Effects of mineral layer inversion on the hydrology and grass yield of a cultivated peat soil

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SUMMARY

In the Nordic countries, some peatlands have been drained and cultivated with grass for animal husbandry. However, there is a challenge for agronomy due to high water content and poor trafficability, while improved drainage can lead to peat degradation. On the Norwegian west coast, we studied the effects of conventional pipe drainage and peat inversion, as a new drainage method to find improved solutions for farming while minimising peat degradation. In the peat inversion method, mineral soil excavated from below the peat is used to form a 0.5–1 m layer on top of peat. Peat inversion was carried out in a 3.5 ha field which was earlier drained with subsurface pipes, while the adjacent 2.7 ha field remained with subsurface pipes placed at 8 m spacing and 1.3 m deep. On adjacent grass-cultivated peatlands we compared water table (WT), volumetric water content (VWC), soil temperature and dry matter yield (DMY) over the period 2014–2019. The mean WT was lower ($p < 0.001$) in the inverted field, at -93 ± 62 cm compared to -53 ± 40 cm in the pipe-drained field. In the inverted field, soils were drier and frost was observed earlier and lasted longer due to the presence of the mineral topsoil. The mean VWC at 0–5 cm depth in the pipe-drained field was 47.4 ± 16.9 % v/v, which was higher ($p < 0.001$) than in the inverted field where the values were 28.6 ± 10.4 and 30.9 ± 10.7 % v/v, depending on mineral soil thickness. However, there was no difference ($p = 0.775$) in mean soil temperature at 0–5 cm depth between inverted and pipe-drained fields. There was a significant difference ($p < 0.001$) between DMY data collected from 2015 to 2018 in the inverted field (11.6 ± 2.32 t ha^{-1} yr^{-1}) and the pipe-drained field (10.4 ± 1.22 t ha^{-1} yr^{-1}) as well as a significant interaction between rainfall and drainage type ($p < 0.001$). Our study indicates that peat inversion lowers the WT and VWC and increases DMY. These findings provide a first estimate on the effects of this alternative drainage option for peatland agriculture in parts of western Norway receiving high precipitation.

KEY WORDS: agriculture, drainage, grasslands, organic soils, peat inversion, pipe drainage

INTRODUCTION

Carbon rich peat soil covers nearly 14 % of Norway's land area (Tanneberger *et al.* 2017). Within this area, 850–1500 km^2 of peatlands have been drained for agriculture since the early 20th century (Malijanen *et al.* 2010 quoted by Kløve *et al.* 2017). To protect these carbon stocks, the Norwegian parliament voted for a ban on cultivation of new peatlands in 2019 (Farstad *et al.* 2022); however, in some cases new drainage permits for natural peatlands may be granted by the local government (County Governor 2021). Western and Northern regions contain the highest percentages of total cultivated peat soils (Grønlund *et al.* 2008), and in these areas forage and feed production are often carried out on small-scale farms. Peatlands represent 7–8 % of all agricultural soils in Norway (Grønlund *et al.* 2008). As the portion of agricultural land is low at around 3 % of the total land area (Strand *et al*. 2021), there is an interest in maintaining land under agricultural production including areas with organic soils. In Norwegian cultivated peatlands, waterlogging, poor trafficability (Grønlund *et al.* 2006) and high variation in yield occur. Due to environmental concerns, there is a need to investigate alternative drainage options which balance the trade-offs between food production and greenhouse gas (GHG) emissions. Alternative management practices such as paludiculture for biomass production have been tested in recent years as an option (Lahtinen *et al.* 2022), and trials have been conducted to extract feed from wetland biomass as an alternative for grass in animal husbandry (Nielsen *et al.* 2021). However, the emission of GHGs can still be an issue as they are sensitive to water table (WT) levels (Berglund *et al.* 2021).

Cultivation on peatlands along the Norwegian west coast is often carried out on peat with a high degree of humification (von Post scale of H6 or higher) and low drainage capacity, where moderate precipitation events can lead to a rapid rise in WT (Hove 1973) which creates difficult conditions for agriculture. Besides wet conditions, frost and freezing can also harm plant growth (Kløve *et al.* 2010). Hence, farmers have adopted different drainage methods to continue cultivation on peatlands. Among them land grading (also called surface grading) combined with open ditches and/or subsurface drainage pipes has been a common approach. The subsurface pipes are typically placed between 4–10 m and 0.8–1.3 m depth (Kløve 1999, Beheim 2006, Kløve *et al.* 2010). In land grading, the land is typically sloped (~5 %) to enhance overland flow and prevent water ponding and ice damage during winter and is combined with open ditches spaced 50 m apart (Kløve *et al.* 2010).

To improve physical and chemical properties of peat for cultivation, adding and mixing mineral soil with peat has been practised since the 17th century (Lende-Njaa 1924 quoted by Sognnes *et al.* 2006). These methods were aimed at increasing yield and trafficability (Göttlich 1990). According to the literature there are three methods for mixing peat with sand. They are *mixed* (a Swedish method), *blanket* ("Rimpau" in Russian), and *German mixed layer* ("Sandmischkultur" in German). In the Swedish method, a sand layer is placed in ploughed horizons and mixed with peat when ploughing. In the Russian method, an arable sandy layer is spread on the surface of the drained peat. The German method utilises specialised machinery that extracts sand underlying the peat soils and later mixes it with the peat (Zakharova *et al.* 2020). Addition of a mineral layer decreases heat capacity and increases thermal conductivity causing the soil to dry out faster in the spring (Celius 1967). A Swedish study found that soil temperature increased during the growing season when a layer of sand was added (von Feilitzen 1912 quoted by Vikeland 1975). Similar results were obtained in Germany (Baden 1952 quoted by Sognnes *et al.* 2006). In Finland, Pessi (1956) found that addition of clay to peat soils resulted in an increase of approximately 1 °C in soil temperature during the summer. In the Pasvik valley of northern Norway, Sveistrup & Haraldsen (1995) examined the effect on grass yield due to the addition of sand to peat under different compaction and non-compaction scenarios. They found that the grass yield increased from 5.3 tons ha^{-1} (without sand addition and compaction) to 6 tons ha^{-1} (with sand addition and no compaction) and 5.5 tons ha^{-1} (with sand addition and compaction). On the western coast of Norway, the effects of adding shell or moraine sand to peat was studied by Sognnes *et al.* (2006). Addition of shell sand or moraine sand gave higher grass yields (11.5 and 10.8 tons ha^{-1} yr^{-1}, respectively) compared to the reference plots which gave 10.4 tons ha^{-1} yr^{-1}. Overall, these methods have shown positive agronomic performance and enhanced trafficability after several years of implementation, although the process involved is time-consuming and rather expensive. As a method to improve growing conditions and trafficability, peat inversion has been practised in Norway since at least 1972 (Solberg 1980). In the peat inversion method mineral soil excavated from below the peat is used to form a 0.5–1 m layer on top of peat. With this method, it is expected that the WT will stay close to the mineral top layer, keeping the peat saturated, which reduces oxygen diffusion and may therefore minimise peat decomposition.

The effects of conventional drainage methods (i.e. pipe drainage with surface grading only or in combination with open ditches) on hydrology, yield and GHG emissions in agricultural peatlands at northern latitudes have been previously studied by Regina *et al.* (2004), Kløve *et al.* (2010) and Berglund *et al.* (2021). In contrast, we are aware of only one study on peat inversion, by Sveistrup & Haraldsen (1997) who studied its effects on trafficability and root growth in grass-cultivated peatlands in northern Norway. Even though peat inversion has been practiced for more than 50 years by Norwegian farmers, its effects on hydrology and agronomy have not been investigated until now. The main objective of the present study is to understand the differences in WT, volumetric water content (VWC), soil temperature and dry matter yield (DMY) due to peat inversion and conventional pipe drainage. Statistical analysis was performed for the data obtained from field experiments carried out between 2014 and 2019 on adjacent grass-cultivated inverted and pipe-drained peatlands on the western coast of Norway. We hypothesised that (1) peat inversion lowers the WT compared to pipe drainage resulting in improved drainage because the mineral top layer and tilted layers have a higher hydraulic conductivity than peat; (2) the mineral top layer in the inverted field results in lower VWC due to its lower porosity; and (3) there was a difference in DMY between the inverted lower and inverted upper fields due to the differences in the thickness of mineral top layer.

