Catena 226 (2023) 107102

Contents lists available at ScienceDirect

Catena

journal homepage: www.elsevier.com/locate/catena

Estimated nutrient leakage from arable land in different bioeconomy scenarios for two areas in central Sweden, determined using a leaching coefficient method

Kristina Mårtensson *, Holger Johnsson, Katarina Kyllmar

Department of Soil and Environment, Swedish University of Agricultural Sciences, P.O. Box 7014, 750 07 Uppsala, Sweden

ARTICLE INFO

Keywords:
Bioeconomy scenarios
Nitrogen and phosphorus leakage
Leaching coefficients
Mitigation measure

ABSTRACT

Knowledge of future developments in agriculture and how these will affect nutrient leakage from arable land is important in efforts to achieve good ecological status of surface waters. This study assessed the impact of five scenarios for a bioresource-based economy, involving use of renewable biological resources from land and sea, on nitrogen (N) and phosphorus (P) leakage from arable land to surface-waters and groundwater. The scenarios (developed in an earlier study) were applied to two areas in central Sweden, leaching region LR-6 (5350 km^2) and catchment C6 (19 km^2). Using the NLeCCS calculation system to produce leakage coefficients, we evaluated the changes in total N and total P leakage from arable soil. The leakage coefficients described agricultural management practices and climate conditions representing the leaching region LR-6 in Sweden and the baseline year was 2016. The scenarios varied from a baseline in terms of crop combination (relative area of different crops) and extent of mitigation measures (e.g. delayed tillage date, buffer zone width and relative area, and catch crop). Expected consumption of meat varied in the scenarios, with lower consumption meaning fewer cattle and consequently less grass ley. The scenarios was supplemented with calculations of introducing mitigation measures up to their maximum potential.

In leaching region LR-6, calculated baseline leakages was 10.5 kg N ha^{-1} $year^{-1}$ and 0.87 kg P ha^{-1} $year^{-1}$, values that varied in the scenarios by −4% to 5% (N) and −6% to 19% (P). In catchment C6 calculated baseline leakages was 7.1 kg N ha^{-1} $year^{-1}$ and 1.11 kg P ha^{-1} $year^{-1}$, and the values in the scenarios varied by −15% to 2% (N) and −5% to 5% (P). Assuming maximum potential of the mitigation measures decreased leakage further, by up to −19%.

Crop combination had a major impact on total N and P leakage in the scenarios. Leakage increased when the amount of grass ley in the rotation decreased, but remained relatively unchanged when the crop combination change only involved annual crops. Frequency of the mitigation measures increased in all scenarios, with associated decreases in N and P leakage that counteracted the increased leakage caused by changes in crop combination. The most effective mitigation measure was catch crop for N leakage and delayed soil tillage for P leakage.

1. Introduction

Identifying measures that effectively reduce nutrient leakage from agriculture is important in efforts to achieve good ecological status of surface waters. The potential for introducing different mitigation measures varies between regions, depending on e.g., occurrence of surface runoff, soil type, and intensity of agricultural operations. Different future scenarios in agriculture in northern Europe will also affect the potential of mitigation measures. The driving forces for land use and land management scenario designs are environmental and economic factors on global and national scale (Hashemi et al., 2016). In farming system scenarios, changes within a land cover class can be relevant, e.g. changes in the crop combination grown (Chaploti et al., 2004; Demissie et al., 2012; Hesse et al., 2008).

This study was a part of the Biowater project (https://biowater.info/). An important task for the *Biowater* project, has been to develop scenarios that describe various possible pathways for a future bioeconomy (Rakovic et al., 2020). Bioeconomy in this context refers to a

* Corresponding author.
E-mail address: Kristina.martensson@slu.se (K. Mårtensson).

https://doi.org/10.1016/j.catena.2023.107102
Received 12 July 2022; Received in revised form 17 March 2023; Accepted 19 March 2023
Available online 27 March 2023

bioresource-based economy, which includes using renewable biological resources from land and sea, such as crops, forests, animals and micro-organisms, to produce food, materials and energy (European Commission, 2018). These scenarios are intended to serve as support for discussions on viable alternatives for future land use and management. The main goal of *Biowater* is to determine the impacts of the bioeconomy on land use, and on freshwater quality and quantity and specific objectives are to quantify the combined effects of land use change, climate change, and industrial innovation on surface water quality.

Nutrient leakage from arable land to surface waters- and groundwater consists partly of leaching of solutes via water movement through the soil profile and partly of transport of particle-bound nutrients via surface runoff. In this study, we considered combined leaching of nitrogen (N) and phosphorus (P) leaving the root-zone, and P in surface runoff leaving the edge of the field, as measures of leakage.

Total leakage of N and P from agricultural land varies from year to year, due to differences in weather conditions and soil cultivation measures. Comparing leakage in individual years when studying the effect of changes in cultivation measures on annual leakage can therefore be misleading, since the changes between years are largely caused by variations in weather conditions. Considering a normalized climate and normalized runoff is thus a better basis for assessing the importance of cultivation measures for nutrient leakage (Johnsson et al., 2022 Lindsjö et al., 2021). In the Nutrient Leaching Coefficient Calculation System (NLeCCS) (Johnsson et al., 2022), N and P leakage is calculated for a longer period of weather data representing a normal climate, with a multi-year average being used to compute nutrient leakage. The NLeCCS system is based on the mathematical simulation models SOIL/SOILN (Jansson & Halldin, 1980; Jansson, 1991; Johnsson et al., 1987) for N and ICECREAM (Rekolainen & Posch, 1993; Tattari et al., 2001; Larsson et al., 2007; Radcliffe et al., 2015) for P, which are linked to the simulation tools SOILNDB (Johnsson et al., 2002) and ICECREAMDB (Johnsson et al., 2006), respectively. ICECREAM has been expanded to describe Nordic conditions and leaching through the soil via macropores (Rekolainen & Posch, 1993; Posch & Rekolainen, 1993; Tattari et al., 2001; Larsson et al., 2007). The NLeCCS method is used to quantify leakage from agricultural sources in Sweden's national reporting to the HELCOM periodical load compilations, e.g. Pollution Load Compilation 7 (PLC7) (HELCOM, 2022; Hansson et al., 2017) and to support water management work in Sweden. The Helsinki Convention, HELCOM, is an intergovernmental organization bridging policy and science on matters related to the environment of the Baltic Sea. The contracting parties of HELCOM is Denmark, Estonia, the European Union, Finland, Germany, Latvia, Lithuania, Poland, Russia and Sweden. The NLeCCS method has also been used for river basin-scale applications, scenarios for measurements to reduce nutrient leaching and climate change scenarios (Kyllmar et al., 2002, 2005; Larsson et al., 2005; Arheimer et al., 2005; Blombäck et al., 2012). Studies seeking to identify the most cost-effective combination of mitigation measures in catchments have used the related Average Nutrient Leaching Calculator (ANLeC) for calculating e.g. potential effects of measures on N and P leakage (Mårtensson et al., 2020) and the potential effect of a possible ban of glyphosate (Mårtensson et al., 2021).

The objectives of the present study were i) to examine the impact of five scenarios developed in the Biowater project on N and P leakage from arable land in two areas in central Sweden; and ii) to quantify the importance of different agri-environmental measures in reducing nutrient leakage. The five scenarios describe possible future developments depending on different societal preferences that would lead to different decisions e.g. changes in diet. The scenarios include changes in the agricultural system from baseline (year 2016) with respect to crop combination (relative area of different crops) and mitigation measures (delayed tillage date, buffer zones, catch crop).

