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Grassland Research

SHORT COMMUNICATION

Impacts of tillage on soil properties and interactions with drainage when reseeding permanent pasture

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Abstract

Background: Grassland reseeding typically requires intensive tillage. This disrupts soil nutrient dynamics, especially under varying drainage conditions.

Methods: This study evaluated the combined effects of tillage legacy, drainage and soil depth on key soil properties within a long-term grassland experiment. Treatments compared two no-tillage durations (5 years of no tillage, 5YNT; 30 years of no tillage, 30YNT), two drainage systems (drained and undrained) and two depths (0–10 and 10–30 cm) following reseeding. Total carbon (TC), total nitrogen (TN), total phosphorus (TP) and pH were measured.

Results: Significant three-way interactions were detected for all variables. At 0–10 cm, undrained 30YNT plots showed 69% greater TC and 66.9% higher TP than the lowest values recorded in 5YNT × drained combinations at 10–30 cm. TN followed a similar pattern, with substantial enrichment under long-term no-tillage. Reseeding reduced TC, TN and TP within 5 years, particularly in surface soils, with the largest proportional losses in undrained plots where nutrient concentrations had been high prior to tillage.

Conclusions: Findings highlight the importance of conserving long-term no-tillage systems to enhance nutrient retention and promote sustainable grassland productivity. Conventional tillage of nutrient-rich pastures should be avoided to prevent major nutrient losses.

KEYWORDS

drained soils, no tillage, pH, total carbon, total nitrogen, total phosphorus, undrained soils

INTRODUCTION

Modern agriculture practices aim to increase yields while preserving soil health and preventing environmental degradation to maintain soil productivity. Grasslands cover about 26% of the world's land area and 80% of agricultural land and thus play a pivotal role in carbon (C) sequestration (Reinsch et al., 2018). As a result, grassland soils are among the most important C stores on the planet (Stockmann et al., 2013). However, a single tillage event (such as ploughing for grass-to-grass reseeding) can significantly reduce soil C stocks (Linsler et al., 2013), with potential negative consequences for the greenhouse gas balance of grassland ecosystems. In the United Kingdom, reseeding of species-rich herbal leys is being promoted by subsidy schemes, potentially leading to more frequent cultivation. The benefits of improved sward quality and productivity must therefore be balanced against the negative impacts of tillage.

The physical and chemical properties of soil are crucial for stable and high yields, but they are markedly affected by tillage. In grassland systems, cultivation to establish new swards (ploughing or harrowing) destroys existing vegetation and enhances productivity (Blair et al., 2018), and yet, it can degrade soil structure, increase erosion and sediment loss (Hassan et al., 2022), reduce soil organic matter (Man et al., 2022) and raise costs (López-Bellido et al., 2019). In contrast, no-tillage (NT) practices mitigate climate change by reducing C emissions and improving soil properties (Kumara et al., 2020), which could enhance stability and reduce erosion. A meta-analysis by Aguilera et al. (2013) reported an average 11.2% increase in soil organic C and a sequestration rate of 0.44 Mg C ha^{-1} year^{-1} under NT compared to conventional tillage. Elias et al. (2023) even found similar soil bulk densities and sward compositions in 20-year NT fields versus 5-year cultivation cycles, questioning the necessity of frequent reseeding. Nevertheless, the impact of reseeding on soil C depends strongly on soil texture and the vertical distribution of carbon in the profile.

