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Effects of spring and autumn tillage, catch crops, and pig manure application on long-term nutrient leaching from a loamy sand

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ABSTRACT

A field experiment with separately tile-drained plots was established on a sandy loam soil in 1993 to investigate management practices that can reduce nutrient leaching. Practices tested included timing of tillage in autumn or spring (ploughing with or without preceding cultivation) and catch crops in systems with mineral fertilizer alone or in combination with pig manure. Drainage water from each plot was collected separately and analyzed for total nitrogen (tot-N), nitrate-N (NO_3-N), total phosphorus (tot-P), phosphate-P (PO_4-P), and potassium (K). Biomass of catch crops, soil mineral N content, and yield of the main crop were also determined. The experimental set-up was modified after 14 years, but the core research questions were the same and the results from the two periods (1993–2006, 2007–2021) were comparable. Spring tillage and undersown catch crops (perennial ryegrass, *Lolium perenne* L.) reduced tot-N leaching and concentrations in drainage water compared with autumn tillage. However, a combination of spring tillage and catch crop increased tot-P leaching and concentrations in drainage water compared with autumn tillage and no catch crop. Use of pig manure increased tot-N leaching and concentrations in drainage water compared with treatments without pig manure, both with and without a catch crop. Treatments without a catch crop showed substantial growth of biomass during autumn in terms of weeds and volunteer plants, but growing a catch crop resulted in more biomass in most years. A catch crop was more effective in reducing N leaching than only weeds and volunteer plants, probably mainly due to its ability to survive winter and take up and store N over a longer period. Leaching of K increased with a catch crop, while the other treatments did not influence K losses. Yield of main crops was not affected by the different treatments.

1. Introduction

Losses of nitrogen (N) and phosphorus (P) from arable land result in eutrophication of aquatic and marine environments (Boesch, 2002). Therefore, management practices that reduce the nutrient load from agriculture under different climate and soil conditions are needed (Withers et al., 2014; Sharpley et al., 2015). Options include appropriate crop rotation and manure management, timing of tillage, and use of catch crops, which may have short-term and long-term effects on soil properties and nutrient losses (Edmeades, 2003; Thorup-Kristensen et al., 2003).

The timing of tillage operations (ploughing or other types of soil cultivation) is important in regulating losses of N and P. Early autumn tillage, instead of late autumn or spring tillage, promotes N mineralization and accumulation of mineral N in the soil, resulting in increased N leaching during autumn and winter (Stenberg et al., 1999). Phosphorus can leave agricultural fields bound to particles (particulate P) or in dissolved form, e.g., as phosphate-P (PO_4-P). Autumn tillage without a winter crop increases the risk of soil erosion during winter and associated losses of particulate P. A no-till or spring tillage system, i.e., leaving the soil undisturbed during winter, protects the soil surface against erosion (Bechmann, 2012). However, it has been shown that no-till, where stable pore systems are developed in the soil, can result in increased losses of dissolved P (Ulén et al., 2010).

The main purpose of catch crops (or cover crops) is to "catch" N by growing and taking up mineral N from the soil during periods when the soil would otherwise be fallow, thereby preventing losses of N via drainage water. Growing catch crops may recycle some N to the following crop, and also increase soil organic matter content and soil fertility in the long-term (Dabney et al., 2010). Catch crops can thus have a long-term positive residual effect on yield of the main crop, but the direct effect can sometimes be low or slightly negative due to immobilization of N or depletion of soil mineral N (Wallgren and Linden, 1994; Känkänen and Eriksson, 2007).

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Catch crops undersown in a spring crop, such as perennial ryegrass (*Lolium perenne* L.) or winter rye (*Secale cereale*) sown after harvest of the main crop, have been proven to reduce soil mineral N content during autumn, and leaching of N during winter and spring (Wallgren and Linden, 1994; Dabney et al., 2001; Känkänen and Eriksson, 2007; Aronsson et al., 2016; Hanrahan et al., 2021). The effect of catch crops on P losses is influenced by the extent to which they reduce soil erosion, and associated particulate P losses, and by P uptake from the soil, which can result in increased losses of dissolved P from degrading catch crop material incorporated or left on the soil surface, especially when exposed to freeze-thaw cycles during winter (Liu et al., 2013; Bechmann et al., 2005). Therefore, the potential risk of PO_4-P leaching during winter must be considered and balanced against the reduction in tot-N leaching when growing a winter catch crop.

Appropriate field application of manure in terms of timing and rates is critical for high nutrient use efficiency and low N and P leaching (Saha et al., 2023). Spring application of liquid manure before sowing, or to a growing crop, generally results in lower losses of N and P than autumn application (Aronsson et al., 2014) and, at appropriate rates, gives similar losses to application of mineral N fertilizer (Wallman and Delin, 2022).

Many studies have examined the short-term effects (1–5 years) of catch crops, manuring, and tillage timing on N and P losses, but there is a lack of knowledge about the long-term effects (over 15–30 years), especially of combinations of these measures. Annual application of catch crops or manure can result in build-up of organic material in the soil, while tillage can speed up degradation and mineralization of organic material (Stokes et al., 1992; Sapkota et al., 2012). The combined effect of these management practices may thus influence losses of N and P. Unlike N and P, leaching of potassium (K) has no detrimental impact on aquatic environments, so few studies have examined the effects of cropping practices on K leaching (Goulding et al., 2021). However, like P, K is a finite resource and soils with a low clay content often require K addition to maintain crop yields and quality.

To maintain studies over a long time is challenging, for example with respect to funding opportunities and for keeping relevance of research questions. The plots in long-term studies are managed in the same way for a long time, but changes in set-up can be both necessary and useful in meeting current questions and conditions, while maintaining the essential values of the studies. For example, catch crops are still very relevant after decades, as interest has broadened over time from their effect in mitigating N leaching to their effect in C storage and mitigation of climate impact. The long-term experiment described in this study, with studies of catch crops since 1993, currently provides data for long-term N modelling and for studies of soil organic C and effects on soil physical properties and microbial biodiversity.

This study examined the long-term (28 years) effects of catch crops, manuring, and tillage timing on N, P, and K losses from a long-term field experiment run over two consecutive periods (1993–2006, 2007–2021) with a slightly different set-up. The treatments compared over all 28 years were autumn and spring tillage with and without an undersown catch crop. During the first 14 years, application of pig manure was also included as a treatment, in comparison with mineral fertilizer alone. The field experiment had separately tile-drained plots for measurement of discharge and nutrients. Soil mineral N content, yield of main crops, and catch crop biomass were also determined.

2. Materials and Methods

2.1. Experimental set-up

The field experiment was established in 1993, on a loamy sand (Table 1) in south-west Sweden (58°27'59.9"N, 13°14'15.3"E), and is still running as part of long-term experiments at the Swedish University of Agricultural Sciences, described in Bergkvist and Öborn (2011). Mean annual precipitation at the site is 678 mm and mean annual temperature is 7.4 °C (SMHI, 1991–2020). The experiment consists of eight separately tile-drained plots (30 m x 28 m) with continuous discharge measurement and flow-proportional sampling of drainage water from each plot. The tile drains are located at 0.9 m depth and approximately 14 m spacing.

During the period 1993–2006, the experimental set-up involved autumn tillage (A) and spring tillage (S), without or with a catch crop (CA, CS) (Table 2). These were combined with either mineral NPK fertilizer (min) or mineral NPK fertilizer and pig slurry (man). Main crops were oats (*Avena sativa*), spring barley (*Hordeum vulgare*), potatoes (*Solanum tuberosum*) and winter rye (*Secale cereale*). For autumn tillage (A, CA), the soil was ploughed in November (to 18–22 cm depth), with preceding stubble cultivations in September (common agricultural practice) in treatment A and no preceding cultivation in treatment CA (where the catch crop was incorporated by November ploughing). The S and CS treatments were ploughed in April, all with one stubble cultivation prior to ploughing. During this period, there were no replicates of the treatments.

In 2007, the experimental set-up was changed to three treatments with two or three replicates; autumn tillage (A), spring tillage (S) and spring tillage in combination with a catch crop (CS) (Table 2). Only mineral (min) fertilizers were used during 2007–2021. The crops were managed according to the farm's cropping system and local practices. Main crops were oats, barley, potatoes, winter rye, and oilseed rape (*Brassica napus*). From 2007, no stubble cultivation was performed prior to ploughing, which was done in November in treatment A_{min} and in March-April in treatments S_{min} and CS_{min}.