The scenarios were applied to two areas (the small catchment C6 and Swedish leaching region 6) that have different crop combinations, soil texture, soil slope, and soil P content. Catchment C6 is situated in leaching region 6 and was assumed to have the same climate. Our analysis did not explicitly consider uncertainty in the scenarios, but potential variation was incorporated by allowing the mitigation measures to achieve their maximum potential with the assumed crop combination in each scenario.

2. Materials and methods

2.1. NLeCCS and ANLeC

We computed overall nutrient leakage and the effect of different mitigation measures on N and P leakage from arable land in the two selected areas using the NLeCCS method (Johnsson et al., 2022) and the recently developed ANLeC (Mårtensson et al., 2020) (Fig. 1).

The NLeCCS method calculates standard N and P leakage rates (mg L^{-1} or kg ha^{-1} $year^{-1}$) from arable land (Johnsson et al., 2022), using 30-year climate data series assumed to represent a normal climate. We obtained climate data for the study region (Stockholm meteorological station) covering the period July 1, 1985 – June 30, 2016 from the Swedish Meteorological and Hydrological Institute, SMHI (Persson, 2018). In NLeCCS total N leakage is represented simply as leaching losses from the rootzone of arable soil, while total P leakage is represented as leaching losses from the rootzone and losses with surface runoff. These standard leakage rates have no spatial resolution and can be used for applications in different scales. The model matrix is based on a combination of 22 agricultural leaching regions in Sweden (Fig. 2), 10 soil types, up to 15 crops, and (for P) land slope and soil P content. Different climate conditions and agricultural management characterize the leaching regions. NLeCCS first calculates time-series of leakage using crop sequences with a repeated 30-year climate, and then uses the values obtained to produce normalized average rates of nutrient leakage representing each leaching region (Johnsson et al., 2022).

In the present analysis, the climate series were run 5000 times to produce a sufficient number of outcomes to allow average nutrient leakage rates to be calculated for different crop combinations (a database with 150,000 leakage values per soil texture class and leaching region was produced). The crop sequences in NLeCCS include a number of different measures and timings for different cultivation events, such as type of fertilizer, fertilization level, timing of applying farmyard manure, timing of tillage, etc. (Table 1). Based on this large number of different combinations of crops and cultivation events in the crop sequence under different meteorological conditions, it is possible to calculate normalized average rates of nutrient leakage that can be used to evaluate the effect of different measures. In this study, they were used as input to ANLeC (see below).

The ANLeC method can be used for calculating average leakage of N and P for a certain area and for assessing the effect of introducing different mitigation measures in the area's cultivation systems on the magnitude of leakage. Simulated standard N and P leakage coefficients from NLeCCS are used for the calculations, combined with information on site-specific conditions for crop distribution, soil type distribution, soil P content, land slope, and runoff, and information on the mitigation measures to be assessed (Mårtensson et al., 2020). The input to ANLeC consists of coefficients for crop combinations over two years, because nutrient leakage from a particular crop in a sequence is affected by the following crop (Johnsson et al., 2019; Mårtensson et al., 2020; Mårtensson et al., 2021). For example, large differences in leakage will occur depending on whether an autumn-harvested crop is followed by an undersown grass ley or by a spring-sown crop. The coefficients for different crop combinations are subdivided to account for various cultivation measures, such as different fertilization regimes, catch crops, tillage date, etc. Basing the coefficients on two-year combinations of crops and measures when used as input to ANLeC gives higher resolution than the NLeCCS standard coefficients used for large-scale (national) nutrient load calculations (Mårtensson et al., 2020). Based on these higher-resolution coefficients, the distribution of crops, and the relative

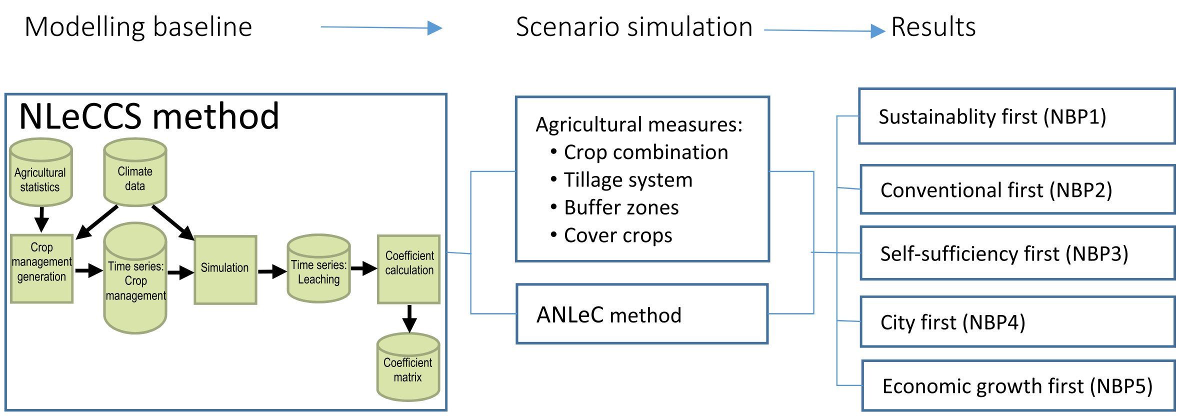

Fig. 1. From baseline with respect to agricultural attributes and assumed mitigation measures (crop, combination, tillage date, buffer zone, catch crop) to Nordic Bioeconomy Pathway (NBP) 1-5. The baseline is calculated with the NLeCCS method, the mitigation measures with the ANLeC method and the results are described per each scenario.

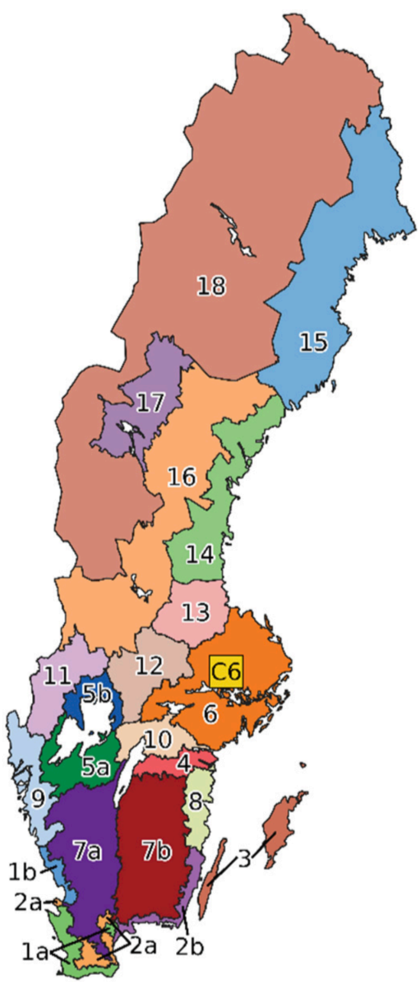

Fig. 2. Map of Sweden showing the leaching regions. The present study included leaching region 6 and catchment C6. The square in leaching region 6 indicating the position of catchment C6 (orange). To maintain confidentiality, the exact position of the catchment is not shown.

Table 1
Example of data included in the crop sequence for leaching region 6, 2016 ().