METHODS

Study site

Our study was carried out on two adjacent grass fields in Farstad (62° 57' 51" N, 7° 08' 19" E), a village in the Hustadvika municipality on the western coast of Norway (Figure 1A). The mean annual precipitation for 2014–2019, recorded at the "Hustadvatn" meteorological station (SN627000; 9 km from the field site) was 2259 mm. On average, 1063 mm of this fell during September–December, after the growing season. The mean annual temperature for 2003–2018, recorded at the "Molde airport" meteorological station (SN62270; 25 km from the field site) was 7.3 °C (Norwegian Meteorological Institute 2022).

Drainage history

The study site was formerly a coastal ombrotrophic peatland. It was first cultivated with grass in 1972, after being drained for the first time. In 1980, the fields were redrained with perforated subsurface pipes (8 m spacing, 1.3 m deep); and in 1982 they were graded to further improve drainage conditions. During 2012–2013, peat inversion was carried out in one of the fields (3.5 ha) while the other field (2.7 ha) remained with pipe drainage. The peat depth in the pipe-drained field is approximately 2 m. The inverted peatland is graded towards a drainage ditch between the experimental fields (Figure 1B). The thickness of the mineral layer is 80–100 cm near the more-elevated centreline of the field (henceforth inverted upper, IU), compared to 45–55 cm in the lower part

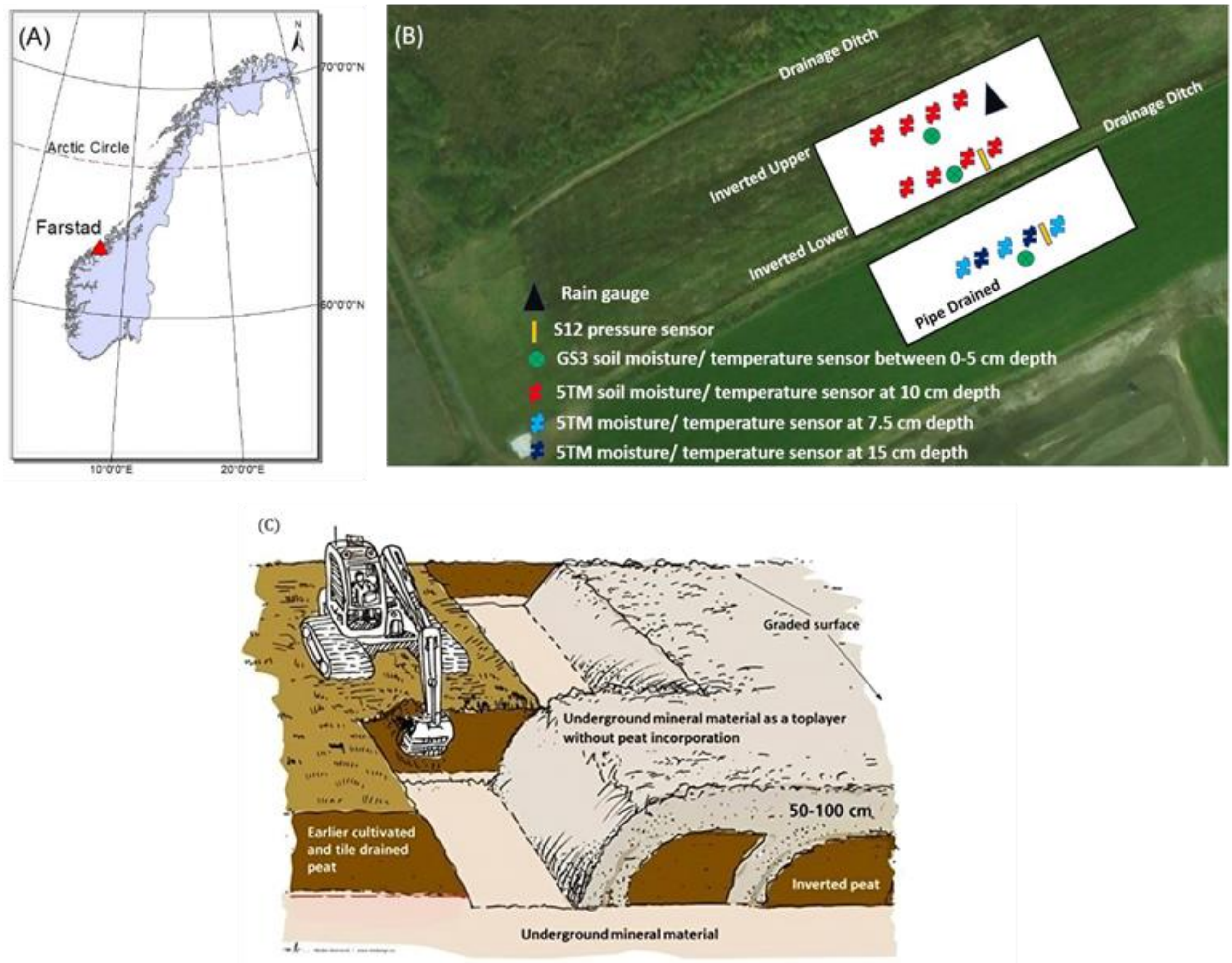

Figure 1. (A) Location of Farstad in Western Norway; (B) layout of drainage trials and placement of sensors in inverted and pipe-drained fields; and (C) illustration of the peat inversion procedure (reprinted from "Drenering 3" by Aamodt 1990).

of the field near the drainage ditch (henceforth inverted lower, IL). During the peat inversion process, the peat soil was covered with the underlying mineral material while maintaining connectivity to the self-draining subsoil through tilted layers that extend from the topsoil to the subsoil (Figure 1C). The thickness of the mineral layer in the inverted upper field (near the centreline of the field) is 80–100 cm, whereas in the inverted lower field (near the drainage ditch) the thickness varies between 45–55 cm. Figure 1B shows the layout of the fields and placement of sensors while Figure 1C depicts the peat inversion procedure.

Harvesting and treatment schedule

In June 2014, a seed mixture consisting of 70 % timothy (*Phleum pratense*), 20 % meadow fescue (*Festuca pratensis*) and 10 % smooth meadow grass (*Poa pratensis*) was sown at 30 kg ha^{-1} on both fields. The 2014–2019 schedules of harvesting, fertilising and compaction on inverted upper, inverted lower and pipe- drained fields are given in Table 1. In line with local management practices the grass was harvested twice a year, in June (first harvest) and August (second harvest) each year. Compaction was carried out in spring, then after the first harvest and after the second harvest. A 5.2-ton tractor was used for compaction in 2015 and 2016, while a 3.9-ton tractor was used in 2017 and 2018.

Hydrological measurements

Soil temperature and volumetric water content

In the pipe-drained field, three 5TM volumetric water content (VWC) and temperature sensors (METER Group, Pullman, WA, USA) were operated at 7.5 cm depth and two at 15 cm depth from April 2017 to October 2018. In the inverted upper and lower fields, four 5TM sensors were in place at 10 cm depth from April 2017 to August 2018. An Em50 (METER Group, Pullman, WA, USA) was used for data logging. In the pipe-drained field, VWC and temperature sensors at 0–5 cm depth were installed from July 2017 to May 2019. In the inverted upper and inverted lower fields, VWC and temperature sensors at 0–5 cm depth were installed from July 2017 to August 2018 and from August 2017 to May 2019, respectively (Table 2 and Figure 1B). VWC and soil temperature at 0–5 cm depth were measured using GS3 water content, electrical conductivity and temperature sensors (METER Group, Pullman, WA, USA). Data were recorded using an Em50 data logger. All VWC and temperature measurements were recorded at hourly intervals.

Table 1. Harvesting, fertilisation and compaction treatment schedule (IU = Inverted Upper, IL = Inverted Lower, PD = Pipe Drained).