For cereal crops and oilseed rape, perennial ryegrass (*Lolium perenne* L.) was used as a catch crop. It was undersown in spring about one week after sowing of main crop, at a seed rate of 8 kg ha^{-1} during 1993–2006 and 10 kg ha^{-1} during 2007–2021. When potatoes were grown (five years), winter rye (*Secale cereale*) or oilseed rape was used as the catch crop, sown after harvest of the potato crop. Winter rye was sown October 10–15 and oilseed rape August 11. No catch crop was grown during six of the years, on three occasions due to sowing a winter crop, i.e., winter wheat, winter rye, and oilseed rape. All fertilizer (mineral fertilizer, pig manure) was applied at sowing of the main crop in April-May. For mineral NPK fertilizer, a split dose was applied in some years. The rate of pig slurry applied during 1993–2006 (12–25 t ha^{-1}) in combination with mineral fertilizer (45 kg NH_4-N ha^{-1}) was adjusted so that the amount of plant-available NH_4-N from the manure matched the amount of mineral N applied in treatments with only mineral fertilizer. Specific information about main crops, rates of manure and mineral fertilizer, etc. is provided in Tables 3 and 4.

Table 1
Soil texture (clay, silt, sand, organic material, %, according to USDA classification) at the study site and total nitrogen (tot-N, %), total carbon (tot-C, %), pH, ammonium lactate-soluble phosphorus (P-AL, mg 100^{-1}) and ammonium lactate-soluble potassium (K-AL, mg 100^{-1}) in the 0–30, 30–60 and 60–90 cm soil layers measured in 2005.

Depth (cm)	Clay %	Silt %	Sand %	Org. m. %	Tot-N %	Tot-C %	pH	P-AL mg 100 g^{-1}	K-AL mg 100 g^{-1}
0–30	6	10	78	5	0.15	2.8	6.5	16.4	9.7
30–60	5	8	84	2	0.03	0.8	6.0	2.3	4.6
60–90	4	9	86	1	0.01	0.4	6.2	2.1	4.0

Table 2
Experimental set-up in the eight separately tile-drained experimental plots during 1993–2006 and 2007–2022. A – autumn tillage, S – spring tillage, C – catch crop, min – mineral fertilizer, man – pig manure.

	Plot	1	2	3	4	5	6	7	8
1993–2006	*Treatment*	A_{min}	A_{man}	CA_{min}	CA_{man}	S_{min}	S_{man}	CS_{min}	CS_{man}
	Pig manure		man		man		man		man
	Catch crop			C	C			C	C
	Stubble cultivation	Twice in autumn	Twice in Autumn			Once in spring	Once in spring	Once in spring	Once in spring
	Ploughing	Autumn	Autumn	Autumn	Autumn	Spring	Spring	Spring	Spring
2007–2021	*Treatment*	CS_{min}	S_{min}	S_{min}	A_{min}	S_{min}	CS_{min}	CS_{min}	A_{min}
	Catch crop	C					C	C	
	Ploughing	Spring	Spring	Spring	Autumn	Spring	Spring	Spring	Autumn

Table 3
Main crops, catch crops, and amounts of N, P, and K supplied by mineral fertilizer and pig manure during the period 1993–2007. For pig manure N refer to tot-N and amount NH_4-N in the manure is presented within parentheses. A – autumn tillage, S – spring tillage, C – catch crop, min – mineral fertilizer, man – pig manure.

Agrohydro-logical year 1 July-30 June	Main crop All plots	Catch crop CA_{min}, CA_{man}, CS_{min}, CS_{man}	Mineral fertilizer[a] kg ha^{-1} A_{min}, CA_{min}, S_{min}, CS_{min}			Mineral fertilizer[a] kg ha^{-1} A_{man}, CA_{man}, S_{man}, CS_{man}			Pig manure[b] kg ha^{-1} A_{man}, CA_{man}, S_{man}, CS_{man}		
			N	P	K	N	P	K	N(NH_4^+)	P	K
1993–1994	Oats	P. ryegrass	90	22	42	45	0	0	90 (50)	26	38
1994–1995	Oats	P. ryegrass	90	15	29	45	0	0	102 (61)	35	48
1995–1996	Barley	P. ryegrass	90	22	42	45	0	0	92 (62)	28	49
1996–1997	Potatoes	Winter rye	90	56	203	45	28	167	90 (55)	16	26
1997–1998	Oats	P. ryegrass	90	22	42	45	0	0	99 (44)	20	30
1998–1999	Barley	P. ryegrass	90	22	42	45	0	0	74 (50)	21	22
1999–2000	Oats	P. ryegrass	90	20	38	45	0	0	75 (42)	29	32
2000–2001	Potatoes	Winter rye	90	56	214	45	28	169	57 (35)	18	20
2001–2002	Barley	P. ryegrass	90	20	38	45	0	0	61 (46)	10	34
2002–2003	Oats	P. ryegrass	90	20	38	45	0	0	80 (54)	16	30
2003–2004	Barley	*No catch crop*	77	0	39	77	0	39	123 (80)	43	65
2004–2005	Oilseed rape	*No catch crop*[d]	205[c]	40	76	131	0	0	0 (0)	0	0
2005–2006	Winter rye	P. ryegrass	90	22	42	45	0	0	85 (63)	11	36
2006–2007	Potatoes	*No catch crop*	90	55	209	90	55	209	0 (0)	0	0

[a]Applied in April-May on one or two occasion to main crop.
[b]Applied in April-May on one occasion at a rate of 12–25 t ha^{-1} before sowing of main crop.
[c]74 kg N ha^{-1} applied in autumn 2003 to main crop, the rest in spring.
[d]Winter rye was sown in all plots without preceding ploughing.

Table 4
Main crops, catch crops, and amounts of N, P, and K supplied by mineral fertilizer during the period 2007–2021.

Agrohydro-logical year 1 July-30 June	Main crop	Catch crop	Mineral fertilizer[a] kg ha^{-1}		
			N	P	K
2007–2008	Barley	P. ryegrass	105	15	50
2008–2009	Oats	P. ryegrass	100	20	40
2009–2010	Barley	P. ryegrass	96	16	20
2010–2011	Potatoes	Winter rye	100	63	238
2011–2012	Oats	*No catch crop*	103	11	19
2012–2013	Barley	*No catch crop*[b]	*n.d.*	*n.d.*	*n.d.*
2013–2014	Winter rye	P. ryegrass	119	0	0
2014–2015	Barley	P. ryegrass	109	5	8
2015–2016	Barley	P. ryegrass	109	7	9
2016–2017	Potatoes	Oilseed rape	72	45	171
2017–2018	Barley	P. ryegrass	128	22	22
2018–2019	Oats	*No catch crop*[c]	88	24	24
2019–2020	Winter wheat	P. ryegrass	192	13	25
2020–2021	Oats	P. ryegrass	106	13	16

[a] Applied to the main crop, usually in April-June.
[b] Winter rye was sown in all plots after ploughing.
[c] Winter wheat was sown in all plots after ploughing.

2.2. Water sampling and analysis

Drainage water from the eight separately tile-drained plots was conducted to an underground monitoring station with a concrete dam, where discharge rates for all plots together were recorded using a Thomson V-notch and drain water level was measured by a displacement body on a weight gauge and recorded by a Campbell logger. After every 0.2 mm discharge, flow-proportional water subsamples (15 ml per occasion) were taken from each plot separately, using peristaltic pumps, and collected in individual polyethylene bottles. The aggregated water samples in the bottles were collected for analysis every two weeks during drainage periods. Standard methods were used to determine the concentrations of tot-N, NO_3-N + nitrite-N (NO_2-N), tot-P, PO_4-P and K in discharge water during the monitoring period 1993–2021 (Table S1 in Supplementary Material (SM)).

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 leaching load for each nutrient were combined to an annual value for the agrohydrological year (1 July-30 June), which was divided by the annual amount of drainage to obtain the mean annual concentrations of nutrients in drainage water.

2.3. Sampling of biomass, determination of crop yield, and chemical analyses

Aboveground biomass of catch crops, weeds, and volunteer plants was sampled in 3–4 randomized sub-plots (0.25 m^2) in all plots (in catch crop treatments, weeds and volunteer plants were included in the sample), at harvest (August), before tillage operations in late autumn (November-December), and before tillage operations in spring (April).

These samples were dried at 60°C and used for determination of dry matter (DM), N and carbon (C) content. Yields of cereal main crops were determined by harvesting three sub-plots (approx. 20 m^2) per plot and analyzing the samples for N, P, and K. Potato yields were determined by harvesting 20 m lengths of two adjacent rows. Concentrations of N, C, P, and K in biomass and grain were determined by 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). In statistics, mean values of the replicates from each plot were used.

2.4. Soil sampling and analysis

Soil samples for determination of mineral N content were taken at harvest (August-September), and before tillage operations in autumn (October-December) and spring (April-May). During 1993–2005, samples were taken on 11 occasions at harvest, eight occasions in autumn, and 10 occasions in spring, while during 2007–2017 samples were taken on four occasions at harvest, nine occasions in autumn, and four occasions in spring. Soil cores (20 mm diameter) were taken to 90 cm depth and divided into three layers (0–30, 30–60, and 60–90 cm). All soil samples were stored deep-frozen (-18°C) until analysis. Concentrations of NO_3-N and NH_4-N in soil samples were analyzed after extraction with 2 M KCl. The extract was analyzed colorimetrically on a Seal AA3 autoanalyzer. Actual water content and dry bulk density (0–30 cm: 1.33 kg dm^{-3}, 30–90 cm: 1.5 kg dm^{-3}) were used when transforming analytical values to kg ha^{-1}.