Crop	Fertilization regime (amount and percentage)	Timing of manure application (season and percentage)	Timing of tillage	Mitigation measures
Spring barley Oats Spring wheat Winter wheat Rye Grass ley Winter rape Spring rape Sugar beets Potatoes Peas and Beans Maize Green fallow Stubble fallow	Mineral fertilizer (e.g., 95 kg N ha^{-1}, 84 %)Farm yard manure with complementary mineral fertilizer (e.g., 36 kg NH_4^+-N ha^{-1}, 48 kg org-N ha^{-1}, 54 kg N ha^{-1}, 16 %)	Autumn (at tillage if autumn tillage or at mean date from statistics) (e.g., Oct 7, 22%)Spring (in conjunction with sowing or at start of vegetation period) (e.g., Apr 30, 88%)	Autumn (soon after harvest if followed by autumn sown crop, at a mean date according to statistics if followed by spring-sown crop, at a specific date, according to rules late autumn if undersown catch crop, e.g., Sep 3 (if followed by autumn sown crop) or Oct 6 (if followed by spring-sown crop), Oct 29 (if catch crop tilled in autumn) Spring (at a mean date according to statistics if spring tillage according to statistics) (e.g., Apr 21)	Buffer zones (e.g., 8.2%)Catch crop (e.g., 1%)

Source: Statistics Sweden, 2017a, 2017b

occurrence of various cultivation measures in a specific area, ANLeC calculates nutrient leakage from arable land in that area. Thus, better precision can be achieved when calculating the leakage from small areas with e.g., crop distribution differing from that in the large regions to which the NLeCCS calculations apply.

In both NLeCCS and ANLeC, P leakage is divided into dissolved-P losses through the soil profile and particulate-P losses from the soil surface, but only total P leakage is reported in this paper.

2.2. Study sites

Leaching region (LR-) 6 in central Sweden (Fig. 2) comprises around 500,000 ha of arable land (2016 data) (Johnsson et al., 2019), which is approximately 20% of Sweden's total area of arable land. Spring and autumn cereals and grass ley dominate the cropping systems in LR-6, while the dominant soil types are silty clay, silty clay loam, and clay loam (Table 2). Mean simulated water discharge from the root-zone for the 30-year period 1985–2015 was 226 mm and mean yearly precipitation was 556 mm. Buffer zones were introduced in LR-6 in 2016 and in this study were assumed to affect 8.2% of its arable land. Catch crops were not commonly implemented in 2016.

Catchment C6, a flat valley with postglacial soil deposits situated within LR-6 (Fig. 2), has 59% arable land (1900 ha) on which mainly winter and spring cereals are grown. In 2016, 4% of the area was fertilized with farmyard manure. The mitigation measures used in C6 are a few buffer zones and catch crops. Approximately 15% of the arable land in C6 was plowed in 2016, with around two-thirds of that area plowed in early autumn and the rest in late autumn (Linefur et al., 2022). Catchment C6 is on average more intensively managed than region LR-6 as a whole and is part of the Swedish Agricultural Monitoring Program, which consists of 21 small agricultural catchments in which stream water quality has been monitored since 1990 (Kyllmar et al., 2014). The program is managed by the Swedish Environmental Protection Agency, with the Swedish University of Agricultural Sciences delegated to carry out the actual monitoring work.

2.3. Nordic bioeconomy pathways

We used the Nordic Bioeconomy Pathways (NBPs) (Rakovic et al., 2020) developed within the *Biowater* project as the basis for establishing five different future scenarios (NBP1-NBP5). Comments on our interpretation of the NPBs and how the different NBPs were adapted to agricultural attributes can be found in Table 3. The agricultural attributes included e.g., cropping system, nutrient loss mitigation measures, and animal husbandry. These agriculture attributes affected the different future scenarios to varying extents. Note that changes in these attributes could affect leakage of N and P in both directions, i.e., increase or decrease.

2.4. Attributes of agricultural field operations

Nine agricultural attributes (Ag1-Ag9) intended to indicate the response of agricultural operations in agricultural fields to different future bioeconomy pathways were established in the *Biowater* project. Four attributes were considered in this study: Diversity of cropping system (Ag1), Conservation efforts in tillage system (Ag2), Implementation of mitigation measures (Ag6), and Implementation of in-field mitigation measures (Ag7).

We interpreted diversity of cropping systems (Ag1) as the number and distribution of crops (*crop combination*) in an area (many crops with equal coverage giving the highest diversity).

As a measure of conservation efforts in tillage systems (Ag2), we assumed a change in *tillage date* to later in autumn if followed by a crop sown in spring, e.g., spring barley, oats, spring wheat, spring oilseed rape, beans, or peas. Tillage was assumed to be delayed to one week after the end of the growing period, which is almost six weeks later than the normal tillage date in autumn. The area available for delayed tillage changed when the crop combination changed, since tillage in late autumn is possible only if the next crop is a spring-sown crop.

As a measure of implementation of mitigation measures (Ag6), we assumed implementation of a *buffer zone*, i.e., a wide grassed strip along

Table 2
Total area (ha), crop type (% of arable area in 2016) and soil texture distribution (% of arable area) in Swedish leaching region LR-6 and in its constituent catchment C6 (Widén-Nilsson et al., 2019). Soil texture classes according to FAO.

		LR- 6	C6
Arable land (ha)		535,000	1946
Crop type on arable land (%)	Cereal	63	67
	Oilseed rape	2	8
	Grass ley	26	10
	Beans and peas	4	5
	Fallow	5	10
Soil texture classes (FAO) on arable land (%)	Sand	0	0
	Loamy sand	2	0
	Sandy loam	3	0
	Loam	9	1
	Silt loam	5	0
	Sandy clay loam	1	0
	Clay loam	16	8
	Silty clay loam	21	7
	Silty clay	40	83
	Clay	4	2

Table 3
Interpretation in the present analysis of the Nordic Bioeconomy Pathways (NBPs) (Rakovic et al., 2020) in relation to baseline and to the chosen agricultural attributes.

NBP	Interpretation in the present analysis
NBP1: Sustainability first	The area of grass ley for fodder production was reduced, due to reduced meat and dairy production and thus reduced numbers of cows. The area of beans and peas for vegetable protein production was increased. The area of fallow in baseline was transformed to grass ley for biogas production instead. The area of other crops (cereals, etc.) was distributed in proportion to their area in the baseline situation, to obtain an unchanged total area of arable land. The area affected by buffer zone and catch crop was increased.
NBP2: Conventional first	Based on trend analysis over recent years, the area of winter cereals was increased in LR-6, spring cereal area was increased in C6, and grass ley area was unchanged in both LR-6 and C6. The area of other crops was distributed in proportion to their area in the baseline situation, to obtain an unchanged total area of arable land.An assumed trend towards delayed tillage was adopted.
NBP3: Self-sufficiency first	The area of grass ley was increased, at the expense of fallow area, due to the increased number of cows required for self-sufficiency. The area of cereals used for fodder (spring barley and oats) was increased due to increased number of pigs. The area of other crops was distributed in proportion to their area in the baseline situation, to obtain an unchanged total area of arable land. A trend for delayed tillage was assumed. Buffer zone width was reduced to increase the area of cultivated land.
NBP4: City first	The area of cash crops such as winter wheat, winter rye, and oilseed rape was increased. The area of grass ley was decreased and the area of fallow was unchanged. The area of other crops was distributed in proportion to their area in the baseline situation, to obtain an unchanged total area of arable land. A trend for delayed tillage was assumed. The area affected by buffer zones and catch crops was increased. Buffer zone width was reduced to increase the area of cultivated land.
NBP5: Economic growth first	The area of cash crops such as winter wheat, winter rye, and oilseed rape was increased. The area of fallow in baseline was used for crop production instead. The area of grass ley was unchanged. The area of other crops was distributed in proportion to their area in the baseline situation, to obtain an unchanged total area of arable land. A trend for delayed tillage was assumed. The area affected by buffer zone and catch crop was increased. Buffer zone width was reduced to increase the area of cultivated land.

the field edge adjacent to open water courses to reduce particulate-P losses via surface runoff. Buffer zone was considered because it was a mitigation measure to reduce P leakage included in the ANLeC-method and it was also subsidized by the Swedish government in 2016. In the case of N leakage, the only effect of buffer zones is that the buffer zone area is covered with grass instead of the regular crop, which can reduce N leaching from this area. The width of the buffer zone was set according to the average width in Sweden (18 m) and the narrowest (6 m) permitted under current regulations (Johnsson et al., 2019). We assumed that buffer zones could be established along the edge of all fields, since we assumed that all fields were connected to a watercourse. A buffer zone was assumed to have no effect on fields with grass ley or fallow. Thus, crop combination affected the potential area of buffer zones. In scenarios NBP1, NBP3, NBP4, and NBP5, the buffer zone measure was targeted at clay soils, where there is greater effect on P leakage (Johnsson et al., 2019).

