	
		O	C	O	C
Tmin [deg C]	Kocinka	1.3-2.2	1.4-2.4	1.4-2.3	1.6-2.6
Tmax [deg C]	Kocinka	0.6-2.7	0.6-2.7	0.7-2.6	0.9-3.2
P [%]	Kocinka	-9.5-15.2	-4.1-19.4	-5.5-16.2	-3.3-28.2

The downscaled climate model data were available for the four models for both the baseline and future period. Thus the climate model data were applied to the hydrological and N models for both the baseline and future periods, so that effects of climate models were estimated by comparing the future period for with the baseline period for each climate model.

5. Modelling water and N flows

5.1 Modelling N leaching using the NLES and Daisy models

5.1.1 The NLES model

The NLES model (Kristensen et al., 2008) is an empirical model for prediction of annual nitrate leaching from arable fields. The model predicts the N leaching based on N applications and crops in the year of leaching, the crops in the previous year, N inputs in mineral, organic N fertilizers and biological N fixation during the previous five years and information on soil type and monthly percolation from the root zone during the last two years. The model was calibrated on N leaching measurements in Denmark. As the model is based on a N leaching dataset that represent the weather, soils and cropping systems in the Norsminde catchment, we find that this model gives the most reliable level of N leaching from the root zone for the period 1990-2010. Since climate and soils of the Kocinka catchment are rather similar to those in Denmark, we also consider it applicable for that catchment.

5.1.2 The Daisy model

To obtain the monthly percolation from the root zone and to calculate the future climatic effects on the nitrogen leaching, we used the soil-water-crop-atmosphere model Daisy (Hansen et al., 1991; Abrahamsen and Hansen, 2000, Hansen et al., 2012). The model is a one-dimensional mechanistic and deterministic model, simulating crop and soil processes as affected by environmental conditions such as water fluxes, water content and temperature. The model simulates the water balance, N balance including N losses (ammonia volatilization and N leaching), soil organic matter turnover and crop growth and yield. Input data includes soil thermal and hydrological properties, daily weather data and field management. The model has been validated on independent data sets with good results (de Willegen, 1991; Diekkrüger et al., 1995; Smith et al., 1997, Kollas et al. 2015).The Daisy model was used to simulate the monthly water balances and to distribute the annual N leaching predicted with NLES4 to monthly N leaching. The Daisy model is also used to bias correct the NLES predicted N leaching for the future climate scenarios.

5.1.3 Modelling climate change effects on N leaching

Nitrate leaching predicted for future climate conditions is subject to several sources of uncertainty. Both the effects of change in farming practice, crop rotations, crop varieties and the change in climatic and atmospheric conditions affect nitrate leaching. The simulations for the both Norsminde and Kocinka catchments under current and future climatic conditions were simulated with a combined model approach using both the Daisy model and the NLES4 model Kristensen et al. (2008).

The Daisy crop parameters were adapted for future climatic conditions and atmospheric CO_2 concentration using the method described in Børgesen and Olesen (2011). Hereby we included the CO_2 effects on crop growth and the N uptake. The indirect effects of the climate change projected with the different regional climate models (RCM) on net N mineralization of soil organic matter and added crop residues, denitrification, and the change in percolation effects on the N leaching are also taken into account. The Daisy model parameters describing the processes of net N mineralization in the soil and denitrification were used unchanged under the future climatic conditions.

The method used to bias correct the annual NLES4 leaching was based on a delta change method (eq. 3). The bias correction factors obtained from the modelling were unique for each of the four future climate projection models RCM's (Table 5.2). The following equation is used to correct annual N leaching on the grid scale level:

$$N\ leaching\ (year\_future) = NLES4\left(year_{future}\right) * Correction\_factor \quad (3)$$

where the correction factor is calculated as:

$$Correction\_factor = \frac{NLEACH\_daisy_{\text{future\_mean\_BL}}}{NLEACH\_daisy_{\text{base\_mean\_}BL}} * \frac{NLES4_{\text{base\_mean\_BL}}}{NLES4_{\text{future\_mean\_}BL}} \quad (4)$$

Where NLEACH_daisy and NLES4 are the nitrate leaching calculated with the Daisy and NLES models, respectively, and future and base refers to future and baseline periods, respectively.

The method to adjust N leaching under future climatic conditions followed a sequence:

1. The N leaching from the NLES4 model was obtained for each of the years under future climatic conditions ($NLES4_{future,year}$). Inter-annual variations in N leaching followed the climatic effects obtained from the climate data of the different RCM's.
2. The ratio between the mean NLES4 leaching for the baseline period (1990-2010, $NLES4_{base}$) and the future period (2040-2060, $NLES4_{future}$) was used to neutralize the general effects of future climate effects on the annual $NLES4_{future,year}$ leaching. In other words the climatic effects on the annual NLES4 leaching was corrected to 1990-2010 level, but keeping the inter-annual variation in N leaching due to the variation in climatic conditions of the future climate data.
3. The climatic effects on N leaching simulated with the Daisy model for the period 1990-2010 and for the period 2040-2060 is used for adjusting the annual $NLES4_{future,year}$ to the level of the future climate.
4. The correction factors using the baseline cropping system was used for all land use scenarios:SSP1, SSP2 and SSP5.

Table 5.1 shows the different correction factors of the different climate models for the model simulations for the future period 2040-2060 for both Norsminde and Kocinka catchments.

Table 5.1 Average correction factors for cropland and grassland used in simulations for Norsminde and Kocinka catchments.

Climate Model	Correction_factor Norsminde	Correction_factor Kocinka
1	1.44	1.30
2	1.24	1.03
3	1.08	1.09
4	1.17	1.08

5.1.4 The regional upscaling approach

For all combinations of crop rotations and the different fertilization schemes (Appendix, Tables A2 and A3) combined with the soil types (Figure 3.2A) within the catchment, model simulations were conducted using both the NLES4 model and the Daisy model. The Daisy model was used to simulate the water balances for all combinations. The NLES4 model was used to predict the N leaching.

The mean results of the modelling are conducted by simulating N leaching and water balances for all crops within the cropping system for 20 years of weather data. To achieve this, the simulation setup is based on perturbations by which each five-year cropping system was initialized in five following years before starting the simulation for the two periods 1990-2010 and 2040–2060, respectively. For the Daisy model simulations we used eight years of warm up period to initialize the soil water content, soil nitrate content and the soil organic matter pools.

The model simulations were conducted on a 1 ha grid scale (100x100 meter) (Figure 3.2B). For each grid cell the dominating soil type within the grid (Figure 3.2) was used as soil input data for both the Daisy water balance simulations and in the NLES4 leaching simulations. Each grid cell is described by one type of dominating land use. For both the cropland and grassland, average results of all crops within the given soil and cropping rotation system combination was used as the climate normalized results for the given crop system. For other land use classes, standard numbers of nitrogen leaching is used (Table 5.2). Standard values are obtained from varies sources. N leaching from nature areas are based on Christensen et al. (1990) and Nielsen et al. (1999). N leaching from forest is highly variable due to the age of the forest and the N deposition, and this was here set to 5 kg N ha^{-1} (Eriksen et al., 2014). For urban areas no measurements are available. Here the N leaching rates from nature is used as a proxy. For set-aside fields, standard nitrate leaching of 12 kg N/ha is used based on measurements (Waagepetersen, 2012). Nitrate leaching from greenhouses are set to 300 kg N/ha due to the high N fertilization rates.

Table 5.2 Standard values of annual N leaching for different land use classes.

Land use	N leaching (kg N ha^{-1})
Nature	2
Forest	5
Urban	2
Water	0
Set-aside	12
Greenhouse	300

Due to the high annual variation in nitrate leaching caused by variation in weather conditions, the mean result of twenty years of model predictions is used as the climate normalized result. By using mean values it is possible to compare the simulation results among the different climate models and the two periods of simulations 1990-2010 and 2040-2060.

To run the MIKE-SHE catchment model (see Section 5.2), monthly nitrate leaching data has to be simulated. The nitrate leaching predicted using the NLES4 model is annual N leaching. As mentioned, the annual N leaching was distributed to monthly values using the Daisy simulated monthly nitrate leaching. For all grids within the catchment the monthly leaching was calculated as:

$$Monthly\_NLES4_{Nleachng} = NLES4\_leaching\_year * \frac{Daisy\_leaching\_month}{Daisy\_leaching\_year} \quad (5)$$

5.2 Dynamic catchment model for Norsminde

A dynamic catchment model based on the MIKE SHE model was used to produce groundwater N-reduction maps for each combination of time period, climate and land use. Each combination resulted in a unique groundwater N reduction map, since the groundwater flow and spatial pattern in N leaching in each scenario model will be different.

5.2.1 Hydrology

The hydrological model was set up in the modelling framework MIKE SHE and was based on the model set up from He et al. (2015). MIKE SHE is a distributed physically-based hydrological model including process descriptions for evapotranspiration, snowmelt, 2D overland flow, 1D unsaturated flow, 3D saturated flow, tile drainage and 1D river flow (Havnø et al., 1995; Refsgaard and Storm, 1995).

The hydrological model was built upon a 3D geological model of the Norsminde catchment that was set up using a combination of boreholes and airborne geophysical data (He et al., 2014). The model has a grid size of 100 m x 100 m and vertically the saturated zone of the model is divided into 24 computational layers of varying thickness. The climate input to the original model was obtained from the Danish Meteorological Institute's (DMI) 10 km grid for daily precipitation and 20 km grid for reference evapotranspiration and air temperature (He et al., 2015). The model was set up as a transient model for 1995-2007 and inversely calibrated using the parameter estimator PEST (Doherty, 2005) against daily discharge data from 3 monitoring stations (Figure 5.1) and 690 hydraulic head measurements in 108 wells for the period 2000-2003 (He et al., 2015). The model performance for simulated discharge at outlet station number 270035 from the Norsminde catchment can be seen in Figure 5.1.

5.2.2 N transport and reduction

The transport of N was simulated using particle tracking in MIKE SHE and the transport model was based on the model set up in Hansen et al. (2014b). The N leaching from NLES4 was applied as a daily input to MIKE SHE for the period 2000-2007. A particle mass of 2 kg N was defined, which means that a N particle was released in a given MIKE SHE grid cell every time the daily N leaching input from NLES to the specific grid cell added up to 2 kg of N. The N particles were released on the water table in MIKE SHE and tracked until they reached the stream or the fjord/ocean.

Other sources of N to the stream system (atmospheric deposition on open water bodies, scattered housing, treatment plant, overflow from rainwater basins and organic N from diffuse terrestrial sources) were added to the simulated N load from groundwater and drains outside the MIKE SHE framework. Data were obtained from the national N model (Højberg et al., 2015) on sub-catchment level (Figure 3.1). The original data source is the Scientific Data Centre for Hydrological point Sources (under the Danish Nature Agency).

N-reduction was included in the model in the groundwater zone and in the stream system. The division between how much N-reduction is going on in the groundwater zone and how much in the stream system was based on the results from the National Danish Nitrogen model (Højberg et al., 2015). N-reduction in groundwater was simulated in the model by introducing a spatially distributed redox interface in the saturated zone (Hansen et al., 2014a). When an N-particle crosses the redox interface, it was assumed to be completely reduced. The amount of N-reduction in the stream system (as percentage of N transported to the stream) was assumed to be constant in time and was included on sub-catchment level (Figure 5.1) and defined as a function of the stream length to the catchment outlet (i.e. the upstream sub-catchments have a larger stream N-reduction than the down-stream sub-catchments). A maximum stream N-reduction value was defined for the sub-catchment with the longest stream length, and the N-reduction value in the other sub-catchments was defined as a fraction of this value. The N-transport was calibrated by adjusting the location of the redox interface (Hansen et al., 2014a) and the maximum stream N-reduction value until the simulated N-transport to st. 270035 matched the observed N-transport for the period 2000-2007 and the assumed split between groundwater and surface water N-reduction was reached. The model performance for simulated N-load at st. 270035 is shown in Figure 5.1B.

