THE EFFECT OF UNDERGROUND DRAINAGE ON PEAT MEADOWS AND INACTIVATION OF THE DRAINAGE IN AN ATTEMPT TO RESTORE THESE MEADOWS, WHICH FAILED AS IT REDUCED THE ABILITY OF SOILS TO RETAIN WATER

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ABSTRACT

Drainage is often used to increase agriculture production, but it has adverse effects on biodiversity and water retention. Here, the effect of subsurface pipe drainage on peat meadows near Senotín (Czechia), which were drained from the mid-1980s to 1990s, was studied. Attempts were made to restore the peat meadows by damming drainage pipes using clay-filled trenches in 1996. In this case study, the effect on the depth of the water table, soil water retention, infiltration and soil temperature were recorded. Measurements of the original peat meadow (undrained site), drained meadow (drained site) and restored meadow (restored site) before restoration and two decades after restoration were recorded. The water table in undrained areas was higher than at drained and restored sites, indicating that drainage had lasting effect on drained and restored sites. Infiltration was lowest at the undrained site, greater at the drained site, and highest at the restored sites. Field water capacity was lowest at the restored site, greater at the drained site and highest at the undrained site. Soil water content at maximum saturation was lowest at the restored site, greater at the drained site and highest at the undrained site. Soil temperature was highest at the restored site with no significant difference between the undrained and drained sites. Soil moisture levels were highest at the undrained site and lowest at the drained site. In addition, the undrained and restored sites did not differ significantly in soil moisture content. In conclusion, restoration did not have a significant effect on the level of the water table, initiation of peat formation or ability of soil to hold water.

Keywords: drainage; peatlands; restoration; soil water retention; soil surface temperature

Introduction

Peatlands are one of the most significant terrestrial carbon sinks and sources (Ussiri and Lal 2017). They comprise about 3% of the entire global terrestrial surface and contain about 25% of the total terrestrial stock of carbon (Waddington et al. 2015). In addition to carbon storage, they are also a significant source of water in the landscape. The perennial availability of water in this unique landscape has resulted in a specialized micro-ecosystem with a distinct biodiversity (Krejčová et al. 2021). Also, their high water table and high soil moisture content along with a low pH, low oxygen content and low soil surface temperatures are significant indicators of peatland development (Minayeva and Sirin 2012). There are a great variety of peaty habitats. Here the focus is on peat meadows where the layer of peat is usually just a few dozen cms thick (van Dijk et al. 2007; Querner et al. 2012; Krejčová et al. 2021).

The drainage of peat soil and consequent use for agriculture results in increases in the depth of the water table, aeration, and pH, which results in increased mineralization of organic matter in the soil and aerobic respiration that results in increased CO_2 emissions (Hergoualc'h and Verchot 2011; Menberu et al. 2016; Krejčová et al. 2021) and a reduction in biodiversity (Pfadenhauer and Grootjans 1999; Krejčová et al. 2021). Peat meadows are particularly sensitive to drainage due to their thin peat layer, which mineralizes completely because of both drainage and subsequent use for agriculture (Krejčová et al. 2021).

Globally, it is estimated that about 15% of the world's peatlands have been drained (Buckmaster et al. 2014), mostly for agricultural purposes (Pfadenhauer and Grootjans 1999). In the Czech Republic, about 27% of the peat landscapes were converted to agricultural fields in the second half of the previous century (Frouz et al. 2010 a, b; Krejčová et al. 2021), which affected the hydrology and hydrochemistry of peatland (Holden et al. 2004; Menberu et al. 2017). Since the early 2000s ecological concerns have resulted in efforts to restore peatlands and several studies report the factors that determine the success of restoration in terms of depth of water table, increases in fauna and soil moisture (Buckmaster et al. 2014).

There is little knowledge on the physical properties of the soil in peatlands mainly due to the spatial variability in their physical and chemical characteristics (Cunliffe et al. 2013). In this study, changes in soil water retention of a peat meadow were recorded 20 years after it was restored by damming the sub-surface drainage system with clay. It was hypothesized that blocking the drainage sys-

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tem will decrease the sub-surface runoff and cause the water table to rise to the level at undrained sites and result in the formation of a layer of peat and increase the capacity of the soil for retaining water.