As a measure of implementation of in-field mitigation measures (Ag7), we assumed introduction of a *catch crop*. Catch or cover crop are used for reducing nutrient leaching, improving soil fertility, and helping control of weeds (Känkänen and Eriksson, 2007). Catch crops grow after the main crop in autumn and they can be either undersown in spring or sown after the harvest of the main crop. Since introduction of a catch crop is only possible when followed by a spring-sown crop, changes to the crop combination affected the potential catch crop area. Catch crop was not included in calculation of P leakage, since its effect on P leakage is uncertain and only partly covered in the model.

Changes to the baseline and NBP1-NBP5 descriptions to reflect changes in agricultural attributes Ag1, Ag2, Ag6, and Ag7 are shown in Table 4. Due to the different crop combination in baseline and the difference in soil texture distribution between LR-6 and C6 (see Table 1), the responses to the NBPs developed differently.

The NBP scenarios were compared with the baseline level, which was set as the standard nutrient leakage for 2016 (Johnsson et al. 2019). The attributes were calculated partly using a subset of 2016 coefficients and partly by making new simulations (for tillage date (Ag2) and buffer zone 6 m (Ag6)), which were performed using the NLeCCS method. The procedure used for calculating the different scenarios is illustrated in Fig. 3.

We also calculated the maximum potential (max) of the calculated mitigation measures, as extension to their full potential in the different NBPs. Since tillage date and catch crop occupy the same position in the crop rotation, they cannot overlap each other and only one of these measures can be implemented at a time. NBP1 included only catch crop, NBP2 and NBP3 included only tillage date, and NBP4 and NBP5 included both tillage date and catch crop but not on the same fields. Thus in NBP4 max and NBP5 max no further implementation of either tillage date or catch crop was possible, since those measures were already used to their full potential. The maximum implementation of buffer zone involved 18-m wide buffer zones on all soil types in all NPB max. The same crop combination as used in calculation of NBP1-NBP5 was used in the NBP1-NBP5 max calculations (of maximum potential of mitigation measures).

Crop combination can be described on a scale from less grass ley-more cereals to more grass ley-less cereal compared with baseline (y-axis in Fig. 3). NBP1 and NBP3 displayed the greatest differences in crop combination compared with baseline. NBP1 had less grass ley due to the assumption of lower consumption of meat and dairy products, while NBP3 had more grass ley due to the assumed increase in self-sufficiency in meat and dairy products. Lack of change on the grass ley-cereal scale did not necessarily mean that there was no change in crop combination, since e.g., the area of spring barley was changed to winter wheat in NBP4 and NBP5. The proportion of mitigation measures adopted is shown on the x-axis in Fig. 3. All five scenarios involved more mitigation measures than baseline, with NBP1, NBP4, and NBP5 having the greatest degree of implementation of mitigation measures.

3. Results

Catchment C6 had higher P leakage than the surrounding region (LR-6), but lower N leakage in both baseline and all NBPs (Table 5 and Table 6). This was caused by differences in soil texture, with the loamier soil types in LR-6 giving higher N and lower P leaching than the more clayey soils in C6.

The differences between the modeled results for baseline and the scenarios were significant. The magnitude of uncertainty was similar in the different calculated values since the same coefficients were included in the calculations. In modeling the coefficients with NLeCCS, uncertainties concerning input data, assumptions, and parameters were included.

3.1. Nitrogen

In baseline, N leaching leakage was 10.5 kg ha^{-1} $year^{-1}$ with a 95%-confidence interval of ± 0.1 kg ha^{-1} $year^{-1}$ in LR-6 and 7.1 kg ha^{-1} $year^{-1}$ with a 95%-confidence interval of ± 0.07 kg ha^{-1} $year^{-1}$ in C6. In LR-6, there were practically no changes in N leakage in NBP1 and NBP5 (±1%) compared with baseline, whereas N leakage increased in NBP4 (4%) and decreased in NBP2 (-4%) and NBP3 (-5%) (Table 5). In C6, there was a small increase in N leakage in NBP2 (2%) compared with baseline, while there was a marked decrease (-15% to −6%) in N leakage in the other NBPs.

Gross changes in N leakage due to implementation of different proportions of agricultural attributes are shown in Fig. 4. A change in crop combination caused both increases and decreases in N leakage in the different scenarios, while introduction of the mitigation measures only caused decreases. In LR-6, no net change occurred in NBP1 as the attributes caused large, but counteracting, changes. Crop combination caused a large increase in N leakage, while buffer zones and catch crops caused a decrease. The crop combination in NBP1 was changed to more grain and less grass ley compared with baseline, as the number of cows was expected to decrease, and that caused an increase in N leakage.

When the maximum potential of mitigation measures (max) was assumed to be implemented, a decrease in N leakage occurred in all scenarios (Fig. 4, bars in brighter color). In LR-6 max, NBP1-NBP3 gave a considerable decrease due to the major potential for further implementation of the mitigation measures in those scenarios. Due to the large increase in winter-sown crops (winter wheat, winter oilseed rape and winter rye) in NBP4 and NBP5 compared with baseline and the other NBPs, the potential for increasing the area with delayed tillage date was small. Consequently, the decrease in N leakage was small. In C6 max, all the NBPs gave a considerable decrease due to the potential for further implementation of catch crop (NBP1), later tillage date (NBP2 and NBP3), and buffer zone (NBP4 and NBP5).

3.2. Phosphorus

In baseline, P leakage was 0.87 kg ha^{-1} and 1.11 kg ha^{-1} with a 95%-confidence interval of ± 0.009 kg ha^{-1} $year^{-1}$ and ± 0.011 kg ha^{-1} $year^{-1}$ in LR-6 and C6, respectively (Table 6). In both LR-6 and C6, scenario NBP1 had higher P leakage than baseline (19% and 5%, respectively). NBP3 and NBP5 showed a decrease, of −3 % and −6 % in LR-6 and −5% and –2% in C6. In NBP4, LR-6 showed an increase (3%), and C6 a decrease (-3%). NBP2 showed leakage that was lower or of the same order of magnitude as in baseline (-2% in LR-6 and 0% in C6) (Table 6). The change in crop combination from grass ley to annual crops in NBP1 caused substantial increases in P leakage in both LR-6 and C6 (Fig. 5). In LR-6 the changed crop combination caused a decrease in NBP2, NBP3, and NBP5 and an increase in NBP4. In C6 the changed crop combination caused an increase in NBP2 and NBP5 and a decrease in NBP3 and NBP5 (Fig. 5). Implementation of delayed tillage date and buffer zone decreased the P leakage in both LR-6 and C6 in NBP2-NBP5. In NBP1 buffer zone caused a decrease in both LR-6 and C6. Delayed

Table 4
Details of the agricultural (Ag) attributes crop combination, tillage date, buffer zone, and catch crop assumed for baseline and for Nordic Bioeconomy Pathways (NBP) 1–5 in Swedish leaching region (LR-) 6 and catchment C6.