Year	Grass harvest	Cattle slurry (54 kg NH_4-N ha^{-1}) and mineral fertiliser (150 kg N ha^{-1} yr^{-1})	Mineral fertiliser (260 kg N ha^{-1} yr^{-1})	Compaction (weight in tons)
2014		IU, IL, PD		
2015	IU, PD		IU, PD	IU, PD (5.2)
2016	IU, PD		IU, PD	IU,PD (5.2)
2017	IU, PD, IL		IU, IL, PD	IU,IL,PD (3.9)
2018	IU, PD, IL		IU, IL, PD	IU,IL,PD (3.9)

Table 2. Summary of hydrological measurements in the fields (VWC = Volumetric Water Content, IL = Inverted Lower, IU = Inverted Upper, PD = Pipe Drained).

Measurement	Installed location/s	Time period
VWC and temperature at 7.5 and 15 cm depths	PD	April 2017–October 2018
VWC and temperature at 10 cm depth	IU and IL	April 2017–August 2018
VWC and temperature at 0–5 cm depth	PD IU IL	July 2017–May 2019 July 2017–August 2018 August 2017–May 2019
Water table level	PD IL	July 2017–Dec 2018 August 2017– December 2018
Rainfall	IU	April 2017–December 2018

Water table
To measure hourly fluctuations of WT, S12S pressure cells (RS Hydro Ltd, Bromsgrove, UK) were immersed in PolyVinyl Chloride (PVC) tubes with a combined length of 200 cm and a diameter of 5 cm. In the inverted lower field, the installed tube had its bottom part (l = 100 cm) perforated to allow water ingress, while the top part (l =100 cm) was unperforated. At this location, the soil profile consisted of mineral soils (0–55 cm), a transition layer with mixed organic and mineral soils (55–70 cm, peat soils (70–130 cm) and mineral soils below 130 cm. Perforated pipes were used along the entire 200 cm depth in the tube installed in the pipe-drained field. The WT measurements in the pipe-drained field started in July 2017, whereas measurements in the inverted lower field started in August 2017. Continuous monitoring of WT was carried out until December 2018 in both fields. The data were recorded using a CR200 data logger (Campbell Scientific, Logan UT, USA).

Rainfall
Hourly rainfall was measured from April 2017 to October 2018 using an ECRN50 single spoon-tipping bucket (METER Group, Pullman WA, USA). The rain gauge was placed in the inverted upper field and was connected to the same Em50 logger as the VWC and temperature sensors. Table 2 summarises the hydrological measurements carried out in the fields.

Soil sampling and soil physical properties analysis
To measure soil physical properties, soil samples were taken from inverted upper, inverted lower and pipe-drained fields between 2014 and 2017 (Table 3). Undisturbed samples were collected using cylinders (each 5 cm in height and 5 cm in diameter) with a volume of ∼100 cm^3. The undisturbed soil cores were then used to determine bulk density by the cylinder method (FAO 2023). The VWC at matric potentials of 20, 100, 1000 and 15,000 hPa was measured in the laboratory. Air permeability was measured at 100 hPa (Green & Fordham 1975). Air-filled porosity at 100 hPa was determined with an air pycnometer (Torsteinsson & Eriksson 1936). Saturated hydraulic conductivity was calculated from air permeability (Sognnes *et al.* 2006, Wells *et al.* 2006). Drainable porosity was taken as the air porosity at 100 hPa, and the total porosity was calculated as the sum of air-filled porosity and VWC at 100 hPa. The plant available water capacity was calculated by taking the difference between VWC at 100 and 15,000 hPa. These measurements were carried out in the soil laboratory at the Norwegian University of Life Sciences (NMBU) in Ås. To determine soil texture, two samples each were taken from inverted upper and inverted lower fields. The soil texture was determined using the pipette method (Palihakkara & Vitharana 2019) in the laboratory.

Measurements of dry matter yield
Dry matter yield (DMY) was measured from three replicates each from pipe-drained, inverted upper and inverted lower fields in plots with areas of 12 m^2. Grass was cut with a two-wheel mower. DMY was measured for two harvests each year and was determined by drying grass samples at 60 °C for 48 hours. In inverted upper and pipe-drained fields, DMY was measured from 2015 to 2018. Since the grass plots in the inverted lower field were established in 2017, DMY data for this field were available only from 2017 and 2018.

Table 3. Sampling times and depths (cm) for soil physical properties and soil texture. To determine soil physical properties, four replicates were collected from the pipe-drained field and six replicates were collected from each of the inverted (upper and lower) fields at each time point and depth. Replicates were not taken to determine soil texture.

Sampling for soil physical properties			
Year	Pipe Drained	Inverted Lower	Inverted Upper
2014	5–10, 25–30, 60–65		5–10, 25–30,60–65
2015	5–10, 25–30		5–10, 25–30
2016	5–10, 25–30		5–10, 25–30
2017		5–10, 25–30	5–10, 25–30
Sampling for soil texture			
2017		10–20, 20–40, 40–52, 40–52 or 55–70	0–20, 20–40, 40–60, 60–70 or 60–80

Statistical analysis

Effect of drainage type on water table, volumetric water content and soil temperature

A non-parametric sign test was performed to test whether there was a statistically significant difference between the WT in the pipe-drained and inverted lower fields. We tested for significant differences between the medians of the mean monthly WT. To test the differences in VWC and temperature at 10 cm depth in inverted upper and inverted lower fields and between 7.5 cm and 15 cm depths in the pipe-drained field, a non-parametric sign test was also used. Additionally, a two-way ANOVA was carried out to determine whether the difference in VWC and soil temperature at 0–5 cm soil depth in inverted lower, inverted upper and pipe-drained fields was statistically significant. The months and fields were treated as blocks. A post-hoc Tukey pairwise comparison test was done to identify which group means of VWC and soil temperature were statistically different. All tests were carried out at $\alpha = 0.05$ and in the SAS Statistical Software (version 9.4, SAS Institute 2024).

The interaction of rainfall and drainage type: effect on dry matter yield

To test the combined effect of rainfall and drainage type on DMY we used a mixed model with annual DMY (sum of 1st and 2nd harvests) as the response variables, and the drainage type and rainfall (cumulative rainfall from the start of the growing season until the second harvest) as the main effects, and year and plot as random effects. A Tukey-Kramer post-hoc test was performed to identify which group means were different from each other at $\alpha = 0.05$ significance level. The start of growing season was defined as the period when the air temperature remained above 5 °C for five consecutive days (Venäläinen & Nordlund 1988). In this study the start date of the growing season was taken as 6th April, derived as the 2014–2018 average start date of the growing season. The cumulative rainfall was calculated from the start of the growing season until the second harvest was taken. Here we used rainfall data from the nearest meteorological station to our study field (station name "Hustadvatn"; Norwegian Meteorological Institute 2022). This was due to the rain gauge installed in our field being in operation only intermittently between 2017 and 2018. These tests were conducted in the SAS Statistical Software (version 9.4, SAS Institute 2024). See Appendix 2 for detailed information.

Effect of drainage type on soil physical properties

A student's t-test was carried out to determine whether there was a statistically significant difference between soil properties (porosity and plant available water capacity) of the inverted and pipe-drained fields. The soil properties data from the inverted upper and inverted lower fields were pooled. Prior to conducting the student's t-test, diagnostic plots were examined to assess the normality of the soil properties data. These tests were conducted in R (version 4.3.1; R Core Team 2024).

Development of van Genuchten curves

The van Genuchten curves (van Genuchten 1980) (Equation 1) were developed to determine the VWC at different pressure (suction) levels in soils in the (lower and upper) inverted and pipe-drained fields. A representative soil water retention curve was developed by averaging VWC values from different soil depth horizons at each pressure head.

$$\theta(h) = \theta r + \frac{\theta s - \theta r}{(1+(\alpha h)^n)^m} \qquad [1]$$

where $\theta(h)$, θ_r and θ_s are current, residual and saturated VWC ($cm^3\ cm^{-3}$), h (cm) is the pressure head, α (cm^{-1}), n and m (both dimensionless) are empirical parameters, and $m = 1-1/n$.