Drainage substantially reduces soil total C and N storage, but it is essential for managing soil water and plant productivity (Ballantine & Tanner, 2013) and preventing waterlogging. The interaction between drainage and tillage is critical to sustainable soil management. Both drainage and tillage influence soil chemical and physical properties (Abid & Lal, 2008), but there is a knowledge gap regarding how several years of no tillage (YNT) and drainage systems (DS) together affect soil nutrients. Rowden Moor grassland (North Wyke) provides an ideal long-term field setting to study these effects. The soils are classified as Hallsworth or Halstow series, poorly drained due to low permeability and limited water storage capacity to a depth of 30 cm, which are typical features of intensively managed grasslands in the western United Kingdom (Harrod & Hogan, 2008). To our knowledge, no previous study has directly combined tillage legacy and drainage treatments at this field scale or with multi-depth resolution on basic soil nutrients in grassland systems. Previous studies, such as Harris et al. (2018), focused solely on the long-term effects of drainage on soil C and N, without considering differences in ploughing history or assessing phosphorus (P) dynamics at the same site. Likewise, Hayes et al. (2022) examined how inversion tillage and reseeding affect surface nutrient, finding large reductions in P after reseeding, but only at the 0–7.5 cm depth and without controlled drainage contrasts. Our novel study fills this gap by leveraging the 1-ha hydrologically isolated Rowden plots to provide robust whole-plot data. This combines both factors: four treatment combinations from drained versus undrained, 5-year versus 30-year no till, and measurements of total carbon (TC), total nitrogen (TN), total phosphorus (TP) and pH at two depths (0–10 and 10–30 cm). The objectives were to determine how these factors and their interactions influence soil nutrient concentrations in an intensively managed grassland in Southwest England.

MATERIALS AND METHODS

Study site

The location of the experiment was at Rowden Moor near North Wyke, Rothamsted Research, Southwest, England. The study area comprises 12 plots, 1 ha each of intensively managed grassland. All 12 plots are surrounded by gravel interceptors, or French drains, to intercept overland surface runoff and surface lateral flow (down to a depth of 30 cm), ensuring that each plot is hydrologically isolated from its neighbouring plots. Additionally, six plots are drained (subsurface) to a depth of 85 cm using a combination of deep gravel-filled trenches and tile drains placed at 40 m intervals across the slope, overlaid with mole drains at 2 m spacing and a depth of 55 cm downslope. A detailed description of the drainage system and site can be found in Harris et al. (2018). Since the 1980s, the experiment has been sheep-grazed and regularly limed and fertilized to maintain productivity. All plots are similar in history, except for our treatments: half were last ploughed in 2017 and half have remained permanent pasture (no till for ≥30 years). All plots were fertilized with 250 kg N ha^{-1} $year^{-1}$.

Experimental design and management

The study was conducted in 2022 using eight plots of 1-ha each. Four of the plots had not been ploughed for over 30 years. The remaining four plots were ploughed and harrowed in 2017 and reseeded with perennial ryegrass *(Lolium perenne* L.) and Festulolium hybrid (*Festulolium*), and then unploughed for 5 years (until summer 2022, 5YNT). Two of the 5YNT and 30YNT plots were drained and the other two were undrained. Therefore, this experiment involved the factorial combination of three factors: YNT (5YNT and 30YNT), DS (drained and undrained) and soil depths (0–10 and 10–30 cm, see the next section), replicated two times. *L. perenne, Agrostis stolonifera* L. and *Holcus lanatus* L. were the dominant grass species in all the plots during soil sampling in August 2022. The plots were grazed by 10 ewes and their lambs from April to October each year.

Soil sampling procedure, processing and analysis

Ten intact soil cores (pseudo-replicates) in each plot were sampled with a 5 cm diameter split soil corer to a depth of 30 cm, with individual cores being evenly spread along a 'W' shape covering each of the 1-ha plots. Each core was subdivided into two depths (0–10 and 10–30 cm). Sampling took place in August 2022. Soil pH was determined using the soil water suspension method. TC and TN concentrations were determined using the LECO Combustion analyser. The TP concentration was analysed using Inductively Coupled Plasma Optical Emission Spectroscopy.

Data analysis

Analysis of variance was performed on the data generated. YNT, DS, soil depths and their interaction were included in the model as a fixed effect. The analysis model included soil cores (pseudo-replicates) nested within plots and soil depths nested within soil cores, which were included as random (blocking). Analyses were performed using GenStat statistical software. The significant difference between means was declared at a 5% probability level and the Tukey HSD post hoc test was used to separate means from the interactions.