NBP	Attributes					
	Crop combination (Diversity of cropping system, Ag1) Crop (%)	LR-6	C6	*Tillage date* (Conservation effort in tillage system, Ag2) (tillage date, available arable land)	*Buffer zone* (Implementation of mitigation measures, Ag6) (available arable land affected by buffer zone)	*Catch crop* (Implementation of in-field mitigation measures, Ag7) (available arable land)
Baseline	Spring barley	21	26	Oct 6	8.2% (LR-6) and 1.2% (C6) Buffer zone width 18 *m*	1 %
	Winter wheat	21	18			
	Grass ley	26	10			
	Winter oilseed rape	2	4			
	Fallow	5	10			
	Oats	11	13			
	Spring wheat	8	10			
	Winter rye	2	1			
	Beans and peas	4	5			
	Spring oilseed rape	0	4			
NBP1	Spring barley	27	26	No impact on tillage date.	75% not on sand, loamy sand or sandy loam. Buffer zone width 18 *m*	75%
	Winter wheat	27	18			
	Grass ley	5	10			
	Winter oilseed rape	3	4			
	Fallow	0	0			
	Oats	14	13			
	Spring wheat	10	10			
	Winter rye	3	1			
	Beans and peas	12	15			
	Spring oilseed rape	0	4			
NBP2	Spring barley	19	32	Nov 15, 25%	8.2% (LR-6), 1.2% (C6) Buffer zone width 18 m.	1%
	Winter wheat	25	14			
	Grass ley	26	10			
	Winter oilseed rape	2	3			
	Fallow	5	8			
	Oats	10	16			
	Spring wheat	7	12			
	Winter rye	2	1			
	Beans and peas	3	4			
	Spring oilseed rape	0	0			
NBP3	Spring barley	25	31	Nov 15, 50%	8.2% (LR-6), 1.2% (C6) on Silty Clay loam, silty clay and clay Buffer zone width 6 m.	1 %
	Winter wheat	17	15			
	Grass ley	31	20			
	Winter oilseed rape	2	3			
	Fallow	0	0			
	Oats	13	15			
	Spring wheat	7	8			
	Winter rye	2	1			
	Beans and peas	3	4			
	Spring oilseed rape	0	3			
NBP4	Spring barley	11	15	Nov 15, 50%	50% not on sand, loamy sand or sandy loam. Buffer zone width 6 m.	50%
	Winter wheat	42	36			
	Grass ley	13	6			
	Winter oilseed rape	14	7			
	Fallow	5	10			
	Oats	6	8			
	Spring wheat	4	6			
	Winter rye	4	2			
	Beans and peas	2	3			
	Spring oilseed rape	0	7			
NBP5	Spring barley	7	18	Nov 15, 50%	50% not on sand, loamy sand or sandy loam. Buffer zone width 6 m.	50%
	Winter wheat	42	36			
	Grass ley	26	10			
	Winter oilseed rape	14	7			
	Fallow	0	0			
	Oats	4	9			
	Spring wheat	3	7			

(*continued on next page*)

Table 4 (*continued*)

NBP	Attributes		
	Winter rye	4	2
	Beans and peas	1	3
	Spring oilseed rape	0	7

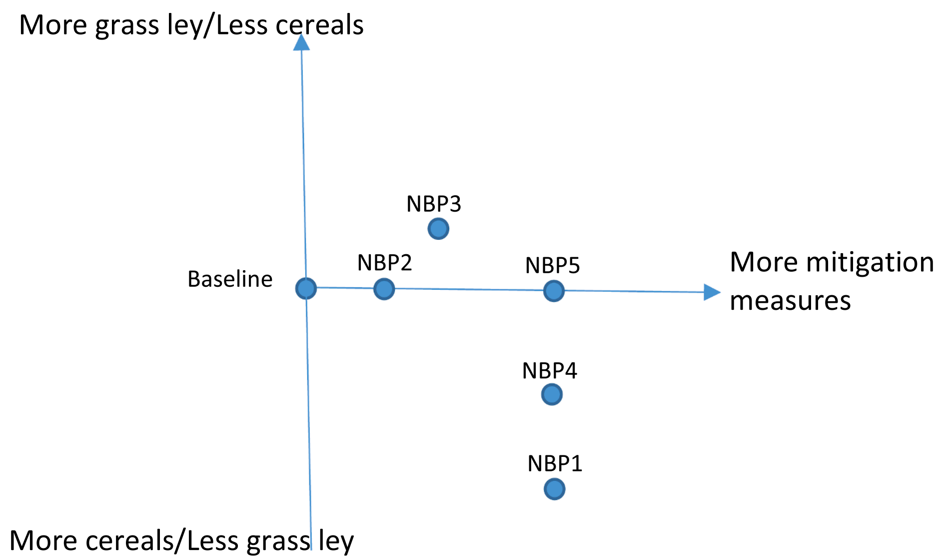

Fig. 3. Changes in Nordic Bioeconomy Pathways (NBP) 1-5 from baseline with respect to crop combination and other assumed mitigation measures (tillage date, buffer zones, catch crop).

Table 5
Leakage of N in baseline (BL), Nordic Bioeconomy Pathways (NBP) 1–5 and maximum use of mitigation measures (max) in Swedish leaching region 6 (LR-6) and catchment C6 (kg ha^{-1} year^{-1}). Figures in brackets show the percentage change from baseline.

	LR-6		LR-6 max		C6		C6 max	
BL	10.5				7.1			
NBP1	10.6	(+1%)	9.7	(-7%)	6.1	(-15%)	5.6	(–22%)
NBP2	10.0	(-4%)	8.5	(-18%)	7.3	(+2%)	6.0	(-16%)
NBP3	9.9	(-5%)	8.7	(-17%)	6.7	(-6%)	5.4	(-25%)
NBP4	10.8	(+4%)	10.2	(-3%)	6.1	(-15%)	5.4	(-24%)
NBP5	10.4	(-1%)	9.8	(-6%)	6.3	(-12%)	5.6	(–22%)

Table 6
Leakage of P in baseline (BL), Nordic Bioeconomy Pathways (NBP) 1–5 and maximum use of mitigation measures (max) in Swedish leaching region 6 (LR-6) and catchment C6 (kg ha^{-1} year^{-1}). Figures in brackets show the percentage change from baseline.

	LR-6		LR-6 max		C6		C6 max	
BL	0.87				1.11			
NBP1	1.03	(+19%)	1.03	(+18%)	1.16	(+5%)	1.16	(+4%)
NBP2	0.85	(-2%)	0.82	(-6%)	1.11	(0%)	1.05	(-5%)
NBP3	0.84	(-3%)	0.81	(-7%)	1.05	(-5%)	1.02	(-8%)
NBP4	0.89	(+3%)	0.89	(+2%)	1.08	(-3%)	1.07	(-3%)
NBP5	0.82	(-6%)	0.82	(-6%)	1.09	(-2%)	1.08	(-2%)

tillage date was more effective mitigation measure than implementing buffer zone (Fig. 5). When the maximum potential of mitigation measures was implemented (LR-6 max and C6 max), P leakage was further reduced, mainly due to the delayed tillage date.

