EFFECTS OF DITCHING ON SOIL STRUCTURE AND VEGETATION COMMUNITY

IN TWO SUBALPINE FENS

By

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Abstract

Fens are perennially wet, groundwater-dominated ecosystems that provide vital refugia for native species during the summer dry season in California, sequester organic carbon, and filter groundwater. This study focused on the impacts of manmade drainage ditches on soil structure and wetland-dependent vegetation in alpine fens in the Childs Meadow complex, an ongoing restoration site in the Lassen National Forest in California. Sample quadrats were located above (upslope) and below drainage ditches in two fen locations within the complex. In each quadrat, soil horizons down to 60 cm were sampled via auger, classified as mineral or organic based on organic carbon content, and analyzed for texture, color and depth to groundwater. Percent cover of representative fen-obligate mosses was estimated in each 40 by 40 cm quadrat. Above-ditch sites had considerably wetter soils with higher organic matter content, as well as greater percent cover of moss. Below ditch sites had reduced organic carbon content, increased grass cover, and greater depth to groundwater. Our results highlight the negative impacts of drainage ditches on soil organic carbon content and wetland plant cover in alpine meadows and provides a baseline of soil and vegetation conditions in two impacted fens in Childs Meadow. This work will be used to guide future restoration of Childs Meadow fens, as well as provide insight into how these fragile ecosystems might recover over time.

Introduction

Fens are some of the most species-rich biomes on earth. Some fens have species diversity of over 40 species per square meter and typical species density of 20-25 species per square meter, though this can vary based on the size and environmental specifics of each fen (Bedford & Godwin, 2003). Fens also act as critical habitat for large mammals and special-status species, such as the willow flycatcher and Yosemite toad in the Sierra Nevada mountain range where surface water in the dry summer season is scarce (Yarnell et al., 2020). Additionally, fens act as large carbon sinks as they are characterized by peat soils (Rydin & Jeglum, 2006). Beyond these ecological benefits, fens can also provide water and carbon storage. Yet despite these benefits, ditching and draining of fens is a common practice, with detrimental impacts.

Fens are critical ecosystems found across the globe. Specific definitions of fens vary across regions and disciplines, but characteristics include the presence of sedges and peat moss, groundwater table perennially at or near the surface, little surface water flow, and less than 25% woody cover (Keddy, 2010; Rydin & Jeglum, 2006; Warner et al., 1997). For the purposes of this study located in California in the Western United States, we define a fen as a perennially wet, groundwater-fed peatland, following the definition provided by Wolf and Cooper (2015) for peatlands in the Sierra Nevada mountain range in California.

Due to the Mediterranean-montane climate of the Sierra Nevada range, which exhibits hot, dry summers and cold, wet winters, groundwater-fed fens are typical in this region versus surface water-fed wetlands such as bogs that are common in areas with abundant summer precipitation and runoff. Fens are fed by continual groundwater inputs allowing them to exhibit wet surfaces year-round and provide refuge to bryophytic plants, especially *Sphagnum* mosses, and other wetland-specific plants such as *Carex* (Vitt et al., 2005). Fens, especially those in the Sierra

Nevada, can also be categorized based on the locations that they form: bedrock contact fens occur where groundwater exits an aquifer onto the surface due to contact with less permeable bedrock, slope fens occur where water exits a hillslope and accumulates in a low point, spring mound fens occur where groundwater is discharged to the surface, and basin fens occur when groundwater accumulates at a topographic low point and creates a fen (Wolf & Cooper, 2015) (Figure 1). The majority of fens in the Sierra Nevada are small slope fens, with common nonvascular plant species *Sphagnum teres* and *Sphagnum subsecundum,* and vascular plant species *Carex limosa*, and *Carex lasiocarpa.* The senescence and burial of these wetland plants over time leads to the creation of the thick peat soils characteristic of fens. These soils only develop under hydrological and topographic conditions conducive to saturation; areas with steep well-drained slopes or lack of year-round water inputs typically support vegetation that dries and decomposes into mineral soils or soils with less than 20% organic carbon as estimated in the field (Wolf, 2017).

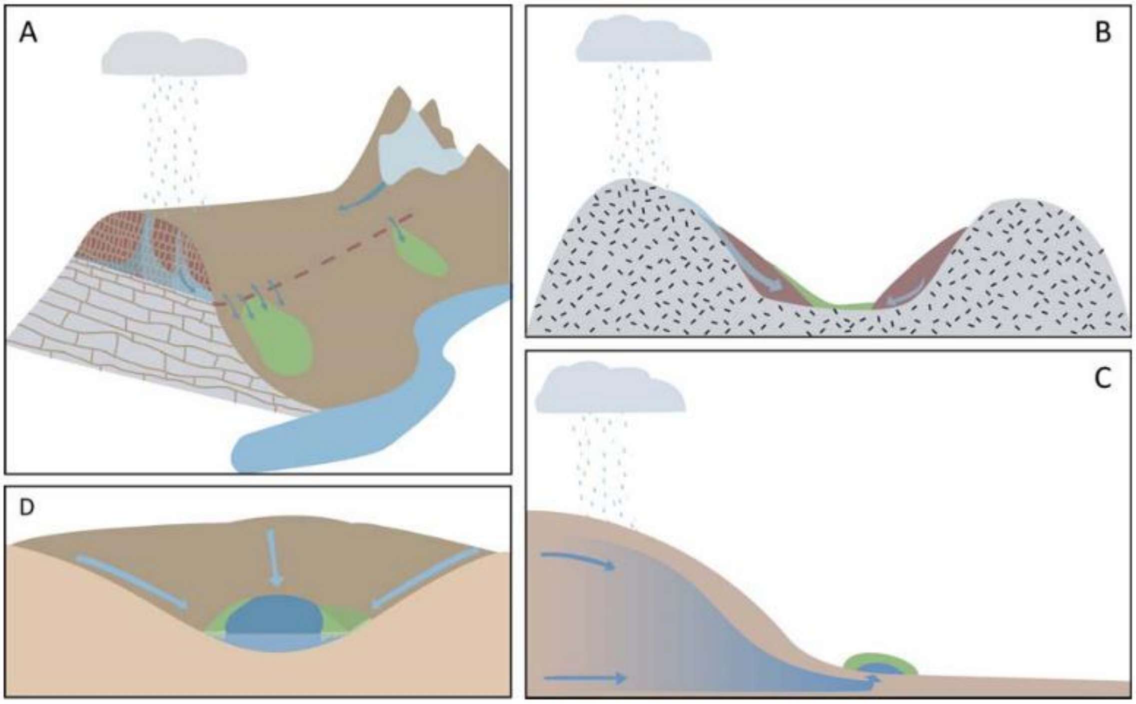

Figure 1: Fen types courtesy of Wolf & Cooper 2015. A: Bedrock Content, B: Slope, C: Spring Mound, D: Basin Fen.