RESULTS

The results of the analyses of variance are provided in Table 1. There was a triple interaction effect between YNT, DS and depth on TC ($p = 0.003$), TN ($p = 0.013$), TP ($p = 0.022$), concentrations and pH ($p = 0.005$) (Figure 1). Generally, differences were found between the YNT and DS combinations at 0–10 cm depth, but not at 10–30 cm depth for TC (Figure 1a). The undrained 30YNT at 0–10 cm (74.9 g kg⁻¹) had 20.1% greater TC concentration than the drained 30YNT at 0–10 cm, 31.0% greater TC concentration than the 5YNT at 0–10 cm and 69.3% greater TC concentration (Figure 1a) than the average value (23.1 g kg⁻¹) from all the three-way interactions at 10–30 cm that did not differ among them. Similarly, the undrained 30YNT at 0–10 cm (6.98 g kg⁻¹) had 15.9% greater TN concentration than the drained 30YNT at 0–10 cm, which in turn was higher (12.2%) than the 5YNT plots at 0–10 cm (Figure 1b). Also, the TN concentration at 10–30 cm depth was lower than any of the YNT and DS combinations at 0–10 cm. At 10–30 cm depth, the undrained 5YNT plots had 27.3% higher TN concentration than those of drained and undrained 30YNT plots at the same depth (Figure 1b). The TP concentration (1034.9 mg kg⁻¹) was 66.9% greater in the undrained 30YNT plots at 0–10 cm depth than the average value of 342 mg kg⁻¹ across YNT × DS combinations at 10–30 cm depth, which did not differ among each other ($p = 0.022$, Figure 1c). For pH, the NYT and DS combinations were similar within depths. However, the undrained 30YNT plots at 0–10 cm were 4.6% lower compared to the undrained 30YNT undrained plots at 10–30 cm (Figure 1d).

TABLE 1 *F*- and *p*-values generated from analysis of variance comparing the effect of YNT, DS, soil depth and their interaction effect on soil properties.

		Variables			
Source of variation		**TC**	**TN**	**TP**	**pH**
YNT	*F*	34.2	19.8	3.71	0.24
	p	0.004	0.011	0.126	0.653
DS	*F*	24.7	20.4	2.52	0.46
	p	0.008	0.011	0.187	0.536
Depth	*F*	1253.8	1129.3	849.5	18.6
	p	<0.001	<0.001	<0.001	<0.001
YNT × DS	*F*	3.98	0.37	0.2	0.02
	p	0.117	0.575	0.648	0.883
YNT × Depth	*F*	130.4	132.7	109.2	2.53
	p	<0.001	<0.001	<0.001	0.116
DS × Depth	*F*	18.8	14.2	7.3	0.05
	p	<0.001	<0.001	0.009	0.822
YNT × DS × Depth	*F*	9.26	6.43	5.5	8.53
	p	0.003	0.013	0.022	0.005

Abbreviations: Depth, soil depth; DS, drainage systems; TC, total carbon; TN, total nitrogen; TP, total phosphorus; YNT, years of no tillage.

DISCUSSION

This study examined the impact of various YNT, DS and soil depth combinations on the chemical composition of soil in a temperate grassland in southwest England. Increased soil TC, TN and TP levels could enhance soil physiochemical properties and boost grass yields. The findings showed that combining longer YNT and