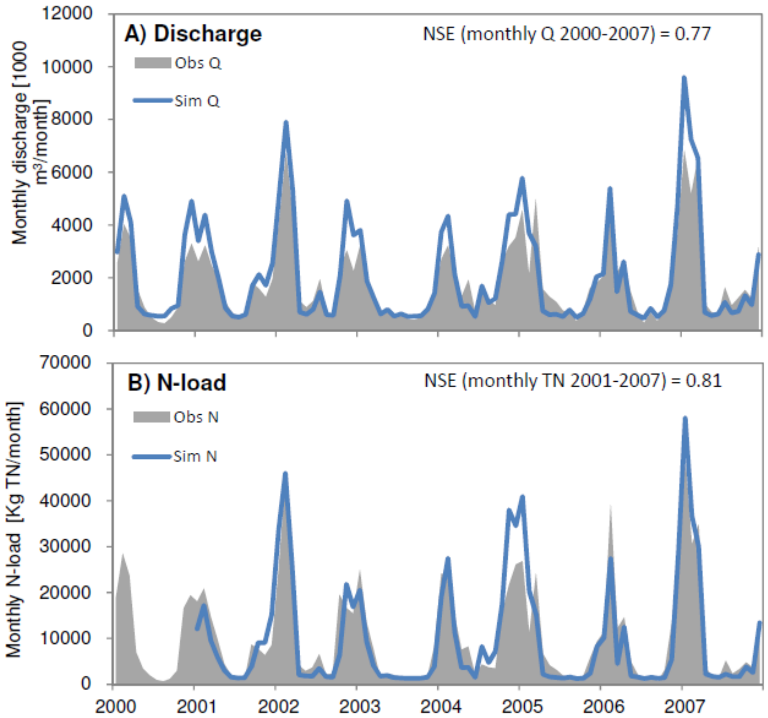


Figure 5.1 Simulated monthly discharge and total N-load at st. 270035 from the original Norsminde model. On the graphs are also shown the performance in terms of Nash Sutcliffe efficiency (NSE, optimal fit between observed and simulated when NSE = 1).

5.3 Scenario models

The scenario models were based on the original Norsminde model with the changes described in the following. The simulation period for the model was changed to 1990-2010 for the present scenarios and 2040-2060 for the future scenarios. Table 5.3 shows the combinations of simulation period, climate and land use that has been simulated.

Table 5.3 Scenario models conducted for Norsminde catchment.

Period	Climate	Land use			
		Baseline	SSP1	SSP2	SSP5
1990-2010	Observed data	X			
	Climate model 1	X	X	X	X
	Climate model 2	X	X	X	X
	Climate model 3	X	X	X	X
	Climate model 4	X	X	X	X
2040-2060	Climate model 1		X	X	X
	Climate model 2		X	X	X
	Climate model 3		X	X	X
	Climate model 4		X	X	X

5.4 Map-based N-load model

The spatially targeted management scenarios were run using a stationary map-based N-load model (Figur 5.3) developed in the study by Hansen et al. (2017). The model was based on results from the dynamic catchment model. The model has a grid resolution of 100 m and calculates a total average yearly mass balance for the Norsminde catchment for a given time period, in this study 1990-2010 or 2040-2060, respectively.

5.4.1 Input maps

The N-load model consists of three input maps (Figure 5.3); a N-leaching map, showing the amount of N leaching from the root zone (kg N ha^{-1} yr^{-1}), a groundwater N-reduction map, showing the amount of nitrate reduced in the groundwater zone (percentage of N-leaching), and a surface water N-reduction map, showing the amount of nitrate reduced in the surface water system (percentage of N transported to stream). The two latter maps were constructed based on results from the dynamic catchment model.

The N-leaching map was constructed by calculating the average annual N-leaching for the period 1990-2010 and 2040-2060 based on the monthly NLES data. The groundwater N-reduction map was constructed by counting the number of N-particles in the dynamic catchment model transported below the redox interface in each grid cell as a percentage of the total number of N-particles added to the grid. The surface water N-reduction map consisted of the calibrated values from the dynamic catchment model. For each climate and SSP, a unique N-leaching map and groundwater N-reduction map were produced. The surface water N-reduction map was assumed to be the same for all scenarios.

The different transport pathways in the groundwater zone are implicitly included in the N-load model in the groundwater N-reduction map. The groundwater N-reduction map shows how large a fraction of the flow from a given grid cell is deep flow that brings nitrate below the redox interface, where it is reduced, and how large a fraction is more shallow flow, whereby nitrate is transported above the redox interface and directly to the stream system without N-reduction taking place. The time lag in groundwater for N-transport in Norsminde is short (few years) since nitrate is only transported in the shallow oxidized groundwater and in tile drains (Hansen et al., 2014a). The time lag in N-transport was included implicitly in the N-load model by considering a 20-year period.

5.4.2 Calculations

Based on the input maps the N-load model performs the following calculations for each 100 m grid cell (i) in the catchment:

N_leaching (i) x (1- GW_N-reduction (i)) = GW_N_transport_to_stream (i)

GW_N_transport_to_stream (i) x (1- SW_N-reduction (i)) = N_load_to_catch_outlet (i)

N_leaching (i): N-leaching from the root zone in grid cell (i) (kg/ha/yr)

GW_N-reduction (i): Amount of N reduced (redox reaction) in groundwater in grid cell (i) (percentage of N-leaching)
GW_N_transport_to_stream (i): Amount of N transported via groundwater and drain flow to the stream in grid cell (i) (kg/ha/yr)
SW_N-reduction (i): Amount of N from grid cell (i) reduced (redox reaction) in surface water (percentage of N transported to stream)
N_load_to_catch_outlet (i): Amount of N from grid cell (i) transported to the catchment outlet (kg/ha/yr)

The N_load_to_catch_outlet map is summed for all grid cells and the contribution of N to the stream system from other N-sources (after N-reduction in the stream system is account for) is added to get the total N-load at the catchment outlet:

$$\sum_{i=1}^{n} \mathrm{N\_load\_to\_catch\_outlet(i)} + \mathrm{Other\_N\_sources} = \mathrm{Total\_N\_load}$$

Other_N_sources: The total input of N from other N-sources to the stream system taking surface water N-reduction into account [kg/yr]
Total_N_load: The sum of N-loads from N-leaching and other N-sources for the entire catchment [kg/yr]

When running the spatially targeted management scenarios, it is the N-leaching map (Figure 5.3) that is changed, and the N-load model is then run with the scenario input. The construction of the management scenarios is described in section 5.5.

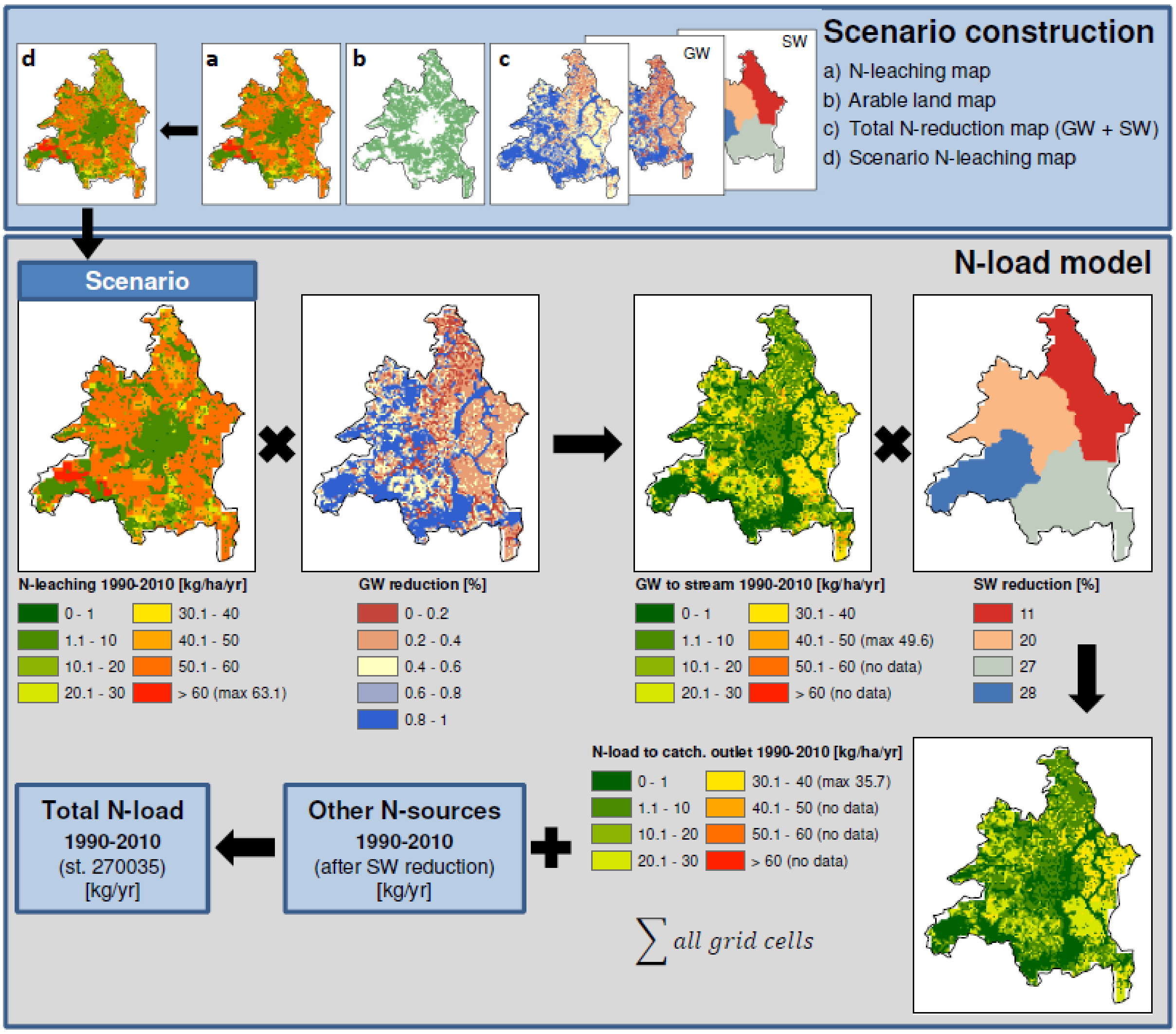


Figure 5.3 Flow chart illustrating the N-load model for Norsminde. The model consists of three input maps based on results from the dynamic catchment model: N-leaching map (amount of N leaching from the root zone), groundwater N-reduction map (fraction of N reduced in the groundwater zone) and a surface water N-reduction map (amount of N reduced in surface waters). When running scenarios it is the N-leaching map in the N-load model that is changed. The scenarios are constructed based on maps of arable land, total N-reduction and the reference N-leaching.

5.5 Scenarios for mitigating N loading

5.5.1 Norsminde

Two ways of spatially targeting the agricultural management were examined in Norsminde: Relocation of the existing agricultural practice according to the N-reduction map and identification of target areas with low N-reduction where mitigation measures should be applied to decrease N-leaching. The management scenarios in this study were constructed by solely changing the N-leaching input in the N-load model (Figure 5.3) based on the changes of the different scenarios.

The construction of the management scenarios was based on three maps (Figure 5.3): The N-leaching map, a map of arable areas and the total N-reduction map. The N-leaching was only changed on the cropland areas (i.e. fields in rotation), which is 64% of the area in Norsminde catchment for the baseline land use, 56% for SSP1, 64% for SSP2 and 74% for SSP5. On the non-arable areas the N-leaching was kept unchanged in both scenarios. The spatial targeted management was done based on the total N-reduction, i.e. both groundwater and surface water N-reduction were taken into account.

5.5.1.1 Relocation of existing agricultural practice

In the relocation scenario the N-leaching on all arable areas in Norsminde was relocated according to the N-reduction map, so that the highest N-leaching rate was placed on the area with highest N-reduction and vice versa. The relocation was done by rank ordering the N-leaching map and the N-reduction map and then moving the N-leaching rate with rank 1 to the grid cell with N-reduction rank 1 and so on. In the Relocation scenario we thus do not move around the actual crops or management practice, but only the N-leaching. We thereby assume that a crop/practice in one grid cell will result in the same N-leaching rate in the grid cell it is moved to, irrespectively of the soil type. The relocation management scenario was not adjusted to reach a specific N-load. Instead, the decrease in N-load obtained from relocation was a result of the scenario.