When the maximum potential of mitigation measures (max) was assumed to be implemented, a further decrease in P leakage occurred in NBP2 and NBP3 compared to the scenario calculation for LR-6 and C6, respectively (Fig. 5, bars in brighter color). In NBP1, NBP4, and NBP5 no or only a small decrease compared to the scenario calculation was found for LR-6 and C6, respectively.

4. Discussion

A previous modeling study (using the SWAT model) of a Danish catchment with scenarios comparable those in Biowater found that the N load decreased in agricultural scenarios called *High-tech agriculture (HT)* and *Agriculture for nature (AN)*, and increased in a *Market-driven agriculture (MD) scenario* (Molina-Navarro et al., 2018). In NBP5 in the present study (comparable with HT), N leakage decreased in LR-6 and C6. In NBP2 (comparable to AN), N leakage decreased in LR-6, increased slightly in C6. MD had no corresponding NBP in our study. Molina-

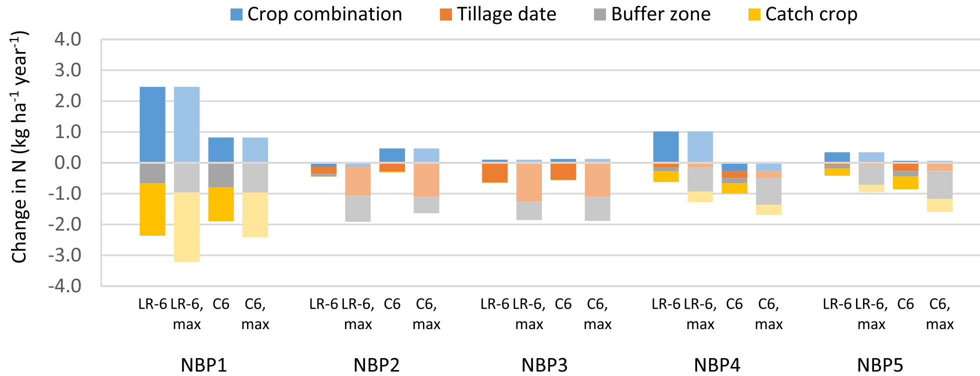

Fig. 4. Changes in N leakage (kg ha^{-1} year^{-1}) compared with baseline and assumed mitigation measures (crop combination, tillage date, buffer zone, catch crop) in Nordic Bioeconomy Pathways (NBP) 1-5 in Swedish leaching region 6 (LR-6) and catchment C6, as average and with maximum implementation of mitigation measures (max, in brighter color).

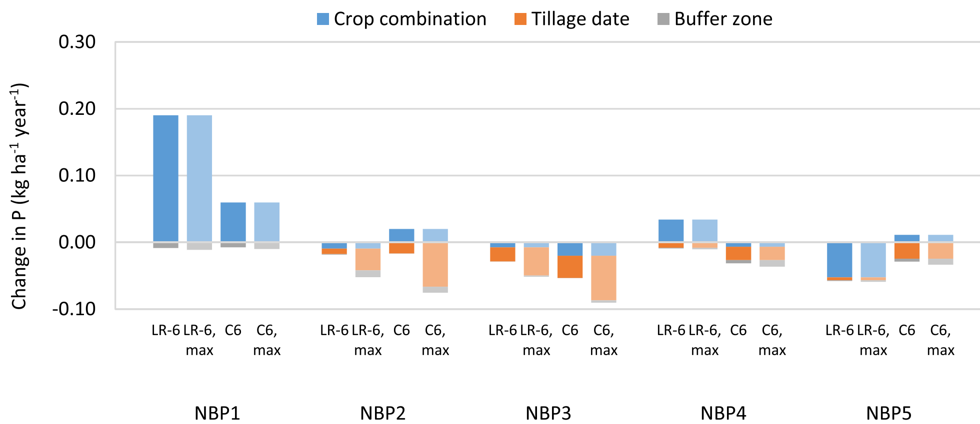

Fig. 5. Changes in P leakage (kg ha^{-1} year^{-1}) compared with baseline and assumed mitigation measures (crop combination, tillage date, buffer zone) in Nordic Bioeconomy Pathways (NBP) 1-5 in Swedish leaching region 6 (LR-6) and catchment C6, as average and with maximum implementation of mitigation measures (max, in brighter color).

Navarro et al. (2018) found that fertilization was the main factor responsible for nitrate (NO_3^-) loads in the catchment when modeled with SWAT. A change of the level of mineral fertilizer was not taken into account in our study since the expected change in harvest with a different mineral fertilizer level was unknown. The yield response is needed in the NLeCCS method. In the study by Molina-Navarro et al. (2018), the P load showed less variation and increased in all calculated scenarios. P leakage did not decrease in the same way as N in that study, since P is not lost directly from fertilizer application but from the soil P pool. In our study, we found unchanged P leakage in the corresponding scenarios, or a decrease caused by changed crop combinations and mitigation measures. Rashid et al. (2022) compared 20 different crop rotations with respect to N leaching and found that it varied from 16 to 85 kg N ha^{-1} year^{-1}, with crop rotations with a high proportion of spring crops without a subsequent catch crop resulting in higher leaching than crop rotations with winter wheat and grass-clover ley. In a study in southwest France, Ferrant et al. (2013) found that if both catch crop and buffer strips were implemented, N leakage to water decreased by 18%. In a study in the Latvian catchment Berze introduction of crop rotation increased the N load by 0.05–0.06 kg N ha^{-1}, whereas no effect was found for P (Carolus et al., 2020). However, the effectiveness of measures was found to vary greatly in Carolus et al (2020), reflecting different levels of implementation (e.g., scope and intensity) and differences in local conditions (e.g., climate, soil and slope gradient). In our study, we also found the crop combination (e.g., presence of ley), catch crop and buffer zones important when determining the N and P leakage.

Timing and technique of soil tillage are considered as important measures to control N and P losses in arable systems. No-till have been proven to decrease P losses compared with autumn plowing on a clay soil (Uusitalo et al., 2018). Delayed tillage after spring cereals to late autumn or spring has been shown to be a measure to reduce N leakage in sandy and loamy soils (Stenberg et al., 1999; Mitchell et al., 2000) whereas the effect on clay soils was small according to Myrbeck et al. (2014). Rankinen et al. (2021) found in a modelling study, where autumn ploughing was replaced by no-till methods, a decrease in total P and nitrate compared to only autumn ploughing. In our study, we introduced delayed soil tillage on 50% of the possible area in NBP3-NBP5 and that reduced both the N and P leakage.

The most important factor influencing nutrient leakage from soil in the present study was crop combination, which on a general level is a result of production conditions (climate, soil texture, etc.), agricultural specialization, and market demand. Thus depending on future developments in climate and in agriculture, the future crop combination will change. The five NBPs studied here involved future development towards increased food production in one way or another, either with increased /production of peas and beans or increased animal production. The crop combination in almost all NBPs was assumed to have less fallow and grass ley than baseline (see Table 4), which increased nutrient leakage. To decrease nutrient leakage from agricultural soil, the crop combination needs to include more grass ley or fallow compared with baseline. The differences in leakage between different crops were not as high for P as for N, confirming previous findings by Johnsson et al. (2019). Hence, the crop combination effect was stronger for N leakage than for P leakage.

