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Improved subsurface drainage increased small grain cereal yield but not the soil carbon stock of a boreal clay soil

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Removal of excess water by soil drainage is a prerequisite of proper yields in boreal agriculture. A functioning drainage system enables farming operations, maintains yields and improves the environmental performance of a field plot. As carbon input to soils in crop residues increases with the yield, increased crop production might benefit the carbon balance of the soil. We document the effects of drainage renovation on the yield and crop residue production of spring cereals at a long-term experimental site on Protovertic luvisol in south-western Finland and discuss their relevance for soil carbon sequestration. The yield and amount of crop residues were monitored continuously before (1985–1990) and after (1992–1997) a drainage renovation. The cereal yields almost doubled, reaching the current average yields, and the amount of crop residue increased by 30% after the improvement of the drainage system. This was, however, not significantly reflected in the soil carbon stock. Drainage renovation can be considered sustainable intensification that provides long-term benefits for crop production, but carbon sequestration likely requires more carbon input than is available in the cereal straw.

Key words: drainage renovation, crop yield, straw yield, carbon sequestration

Introduction

In humid regions, artificial soil drainage is a prerequisite of crop production in agricultural fields. The drainage system should be designed to ensure proper growing conditions for the crop with minimum negative environmental effects (Ayars and Evans 2015). Excess wetness limits root growth and nutrient uptake and promotes root senescence and root lodging (Mariani and Ferrante 2017). Wet conditions enhance the virulence of many plant diseases (Hossain et al. 2024). In addition to the direct effects on growth, wet soils complicate agricultural practices using heavy machinery, leading to non-optimal timing of operations, further increasing the risk of yield losses. Decreased rate of organic matter mineralisation in wet soils may lead to low nitrogen use efficiency (Castellano et al. 2019), and relieving the impacts of excess moisture by excess fertilisation has environmental consequences (Mariani and Ferrante 2017). The role of drainage is further emphasized with the more frequent extreme weather events in the future climate (Schultz et al. 2007).

European yield statistics reveal stagnation in the yield development since 1990's which is clearly one factor challenging the maintenance of soil carbon stocks (Wiesmeier et al. 2015). While filling the yield gaps may require intensification that has negative environmental consequences (Licker et al. 2010), drainage renewal can be considered sustainable intensification: activity that improves yields without adverse environmental impact or the need to clear additional agricultural land (Pretty and Bharucha 2014). In addition to economic benefits, yield increase by drainage improvement could be beneficial for the development of the carbon storage of agricultural soils as the amount of crop residue correlates well with the carbon stock changes in soil (Blanco-Canqui and Lal 2009). As the root biomass is well correlated with the above-ground biomass (Palosuo et al. 2015), and is a significant source of soil carbon (Kätterer et al. 2011), the potential increase in the amount of root biomass, especially if the rooting depth increases, adds to the below-ground carbon input. Soil carbon loss in erosion can be diminished with drainage renovation as a partly blocked drainage system leads water out from the field increasingly as surface runoff instead of the subsurface route (Turtola and Paajanen 1995, Firoozi and Firoozi 2024). However, both increased carbon content (Bernard et al. 2022) and better aeration (Davidson et al. 1998, Schaufler et al. 2010) can stimulate mineralisation, partly counteracting the increase in carbon input.

There is scarce evidence of the environmental impacts of drainage management options (Hall et al. 2024), and drainage renovation is often neglected as a means of increasing yields (Pretty et al. 2018). Farmers generally acknowledge the importance of drainage, and understanding its significance for improved yields has increased lately (Lehtonen et al. 2018). Our aim was to highlight the role of subsurface drainage renovation as means of sustainable intensification in clay soil croplands of the humid boreal climatic conditions and to assess if the

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increase in yield and crop residues after drainage improvement can accrue soil carbon stock. The drainage system of the field was improved in 1991 because the field suffered from poor yields and high surface runoff rates leading to high erosion and nutrient losses. Yields and crop residues were measured annually and soil carbon content twice in the study period 1985–2000. We hypothesized that the crop yield, amount of crop residues and soil carbon stock increase after drainage renovation.

