Restoring sedges and mosses into frost heaving iron fens, San Juan Mountains, Colorado

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SUMMARY

Rare iron fens in the San Juan Mountains of Colorado are frequently in poor condition due to mining, roads and ditches, which have left much of the fen completely bare of vegetation. Natural revegetation is slow to occur in the bare areas because of severe frost heave in the cold mountain climate. Therefore, experimental revegetation plots were conducted in a factorial design with mulching and no mulching, crossed with moss diaspores, sedge transplants, and moss and sedge combined. Mulching influenced surface soil temperatures by reducing the midday highs and increasing the night-time lows, which decreased the frequency and amount of frost heave. Peat moisture also modified frost heave, with the greatest frost heaving occurring near 75 % peat moisture content (water table 10–20 cm below the surface) and the least when soils were either wetter or drier. Moss survival was dependent on mulch, with no moss surviving in plots without mulch. Mulching also increased sedge transplant survival. In summary, mulching significantly increased the success of vegetation restoration efforts for frost heave areas in mountain fens.

KEY WORDS: *Carex*, mountain, restoration, mulching, peatlands, *Sphagnum*.

INTRODUCTION

Fens are common in many mountain ranges (Chadde *et al*. 1998, Patterson & Cooper 2007, Cooper *et al*. 2010), including the San Juan Mountains of Colorado (Chimner *et al*. 2010). In the majority of fens in the San Juan Mountains, pH ranges from slightly acidic (pH ~5.5) to slightly basic (pH >7.5), influenced by the bedrock that groundwater has been in contact with (Cooper & Andrus 1994, Cooper 1996, Chimner *et al*. 2010). However, several rare acid fens "iron fens" with pH <4.5 also occur in the San Juan Mountains (Cooper *et al*. 2002, Chimner *et al*. 2010). Iron fens form in areas that receive naturally low pH groundwater from weathering of iron pyrite, which oxidises to form sulphuric acid, creating acidic groundwater (Cooper *et al*. 2002).

Iron fens in the San Juan Mountains have unique plant communities. Most are treeless and have a dense cover of sedges (30 species in total), willows (six species) and several species of brown mosses (e.g. *Warnstorfia fluitans, Aulacomnium palustre, Ptychostomum pseudotriquetrum* and *Climacium dendroides*) (Chimner *et al*. 2010). In iron fens, however, the most common plants are bog birch (*Betula glandulosa*), Engelmann spruce (*Picea engelmannii*) and water sedge (*Carex aquatilis*). There is also a dense cover of *Sphagnum* mosses (Chimner *et al*. 2010), the most common *Sphagnum* species being *S. russowii, S. fimbriatum* and *S. angustifolium*. In addition, two rare Arctic *Sphagnum* species (*S. balticum* and *S. obtusum*) that occur in several San Juan iron fens are disjunct by more than 2,000 km from their main ranges in Canada (Cooper *et al*. 2002, Chimner *et al*. 2010).

A four-year assessment of fens in the San Juan Mountains found that many fens were impacted by roads, mining and ditching (Chimner *et al*. 2010). In addition, two fen types were disproportionally impacted and in need of restoration. These include the rare iron fens, which were frequently in poor condition, with six out of 15 surveyed requiring restoration. Some of the iron fens were found to have been partially buried by tailing piles, as they were often located next to metal mines. It was also discovered that many of the iron fens were mined for "bog iron ore", which left much of the fen completely bare of vegetation even a century later, with bare soils undergoing severe frost heave, erosion and decomposition (Figure 1).

Frost heave is the process of soils being uplifted by needle ice when the temperature fluctuates diurnally between values above and below 0 °C (Groeneveld & Rochefort 2002). Many cycles of freezing and thawing can loosen the surface peat, break plant fragments and increase erosion (especially on slopes) (Groeneveld & Rochefort 2002). Mulching with straw is the commonly recommended method for restoring peatlands undergoing frost heave (Rochefort *et al*. 2003, Groeneveld & Rochefort 2005). However, mulching

Figure 1. Photo of Ophir Pass Fen showing frost heave patterns on a steeply eroding slope.

has never been tested in mountainous conditions or in iron fens. Therefore, the objective of this study was to determine whether mulching facilitated the growth of mosses and sedges in bare peat that is undergoing frost heave in mountain iron fens.