RESULTS

Water table

Generally, the WT followed the pattern of the rainfall in both inverted lower and pipe-drained fields (Figure 2). Except for a few occasions, the WT in the inverted lower field was consistently lower than in the pipe-drained field. The mean WT was lower in the inverted field at -93 ± 62 cm compared to -53 ± 40 cm in the pipe-drained field (non-parametric sign test, $p < 0.001$). The variability of the WT in the inverted lower field was higher than that of the pipe-drained field. The WT range in the inverted lower field (-198–0 cm) was higher than in the pipe-drained field (-119–0 cm). During the first week of October 2017, the WT was around -80 and -120 cm in the pipe-drained and inverted lower fields, respectively. However, following a series of rainfall events the WT fluctuated near the surface for most of the time until the end of November 2017. There was a closer agreement in WT between pipe-drained and inverted lower fields from early November to the end of December in 2017 and also from early September to the end of October in 2018. These observations suggest that the WT responds similarly to continuous rainfall events in both drainage systems. On the other hand, clear differences in the magnitudes of WT were observed from February to March in 2018, with deeper WT in the inverted field than in the pipe-drained field.

Volumetric water content

VWC at 0–5 cm soil depth followed a similar pattern in the inverted and the pipe-drained fields (Figure 3). VWC in the pipe-drained field had a higher mean of 47.4 ± 16.9 % v/v and a wider range of 16.2–74.6 % v/v compared to VWC in the inverted upper and inverted lower fields which had means of 28.6 ± 10.4 and 30.9 ± 10.7 % v/v and ranges of 9–50.2 % and 9.6–50.7 % v/v, respectively (two-way ANOVA test, $p < 0.001$). The electromagnetic sensors used in this study measure soil liquid water content. During periods of frost (indicated by shaded bars) in the winter (December–February), readings may show low values that do not reflect the true VWC of the soil. Furthermore, the maximum value of VWC is determined by soil porosity. Figure A1.1 (A and B) in Appendix 1 shows the VWC fluctuations at 7.5 and 15 cm soil depths, respectively, in the pipe drained field whereas Figure A1.1 (C and D) shows VWC fluctuations at 10 cm soil depth in the inverted upper and inverted lower fields, respectively. There was a difference in VWC ($p = 0.01$) between the inverted upper field (22 ± 5.45 % v/v) and the inverted lower field (25 ± 6.8 % v/v) at 10 cm depth. However, there was no difference in VWC between 7.5 cm (62 ± 24 % v/v) and 15 cm (60 ± 20 % v/v) depth in the pipe-drained field ($p = 0.791$).

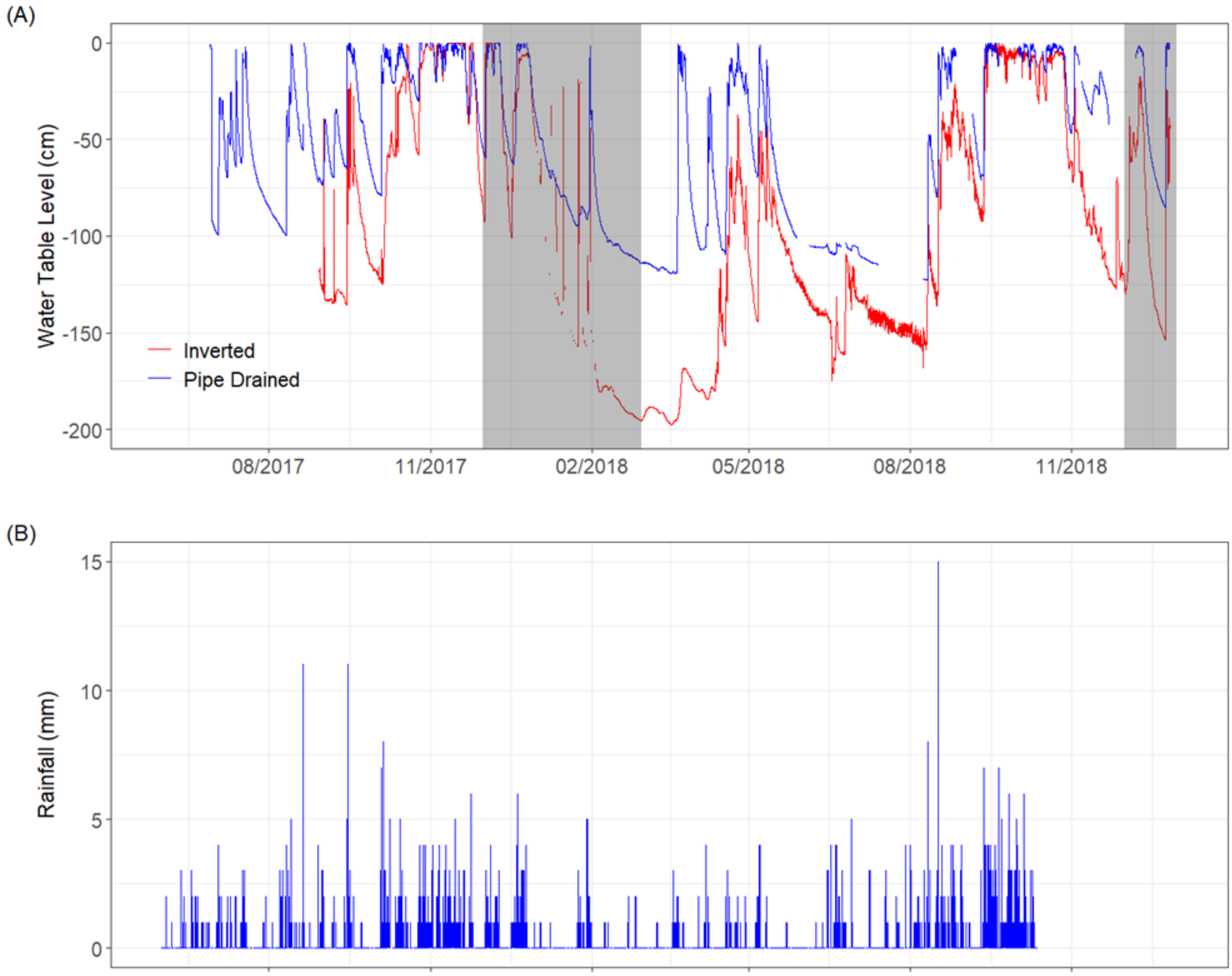

Figure 2. (A) Hourly water table level in pipe-drained and inverted fields (red colour: inverted field; blue colour: pipe-drained field). (B) Hourly rainfall. Shaded bars in (A) denote the winter season between December and February.

Dry matter yield

The drainage type had an effect on the dry matter yield (DMY) ($p < 0.001$) (Table A2.2 in Appendix 2). There was a significant interaction between rainfall and drainage type ($p < 0.001$) (Table A2.2). In 2015–2018, on average the inverted upper field produced 0.8 tons ha^{-1} yr^{-1} more DMY than the pipe-drained field. The 2015–2018 mean DMY in the inverted upper and pipe-drained fields were 11.6 and 10.4 tons ha^{-1} yr^{-1}, respectively. The experimental plots in the inverted lower fields were established in 2017, so their DMY was measured only during 2017–2018. The mean DMY in the inverted lower and inverted upper fields during this period was 10.7 and 9.5 tons ha^{-1} yr^{-1}. The post-hoc test confirmed that there was a significant difference in DMY between the inverted upper and inverted lower fields (Table A2.3). The effect of drainage type on DMY was stronger in the inverted field compared to the pipe-drained field (Table A2.1). Also, the DMY showed a considerable variability across the experimental plots in the inverted upper field which could be due to the heterogeneity of the soils (Figure 4A). In the inverted field the DMY was reduced in the dry year of 2018 (Figure 4). However, all experimental plots had the lowest DMY during the first harvest in 2018. In our study the highest DMY on the inverted field was found a year after the inverted upper field was established, which was two years after the inversion was completed.