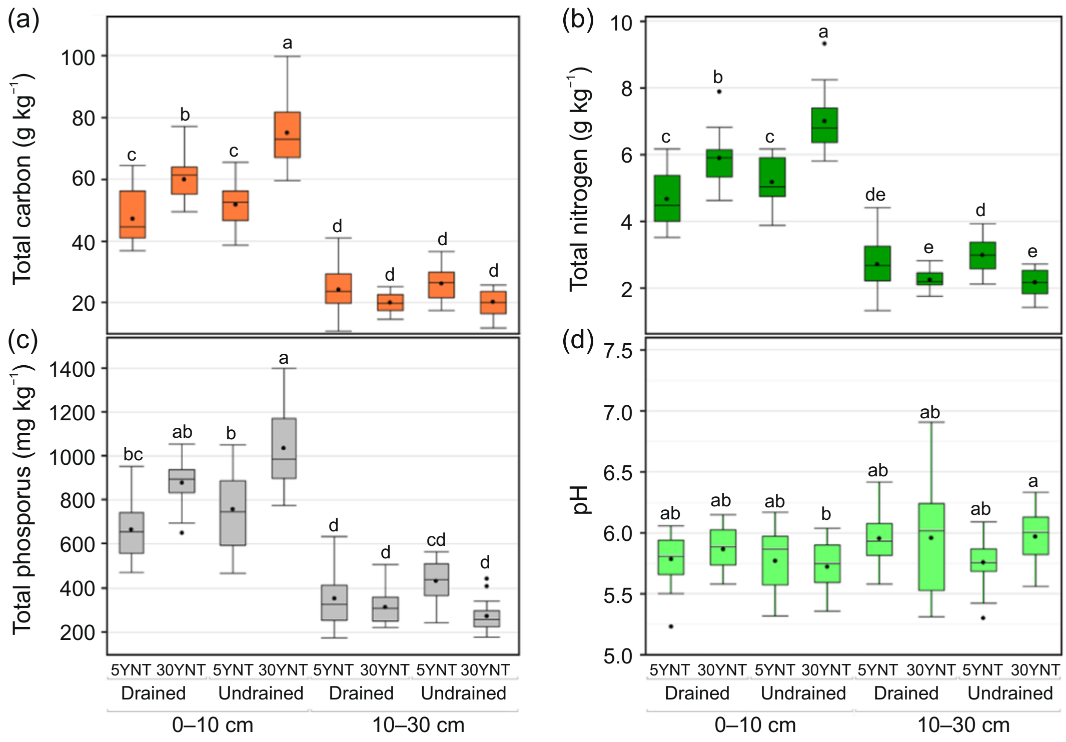

FIGURE 1 Box plots with the interaction between drainage system (drained and undrained), years of no-tillage (5YNT and 30YNT) and soil depths (0–10 and 10–30 cm) for (a) total carbon and (b) total nitrogen, (c) total phosphorus concentrations and (d) pH. Error bars represent upper and lower percentiles. Plots with different letters differ significantly. Each boxplot represents $n = 20$ samples per treatment combination. 5YNT, 5 years of no tillage; 30YNT, 30 years of no tillage.

undrained soil conditions increased macronutrient (TC and TN) concentrations in the soil's upper layer (0–10 cm), which could offer long-term environmental benefits. Soil TP concentration seemed to benefit from longer YNT under drained and undrained conditions. Conservation tillage reduces soil compaction and disturbance caused by mechanical farming tools, which can improve soil structure on farmland, increasing the accumulation of organic matter and C in the soil (Lv et al., 2023). These benefits are potentially undone by a single reseeding event. Elias et al. (2023) proposed that combining inversion tillage with reseeding herbal leys should be targeted at fields with low carbon saturation and fields with high existing stocks should be protected by extending no-tillage periods.

Research on the interaction between tillage methods, DS and soil depths regarding soil properties is scarce in grassland systems at large plot level. Most work has focused on either tillage or drainage systems and a combination of other factors. Previous findings showed higher soil TC and TN concentrations when tillage is reduced (Lv et al., 2023) and higher soil TC and TN concentrations in the upper soil layers (Six et al., 2002), which is consistent with our results. Soils that have not been tilled are known to have higher surface crop residues, which can reduce evaporation and conserve soil moisture. This promotes slow biological degradation of organic C, promoting soil aggregation, improved temperature regulation and increased total soil C stocks (López-Bellido et al., 2019). The reduced oxygen availability below the surface in NT systems also decreases decomposition rates, causing soil organic matter (OM) to be retained as buried residues in tillage soils to decompose at 3.4 times the rate of residues left on the soil surface (Beare et al., 1994). In contrast, soil tillage improves aeration, accelerating the decomposition of OM and mineralization of organic N into soluble forms, easily lost through leaching (Vilakazi et al., 2022). Furthermore, conventional tillage is known to break down soil aggregates, and the organic material held within them is mineralized by microbial organisms, eventually decreasing the soil C content. Undrained plots are known to have greater TC and TN due to the reduced decomposition rate of OM and their higher moisture contents (Harris et al., 2018), which is consistent with our findings, as the undrained plots generally had higher soil TC and TN concentrations compared to the drained plots at 0–10 cm depth. The lack of differences between the treatments in TC at depth (10–30 cm) indicates that in the fine-textured soil at Rowden with high carbon saturation after many years of NT, the potential benefits of inversion tillage suggested by Elias et al. (2023) were not observed.