METHODS

Sites

This research was carried out in the San Juan Mountains of south-west Colorado, USA; a geologically complex mountain range with rocks ranging in age from Precambrian crystalline rocks to unsorted Quaternary deposits of glacial, colluvial and alluvial origin. Altitudes in the San Juan Mountains range from 1,500 m up to 4,300 m a.s.l. Higher altitudes are typically glaciated with broad u-shaped valleys, tarns, cirque lakes and glacial moraines; while narrower river valleys cut through at lower altitudes. Higher altitude systems are snow driven, mid-altitude areas receive a mixture of snow and rain, and lower altitudes are dominated by rainfall.

During the early summer of 2007, I initiated experimental mulching at three physically disturbed iron fens (Table 1): Ophir Pass Fen (37^o 50’ 59” N and 107^o 46’ 18” W), Cement Creek Fen (37^o 53’ 50” N and 107^o 38’ 44” W) and Chattanooga Fen (37^o 52’ 01” N and 107^o 43’ 29” W). There is no record of what caused the large disturbances in any of the fens. It is presumed that Cement Creek Fen was disturbed by mining as a heavy metal mine opened just off site in 1899. Ophir Pass was thought to have been mined for bog iron to use as paint pigments sometime before the 1950s (several other nearby iron fens were also mined for bog iron). It is less clear what happened to Chattanooga Fen, but it too has been bare for many decades. The remnant vegetation is similar at all three fens and dominated by several species of *Sphagnum* mosses, *Carex aquatilis* and bog birch (*Betula glandulosa)*. All three fens are sloping with Ophir being the steepest (>21% slope), Cement Creek moderately sloping (>10%), and Chattanooga Fen the least inclined (<5%).

Table 1. Summary characteristics of the three study sites. WT level indicates the three-year average of groundwater levels in cm below the soil surface; bare size indicates the size of the bare peat in each fen; and pH is an average value measured in the groundwater.

Site	Chattanooga	Cement Creek	Ophir Pass
Altitude (m)	3,121	3,301	3,517
Fen size (ha)	7	1.5	0.65
Bare size (ha)	0.004	1.35	0.21
WT level (cm)	36	18	19
pH	3.44	3.79	3.75

Experimental design

At each site, I established six 1 × 1 m plots in three separate blocks in different parts of the fen, for a total of 18 plots per fen. Revegetation was done in a factorial design with mulching and no mulching and crossed with moss, sedge, and moss and sedge. The mosses used were *Sphagnum angustifolium*, *S. fuscum*, *S. russowii* and *Polytrichum strictum* with each moss spread in equal amounts. *S. russowii* and *S. angustifolium* were used because they are the most common *Sphagnum* mosses in iron fens (Chimner *et al*. 2010) and *S. fuscum* and *P. strictum* were used because they have been commonly used in restoring cutover peatlands (Groenveld & Rochefort 2005, Chirino *et al*. 2006). Owing to the low cover of mosses in Ophir and Cement Creek Fens, all moss was gathered from Chattanooga Fen. The moss was gathered across a wide area; by cutting off the top 5–10 cm with scissors, chopping this into small fragments (greater than 1 cm in length), and spreading uniformly across the plots (Rochefort & Bastien 1998). The quantity of moss used was a one-gallon (4.4 L) ziplock bag for each plot.

The only species of sedge planted was *Carex aquatilis,* which was found to be the most common sedge in the San Juan iron fens (Chimner *et al*. 2010). The sedges were collected by digging up the plants and separating out the rhizomes. Sedges were planted by inserting one rhizome section with at least two stems attached into the ground (Cooper & MacDonald 2000). A total of nine sedge “transplants” were planted in three rows per 1 × 1 m plot (actually covering the inner 0.75 m × 0.75 m of the plots). A mixed planting treatment consisted of sedges and mosses combined using the methods described above. All treatments were also conducted with mulch and no mulch, for a total of six plots per block. Initially, certified weed-free straw mulch was applied after the planting and kept in place with staked-down garden netting to keep the straw in place. Owing to the compression of the straw mulch after one winter, all sites were remulched with Excelsior mulch (shredded aspen) in year two. Remulching did not take place in years three or four.