The crop distribution in NBP1 was changed to more grain and less grass ley compared with baseline, as the number of cows was expected to decrease. This caused an increase in both P and N leakage. Implementation of mitigation measures counteracted some, but not all, of the increased leakage caused by the change in crop combination. In this context, it is important to consider other sustainable solutions for retaining grass ley in the crop rotation. These include, e.g., growing grass as a source of biomass to produce high-quality protein for monogastric animals (Jørgensen et al., 2021) or to produce biogas for fuel or heating (Bedoić et al., 2019, Rodriguez et al., 2017).

Not all possible mitigation measures were used in the NBP scenarios, e.g., in NBP2 delayed tillage date was implemented on 25% of the possible area. It is unlikely that mitigation measures could be implemented on all possible occasions and sites as assumed in NBP max, but it is likely that implementation can be increased in LR-6 and C6 compared with the baseline. Our results were highly dependent on the extent of mitigation measures implemented, as demonstrated by the estimated max values.

5. Conclusions

The different bioeconomy scenarios allow for many interpretations, and the interpretations applied have a major influence on the results, e.g. a scenario including less meat consumption can in another context than central Sweden lead to another development than less growing of ley. Many factors are dependent on each other and many assumptions have to be made. In the present analysis, crop combination had a greater influence on N and P leakage than mitigation measures. Even if future scenarios are well described and the direction of development is clear, crop combination is dependent on many factors, e.g., farm specialization, market demand, cost of input mean, climate change, and weather variations.

Crop combination is thus more difficult to predict than the extent of mitigation measures, since it is the outcome of a complex balance of decisions on local and national scale. The extent of mitigation measures is also dependent on local and national conditions but much more dependent on the support system. The acreage of grass ley was the most important factor when determining overall leakage losses in this study. The most effective mitigation measure for N leakage was catch crop, while for P leakage it was delayed soil tillage.

There was uncertainty in the scenarios on the extent of the mitigation measures. The values we obtained for the maximum effect of the mitigation measures show that there is further reduction potential of these measures in future bioeconomy scenarios.

Declaration of Competing Interest

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

Data availability

Data will be made available on request.

Acknowledgements

This study was part of the Nordic Centre of Excellence BIOWATER project funded by Nordforsk (Project number 82263).

References

Arheimer, B., Andreasson, J., Fogelberg, S., Johnsson, H., Pers, C., Persson, K., 2005. Climate change impact on water quality: model results from southern Sweden. Ambio 34, 559–566.

Bedoić, R., Čuček, L., Ćosić, B., Krajnc, D., Smoljanić, G., Kravanja, Z., Ljubas, D., Pukšec, T., Duić, N., 2019. Green biomass to biogas – A study on anaerobic digestion of residue grass. J. Clean. Product. 213, 700-709. ISSN 0959-6526.

Blombäck, K., Börgesen, C.D., Eckersten, H., Gielczewski, M., Piniewski, M., Sundin, S., Tattari, S., Väisänen, S., 2012. Productive agriculture adapted to reduced nutrient losses in future climate – Model and stakeholder based scenarios of Baltic Sea catchments. Baltic Compass report.

Carolus, J.F., Bartosova, A., Olsen, S.B., Jomaa, S., Veinbergs, A., Zīlāns, A., Pedersen, S. M., Schwarz, G., Rode, M., Tonderski, K., 2020. Nutrient mitigation under the impact of climate and land-use changes: a hydro-economic approach to participatory catchment management. J. Environ. Manage. 271, 110976.

Chaploti, V., Saleh, A., Jaynes, D.B., Arnold, J., 2004. Predicting water, sediment and NO_3-N under scenarios of land-use and management practices in a flat watershed. Water Air Soil Pollut. 154, 271–293.

Demissie, Y., Yan, E., Wu, M., 2012. Assessing regional hydrology and water quality implications of large-scale biofuel feedstock production in the Upper Mississippi river basin. Environ. Sci. Tech. 46, 9174–9182.

European Commission, Directorate-General for Research and Innovation. 2018. A sustainable bioeconomy for Europe: strengthening the connection between economy, society and the environment: updated bioeconomy strategy. Publications Office, 2018.

Ferrant, S., Durand, P., Justes, E., Probst, J.L., Sanchez-Perez, J.M., 2013. Simulating the long term impact of nitrate mitigation scenarios in a pilot study basin. Agric Water Manage 124, 85–96.

Hansson, K., Ejhed, H., Widén-Nilsson, E., Johnsson, H., Tengdelius Brunell, J., Gustavsson, H., Hytteborn, J., Åkerblom, S., 2017. Näringsbelastningen på Östersjön och Västerhavet 2017 Sveriges underlag till HELCOM:s sjunde Pollution Load Compilation. Havs- och vattenmyndighetens rapport 2019, 20 in Swedish.

Hashemi, F., Olesen, J., Dalgaard, T., Børgesen, C., 2016. Review of scenario analyses to reduce agricultural nitrogen and phosphorus loading to the aquatic environment. Sci. Total Environ. 573, 608–626.

HELCOM, 2022. Pollution load on the Baltic Sea. Summary of the HELCOM Seventh Pollution LoadCompilation (PLC-7).

Hesse, C., Krysanova, V., Päzolt, J., Hattermann, F.F., 2008. Eco-hydrological modelling in a highly regulated lowland catchment to find measures for improving water quality. Ecol. Model. 218, 135–148.

Jansson, P.-E., Halldin, S., 1980. Model for annual water and energy flow in a layered soil. In: Comparison of Forest Water and Energy Exchange Models. International Society for Ecological Modelling, Copenhagen, pp. 145–163.

Jansson, P.-E., 1991. Simulation model for soil water and heat conditions. Description of the SOIL model. Report 165, Department of Soil Sciences, Division of Biogeophysics, SLU, P.O. Box 7014, SE-75007, Uppsala, Sweden. 72 pp.

Johnsson, H., Bergström, L., Jansson, P.-E., Paustian, K., 1987. Simulated nitrogen dynamics and losses in a layered agricultural soil. Agricult. Ecosyst. Environ. 18, 333–356.

Johnsson, H., Larsson, M., Brandt, M., Pers, L., Rosberg, J., 2006. Framtagning av nytt fosforberäkningssätt för beräkningssystem för diffus belastning, retention och tillförsel till havet för PLC5 rapporteringen 2007. SMED Rapport Nr 16, 2006 in Swedish.

Johnsson, H., Larsson, M., Mårtensson, K., Hoffmann, M., 2002. SOILNDB: A decision support tool for assessing nitrogen leaching losses from arable land. Environ. Model. Softw. 17, 505–517.

Johnsson, H., Mårtensson, K., Lindsjö, A., Persson, K., Andrist Rangel, Y., Blombäck, K., 2019. Läckage av näringsämnen från svensk åkermark Beräkningar av normalläckage av kväve och fosfor för 2016. SMED Rapport Nr 5, 2019 in Swedish.

Johnsson, H., Mårtensson, K., Lindsjö, A., Persson, K., Blombäck, K., 2022. NLeCCS - a system for calculating nutrient leakage from arable land. Sveriges lantbruksuniversitet, Ekohydrologi, p. 177.

Jørgensen U., Kristensen T., Jørgensen J.R., Kongsted A.G., De Notaris C., Nielsen C., Mortensen E.Ø., Ambye-Jensen M., Jensen S.K., Stødkilde-Jørgensen L., Dalsgaard T. K., Møller A.H., Sørensen C.G., Asp T., Olsen F.L., Gylling M., 2021. Green biorefining of grassland biomass. 121 pp. Advisory report from DCA – Danish Centre for Food and Agriculture, Aarhus Universitet. DCA report NO. 193 2021.

