EFFECTS OF DRAINAGE SYSTEM DESIGN ON NUTRIENT LEACHING AND CROP YIELD

Collection
Research Brief

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HIGHLIGHTS

- Tested drainage system designs had no clear effect on the total amount of drainage discharge.
- Tested drainage system designs had a clear effect on nutrient loads in drainage discharge.
- Corrugated plastic pipe drainage systems had higher N loads and lower P loads than tile drainage systems.
- Corrugated plastic pipe drainage systems gave higher yields than tile drainage systems and can be a profitable on-farm investment.

ABSTRACT. *A clear strategy for adapting agricultural drainage to future climate change is important for environmental and economic reasons. In a study aimed at developing recommendations for the subsurface drainage design in clay soils, we evaluated the impact of replacing an old drainage system (1920) with new systems (2018) on nutrient leaching and crop yield. Our field experiment included 12 individually drained plots divided into four treatments: (A) old system with clay tiles at 10 m spacing, without an envelope; (B) new system with plastic pipes at 10 m spacing, gravel envelope; (C) new system with plastic pipes at 5 m spacing, gravel envelope; and (D) new system with plastic pipes at 10 m spacing, gravel envelope and lime incorporated in trench backfill. We conducted flow measurement and flow-proportional, logger-controlled water sampling of the drainage discharge from each plot at a measuring station. Preliminary results (first two years) show a clear effect of the new drainage systems on phosphorus and nitrogen loads in drainage discharge. The lowest total load of phosphorus and highest total load of nitrogen in all treatments were observed in treatment D (with 10 m drain spacing and lime incorporated in trench backfill). The highest total phosphorus load and lowest total nitrogen load in all treatments were observed for the old tile drainage system with 10 m drain spacing (treatment A). The environmental impact of new drainage systems on clay soils may thus be a trade-off between decreased phosphorus loads and increased nitrogen loads with more intensive drainage. Crop data from two experimental years indicated that investing in new drainage systems can be profitable for farmers, as crop yield was 3%-20% higher with new drainage systems compared with old tile drainage. More experimental years are needed to determine the long-term effects of the different drainage system designs.*

Keywords. *Drain envelope, Drain spacing, Nitrogen load, Phosphorus load, Subsurface drainage.*

Global climate change during the past century, and particularly in recent decades, is now widely accepted (Cook et al., 2016). In northern Europe, future precipitation is projected to increase on average (Jacob et al., 2014; Strandberg et al., 2014; Grusson et al., 2021). Adaptation of Nordic agricultural systems is thus necessary, and work is ongoing (Juhola et al., 2017). Climate adaptation measures must be designed for local or at most regional level, including appropriate agricultural drainage strategies that are important for environmental and economic reasons. There are indications of the environmental benefits of properly designed drainage systems, such as reduced losses of nutrients and pesticides by properly designed subsurface drains (Kladivko et al., 1999; Kladivko et al., 2004; Skaggs et al., 2005), but direct confirmatory data from field studies in northern Europe are currently lacking. Subsurface drainage design is also known to affect crop yield levels, e.g., in a study in Indiana, U.S., significant drain spacing effects, especially on grain yield, occurred more frequently for 20-m spacing than for 10- and 5-m spacing, and 10-year average corn yield was highest for 5-m spacing and lowest for non-drained (control) plots (Kladivko, Willoughby, & Santini, 2005). According to Kladivko and Bowling (2021), more work is needed to develop approaches to optimize drainage design for both crop yield and water quality purposes. To improve infiltration and reduce phosphorus

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losses from arable land by surface runoff, installation/renovation of drainage systems is very important (Bengtson et al., 1995). To further improve infiltration, quicklime (CaO), also known as burnt lime, can be added to trench backfill (Lindström and Ulén, 2003). This measure can reduce surface runoff by improving soil structure in clay soils, thus preventing soil erosion and losses of particle-bound phosphorus. Furthermore, dissolved reactive phosphorus in drainage discharge can be effectively retained through surface precipitation with calcium (Ca) and magnesium (Mg) cations (Penn et al., 2007; Penn et al., 2017; Stoner et al., 2012).