5.5.1.2 Target areas with low N-reduction

In the target area scenario were target areas, where N-measures should be applied to lower the N-leaching, identified as the areas with lowest N-reduction. The N-leaching on target areas was set to 12 kg N ha^{-1} yr^{-1}, which is the Danish standard value used for set-aside land (Eriksen et al., 2015). The N-leaching on areas that were not defined as target areas (non-target areas) was unchanged. The target areas were defined as all areas with a N-reduction below the “N-reduction threshold”. The “N-reduction threshold” parameter controls how large and which areas were identified as target areas, and this parameter was manually adjusted until a 20% decrease in N-load was reached.

5.5.2 Kocinka

Spatial differentiation of land use change for SSP1 and SSP5 was based on baseline data pattern of land use - crop rotation system and soil types.

In SSP1 cropping land was decreased by 10%. Cropland on the less productive soils was transformed to grasslands and forests if located adjacent to these land use classes, resulting in 542 ha increase of forests and 541 ha increase of grasslands. Mainly crop rotation system 3 (CRP3) that is assumed intended for the feeding of livestock was transformed to grassland or forest. This reduction in the feed crops area is a result of the reduction of animal stock. Sandy soils are less fertile than sandy loamy soils, so the reduction of cultivation should first take place on areas occupied by the sandy soils.

In SSP5 the cropping land was increased by 10%. Croplands with CRP3 were expanded by transformation of 541 ha of grasslands on sandy loam soils. Croplands with CRP4 were expanded by transformation of 85 ha of the remaining grasslands on sandy loam soils and of 455 ha of grassland on sandy soils. It is assumed that the expansion will take place on the most productive soil types. Cropping systems CRP3 and CRP4 was assumed to expand to feed the increase of animal stock.

The Kocinka catchment has a complicated hydrogeology. Surface water flow is strongly dependent on groundwater inflows from fissured-porous karstic aquifer - the Upper Jurassic aquifer- that is a part of one of the largest groundwater bodies in Poland – the Major Groundwater Basin 326. Because of the overall limited denitrification capacity in the system, the management of nitrate pollution cannot rely on allocation of agriculture to areas with higher denitrification potential. Differentiated regulations based on moving agricultural production to soils with lower nitrate leaching is not applicable in the catchment, because the only soils with low leaching potential are organic soils in river valleys where extensive drainage, implying the generation of drainage fluxes, is necessary. The potential for differentiated regulation is limited also by a small pool of more productive soils in the catchment.

Modelling approaches used to assess effects of the land use scenarios is based on the model of nitrate leaching from the root zone (N-LES4) coupled with the numerical model of groundwater flow and nitrate transport built and developed in Visual MODFLOW and M3TD software (Nilson and Thomas, 2010). The input data of the nitrate leaching was spatially explicit depending on previous patterns of soil, depth to groundwater table and crop rotation system. The model simulations were conducted on a 1 ha grid scale (100 x 100 meter).

Effects of scenarios were compared for the period 2040-2060. Total travel time of water through the unsaturated and saturated zones can be considered a quantitative measure of the lagtime of contaminant transport. N outflow from the Kocinka catchment is delayed due to time lags in groundwater flow of 25 years on the average and is spatially differentiated (Figure 5.3). In order to take into account these time lags, the input data cover the period from 1950 to 2060.

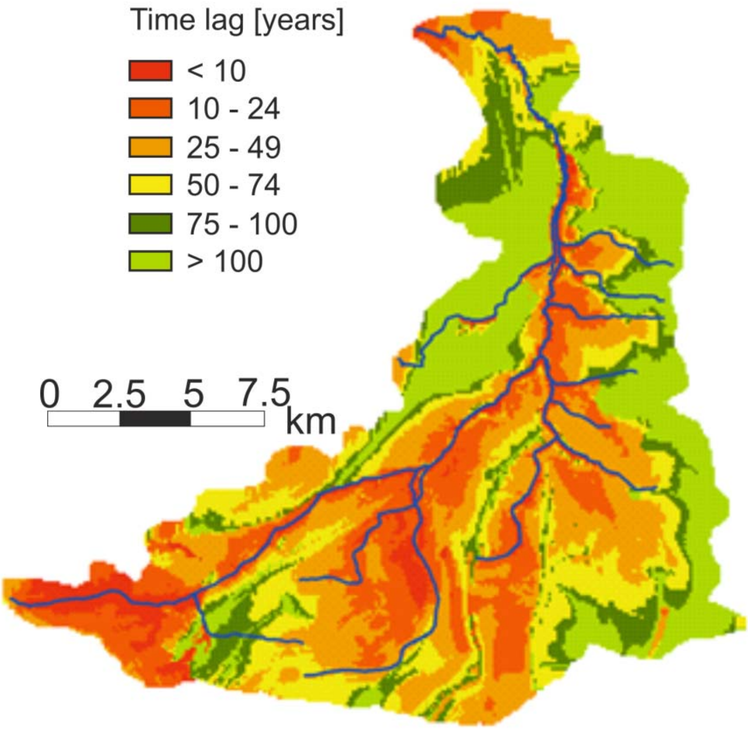


Figure 5.3. Time lags for water flows in the Kocinka catchment (Wachniew et all., 2018).

There are two sources of nitrate to groundwater in the Kocinka river catchment: agriculture and sewage. Inputs to the model from 1950 to 2010 include both sources of emission (Wachniew et al., 2018). Simulations for the future period from 2010 to 2060 include only agricultural N emissions.

The NLES4 model was used to estimate N leaching for three future socio-economic scenarios (the Shared Socio-Economic Pathways): SSP1, SSP2, SSP5 and four climate variants (CM1-CM4) based on RCP8.5. Four extreme scenarios were selected for the presentation of yearly N outflow from the Kocinka catchment (Figure 5.4):

- Lowest emission scenario: SSP1- CM2 (CM5A-MR_WRF-JPSL)
- Average emission scenario: SSP2- CM3 (CNRM-CM5_RCA4)
- Highest emission scenario: SSP5- CM1 (MPI-ESM-LR_CCLM).

In addition, an Ecological agriculture variant was tested. This variant is based on leaching similar to SSP1-CM2 (CM5A-MR_WRF-JPSL), but areas with time lag below 10 years are chosen to have leaching like a natural area (2 kg N/ha). These changes covered the area of 5% of the catchment (1300 ha). Area with the shortest lag time are mainly near river valley and they have permeable soils. Reduction of nitrate loads there can be implemented through wetlands and closed circuit greenhouse agriculture.

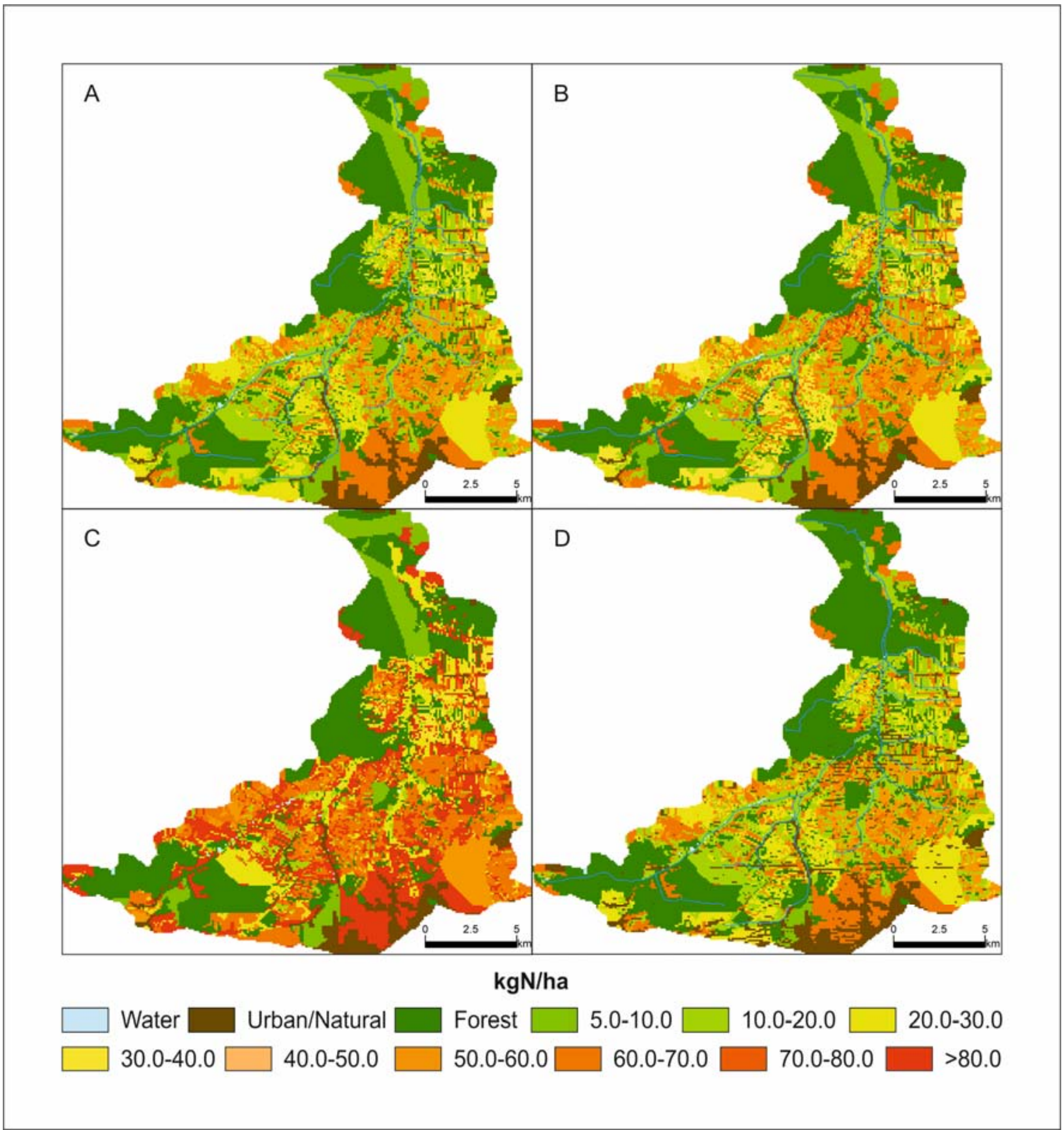


Figure 5.4. Spatially differentiated N leaching for selected scenarious: A: SSP1- CM2, B: SSP2- CM3 C: SSP5- CM1, D: Ecological agriculture – leaching like in A,changes introduced for areas where time lags are below 10 years (2 kg N/ha).

6. Results

6.1 Norsminde

6.1.1 Water balance

Figure 6.1 shows the estimated future changes in water balance components (precipitation, evapotranspiration and percolation/drain flow) compared to the baseline. Three of the four climate models gives an increase in average annual precipitation. Climate model 1 (CM1) gives a slight increase of 5%, whereas climate model 2 (CM2) and climate model 3 (CM3) give the highest increases of 19% and 17%. Climate model 4 (CM4) gives a slight decrease in annual precipitation of 2%. The monthly distribution of precipitation over the year differs between the four climate models.

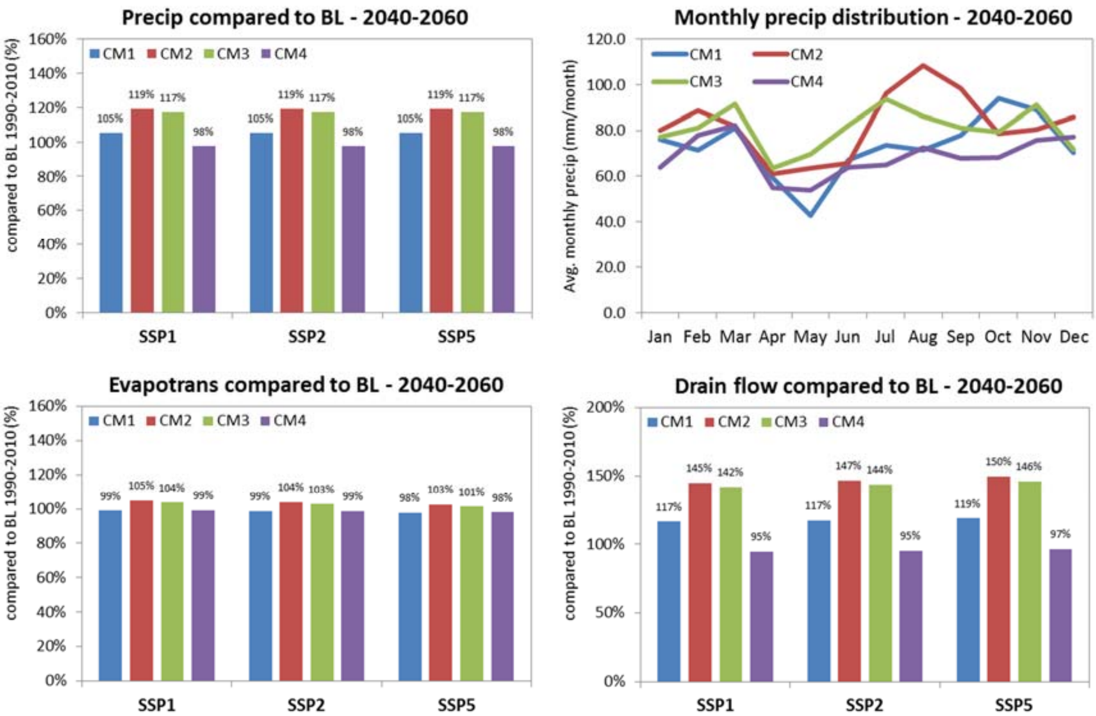


Figure 6.1 Water balance components for the future scenario models. The top left graph shows the average yearly precipitation in 2040-2060 relative to the baseline. The top right graph shows the monthly distribution of precipitation for 2040-2060. The lower left graph shows the evapotranspiration in 2040-2060 relative to the baseline. The lower right graph shows the drain flow in 2040-2060 relative to the baseline.