Despite their pronounced ecological benefits, fens are disappearing at an alarming rate (Vitt et al., 2005). Fens have been drained over the last century in order to facilitate grazing, agriculture, forestry, and to provide water to downslope areas. When fens are drained, these organic-rich, newly dried soils are very productive for agriculture or forestry, and water no longer impounded in fens can be drained and transported to downstream users (Rossi et al., 2012). Drainage has largely been conducted by digging ditches in order to interrupt and redirect shallow subsurface groundwater flow, resulting in dewatered downslope areas. Additionally, draining fens causes a disconnect in groundwater connectivity, which can alter downslope soil and vegetation conditions. Figure 2a provides a conceptual illustration of the effects of ditching on groundwater, soil, and vegetation conditions in a fen. Downslope of the ditch, groundwater levels decrease drying out shallow soils and converting wetland vegetation to xeric vegetation.

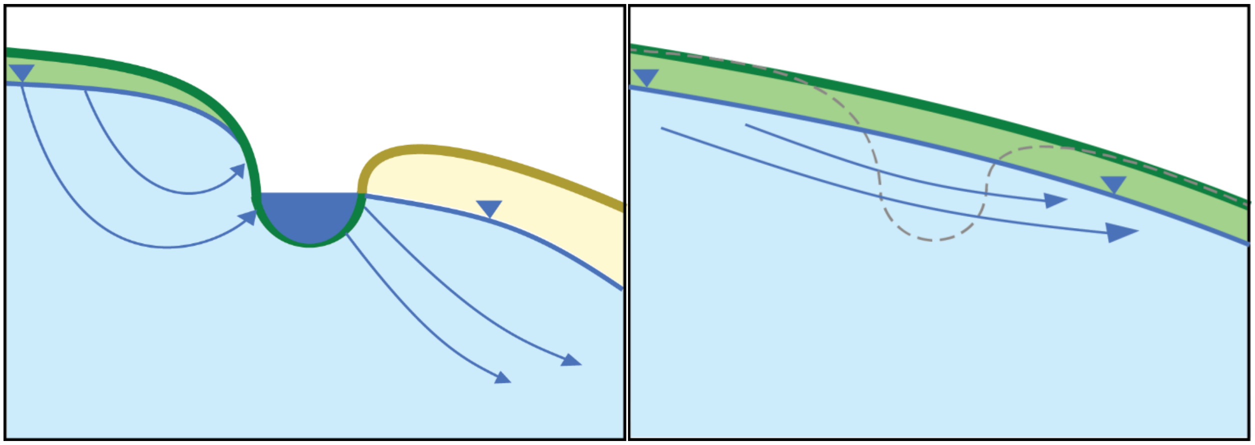

Figure 2a: Conceptual schematic of the impacts of a drainage ditch in a slope fen on groundwater level , surface vegetation, and soil conditions. Green shading indicates peat and saturated soil conditions, while yellow shading represents dry soil. Dark green line represents wetland vegetation, while dark yellow line represents xeric or mesic vegetation. Light blue shading represents groundwater levels and blue arrows indicate groundwater flow paths.	*Figure 2b: Conceptual schematic of slope fen after filling of drainage ditch with proposed recovery of water table indicated by light blue shading and blue arrows and proposed recovery of surface vegetation indicated in green shading and lines. Dashed brown line indicates previous location of ditch.*

Childs Meadow is in the northern end of the Sierra Nevada mountain range in Tehama County, California. Due to almost a century of grazing, there has been a significant negative impact on this meadow’s carbon storage and water holding capacity (Yarnell et al., 2020). Current restoration projects in the meadow include installation of beaver dam analogs along the central stream channel to slow and impound streamflow and cattle exclusion from the area around the central stream channel in order to encourage vegetation growth (Yarnell et al., 2020). However, no restoration has been completed to date on the fens studied here, though their restoration is expected to increase soil carbon storage and water retention in the meadow complex. The research completed here and the restoration to follow adds to the very limited research that has been conducted on the effects of ditches in fens or on the effectiveness of filling drainage ditches with the intent of restoring groundwater connectivity, hydrogeomorphology, or downslope vegetation community in fens or other wetlands.

The work conducted here constitutes a baseline of pre-restoration data in the two particular fens studied, which can be used in comparisons after future restoration projects and adds to the overall body of work on fen restoration. We investigated the differences in wetland-obligate vegetation cover and in soil texture, color, and organic content upslope and downslope of drainage ditches in these fens. In this study, we hypothesized that the drainage ditches in the fens in Childs Meadow disrupted the flow of groundwater and created different soil and vegetation conditions as a result, indicated by soil color and texture and cover of specific wetland-obligate plants.

Methods

This study was conducted in the Childs Meadow complex in the Lassen National Forest. Childs Meadow is a 290-acre sub-alpine meadow with an ongoing restoration project since 2015. As mentioned above, the primary goals of this restoration project are to improve hydrogeomorphic connectivity in the meadow, to increase carbon storage in soils, and to improve populations of Cascades Frogs and willow flycatchers (Yarnell et al., 2020). This restoration has focused on the central stream channel in the meadow, and no restoration has yet been done on the fens studied here.

As part of the restoration, hydrogeomorphic conditions including groundwater level were measured at 45 well locations on twelve cross sections throughout the meadow (Yarnell et al., 2020). The water level measured at each of these wells was compiled to show the overall groundwater distribution in the meadow. In functioning meadow systems, groundwater levels are typically high supporting wet soils, while degraded meadow conditions are characterized by low groundwater levels and drier soils (Viers et al., 2013).