In an ongoing project aiming to develop recommendations for primary/renewed subsurface drainage of clay soils, we are studying how different drainage strategies affect nutrient loads and crop yield. In this paper, we report the first two years of results on the impact of drain spacing in newly installed drainage systems with different drain envelopes on nitrogen and phosphorus loads and on crop yield.

Material and Methods

Different experimental drainage systems were established in 2018 at an old tile-drained field site in Gölja, central Sweden (59°48’26’’N; 16°47’09’’E), on clay soil (mean 37% clay in topsoil, 52% clay in subsoil) with high organic matter content (mean 5% in topsoil) and pH ranging between 5.9 and 7.1. The field at the site is under conventional cultivation by the farmer, with a four-year crop rotation of winter wheat, spring canola, spring wheat, and peas. In 2020 (winter wheat), the fertilization rate was 200 kg nitrogen (75% NO_3-N and 25% NH_4-N) and 34.5 kg phosphorus (100% PO_4-P) per ha, and in 2021 (spring canola), it was 140 kg nitrogen (44% NO_3-N and 56% NH_4-N) and 24 kg phosphorus (100% PO_4-P) per ha.

The field site was originally systematically subsurface drained, with clay tile drains to 1 m depth, in 1920. In 2018, experimental plots were re-drained with corrugated plastic pipes to 1 m depth, and the old drainage system was plugged in those plots. Four drainage treatments (A-D) are in place, each with three replicates, giving 12 experimental plots (fig. 1). The drainage treatments, which represent different strategies for subsurface drainage in terms of types of pipe material, drain spacing, and drain envelope, are: (A) old drainage system with clay tiles at 10 m spacing, no envelope (control); (B) new drainage system with plastic pipes at 10 m spacing, gravel envelope; (C) new drainage system with plastic pipes at 5 m spacing, gravel envelope ; and (D) new drainage system with plastic pipes at 10 m spacing, gravel envelope, and lime incorporated in trench backfill. The drain depth in all treatments (A-D) is 1 m.

The yearly long-term reference precipitation (1991-2020) at the field site is 549 mm, and the yearly reference temperature is 6.3 C° (SMHI’s meteorological station in Sala). Precipitation during the experimental years was 628 mm from July 2019 to June 2020 and 538 mm from July 2020 to June 2021 (fig. 2). In 2019/20, precipitation was 37% higher than normal in autumn (until December). In 2020/21, precipitation was lower than normal in autumn and in spring with no precipitation in November. Exceptions were found in October, when precipitation was nearly twice the long-term mean (98 mm compared to 53 mm), and in May, when precipitation was 90 mm, significantly higher than the long-term mean of 39 mm.

Measurements

The drain discharge from each individual experimental plot is carried by collector pipelines (PE-50 mm) to a measuring station for flow measurement and water sampling. Drain discharge is measured with two-sided tipping buckets

