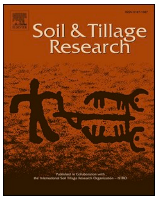
Soil & Tillage Research 250 (2025) 106515

Contents lists available at ScienceDirect

Soil & Tillage Research

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



Conventional and reduced tillage, and set-aside land – Effects on nitrogen, phosphorus and potassium subsurface leaching from a clay soil during 9 years

Lisbet Norberg *, Helena Aronsson

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

ARTICLE INFO

Keywords:
Clay soil
Green fallow
Mouldboard ploughing
NO_3-N
Nutrient leaching
PO_4-P
Tile drains

ABSTRACT

This study investigated the effect of two different autumn tillage intensities, and a permanent green fallow, on subsurface nutrient leaching losses during nine years, with the overall aim to evaluate strategies for reduced nutrient load from arable land. The main hypotheses were that crop production results in larger leaching losses of nitrogen (N), phosphorus (P) and potassium (K) than a green fallow, and that reduced tillage (RT) is a measure for reduced N leaching without reduction of grain yields compared to conventional tillage (CT). The field site was a clay soil (47 % clay, Uderic Haploboroll) in south-west Sweden and the field experiment was equipped with separately tile-drained plots to record the subsurface drainage water flow. The water was analyzed for total N, nitrate-N, total P, phosphate-P and K. Grain yields of main crops and contents of soil mineral N were also determined. Long-term average and most annual means show no significant impact of tillage system, concerning N, P and K leaching losses or yields of main crops. There were indications of higher N leaching using CT compared to RT. Average leaching losses were 3.9 kg N ha^{-1} yr^{-1}, 0.4 kg P ha^{-1} yr^{-1} and 6.5 kg K ha^{-1} yr^{-1} from the tilled plots. In 9-year average, the permanent green fallow reduced the soil mineral N content in autumn and decreased the transport of nitrate-N in drainage water compared to both tillage systems. However, green fallow could not be considered a mitigation option for P and K leaching losses.

1. Introduction

Cropping systems with reduced tillage or no-till are considered to have several advantages over conventional mouldboard ploughing systems. Such advantages include being more cost-effective, especially since less requirement of fuel and labor can compensate for similar or lightly lower yields than in conventional ploughed systems, as was presented in a Scandinavian review (Rasmussen, 1999). Moreover, systems with reduced tillage or no-till provide a protection from soil erosion (Schoumans et al., 2014), an increased abundance of earthworms (Briones and Schmidt, 2017), and a build-up of soil organic carbon in the upper topsoil layers (Luo et al., 2010, Ogle et al., 2019). This is because traditional mouldboard ploughing, referred to as conventional tillage (CT) in this study, involves soil inversion to approximately 20 cm depth whilst reduced tillage (RT) is non-inversive with a tillage depth of 5–10 cm and keeps the soil surface partly covered with crop residues.

The physical properties of soil are directly affected by the type of tillage system that is used. For example, Czyz and Dexter (2009) found that RT increased soil stability, water content, and bulk density in the top layer (0–15 cm) compared to CT on a silt loam. Further, a study on clay soils found that RT had higher aggregate stability and a lower risk of particle losses from the topsoil (0–20 cm) compared to CT (Etana et al., 2009). However, Turtola et al. (2007) observed that the risk of surface runoff was higher when using RT compared to CT on clay soil. This was explained by that RT systems having a lower depressional water storage capacity, which reduces the water infiltration.

The impact of the tillage system on the soil's physical properties can alter the conditions for microbial activity and thus the turnover of carbon and nutrients, e.g. mineralization, which changes the basis for nutrient plant-availability and leaching losses from the field to the drainage system. Excessive nitrogen (N) and phosphorus (P) load on water ecosystems e.g. due to agricultural non-point source pollution, cause problems with eutrophication all over the world. Adaptation of tillage and crop management practices in order to reduce the risk of nutrient load from arable fields is a continuous research topic (Liu et al.,

---

* Corresponding author.
E-mail address: lisbet.norberg@slu.se (L. Norberg).

https://doi.org/10.1016/j.still.2025.106515
Received 4 September 2024; Received in revised form 19 February 2025; Accepted 20 February 2025

2024). Much is known about the effects of tillage timing and intensity on N leaching losses from sandy soils (e.g. Stenberg et al., 1999; Hansen and Djurhuus, 1997) but less is known for clay soils. For P, transport pathways through surface runoff or subsurface flow determine in which form and to what extent P is lost from the field. Here, the soil texture and structure in combination with tillage practices and crop management are among the most important factors (Sharpley et al., 2015).

A review of different soil types by Schoumans et al. (2014) concluded that RT or no-till can reduce erosion, surface runoff and transport of particulate P whilst CT can reduce the leaching of dissolved P. However, in a cold climate field experiment on a silt loam, total P losses via snowmelt runoff were lower from CT plots compared to RT plots and from both systems soluble P (75 %) dominated total P loss (Hansen et al., 2000). These findings indicate that RT can decrease surface runoff and transport of particles during spring and summer period compared to CT, whereas cold climates with a snow cover during winter this difference can be counteracted by relatively large losses of P during snowmelt (Norberg et al., 2022).

During winter, after the autumn tillage, the residue cover of the soil surface in RT systems can be up to 40 %, whilst CT will only reach up to 10 % (Hansen et al., 2000). The plant material present on the soil surface is objected to freeze-thaw cycles that releases dissolved P (Bechmann et al., 2005), which is one of the reasons for higher levels of dissolved P leaching from RT systems. This was confirmed by the review of Ulén et al. (2010), in which field experiments carried out in Scandinavia showed that dissolved P increased up to fourfold with RT compared to CT. Regarding no-till systems, the formation of stable macropores may promote a fast transportation of dissolved P downwards (Djodjic et al., 2002), and this may also be true for systems with shallow tillage. However, the development of preferential flow pathways under a permanent crop cover (Kramers et al., 2009) may enhance the transport of dissolved P downward (Ulén and Etana, 2010). On the other hand, permanent grass cover can significantly reduce soil and particulate P erosion from clay soils compared to tilled arable cropping systems (Schoumans et al., 2014; Turtola and Jaakkola, 1995).

In a Finnish study on a clay loam (40 % clay), the total N losses in subsurface drainage water was higher using CT compared to RT (Koskiaho et al., 2002). An explanation might be that less tillage enable less N mineralization and less accumulation of leachable N in the soil, which was shown by Stenberg et al. (1999). Also, it is important to note that RT can result in less efficient weed control, and thereby increased N uptake in weeds during autumn (Norberg and Aronsson, 2024), which may contribute to less N leaching from RT, compared to CT. Autumn is the time of the year when the risk of N leaching losses is the greatest because of low uptake of N by plants in combination with large drainage flow due to low uptake by plants and low evapotranspiration (Norberg et al., 2022). In turn, Myrbeck et al. (2012) observed no difference in soil mineral N content between RT and CT during the autumnal period. Delayed or omitted tillage in autumn, compared to tillage in early autumn, effectively reduces the accumulation of mineral N in the soil. Previous studies investigating this topic suggest that the time of tillage, as opposed to the tillage depth or tillage method, is a major factor for a reduced risk of N leaching on sandy soils (Hansen and Djurhuus, 1997; Stenberg et al., 1999; Stokes et al., 1992). The risk of N leaching losses is generally lower with a permanent grass cover compared to tilled soil (Cameron et al., 2013), due to both a continuous period of plant uptake of N and an undisturbed crop cover.