Soil physical properties

There were considerable differences in soil physical properties between peat and mineral soils (Table 4). The porosity of peat in the pipe-drained field varied across the range 80–91 % v/v whereas in the mineral soils of the inverted field the range was 27–60 % v/v. The range of plant available water capacity in the pipe-drained field was 45–72 % v/v whereas in the inverted field this range was 2.6–27 % v/v. The mean porosity of peat in the pipe-drained field was higher than that of mineral soils in the inverted field (student's t test, $p < 0.05$). Moreover, the mean plant available water capacity of peat in the pipe-drained

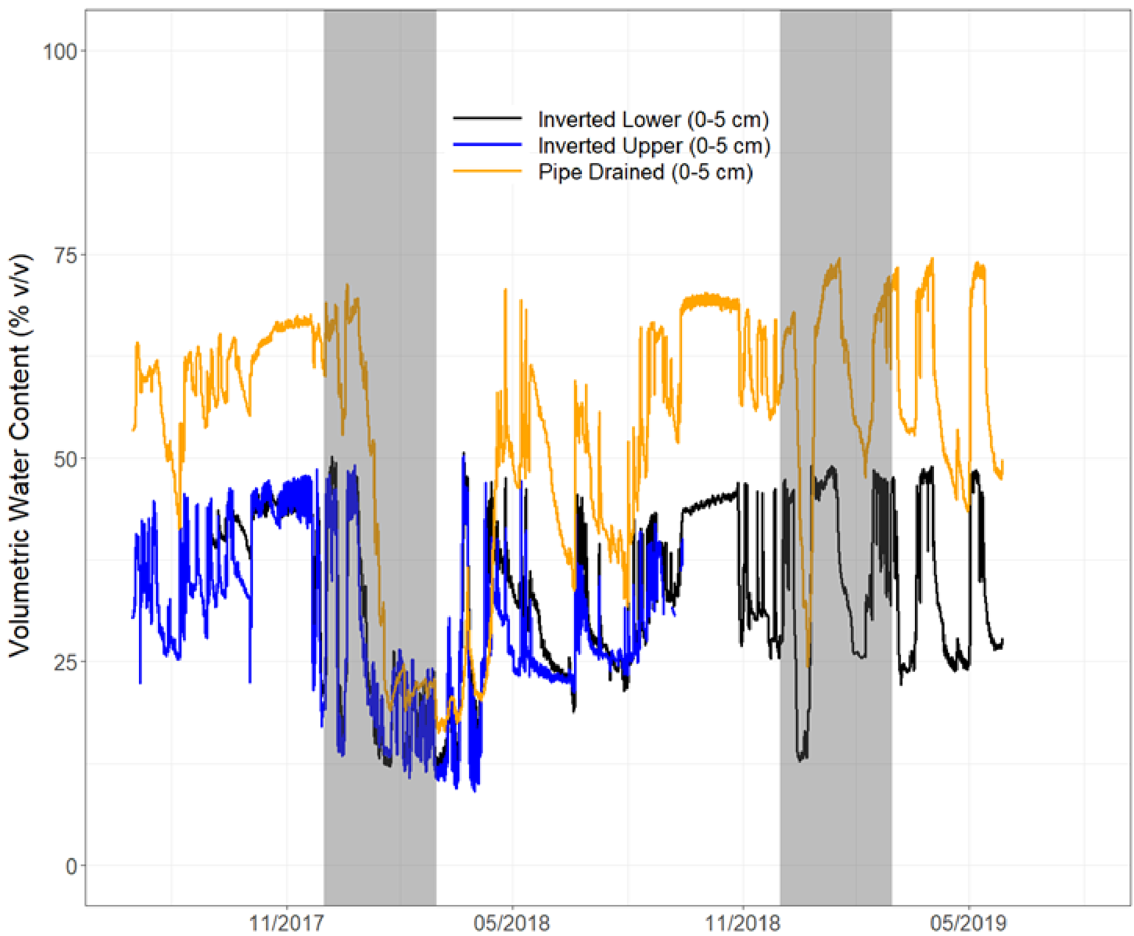

Figure 3. Volumetric water content at 0–5 cm soil depth in pipe-drained and inverted (lower and upper) fields. Shaded bars denote the winter season December–February.

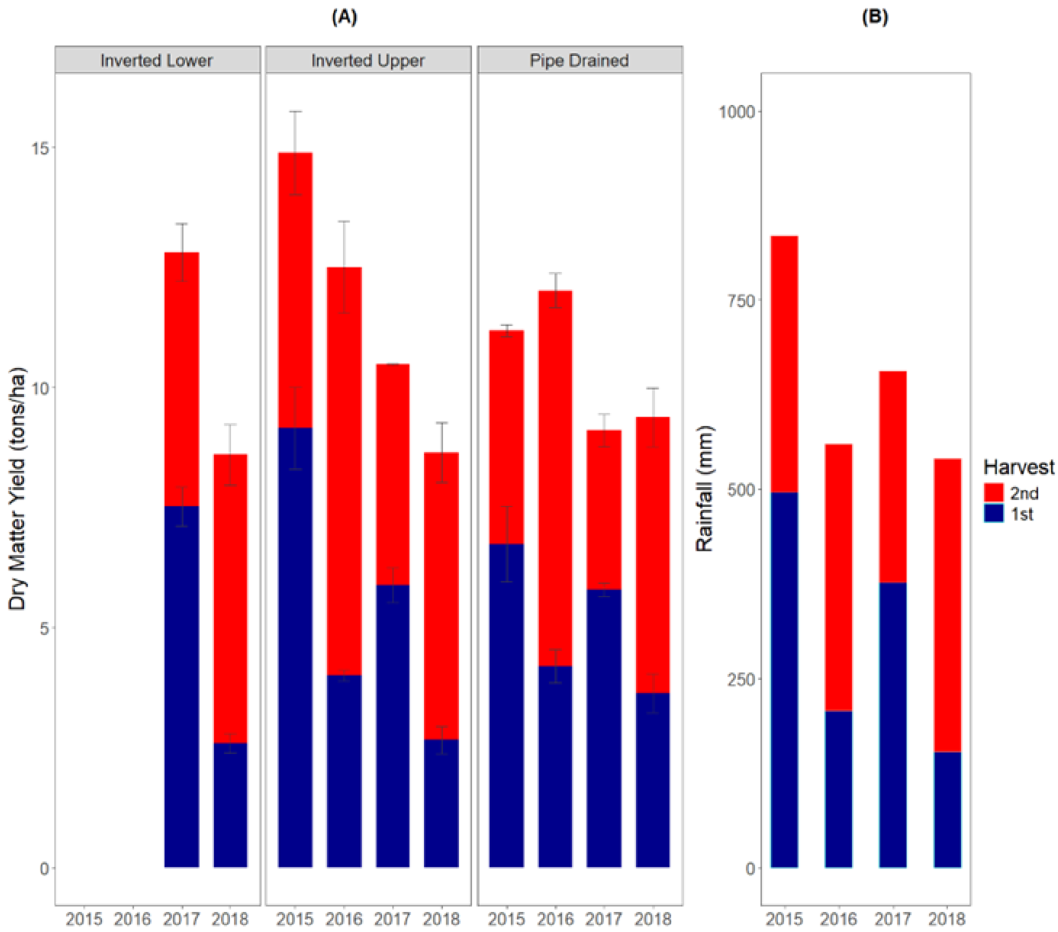

Figure 4. (A) Dry matter yield and (B) Rainfall affecting first harvest and second harvest. Error bars in (A) show the standard deviation of dry matter yield from replicates.

Table 4. Soil physical properties in the pipe-drained and inverted (lower and upper) fields. Mean ± standard deviation, n = number of samples.