2.5. Statistics

Normality was tested with an Anderson-Darling test. Annual loads and concentrations of nutrients and yields met the requirements for normality. Data on biomass, N and C in biomass, and soil mineral N were log-transformed before statistical analysis. A mixed model was used to test for differences between treatments in the two different monitoring periods (1993–2006, 2007–2021), concentrations and loads of nutrients, biomass, N and C in biomass, and soil mineral N. Treatment and year were set as fixed factors, while in the repeated structure plot was set as the subject variable and year as repeated continuous variable. Within-year differences between treatments during the period 2007–2021 were tested with one-way ANOVA. When significant effects ($p<0.05$) were found, Tukey HSD test was used to compare mean values. Students' t-test was used to test for differences between plots 5 and 7 (S_{min} and CS_{min}). Statistical analyses were performed with JMP Pro 17 (SAS Institute Inc.).

3. Results

3.1. Hydrology and leaching

Mean annual precipitation during the monitoring period 1993–2021 was 685 mm and mean air temperature was 7.4°C (Fig. 1). During the full 28-year monitoring period, discharge from the plots usually occurred from September to April, while discharge from May to July was low in most years as transpiration and evaporation resulted in negative water balance (Fig. 1b). On average, annual discharge was 172 mm, ranging from 78 mm in 2002–2003–315 mm in 1994–1995 (Fig. 1a). Around 25% of yearly precipitation ended up as discharge (Fig. 1a), which is only 65% of the calculated long-term water balance for the region (Smhi., 2024). This indicated that some drainage water by-passed the drain-tiles and was not captured for measurements. However, the proportion of discharge of yearly precipitation varied between 12% and 42% and this variation could be related to the temporal distribution of precipitation, as high precipitation in summer resulted in less discharge than high precipitation in autumn (not shown). However, there was a

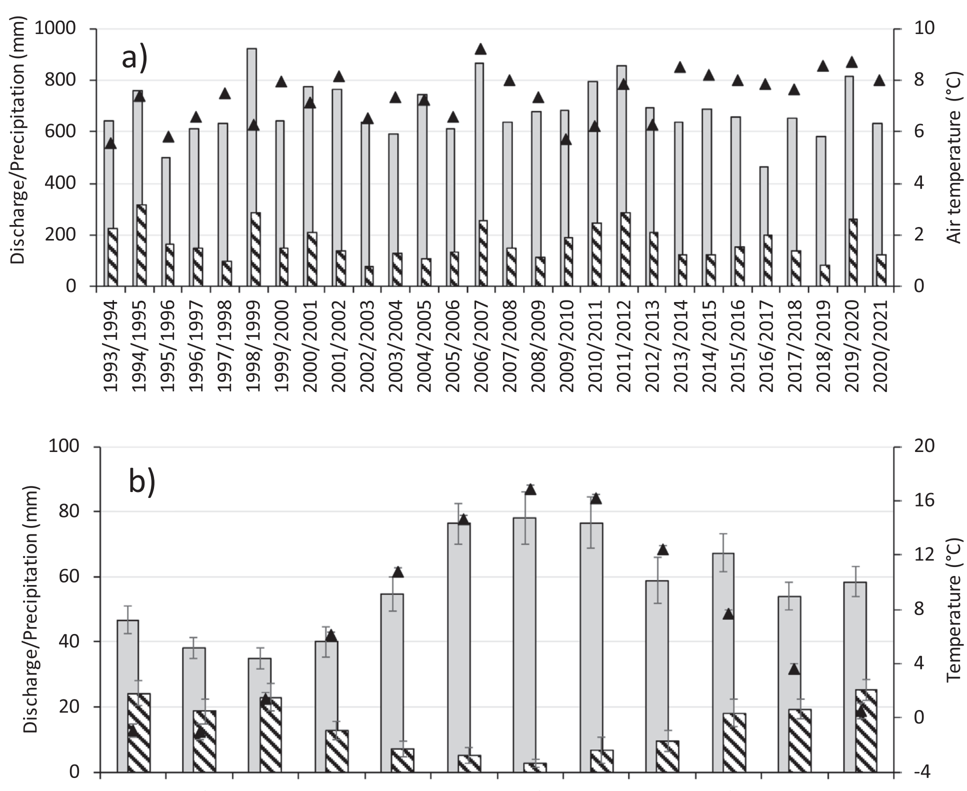

Fig. 1. Mean (n=28) (a) annual and (b) monthly precipitation (grey bars, mm), discharge from experimental plots (striped bars, mm), and air temperature (black triangles, °C) during 1993–2021. Standard error indicated on top of each bar.

positive linear relationship between yearly precipitation and yearly discharge ($p=0.0004$).

Mean yearly leaching of tot-N in drainage water from all plots was 17.8 kg ha^{-1} (range 5.2–40.4 kg ha^{-1}) during the 28-year monitoring period (1993–2021). The corresponding concentration in water was 10.3 mg N L^{-1} (range 5.6–19.9 mg N L^{-1}). Mean yearly leaching of tot-P was 0.04 kg ha^{-1} (range 0.015–0.07 kg ha^{-1}) and the concentration in water was 0.02 mg P L^{-1} (range 0.012–0.050 mg P L^{-1}). Mean yearly leaching of K was 18.2 kg ha^{-1} (range 6.4–33.7 kg ha^{-1}) and the concentration in water was 9.9 mg L^{-1} (range 7.9–11.8 mg L^{-1}).

3.2. Leaching and concentrations of N, P, and K in discharge during 1993–2007

During the first experimental period (1993–2007, years used as replicates), it was possible to compare spring tillage with autumn tillage involving stubble cultivation in September and ploughing in November, with and without a catch crop, all with and without pig manure application. On average, the treatments with pig manure received slightly more N (mineral fertilizer N + pig manure NH_4 = 103 kg ha^{-1}) than the treatments with only mineral N fertilizer (97 kg ha^{-1}). For P, the average dose (mineral + manure) during the period was almost the same for treatments with and without pig manure (27 and 28 kg P ha^{-1}, respectively), while it was slightly lower in treatments with manure for K (72 and 78 kg ha^{-1}, respectively).

Leaching and concentrations of tot-N and NO_3-N in drainage water were highest for the treatment combining pig manure application and autumn tillage (A_{man}) and lowest for the treatment combining a catch crop and spring tillage (CS_{min}) (Fig. 2). For the treatments with mineral N and pig manure + mineral N, N leaching decreased in the order: $A_{min}>CA_{min}>S_{min}>CS_{min}$ (differences between CA_{min} and S_{min} not significant) and $A_{man}>CA_{man}>S_{man}>CS_{man}$ (differences between CA_{man} and S_{man} not significant). The pig manure treatments had higher N leaching and concentrations in water than the corresponding treatments without manure application, although the differences were not always statistically significant (Fig. 2). Leaching and concentrations of tot-P and PO_4-P in drainage water varied considerably between years, but did not show any significant differences between treatments (Fig. 2). However, there was a tendency for higher leaching and concentrations of P in drainage water when spring tillage was combined with a catch crop and/or pig manure.

The treatments with a catch crop and spring tillage (CS_{min}, CS_{man}) had significantly higher leaching and concentrations of K than all other treatments, while the values were lowest for the corresponding treatments with autumn tillage (CA_{min}, CA_{man}) (Fig. 2).

3.3. Leaching and concentrations of N, P, and K during 2007–2021

In the period 2007–2021, when conventional autumn tillage was compared with spring tillage with and without a catch crop, leaching and concentrations of tot-N and NO_3-N in drainage water decreased in the order: $A_{min}>S_{min}>CS_{min}$, but differences between spring tillage with a catch crop (CS_{min}) and spring tillage were only significant for concentrations of tot-N (Table 5). The concentration of tot-N in drainage water decreased by 1.6 mg L^{-1} with spring tillage compared with autumn tillage, and growing a catch crop decreased the concentration by a further 1.2 mg L^{-1} (Table 5). Tot-P showed the opposite trend, with the lowest leaching and concentrations in drainage water from the autumn tillage treatment, while spring tillage increased the values slightly (not significant) and adding a catch crop gave the highest (significant) values of tot-P leaching and P concentrations in drainage water (Table 5). Treatment effects on N and P leaching were observed during most years and were significant in some years (Fig. 3). Even though the eight plots had different pre-histories since the first experimental period, a significant treatment effect was evident already in the first year (Fig. 3).