The depth of the tillage directly affects the distribution of the soil's organic matter and the nutrients within it. In a Belgian study on silt loam soils, the total N stock in the 0–40 cm depth layer was the same for RT and CT (D'haene et al., 2008). Notably, however, the same study observed a higher N mineralization rate in the 0–15 cm layer in the fields with RT in comparison to the fields with CT. This difference was due to a greater microbial biomass N content and a more pronounced stratification of total N and C:N ratio in the RT fields. Furthermore, it was revealed that after 40 years of using RT in Germany, the concentration of N in the 0–20 cm depth layer was higher compared to that of CT. This is not only due to a larger input of crop residues in the shallow soil layer but also a result of more stable macroaggregates that were able to protect organic material from degradation (Jacobs et al., 2009).

Potassium (K) is, unlike P and N, not a water pollutant but an essential crop nutrient. In concern to clay soils, an abundance of K within the soil may also often supply cereal crops with K. The leaching losses of K are quite low due to adsorption to clay minerals, rather, K is more likely to be lost by erosion (Goulding et al., 2021), while from sandy soils the leaching of K is greater (Yläranta et al., 1996). This was shown in studies on organic and conventional cropping systems on both clay and sandy soils in Sweden. Here, the clay soil in both systems had K leaching losses of 5–10 kg K ha^{-1} yr^{-1} (Aronsson et al., 2007) whilst the sandy soil, had K leaching losses of 16 kg K ha^{-1} yr^{-1} from the organic cropping system and 23–27 kg K ha^{-1} yr^{-1} from the conventional cropping system (Torstensson et al., 2006).

To perform an accurate assessment on the impact of tillage strategies on nutrient leaching losses, field studies under ordinary farm management practices, with direct measurements of drainage losses, are important. A build-up of soil conditions, which are formed by using tillage systems over long periods, alter the soil properties, change the nutrient turnover, and change the risk of leaching. This highlights the importance of following soil management practices over the course of several years.

The aim of this study was to assess if reduced tillage (RT) changes the concentrations and leaching losses of N, P and K in subsurface drainage water, compared to conventional mouldboard ploughing (CT), through a seasonal, annual and long-term perspective on a clay soil. This study defined RT as a non-inversion shallow tillage with a disc cultivator to 5–10 cm depth and CT as an inversive mouldboard ploughing to 20 cm depth, preceded by 1–2 stubble cultivations (5–10 cm depth). In the long-term (9 years) perspective, the two tillage strategies were compared with an unfertilized permanent green fallow that was used as a reference for undisturbed soil. The study also included an assessment of the soil mineral N content and yields of main crops (cereals and oilseed crops). The research hypotheses were, i) for RT, subsurface leaching losses of total N and nitrate-N (NO_3-N) are lower, total P and K equal and dissolved P (PO_4-P) higher, compared to CT, ii) N, P and K subsurface leaching losses are lower from permanent green fallow compared to CT and RT, iii) permanent green fallow has a greater capacity to reduce soil mineral N content in autumn than CT and RT and iv) crop yields do not differ between CT and RT.

2. Materials and methods

The field experiment, coded R0–8419, was established in 1993 at the research station Lanna in southwest Sweden (58°20'46.0"N 13°07'23.9"E). The experiment is still running as part of the Swedish University of Agricultural Sciences long-term field experiments, as noted in Bergkvist and Öborn (2011). This paper presents findings from the period 2008–2017. Results from the period before this were presented in Aronsson et al. (2007) and Aronsson and Stenberg (2010). The mean annual precipitation at the site is 584 mm and the mean annual temperature is 7.3 °C (SMHI, 1991–2020). The experiment consists of seven separately tile-drained plots, each measuring 42x100m. The site slope is less than 1 % and therefore surface runoff can be considered negligible. The soil is an Uderic Haploboroll according to the USDA classification system, with 47 % clay content (particle size <0.002 mm) in the topsoil (0–30 cm depth) and up to 61 % in the subsoil (30–60 cm depth, Table 1). From an agronomic perspective, both the P and K contents of the topsoil are considered to range from moderate to good (Table 1). Soil P and K content was determined by extraction with ammonium-lactate at pH 3.75 and analysed with ICP-OES (SS 028310:1993, modified).

In the experiment, three of the plots were conventionally tilled (CT) i.e. mouldboard ploughed (approximately 20 cm depth) whilst a different three set of plots used a reduced tillage system (RT) i.e. shallow

Table 1

Soil texture (clay <0.002 mm, silt 0.002–0.06 mm, sand 0.06–2 mm, %) at the study site and total nitrogen (tot-N, %), total carbon (tot-C, %), pH (H_2O), ammonium lactate-soluble phosphorus (P-AL, mg 100 g^{-1}) and ammonium lactate-soluble potassium (K-AL, mg 100 g^{-1}) in the 0–30, 30–60 and 60–90 cm soil layers measured in 2005.

Depth (cm)	Clay %	Silt %	Sand %	Tot-N %	Tot-C %	pH	P-AL mg 100 g^{-1}	K-AL mg 100 g^{-1}
0–30	47	46	7	0.18	1.96	7.3	7.2	14.5
30–60	56	41	3	0.05	0.48	7.4	8.6	17.5
60–90	61	37	2	0.02	0.36	7.5	16.4	22.1

tilled with disc cultivator (approximately 5–10 cm depth). Both of these tillage treatments were performed in autumn (August-October) (Table 2). The mouldboard ploughing was preceded by shallow tillage. In 2009, the crop in the RT plots was directly drilled without any preceding tillage. Except for the soil management, the six plots were managed in the same way. Prior to the sowing in autumn or spring, the soil was harrowed. The crops grown were winter wheat (*Triticum aestivum*), spring barley (*Hordeum vulgare*), oats (*Avena sativa*), winter oilseed rape (*Brassica napus*) and linseed (*Linum usitatissimum*). During the nine-year experimental period, the annual average nitrogen fertilization was 127 kg N ha^{-1} yr^{-1}, phosphorus 4.7 kg P ha^{-1} yr^{-1} and potassium 5.8 kg K ha^{-1} yr^{-1} to both tillage systems (Table 2). All fertilizers were applied as mineral fertilizers. The rates of P and K application were adapted for the content of plant-available amounts in the soil (extracted with ammonium-lactate), even though applied only three times during the nine-year period, while N was applied according to regional recommendations.

The seventh plot on the field was under a permanent green fallow (a grass-clover mixture) since 1993. The aboveground biomass was cut and sampled once a year, usually in July, before being left on the ground. Although the green fallow was never fertilized, a natural N-fixation by the clover likely occurred. Data for the green fallow was only used in long-term comparisons since it did not have replicates.