Site and depth	Bulk density (g cm^{-3})	Porosity (% v/v)	Drainable porosity (% v/v)	Saturated hydraulic conductivity (cm h^{-1})	Plant available water capacity (% v/v)
Pipe drained					
5–10 cm (n=12)	0.23 ± 0.03	85 ± 2	11 ± 4	7 ± 10	56 ± 5
25–30 cm (n=12)	0.21 ± 0.05	86 ± 3	15 ± 5	9 ± 10	58 ± 9
60–65 cm (n=4)	0.14 ± 0.01	90 ± 1	13 ± 3	25 ± 18	70 ± 3
Inverted upper					
5–10 cm (n=24)	1.64 ± 0.23	39 ± 8	15 ± 9	20 ± 34	19 ± 4
25–30 cm (n=24)	1.70 ± 0.37	37 ± 4	14 ± 10	7 ± 14	18 ± 6
60–65 cm (n=6)	1.72 ± 0.03	35 ± 1	7 ± 2	1 ± 1	22 ± 3
Inverted lower					
5–10 cm (n=6)	1.86 ± 0.02	32 ± 4	4 ± 3	0.06 ± 0.12	21 ± 2
25–30 cm (n=6)	1.83 ± 0.02	33 ± 1	7 ± 3	0.27 ± 0.14	18 ± 2

field was higher compared to that of the mineral soils in the inverted field (student's t test, $p < 0.05$). The bulk density range of samples taken from mineral soils in the inverted field was 1–1.94 g cm^{-3} whereas the bulk density range in the pipe-drained field was 0.13–0.31 g cm^{-3}. In the pipe-drained field, the decrease of bulk density with increasing peat depth could account for the increase in the saturated hydraulic conductivity (Table 4) as explained by Liu & Lennartz (2019). The soils in the inverted lower field have a finer texture, with lower sand content than the soils in the inverted upper field. The lowest sand content (25.6 %) was found in the 0–20 cm layer at location 1 in the inverted lower field. The highest sand content (82.6 %) was found at 40–60 cm depth at location 2 in the inverted upper field (Table 5).

The van Genuchten Curves (van Genuchten 1980) developed for mineral and peat soils are shown in Figure 5. The plant available water capacity was highest in the pipe-drained field, which was 0.65 v/v followed by inverted lower and inverted upper fields which had values of 0.20 and 0.15 v/v, respectively. The fitted values in the van Genuchten equation are given in Table A1.1 (see Appendix 1).

Soil temperature

We observed that the frost at 0–5 cm soil depth in the inverted field appeared earlier and lasted longer when compared to the pipe-drained field (Figure 6). There was no difference in mean soil temperature between inverted and pipe-drained fields ($p = 0.775$). The frost can be seen with the moisture probes as a sudden decrease in VWC to very low values when the temperature is close to 0 °C. In the inverted fields, the frost was seen from as early as November 2017 and lasted until at least April 2018 (for nearly 6 months), whereas in the pipe-drained field frost was seen from January to April 2018 (for nearly 4 months). Similar observations were seen in the winter months through December 2018 to February 2019 in pipe-drained and inverted lower fields. The temperature levels mostly remained constant (around 0 °C) in the pipe-drained field from early January to end of February of 2018 with only a few exceptions. During the growing season (from 15th April to 15th September 2018) at 0–5 cm depth, the soils in the inverted upper and inverted lower fields had a mean temperature of 13.6 °C compared to 12.3 °C in the pipe-drained field. We also observed that the variability in soil

Table 5. Soil texture in inverted upper and inverted lower fields.

	Clay (%)	Silt (%)	Sand (%)			
			Fine	Medium	Coarse	Total Sand
Inverted Upper Location 1						
0–20 cm	5.8	35.5	41.5	12.6	4.6	58.7
20–40 cm	9.3	34.8	39.0	13.1	3.8	55.9
40–60 cm	9.4	31.7	38.1	13.5	7.3	58.9
60–70 cm	9.1	34.4	38.5	13.7	4.3	56.5
Inverted Upper Location 2						
0–20 cm	9.5	34.7	32.6	12.2	11.0	55.8
20–40 cm	8.5	40.9	37.7	10.0	2.9	50.6
40–60 cm	2.7	14.7	19.9	17.3	45.4	82.6
60–80 cm	9.7	26.1	20.2	13.0	31.0	64.2
Inverted Lower Location 1						
0–20 cm	20.1	54.3	20.1	4.2	1.3	25.6
20–40 cm	11.6	43.1	35.2	9.0	1.1	45.3
40–52 cm	10.8	42.1	35.4	10.1	1.6	47.1
55–70 cm	5.0	24.9	34.3	19.5	16.4	70.2
Inverted Lower Location 2						
0–20 cm	9.8	41.2	34.9	11.0	3.1	49.0
20–40 cm	8.9	37.2	38.9	12.3	2.7	53.9
40–52 cm	8.5	38.8	37.0	11.3	4.4	52.7

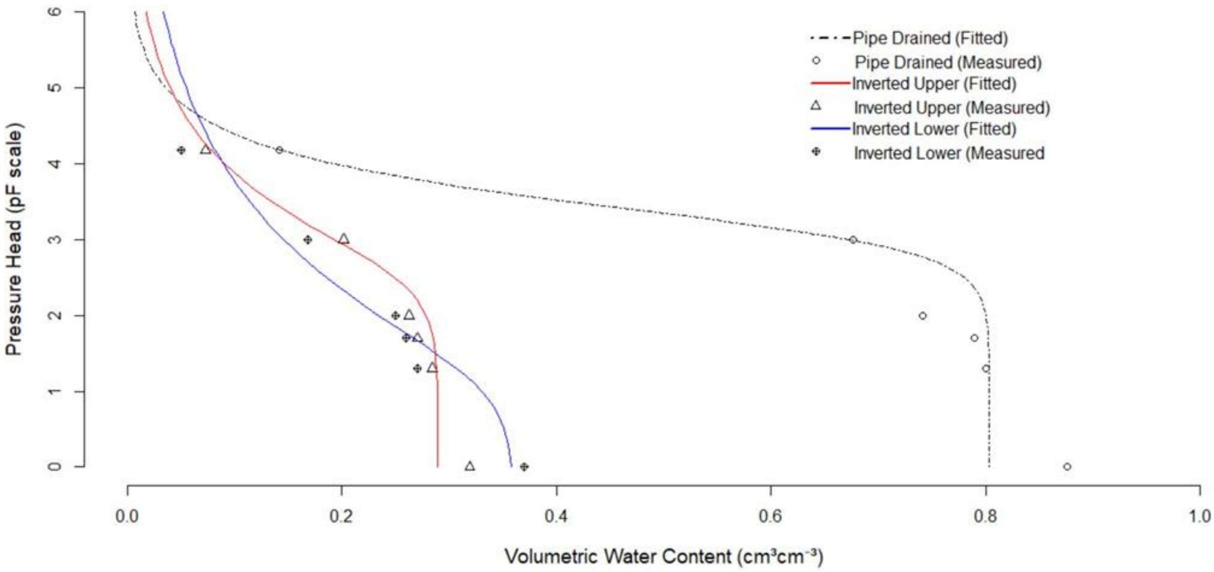

Figure 5. Fitted soil water retention curves and measured points for mineral and peat soils. pF = log |h| [hPa] where h (hPa) is the pressure head.