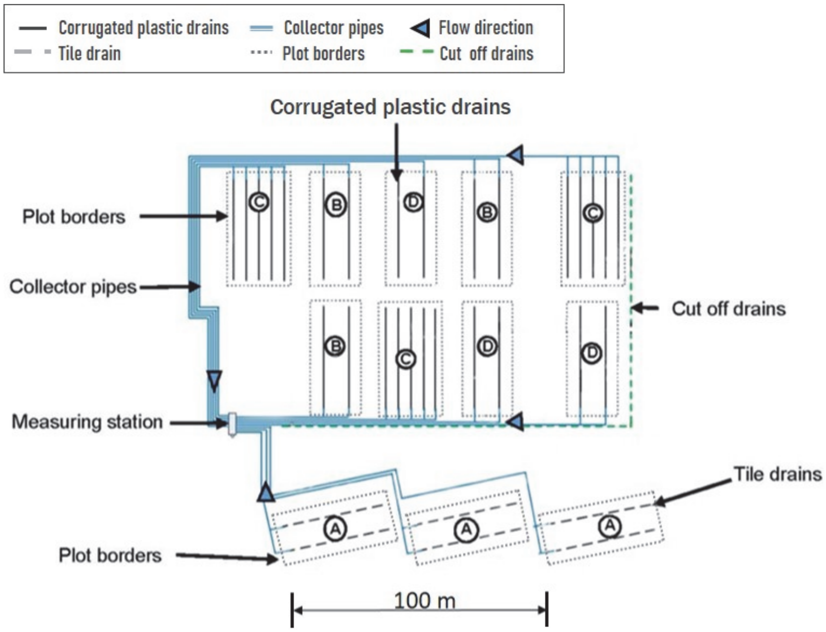

Figure 1. Experimental set-up in a drainage trial in central Sweden with four treatments: (A) old tile system, 10 m drain spacing, (B) new plastic pipe system, 10 m drain spacing, gravel envelope, (C) new plastic pipe system, 5 m drain spacing, gravel envelope and (D) new plastic pipe system, 10 m drain spacing, gravel envelope and lime incorporated in trench backfill.

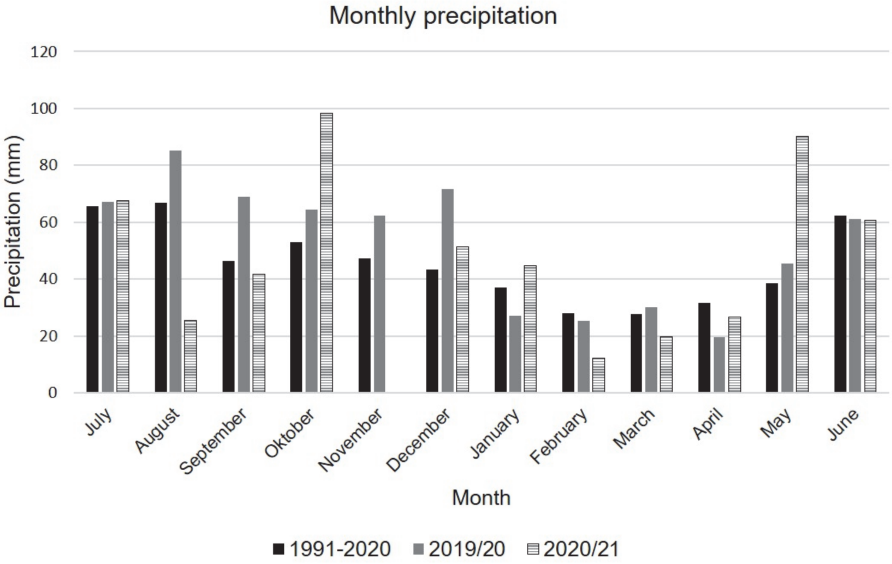

Figure 2. Precipitation during the experimental years July 2019-June 2020 and July 2020-June 2021. Long-term reference precipitation data (1991-2020) are from SMHI's meteorological station in Sala.

connected to a multichannel data logger (CR1000X, Campbell Scientific), which records discharge per hour. The data logger controls the collection of flow-proportional water samples. Composite water samples are collected every 14 days for analyses of different forms of phosphorus (PO_4-P filtered, Tot-P, Tot-P filtered) and nitrogen (NH_4-N, NO_2+NO_3-N, Tot-N) at the Department of Aquatic Sciences and Assessment, SLU, according to methods described in ISO 5667-4:2016 (Water quality-Sampling-Part 4: Guidance on sampling from lakes, natural and man-made).