Material and methods

Site, management and crop and soil sampling

The study site was located in Jokioinen, southwestern Finland (60˚49’ N, 23˚30’ E, about 100 m a.s.l., slope 1–4%, mean 2%) where the weather is boreal humid, with annual mean temperature of 5.2±0.9 °C and annual precipitation of 620±90 mm in the long-term reference period 1991–2020 (Jokinen et al. 2021). Soil surface is frozen and has snow cover typically from December to March. The soil is Protovertic Luvisol with topsoil clay, silt and sand contents of 60, 16 and 24%, respectively (0–30 cm). The experimental field was established in 1975, and it consists of four 0.5 ha plots that are further divided in four 33 m × 33 m subplots with identical subsurface drainage systems (Fig. 1). Site design is described in detail in Turtola and Paajanen (1995) and in Uusitalo et al. (2018).

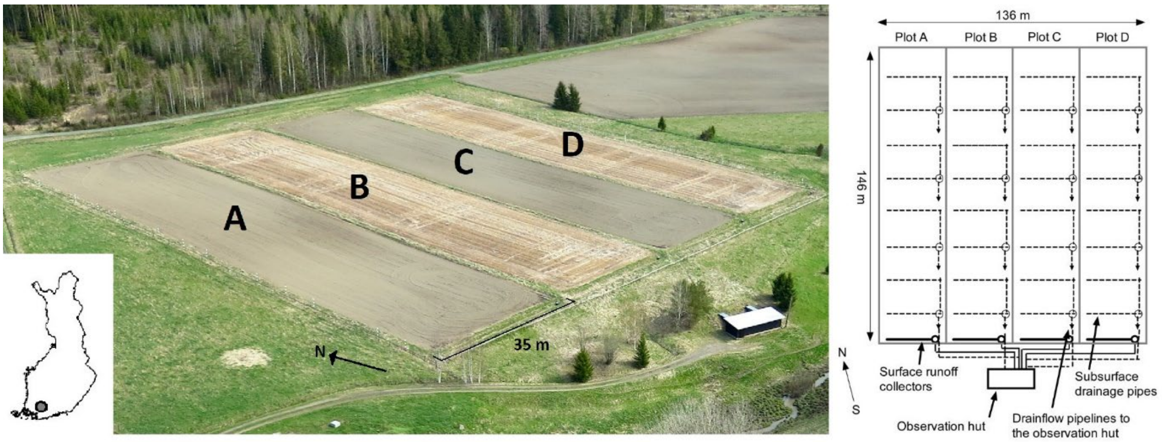

Fig. 1. Experimental field location and layout with four plots and 16 subplots within the main plots (modified from Uusitalo et al. [2018] and Honkanen et al. [2024]).

The site has been mainly in cereal cultivation, but the soil has been occasionally fallowed or been in timothy (*Phleum pratense* L.) or ryegrass (*Lolium perenne* L.), or mixed grass (timothy, meadow fescue, *Festuca pratensis* Huds. and red clover, *Trifolium pratense* L.) cultivation (Table 1). The cereals grown were spring or winter wheat (*Triticum aestivum* L.) or spring barley (*Hordeum vulgare* L.). Soil management has been autumn ploughing (mouldboard ploughing; MP) in plots A and C in all cereal years. Reduced tillage (RT) was practiced in 1991–1997 in plots B and D.

Table 1. Crops and treatments by plot

Year	Plot A	Plot B	Plot C	Plot D	Tillage
1985–86	Wheat	Wheat	Wheat	Wheat	Autumn MP
1987	Fallow	Fallow	Ryegrass	Timothy	Autumn MP (B+C)
1988	Fallow	Barley	Barley	Timothy	Autumn MP (B+C)
1989	Fallow	Fallow	Ryegrass	Timothy	Autumn MP
1990	Barley	Barley	Barley	Barley	Autumn MP
1991	Barley	Barley	Barley	Barley	Autumn MP
1992	Barley+ undersown grass	Barley+ undersown grass	Barley+ undersown grass	Barley+ undersown grass	No tillage
1993	Timothy, meadow fescue, red clover	Timothy, meadow fescue, red clover	Timothy, meadow fescue, red clover	Timothy, meadow fescue, red clover	A+C autumn MP
1994–95	Barley	Barley	Barley	Barley	A+C autumn MP; B+D reduced spring tillage
1996–99	Barley	Barley	Barley	Barley	A+C autumn MP; B+D reduced autumn tillage

The cereals were spring sown, and the fallow was bare fallow ploughed three times per year. Drainage renovation was done in 1991. MP=mouldboard ploughing