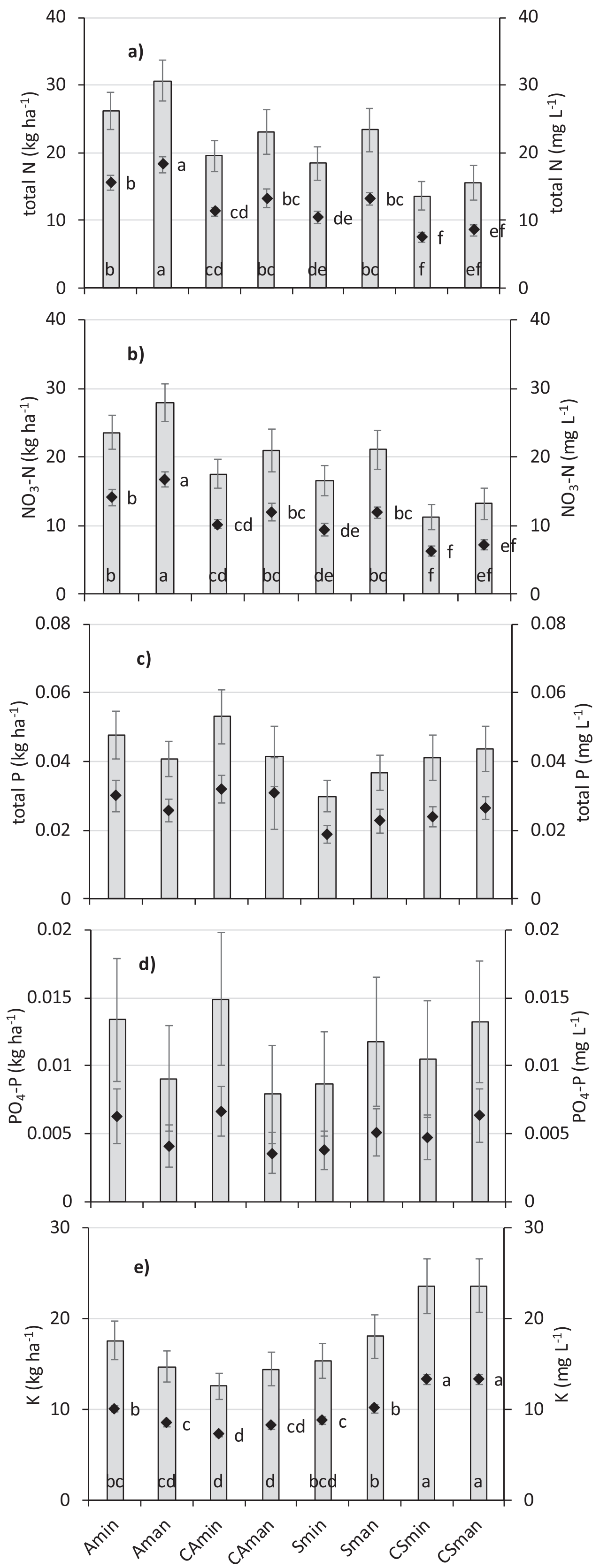

Fig. 2. Mean leaching (bars, kg ha^{-1}) and concentrations in drainage water (points, mg L^{-1}) of (a) total nitrogen (N), (b) nitrate-nitrogen (NO_3-N), (c) total phosphorus (P), (d) phosphate-phosphorus (PO_4-P), and (e) potassium (K) during 1993–2007. Standard error indicated on top of bars. Different letters denote significantly different mean values ($p<0.05$; $n=14$ (PO_4-P=9)).

Table 5
Mean leaching (kg ha^{-1}) and concentrations (mg L^{-1}) of total nitrogen (N) and total phosphorus (P) in drainage water in the treatments autumn tillage (A_{min}), spring tillage (S_{min}), and spring tillage+catch crop (CS_{min}) during the period 2007–2021 and of nitrate-N (NO_3-N), phosphate-P (PO_4-P), and potassium (K) during the period 2007–2011. Mean, standard error in brackets. Different letters denote significantly different mean values ($p<0.05$; Tot-P, tot-N, n=14, NO_3-N, PO_4-P, K, n=5).

		Autumn tillage A_{min}	Spring tillage S_{min}	Spring tillage+catch crop CS_{min}
Total-N	kg ha^{-1}	17.3[a] (1.59)	14.6[b] (1.13)	12.7[b] (1.13)
	mg L^{-1}	10.0[a] (0.62)	8.4[b] (0.39)	7.2[c] (0.40)
NO_3-N	kg ha^{-1}	18.4 (2.61)	15.3 (2.05)	14.4 (2.19)
	mg L^{-1}	9.3[a] (0.73)	7.5[b] (0.54)	7.0[b] (0.65)
Total-P	kg ha^{-1}	0.029[b] (0.0021)	0.032[b] (0.0022)	0.042[a] (0.0025)
	mg L^{-1}	0.018[b] (0.0016)	0.020[b] (0.0018)	0.026[a] (0.0019)
PO_4-P	kg ha^{-1}	0.015 (0.0018)	0.018 (0.0015)	0.017 (0.0014)
	mg L^{-1}	0.008 (0.0009)	0.010 (0.0007)	0.009 (0.0008)
K	kg ha^{-1}	20.9 (3.13)	17.6 (2.40)	21.7 (2.71)
	mg L^{-1}	10.4 (0.75)	8.6 (0.50)	10.6 (0.53)

Analysis of NO_3-N, PO_4-P, and K was only performed in five years (2007–2011). In that period, NO_3-N showed the same trend as tot-N, while PO_4-P did not differ significantly between treatments, although spring tillage gave the highest leaching of PO_4-P (Table 5). Potassium leaching did not show significant differences between the treatments (Table 5). During this period (2007–2011), the discharge and thus, leaching was on average slightly higher than for the period 2007–2021, which can be noticed e.g. by the leaching of NO_3-N being higher than the leaching of tot-N (Table 5).

3.4. Leaching and concentrations of N, P, and K in drainage water from two plots during 1993–2021

Plot 5 (S_{min}) and plot 7 (CS_{min}), see Table 2, differed only in use of a catch crop over the whole 28-year period, which enabled comparison of the long-term effect of a yearly catch crop in a spring tillage system with only mineral N fertilizer. A catch crop (most years perennial ryegrass) was grown in plot 7 in all except six years, in three of which a winter crop was grown instead. In almost every year and as a long-term average, use of a catch crop (plot 7) resulted in higher leaching and higher concentrations of tot-P and K in drainage water, but lower leaching and lower concentrations of tot-N in drainage water, compared with no catch crop (plot 5) (Fig. 4).

Mean CS_{min}:S_{min} ratio over 28 years of leaching was 0.8 for N, 1.4 for P, and 1.5 for K. For P, there was no trend over time ($p>0.05$). For N, there was positive trend for CS_{min}:S_{min} over the period ($p<0.05$), indicating that the effectiveness of the catch crop in reducing N leaching decreased over time. For K, there was a negative trend ($p<0.01$) for CS_{min}:S_{min}, indicating that effect of the catch crop in increasing K leaching also decreased over time.

3.5. Influence of main crops on leaching

As can be seen in Figs. 3 and 4, there were large annual variations in leaching of nutrients, which can be attributed to differences in weather conditions, but also to the different main crops. The main crops grown were mostly spring cereals (oats or barley), but in five years the field was cropped with potatoes and in three years with a winter crop (winter wheat, winter rye, oilseed rape). Significantly larger leaching losses of both N and K were detected after potatoes (28.9 and 22.9 kg ha^{-1} for N and K, respectively) compared with spring cereals (18.4 and 16.7 kg ha^{-1} for N and K, respectively) (all values from plots without a catch crop), while no significant difference between crops was seen for P.

3.6. Biomass and N and C content of catch crops and weeds

In 1993–2005, aboveground biomass of catch crops, weeds, and volunteer plants was sampled on three occasions: 1) in all plots at harvest (only for years with undersown catch crops), 2) in the spring tillage plots and the two plots with a catch crop before autumn tillage, and 3) in the spring tillage plots before tillage was performed. On all three sampling occasions, the treatments with a catch crop had more biomass than treatments without a catch crop, so the content of N in biomass was also higher (Table 6). The average content in catch crop biomass at sampling in November was 12.8 kg N ha^{-1}, which represented an increase of 6.3 kg N since sampling at harvest. The content in spring was 11.6 kg N in CS treatments. Thus, there was no net increase in aboveground biomass over winter. In S treatments, there was a decrease in weed biomass over winter and in spring, only 2.5 kg N ha^{-1} was remaining in biomass. There were no significant differences between the CS_{min} and CS_{man} treatments and thus no clear effect of manure application on growth of catch crops.