2.1. *Water sampling and analysis*

The tiles in the separately tile-drained plots were placed approximately 14 m apart, at a depth of 1.0 m. The drainage system for each plot was conducted to separate measuring wells and the water flow was recorded by pump devices. The pump operation time was then logged with a water-meter connected to a datalogger (Aronsson and Stenberg, 2010; Aronsson et al., 2007). After a reconstruction in October 2013, all plot drainage systems were led to a common underground measuring station where each plot's drain water flow was recorded in separate small basins using a Thomson v-notch (opening angel of 90°). The water level in the basin was determined by a displacement body and load cell connected to a datalogger. For both water flow systems, the calculated values of the accumulated daily drainage volumes were stored for each plot and flow-proportional water samples were taken.

After every approximately 0.2 mm discharge, water subsamples (approximately 15 ml per occasion) were taken automatically from each plot separately, using a peristaltic pump and collected in individual polyethylene bottles. The water samples in the bottles were collected for analysis every two weeks during drainage periods. Water was usually not sampled during the summer period and depending on the yearly variation in precipitation and weather, the number of samples varied between years with an average of nine samples per year. No samples were taken during the first half of 2012 due to technical issues, so the agrohydological year of 2011/2012 is only represented by the period July-December 2011.

Standard methods were used to determine the concentrations in discharge water of total N, total P, phosphate-P (PO_4-P) and K during 2008–2017 and NO_3-N + nitrite-N (NO_2-N) during 2008–2012 (information of analysis methods in Norberg and Aronsson 2024).

The daily nutrient leaching amount was calculated by multiplying the nutrient concentrations in each sample by the daily amount of drainage during the two-week period prior to the sampling date. The daily values of the leaching load for each nutrient were combined to provide a monthly value, which was then combined to give an annual value for the agrohydrological year (1 July-30 June). This value was then accordingly divided by the monthly and annual amount of drainage to obtain the mean monthly and annual concentrations, respectively, of nutrients in drainage water.

Table 2

Dates for soil management (stubble cultivation (SC, 5–10 cm depth) and mouldboard ploughing (MP, 20 cm depth)), main crop and date of sowing, date of fertilizer application and amount of applied nitrogen (N), phosphorus (P) and potassium (P), for the two tillage systems (conventional tillage and reduced tillage) during the period 2008–2017.

Agrohydro-logical year	Conventional tillage		Reduced tillage	Main crop and sowing date	Applied Fertilizer (kg ha^{-1})			
July – June	Date SC	Date MP	Date SC		Date	N	P	K
2008/2009	2008–07–29	2008–07–30	2008–07–29 2008–07–30	Oilseed rape 2008–08–16	2009–04–07	90	11	21
2009/2010	2009–08–12 2009–09–08	2009–09–04	Direct drill	Winter wheat 2009–09–14	2010–04–22 2010–05–10	130 10		
2010/2011	2010–08–12	2010–09–04	2010–08–12	Barley 2011–04–19	2011–04–19	80		
2011/2012		2011–10–24	2011–10–24	Oats 2012–03–28	2012–03–28 2012–05–08	60 60		
2012/2013	2012–10–24	2012–10–24	2012–10–24	Oilseed lin 2013–05–07	2013–05–07	120		
2013/2014		2013–08–30	2013–09–05	Winter wheat 2013–09–06	2014–04–14 2014–05–19	80 80		
2014/2015		2014–10–22	2014–10–15	Barley 2015–04–10	2015–04–10 2015–05–21	55 16	15	15
2015/2016	2015–08–18	2015–08–19	2015–08–18 2015–08–19	Oilseed rape 2015–08–20	2015–08–20 2016–03–22 2016–04–26	60 70 70	16	16
2016/2017	2016–09–05	2016–09–06	2016–09–05	Winter wheat 2016–09–07	2017–03–28 2017–05–05	80 80		

2.2. Sampling and analysis of crop yield

Three subplots (approximately 20 m^2) were harvested in each plot to determine the crop yield. Concentrations of N, P, and K in grain were determined through dry combustion according to ISO 10694 (1995) and ISO 13878 (1998), using an elemental analyzer for macro samples (LECO TruMac® CN analyzer, St. Joseph, MI, USA). Concentrations were then calculated based on dry weight (DW).

2.3. Soil sampling and analysis of soil mineral N

Soil samples were taken to determine the mineral N content in spring (April-May), harvest (August-September) and late autumn (October-December). Soil cores (20 mm diameter, 30 cm height) were taken from 0 to 30, 30–60, and 60–90 cm depth (24 replicates in 0–30 cm, 12 replicates in 30–90 cm). All soil samples were stored at a deep-frozen temperature (-18°C) until analysis. Concentrations of NO_3-N and NH_4-N in soil samples were extracted with 2 M KCl and then analyzed colorimetrically. Actual volumetric water content and dry bulk density (0–30 cm: 1330 kg m^{-3}, 30–90 cm: 1500 kg m^{-3}, respectively) were used when transforming analytical values to kg ha^{-1}.

2.4. Statistics

A mixed model was used to test for differences in concentrations, loads of nutrients, and soil mineral N between the treatments (CT, RT and green fallow) from 2008 to 2017. Treatments were set as fixed factors, whilst in the repeated structure the plot was set as the subject variable and the year as the repeated continuous variable. When a significant effect ($p < 0.05$) were found, Tukey HSD test was used to compare mean values. Within-year differences between soil management treatments were tested with a Student's *t*-test for both the leaching and the concentrations of nutrients. Within-year differences between soil management treatments were tested with a Kruskal-Wallis test for yields, N, P and K in grains since it did not meet normality requirements. The mean values of the three replicates from each plot were used in the Kruskal-Wallis test. Normality was tested with an Anderson-Darling test. Annual and monthly leaching and concentrations of nutrients, along with the soil mineral N, were log-transformed before statistical analysis. Statistical analyses were performed with JMP Pro 17 (SAS Institute Inc.).

3. Results and discussion

3.1. Subsurface discharge from conventional tillage, reduced tillage and green fallow

Discharge was higher in CT than from RT in most months for long-term monthly mean, single years and in long-term annual mean (10 % higher), but not statistically significant ($p < 0.05$, Table 3, Fig. 1a, Fig. 2a). Annual discharge ranged from 396 mm for CT in 2012/2013–66 mm for RT in 2016/2017 (Fig. 1a). The agrohydrological year of 2016/2017 was notably dryer than usual with only 381 mm rain (Fig. 1a), compared to the 30-year average of 584 mm (SMHI, 1991–2020). A Finnish study also found CT to have a greater amount of discharge than RT during the 12-year study time (Koskiaho et al., 2002). Furthermore, the same study discovered that any occasional flow peaks during winter were only observed in CT. In contrast, no such differences in flow peaks between CT and RT were notable within this study. Discharge was high during most autumn and winter months (September-January) and in March (Fig. 2a) when snowmelt and the thawing of soil frost typically occurs. During the summer months, May-August, the discharge was either low or absent (Fig. 2a), as most precipitation was used by growing crops or evaporated.

The seasonal variation followed the same trend as in a similar tile-drained field experiment in the same region but on a sandy soil (Norberg and Aronsson, 2024). From the sandy soil, the discharge was found to be generally lower (172 mm yr^{-1}, average during 28 years) with around 25 % of the precipitation becoming discharge, compared to this experiment were approximately 42 % of the yearly precipitation ended up as discharge from the tilled plots. The combination of evapotranspiration, surface runoff and the percolating water (which partly bypasses drain-tiles) can explain why drainage is lower than precipitation (Figs. 1a and 2a). The results indicate that a greater volume of the percolated water was captured by the drainage system on this clay soil compared to the sandy soil (Norberg and Aronsson, 2024).