Autumn mouldboard ploughing was done to the depth of about 20 cm and the plots with reduced tillage were tilled to 8 cm with one pass using either Kverneland Turbo 2 or Kongskilde Vibroflex stubble cultivators in the autumn and a power harrow in the spring. Cereals were grown using typical farm machinery and annual mineral NPK fertilizers rates (average 92-15-28 kg ha^{-1} yr^{-1}) and pesticides as needed. Dry grain yield was measured annually with a combine harvester in a 48 m^2 area. Above ground biomass was manually measured in two locations of each 33 × 33 m subplot from 0.5 m^2 area by cutting at soil surface level and weighed to estimate mass of the straw or grass residue. The biomass of roots was calculated using the root to shoot ratios as described in (Palosuo et al. 2015). The root biomass of grasses was calculated in the same way as for the cereals, as the constant coefficient defined for grass roots was found to be too high in this case as the grass yield and number of grass years in the rotation were lower than average. The carbon content of the residues was assumed to be 45% (Jensen et al. 2005).

Details of the drainage design are described in Turtola and Paajanen (1995). In the renovation, the new plastic drainpipes were installed at the same depth as the old ones but 0.3 m from the old pipes and connected to the old crossing pipes. A 15 cm layer of gravel was placed at the bottom of the trench, and there were five additional 40–50 cm deep gravel deposits per 33 meters of drain. The trenches were filled with loose topsoil in the upper part of the field and wood chips in the lower part.

Precipitation and temperature data were obtained from an observation station of Finnish Meteorological Institute located less than one kilometre from the site (FMI 2024).

Samples for soil organic carbon analysis were collected in Oct 1990 and Sep 2000. In 1990, one sample formed of ca. 10 subsamples from the 0–25 cm layer of each subplot was taken. In 2000, three samples consisting of ca. 10 subsamples per subplot from the layers 0–5 cm, 5–10 cm and 10–25 cm were taken, forming one replicate from each subplot. The samples were air dried and sieved (2 mm). Carbon concentration was analyzed using dry combustion (LECO TruMac CN, LECO corporation, MI). Carbon stocks were calculated with the equivalent soil mass method for the surface layer (200 kg m^{-2}; approx. 25 cm) (Ellert and Bettany 1995, Heikkinen et al. 2021a). Bulk density of six 10 cm soil layers at the depth of 0–60 cm was measured from samples of 200 cm^3 in 1984 and 2008. Negligible variation in bulk densities was assumed and thus bulk density values measured in 1984 were used for all layers sampled in 1990 and bulk density values measured in 2008 were used for 2000.

Statistical analyses

Years 1985–86, 1988, and 1990 represented the period before the drainage renovation, while 1992 and 1994–97 represented the period after it. Year 1991 was excluded because the drainage renovation markedly disturbed the sites that year. Two response variables, grain yield and crop residue biomass, were analyzed using generalized linear mixed models (GLMMs). For both variables, the fixed effects included treatment period (before and after) and tillage timing and method (mouldboard ploughing in the autumn, reduced tillage in the autumn or spring).

Random effects accounted for the hierarchical structure of the experimental design: field row nested within year, field column nested within year, and crop species nested within year. The latter accounted for spring wheat being cultivated instead of barley in two years during the control period. Repeated measurements across years within plots were modelled using either an autoregressive (AR1) or compound symmetry (CS) covariance structure, with plot as the subject.

A simplified GLMM was applied for carbon stock in the topsoil in 1990 and 2000 (combined plots of A and C vs. B and D). Field row and column were treated as random effects, and repeated measurements across years within plots were modelled using a heterogeneous compound symmetry (CSH) covariance structure, allowing separate variances for both years.

For grain yield, a normal distribution was assumed, whereas crop residue biomass and carbon stock were modelled using a gamma distribution with a log link to account for skewness. Degrees of freedom were estimated using the Kenward–Roger method. Least squares means were computed for the fixed effects, with Tukey adjustment applied for pairwise comparisons. For carbon stock, the Westfall method was used to account for two comparisons between years. The significance level was set at $\alpha=0.05$. Model diagnostics included residual analysis and covariance parameter tests to evaluate the necessity of random effects. Model comparisons were based on corrected Akaike information criterion (AICC) values, and R^2 values were calculated using the SAS macro GOF. All analyses were conducted using the GLIMMIX procedure in SAS software (Version 9.4, SAS Institute Inc., Cary, NC).