In 2007–2017, biomass of catch crops, weeds, and volunteer plants was sampled in all plots in late autumn (October-November). In some years, the amount of weed and volunteer plant biomass in the treatments without an undersown catch crop was similar to that in the treatment with perennial ryegrass, but on average across the nine years the catch crop treatment had almost double the amount of biomass, N content, and C content (Table 7). Content of N and C in biomass from treatments with a catch crop was 2.3% (SE 0.1) and 45% (SE 0.2), respectively, while the content in treatments without catch crop (only weed biomass) was 2.7% (SE 0.1) and 43% (SE 0.4), respectively.

3.7. Yield of main crop

During the first monitoring period, 1993–2006, there were no replicates of the treatments, so it was impossible to perform comparisons of crop yields within each year. The main crops were different in each year, so long-term compilation was also not possible (data not shown).

During the second monitoring period (2007–2021) there were replicates, making it possible to compare yields and content of N, P, and K in grain between the three treatments. Spring tillage combined with a catch crop did not have an impact on yield in any of the years, compared with autumn tillage (data not shown). In some years there were significant differences in grain content of N and P between treatments, but no clear trends (data not shown).

3.8. Soil mineral N

In 1999–2005, within the first monitoring period, soil mineral N content (NO_3-N and NH_4-N) was analyzed to 90 cm depth at harvest, and in autumn and spring. There was a tendency for higher mineral N content in the soil profile in treatments with pig manure on all occasions (Fig. 5a). In autumn (October-December), mineral N content was significantly higher in the treatments with stubble cultivation in September (A_{min} and A_{man}) than in the other treatments, probably due to stubble cultivation leaving the soil tilled and not covered with catch crops or weeds on the sampling occasion (Fig. 5a). In spring, the spring tillage and catch crop treatments had significantly lower soil mineral N content than the other treatments (Fig. 5a).

In part of the second monitoring period, 2007–2017, samples for soil mineral N analysis were taken with similar frequency as in the first

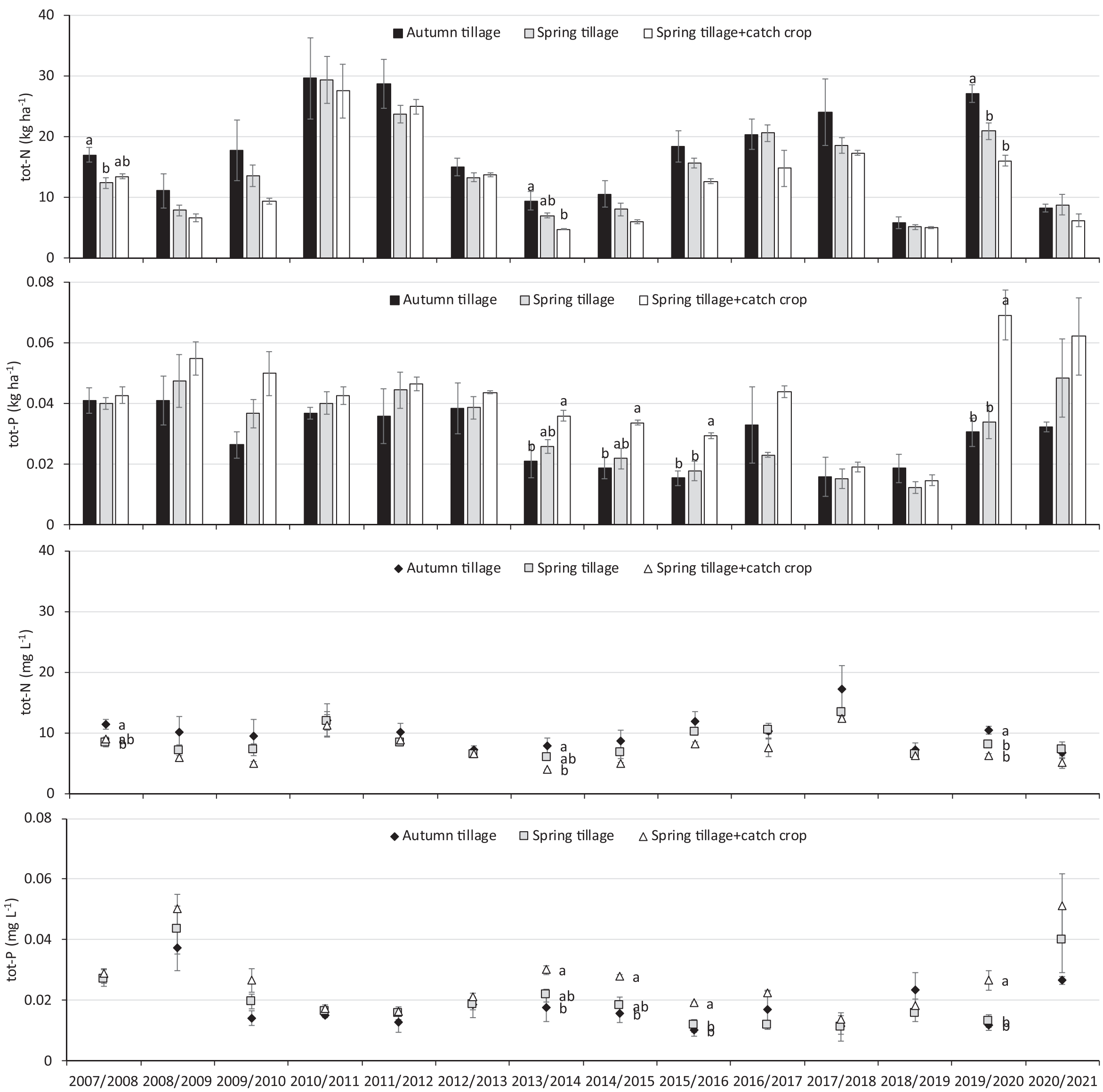

Fig. 3. Mean yearly leaching (bars, above) and concentrations in drainage water (points, below) of total nitrogen (N) and total phosphorus (P) in the treatments autumn tillage (A_{min}), spring tillage (S_{min}), and spring tillage+catch crop (CS_{min}), 2007–2021. Different letters denote significantly different mean values ($p<0.05$, n=2–3).

period. The results showed no difference between treatments at harvest. From harvest until late autumn, the mineral N content of the topsoil decreased in all treatments, mainly due to uptake in weeds and catch crops, but to a minor extent also due to transport of N downwards. The catch crop treatment, $CS_{min,}$ had significantly lower mineral N content in the soil profile than the other treatments in late autumn (Fig. 5b). Here, the reduction of mineral N in the topsoil during autumn was in total 16 kg ha^{-1}, of which 15 kg seemed to be due to crop uptake and 1 kg due to transport below the topsoil. For the other two treatments the reduction of mineral N in the topsoil during autumn was 12 kg ha^{-1} where 9 kg seemed to be taken up by crops and 3 kg was transported downwards.

In spring, both S_{min} and CS_{min} had significantly lower mineral N content than the A_{min} treatment, where there was an accumulation of mineral N in the subsoil (Fig. 5b). This could indicate both less uptake by crops over winter than in S_{min} and CS_{min}, and larger N mineralization in A_{min}. It also showed that even if not all mineral N was lost through leaching it was not available for the crop (30–90 cm depth). During the second period, there was no stubble cultivation prior to ploughing in A_{min}.

4. Discussion

This study present results from one of the Swedish long-term field experiments, which was started in 1993 with the aim to find ways for Swedish agriculture to reduce nutrient leaching losses and meet the national environmental goal *No eutrophication* and the requirements of the EU Water Framework Directive. The knowledge gained about effects of catch crops has been implemented in national advisory programs and subsidy programs for growing catch crops. The experimental set-up was changed once since start in 1993, but the core questions were kept. The change was implemented to enable statistical analysis of replicates and to decrease costs by excluding manure treatments. Long-term effects of manuring in combination with catch crops are highly interesting, but a decision was made to prioritize statistically secure evaluation of treatments, with the focus on catch crops. The two experimental periods in many ways resulted in similar conclusions, so changes were assessed for the whole 28-year period.