The evapotranspiration varies depending on climate models and SSPs. In climate model 1 and 4, the evapotranspiration decreases with 1% for SSP1 and SSP2 and 2% for SSP5. In climate model 2 and 3 the evapotranspiration increases with 4-5% for SSP1 and SSP2 and 1-3% for SSP5. The drain flow component increases much more than the increase in precipitation for climate model 2 and 3. This indicates that these two climate models result in more shallow flow paths.

6.1.2 Nitrate leaching for Norsminde agricultural area

The N leaching under the different SSP scenarios are affected by three different factors: land use (proportion of agriculture), fertilization rates and structure of the crop rotations. The land use changes with different cropland shares of the total catchment between the land use scenarios, which affects the share of cropland, forest and grassland (Figure 4.3). The second impact is the differences in fertilisation of the different cropping systems. Intensification of the fertilisation and animal production resulting in higher fertilisation rates with both organic and mineral fertilisers in SSP5 and an extensification in SSP1. The crop rotations are also changed between the scenarios, relating to both crops and catch crops (Table 4.1) and fertilisation (Table 4.2). The basic changes in the crop rotations have been introduced in all combinations of soil type, farm type and under the nine different climatic conditions. The results in Figure 6.2 present the aggregated mean N leaching results for the cropland area.

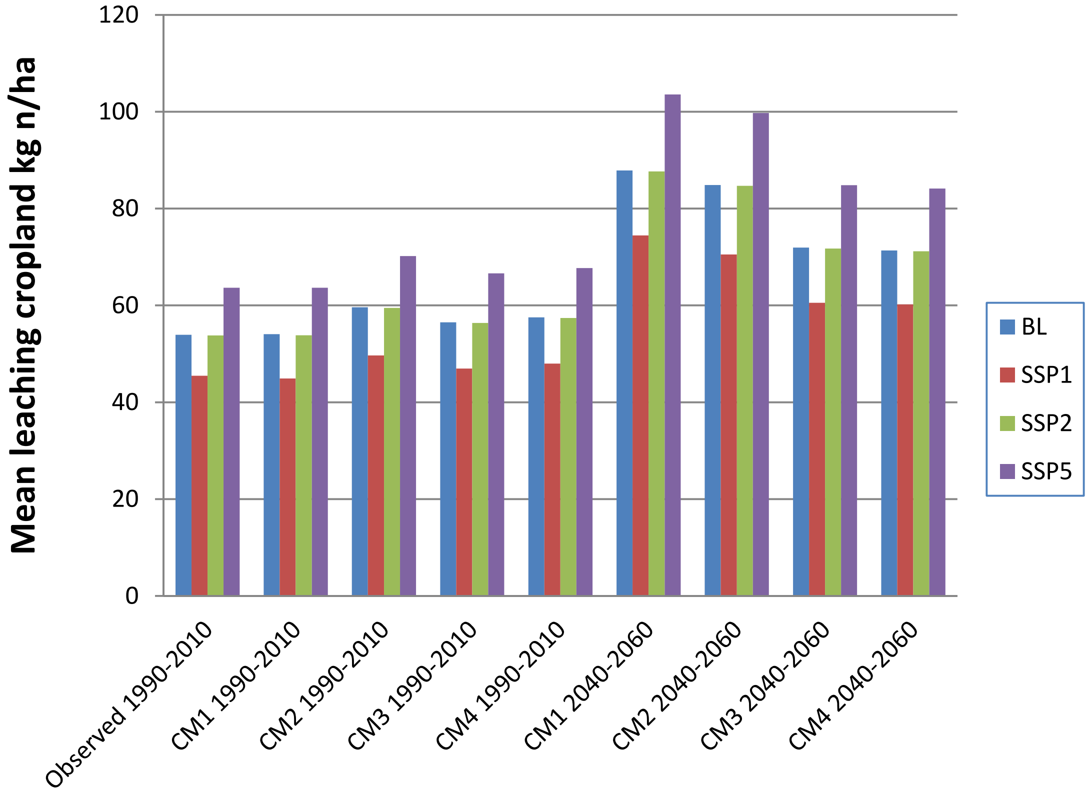
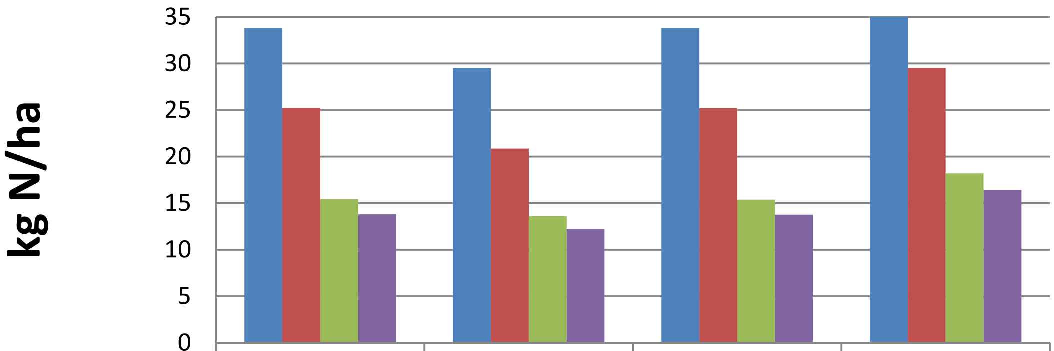


Figure 6.2. Mean nitrogen leaching affected by different land use scenarios and projections of future climatic conditions for the agricultural area.

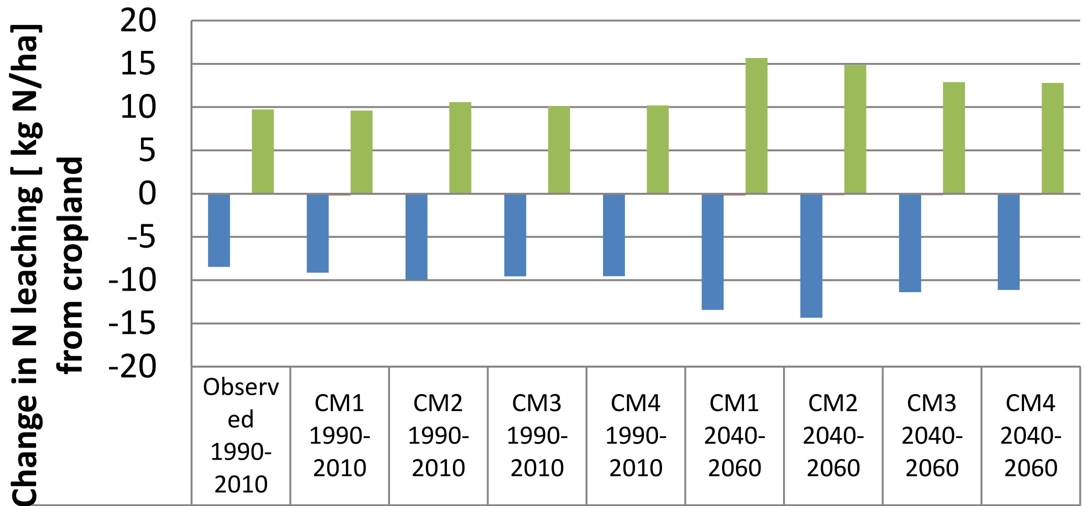
The effect of the specific climate model on the simulated nitrate leaching is also illustrated in Figure 6.3. These results were calculated with the NLES model, but scaled with the climate effects generated by the Daisy model simulations (see Subsections 5.1.3-5.1.4). The climate effects are combinations of weather impacts on crop N uptake related to the crop growth, the denitrification processes, the soil N turnover processes and the nitrate leaching driven by the percolation. The highest impact is found for CM1 with an increase of between 30 and 40 kg N ha^{-1} and the lowest impact if found for CM4 with an increase between 12 and 16 kg N ha^{-1}. The effects are generally smallest for SSP1 and highest for SSP5.



	BL	SSP1	SSP2	SSP5
CM1 2040-2060	34	30	34	40
CM2 2040-2060	25	21	25	30
CM3 2040-2060	15	14	15	18
CM4 2040-2060	14	12	14	16

Figure 6.3. Effect of climate change on nitrate leaching from cropland for different climate models (difference between projection and baseline period).

Between the climate models (CM1..CM4) the changes in N leaching for SSP1, SSP2 and SSP5 under current climatic conditions (1990-2010) are at the same level (Figure 6.4). SSP1 has a reduced N leaching of 8 kg N ha^{-1} using observed climatic data and the reduction using climate model predicted climatic conditions is 9-10 kg N ha^{-1}. Under future climatic conditions, there are greater differences between the SSPs. Here the reduction for SSP1 is between 11 and 13 kg N ha^{-1}. For SSP5 the increase in N leaching under current climatic conditions is found to be between 10 and 11 kg N ha^{-1}. Under future climatic conditions the increase is found to be between 13 and 16 kg N ha^{-1}. Here CM1 gives the highest increase in N leaching.



	Observed 1990-2010	CM1 1990-2010	CM2 1990-2010	CM3 1990-2010	CM4 1990-2010	CM1 2040-2060	CM2 2040-2060	CM3 2040-2060	CM4 2040-2060
Effekt SSP1	-8	-9	-10	-10	-10	-13	-14	-11	-11
Effect SSP2	0	0	0	0	0	0	0	0	0
Effect SSP5	10	10	11	10	10	16	15	13	13

Figure 6.4. Mean change in N leaching from cropland affected by different scenarios and climate model projections of future climatic conditions compared with baseline land use.

6.1.3 Nitrate leaching for Norsminde catchment

Modelling nitrate leaching for the entire catchment must include leaching from cropland and permanent grass – but also from forest, urban, set-aside and nature areas. The N leaching from these areas was calculated using standard values (Table 5.1). As cropland covers 65% the N leaching level in BL and SSP2, 57% in SSP1 and 74% in SSP5, the average leaching is dominated by the cropland leaching. This share of total N leaching is therefore also lower in SSP1 and higher in SSP5 compared with BL and SSP2 (Figure 6.5). The effects of intensification of the agriculture through higher use of manure and fertilizers is seen in the considerably higher catchment N leaching of SSP5, compared with SSP2.