The ability of a fen to store soil organic matter and support wetland vegetation is related to their hydrogeomorphology. The fens studied here were referred to as the cross-section seven fen (XS7 Fen) and western finger fen (WF Fen) due to their locations within the greater meadow, shown in figure 3. Five study quadrats were placed above (upslope) and five below drainage ditches in two fens in Childs Meadow. In the XS7 fen, 40cm by 40cm quadrats were located approximately 30 feet apart in a line parallel to the drainage ditch. Appropriate sites were identified first in the wet portion of the fen above (upslope of) the ditch (identified as A) and corresponding sites were identified below (downslope of) the ditch at approximately equal spacing, perpendicular to the ditch. (identified as B) (Figure 3). Due to more complex terrain surrounding the WF fen site, appropriate quadrat sites were determined in the upslope side of the fen based on representation of the general fen area and were not equidistant from each other. Quadrat sites downslope of the ditch were determined to be in line with the upstream A sites, perpendicular to the ditch and of roughly equal elevation. There is a logging road built into the forested area to the north and west of the WF fen that is very near the study site. Additionally, this site had a much deeper ditch than the XS7 fen, and the ditch exhibited headcutting in multiple places before flowing out of the fen and into the central meadow complex where the ditch was much shallower.

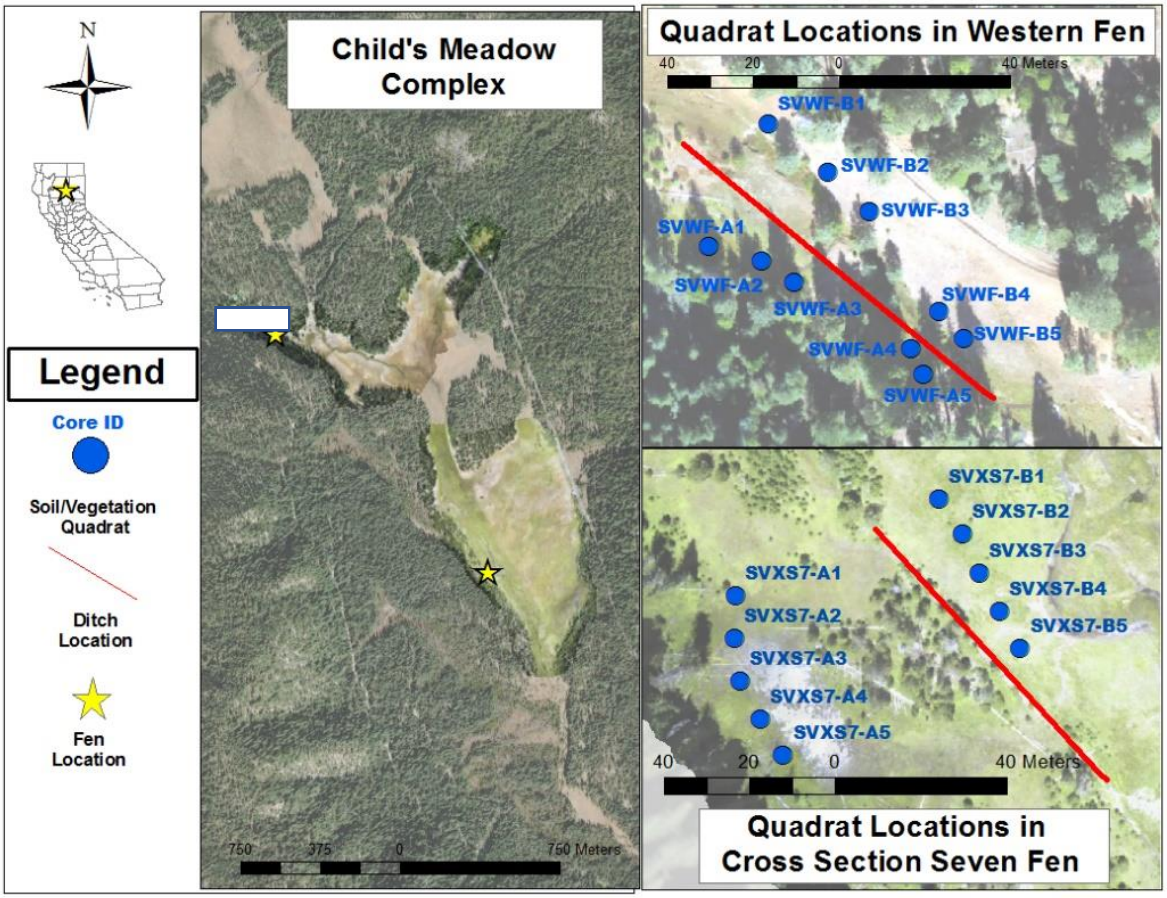

Figure 3: A map of the study site with fen locations (yellow stars) ditch locations (red lines) and soil core locations with core ID number (blue circle)

Quadrats were marked with rebar in the southeast corner, and soil cores were dug in the northeast corner. Cores were dug using a two-inch diameter barrel hand auger in 10 cm increments to a depth of 60 centimeters. Samples were deposited onto a tarp in the reverse order from which they were removed (topsoil first to deepest soil last). Samples were then grouped into horizons based on color and texture, and each horizon was sorted into “organic” or “mineral” categories using Natural Resources Conservation Service (NRCS) field criteria (Soil Survey Staff, 2014). Broadly, organic soils had either >20% organic carbon content if saturated with water for less than 30 days of the year, or >18% organic carbon content if saturated for more than 30 days of the year.

Soil texture was determined in the field based on one of three methods: (a) if the soil was mineral, texture was determined using the NRCS texture by feel method (Thien, 1979), (b) if the soil was organic and dry, texture was determined using rubbed fiber content and classified as fibric, hemic, or sapric, and (c) if soil was organic and wet, texture was determined as peat, mucky peat, or muck then reclassified into fibric, hemic, or sapric based on state of decomposition. Soils were classified as organic or mineral based on visual assessment of color and texture as well as evidence of organic materials in the soil. Gravel percentage in soils was estimated based on textural and visual analysis. Soil color was determined visually using the Munsell Color system (Munsell Color, 2010). Samples were collected in September-November 2020, which was the dry season in the Childs Meadow complex.

Vegetation community was assessed in each quadrat by identifying the presence and percent coverage of select wetland obligate species, including moss, Carex-genus sedges, and Eleocharis-genus grasses. Since species could not be determined in-situ, all low-growing bryophytic plants were identified as moss. Moss was identified to family level (e.g. Sphagnum), as all mosses have similar habitat requirements and the presence of most mosses is indicative of perennially wet, or at the very least, moist and shady conditions. However, the location of these fens in the meadow is not conducive to the moist and shady conditions required to grow moss, so moss presence was taken as an indicator of wet conditions due to high groundwater. Due to late season sampling (vegetation surveys were completed in late October as fens were starting to freeze over) as well as destruction of plants by cattle presence earlier in the summer, it was not possible to determine all plant species. These three vegetative groups were selected as indicators of fen conditions, primarily because moss was a good indicator of wet areas, Carex is common in wetlands, Eleocharis can be found in drier areas, and all were easily identifiable in the quadrats.