Once each summer, I monitored sedge transplants for survival and number of stems growing in each plot. Mosses were assessed visually in the first three years, and percent cover was measured by the pin drop method during the fourth year. Soil temperature, soil moisture, groundwater levels and frost heave were also monitored. Soil temperature was monitored at one block per site using temperature sensors (ibuttons) that were placed in sealed plastic bags on the soil surface in each plot for logging continuous temperature data. Soil moisture was measure in each plot (monthly) using a soil moisture probe (Campbell Hydrosense). One slotted plastic PVC well was installed in the middle of each block (total nine wells) for measuring groundwater levels. One well from each fen was equipped with a continuously measuring pressure transducer (Global Water, Ohio). All other wells were measured by hand monthly during the summer. Frost heave was determined in the spring/early summer 2008 by inserting three wooden stakes in each plot. The amount of frost heave was determined by measuring the distance the wooden stakes moved vertically every week. After measuring, the stakes were reset to their original positions.

Statistical Analysis

A repeated measures factorial analysis of variance was conducted using PROC MIXED to test for experimental differences in sedge transplant survival and sedge stem numbers (SAS 2009). Site and mulch and interaction were treated as fixed effects, replication*mulch was treated as random effects and sample years were treated as repeated measures. I used compound symmetry covariance structure for repeated measures analysis as determined by looking at the fit statistics and the Kenward and Roger’s correction for degrees of freedom. An ANOVA using PROC MIXED (SAS 2009) was conducted to test the influence of mulch on the average vertical frost heave. Differences between all treatments were conducted using Tukey's post-hoc test with differences at $P<0.05$ considered significant.

RESULTS

Mulching attenuated surface soil temperatures by reducing the daytime highs and increasing the night-time lows (Figure 2). Vertical displacement of the wooden stakes from frost heave was significantly reduced ($P < 0.001$) by mulching (Table 2). The wooden stakes heaved an average of ~20 cm in the spring without mulch compared to ~12 cm with mulch (Figure 3). Frost heave was correlated with soil moisture, with the highest rates occurring near 75% soil moisture content (a water table level of ~10–20 cm below soil surface) and dropped when the soils were wetter or drier (Figure 4).

Mulching significantly increased the survival of sedge transplants after four growing seasons (Table 3, Figure 5). Site and mulch × site interaction were also significant factors affecting transplant survival (Table 3). The overall number of stems per

Table 2. Results of ANOVA designed to test the effect of mulch and site on frost heave.

Effect	Num DF	Den DF	F	P
mulch	1	66	7.80	0.007
site	2	66	3.33	0.04
mulch*site	2	66	0.21	0.81

Table 3. Results of repeated measures ANOVA data designed to test the singular and interactive effect of mulch and site on sedge transplant survival.

Effect	Num DF	Den DF	F	P
mulch	1	137	4.28	0.041
site	2	132	47.57	<0.001
mulch*site	2	137	5.01	0.008