Aboveground crop biomass is sampled at harvest, in two microplots (each 42 m^2), orientated perpendicular to the drains, that are harvested separately in each plot. For winter wheat yield in 2020, thousand-grain weight per gram of dry matter (TGW DM g), kernel protein content, gluten content, and starch content as a percentage of DM (%DM) were determined. For canola yield in 2021, thousand-grain weight at 9% water content (TGW 9% w.c.), grain nitrogen content, oil content as a percentage of DM (%DM), and grain chlorophyll content (ppm DM) were determined.

Analysis of variance (ANOVA, main effect) was used to determine whether the different drainage treatments had a significant effect on drainage discharge, nutrient loads, and crop yield in 2020 and 2021. The Tukey test was used to identify significant differences between treatments.

RESULTS

DRAIN DISCHARGE AND NUTRIENT LOSSES

Drainage discharge measurement and chemical analysis of drainage water began in October 2019 (table 1, figs. 3-5). No major differences in drainage discharge amounts from the different treatments were observed, although treatment C (5 m drain spacing) had the lowest drainage discharge in both experimental years. The lowest phosphorus loads and highest nitrogen loads were detected in drainage discharge from plots with lime incorporated in trench backfill (treatment D). The highest phosphorus loads and lowest nitrogen loads were detected in drainage discharge from plots with the old tile drainage system (treatment A).

Cumulative total unfiltered phosphorus loads 2019/2020 and 2020/2021 are shown in figure 4. In 2019/2020, the greatest loads of phosphorus occurred in autumn due to high precipitation, after harvest and planting of winter wheat. The ratio of particulate phosphorus ranged from 73% in treatment A to 86% in treatment B. In 2020/2021, the phosphorus loads in drainage discharge from all plots were much lower than in the previous year and peaked slightly in spring, after soil fertilization and seeding with canola. The ratio of particulate phosphorus ranged from 43% in treatment A to 70% in treatment B. In both experimental years, phosphorus loads from the old tile drainage system (A) were over twice those from the new drainage systems (B-D).

Cumulative total nitrogen loads 2019/2020 and 2020/2021 (fig. 5) followed the same pattern as the total phosphorus loads. Thus, in 2019/2020, the greatest loads of total nitrogen occurred in autumn and in 2020/2021, total nitrogen loads were highest in the spring, after fertilization and planting. However, in both experimental years, total nitrogen loads were higher from the new drainage systems (B-D) than from the old tile drainage system (A). From 2019 to 2020, the ratio of nitrate nitrogen ranged from 88% in treatment A to 99% in treatment C; in 2020/2021, it exceeded 90% across all treatments.

CROP YIELD

The quantity and quality of crop yield in the experimental years are summarized in table 2 (winter wheat, 2020) and table 3 (canola, 2021). The new drainage systems (B-D) increased yield in both experimental years, with the greatest additional yield in treatment D (with lime incorporated in trench backfill).

Table 1. Drainage discharge (mm) and loads of total phosphorus, particulate phosphorus, total nitrogen, and nitrate nitrogen (kg ha^{-1}) for the periods October 2019 to June 2020 (2019/2020) and July 2020 to June 2021 (2020/2021), from experimental plots with: (A) old tile system (10 m drain spacing); (B) new plastic pipe system (10 m drain spacing); (C) new plastic pipe system (5 m drain spacing); and (D) new plastic pipe system (10 m drain spacing with lime incorporated in trench backfill). Different letters (a, b) indicate significant differences (p<0.05) between treatments.