Vegetation cover was analyzed by site and vegetation type using Mann-Whitney U tests with a significance level of $p = 0.05$. Samples were compared above and below the drainage ditch at each study site separately. The Mann-Whitney U test was selected as the data was not normally distributed or assumed to have equal variances (Mann & Whitney, 1947). Due to the complexity and categorical nature of the soil core data, soil texture and color were not analyzed statistically but rather compared qualitatively within each study site.

Results

Vegetation

Despite small sample sizes, the vegetation surveys showed a significant difference in percent cover of moss above and below the drainage ditch at both study sites (Figure 4, Table 1). All below-ditch quadrats had 0% moss cover, while 9 of 10 above-ditch quadrats (both study sites) had some moss cover, and 8 of 10 quadrats had at least 50% moss cover. There was less variation in *Carex* sp. cover at each study site, ranging from 0% to a maximum of 32% cover; however, *Carex* sedges did have significantly greater coverage in above-ditch quadrats in the WF fen (Table 1). *Elocharis* sp. occurred more consistently across all quadrats in both study areas, and the percent cover was found to be not significantly different between above-ditch and below-ditch quadrats in either fen.

Table 1: Results from Mann-Whitney U test of vegetation cover in sample quadrats above (n=5) vs below (n=5) ditch in each fen. p-values < 0.05 were considered significant and starred, p-Values < 0.01 are starred twice.

	Mann-Whitney U Test Results			
	XS7		*WF*	
Moss	p = 0.025*	W = 22.5	p = 0.007**	W = 25
Elocharis sp	p = 1	W = 12.5	p = 0.094	W = 21
Carex sp	p = 0.289	W = 18	p = 0.023*	W = 23.5

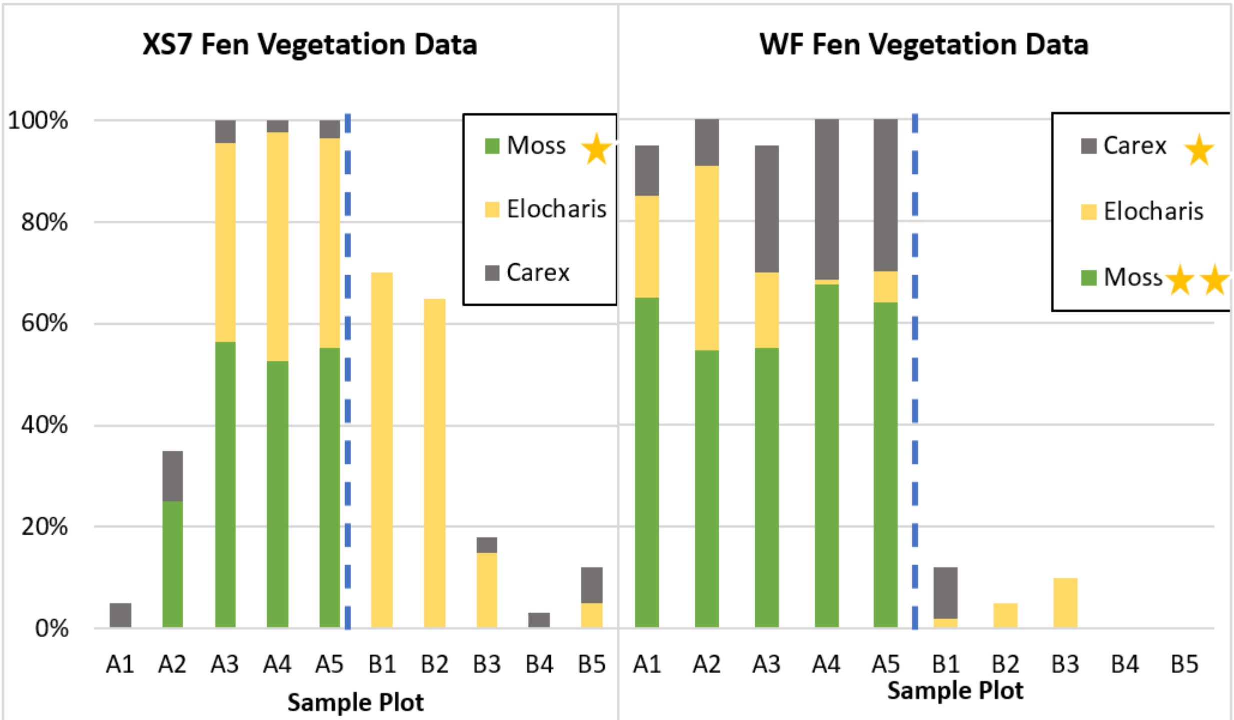

Figure 4: Percent cover of target vegetation species in study quadrats at each fen study location collected in fall 2020. Above-ditch quadrats are denoted as "A" and below-ditch quadrats are denoted as "B". Stars in legend represent significance to p=0.05 (*) or p<0.01 (**).

Soil Texture

XS7 Fen

Soils in the above-ditch quadrats in the XS7 fen were dominated by organic horizons (Figure 5). Quadrats A2, A3, A4, and A5 had organic horizons at the soil surface, and all quadrats except A3 had loam in the lower layers. Lower soil horizons had higher clay content and lower organic carbon content. Quadrats A3, A4, and A5 were wetter at the surface, but had lower moisture content and aggregates with dry interiors in deeper mineral soil layers. Soil horizons were less distinct in these quadrats as soils were wetter, though there was a transition from darker colored organic horizons to lighter colored mineral horizons with increasing depth. Orange redoximorphic features were present in the lower layers of all above-ditch quadrats starting near 25cm deep. The coloration and composition of soils in quadrat A1 were more similar to that of below-ditch quadrats.

Below-ditch soils in the XS7 fen were lacking in organic horizons, excluding live roots at the surface (Figure 6). Upper layers had higher loam contents, while deeper layers were primarily composed of clay. All soil in these quadrats was dry at the time of survey. Orange mottling was found in lower layers of quadrats B2-B5, which is indicative of redox activity. Below-ditch soils had distinct A and E horizons, with lighter coloration in upper layers than seen in the above-ditch quadrats and bleaching in the lower layers. These soils were lighter in color than the above-ditch soils, both in gleyed, or gray-colored layers, and non-gleyed layers.