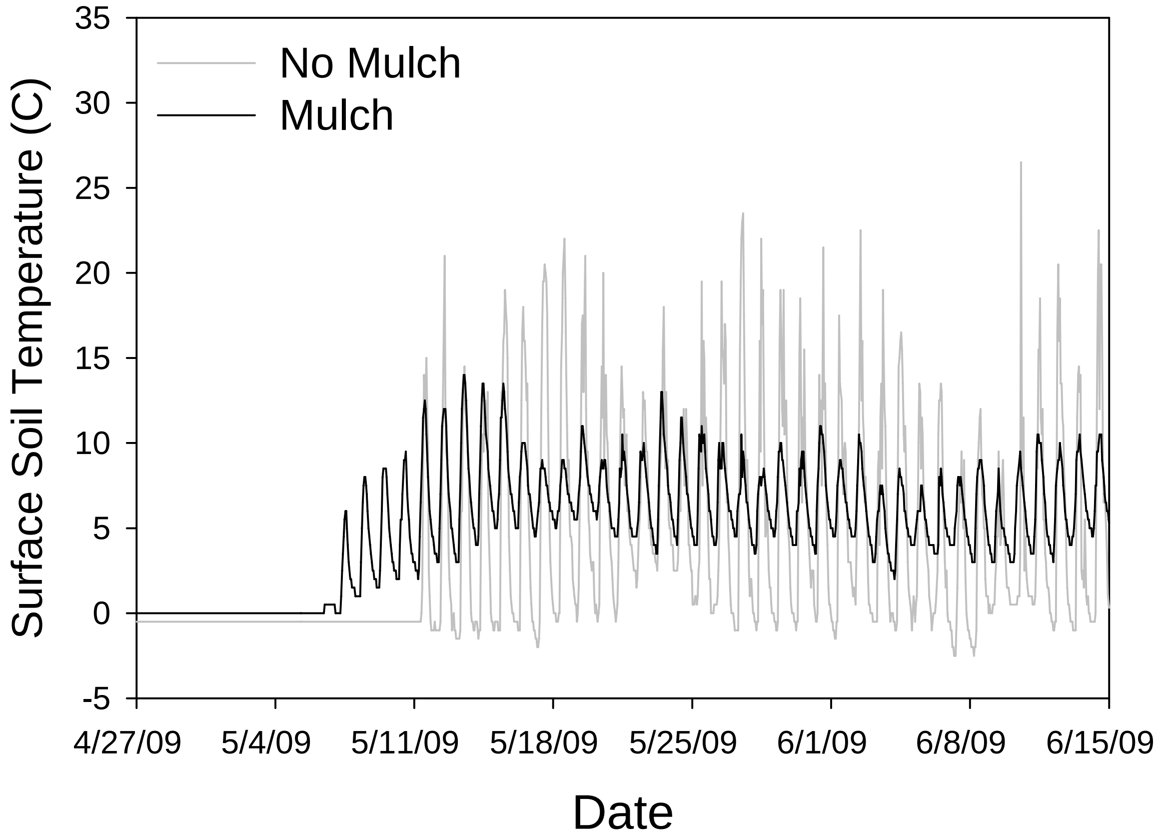

Figure 2. Example surface soil temperature profiles with Excelsior mulch and no mulch treatments during 2009.

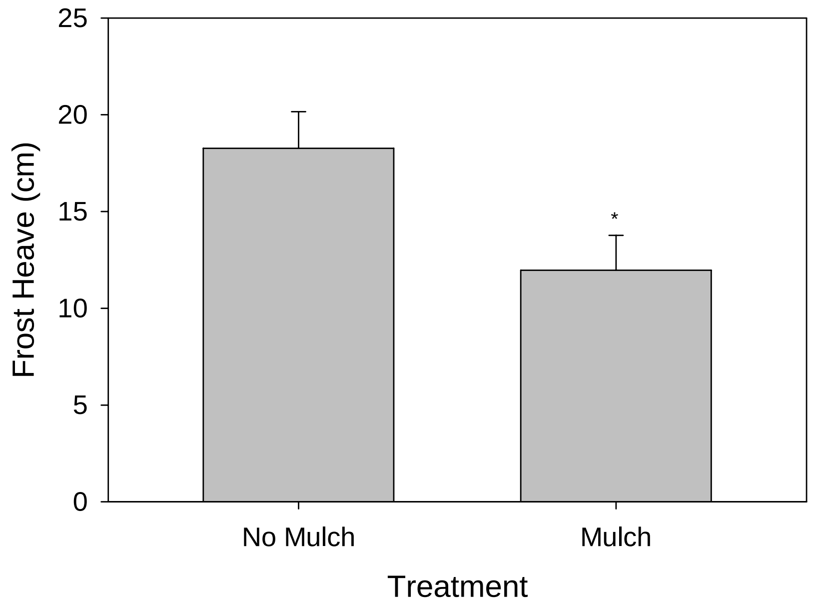

Figure 3. Total frost heave (cm) and standard error of mulched and unmulched plots measured during a four-week period immediately after snowmelt in June 2008. Asterisk indicates $p < 0.05$ from ANOVA.