	Drainage Discharge (mm)		Total Phosphorus (kg ha^{-1})		Particulate Phosphorus (kg ha^{-1})		Total Nitrogen (kg ha^{-1})		Nitrate Nitrogen (kg ha^{-1})	
Treatment	2019/2020	2020/2021	2019/2020	2020/2021	2019/2020	2020/2021	2019/2020	2020/2021	2019/2020	2020/2021
A	138	184	0.54^{a}	0.25^{a}	0.41^{a}	0.10	11.8	19.2	10.4	17.6
B	139	183	0.30^{ab}	0.12^{b}	0.26^{ab}	0.08	15.5	25.4	14.7	23.7
C	128	168	0.18^{b}	0.11^{b}	0.10^{ab}	0.07	15.8	24.8	15.2	23.2
D	137	196	0.10^{b}	0.08^{b}	0.08^{b}	0.05	17.3	27.4	17.2	25.7
Average	136	183	0.30	0.14	0.23	0.08	15.0	24.2	14.3	22.5
OBS	12	12	12	12	12	12	12	12	12	12
PROB F1	0.980	0.896	0.010	0.003	0.020	0.077	0.202	0.235	0.088	0.203
CV%	24	24	40	28	42	30	19	19	19	19
LSD	66	82	0.24	0.07	0.20	0.04	5.9	8.6	5.6	8.1

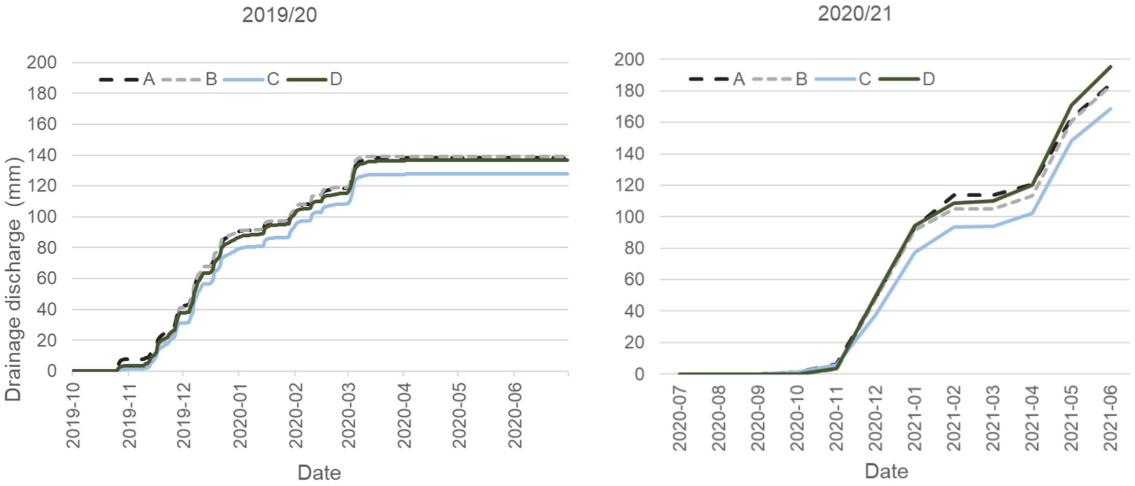

Figure 3. Cumulative drainage discharge (mm) during the periods November 2019 to June 2020 and July 2020 to June 2021 from experimental plots with (A) old tile system, 10 m drain spacing, (B) new plastic pipe system, 10 m drain spacing, (C) new plastic pipe system, 5 m drain spacing, and (D) new plastic pipe system, 10 m drain spacing, and lime incorporated in trench backfill.