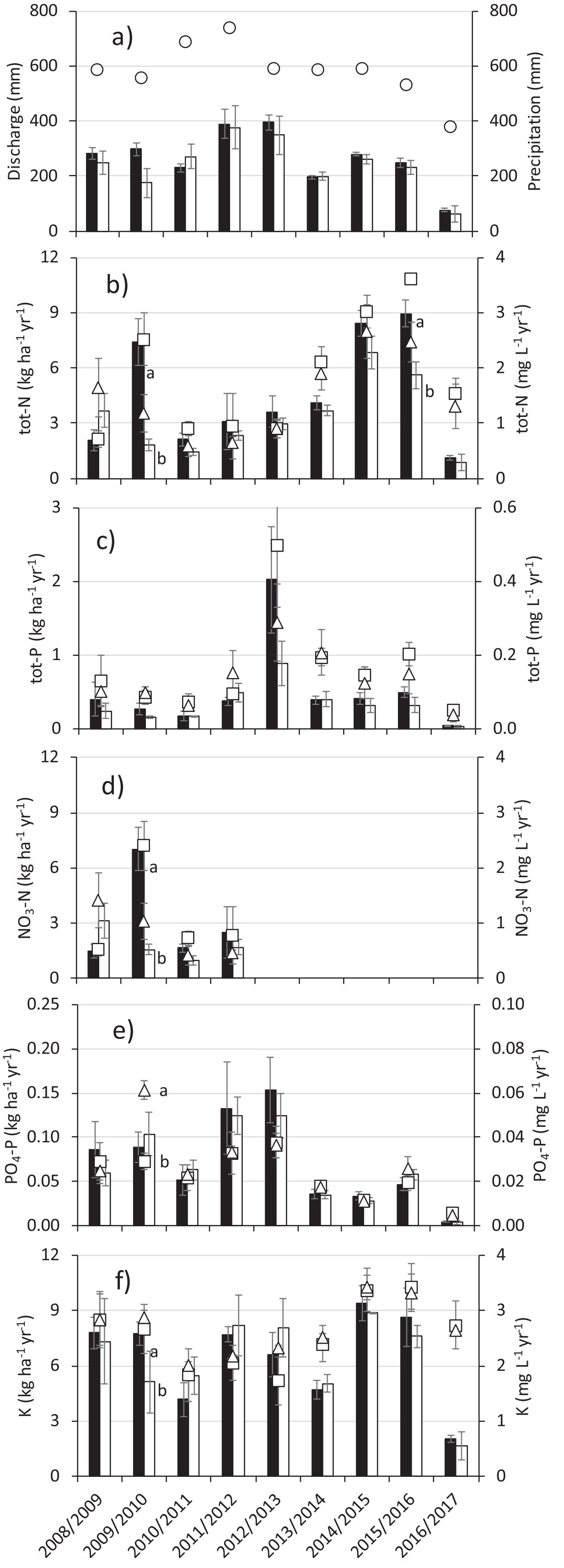
This study measured the subsurface drainage water, with the risk of surface runoff considered to be small, since the experimental site was located on a flat landscape. However, a Finnish study investigating clay soil (>60 % clay) with a mean slope of 2 % showed that about 20 %, 40 % and 60 % of the total water flow (surface runoff plus subsurface drainage) was surface runoff from CT soil, RT soil and soil covered by grass, respectively (Turtola et al., 2007). A similar trend can be seen in our study since annual mean discharge was the highest from the CT treatment and the lowest from the green fallow (Table 3), perhaps suggesting different shares of surface runoff. However, from this flat field there were no visual indications of surface runoff. In contrast to P, where surface runoff can constitute the main pathway for losses under certain circumstances, the losses of N display the opposite trend, with consistently higher losses via subsurface drainage water than with surface runoff (Norberg et al., 2022).

3.2. Nutrient leaching from conventional and reduced tillage

The nine years of measurements used for this study show that the long-term average tot-N leaching losses (kg ha^{-1} yr^{-1}) were not affected by the soil tillage strategy from this clay soil (Table 3). Consequently, our first hypothesis that RT would result in lower N leaching than CT could not be confirmed. However, the long-term average and the within year comparison of the two soil tillage systems illustrates a trend of higher tot-N drainage water concentrations and leaching using the CT treatment compared to RT treatment (Table 3, Fig. 1b). For two of the years CT had significantly higher concentrations and leaching of tot-N,

Table 3
Mean annual subsurface leaching (kg ha^{-1} yr^{-1}) and flow-weighted concentrations (mg L^{-1} yr^{-1}) of total nitrogen (tot-N), total phosphorus (tot-P), phosphate-P (PO_4-P) and potassium (K) in drainage water, and discharge (mm) for the treatments conventional tillage, reduced tillage and permanent green fallow during the period 2008–2017, and of nitrate-N (NO_3-N) during the period of 2008–2012. Mean, standard error in brackets. Different letters denote significantly different mean values ($p < 0.05$).

	Conventional tillage		Reduced tillage		Green fallow	
	kg ha^{-1} yr^{-1}	mg L^{-1} yr^{-1}	kg ha^{-1} yr^{-1}	mg L^{-1} yr^{-1}	kg ha^{-1} yr^{-1}	mg L^{-1} yr^{-1}
tot-N	4.6^a(0.59)	1.8 (0.21)	3.2^{ab}(0.39)	1.5 (0.17)	2.0^b(0.67)	0.9 (0.26)
NO_3-N	3.1^a(0.79)	1.1 (0.27)	1.8^a(0.34)	0.8 (0.18)	0.4^b(0.09)	0.2 (0.03)
tot-P	0.51 (0.130)	0.16 (0.031)	0.33 (0.058)	0.14 (0.020)	0.63 (0.288)	0.23 (0.082)
PO_4-P	0.07 (0.011)	0.02 (0.002)	0.07 (0.009)	0.03 (0.003)	0.08 (0.017)	0.03 (0.005)
K	6.5 (0.51)	2.6 (0.16)	6.4 (0.56)	2.7 (0.11)	7.9 (0.97)	3.4 (0.30)
Discharge	266 (19.2) mm		242 (21.6) mm		234 (23.0) mm	



(caption on next column)

Fig. 1. Annual subsurface discharge and precipitation (a, bars and circles, respectively, mm), and annual subsurface leaching (bars, kg ha^{-1}yr^{-1}) and flow-weighted concentrations (points, mg L^{-1}yr^{-1}) of b) total nitrogen (tot-N), c) total phosphorus (tot-P), d) nitrate-N (NO$_3$-N), e) phosphate-P (PO$_4$-P) and f) potassium (K) from conventional tillage (black bars, squares) and reduced tillage (white bars, triangles). Data presented as mean and standard error for agrohydrological year (1st July – 30th June). Means within years annotated with different letters are significantly different ($n = 3$, $p < 0.05$). Note: The year 2011/2012 is only represented by the period July – December 2011 due to technical issues.