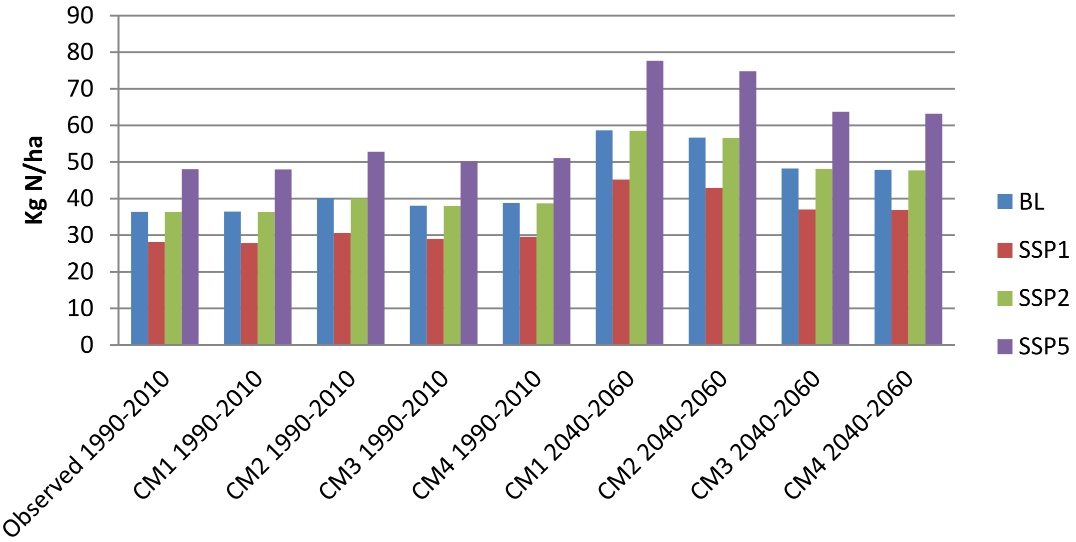


Figure 6.5. Mean nitrogen leaching (kg N/ha) for the Norsminde catchment.

The relative changes in catchment N leaching are shown in Figure 6.6. This illustrates the large differences in N leaching between the different climate models, and these differences are comparable with those of the effects of different SSPs. SSP1 results in a decrease of N-leaching of 24%, SSP2 result in no change in N-leaching compared to the baseline and SSP5 result in an increase in N-leaching of 32%.

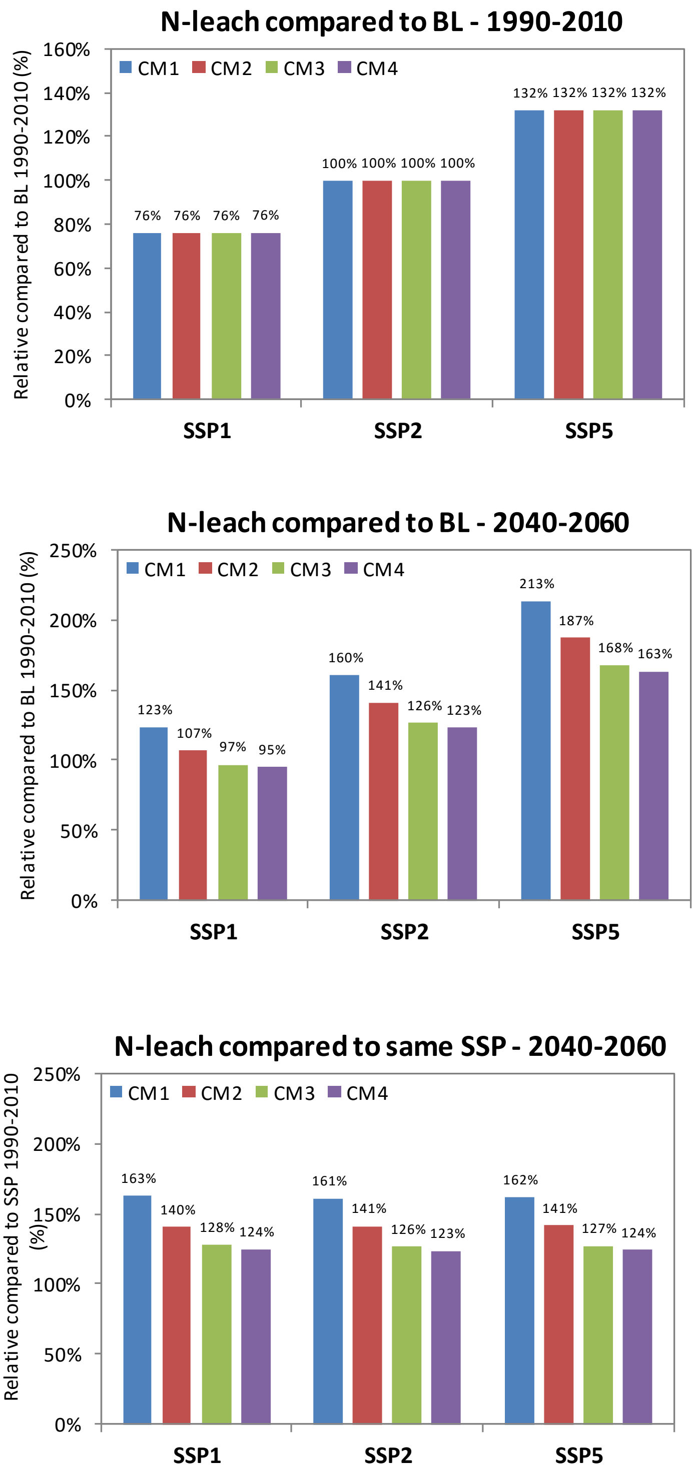


Figure 6.6. Relative catchment N leaching compared to baseline. The upper graph shows the values for each SSP in 1990-2010 compared to the baseline (i.e. only land use effect), the middle row show values in 2040-2060 compared to the baseline (i.e. both land use and climate effect) and the lower row show values in 2040-2060 compared to the same SSP 1990-2010 (i.e. only climate effect).

6.1.4 N loads to Norsminde Fjord

The N loads were calculated using the N load model described in section 5.4. This model depends on the groundwater N reduction (GW%, N reduced in groundwater as percentage of N-leaching), and the N leaching, which was described in section 6.1.3.

6.1.4.1 Present period 1990-2010

The changes in N-load and N-reduction in groundwater compared to the baseline for the three SSPs for the present period are shown in Figures 6.7 and 6.8 (upper graph). The four climate models predict the same changes for the present period for each SSP. Thus, the changes are only due to changes in land use. For the total N-load at st. 270035, the numbers are slightly different: 22% decrease for SSP1 and 27% increase for SSP5 (Figure 6.7). The reason for this is the contribution to the total N-load from other N-sources that is assumed to be constant. The N-reduction in groundwater (GW%) is unchanged for SSP2 and SSP5, whereas a small increase of 1-2% is seen for SSP1 (Figure 6.8).

6.1.4.2 Future period 2040-2060

The projected changes for the future period are seen in Figures 6.7 and 6.8 (middle and lower graphs). The graphs in the middle row are compared to the baseline, and thus show the effect of both land use and climate changes. The lower graphs in the figures compare results compared to the same SSP for 1990-2010 and therefore show only the climate effect.

In the future climate the four climate models are seen to project different changes in N-load and GW%. All four climate models predict an increase in N-load when only looking at the climate effect (Figure 6.7, lower graph). Climate model CM1 predicts the highest N-leaching and N-load and climate model CM4 the lowest (Figure 6.6). However the differences between the climate models in the predicted increase in N-leaching is different from the predicted increase in N-load (Figure 6.7). For example, the difference in the N-leaching increase between climate model 3 and 4 is 3-4%, whereas the difference in the N-load increase is 18-19%. The reason for this is, that the N-reduction in groundwater (GW%) is 13% lower in CM3, whereas for CM4 the GW% is unchanged (Figure 6.8).

When looking at both the land use and climate effect, the N-leaching in the future is projected to change between a 5% decrease to a 23% increase (Figure 6.6) and for the N-load between a 6% decrease and a 26% increase for SSP1 (Figure 6.7). For SSP2 the N-leaching is projected to increase by 23%-60% and the N-load by 20%-59%. For SSP5 the N-leaching is projected to increase by 63%-113% and the N-load by 52%-106%.

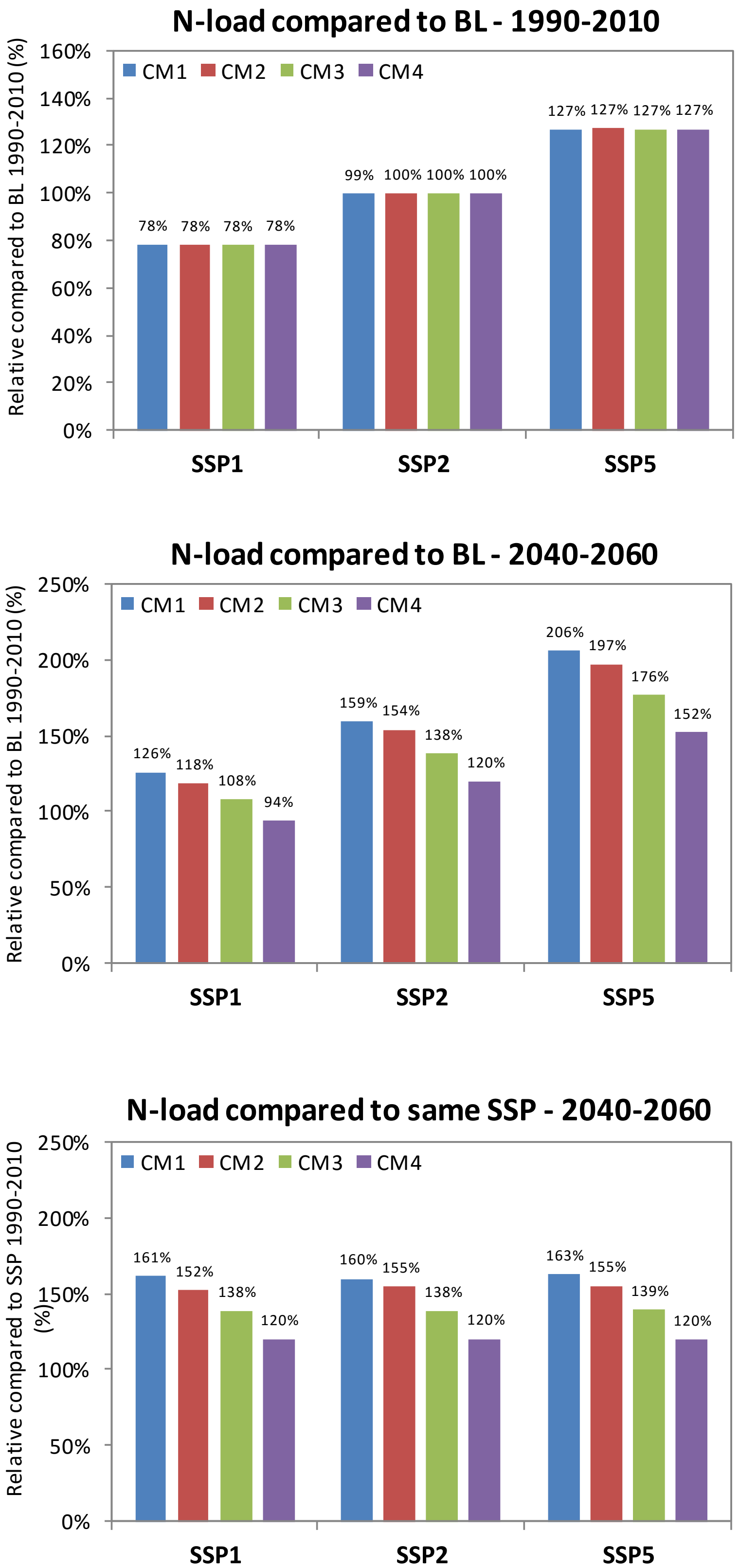
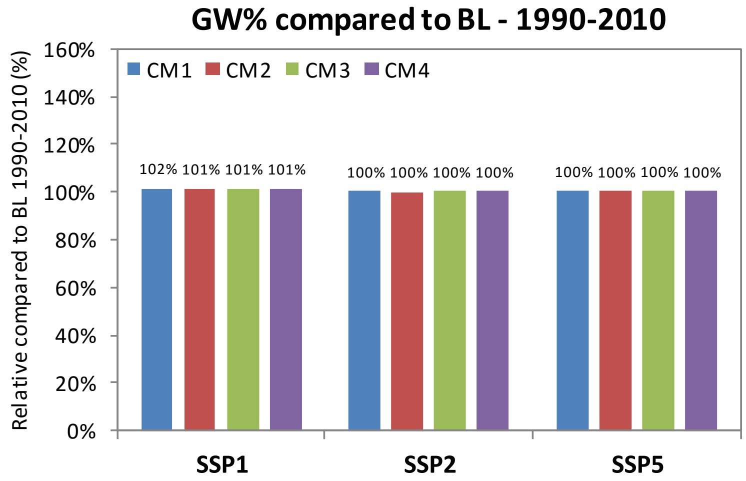
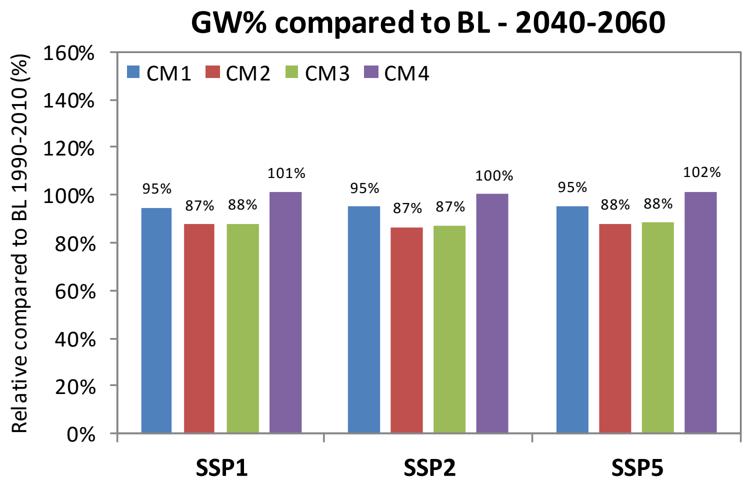


Figure 6.7. Relative catchment N loads compared to baseline. The upper graph shows the N-loads for each SSP in 1990-2010 relative to the baseline (i.e. only land use effect), the middle graph shows N-load in 2040-2060 relative to the baseline (i.e. both land use and climate effect) and the lower graph show N-loads in 2040-2060 relative to the same SSP 1990-2010 (i.e. only climate effect).