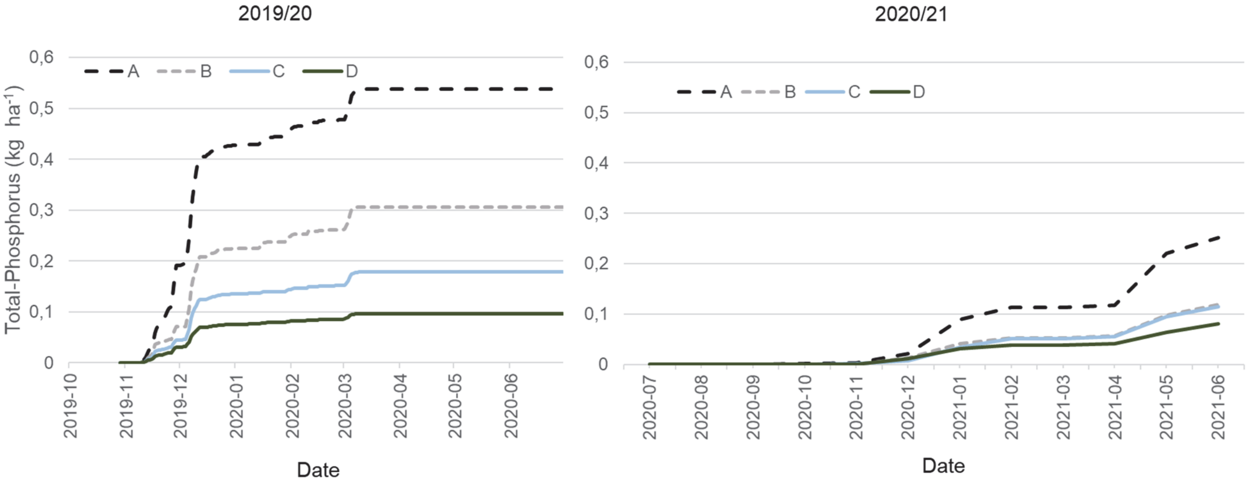

Figure 4. Cumulative total unfiltered phosphorus load (kg ha^{-1}) from November 2019 to June 2020 and July 2020 to June 2021 in drainage discharge from experimental plots with: (A) old tile system (10 m drain spacing); (B) new plastic pipe system (10 m drain spacing); (C) new plastic pipe system (5 m drain spacing); and (D) new plastic pipe system, (10 m drain spacing with lime incorporated in trench backfill).

Discussion

Compared with the old tile drainage system, the new drainage systems established in our field trial at a site with clay soil had no effect on the total amount of drainage discharge, although the treatment with 5 m of drain spacing (treatment C) gave lower amounts of discharge in both years. This indicates that the old system still works, as all plots had a one-meter drain depth and should, when drained to equilibrium, have the same amount of drainage discharge. However, based on results from the first two years, the new plastic pipe drainage systems had a clear effect on the phosphorus and nitrogen loads in drainage discharge, with higher

Figure 5. Cumulative total nitrogen load (kg ha^{-1}) during the periods November 2019 to June 2020 and July 2020 to June 2021 in drainage water from experimental plots with (A) old tile system, 10 m drain spacing, (B) new plastic pipe system, 10 m drain spacing, (C) new plastic pipe system, 5 m drain spacing and (D) new plastic pipe system, 10 m drain spacing and lime incorporated in trench backfill.

Table 2. Winter wheat yield at the experimental site, 2020. Field yield of at 15% water content (w.c.), relative total yield (treatment A = 100), thousand-grain weight per gram of dry matter (TGW DM g), and kernel protein content, gluten content, and starch content as a percentage of DM (%DM).

Treatment	Winter Wheat Yield w.c. 15% (kg ha^{-1})	Relative Total Yield	TGW DM (g)	Protein (%DM)	Gluten (%DM)	Starch (%DM)
A	8750	100	42.1	12.0	26.8	68.1
B	9810	112	44.4	11.6	25.9	68.7
C	9710	111	44.4	11.9	26.2	68.1
D	10496	120	43.9	11.8	26.5	68.6
Average	9691		43.7	11.8	26.4	68.4
OBS	12		12	12	12	12
PROB F1	0.20		0.20	0.75	0.51	0.73
CV%	53		3	3	3	3
LSD	1692		0.8	0.8	1.5	1.7

Table 3. Canola yield at the experimental site, 2021. Field yield as kg dry matter content per ha (DM kg ha^{-1}), relative total yield (treatment A = 100), thousand-grain weight (g) at 9% water content (TGW 9% w.c.), grain nitrogen content as a percentage of DM (%DM), oil content (%DM), and grain chlorophyll content (ppm DM).