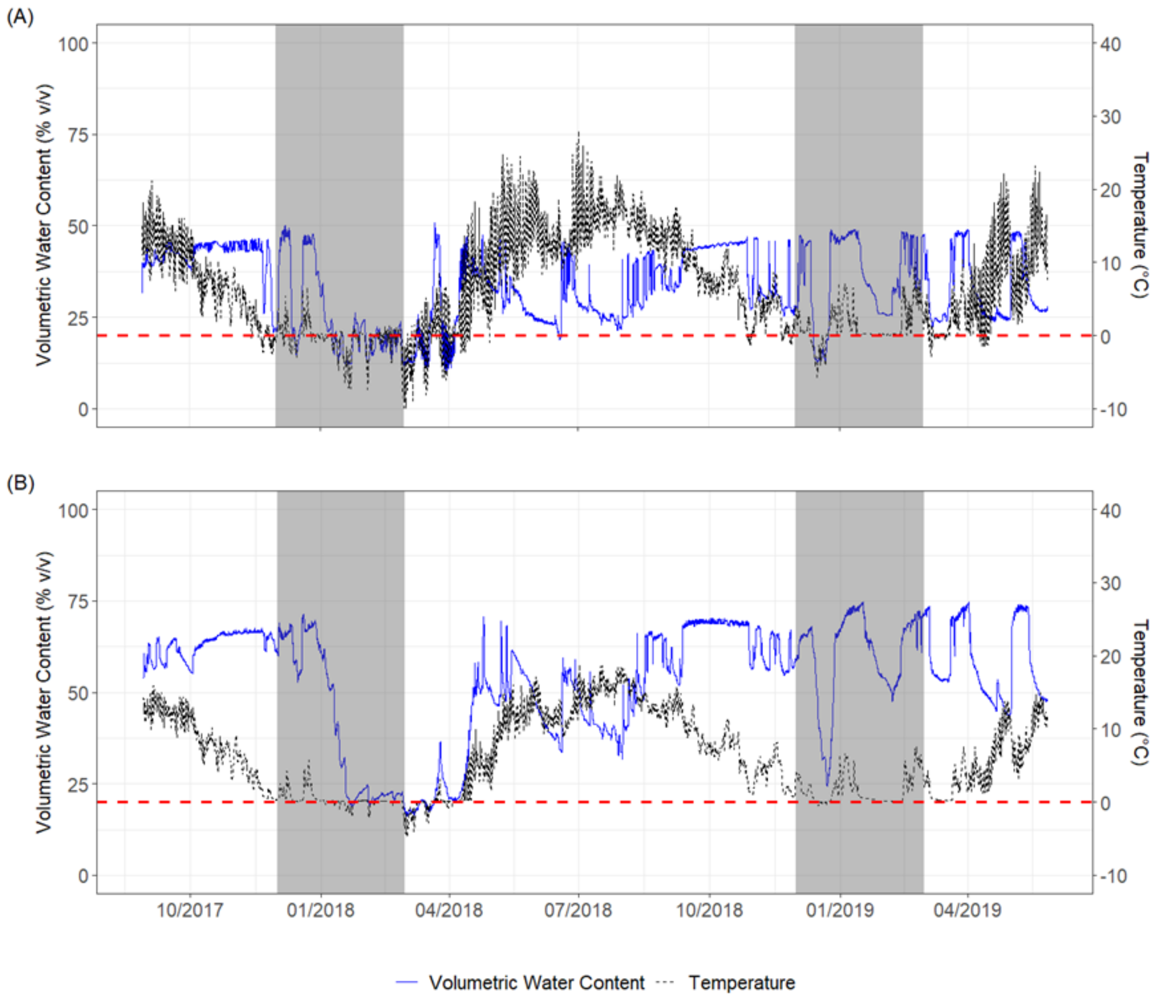

Figure 6. Temperature and volumetric water content variation at depth 0–5 cm in inverted lower field (A) and pipe-drained field (B). Shaded bars denote the winter season December–February. The dashed red line indicates T = 0 °C.

temperature was higher in the inverted upper and lower fields, which had SD = 6.4 and 9.9 °C, compared to the pipe-drained field which had SD = 5.4 °C. Figure A1.1 (A and B) shows soil temperature variations in the pipe drained field at 7.5 and 15 cm depths, respectively, while Figure A1.1 (C and D) shows soil temperature variations at 10 cm depth in the inverted upper and lower fields, respectively. There was no statistically significant difference in soil temperature ($p = 0.359$) at 10 cm depth in inverted upper (9.13 ± 5.93 °C) and inverted lower (9 ± 6.38 °C) fields. In the pipe-drained field, there was no difference in soil temperature ($p = 0.9$) between 7.5 cm (8.28 ± 5.79 °C) and 15 cm (7.98 ± 5.78 °C) depths.

DISCUSSION

The WT in the pipe-drained field was higher (-53 ± 40 cm) than that in the inverted lower field (-93 ± 62 cm) ($p < 0.001$). The higher drawdown of WT in the inverted field (Figure 2) was due to the higher hydraulic conductivity of the mineral topsoil layer and tilted layers (Figure 1C) resulting in faster and deeper drainage through the mineral layers. During the dry summer of 2018, the WT in the pipe-drained and inverted lower fields dropped to -110 and -150 cm, respectively (Figure 2). Higher rates of evapotranspiration combined with prolonged periods lacking rainfall explain the higher WT drawdowns during the dry summer. On several occasions during the winter (December 2017 to February 2018) the WT was approximately -110 and -180 cm in the pipe-drained and inverted lower fields, respectively. This was caused by cold conditions with limited infiltration due to precipitation occurring as snow or ice and frost preventing infiltration. Besides climate, soil physical properties (i.e. hydraulic conductivity, porosity) and drainage intensity affect WT (Mustamo *et al.* 2016). The measured soil hydraulic properties of peat reported in the present study fall within the ranges reported in literature for cultivated northern peatlands; e.g., for porosity (Mustamo *et al.* 2016), saturated hydraulic conductivity (Berglund & Berglund 2011) and drainable porosity (also called specific yield) (Menberu *et al.* 2021), all of which are important in groundwater flow processes. The presence of the top mineral cover layer in the inverted field resulted in a lower VWC at 0–5 cm compared to the pipe-drained field at the same depth ($p < 0.001$). At this depth the variability in temperature was higher in the inverted upper and lower fields (SD = 6.4 and 9.9 °C) compared to the pipe-drained field (SD = 5.4 °C). A possible reason for the differences in temperature variability could be due to differing heat capacities of wet peat and mineral soils.

Our study on the western coast of Norway indicates that peat inversion increases DMY compared to pipe drainage. The mean DMY from 2015 to 2018 in inverted upper and pipe-drained fields was 11.6 and 10.4 tons ha^{-1} yr^{-1}, respectively. The 2017–2018 mean DMY in the inverted lower field was 10.7 tons ha^{-1} yr^{-1}. In contrast to the inverted field, which had a SD of 2.32 tons ha^{-1} yr^{-1}, the pipe-drained field provided more stable yields, with a SD of 1.22 tons ha^{-1} yr^{-1}. Moreover, the thickness of the mineral cover layer is higher in the inverted lower field compared to the inverted upper field which could have contributed to the differences in DMY as seen in this study. However, a long-term experiment should be carried out to validate this finding since the properties of the mineral topsoil might change through ongoing cultivation. In contrast to our findings, the study done by Sveistrup & Haraldsen (1997) in northern Norway found that the combination of surface grading and open ditches is more effective than peat inversion in terms of trafficability and root growth. However, precipitation and temperature in northern Norway are lower than in western Norway (Norwegian Meteorological Institute 2022) where our study was conducted, which could explain these differences. During the period 1900–2019, precipitation has increased in Norway (Konstali & Sorteberg 2022) aligning with IPCC (2022) projections of wetter climates in the Northern Hemisphere during this century. Hence, peat inversion could be a suitable drainage method under wet climates in future, although it seems to be less effective for DMY production in dry climates and dry regions (Figure 3). The mean DMY obtained from our experiments are higher than the 7 tons ha^{-1} yr^{-1} obtained for grasslands in Western Norway (Statistics Norway 2024). Effects of inversion on DMY has not been well documented before, but improved DMY due to mineral soils addition was observed by Pessi (1956), Sveistrup & Haraldsen (1995) and Sognnes *et al.* (2006).

It is well documented that CO_2 fluxes increase when the WT drops (Couwenberg *et al.* 2011, Anu Wille *et al*. 2023, Pärn *et al.* 2023). The effect of peat inversion on GHG emissions still remains uncertain. The mineral soil coverage might compact the peat underneath, reducing oxygen availability and aerobic decomposition (Wang *et al.* 2021). Detailed measurements of carbon and GHG fluxes are essential to validate whether peat inversion reduces GHG emissions and slows down peat degradation while providing higher economic returns for farmers in the long run. Peat inversion should be evaluated alongside other management options to enable sustainable use of peatlands. Options such as paludiculture are still under research in boreal climates but could be challenging in some regions of Norway due to complex topography, in addition to limited demand for non-forest biomass and limited choices for crop cultivation due to climatic conditions.

Thus, overall, in these grass-cultivated peatlands on the western coast of Norway, peat inversion lowers the water table and provides drier soils compared to pipe drainage. We also found that peat inversion provides higher grass yields. The inverted fields are more sensitive to drought stress which can be a concern in dry years and dry regions. However, in areas with high precipitation such as western Norway, peat inversion is a strategy to lower the water table and the volumetric water content. Long-term agronomic benefits of peat inversion and its effect on greenhouse gases should be assessed to determine whether peat inversion is a sustainable drainage method.