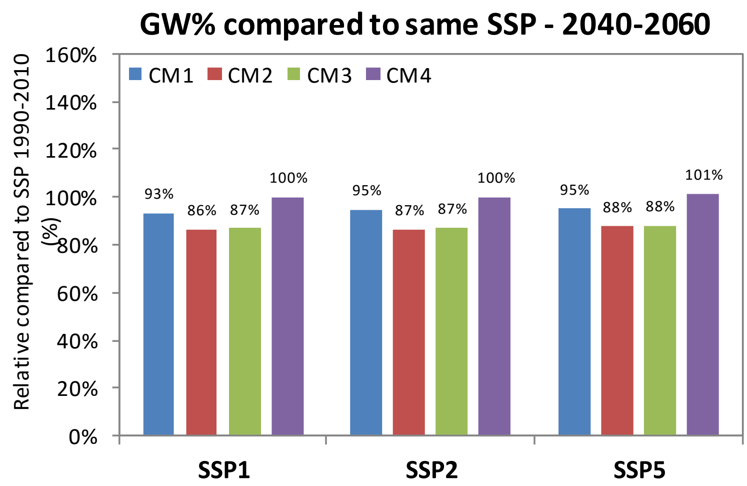


Figure 6.8. Relative groundwater N reduction (GW%) compared to baseline. The upper graph shows the values for each SSP in 1990-2010 compared to baseline (i.e. only land use effect), the middle row show values in 2040-2060 compared to baseline (i.e. both land use and climate effect) and the lower row show values in 2040-2060 compared to the same SSP 1990-2010 (i.e. only climate effect).

6.1.5 Covariance analysis

Table 6.1 shows the results from a covariance analysis on how large a contribution to the total variance in future predicted changes in the N-leaching, N-load and GW% comes from the differences between the climate models and differences between the SSPs. For N-leaching and N-load the differences between the SSPs give rise to 81% and 77% of the total variance. However, for GW% the differences between the climate models result in 99% of the total variance.

Table 6.1 Covariance analysis on changes in N-leaching, N-load and GW% for 2040-2060 compared to baseline. The number indicates the contribution to the total variance on the future estimates from the climate models and the land use scenarios.

	Climate models	SSPs
N-leaching	20%	81%
N-load	24%	77%
GW%	99%	1%

6.1.6 Spatially targeted measures

6.1.6.1 Target areas with low N-reduction

Figure 6.9 shows the set-aside area needed for each scenario in order to decrease the N-load by 20% compared to the baseline. Under the current climate no set-aside is needed for SSP1, since the N-load is already 22% lower than the baseline. For SSP2, 843-870 ha of set-aside is needed and for SSP5 1718-1773 ha. In the climate change projections, the need for set-aside increases, because of the future increase in N-load. For SSP1 the set-aside area must be between 571-1449 ha, for SSP2 between 1388-2191 ha and for SSP5 between 2147-2964 ha. The catchment area (to st. 270035) is 8080 ha, so large parts of the catchment (for SSP5 up to 37%) possibly need to be converted to set-aside and thus taken out of agricultural production.

The set-aside is spatially targeted to areas with low groundwater N-reduction. Therefore the GW% for the entire catchment increases (Figure 6.10).

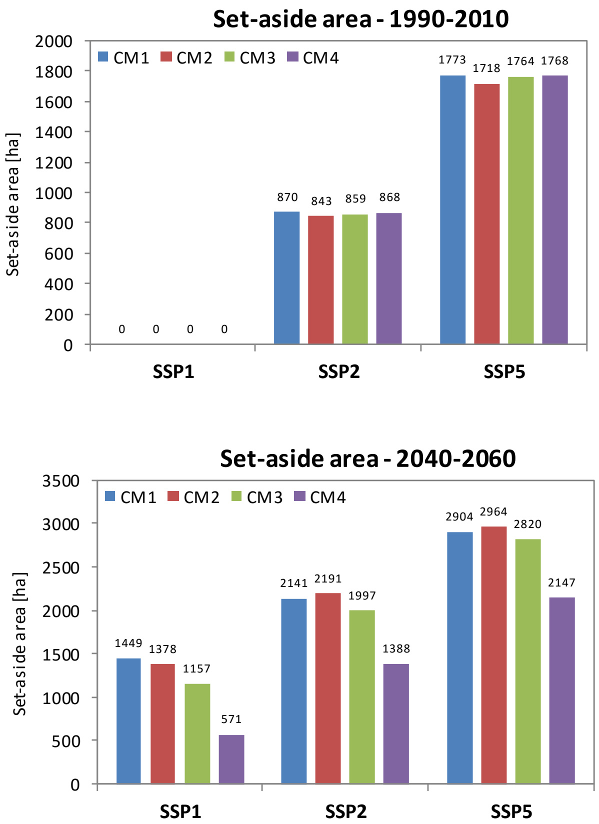


Figure 6.9. Set-aside area needed to decrease the N-load by 20% compared to the baseline.

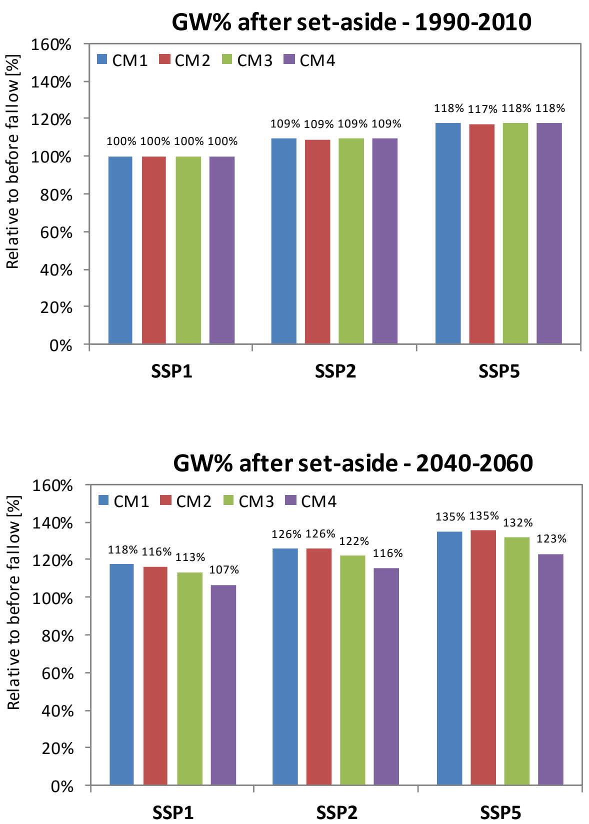
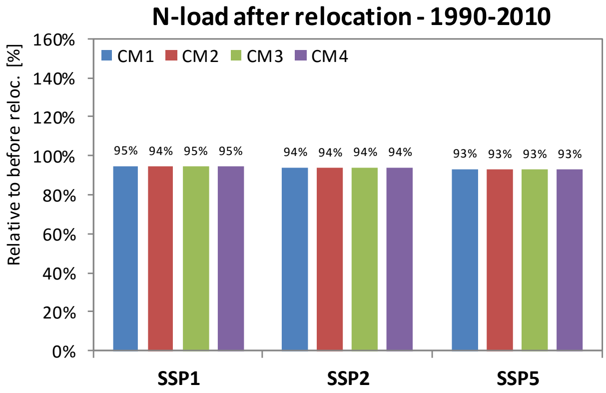


Figure 6.10. Relative GW% after set-aside application compared to before situation.

6.1.6.2 Relocation

The effect of relocation of agricultural production to reduce N loads is not affected by climate models or SSPs (Figure 6.11). The decrease in N load is almost the same (5-7% decrease) for all scenarios both under present and future climate. This occurs because N leaching estimates vary largely in the same way among different soil and farming systems in all scenario+climate combinations.



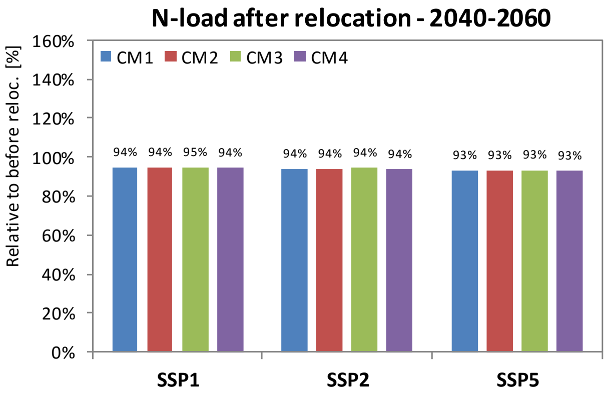
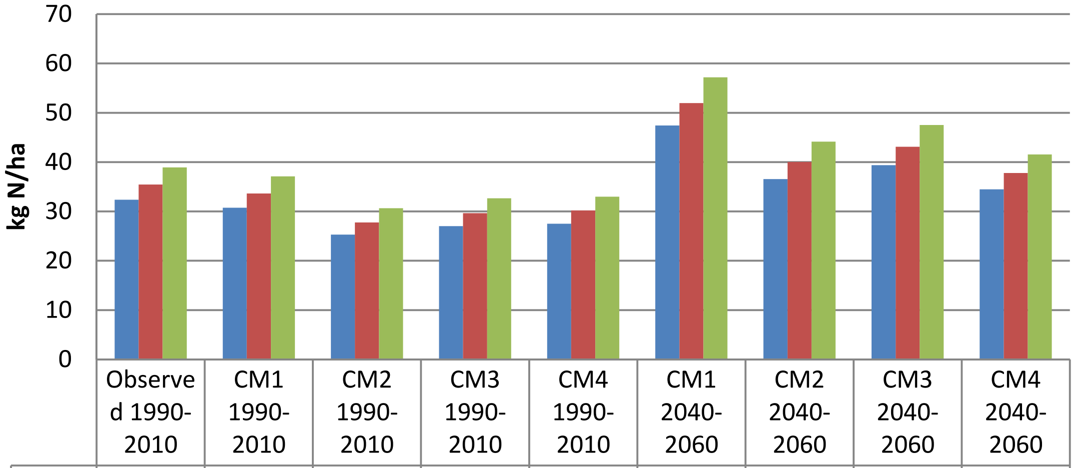


Figure 6.11. N-load after relocation relative to before situation.