Treatment	Canola Yield DM (kg ha^{-1})	Relative Total Yield	TGW 9% w.c. (g)	Nitrogen (%DM)	Oil (%DM)	Chlorophyll (ppm DM)
A	2430	100	4.3	3.6	48.2	17.4
B	2536	104	4.1	3.5	47.8	18.1
C	2501	103	4.1	3.5	48.1	20.2
D	2796	114	3.8	3.5	48.0	19.6
Average	2559		4.1	3.5	48.0	18.8
OBS	12		12	12	12	12
PROB F1	0.21		0.01	0.54	0.95	0.43
CV%	7		3	2	2	12
LSD	346		0.3	0.2	1.8	4.2

nitrogen loads and lower phosphorus loads with all new systems than with the old tile drainage system. The total load of phosphorus in discharge was lowest, but the total load of nitrogen was highest in the new drainage system with 10 m drain spacing and lime incorporated in trench backfill (treatment D), which is in line with results reported from previous studies (Kirkkala et al., 2011; Ulén et al., 2018). Total phosphorus load was highest and total nitrogen load was lowest in the old tile drainage system with 10 m drain spacing (treatment A).

Trenching to install new drains is a massive operation involving intensive soil disturbance, and the associated tillage and breaking up of organic-matter rich topsoil could be expected to have a major impact on nutrient losses via drainage discharge at the experimental site (Sharifi et al., 2008). The higher nitrogen loads and lower phosphorus loads in plots with the new drainage systems might be due to increased mineralization in drained and aerated soil, resulting in increased mobilization of nitrogen. Also, disrupting soil macropores will reduce preferential flow and thus decrease P losses (Djodjic et al., 2002). The lime incorporated in trench backfill in treatment D effectively retained phosphorus and thereby gave the lowest phosphorus loads of all treatments. The high total phosphorus loads in drainage discharge from plots with the old tile drainage system (10 m drain spacing, no filtering envelope) in undisturbed soil may be explained by clay tiles without a filtering envelope having higher resistance to entry of water (Dierickx, 1993). This could result in a buildup of sediment in the vicinity of the tiles, acting as a source of phosphorus in drain discharge. In the first experimental year, the ratio of particulate phosphorus to total phosphorus was about 80% in all treatments. The second year, the ratio decreased to 43% in the drainage discharge from the clay tile treatment and to about 65% in the plastic pipe treatments. This indicates an increased risk for soil disturbance and sediment transport when installing new drainage. The low total nitrogen loads in the clay tile treatment could be due to the plots with undisturbed soil having lower mineralization rates, and thereby a lower amount of nitrogen readily available for leaching. However, high rainfall during May after fertilization in the second experimental year resulted in large nitrogen loads in all treatments.

In the first experimental year, with higher rainfall than normal, crop yield was 11%-20% higher in plots with new drainage systems than in plots with the old tile drainage system. In the second experimental year, when total rainfall was lower than normal, high rainfall during May affected crop establishment and, in combination with a hot spell in July, created very poor conditions for spring-sown crops. However, yield in plots with new drainage systems was still 3%-14% higher than in plots with the old tile drainage system. The yield data from two experimental years indicates that investing in a new drainage system can be a profitable measure for farmers, but data from more experimental years are needed to confirm the long-term effects of different types of drainage systems.

CONCLUSIONS

Compared with the old tile drainage system, the new drainage systems studied had no effect on the total amount of drainage discharge. However, in the first two years, they had a clear effect on phosphorus and nitrogen loads in drainage discharge, with higher nitrogen loads and lower phosphorus loads than in the old tile drainage system in all cases. In terms of environmental impact, new drainage systems on clay soils may thus involve a trade-off between lower phosphorus loads and higher nitrogen losses via discharge. In terms of economic impact, the results indicated that investing in new drainage systems might be profitable, as crop yield (winter wheat, spring canola) was 3%-20% higher with the new drainage systems compared with the old tile drainage system.

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