None of the soils observed either upslope or downslope of the drainage ditches exhibited the thick peat layers that we expected as characteristic of peatland soils. The organic horizons observed both above and below drainage ditches in the XS7 fen were a maximum of 30cm deep and in several cores completely nonexistent. The rest of the XS7 soils were primarily composed of inorganic components throughout the cores.

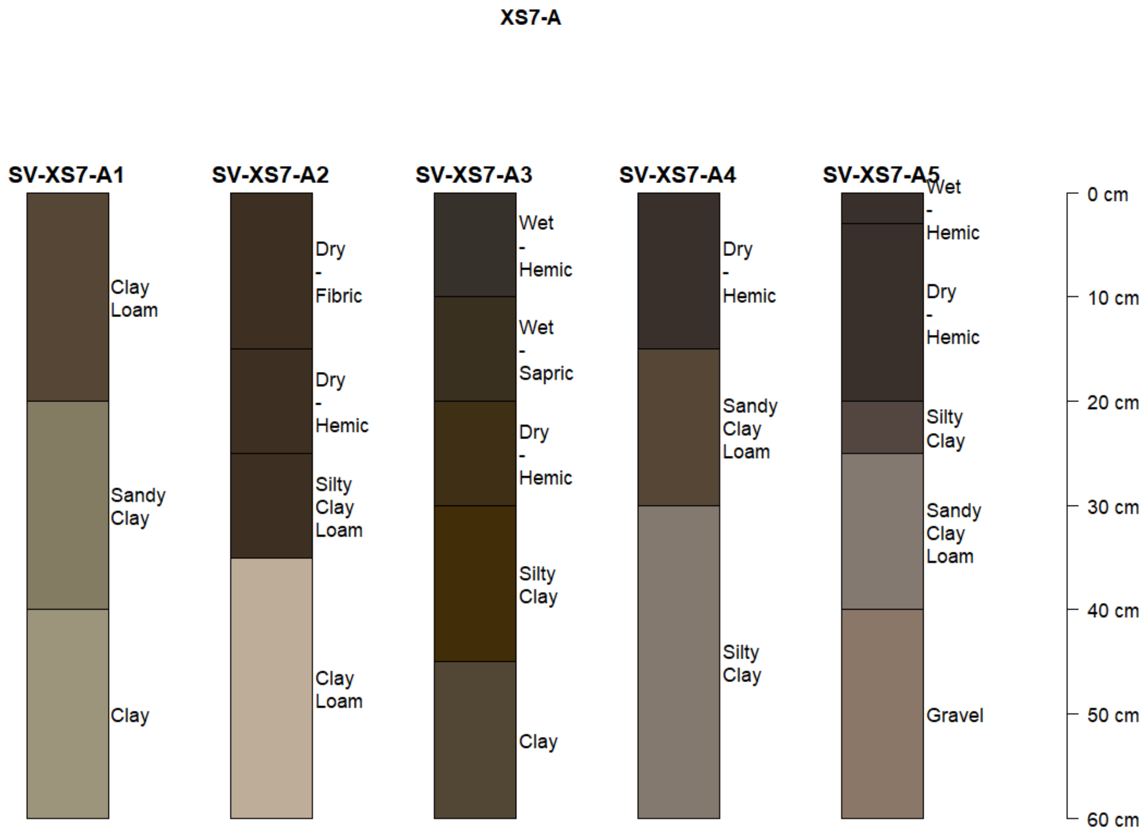

Figure 5: Representation of soil cores collected from each quadrat above the drainage ditch in XS7 fen. Columns reflect depth of each layer in cm.

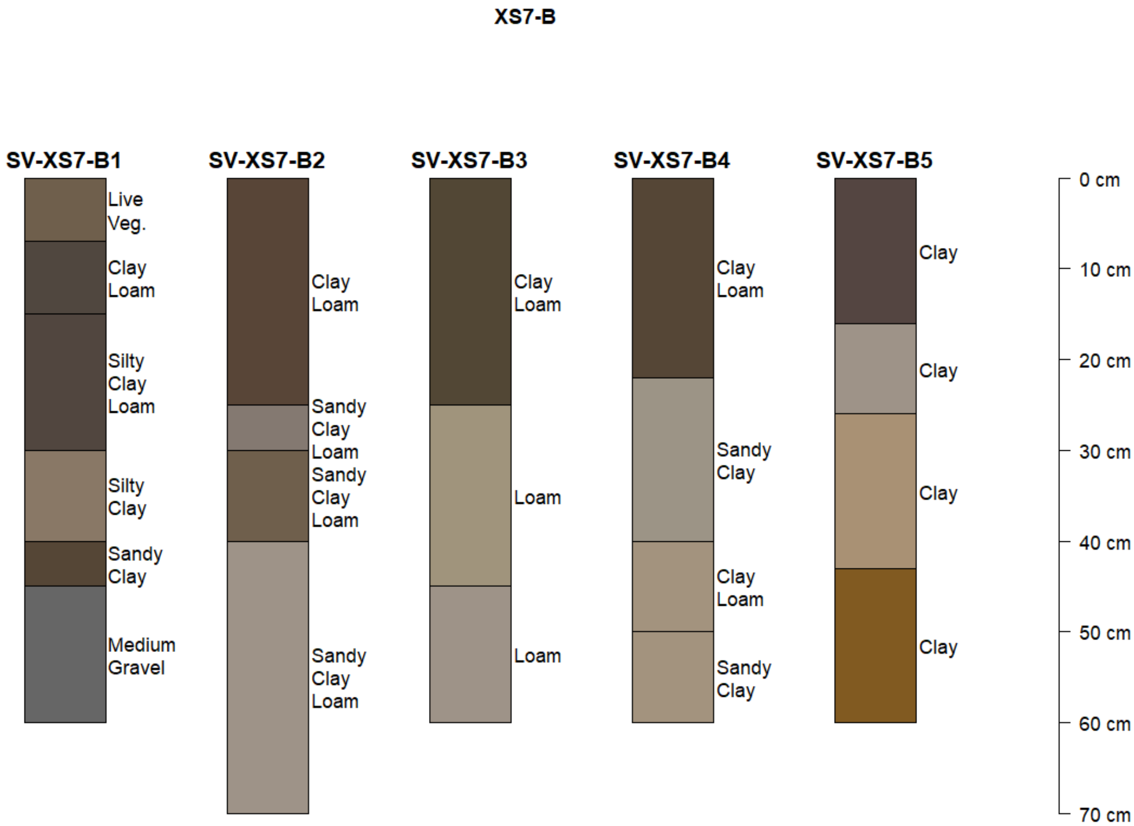

Figure 6: Representation of soil cores collected from each quadrat below the drainage ditch in XS7 fen. Columns reflect depth of each layer in cm.