Material and Methods

Study site

The study area is situated close to the village of Senotín in Czechia, South Bohemia (49.0640289°N, 15.1474864°E). The topography at the site is a gentle slope of between 2–10% at an altitude of 650 m a. s. l. The area has a mean annual temperature of 6 °C and mean annual precipitation of 700 mm (Krejčová et al. 2021). The soils at this site are mainly peaty along with historic cambisols and histosols. In the mid and late 1980s, wet meadows were drained for agriculture using underground drainage pipes (Frouz et al. 2010 a, b), although some remnants of undrained wet meadows remain. In 1993, studies were undertaken at this site to determine the effect of underground drainage on the hydrology and biodiversity. In 1996, about 3 ha of the drained meadows was reclaimed by constructing long 2 m deep trenches extending about 0.5 m below the surface. Trenches were filled with compacted clay as a sealant with soil above for infiltration. Trees were later planted on the clay barriers to reduce run-off and stabilize the field water capacity and raise the water table (Fig. 1). The success of peatland restoration was determined by comparing it with a wet undrained peaty meadow (a positive control) and drained meadow, which served as a negative control. Key hydrological parameters including depth of water table, field water capacity, soil water content at maximum saturation and field water capacity were measured before restoration in 1995 (historical) and recently in 2018 and 2023. In addition, soil moisture and soil surface and air temperatures were measured in 2018–2020 and *in situ* infiltration in 2023 to provide a more comprehensive understanding of restoration.

Data collection

Water table depth was monitored at four locations at each of the three sites using perforated plastic pipes buried 60 cm below the soil. Sticks were inserted into the pipes and then withdrawn and length of stick that was wet was used to determine the depth of the water table. Measurements were collected in 1995 and 2018 at three monthly intervals from May 1995 to May 1996 and from May 2017 to June 2018, after which the average depths at each site and in each year were calculated.

Fifteen measurements of infiltration were recorded in 2023 at five different locations at each of the three sites using a mini-disk infiltrometer. Soil water content at maximum saturation and field water capacity of 15 samples of soil from three sites from an undisturbed area using a corer the inner diameter of which was 5 cm and length 5 cm in 2023. The initial weight of the samples was recorded. Water was extracted from the samples in the laboratory at room temperature for three days using a 1500F 15 bar pressure plate extractor (30 cm diameter). After three days, the samples were weighed to determine maximum saturation and then dewatered under a constant pressure of −0.33 bar, to determine field water capacity. The wet weight of the samples was recorded and then dried at 105 °C for 48 hours. Maximum water saturation and field water capacity were expressed in terms of volumetric water content. Volumetric soil