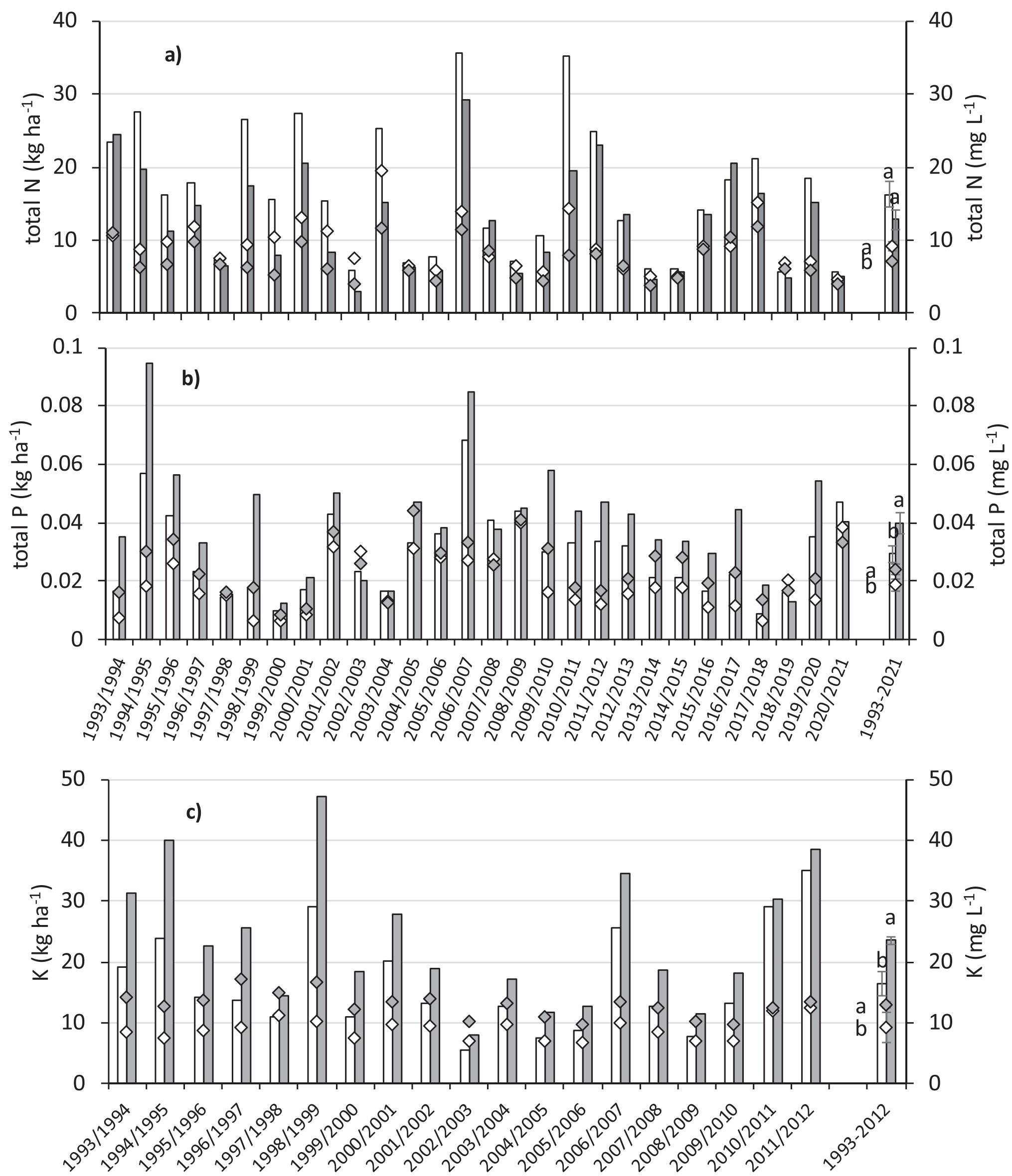

Fig. 4. Leaching (bars, kg ha^{-1}) and concentrations in drainage water (squares, mg L^{-1}) of (a) total nitrogen (N), (b) total phosphorus (P) and (c) potassium (K) from plot 5 (without catch crop, white bars) and plot 7 (with catch crop, grey bars), both with spring tillage and mineral fertilizer application. Mean for the period 1993–2021 for N and P, 1993–2012 for K and standard error. Different letters denote significant difference (t-test, p<0.05).

Table 6
Mean biomass of catch crop and/or weeds and content of nitrogen (N) in biomass, 1993–2005. Standard error in brackets. Different letters denote significantly different mean values (p<0.05). A – autumn tillage, S – spring tillage, C – cover crop, min – mineral fertilizer, man – pig manure.

	At harvest		*Late autumn*		*Spring*	
	Biomass kg DW ha^{-1}	N in biomass kg ha^{-1}	Biomass kg DW ha^{-1}	N in biomass kg ha^{-1}	Biomass kg DW ha^{-1}	N in biomass kg ha^{-1}
A_{min}	229^{b} (172)	4.6 ^{cd} (3.1)				
A_{man}	240^{b} (202)	5.4^{bcd} (3.8)				
CA_{min}	377^{a} (116)	7.0^{a} (2.1)	652^{ab} (97)	11.0^{abc} (1.5)		
CA_{man}	297^{a} (51)	5.4^{abc} (1.1)	791^{ab} (149)	15.0^{ab} (2.6)		
S_{min}	119^{b} (65)	2.6^{d} (1.5)	442^{bc} (166)	10.0^{bc} (3.5)	162^{bc} (86)	3.7^{b} (1.7)
S_{man}	96^{b} (51)	1.9^{d} (1.1)	279^{c} (111)	7.4^{c} (2.8)	34^{c} (10)	1.2^{b} (0.3)
CS_{min}	425^{a} (105)	6.6^{ab} (2.3)	568^{ab} (110)	11.4^{ab} (2.0)	448^{ab} (86)	10.8^{a} (1.9)
CS_{man}	406^{a} (119)	6.9^{ab} (2.8)	685^{a} (129)	13.7^{a} (2.2)	496^{a} (85)	12.4^{a} (2.1)

4.1. Leaching of N, P, and K

There was great variation in nutrient leaching during the 28-year period, partly due to variations in annual precipitation and temperature, as seen in a recent study of agricultural catchments in Sweden (Ezzati et al., 2023). Mean annual leaching losses of tot-N (18 kg ha^{-1})

Table 7
Average biomass of catch crops including weeds (kg DW ha^{-1}) and content of nitrogen (N) and carbon (C) in biomass (kg ha^{-1}) in the treatments autumn tillage (A_{min}), spring tillage (S_{min}), and spring tillage+catch crop (CS_{min}) in autumn before autumn tillage, 2007–2017. Different letters denote significantly different mean values ($p<0.05$, n=9).

	Biomass kg DW ha^{-1}	N in biomass kg ha^{-1}	C in biomass kg ha^{-1}	C:N ratio in biomass
A_{min}	392^{ab} (94)	10^{ab} (2.5)	163^{b} (37)	16
S_{min}	351^{b} (74)	9^{b} (2.0)	147^{b} (29)	16
CS_{min}	609^{a} (137)	14^{a} (3.5)	269^{a} (59)	19

and K (18 kg ha^{-1}) from the field were within the range reported in some Swedish studies (Aronsson et al., 2015; Wallman and Delin, 2022), although considerably higher N leaching losses have been reported for sandy soils in Sweden (Torstensson et al., 2006). Of the tot-N found in drainage water, NO_3-N constituted 99%. The drainage constituted 25% of precipitation on annual basis, which was in the same range as in Norberg and Aronsson (2020) but about half of that in Torstensson and Aronsson (2000), both studies on similar tile-drained plot experiments. There was thus by-pass of water that was not collected by the drain-tiles since our measured average drainage was only 65% of the long-term (1981–2010) estimated average water balance for the region (Smhi., 2024). Consequently, also total N leaching from 90 cm depth was underestimated to the same extent. Therefore, the values for N leaching should mainly be used for comparions between treatments. For appropriate quantification of N leaching from the rootzone, the measurements of concentrations in drainage water would preferably be complemented with a water balance model.

The topsoil at the field site had relatively high soil test P values (P-AL=16.4 mg 100 g^{-1}), but leaching losses of tot-P were very low (mean 0.038 kg ha^{-1}) compared with in other studies on similar soil types (Aronsson et al., 2015; Andersson et al., 2015). The low P losses can be due to low transport of particles downwards, as the sandy soil profile had no visible cracks and only a few macropores in the subsoil. Of the tot-P found in drainage water, on average 35% was in the form of PO_4-P. There was probably high sorption capacity for soluble P in the subsoil, as a result of presence of iron and/or aluminum oxides (Andersson et al., 2015).