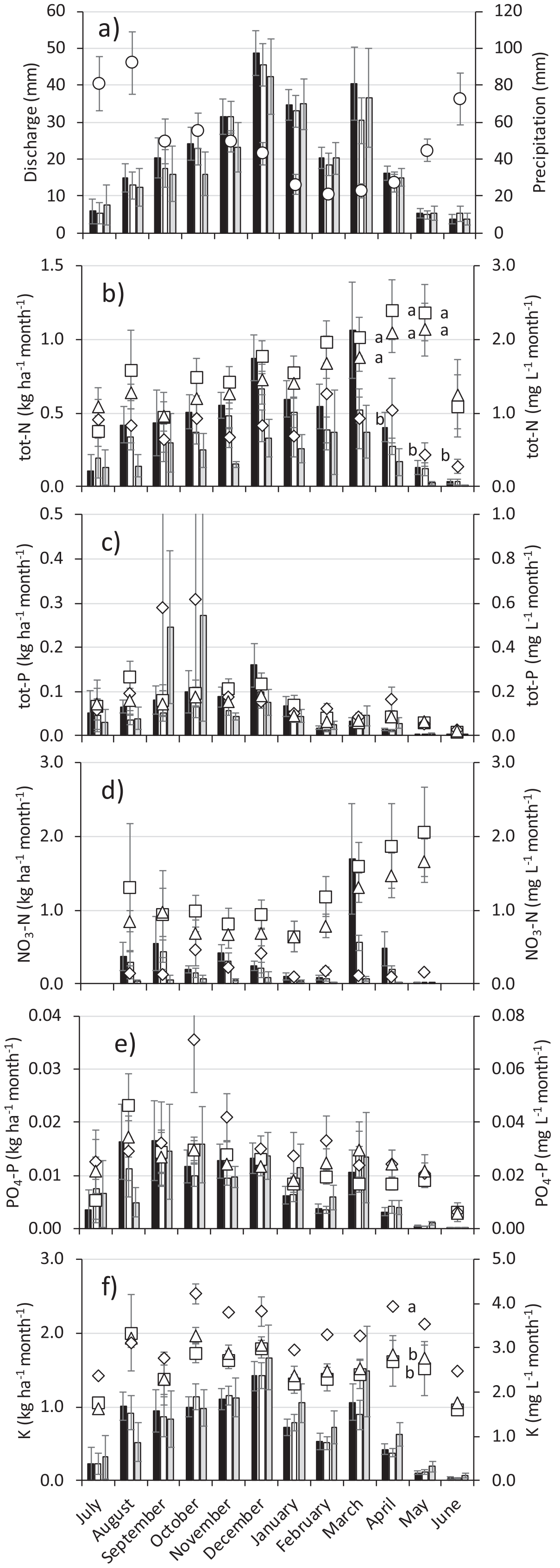
most distinct in the agrohydrological year of 2009/2010 (Fig. 1b and d). This was likely because the winter wheat was directly drilled in RT, i.e. no tillage at all was used in autumn 2009 in RT (Table 2). This indicates that a no-till management could mitigate N losses compared to both RT and CT, and indicated that tillage itself, rather than tillage intensity, is of major importance for N leaching (e.g. Hansen and Djurhuus, 1997).

The seasonal variation of N leaching indicates the same trend as the long-term and annual values, with higher values for CT compared to RT (Fig. 2b). Notably, December and March (the two months with the largest water flows), stand out with large losses of tot-N using CT compared to RT. April and May had the highest concentrations of tot-N from both tilled treatments (Fig. 2b). Nitrate-N peaked for CT in March (Fig. 2d). Furthermore, tot-P had very low leaching losses throughout May-June and the largest losses from October-January, with a trend of CT having higher values than RT (Fig. 2c). The concentrations of tot-P were higher the second half of the year (July-December) with highest values from using CT in July and August (Fig. 2c).

Tot-P and PO$_4$-P were found to be more variable between years than N and there were few years that were statistically significant between treatments (Fig. 1c and e). There were no observed differences in tot-P losses with subsurface drainage water between CT and RT (annual or long-term average, Fig. 1, Table 3), which supports our first hypothesis. Koskiaho et al. (2002) made similar observations, where RT had only little effect on tot-P losses with drainage water compared to CT. However, in that study, the dissolved reactive P increased in RT compared to CT, which was the first hypothesis for our study, according to the assumption that a soil with less disturbance supports fast transport pathways of solutes downwards in macropores (King et al., 2015). The long-term average of our study (Table 3) could not support this hypothesis, but in one of the years, 2009/2010, when direct drill of winter wheat was practiced instead of RT, there was a significant difference of PO$_4$-P leaching between RT and CT (Fig. 1e, Table 3). The higher losses of PO$_4$-P from RT in 2009/2010 could be a result of PO$_4$-P release from plant material left over winter on the soil surface (Bechmann et al., 2005) following direct drill of winter wheat, instead of the usual shallow tillage before sowing.

In a similar separately tile-drained field experiment on a clay loam in south-west Sweden, concentrations of 0.1–0.3 mg tot-P L^{-1} yr^{-1} and 6–21 mg tot-N L^{-1} yr^{-1} were measured (Norberg and Aronsson, 2022). This comparison shows that the concentrations of N were very low from the current study, while the concentration of P were in the same range. The high P content in the subsoil (Table 1) indicates that the indigenous P content of the soil is high in deeper layers, mainly bound as Ca-P (Andersson et al., 2013), and this may contribute to subsurface leaching as well.

Potassium leaching and concentrations were similar for the CT and RT systems in most single years and for the long-term average (Fig. 1f, Table 3), which was in accordance with the first hypothesis for the two tillage systems. The seasonal leaching losses of K followed the same pattern as the discharge with the largest losses occurring during the winter period, October-March (Fig. 2f).



(caption on next column)

Fig. 2. Long-term monthly mean subsurface discharge and precipitation (a, bars and circles, respectively, mm), subsurface leaching (kg ha^{-1} $month^{-1}$, bars) and flow-weighted concentrations (mg L^{-1} $month^{-1}$, points) of b) total nitrogen (tot-N), c) total phosphorus (tot-P), d) nitrate-N (NO_3-N), e) phosphate-P (PO_4-P) and f) potassium (K), from conventional tillage (black bars, squares), reduced tillage (white bars, triangles) and green fallow (grey bars, rhombus). Data presented as mean and standard error include the years2008–2017 except for NO_3-N for which the data relates to the years2008–2012. Means within months annotated with different letters are significantly different ($p < 0.05$).

3.3. Long-term nutrient leaching from green fallow and the two tillage systems

The green fallow was only included in the comparison of the long-term mean values between the treatments since this treatment had no replicates. The green fallow had a lower amount of discharge than CT and RT in October-December, but no difference during the rest of the year (Fig. 2a). In comparison with CT, the green fallow had lower leaching losses of tot-N and NO_3-N, while in comparison with RT it was only significant for NO3-N (Table 3). There were no differences for tot-P and PO_4-P in comparison with both tillage treatments. For K, there was a trend of increased leaching from the green fallow compared to the tilled plots for the nine-year mean (Table 3). Thus, the results for NO_3-N and partly tot-N supported the second hypothesis while results for tot-P, PO_4-P and K did not. This indicates that to take arable land out of production and stop fertilizing would not be a solution for reduction of P and K leaching losses from a clay soil like this. Recirculation of nutrients from plant material left on the field and mobilization from soil reserves would still have a considerable impact on water quality, despite the fact of a permanent crop growing. However, long-term N leaching losses from the green fallow was only 43 % of the losses from CT (Table 3). This is similar to the values found in a Scandinavian review, with undersown grass cover crops, mainly on sandy soils (Aronsson et al., 2016).