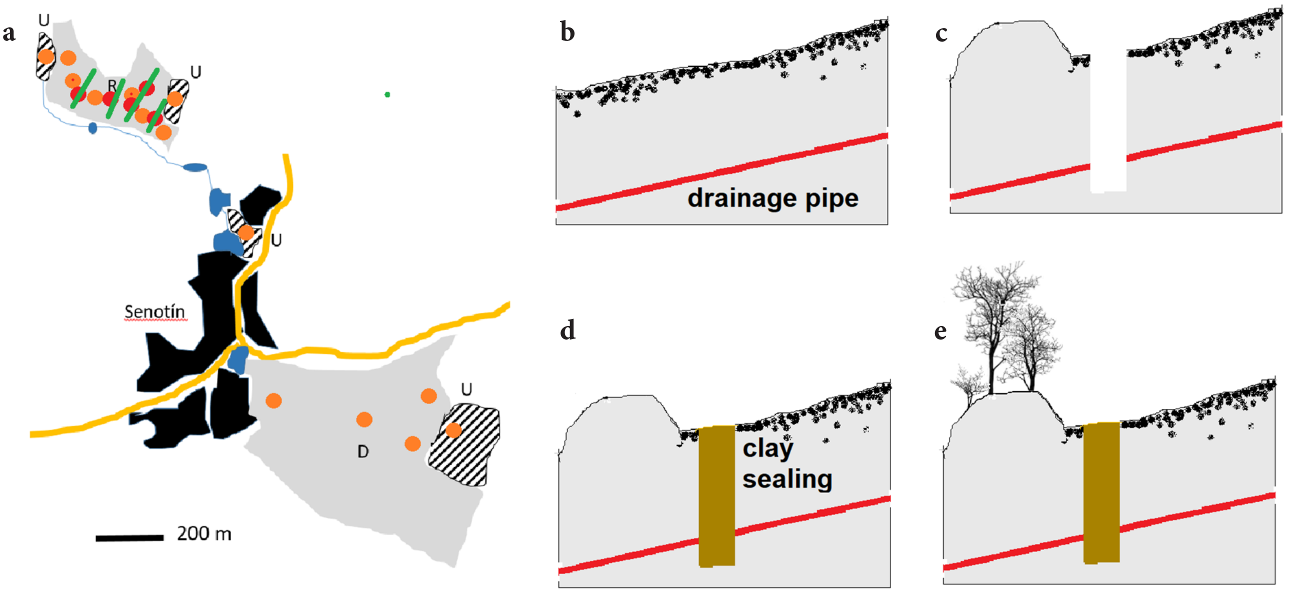

Fig. 1 Map of the sites sampled (a) near Senotín, showing position of undrained remnants of original site (U), drained site (D) and drained site that was restored (R), orange dots show where soil was sampled, red circles the location of soil moisture and soil surface temperature sensors, figures b-e show damming of the drainage pipes used in restoration.

moisture was measured throughout 2020 at three locations at each of the undrained, drained and restored sites. Measurements were taken at a depth of 15 cm using the SMT 100 and data recorded using a MicroLog SDI MP data logger.

The difference between air temperature and surface temperature at noon was used as a proxy for evapotranspiration. A big difference between surface temperature and soil surface temperature indicates that a greater proportion of incoming radiation was turned to sensible heat, whereas a small or even negative difference indicate a greater proportion was latent heat, i.e., from soil evaporation and plant transpiration processes. Soil surface temperature was measured using an infra-radiometer Apogee Instruments SI-411, while air temperature and humidity were recorded using EMS 33S. Data were collected using a MicroLog SDI MP data logger. Only noon data points were used, ensuring that all the locations were fully exposed to solar radiation and not shaded by surrounding vegetation.

Statistical analysis

A two-way ANOVA test was used to determine the effect of time of sampling (historical vs recent) and type of site (undrained, drained, and restored) on field water capacity, water saturation and water table depth. A one-way ANOVA test was used to determine the effect of type of site on the mean differences between soil surface and air temperature, soil moisture and infiltration. A Tukey post hoc analysis was used to determine whether the differences between types of sites were significant at a significance level (alpha level) of 0.05. All computations were done using Statistica 13.0.

Results

There was a significant difference in level of the water table at the individual sites ($p < 0.001$). The undrained site had a significantly higher water table than the drained and restored sites (Fig. 2a), with no significant difference between years. There was a statistically significant interaction between type of site and when sampled ($p < 0.001$). This is because the water table was closer to the soil surface in 2018 than in 1996 at the undrained site but not at the restored and drained sites.

Infiltration was lowest at the undrained site, higher at the drained site and highest at the restored site, which indicates a significant difference between sites ($p < 0.001$). Post hoc analysis revealed significant differences in in-