Phosphorus is an essential element for plant growth and development, and its availability is affected by physical soil manipulation (Lv et al., 2023). Higher concentrations of P in the upper soil layers in NT systems have been reported (Nze Memiaghe et al., 2022). It is important to note that a slower decomposition of plant residues under NT may prevent the rapid mineralization of organic P and its translocation through the soil profile, due to the accumulation of plant residues on the soil surface, resulting in decreased aeration and increased soil moisture content. Furthermore, under tillage systems, organic P is rapidly mineralized, providing P for plant and microbial compared to conservation tillage (Vilakazi et al., 2022).

Reports indicate that no-tillage practices and undrained soil conditions can enhance C sequestration by minimizing OM breakdown and increasing C accumulation. Long-term NT management in undrained soils may effectively boost TC and TN concentrations in the upper soil layers, as observed in our study, and could help to mitigate greenhouse gas emissions and support climate change efforts. This approach is important to avoid the traditional 5-year tillage cycle stocks (Elias et al., 2023), especially in soils with significant chemical concentrations specifically targeting soil with low nutrient concentrations and stocks.

Data and reports on the impact of tillage systems on soil pH are highly variable, primarily due to variations in pedoclimatic conditions, cropping systems and combined field operations at different experimental sites (Sadiq et al., 2021). In the United Kingdom, the recommended pH level for grassland soils is 6.0 (Defra, 2010). Even though all the treatments combinations from the three-way interaction were almost statistically similar in their values, drained 5YNT (5.95) and undrained 30YNT (5.96) at 10–30 cm depth showed the closest pH levels to the recommended value. This could potentially reduce the costs associated with liming to achieve the optimal pH targets for sustainable grassland, especially for legumes and herbal leys pastures in such practices.

CONCLUSIONS

This study demonstrates that long-term no tillage, particularly under undrained conditions, substantially enhances the retention of soil carbon, nitrogen and phosphorus in the surface layer of permanent grassland soils. These benefits can be largely reversed by a single reseeding event involving tillage, and the greatest proportional nutrient losses could occur in soils that initially had high nutrient stocks. Strong interactions between tillage legacy, drainage and soil depth highlight that soil management outcomes cannot be evaluated in isolation. The pronounced stratification of nutrients in the topsoil underscores the importance of conserving long-established no-tillage systems, especially in undrained grasslands, to maintain soil fertility and support sustainable productivity. Field-level assessment of existing soil carbon and nutrient status can help identify grasslands that should be protected from cultivation versus those more suitable for reseeding within agri-environment schemes.

AUTHOR CONTRIBUTIONS

Tersur T. Akpensuen: Conceptualization; methodology; data curation; investigation; validation; formal analysis; writing—original draft; visualization. **Charlie Morten**: Data curation; investigation; writing—review and editing. **Andrew Mead:** Methodology; data curation; formal analysis; writing—review and editing. **Martin S. A. Blackwell:** Methodology; writing—review and editing. **M. Jordana Rivero:** Methodology; writing—review and editing; validation; supervision. **Jonathan Storkey**: Methodology; project administration; resources; funding acquisition; writing—review and editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

Data can be obtained from the Rothamsted Research repository at: https://doi.org/10.23637/mx8uwhme.

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