WF Fen

Soils above the drainage ditch in the WF fen tended to have clay loams and close to 25% fine gravels. Some quadrats had organic soils near the top or bottom layers. Cores A2 and A5 had organic surface horizons, and A1 had a deeper organic horizon (Figure 7). Deeper soil horizons were also wet and had gravel mixed with higher mineral content layers. Quadrats A2-A5 had orange and blue mottling in lower layers. Additionally, all WF fen above-ditch quadrats were saturated with shallow groundwater. Soil color in upper layers was dark, while lower layers had gleyed coloration.

Below-ditch soils in the WF fen were uniformly dry and had more loam and sand than clay and organic material (Figure 8). There was very little organic matter found in these cores, and the gravel layers seen in the above-ditch quadrats were not present in the lower layers of the below-ditch quadrats. Soils were generally lighter in color than above-ditch soils and did not have gleyed color. As in the XS7 fen, no soils exhibited the characteristic thick peat layers expected of peatland soils.

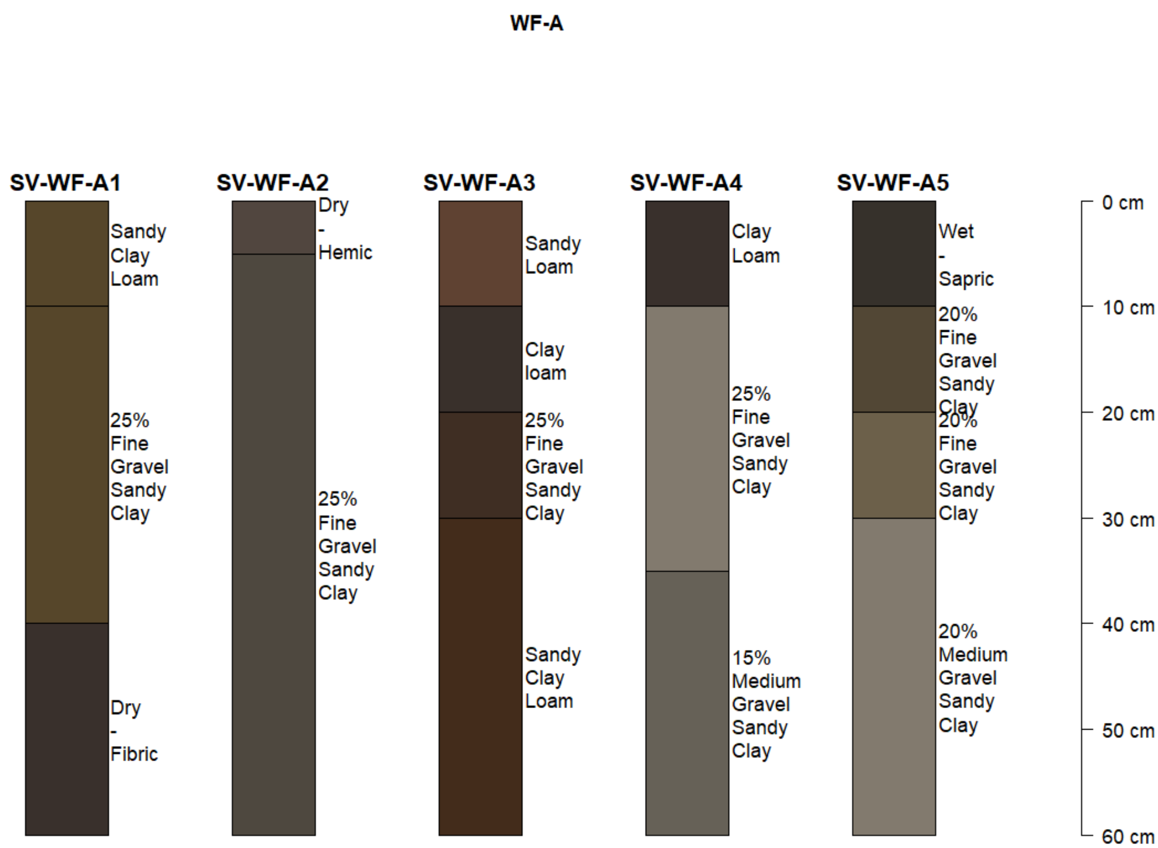

Figure 7: Representation of soil cores collected from each quadrat above the drainage ditch in WF fen. Columns reflect depth of each layer in cm. Soil textures from NRCS texture by feel (labels), and soil color from Munsell soil color.