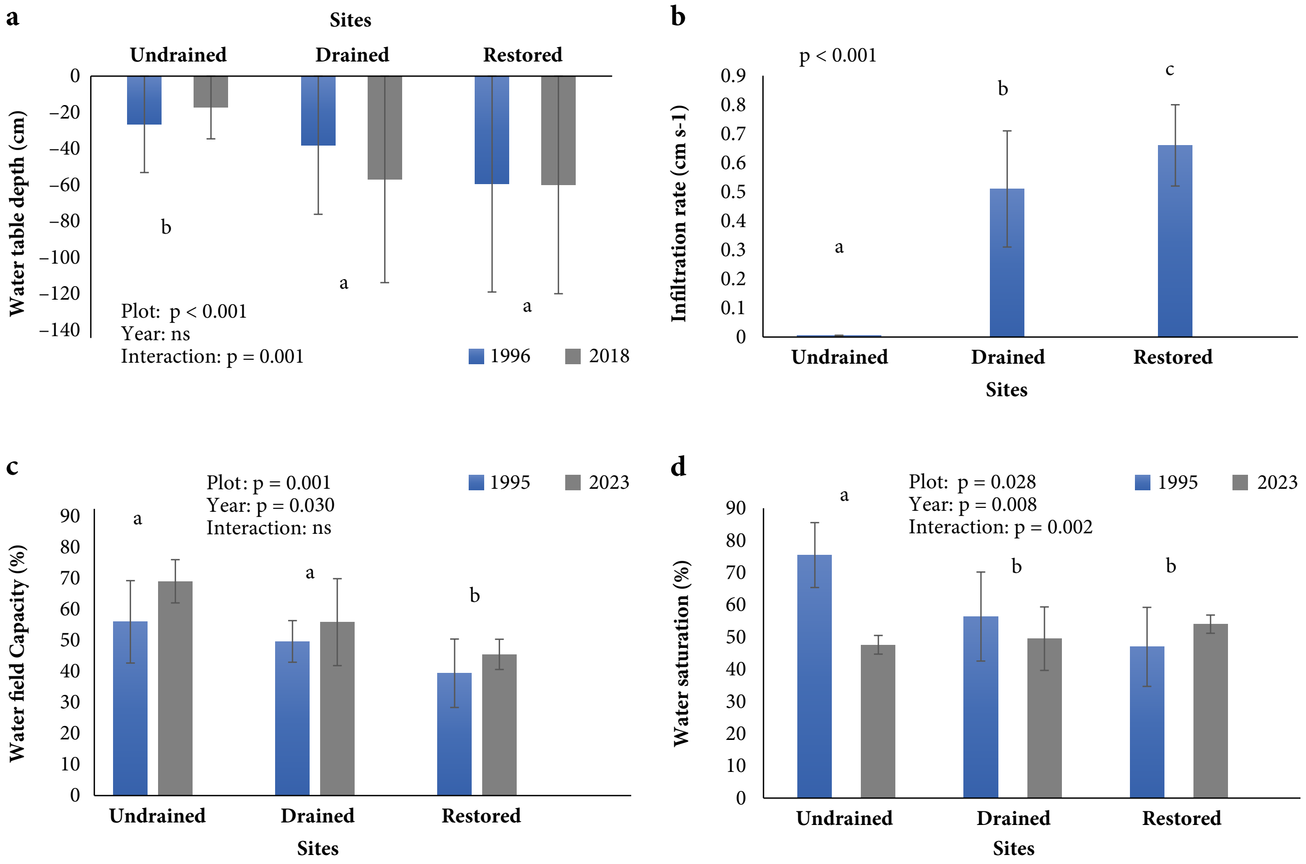

Fig. 2 Comparison of depth of water table (a), infiltration (b), field water capacity (c) and water saturation (d) at the three sites (undrained, drained, restored). Values are means ± SD. For a, b and d, historical (1995) and recent (2018–2023) values are given and results of a two-way ANOVAs are in the tables on the figures. Infiltration was measured in 2023 and one-way ANOVA results are presented. Statistically homogeneous sites are indicated by the same letters (Tukey post hoc test, $p < 0.05$).