Results

Crop yield

The decreasing trend in crop yield is clearly seen in the time series during 1983–1990, as is the improvement after 1991 when the drainage renovation took place (Fig. 2). Crop yields almost doubled after the drainage renovation compared to the preceding period with poor drainage; the difference in yields was 1710 kg ha^{-1} between the two periods (Table 2).

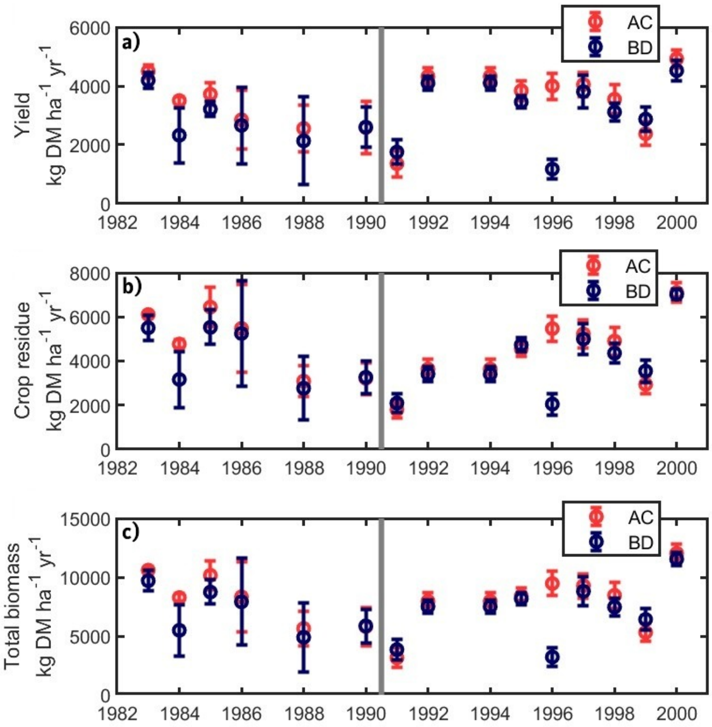

Fig. 2. Annual cereal yield (mean±standard deviation) (a), above and below ground crop residue (b) and the sum of yield and residue (c) in plots A+C and B+D in 1983 – 2000. Grey vertical bar denotes drainage renovation. The plots consisted of four subplots each; plots A and C were mouldboard ploughed and B and D were in no-till for some years. Values from years without cereal crop are missing from the figure.

It is pertinent to investigate the effect of soil tillage method and timing on the yields as there were some differences in the soil management between the compared periods; before 1991, all cereal plots were autumn ploughed, whereas after that some were minimum tilled in the spring tilled or autumn (Table 1). Autumn mouldboard ploughed plots produced the highest yields (Table 2). Reduced tillage in the autumn decreased yield by 1560 kg ha^{-1} compared to mouldboard plough (*p*< 0.001) or by 1510 kg ha^{-1} compared to reduced tillage in the spring (*p*= 0.011).

Table 2. Estimated crop yields (kg DM ha^{-1}) during 1985–1997 as affected by drainage renovation period and soil tillage method, with pairwise comparisons

Effect	Specifier	Estimate	Standard Error	DF	t -value	*p* -value
Period	Before	1829	567	12.5	3.23	0.007
	After	3543	478	8.6	7.42	0.000
	Before vs. after	-1714	723	9.7	-2.37	0.040
Tillage	RT autumn	1663	496	30.3	3.35	0.002
	RT spring	3171	470	23.6	6.74	<0.001
	MP autumn	3224	374	10.5	8.63	<0.001
	RT autumn vs. RT spring	-1508	485	32.7	-3.11	0.011
	RT autumn vs. MP autumn	-1562	384	40.0	-4.06	0.001
	RT spring vs. MP autumn	-53.76	379	40.8	-0.14	0.989

RT=reduced tillage; MP=mouldboard ploughing

Crop residues and soil carbon

The amount of above- and below-ground crop residues followed the trend in crop yields (Fig. 2), but the difference between the periods was not statistically significant (Table 3). The relative increase rate was lower than that in the case of crop yield; the amount of crop residues was approximately 30% higher after than before the renovation (the difference was 930 kg ha^{-1}). An increase of this magnitude in the crop residues suggests about 420 kg of extra carbon input to the soil annually. The effects of the tillage timing and method were similar to those on yield.