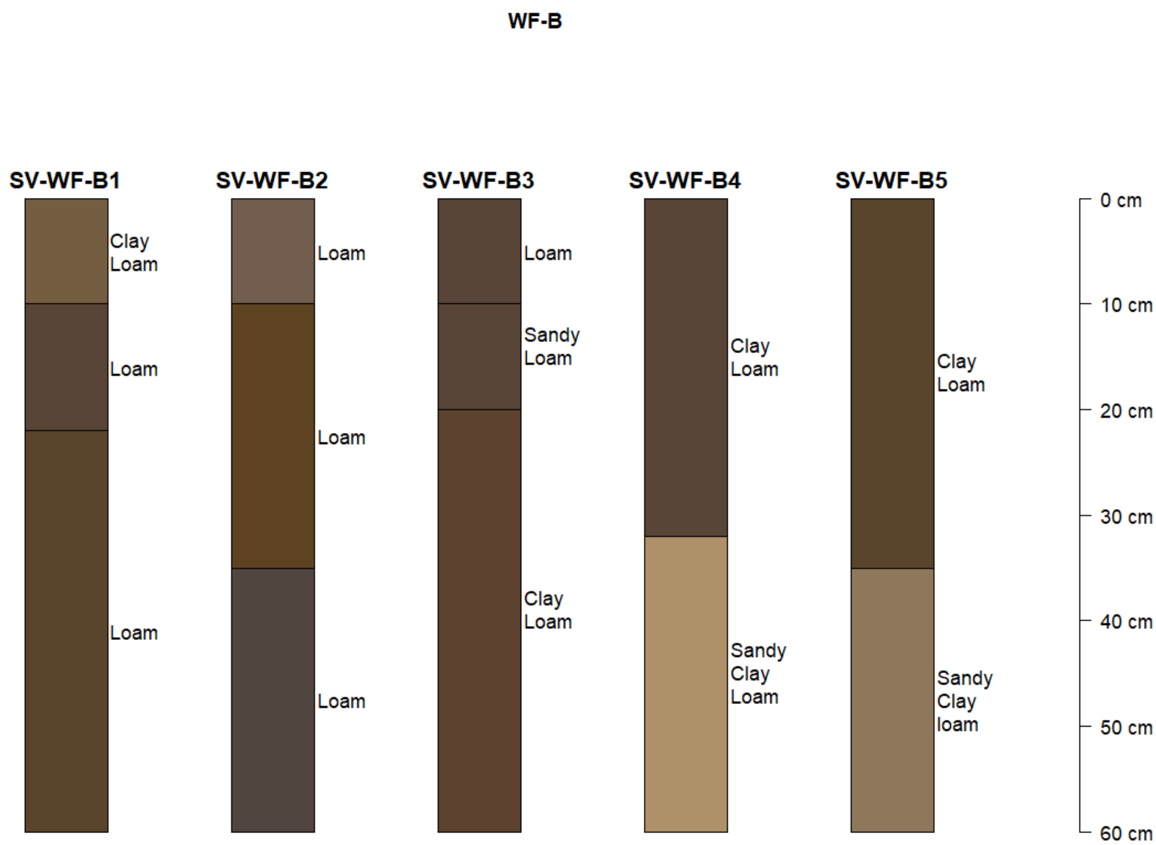

Figure 8: Representation of soil cores collected from each quadrat below the drainage ditch in WF fen. Columns reflect depth of each layer in cm. Soil textures from NRCS texture by feel (labels), and soil color from Munsell soil color.

Discussion

Vegetation

The results of the vegetation surveys reflected the hypothesis that quadrats above the drainage ditch would have increased coverage of wetland-obligate plants. The consistent presence of water in above-ditch quadrats sustained greater vegetation cover of indicator species and supported the growth of moss, which requires a predominately wet environment. The presence of moss in above-ditch sites was a contributor to the darker soil colors and presence of fibric organic matter, while the dry conditions and lack of groundwater or high water table prevented moss from growing in downslope sites. *Carex* or sedges are common wetland plants, but as they are vascular, they are more drought-tolerant than nonvascular moss species. This characteristic can explain why *Carex* was observed both above and below the ditch at each study site. The fact that there was only a significant difference in *Carex* in the WF fen indicates a larger difference in water availability than in the XS7 fen. While the XS7 fen was near the central stream channel with a shallower ditch, the WF fen had a much deeper ditch, likely perpetuating this more significant difference in vegetation cover between treatments. One thing of note was that due to late-season sampling and extensive cattle grazing, many vegetation specimens were unidentifiable, and quadrats had far less total vegetation than they would in spring. Above-ditch quadrants averaged 68% total indicator species cover in the XS7 fen and 98% total indicator species cover in the WF fen, while below-ditch cores averaged 34% and 25% indicator species cover in the XS7 fen and WF fen, respectively.

The significant difference in moss between upslope and downslope quadrats was expected, as there was a noticeable difference in water availability above and below both ditches. The lack of groundwater connectivity due to the ditch made it impossible for wetland-obligate plants such as mosses to grow below ditches, facilitating the dominance of xeric plants that can survive dry periods. It is important to note that these studies were not censuses of every plant in every plot, but counts of significant, identifiable plants. Vegetation in the fens was also affected by late-season sampling (most plants were dry and/or dormant) and cattle grazing, which made many plants unidentifiable.

Peat development in fens is caused by high amounts of vegetation in a wet environment that doesn't allow decomposition. However, none of the soil cores had primarily peat content, which could indicate changing wet-dry conditions where organic matter decomposes, leaving mineral soils.

Soil Texture

The absence of the thick peat layer in soils upslope of drainage ditches may be due to one of two sources. First this could result from seasonal variation in the water table, which drops in the summer and fall, exposing buried organic material to oxygen allowing it to decompose and leave a loamy soil with redoximorphic features. Blue mottles, as seen in upslope plots in the WF fen, occur in saturated, anaerobic, and reducing conditions and are concentrations of reduced iron, while orange mottles, or accumulations of iron oxides, occur in oxidizing, aerobic conditions. In oxidizing conditions, soil microbes break down organic matter in the presence of oxygen for their own metabolic needs. However, when soils are flooded, microbes cannot use oxygen in their metabolism and instead use alternative elements (Nitrogen, Manganese, etc.) for much slower less efficient metabolic pathways (Vepraskas et al., 2008). The presence of both orange and blue mottles at similar levels in WF cores and the presence of orange mottles in the XS7 fen indicate seasonal aerobic or dry conditions that could have caused existing organic matter to decompose.

However, the lack of a thick peat layer may also be caused by the fens not being as old as hypothesized. The presence of gravel in lower layers of soil cores in the WF fen is indicative of disturbance, possibly from road outwash or mass wasting, which could mean that these fens are not permanent, stationary features of the meadow complex but newer or more mobile features. Thick peat layers in fens take thousands of years to develop, and if the fens studied here are younger, they may not have had time to develop characteristic peat layers. Alternatively, periodic drainage in the fens may be preventing long-term peat build-up. The absence of extensive impermeable soil layers that prevent surface and groundwater from draining may allow for groundwater to leach away and soils to periodically dry, in times of drought for example, before there is extended accumulation of a thick peat layer. Though clay layers were observed in some soil cores, it is possible that the clay layers are not spatially connected throughout the fens, which may allow for periodic draining when groundwater inputs are very low.