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AUTHOR CONTRIBUTIONS

MBG carried out the analysis, wrote the first draft, revised the manuscript with the assistance of co-authors, and is the lead author; MT supervised the work, assisted in the analysis, and reviewed and edited the manuscript; SR originated and planned the work, supervised the work, and reviewed and edited the manuscript; BK originated and planned the work, supervised the work, and reviewed and edited the manuscript.

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Appendix 1

Table A1.1. Fitted values in van Genuchten curves for mineral and peat soils.

Field/soil type	α	θs	θr	n
Inverted Upper/mineral	0.070	0.360	0	1.213
Inverted Lower/mineral	0.003	0.289	0	1.356
Pipe drained/peat	0.001	0.803	0	1.736

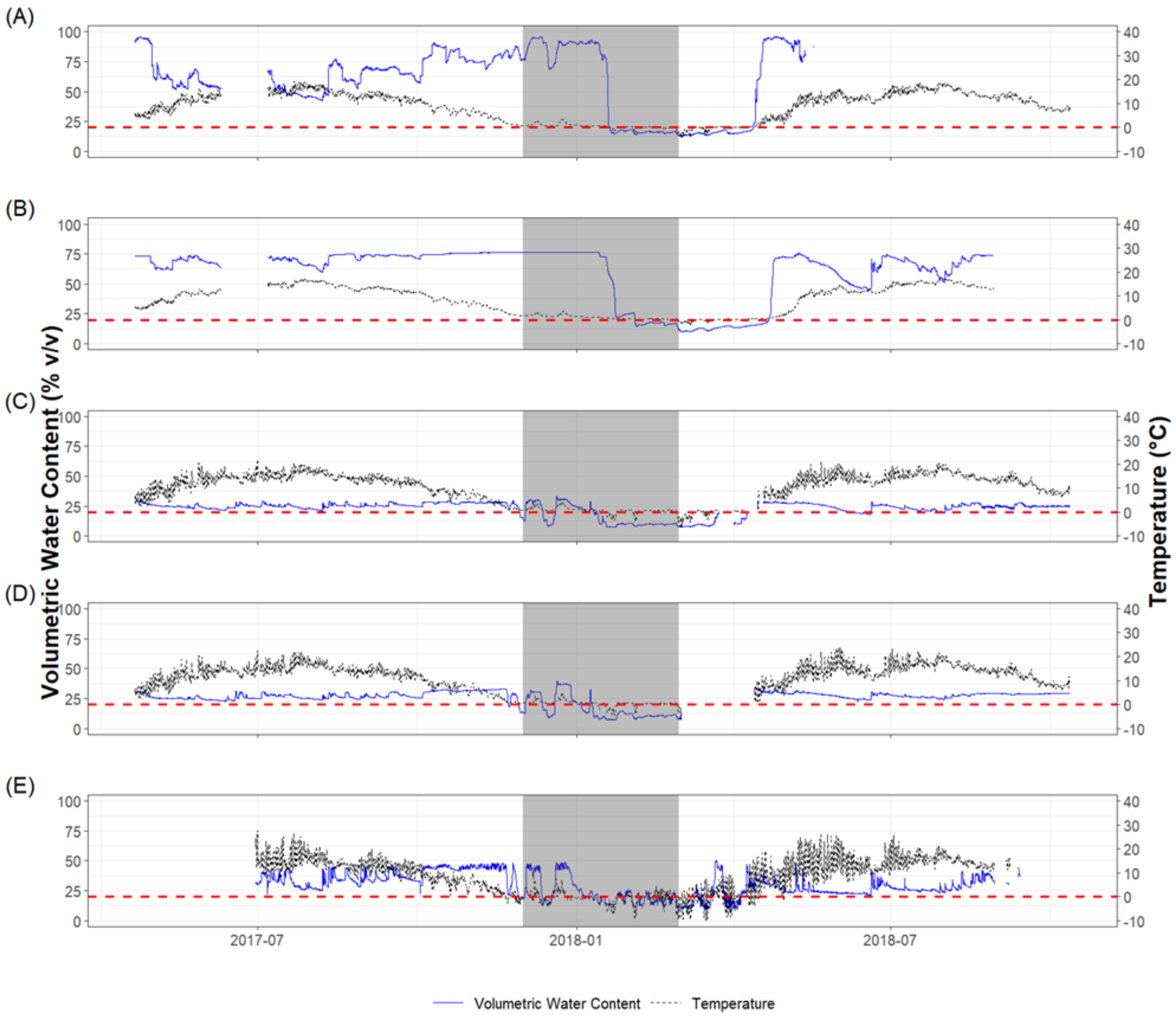

Figure A1.1. Temperature and volumetric water content variation in (A) 7.5 cm in the pipe drained field, (B) 15 cm in the pipe drained field, (C) 10 cm in the inverted upper field, (D) 10 cm in the inverted lower field, (E) 0–5 cm in the inverted upper field.

Appendix 2

A mixed model was used to evaluate the combined effect of rainfall and drainage type on dry matter yield:

$$y_{ijk} = m + t_i + b \cdot x_{ijk} + g_i \cdot x_{ijk} + Y_j + F_{k(i)} + e_{ijk} \quad [2]$$

where y_{ijk} is the observation of the response variable (grass yield from the 1st harvest, grass yield from the 2nd harvest, or the sum of grass yield from the 1st harvest and grass yield from the 2nd harvest) from drainage type i, year j, and replicate k. m is a general mean (parameter), t_i is the main effect of drainage type i (parameter), x_{ijk} is the rainfall corresponding to y_{ijk}, b (parameter) and g_i (parameter) are regression coefficients describing a linear relation between x_{ijk} and y_{ijk} (in reality between x_{ijk} and the expected value of y_{ijk}, and these linear relations may be different for the three drainage types because both the y-intercept of the line, $m + t_i$, and the slope of the line, $b + g_i$, depend on drainage type, i), Y_j is a random effect of year j, $F_{k(i)}$ is a random effect of replicate k within drainage i, and e_{ijk} is the error term corresponding to y_{ijk}. The Y_j, $F_{k(i)}$ and e_{ijk} values are all assumed to be independent and normally distributed random variables with expected value 0 and with their respective variances. All parameters in the model, that means m, the t_i values, b, the g_i values and the three variances of, respectively, the Y_j, the $F_{k(i)}$ and the e_{ijk} values, are estimated using the data.

Table A2.1. Solutions for Fixed Effects

Effect	drainage	Estimate	Standard Error	DF	t Value	Pr > |t|
Intercept		8.3825	5.6178	2.105	1.49	0.2682
drainage	InvLow	-15.4365	4.0737	16.14	-3.79	0.0016
drainage	InvUp	-6.8264	1.7649	17.56	-3.87	0.0012
drainage	PipeDra	0	.	.	.	.
raintot		0.002925	0.008528	2.1	0.34	0.7629
raintot*drainage	InvLow	0.02923	0.006736	15.76	4.34	0.0005
raintot*drainage	InvUp	0.01263	0.002651	15.54	4.76	0.0002
raintot*drainage	PipeDra	0	.	.	.	.

Table A2.2. Tukey-Kramer Grouping for drainage Least Squares Means (Alpha = 0.05).

Effect	Num DF	Den DF	F Value	Pr > F
drainage	2	16.8	12.05	0.0006
raintot	1	2.205	3.82	0.1780
raintot*drainage	2	15.65	17.36	0.0001

Table A2.3. Type III Tests of Fixed Effects (LS-means with same letter are not significantly different).

drainage	raintot	Estimate	
InvLow	638.10	13.4635	A
	638.10		
InvUp	638.10	11.4804	B
	638.10		
PipeDra	638.10	10.2488	C

Table A2.4. Least square estimates.

Effect	Label	raintot	Estimate	Standard Error	DF	t Value	Pr > |t|
drainage	Contrast: 0.5*(InvLow + InvUp) - PipeDra	638.10	2.2231	0.3982	7.069	5.58	0.0008

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