Table 3. Estimated annual above-ground and below-ground crop residues (kg DM ha^{-1}) during 1985–1997 as affected by drainage renovation period and soil tillage method, with pairwise comparisons

Effect	Specifier	Estimate	Standard Error	DF	t -value	*p* -value
Period	Before	3022	622	10.3	4.86	0.001
	After	3951	523	8.1	7.56	0.000
	Before vs. after	-929	763	7.7	-1.22	0.260
Tillage	RT autumn	2373	564	23.5	4.21	0.000
	RT spring	4040	533	19.5	7.59	0.000
	MP autumn	4046	424	10.2	9.55	0.000
	RT autumn vs. RT spring	-1677	557	26.5	-3.00	0.016
	RT autumn vs. MP autumn	-1673	434	26.7	-3.86	0.002
	RT spring vs. MP autumn	-5.6	429	29.2	-0.01	1.000

RT=reduced tillage; MP=mouldboard ploughing

The mean carbon stock in the 200 kg mineral soil mass (~0–25 cm layer) was 5.44±0.15 kg in 1990 and 5.54±0.24 kg in 2000, and the difference between years was not statistically different. Because no measurements were available before 1990, we investigated the general effect of crop residues on the soil carbon stock at this site using the cumulative crop residues per study plot from all crops in 1983–2000 and the soil carbon stock in 2000. Although a positive trend of soil carbon with increasing crop residue was observed, cumulative residues explained little of the variation in topsoil carbon in 2000 (Fig. 3).

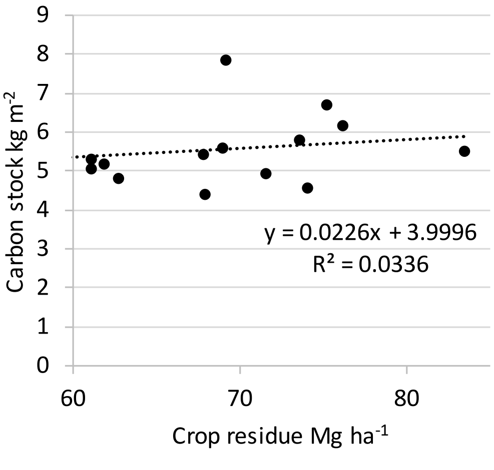

Fig. 3. Relationship between the carbon stock of the topsoil (200 kg m^{-2} soil mass) in 2000 and the cumulative crop residue amount during 1983–2000 for each subplot.

Discussion

The improved functioning of the drainage system after installation of the new pipes and more permeating matter in the trench above them was clearly manifested in the cereal yield levels. The yields were below the national mean yield before 1991 but the yields in 1992–1997 were close to the current mean annual yield of barley (3370 kg DM ha^{-1} in 2020–2025; Luke 2025), showcasing the economic benefits of the investment in the drainage system. Based on the more recent yield data, the benefits are long-term as the mean yield has still not lowered to the levels of the 1980's (results not shown). Improved oxygen availability due to lower soil moisture is the likely reason for the yield improvement after 1991 at our site as there were no changes in fertilization or climatic variables. There are many earlier observations of reduced yields caused by varying periods of waterlogging (van der Paauw 1972, Cannell et al. 1980). The yield losses caused by soil wetness are mainly due to low oxygen availability for roots causing a reduction of oxygen and a response in tissue level often leading to cell damage or death (Drew 1997).

Our hypothesis on the increase of soil carbon stock after drainage renovation was not confirmed. We do not know if the drainage renovation was able to turn the trend in carbon stock in the long term, but the estimates based on the available samplings suggest that despite the increased carbon input from the crop residues the soil carbon stock did not increase significantly in 1990–2000. However, it did not decrease as commonly found for cultivated soils (Bellamy et al. 2005, Heikkinen et al. 2022), suggesting that it might be possible to prove the potential benefits e.g. with a larger number of soil samples (Heikkinen et al. 2021a). However, also the analysis based on the carbon measurements and long-term residue input showed that there was a weak connection between the cumulative amount of crop residues and the carbon stock in 2000. Our results are in line with other data from northern European studies. It was found in a Swedish study that cereal straw without any extra carbon input was not sufficient to maintain the carbon stock of agricultural soil (Kätterer et al. 2011). No carbon sequestration but maintenance of the soil carbon stock was observed with a similar straw amendment (4 Mg ha^{-1}) in a Danish long-term study (Jensen et al. 2022).