The seasonal pattern complements the long-term annual mean with lower concentrations and losses of tot-N and NO_3-N in most months (Fig. 2b, d), even though it was not statistically significant except for tot-N in March-May. This is probably due to the fact that during March-May, the green fallow had started growing while the tilled systems were still not sown yet (if spring sown cereal) or in an early growth stage (if autumn sown cereal). Approximately, 80 %, 75 % and 33 % of tot-N was in the nitrate form (NO_3-N) for the treatments CT, RT and green fallow, respectively, for the four years (2008–2012) when this comparison can be made. Thus, a much greater part of tot-N was present in other forms e. g. soluble organic N or NH_4-N, in the drainage water from the green fallow. Generally, 75–95 % of tot-N in subsurface drainage water from Swedish arable fields are in the nitrate form (Norberg et al., 2024).

Potassium concentrations were higher in most months of the year from the green fallow compared to CT and RT, though not statistically significant except for May (Fig. 2f). In a study of cover crops on a sandy soil (Norberg and Aronsson, 2024), it was shown that soil with a crop cover over winter can have higher K leaching than soil with tillage in autumn. This could possibly be due to the release of K ions from plant cells when there is frost, similar to what has been found for P in cover crops exposed to freezing and then irrigation (Liu et al., 2014). In a soil with developed macropores, as could be the case for the permanent green fallow on this clay soil, fast transport of solutes may occur under certain circumstances (Miranda-Vélez et al., 2022).

3.4. Content of soil mineral nitrogen

Mineral N in the soil profile was significantly lower in the green fallow compared to the two soil tillage treatments in late autumn (Fig. 3), which supports the third hypothesis. During harvest and in spring the trend was the same but not statistically significant ($p < 0.05$, Fig. 3). For all three treatments, the soil mineral N content was lowest at

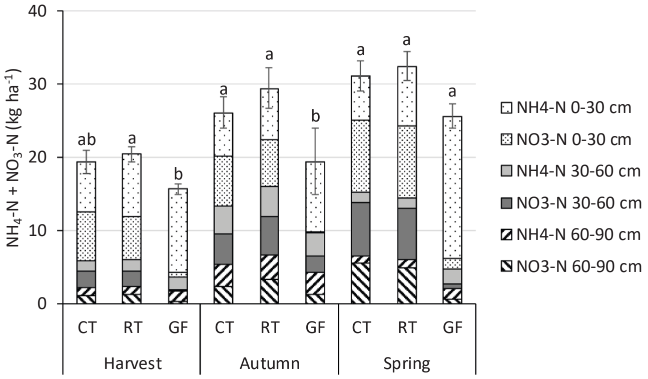


Fig. 3. Mineral nitrogen content (NH_4-N and NO_3-N, kg ha^{-1}) in the soil profile (0–30, 30–60 and 60–90 cm depth) at harvest, in late autumn, and in spring in the different treatments (conventional tillage (CT), reduced tillage (RT) and green fallow (GF)) from harvest 2008 – harvest 2017. Data presented as mean for 0–30, 30–60, 60–90 cm and standard error for 0–90 cm. Means for the 0–90 cm layer within sampling occasions annotated with different letters are significantly different ($p < 0.05$).

harvest, when the crop has used N during the growing season, and then increased until late autumn.

In the green fallow, most soil mineral N (93–97 %) in the upper layer (0–30 cm depth) occurred as NH_4-N compared to the tilled soil where 41–62 % was in the form of NO_3-N (Fig. 3). This was the case across all sampling occasions and could explain why the proportion of NO_3-N in drainage water was low from the green fallow. Thus, there seemed to be a transport of NH_4-N through the soil despite the high ability of clay minerals to adsorb positive ions like NH_4^+. Preferential transport pathways may be a possible explanation (Miranda-Véles et al., 2022).

It would have been reasonable to assume that there were greater amounts of mineral N in the topsoil using CT compared to RT in late autumn, since there was a tendency for larger N leaching in CT in the following winter and spring. However, this was not the case, and there was no indication that a more thorough tillage using CT would have caused a larger N mineralization, as was shown in earlier studies on a sandy soil (Stenberg et al., 1999). In this study, both tillage treatments were tilled at the same time, most often in August or September (Table 2). Several studies have shown that postponed tillage from early autumn to late autumn or spring is one of the most important measures for reduced N leaching (Stenberg et al., 1999), preferably in combination with a cover crop (Norberg and Aronsson, 2024). This is particularly true for sandy soils, as on clay soils mineral N may be preserved within the soil to a greater extent during winter or lost through denitrification.

The N leaching losses were low in the present study, only 3.9 kg N ha^{-1} yr^{-1}, which may indicate that mineral N was preserved in the soil and/or that denitrification occurred. As shown in Fig. 3, mineral N did not decrease over winter and spring, which can explain why leaching was low.

In the study by Aronsson and Stenberg (2010), the soil mineral N content (0–90 cm depth) across treatments and time of the year was in the range of 13–45 kg N ha^{-1}, with the lowest values in August and the highest values in April. In a study by Myrbeck et al. (2012), performed on the same research station as this study, it was concluded that the transport of the soil mineral N to deeper layers was limited and the soil mineral N content did not decrease during winter, suggesting a low risk of N leaching. In comparison with the sandy soil in Norberg and Aronsson (2024) which had approximately the same amount of mineral N in the soil profile during harvest as this study, the leaching losses of N was 17.3 kg N ha^{-1}. Thus, much of the N in the soil profile was lost during winter from the sandy soil while the clay soil in this study was able to preserve N to a larger extent.

3.5. Grain yields and biomass in the green fallow

The yield of main crop was often higher in CT compared to RT, but only significant in two years (2010, winter wheat and 2016, oilseed rape, Table 4), which then only partly support the fourth hypothesis. Kauppi et al. (2024) saw no difference in the yield of barley between CT and RT. The content of N, P and K in grain was also often higher in CT but this was not consistent (Table 4).

On average during the nine years, 94 kg N ha^{-1}, 21 kg P ha^{-1} and 29 kg K ha^{-1} was removed yearly from the tilled plots with the grain. The yearly mean of fertilizer applications was 127 kg N ha^{-1}, 4.7 kg P ha^{-1} and 5.8 kg K ha^{-1} as mineral fertilizer (Table 2). Nitrogen was applied annually, but P and K was applied on only three occasions (Table 2). Over the nine-year study period, the average annual nutrient balance (fertilizer minus harvest and leaching) for the tilled plots were + 29 kg N ha^{-1} yr^{-1}, −17 kg P ha^{-1} yr^{-1} and −30 kg K ha^{-1} yr^{-1}, respectively. Consequently, the tilled systems had a surplus of N but a deficit of P and K, which was compensated by the naturally P and K rich soil that could support the crop. In the long-term, fertilization with additional P and K will probably be needed in order to maintain P and K availability in the soil and preserve soil fertility.