6.2 Kocinka

6.2.1 Nitrate leaching from agricultural land.

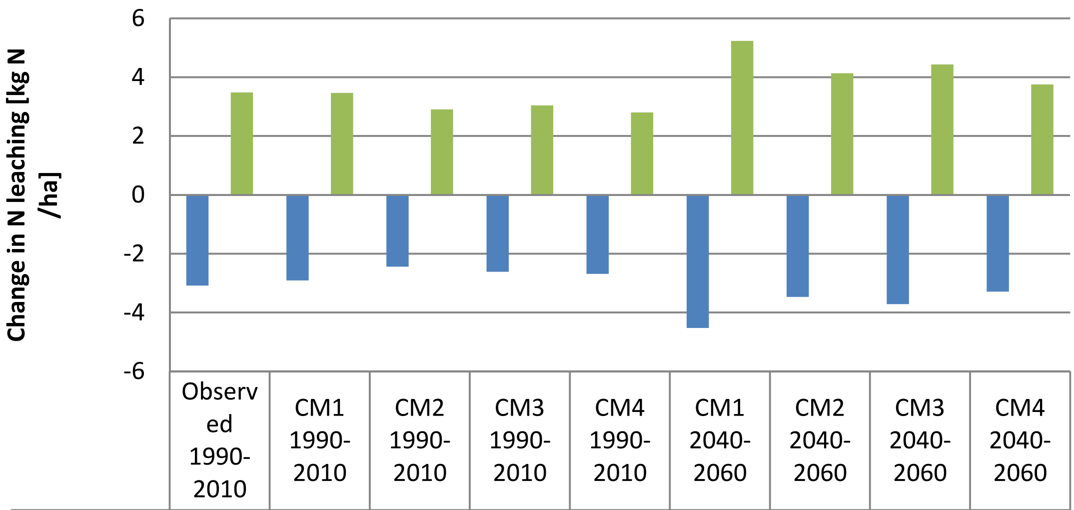
Figure 6.12 shows the mean N leaching from agriculture land (cropland + permanent grass) in the Kocinka catchment. The area covers 56% in the baseline situation, and in SSP5 the share of the agricultural area is 58%. For SSP1, with a lower N fertilizer input compared to SSP2, the N leaching was reduced with 2 and 3 kg N ha^{-1} under current climate and the reduction is estimated to be between 3 and 5 kg N ha^{-1} under future climate conditions.



	Observed 1990-2010	CM1 1990-2010	CM2 1990-2010	CM3 1990-2010	CM4 1990-2010	CM1 2040-2060	CM2 2040-2060	CM3 2040-2060	CM4 2040-2060
ssp1	32	31	25	27	28	47	37	39	34
ssp2	35	34	28	30	30	52	40	43	38
ssp5	39	37	31	33	33	57	44	48	42

Figure 6.12. Mean N leaching from agricultural land using different climate models and socio-economic scenarios in the Kocinka catchment.

The lowest N leaching level is simulated using CM2, and the highest N leaching with CM1. For all SSPs, the average N leaching from agricultural land in 2040-2060 is higher than in 1990-2010. This is primarily an effect of lower yields under future climatic conditions (simulated with the Daisy model) and an increase in rainfall resulting in higher annual percolation rates. The highest increase in N leaching was found for CM1 and the lowest was found for CM4.



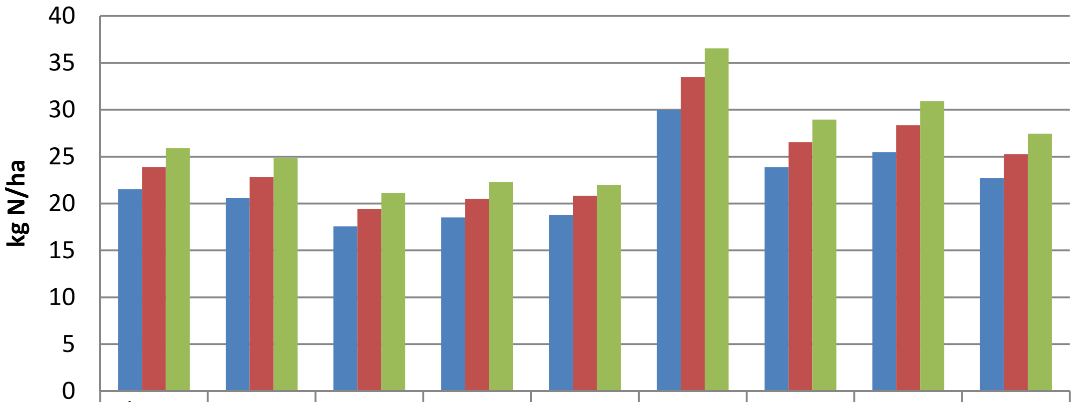
	Observed 1990-2010	CM1 1990-2010	CM2 1990-2010	CM3 1990-2010	CM4 1990-2010	CM1 2040-2060	CM2 2040-2060	CM3 2040-2060	CM4 2040-2060
Effekt SSP1	-3	-3	-2	-3	-3	-5	-3	-4	-3
Effect SSP2	0	0	0	0	0	0	0	0	0
Effect SSP5	3	3	3	3	3	5	4	4	4

Figure 6.13. Mean change in N leaching from agricultural land compared with SSP2 for different climate models and SSP's in the Kocinka catchment.

Effects of land use scenarios SSP1 and SSP5 compared with SSP2 are shown in Figure 6.13. Under the current climate 1990-2010 the reduction in the nitrogen leaching of SSP1 varied between 2 and 3 kg N ha^{-1}. Under future climatic conditions the reduction was between 3 and 5 kg N ha^{-1}. SSP5 resulted in an increased N leaching under current climatic conditions of 3 kg N ha^{-1} and under future climatic condition an increase of 4 and 5 kg N ha^{-1}.

6.2.2 Nitrogen leaching from Kocinka catchment.

The mean N leaching for the entire catchment is a weighted average result of both agricultural and non-agricultural land. Standard values of N leaching (Table 5.1) was used to calculate the N leaching from these areas.



	Observed 1990-2010	CM1 1990-2010	CM2 1990-2010	CM3 1990-2010	CM4 1990-2010	CM1 2040-2060	CM2 2040-2060	CM3 2040-2060	CM4 2040-2060
SSP1	22	21	18	19	19	30	24	25	23
SSP2	24	23	19	21	21	34	27	28	25
SSP5	26	25	21	22	22	37	29	31	27

Figure 6.14. Mean N leaching (kg N ha^{-1}) from total catchment area climate and socioeconomic scenarios.

The mean N leaching of the Kocinka catchment is presented in Figure 6.14. In general the N leaching (kg N ha^{-1}) including the non-agricultural areas is 63-70% of the mean N leaching from the agricultural area. The range 63-70% results from different shares of agricultural area of the total catchment in the different SSPs and due to the different average N leaching levels from the agricultural land due to differences in fertilization rates and as a result of the climate change effects.

The effect of climate change on N leaching varied primarily between different climate models. The largest relative increase in N leaching was found for CM3 with 54% and the lowest with CM2 with 19%. These relative changes were not affected by SSPs.

6.2.3 Simulated N outflow from catchment

Selected scenarios were used to simulate N outflows from the Kocinka catchment using the MODFLOW model (Figure 6.15). Differences in N outflows between selected scenarios are below 10% (compared to the average value 2040-2060). Responses in N outflow are proportional to changes in N fertilization (N input). The total outflow N of the catchment in scenario A is 519 Mg per year. For scenarios B, C and D they are by 3% higher and 4 and 6% lower than for A.

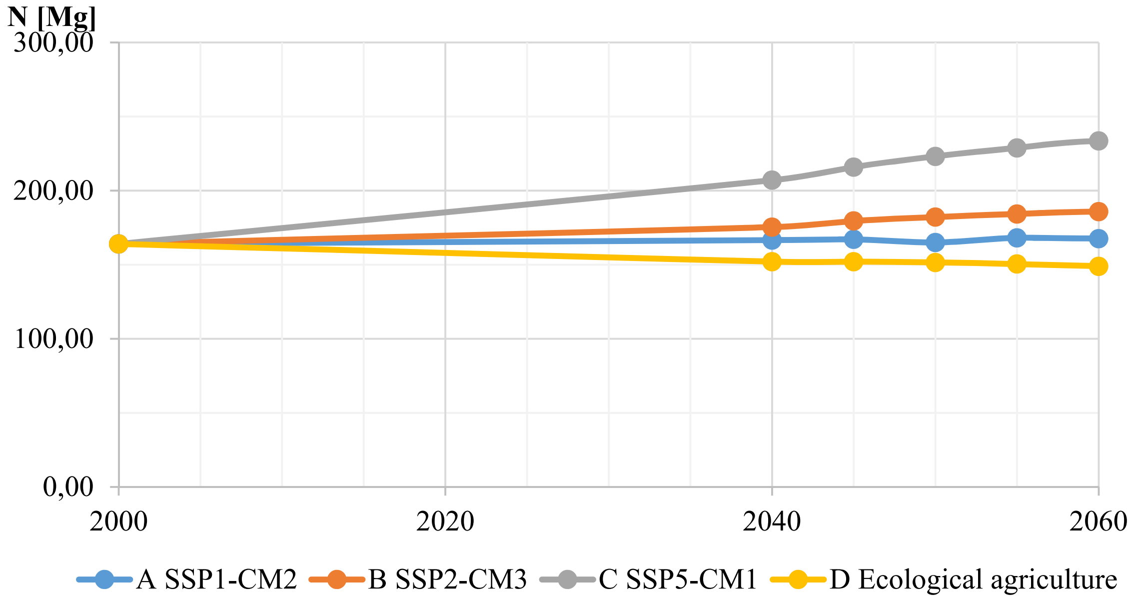


Figure 6.15. Simulated annual N outflow from the Kocinka catchment in selected future scenarios from Figure 5.4.

The scenario analysis shows that even radical changes in land use bring little reduction in nitrate leaching compared to the baseline scenario (year 2000). However, there are still scope from changes in N leaching by changing agricultural practices, e.g. use of cover crops. The time trends in Figure 6.15 over the period 2040-2060 is caused by the time lag in responses due to the long residence times in groundwater. The results show that the N outflow from a catchment with significant time lag cannot be reliably modelled by models, which do not represent groundwater flow with sufficient detail, addressing lag times in N transport through the subsurface. The capabilities of the hydrogeological models in predicting N exports from catchments can be improved through coupling with models of N leaching from soils. For the successful implementation of measures to reduce the N outflow from agriculture in the catchment area, it is important to include expected lag times in response to the undertaken measures in management recommendations.

7. Discussion

Water pollution are among the main environmental challenges faced by the European Union and the countries surrounding the Baltic Sea, and multiple stressors compromise the ecological integrity of the both freshwater and marine ecosystems. To enhance the quality of the Baltic Sea, there is a need to reduce the nutrient inputs of both N and P substantially (Wulff et al., 2014). Providing policy pathways that will achieve this requires consideration of the many factors that will be influencing nutrient loadings, in addition to those being affected by specific nutrient load reduction measures. This study focused on the impacts of future socioeconomic pathways and climate change on nitrate leaching from two agricultural catchments in the Baltic Sea area (Norsminde in Denmark and Kocinka in Poland).

Estimating N loads to the sea under future conditions is influenced by numerous uncertainties, not least those associated with changes in land use and climate (Molina-Navarro et al., 2018). Land use, in particular agricultural land use, is known to be the major factor affecting nutrient loadings (Hashemi et al., 2016). The current study applied scenarios (SSP1 and SSP5) that provided both a decrease and an increase in agricultural land use; however, these scenarios were also associated with decreases and increases, respectively, in land management intensity as described by livestock density and fertilisation rates. The time period of 2040-2060 was selected for the climate change projections, since this provides a relevant temporal perspective for policy decisions.

7.1 Modelling methodology

The results presented depends on the choice of future conditions as represented by SSPs and climate models. The climate models were selected from the CORDEX database to represent a range of climatic conditions under the RCP8.5 emission scenario. 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.

Only three out of a total of five SSPs developed for the Baltic Sea area (Zandersen et al., 2018) were included in the current study. However, these SSPs were selected to span the full range of possible land use changes, i.e. from reduction to increase in land use and intensity of land management. The choice of change in land use and intensity of agricultural management in these scenarios are 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 method provides a simple methodology for incorporating effects of changes in agricultural management on N leaching and since this model is empirically founded on actual measurements. However, NLES does not include all relevant climate effects, but only the effect of percolation (and thus precipitation) on N leaching. The dynamic Daisy model was therefore used to derive correction factors for each catchment and climate model by which the leaching from NLES was scaled to correspond to the future climatic conditions. This approach assumes that the setup of Daisy well covers the factors affecting N leaching in the future. It is also dependent on the choice of the dynamic model and its parameterization. Öztürk et al. (2018) compared N leaching of a winter wheat monoculture at different fertilisation rates in Denmark using three different models: Daisy, FASSET and SWAT. All these models simulated higher N leaching under climate change compared to the baseline climate; however, the increases were higher for FASSET and SWAT than for Daisy.