XS7 Fen

The above-ditch soils in XS7 fen had an unexpected structure: upper layers were wet organic material, while lower layers had more mineral material. We noted the presence of a clay layer in several quadrats both upslope and downslope of the ditch at the same depth (~40cm). Although it was not present in all cores, the clay layer was likely formed from the erosion of loamy soils into clays or from an earlier erosional/depositional event, and it may have created an impermeable layer that helps to keep upper soil horizons wet. The saturated soil horizon overlaying clay-rich lower horizons was colonized by wetland species that formed the organic horizons observed. This is characteristic of a mound fen (figure 1). Following draining by the ditch and subsequent drying, any organic matter likely decomposed, transforming the clay soils into clay loams, as observed in the below-ditch soils. Further, the presence of a clay layer with orange redoximorphic mottles, as found in the below-ditch soils, indicates wet-dry cycles over time. Seasonal water flowing over or through the clay soils creates temporary saturated anoxic conditions that become aerobic when the soils dry out, and orange mottles form as iron oxidizes. If groundwater connectivity were restored between the above-ditch and below-ditch soils, it is possible that the below-ditch soils would be saturated for extended periods creating longer-term anoxic conditions and potential organic accumulation.

Soils in quadrat A1 in the XS7 fen were more similar to those in below-ditch quadrats as they were composed of mineral horizons and had root layers. These soils were uniformly dry with loam in upper layers. If these layers have been cut off from groundwater flow and dried, the clay soils seen in the upper layers may have been leached and left the sandy loams seen in the lower layers.

WF Fen

The soil textures found in the WF fen were counterintuitive as the above-ditch soils were wet but not loamy, and the upper organic layers had high amounts of clay and gravel. There was one exception to this, as quadrat A1 had organic material as the deepest layer, likely a result of burial. However, below-ditch soils were dry but loamy, which could be more indicative of soils with decomposed organic matter or more weathered mineral soils. Additionally, below ditch soils were completely dry at the time of sampling. These patterns may be a result of the much larger size of the ditch and more extensive draining in this site relative to the smaller ditch in the XS7 fen.

Gravel found in both upper and lower soils of the WF fen may be a result of outwash from the construction of logging roads, which may have covered the initial fen surface as evidenced by the buried organics in quadrat A1. These gravels may then have been covered by the subsequent accumulation of clay and vegetation supported by groundwater in shallow saturated conditions underlain by less permeable clays. The loams seen in soils below the drainage ditch likely indicate the previous presence of organics, as organic matter decomposition often results in loamy soils, or they could be the result of abiotic soil aging, as gravelly soils weather to more loamy or clayey textures over time.

Soil Color

Dark soil colors in above-ditch quadrats are indicative of wet organics, while lighter soils in below-ditch quadrats indicate lower organic carbon content and more decomposition. Gleys, gray soils created as minerals leach, indicate anoxic conditions or leaching in wet or previously wet soils. The mottles observed in some soil samples indicate redox activity in wet conditions and the reduction or oxidation of iron (Vepraskas et al., 2008). The blue mottles found in WF fen-A4 and A5 indicate the presence of reduced iron and thus reflect anoxic conditions, while the orange mottles indicate the presence of oxidized iron and thus reflect cycles of wetting and drying. Layers with orange mottling were likely better drained and may indicate presence of organics or roots, which can create aerobic pockets in otherwise anaerobic soil conditions, although we did not see evidence of root channels in any cores (Vepraskas et al., 2008).

Hydrology

Though the fens studied in Childs Meadow were of different types (WF is a hillslope fen and XS7 is a mound fen) the effect of the drainage ditch was the same. In each fen, the drainage ditch reduced the groundwater connectivity and caused downslope soils to dry out and lose organic soil components. Because the sites were sampled during the dry season, only quadrats above drainage ditches were wet; however, in the wet winter and spring season when surface water is more abundant, it is possible that the quadrats above and below the ditches would have wetter soils. Since the below-ditch soils dry out in the summer, they do not contribute to carbon storage or water availability during the dry season.

There are two groundwater monitoring wells in the XS7 fen as part of a network of monitoring wells across the meadow complex. These wells showed consistently higher groundwater levels in the above-ditch wells than in the downslope wells throughout the sampling season and over multiple years (Yarnell et al., 2020). This discrepancy in groundwater levels between wells very near to each other is the most likely cause of the vegetation and soil differences seen above and below the XS7 ditch. Cores dug in the XS7 fen were deeper than the monitoring well and showed unsaturated soils beneath the saturated upper soil horizons, supporting the observation that the XS7 fen is a mound fen and not a slope fen. The cores also illustrated that this fen is not sourced from the primary groundwater aquifer in the meadow complex and is instead a separate source of groundwater.

Unlike in the XS7 fen, there were no groundwater monitoring wells in the WF fen during this study. However, we observed saturated soil conditions high shallow groundwater levels in above-ditch cores, while below-ditch cores were uniformly dry. The groundwater present in upslope cores flows though the shallow subsurface and into the drainage ditch where it flows downstream as channelized surface runoff. Given that the groundwater flows through the shallow subsurface before reaching the ditch, restoration efforts that fill the ditch with appropriately textured material will likely create groundwater connectivity throughout the study site and potentially create fen-like conditions in the downslope areas.

Conclusion

In this study, we investigated the differences in wetland-specific vegetation, soil color, soil texture, and organic matter content upslope and downslope of a drainage ditch in two impacted fens. Downslope of drainage ditches, we expected to see drier, mineral-dominated soils with less buried organic matter and lower cover of wetland indicator species. Above ditches, we expected the opposite: wetter organic-rich soils and high percentage of moss cover. We found these expected conditions in both fens studied, although we also found much less buried organic matter in upslope soil cores at both study sites than expected. Upslope of ditches, soils were wet, with dark colored organics in the XS7 fen and a mixture of dark colored organics and gleyed clays in the WF fen. Below drainage ditches, soils were uniformly dry and loamy, with medium brown coloration and lower cover of wetland-indicator plants. When the ditches in these fens are filled in future restorations, this data will act as a baseline for success in replicating un-drained conditions. If, after filling, downslope soils and vegetation resembles upslope, that is a strong indicator for successful restoration.

The next question to ask is how might these fens react to restoration of ditches? Filling these drainage ditches with appropriately textured soil is expected to increase groundwater levels below the ditches, facilitating groundwater connectivity between upslope and downslope, and creating anaerobic conditions in the previously dry, aerobic soils. This could encourage the colonization of wetland plants into presently xeric areas and over time increase soil carbon storage as mosses grow and then are buried in anoxic soils. Downslope regions are expected to exhibit the organic soils and wetland vegetation currently observed above the ditches, as fen habitat expands into presently dry areas (Figure 2b). Overall, this study adds to the existing restoration research in the meadow by establishing a baseline for comparison following restoration activities in these and other wetlands.

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