The green fallow yielded, on average during eight years (2008–2017), 4050 kg dry weight biomass ha^{-1} after cutting in July, which contained 34 kg N ha^{-1} that was left on the ground. The green fallow never received any fertilizer but an unknown addition of N to the system by N fixation in clover plants occurred.

3.6. Conclusion

This study performed on a clay soil in south-west Sweden assessed subsurface nutrient leaching from common crop production represented by two different autumn tillage intensities i.e. non-inversion reduced tillage (RT) and inversion conventional tillage (CT). The two tillage intensities was compared to unfertilized set-aside land represented by a permanent green fallow since 15 years prior to the start of the study period.

Reduced tillage in autumn instead of conventional tillage was hypothesized to result in lower subsurface leaching of tot-N and NO_3-N. This could not be statistically verified but a strong trend was seen, which supported this. However, the overall N leaching in this study was low (2.0–4.6 kg ha^{-1} yr^{-1}). The leaching losses of tot-P, PO_4-P and K were similar, and most years, grain yields did not differ between the two tillage systems. This soil had a high capacity to provide P and K to the crops, and despite low inputs of P and K with fertilizers, grain yields were satisfactory in both tillage systems.

We found that the permanent green fallow, instead of reduced or conventionally tilled soil, reduced the soil mineral N content in autumn and the annual leaching losses of NO_3-N. On the other hand, leaching of total P, PO_4-P and K did not significantly differ between the three treatments even if a trend of higher leaching of K from the green fallow was seen.

In conclusion, a trend of increased N leaching losses with increased land-use intensity (green fallow< RT<CT) was seen from this clay soil, while the leaching of P and K was not mitigated by reduced tillage intensity or by converting arable land to set-aside land.

CRediT authorship contribution statement

Norberg Lisbet: Writing – original draft, Methodology, Formal analysis, Conceptualization. **Aronsson Helena:** Writing – review & editing, Validation, Project administration.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence

Table 4

Yield of main crop (kg ha^{-1}, dry weight) and content of nitrogen (N), phosphorus (P) and potassium (K) in grain (kg ha^{-1}) in the treatments conventional tillage and reduced tillage, during 2009–2017. Mean, standard error in brackets. Different letters means statistically significant difference between treatments ($n = 3$, $p < 0.05$).

	Conventional tillage				Reduced tillage			
	Yield	N	P	K	Yield	N	P	K
	kg ha^{-1}				kg ha^{-1}			
2009 Oilseed rape	2110 (212)	n.d.	n.d.	n.d.	2440 (288)	n.d.	n.d.	n.d.
2010 Winter wheat	6960^a(127)	130^a(5.1)	25^a(0.9)	28^a(0.7)	6160^b(149)	120^b(3.8)	21^b(0.6)	24^b(0.5)
2011 Spring barley	6390 (16)	98 (0.5)	23^a(0.1)	36^a(0.5)	6120 (176)	93 (3.6)	21^b(0.7)	34^b(0.8)
2012 Oats	5370 (106)	80 (4.0)	20 (0.5)	27 (0.6)	5600 (207)	87 (3.4)	20 (1.4)	27 (1.2)
2013 Linseed	650 (158)	19 (5.1)	n.d.	n.d.	810 (55)	25 (2.0)	n.d.	n.d.
2014 Winter wheat	8390 (152)	156 (2.7)	26 (0.3)	37 (0.5)	6530(1116)	119(20.6)	20 (3.4)	29 (4.9)
2015 Spring barley	5550 (158)	72 (1.9)	20 (0.5)	32 (0.9)	5890 (241)	75 (6.4)	21 (1.3)	34 (1.9)
2016 Oilseed rape	3220^a(114)	91 (1.7)	18 (1.1)	19 (0.6)	2760^b(76)	81 (3.4)	15 (0.9)	16 (0.7)
2017 Winter wheat	8260 (44)	137 (0.1)	24 (0.6)	33 (0.7)	7550 (454)	125 (9.0)	22 (1.0)	30 (1.1)

n.d. not determined.

the work reported in this paper.

Acknowledgements

This study is part of and funded by the Swedish University of Agricultural Sciences (SLU) long-term field experiments and was co-funded by the Swedish Board of Agriculture. We wish to thank the staff at Lanna Research station, the Soil and Plant laboratory at the Department of Soil and Environment, the Water Laboratory at the Department of Aquatic Sciences and Assessment (all SLU), and our experimental technician Maria Blomberg.

Data availability

Data will be made available on request.

References

Andersson, H., Bergström, L., Djodjic, F., Ulén, B., Kirchmann, H., 2013. Topsoil and subsoil properties influence phosphorus leaching from four agricultural soils. J. Environ. Qual. 42, 455–463.

Aronsson, H., Stenberg, M., 2010. Leaching of nitrogen from a 3-yr grain crop rotation on a clay soil. Soil Use Manag. 26, 274–285.

Aronsson, H., Torstensson, G., Bergstrom, L., 2007. Leaching and crop uptake of N, P and K from organic and conventional cropping systems on a clay soil. Soil Use Manag. 23, 71–81.

Aronsson, H., Hansen, E.M., Thomsen, I.K., Liu, J., Ogaard, A.F., Känkänen, H., et al., 2016. The ability of cover crops to reduce nitrogen and phosphorus losses from arable land in southern Scandinavia and Finland. J. Soil Water Conserv. 71 (1), 41–55.

Bechmann, M.E., Kleinman, P.J.A., Sharpley, A.N., Saporito, L.S., 2005. Freeze–thaw effects on phosphorus loss in runoff from manured and catch-cropped soils. J. Environ. Qual. 34, 2301–2309.

Bergkvist, G., Öborn, I., 2011. Long-term field experiments in Sweden-what are they designed to study and what could they be used for? Asp. Appl. Biol. 75–85.

Briones, M.J.I., Schmidt, O., 2017. Conventional tillage decreases the abundance and biomass of earthworms and alters their community structure in a global meta-analysis. Glob. Change Biol. 23, 4396–4419.

Cameron, K.C., Di, H.J., Moir, J.L., 2013. Nitrogen losses from the soil/plant system: a review. Ann. Appl. Biol. 162, 145–173.

Czyz, E., Dexter, A., 2009. Soil physical properties as affected by traditional, reduced and no-tillage for winter wheat. Int. Agrophys. 23, 319–326.

D'haene, K., Vandenbruwane, J., De Neve, S., Gabriels, D., Salomez, J., Hofman, G., 2008. The effect of reduced tillage on nitrogen dynamics in silt loam soils. Eur. J. Agron. 28, 449–460.

Djodjic, F., Bergstrom, L., Ulen, B., 2002. Phosphorus losses from a structured clay soil in relation to tillage practices. Soil Use Manag. 18, 79–83.

Etana, A., Rydberg, T., Arvidsson, J., 2009. Readily dispersible clay and particle transport in five Swedish soils under long-term shallow tillage and mouldboard ploughing. Soil Tillage Res. 106, 79–84.