The K status of the soil was moderate with respect to plant-available amounts (9.7 mg K-AL 100 g^{-1}), which means that K fertilization is recommended for all crops. Leaching losses of K (18 kg ha^{-1}) comprised a substantial part of added K (application rate 20–50 kg ha^{-1} in most years). Leaching of K from sandy soils can be substantially greater than from clay soils, due to fewer sorption sites in coarse-textured soils (Torstensson et al., 2006; Aronsson et al., 2007; Goulding et al., 2021), although the opposite has also been found (Alfaro et al., 2004). High K leaching from clay soils is due to rapid transport of soluble K or particulate K via the macropores present in clay soils. Besides soil texture and structure, K leaching may also be affected by other factors. For example, presence of calcium ions (e.g., after liming or irrigation) has been shown to increase K leaching due to replacement of K ions on mineral surfaces (Kolahchi and Jalali, 2007), while presence of NO_3-ions together with K-ions will favor leaching of both elements, by transport as

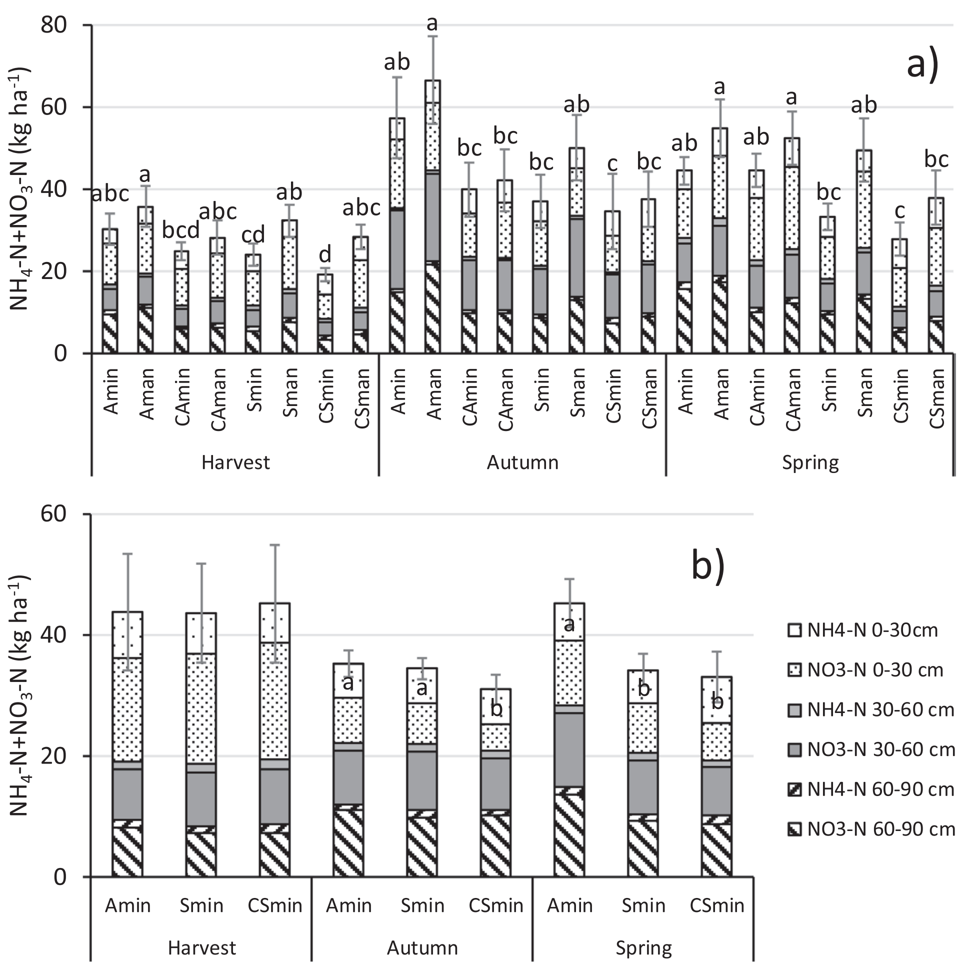

Fig. 5. Mineral nitrogen content (NH_4-N and NO_3-N, kg ha^{-1}) in the soil profile (0–30, 30–60, and 60–90 cm depth) at harvest, autumn, and spring in the different treatments for (a) 1999–2006 and (b) 2007–2017. Mean for 0–30, 30–60, 60–90 cm, standard error for 0–90 cm. Means for the 0–90 cm layer within sampling occasions annotated with different letters are significantly different ($p<0.05$).

ion pairs. Application rates of K were high during the years with potatoes (200 kg ha^{-1}), but despite the large difference in application rate between cereal and potatoes, there was no relationship between applied K and K concentration in drainage water or K leaching. Askegaard, Eriksen (2000) concluded that K leaching is a result of history rather than the current K budget, with a time lag before K leaching losses. A fertilization history with high rates of K fertilizer or animal manure over time may result in K saturation of the soil and increased leaching as sorption sites become occupied (Goulding et al., 2021; Rosolem et al., 2010). However, this was obviously not the case in this study, where manure application rates were moderate.

The crop rotation was dominated by spring cereals but with potatoes during some years, after which winter rye was sown as a catch crop instead of undersown ryegrass. Leaching of N was considerably higher after potatoes than after cereals, but was reduced (10%) by presence of a catch crop (Table 3 & 4, Fig. 4). However, leaching of P and K seemed not to be substantially affected by the potato crop, despite high K fertilizer rates for this crop. This might be a result of the crops utilizing applied K rather well and of some sorption of K to the soil matrix. Higher N leaching after potatoes than after spring cereals, but with P leaching unaffected, was also found by Neumann et al. (2012).

4.2. Effects of time of tillage on leaching

Time of tillage (cultivation + ploughing or just ploughing) had an impact on N leaching during both experimental periods. Spring tillage treatments without catch crops (S_{min}, S_{man}) had lower N concentrations in water and leaching losses than treatments without catch crops and tillage in autumn (A_{min}, A_{man}). The term tillage here refers to cultivation followed by ploughing in 1993–2005 and only ploughing in 2006–2021. Postponing tillage from autumn to spring has been shown to reduce the risk of N leaching from sandy soils in Denmark and southern Sweden (e. g., Wallgren and Linden, 1994; Hansen and Djurhuus, 1997; Stenberg et al., 1999; Myrbeck and Stenberg, 2014). The present study showed that it is also the case for agricultural areas with a slightly colder climate, verifying information used when developing a subsidy for spring ploughing that was offered to farmers in Sweden from 1995. Avoiding tillage in early autumn results in less mineralization, and thereby less accumulation of leachable N in the soil during autumn. Soil tillage also interrupts growth of weeds and volunteer plants and their N uptake, and thereby elevate losses (Myrbeck et al., 2012).

During the first period (1993–2006), spring tillage (stubble-cultivation once followed by ploughing) and catch crop treatments were compared with conventional autumn tillage, where the soil was stubble-cultivated twice in September and ploughed in November. Stubble cultivation is a common strategy for weed control, so the amount of weed biomass was low in late autumn (not measured) and there was an increase in soil mineral N in autumn in treatment A_{min} and especially in A_{man} (Fig. 5a). During the period 2007–2021, there was no stubble cultivation before ploughing in A_{min} and weed growth produced biomass of approximately 70% of the amount in catch crop treatments before autumn ploughing. This can explain the smaller differences in soil mineral N between the treatments at autumn sampling compared with the first period. Despite this, the catch crop treatment (CS_{min}) had significantly lower soil mineral N than the other two treatments (A_{min}, S_{min}), which indicates that the catch crop was more effective in taking up soil N than weeds (Fig. 5b). Furthermore, spring ploughing (S_{min}) had 16% lower N leaching than ploughing in November (A_{min}).

However, time of tillage did not have any significant impact on concentrations or leaching losses of tot-P and PO_4-P (Fig. 2 and Table 5) or on losses of K, although there was a tendency for higher concentrations and losses of K with spring compared with autumn tillage during the first monitoring period (Fig. 2).

A previous review of Scandinavian soils concluded that spring tillage reduces P losses compared with autumn tillage and can be an important method for reducing erosion and P loss from soils (Ulén et al., 2010). However, the studies reviewed were mainly on clayey soils, where losses of particulate P are a major issue, which was not the case for our sandy loam soil, where P losses were very low.

4.3. Effects of catch crops on N leaching

Growing a catch crop of perennial ryegrass until spring reduced drainage water concentrations and leaching losses of total N and NO_3-N even further than just postponing tillage until spring (Fig. 2, Table 5). During the second monitoring period, the yearly leaching load of tot-N decreased by on average 28% (range 7–50%) with a catch crop in combination with spring tillage (CS_{min}), compared with autumn tillage without a catch crop (A_{min}) (Table 5). Adding a catch crop to the spring tillage treatment (CS_{min}) gave a reduction in N leaching of around 14% compared with spring tillage without a catch crop (S_{min}). One explanation is lower soil mineral N content to 90 cm depth in autumn and spring in the treatment with a catch crop (CS_{min}) than in treatments without (A_{min}, S_{min}) (Fig. 5b). This indicates that N was taken up by the catch crop instead of being transported downwards in the soil profile and lost with drainage water. In a Danish field study, inclusion of a catch crop reduced nitrate leaching from three different sandy soils by 26–38% (Askegaard et al., 2005).

In spring, before spring tillage in the first monitoring period, the catch crop had much better growth and showed greater potential for reducing N leaching than the treatments without an undersown catch crop (Table 6). Perennial ryegrass had a higher ability to survive the winter, start growing early in spring, and take up N during a longer period than weeds and volunteer plants. Weeds and volunteer plants were present, sometimes in similar amounts of biomass in autumn as in the undersown catch crop treatments (Tables 6 and 7). This contributed to reduced N leaching, but propagation of perennial weeds, like couch grass, may be a problem in the long term and would require chemical weed control. A catch crop can reduce the amount of weeds (Bergkvist et al., 2010) and, with different management strategies, it can potentially replace or complement mechanical treatments by combining weed control and reduced N leaching (Aronsson et al., 2015).