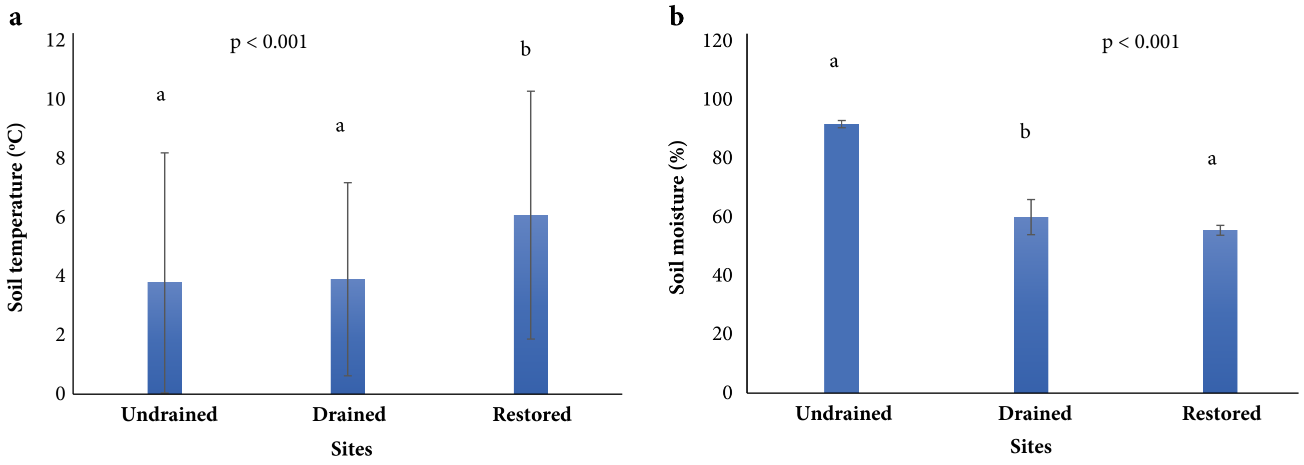

Fig. 3 Difference between soil surface temperature and air temperature (a) and soil moisture (b) in undrained, drained, and restored sites in 2020. Statistically homogeneous sites are indicated by the same letter (Tukey post hoc test, $p < 0.05$). The probability value on figures is the result of one-way ANOVA showing differences between sites.

filtration recorded for undrained and restored sites ($p < 0.01$), undrained and drained sites ($p < 0.01$) and restored and drained sites ($p < 0.05$) (Fig. 2b).

Field water capacity varied significantly across sites with the restored site having the lowest field water capacity, drained sites a higher value and undrained site the highest ($p < 0.01$). Significant difference in the field water capacity was recorded between the undrained and restored sites ($p < 0.001$) (Fig. 2c). The year of sampling had a significant effect on field water capacity ($p < 0.03$), with it being higher in 2023 than in 1995.

The degree of soil water content at saturation varied significantly between sites ($p < 0.001$) (Fig. 2d). The soil water content at saturation was low at the restored site, higher at the drained site and highest at the undrained site. Soil water content at saturation was significantly different between the undrained and restored sites ($p < 0.001$) and the undrained and drained sites ($p < 0.005$), with no significant interaction between site and when sampled on the degree of water saturation.

The difference in mean temperatures of air and soil differed significantly at the three sites ($p < 0.001$), with the greatest temperature recorded at the restored site and lowest at the drained site. There was a significant difference between undrained and restored sites ($p < 0.01$) and between drained and restored sites ($p < 0.05$). However, no significant difference was found between undrained and drained sites (Fig. 3a).

Soil moisture levels significantly differed at the three sites (undrained, drained,, and restored) ($p < 0.001$) (Fig. 3b). There was a significant difference between the drained and undrained sites ($p < 0.01$), but not between the restored and drained sites (Fig. 3b).

Discussion

The results of this study indicate that draining resulted in a significant increase in the depth of the water table, which is in accordance with previous studies (Price et al. 2003; Cunliffe et al. 2013; Menberu et al. 2018).