Goulding, K., Murrell, T.S., Mikkelsen, R.L., Rosolem, C., Johnston, J., Wang, H., Alfaro, M.A., 2021. Outputs: potassium losses from agricultural systems. In: Murrell, T.S., Mikkelsen, R.L., Sulewski, G., Norton, R., Thompson, M.L. (Eds.), Improving Potassium Recommendations for Agricultural Crops. Springer, Cham.

Hansen, E.M., Djurhuus, J., 1997. Nitrate leaching as influenced by soil tillage and catch crop. Soil Tillage Res. 41, 203–219.

Hansen, N.C., Gupta, S.C., Moncrief, J.F., 2000. Snowmelt runoff, sediment, and phosphorus losses under three different tillage systems. Soil Tillage Res. 57, 93–100.

Jacobs, A., Rauber, R., Ludwig, B., 2009. Impact of reduced tillage on carbon and nitrogen storage of two Haplic Luvisols after 40 years. Soil Tillage Res. 102, 158–164.

Kauppi, K., Kaseva, J., Jalli, M., Palojärvi, A., Alakukku, L., 2024. Long-term nitrogen and phosphorus balances for spring barley (Hordeum vulgare L.) cultivation as affected by primary tillage of a Nordic clay soil. Eur. J. Agron. 155, 127131.

King, K.W., Williams, M.R., Macrae, M.L., Fausey, N.R., Frankenberger, J., Smith, D.R., Kleinman, P.J.A., Brown, L.C., 2015. Phosphorus transport in agricultural subsurface drainage: a review. J. Environ. Qual. 44, 467–485.

Koskiaho, J., Kivisaari, S., Vermeulen, S., 2002. Reduced tillage: Influence on erosion and nutrient losses in a clayey field in southern Finland. Agric. Food Sci. 11, 37–50.

Kramers, G., Richards, K.G., Holden, N.M., 2009. Assessing the potential for the occurrence and character of preferential flow in three Irish grassland soils using image analysis. Geoderma 153, 362–371.

Liu, J., Ulén, B., Bergkvist, G., Aronsson, H., 2014. Freezing-thawing effects on phosphorus leaching from catch crops. Nutr. Cycl. Agroecosyst. 99, 17–30.

Liu, J., Djodjic, F., Ulén, B., Aronsson, H., Bechmann, M., Bergström, L., Krogstad, T., Kyllmar, K., 2024. Toward better targeting of mitigation measures for reducing phosphorus losses from land to water: Andrew Sharpley's legacy in Norway and Sweden. J. Environ. Qual. 1–11.

Luo, Z.K., Wang, E.L., Sun, O.J., 2010. Soil carbon change and its responses to agricultural practices in Australian agro-ecosystems: a review and synthesis. Geoderma 155, 211–223.

Miranda-Véles, J.F., Diamantopoulos, E., Vogeler, I., 2022. Does macropore flow in no-till systems bypass mobile soil nitrogen after harvest? Soil Tillage Res. 221, 105408.

Myrbeck, A., Stenberg, M., Arvidsson, J., Rydberg, T., 2012. Effects of autumn tillage of clay soil on mineral N content, spring cereal yield and soil structure over time. Eur. J. Agron. 37, 96–104.

Norberg, L., Aronsson, H., 2022. Mitigating phosphorus leaching from a clay loam through structure liming. Acta Agric. Scand. Sect. B-Soil Plant Sci. 72, 987–996.

Norberg, L., Aronsson, H., 2024. Effects of spring and autumn tillage, catch crops, and pig manure application on long-term nutrient leaching from a loamy sand. Eur. J. Agron. 156.

Norberg, L., Linefur, H., Andersson, S., Blomberg, M., Kyllmar, K., 2022. Nutrient losses over time via surface runoff and subsurface drainage from an agricultural field in northern Sweden. J. Environ. Qual. 51, 1235–1245.

Norberg, L., Linefur, H., Blomberg, M., Valdén, R., Mårtensson, K., Persson, K. & Kyllmar, K. 2024. Växtnäringsförluster från åkermark 2022/2023. Ekohydrologi 184 (In Swedish), Uppsala.

Ogle, S.M., Alsaker, C., Baldock, J., Bernoux, M., Breidt, F.J., Mcconkey, B., Regina, K., Vazquez-Amabile, G.G., 2019. Climate and soil characteristics determine where no-till management can store carbon in soils and mitigate greenhouse gas emissions. Sci. Rep. 9.

Rasmussen, K.J., 1999. Impact of ploughless soil tillage on yield and soil quality: a Scandinavian review. Soil Tillage Res. 53 (1), 3–14.

Schoumans, O.F., Chardon, W.J., Bechmann, M.E., Gascuel-Odoux, C., Hofman, G., Kronvang, B., Rubæk, G.H., Ulén, B., Dorioz, J.M., 2014. Mitigation options to reduce phosphorus losses from the agricultural sector and improve surface water quality: A review. Sci. Total Environ. 468-469, 1255–1266.

Sharpley, A.N., Bergström, L., Aronsson, H., Bechmann, M., Bolster, C.A., Börling, K., Djodjic, F., Jarvie, H.P., Schoumans, O.F., Stamm, C., Tonderski, K.S., Ulén, B., Uusitalo, R., Withers, P.J.A., 2015. Future agriculture with minimized phosphorus losses to waters: Research needs and direction. Ambio 44 (. 2), 163–179.

Stenberg, M., Aronsson, H., Linden, B., Rydberg, T., Gustafson, A., 1999. Soil mineral nitrogen and nitrate leaching losses in soil tillage systems combined with a catch crop. Soil Tillage Res. 50, 115–125.

Stokes, D.T., Scott, R.K., Tilston, C.H., Cowie, G., Sylvester-Bradley, R., 1992. The effect of time of soil disturbance on nitrate mineralization. Asp. Appl. Biol. 279–282.

Torstensson, G., Aronsson, H., Bergström, L., 2006. Nutrient use efficiencies and leaching of organic and conventional cropping systems in Sweden. Agron. J. 98, 603–615.

Turtola, E., Jaakkola, A., 1995. Loss of phosphorus by surface runoff and leaching from a heavy clay soil under barley and grass ley in Finland. Acta Agric. Scand. Sect. B-Soil Plant Sci. 45, 159–165.

Turtola, E., Alakukku, L., Uusitalo, R., Kaseva, A., 2007. Surface runoff, subsurface drainflow and soil erosion as affected by tillage in a clayey Finnish soil. Agric. Food Sci. 16, 332–351.

Ulén, B., Etana, A., 2010. Risk of phosphorus leaching from low input grassland areas. Geoderma 158, 359–365.

Ulén, B., Aronsson, H., Bechmann, M., Krogstad, T., Oygarden, L., Stenberg, M., 2010. Soil tillage methods to control phosphorus loss and potential side-effects: a Scandinavian review. Soil Use Manag. 26, 94–107.

Yläranta, T., Uusi-Kämppä, J., Jaakkola, A., 1996. Leaching of phosphorus, calcium, magnesium and potassium in barley, grass and fallow lysimeters. Acta Agric. Scand. Sect. B-Soil Plant Sci. 46, 9–17.