Uptake of N in an undersown catch crop is dependent on its growth during summer, as influenced by weather conditions and competition with the main crop (Wallgren and Linden, 1994), and also on conditions for growth during autumn (Aronsson et al., 2016). Perennial ryegrass can produce aboveground biomass of 1000 kg DM ha^{-1} and roots to 1 m depth in autumn, reducing soil mineral N content in the soil profile (Sapkota et al., 2012). The catch crops in this study had biomass of around 300–800 kg DM ha^{-1} in autumn, which is quite low but reasonable for the region. Winter rye was used as a catch crop after harvest during three of the five years with potatoes (1996, 2000 and 2010) and winter rape was used in one year (2016). Due to late harvest of potatoes, the winter rye was sown in October. The growth was not substantial as expected for this late time of sowing, but there was a not negligible uptake of N of the catch crop (4–10 kg N ha_{-1} in abovegrund biomass). There were tendencies for effects of the winter rye catch crop on N leaching, except for 2010 (Figs. 3 and 4). In 2016, the potatoes were harvested in August and oilseed rape as a catch crop grew very well, and reduced N leaching, although not significantly (Fig. 4). Similar results were found in another Swedish study by Neuman et al. (2012). They found that triticale sown in October after harvest of late potatoes did not satisfactorily reduce N leaching, while oilseed radish after potatoes harvested in August did.

4.4. Effects of catch crops on P and K leaching

In contrast to N, the concentrations and leaching losses of tot-P increased in treatments with a catch crop compared with treatments without (tendency during the first period (Fig. 2), statistically significant difference during the second period (Table 5)). Similarly, Aronsson et al. (2015) and Hanrahan et al. (2021) observed a trend for raised P losses with catch crops compared to treatments without catch crops. However, a review by Aronsson et al. (2016) concluded that P losses can increase by up to 86%, or decrease by up to 43%, with a ryegrass catch crop compared with a control without a catch crop. For example, Bechmann et al. (2005) found that tot-P runoff from soils with a catch crop was only around 25% of that from bare soil, probably due to less erosion, while Norberg and Aronsson (2020) saw no impact of catch crops on P leaching.

Losses of dissolved P (PO_4-P) did not show as clear a trend as tot-P, and the spring tillage with catch crop treatment (SC_{min}) had similar losses of PO_4-P as the treatment with spring tillage without a catch crop (S_{min}) during the second monitoring period (Table 5). Several studies, e.g., Liu et al. (2019), have observed release of dissolved P from catch crops after freeze-thaw cycles. In this study, there was a substantial growth of weeds in the treatment without a catch crop (S_{min}). During earlier years, when catch crop and weed biomass were measured also in spring (Table 6), it was observed that weed biomass was smaller but more severely affected by winter than catch crop biomass, which may explain the results. On average during 1993–2021, 35% of P losses were in dissolved form (PO_4-P), which is in line with reported concentrations in a nearby stream with similar soil types in the catchment (Linefur et al., 2022).

The spring tillage treatments with a catch crop (CS) had significantly greater losses of K than the treatments without (S) (Fig. 4, Table 5). One possible explanation is that K, which occurs as ions in plant cells, was rapidly released from catch crops and weeds dying over winter and thereby contributed to a pool of leachable K.

4.5. Effects of pig manure on leaching

Application of pig manure increased water concentrations and leaching losses of tot-N and NO_3-N by 14–21% (Fig. 2), with significant differences for A_{min} versus A_{man}. In a Danish field study, there were no differences in NO_3-N leaching from sandy soils with or without manure application (Askegaard et al., 2005). A study by Torstensson and Aronsson (2000) concluded that the dose of manure applied in combination with mineral N needs careful adaptation to reduce the risk of N losses, but also that a catch crop will buffer accidentally high amounts of mineral N due to over-application of N with manure. This could not be confirmed here, since average growth of the catch crops was not significantly greater in treatments with manure despite somewhat larger amounts of mineral N in the soil (Table 6).

The pig manure was applied in spring and the dose of NH_4-N it supplied was the same as in treatments with mineral fertilizer, which ended up with a (practically negligible) 6 kg NH_4-N ha^{-1} more in manured plots. The mean rate of organic N (tot-N - NH_4-N) applied in plots with manure was 32 kg N ha^{-1} and thus there was potential for increased N mineralization, which was probably the main reason for the higher amounts of mineral N (Fig. 5) in the soil and the greater N leaching in plots with manure. The catch crop could not utilize this extra N.

Losses of total P and PO_4-P were low. Since P application with manure was not greater than in treatments without manure, this lack of difference in P losses was expected, in line with findings by Van Es et al., (2004), that P leaching losses following manure application are not a major problem on loamy sand soils. Moreover, Aronsson et al. (2014) showed that application of pig manure in April to spring cereals did not increase tot-P losses, but increased tot-N losses, compared with control plots.

Pig manure did not have any influence on K concentration or leaching (Fig. 2), which was expected since the mean rate of K application in treatments with manure was slightly lower than in the treatments with only mineral fertilizer

4.6. Long-and short-term trends of catch crops

The long-term data on drainage water concentrations and leaching of N showed that the treatment effects (tillage and catch crop) appeared in most years and persisted over time, although there were substantial variations between years (Figs. 3 and 4). This shows the importance of long time-series to reveal the robustness of measures, but also trends over time. For N, but not for P, there was a significant trend for a reduced catch crop effect over time, analyzed as the ratio of treatments with spring tillage with and without a catch crop (CS_{min}:S_{min}). Reduced effect of catch crops over time can be expected due to long-term build-up of soil organic matter, as N that would otherwise have been lost is accumulated in the soil (Thorup-Kristensen et al., 2003). The N content in aboveground catch crop biomass in late autumn was 7–15 kg ha^{-1} and the catch crop stored 5–11 kg N ha^{-1} per year more in aboveground plant material over winter than in treatments where just weeds were growing. Catch crop growth was moderate in a Scandinavian context, where average N content of 7–38 kg ha^{-1} have been reported for perennial ryegrass catch crops (meta-study by Aronsson et al., 2016). From the results, it was not possible to confirm if the trend found was a result of increased N storage and mineralization over time in the catch crop treatment or due to other factors. Examination of soil organic N content and evaluation with a process-based N model are needed to investigate N storage and flows more thoroughly.

In this study, where catch crops were grown every year, we could not fully evaluate the residual effects of a catch crop on the yield of the crop grown afterwards, since there were effects of competition between current main crop and catch crop and an N fertilizer effect on the next main crop. However, the C:N ratio of catch crop biomass was 19, indicating net mineralization of N after incorporation of the catch crop and also of weed biomass (Stevenson, 1986), which had even lower C:N ratio (16). There were no observed differences in yields between treatments with and without catch crops, which indicates that the main crop had sufficient access to essential nutrients in all treatments, due to application of pig manure and mineral fertilizer. Stenberg et al. (1999), who studied similar treatments on a sandy soil in southern Sweden, saw no effect on grain yields due to catch crops or autumn or spring tillage during the year before, while a meta-analysis by Tonitto et al. (2006) concluded that residual effects of grass catch crops on the main crops during the following year are often negligible. Constantin et al. (2023) developed a tool for estimation of residual effects of catch crops for the following crop, based on data from France. They estimated values for N availability from grass catch crops during 6 months after incorporation to vary between 0 and 50 kg N ha^{-1}.

5. Conclusions

This study evaluated 28 years of results from a field experiment assessing cropping practices to reduce nutrient leaching. Autumn and spring ploughing (with/without a catch crop) were compared with respect to leaching of N, P, and K. The effect of applying pig manure in these treatments was assessed during part of the 28-year period.

Growing a catch crop (incorporated in autumn or spring) proved to be a robust measure for reducing annual N leaching, although the effectiveness seemed to decline slowly over time. Pig manure application in spring resulted in increased mineral N content in soil during autumn and increased N leaching over winter, but losses of P and K were not affected.

Phosphorus leaching from soil increased with a catch crop, but was negligible owing to the very low overall P leaching from the loamy sand soil at the study site. Thus, soil properties such as P transport pathways and binding capacity should be considered choosing an on-farm strategy to reduce either N or P losses.

Potassium leaching was considerable (40–90% of K applied to cereals) and growing a catch crops increased these losses. While K losses are not an environmental concern, they should be considered since K is a finite resource.

Running long-term studies over decades can be a challenge due to costs, acceptable statistical evaluation methods, and changing societal relevance, but long-term studies are very important in order to confirm the cumulative outcome of mitigation measures and explore long-term trends appearing slowly due to altered conditions or build-up effects and climate change. The set-up in the field experiment was changed after 14 years but the core values were retained, making results from both periods comparable.

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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.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.eja.2024.127156.

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