Despite restoration, there was no significant decrease in the depth of the water table or initiation of peat formation. This failure may be attributed to the hilly character of the sites (Price et al. 2003; Cunliffe et al. 2013; Menberu et al. 2018; Krejčová et al. 2021). Due to the slope a decrease in the depth of the water table only occurred around where infiltration was blocked and most of the area remained unrestored. At the same time, there was a loss of organic matter and water retention capacity due to drainage. A relatively low water table and high surface temperatures promote mineralization, prevent accumulation of organic matter and restoration of the retention capacity, which largely depend on organic matter (peat) restoration (Moskal et al. 2011). Alternative strategies that take into consideration the gradient of a site may be necessary for successful restoration, as suggested by Krejčová et al. (2021).

In some parameters, the restored site appears to be worse in terms of water retention than the drained site (control). It is likely that this is due to initial soil conditions. Although during the restoration in 1995 the comparability of the sites was considered, drainage increased the depth of the water table, water saturation and field water capacity at the restored site before restoration (in 1995) than at the control and drained sites (although the difference was not always significant, this trend appears in several parameters). Thus, it is likely that the poor initial conditions may magnify over time despite restoration.

The low level of infiltration at the undrained site was due to the proximity of the water table to the soil surface. Frouz et al. (2010a, b) report that tillage increase sand content of the surface layer of soil at drained sites, which may increase infiltration, which may be even enhanced by prevailing subsurface runoff, which is also likely to persist in restored drained sites. Moreover, grassy vegetation at the restored site, as reported by Krejčová et al. (2021), could affect the level of infiltration, as plant roots support water percolation. Furthermore, the relatively higher level of infiltration at the drained site, compared to the restored site, could be attributed to the creation of cracks in the soil due to it drying out as a result draining the peat.

The consistently low levels of field water capacity and water saturation at the restored sites, historically and recently, may be linked to soil compaction during site restoration, which altered soil structure and inhibited the burrowing activities of soil micro fauna (Liu et al. 2022). In addition, the absence of native vegetation can be linked to low water absorption of restored peatland soils (Li et al. 2018). However, the observed gradual increase in field water capacity at all the sites from 1995–2023 can be attributed to several specific factors, such as absence of tillage and the natural succession of vegetation over time.

High infiltration, low water retention and low soil moisture are linked to reduced water availability in the surface layer of soil, which limit evaporative cooling and result in high soil temperatures (relative to air temperature), as recorded at the restored site (Ochsner et al. 2001; Lu et al. 2007; Mathur et al. 2014; Cawson et al. 2016). Lower temperatures recorded at the undrained sites could be linked to high field water capacity facilitating the cooling of the soil due to evapotranspiration (Bridgham and Richardson 1992). These variations in temperature indicate that draining peatland and subsequent alterations in the hydrologic regime have a significant effect on soil temperature dynamics (Tarnawski and Leong 2000; Hora 2011; Menberu et al. 2018). The higher the temperature of the soil, the faster the decomposition, which limits the build-up of soil organic matter (Swails et al. 2022).

Aerobic soil respiration which is linked to low soil moisture content and higher temperature may eventually contribute to the loss of peaty layers and subsequent drop in water table levels (Grayson et al. 2010; Lundin et al. 2017). Lower temperatures exhibited at the undrained and drained sites could be linked to the high-water field capacity and vegetation cover which facilitates cooling of the soil, hence, hindering aerobic respiration (Bridgham and Richardson 1992; Kluber et al. 2014; Wang et al. 2015; Drexler et al. 2017; Gutenberg et al. 2019; Huang et al. 2021).

Conclusion

In conclusion: restoration did not result in a significant decrease in the depth of the water table or in the initiation of peat formation. The hilly nature of the sites and the mineralization of organic matter post-drainage, coupled with low water retention, contributed to this failure. Factors such as proximity of the water table, early development of vegetation that obstructs the percolation of water and cracks in the soil due to draining the peat, influenced the level of infiltration. Persistently low field water capacity at restored sites was linked to soil compaction and destruction of native vegetation. However, a gradual increase in field water capacity from 1995–2023 was recorded, which is attributed to factors like absence of tillage and natural succession. High levels of infiltration, low water retention and soil moisture were associated with higher soil temperatures at the restored site than at undrained and drained sites, which are associated with a high field water capacity limiting aerobic respiration.

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