The increase in the carbon input to the soil in crop residues after the drainage renovation was ca. 420 kg C ha^{-1} which is quite modest and not likely to lead in a significant increase in the carbon stock. Much higher carbon input was estimated necessary for net carbon sequestration in a study on the chemical quality and decay rates of different materials in a similar soil type (Heikkinen et al. 2021b). Straw was not one of the studied materials in that study, but it was estimated that more than 4000 kg of clover shoots (1900 kg C) or 1400 kg of its roots (630 kg C) would be needed for the 4 permille increase defined in a global initiative (Soussana et al. 2019). Our estimates of the crop residues are coarse as the below-ground residues were not measured but modelled without considering the potential differences in root mass related to weather variations between years that may affect root mass.

A study on the carbon balance of this site in 2019–2020 revealed that the ecosystem respiration on average exceeded the carbon fixation by the crop (Honkanen et al. 2024), indicating low probability for net carbon sequestration. There are many factors complicating the simple assumption that higher carbon input leads to soil carbon sequestration. The net carbon balance depends also on the rate of organic matter decomposition rate and although the carbon input increases, the well-drained soil after the drainage renovation might favour decomposition that is limited by high soil moisture (Davidson et al. 1998, Moyano et al. 2012). Increased fresh carbon input may also enhance decomposition of soil organic matter as has been found in studies on priming effect (Bernard et al. 2022). About 60% of soil carbon is below the top 15 cm of agricultural soils in Finland (Palosuo et al. 2015), but our experimental design did not enable assessing the role of the deeper soil layers, where the drainage renovation alters both carbon input in roots and potentially decomposition rate.

The effect of drainage improvement on the soil carbon stock is not limited to the amount of carbon input in crop residues and their decomposition as it also affects the output of dissolved and particulate carbon in the discharge. Erosion is a globally significant route of carbon displacement as 5.7 Pg of carbon is estimated to be transported in erosion annually (Lal 2019). It was observed in an earlier study at the same site that the total amount of erosion declined after the drainage renovation at this site along with a rise in the proportion of drainage of the total runoff from 19 to 84% in the cereal years (Turtola and Paajanen 1995). More recent studies at this site showed that the waterborne carbon losses are a remarkable proportion of the total losses, 25–52 kg ha^{-1} year^{-1} of dissolved carbon in 2012–2014 (Manninen et al. 2018) and 19–71 kg ha^{-1} year^{-1} of dissolved and particulate carbon in 2015–2016 (Manninen et al. 2023).

Changes in the water flow route after drainage renovation may also impact the yield level indirectly, via nutrient losses affecting availability of nutrients for the crop. Earlier findings showed that the increase in the proportion of water discharge through the drainage instead of surface runoff had some influence on losses of phosphorus and nitrogen (Turtola and Paajanen 1995) but the moderate changes likely have more importance for the environmental impacts than for crop growth.

Our results on the effect of tillage timing and method indicate that reduced tillage in the autumn lowered the yields as compared to the most conventional management, mouldboard ploughing in the autumn. As the alternative soil tillage methods occurred only after the drainage renovation, the results indicate that the difference between the periods before and after the drainage renovation would have been even larger had the soil management been autumn mouldboard ploughing throughout the study period. Slightly decreasing (–2%) cereal yields in shallow tillage were also found in a large Swedish study (Arvidsson et al. 2014). In our study the decline was larger, but it may be partly explained by the short application time of minimum tillage. A global meta-analysis found that five years or more in no-till alleviated the yield decline in no-till management (Pittelkow et al. 2015). One reason for the yield decline with reduced tillage may be that the heavy clay is denser and restricts water infiltration as reported for no-till treatment in (Alakukku et al. 2012, Kauppi et al. 2024). However, the same properties may lead to better yield during a dry year (Kauppi et al. 2024), and increasing clay content did not play a significant role in yield in a Swedish study comparing several sites (Arvidsson et al. 2014).

Conclusions

Our results highlight the importance of functioning drainage in securing proper yield of small grain cereals in the boreal climatic conditions. Drainage renovation can thus be recommended as a method of sustainable intensification if soil wetness is the likely reason for low productivity. Our hypothesis on the increase of soil carbon stock after drainage renovation was not confirmed, highlighting the importance of counteracting factors after improved drainage, like increased decomposition rate due to better soil aeration or priming caused by the fresh residue input. The results indicate that significant soil carbon sequestration requires more carbon input than contained in the cereal residues, urging solutions for increasing the carbon input e.g. through cover crops or diversified crop rotations.

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