Kyllmar, K., Johnsson, H. & Mårtensson, K. 2002. Metod för bestämning av jordbrukets kvävebelastning i mindre avrinningsområden samt effekter av läckagereducerande åtgärder- Redovisning av projektet "gröna fält och blåa hav". Ekohydrologi 70, Uppsala. (in Swedish).

Kyllmar, K., Mårtensson, K., Johnsson, H., 2005. Model-based coefficient method for calculation of N leaching from agricultural fields applied to small catchments and the effect of leaching reducing measures. J. Hydrol. 304, 343–354.

Kyllmar, K., Stjernman L., Forsberg, Andersson, S., Mårtensson, K., 2014. Small agricultural monitoring catchments in Sweden representing environmental impact. Agric. Ecosyst. Environ. 198, 25-35.

Känkänen and Eriksson, 2007. Effects of undersown crops on soil mineral N and grain yield of spring barley. Eur. J. Agron. 27 (1), 25–34.

Larsson, M., Kyllmar, K., Jonasson, L., Johnsson, H., 2005. Estimating reduction of nitrogen leaching from arable land and the related costs. Ambio 34, 538–543.

Larsson, M., Persson, K., Ulén, B., Lindsjö, A., Jarvis, N.J., 2007. A dual porosity model to quantify phosphorus losses from macroporous soils. Ecol. Model. 205, 123–134.

Lindsjö, A., Mårtensson, K., Persson, K., Widén-Nilsson, E., Blombäck K. & Johnsson, H. 2021. Effekt av normaliseringsperiod för avrinning med avseende på koncentrationerna av jordbruksläckaget SMED Rapport Nr 32 2021 (in Swedish).

Linefur, H., Norberg, L., Kyllmar, K., Andersson, S., Blomberg, M., 2022. Växtnäringsförluster i små jordbruksdominerade avrinningsområden 2020/2021: årsredovisning för miljöövervakningsprogrammet Typområden på jordbruksmark. Sveriges lantbruksuniversitet, Ekohydrologi, p. 175.

Mitchell, R.D.J., Harrison, R., Russell, K.J., Webb, J., 2000. The effect of crop residue incorporation date on soil inorganic nitrogen, nitrate leaching and nitrogen mineralization. Biol. Fertil. Soils 32, 294–301.
Molina-Navarro, E., Andersen, H.E., Nielsen, A., Thodsen, H., Trolle, D., 2018. Quantifying the combined effects of land use and climate changes on stream flow and nutrient loads: a modelling approach in the Odense Fjord catchment (Denmark). Sci. Total Environ. 621, 253–264.
Myrbeck, Å., Arvidsson, J., Keller, T., 2014. 2014 Effect of time of autumn primary tillage on soil structure, grain yield and risk of nitrogen leaching in two Swedish clay soils. Acta Agriculturae Scandinavica, Section B-Soil & Plant Science 64 (1), 33–44.
Mårtensson, K., Johnsson, H., Collentine, D., Kyllmar, K., Persson, K., Djodjic, F. & Lindsjö, A., 2020. Åtgärdsscenarier för minskat näringsläckage från åkermark : beräkningar för ett urval av delavinningsområden inom LEVA-områden. Sveriges lantbruksuniversitet. Ekohydrologi 169. (in Swedish).
Mårtensson, K., Lindsjö, A., Persson, K., Blombäck, K. and Johnsson, H., 2021. Beräkning av effekten av ett eventuellt förbud mot växtskyddsmedlet glyfosat på läckaget av växtnäring från åkermark i Sverige. Dept. of Soil and Environment, Sveriges lantbruksuniversitet. Ekohydrologi; 173 (in Swedish).
Persson, K., 2018. Klimatdatabasen version PLC7. Teknisk dokumentation. Dept. of Soil and Environment, Sveriges lantbruksuniversitet. (in Swedish).
Posch, M., Rekolainen, S., 1993. Erosivity factor in the Universal Soil Loss Equation estimated from Finnish rainfall data. Agric. Sci. Finland 2, 271–279.
Radcliffe, D.E., Reid, D.K., Blombäck, K., Bolster, C.H., Collick, A.S., Easton, Z.M., Francesconi, W., Fuka, D.R., Johnsson, H., King, K., Larsbo, M., Youssef, M.A., Mulkey, A.S., Nelson, N.O., Persson, K., Ramirez-Avila, J.J., Schmieder, F., & Smith, D.R., 2015. Applicability of models to predict phosphorus losses in drained fields: A review. Journal of Environmental Quality 2015 Vol.44 No.2 pp.614-628.
Rakovic, J., Futter, M.N., Kyllmar, K., Rankinen, K., Stutter, M.I., Vermaat, J., Collentine, D., 2020. Nordic Bioeconomy Pathways: Future narratives for assessment of water-related ecosystem services in agricultural and forest management. Ambio 49 (11), 1710–1721.
Rankinen, K., Turtola, E., Lemola, R., Futter, M., Cano Bernal, J.E., 2021. Nutrient load mitigation with wintertime cover as estimated by the INCA model. Water 2021 (13), 450.
Rashid, M.A., Bruun, S., Styczen, M.E., Ørum, J.E., Kynding Borgen, S., Kaag, T.I., Stoumann Jensen, L., 2022. Scenario analysis using the Daisy model to assess and mitigate nitrate leaching from complex agro-environmental settings in Denmark. Sci. Total Environ. 816, 151518.
Rekolainen, S., Posch, M., 1993. Adapting the CREAMS model for Finnish conditions. Nordic Hydrol. 24, 309–322.
Rodriguez, C., Alaswad, A., Benyounis, K.Y., Olabi, A.G., 2017. Pretreatment techniques used in biogas production from grass. Renew. Sustain. Energy Rev. 68 (2), 1193–1204.
Statistics Sweden, 2017a. Odlingsåtgärder i jordbruket 2016 Träda, slåttervall, jordbearbetning, fånggrödor samt spridning av kalk på åkermark. Statistiska meddelanden. MI 30 SM 1703 (in Swedish.
Statistics Sweden, 2017b. Gödselmedel i jordbruket 2015/2016. Mineral- och stallgödsel till olika grödor samt hantering och lagring av stallgödsel. Statistiska meddelanden. MI 30 SM 1702 (in Swedish.
Stenberg, M., Aronsson, H., Lindén, B., Rydberg, T., Gustafsson, A., 1999. Soil mineral nitrogen and nitrateleaching losses in soil tillage systems combined with a catch crop. Soil Till Res. 50, 115–125.
Tattari, S., Bärlund, I., Rekolainen, S., Posch, M., Siimes, K., Tuhkanen, H.-R., Yli-Halla, M., 2001. Modelling sediment yield and phosphorus transport in Finnish clayey soils. Trans. ASAE 44, 297–307.
Uusitalo, R., Lemola, R., Turtola, E., 2018. Surface and Subsurface Phosphorus Discharge from a Clay Soil in a Nine-Year Study Comparing No-Till and Plowing. J. Environ. Qual. Vol. 47 (6), 1305–1572.
Widén-Nilsson, E., Djodjic, F., Hellgren, S., Hellsten, S., Olshammar, M., Sandström, S., Tengdelius Brunell, J., 2019. Kartdata till PLC7. Underlagsrapport till Pollution Load Compilation 7 rörande markanvändning, vattenförekomstområden, regionindelning, jordbruksmarkens jordart, lutning och fosforhalt samt medelvärdesberäkningar. SMED Rapport Nr 7 2019 (in Swedish).