The use of the 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. Especially 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 higher N fertilisation level. However, the higher N mineralization in autumn and winter will directly affect N leaching in all SSPs. The higher net N mineralisation also affects denitrification, resulting in a higher denitrification as also shown by Öztürk et al. (2018). The N leaching is also affected by the effects of climate change on 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.

The modelling of water and N flows in the MIKE SHE model also involved a number of assumptions, of which the following may be most important:

- The depth to the redox interface was assumed unchanged in the future. This assumption is believed to be reasonable, since the migration rate of the redox interface is on the millimetre scale per year (0.5 mm yr^{-1} assuming nitrate input of 25 mg/l, oxygen input of 11.4 mg/l, flow across redox interface of 100 mm yr^{-1} and redox capacity of 459 meq-e kg^{-1} (average of measurements in Norsminde)).
- We assume the surface water N-reduction to be unchanged in future. This may not be the case if the N-reduction in surface water is dependent on temperature. However, the way surface water N-reduction was implemented in the Norsminde model as a function of stream length (i.e. transport time) did not make it possible to make an estimate of the future change in surface water N-reduction.
- We assume the groundwater abstraction in the future to be equal to the average abstraction for 2006-2010.

7.2 Climate effects on N leaching

The simulated effects of climate change shows an increase in N leaching of 23% to 63% for Norsminde and 19% to 54% for Kocinka. These changes were almost solely determined by the climate models, since the setup of the modelling procedure meant that other factors within the SSPs that may otherwise be interacting with climate were assumed constant.

There are only a few studies that have explored the effect of climate change on nitrate leaching from cropping systems, where conditions beyond monocultures have been studied. Dolta 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. They considered different time slices and two different climate models under the SRES A1B emission scenario, which in terms of climate change for the period 2040-2060 compares to RCP8.5. For the future time slice of 2040-2060 they found increased N leaching of 38% to 70% for arable cropping systems, and these changes were not affected 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 found with climate change by Öztürk et al. (2018) for the FASSET compared with Daisy.

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 affecting leaching the most, but increasing temperature was also found to enhance N leaching from both spring barley and winter wheat with about 12% for a 1°C. For the climate change scenarios applied in the current study, the temperature changes were in the order of 1.0-2.5°C, which according to the study of Jabloun et al. (2015) would mean increased N leaching of 12 to 30%. This effect, caused by higher temperature should be compared with the correction factors for NLES derived from comparing Daisy and NLES simulation (Table 5.1), where correction factors range from 8 to 44%, which is slightly greater than the range suggested by Jabloun et al. (2015), but largely in accordance.

The responses of N leaching to climate change is 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). This is illustrated by a model-based study for different sites in Europe, where the LPJ-GUESS model was used for regions across Europe to assess the effect on N-leaching for different future time slices (Blanke et al., 2017). The results showed lower N leaching for the Boreal region (corresponding to northern parts of the Baltic Sea) with climate change and increased leaching for the Atlantic North region (corresponding to southern parts of the Baltic Sea). Therefore responses will likely vary between different countries of the Baltic Sea area, but it seems that other studies corroborate our results that N leaching will increase under climate change in the two studied catchments.

7.3 Combined socio-economic and climate effects on N loads

Our results show that both socio-economic changes as represented by SSPs and climate change are important in determining N leaching and subsequent N loadings to the sea. For the Norsminde catchment, modelling showed that the reduction of nitrate in the groundwater was affected by the climate models. This meant that the groundwater reduction was reduced with climate scenarios that involved a wetter climate, since water retention time was reduced. 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 leaching N flowing to the sea.

Land use has little effect on runoff and on groundwater retention, as also found in other studies (Molina-Navarro et al., 2018). The main effects of land use change is therefore on the loss of nutrients (in this case N). This is illustrated by the changes in N leaching from the agricultural land that is highly affected by the intensity of land management, in particular the N fertilization rates, but also the use of manure and the efficiency in the use of N in the manure plays a large role. At the catchment scale, also the proportion of land in agriculture is a vital aspect to be considered.

However, our results show that in terms of N loading, scenarios of land use change and management (SSPs) impact N loads at similar levels as climate change. Thus, the N loadings under the sustainability scenario gave similar N leaching and N loads under the projected climate change as those obtained for the baseline conditions under the current climate. 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 a future climate. Therefore, new cropping systems, management methods and technologies need to be implemented to meet targets.

7.4 Comparison with Baltic Sea scale results

Soils2Sea has applied the HYPE model for simulating effect of land use and climate on N loads to the Baltic Sea basin (Bartosova et al., 2018). The results of the HYPE model showed only small effects of climate change on N leaching and loads to the Baltic Sea. This contrasts with the increased N leaching simulated with the Daisy and NLES models in this report. Therefore, results were extracted for the Norsminde catchment from the Baltic HYPE model scenario analyses. These results from HYPE showed an average reduction of 3% in total N loads from Norsminde as consequence of climate change with some variation among climate models (data not shown). This contrasts with the estimated increases of N loadings in the current report of 20-60%. These large differences may have several causes, and the structure of the different models is likely one of them. Such large changes warrant further studies to better quantify the projected changes and their drivers. The SSP scenarios for these two catchments only included changes in agricultural activities and land use.

7.5 Mitigation of N loads

A range of land use and management measures as well as specific technologies can be implemented to reduce N leaching and N loads from agricultural systems (Hashemi et al., 2016). Our study shows that management changes that involved spatial targeting would have similar efficiency under projected climate change as in the current climate. However, given that climate change generally leads to higher N loads, such measures will have to be applied to a greater extent, which tends to reduce the efficiency of spatially targeting (Hashemi et al., 2018).

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Appendix A

Table A1. Soil texture and organic matter content in three main horizons setup to describe the georegion East Denmark. Texture follows Danish soil texture classes.

Soil id	Ge-ol-ogy	Hori-zon	Clay <2μm	Silt 2-63 μm	Fine-sand 63-200 μm	Coarse sand 200-500 μm	Org matter	Bulk density	Max root depth	Drains
			(%)	(%)	(%)	(%)	(%)	(g cm^{-3})	cm	
LS	MS	A	8.5	11.7	47.3	30.1	2.4	1.41	80	Tile
	MS	B	8.8	9.7	42.3	38.2	1.1	1.52		
	MS	C	9.2	9.0	42.8	38.8	0.2	1.73		
LS_L	ML	A	8.5	11.7	47.3	30.1	2.4	1.41	150	Tile
	ML	B	15.7	13.8	42.8	26.7	1.0	1.70		
	ML	C	18.9	13.1	42.3	25.4	0.3	1.67		
LS	DS	A	8.5	11.7	47.3	30.1	2.4	1.38	100	No
	DS	B	7.9	9.0	42.0	40.1	1.0	1.46		
	DS	C	8.2	6.0	44.0	41.5	0.3	1.66		
SL_L	ML	A	12.2	14.5	45.5	25.4	2.4	1.54	150	Tile
	ML	B	15.7	13.8	42.8	26.7	1.0	1.70		
	ML	C	18.9	13.1	42.3	25.4	0.3	1.67		
L	DS	A	17.0	16.6	42.0	21.8	2.6	1.58	150	Tile
	DS	B	15.7	13.8	42.8	26.7	1.0	1.70		
	DS	C	18.9	13.1	42.3	25.4	0.3	1.67		
SL_GWT	FS	1	7.4	7.9	47.8	32.6	4.3	1.320	80	High ground water
	FS	2	8.4	8.0	37.8	42.2	3.6	1.420		
	FS	3	9.3	6.9	34.6	48.1	1.1	1.600		
Org	FT	1	7.5	7.1	32.7	30.9	21.7	0.540	80	High ground water
	FT	2	8.0	7.2	32.9	38.1	13.7	0.540		
	FS	3	9.3	6.9	34.6	48.1	1.1	1.600		

DS = diluvial sand, MS=Moraine sand, ML = Moraine clay, FS=Fresh water sand, L: Loam, LS: Loamy sand, S Sand, Org: Organic

Table A2. Nitrogen fertilisation scheme for each of the crops P1…P10 (pig/plant crop rotation) and C1..C5 (dairy/cattle crop rotation) used in the simulations for Norsminde.

	Baseline			SSP1			SSP2			SSp5		
	Kg N/ha	Kg N/ha	Kg N/ha	Kg N/ha	Kg N/ha	Kg N/ha	Kg N/ha	Kg N/ha	Kg N/ha	Kg N/ha	Kg N/ha	Kg N/ha
Pig and plant	N-rate	Min N	Man N	N-rate	Min N	Man N	N-rate	Min N	Manure N	N-rate	Min N	Manure N
p1	223	126	150	212	156	75	223	118	150	234	99	225
p2	177	102	80	190	137	40	200	121	80	210	115	120
p3	200	148	80	190	160	40	200	144	80	210	138	120
p4	200	155	70	190	164	35	200	151	70	210	147	105
p5	195	156	60	140	100	30	195	153	60	205	151	90
p6	147	78	80	140	93	40	147	74	80	154	82	120
p7	140	91	75	133	105	38	140	88	75	147	80	113
p8	200	122	85	95	40	43	200	118	85	210	111	128
p9	200	135	100	190	153	50	200	130	100	210	120	150
p10	200	135	100	190	153	50	200	130	100	210	120	150
Mean	188	125	88	167	126	44	191	123	88	200	116	132
Perm Grass	75	143	50	71	153	25	75	140	50	79	149	50
Dairy Cattle												
D1	200	149	79	190	160	40	200	145	79	167	1	119
D2	156	107	76	148	103	38	156	103	76	164	95	114
D3	150	36	150	143	69	75	150	28	150	158	23	225
D4	287	222	100	273	235	50	287	217	100	301	211	150
D5	130	22	20	124	21	10	130	21	20	301	283	30
Mean	148	71	85	175	118	43	185	103	85	218	123	128

Table A3. Nitrogen fertilisation scheme for each of the crops P1…P10 (pig/plant crop rotation) and C1..C5 (dairy/cattle crop rotation) used in the simulations for Kocinka.

	SSP1			**SSP2**			**SSP5**		
	Kg N/ha	Kg N/ha	Kg N/ha	Kg N/ha	Kg N/ha	Kg N/ha	Kg N/ha	Kg N/ha	Kg N/ha
Crop rotation	N-rate	Min N	Man N	N-rate	Min N	Man N	N-rate	Min N	Man N
CRP1	0	0	0	0	0	0	0	0	0
Spring wheat	125	119	0	125	125	0	125	131	0
Spring barley	100	95	0	100	100	0	100	105	0
Winter rye	56	29	53	56	70	62	56	32	67
Winter rye	56	29	53	56	70	62	56	32	67
Winter wheat	130	124	0	130	130	0	130	136	0
Mean	93	79	21	93	99	25	93	87	27
Crp2									
Winter barley	100	95	0	100	100	0	100	105	0
Winter barley	100	95	0	100	100	0	100	105	0
Spring barley	100	95	0	100	100	0	100	105	0
Spring barley	100	95	0	100	100	0	100	105	0
Winter triticale	95	90	0	95	95	0	95	99	0
Mean	99	94	0	99	99	0	99	104	0
Crp3									
Winter triticale	95	90	0	95	95	0	95	99	0
Winter rye	106	67	53	106	70	62	106	32	67
Winter triticale	95	90	0	95	95	0	95	99	0
Spring oat	100	95	0	100	100	0	100	105	0
Spring oat	100	95	0	100	100	0	100	105	0
Mean	99	87	11	99	92	12	99	88	13
Crp4									
Spring oat	100	95	0	100	100	0	100	105	0
Spring oat	100	95	0	100	100	0	100	105	0
Spring maize	120	76	53	120	120	62	120	84	67
Spring barley	100	95	0	100	100	0	100	105	0
Winter barley	100	95	0	100	100	0	100	0	0
Mean	104	91	11	104	104	12	104	80	13
Crp5									
Permanent grass	33	0	4	33	0	23	33	0	67
Crp6									
Potato	52	0	107	52	0	124	52	0	134
Crp7									
S beet	46	67	0	46	70	0	46	17	94

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