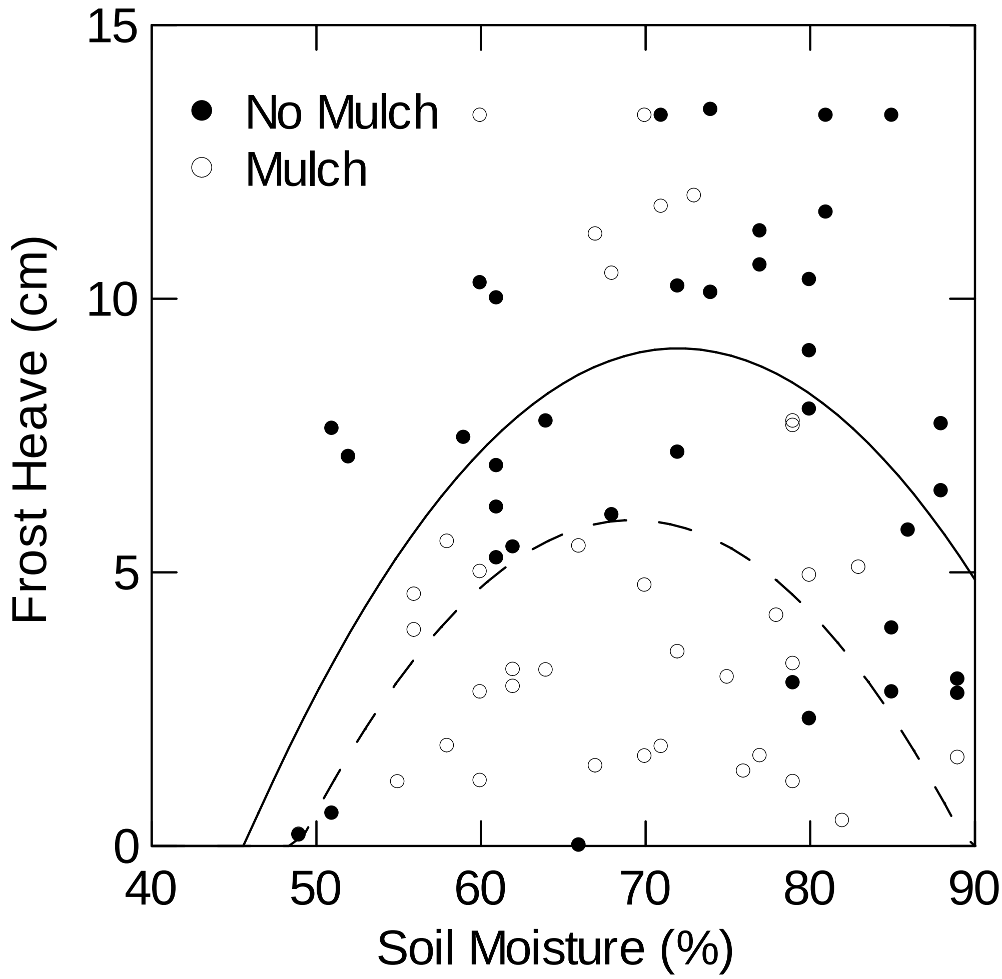

Figure 4. Relationship between soil moisture and vertical displacement from frost heave for mulch (dashed line) and no mulch (solid line) plots.

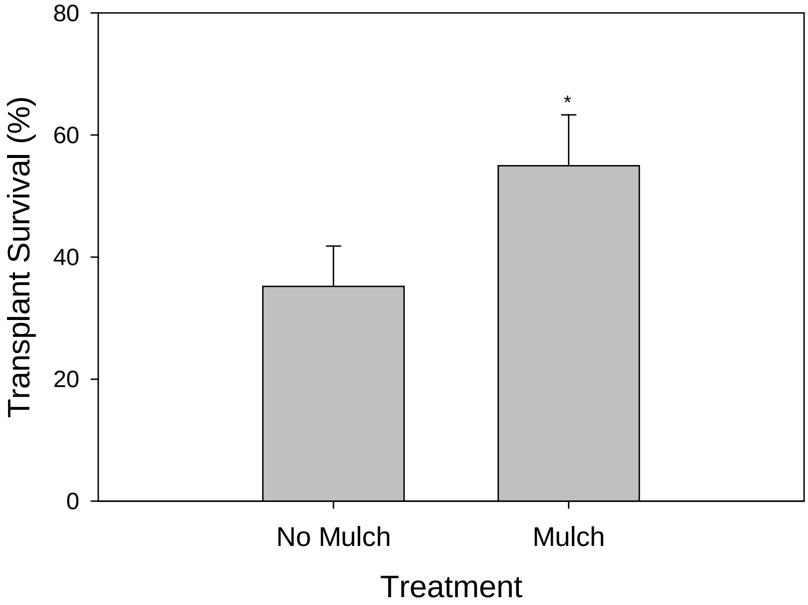

Figure 5. Sedge transplant survival after three growing seasons by mulch treatment. Asterisk indicates $p < 0.05$ from repeated measures ANOVA.

plot was not significantly affected by mulch, but it was by site (Table 4). New sedge stems were not produced during the first growing season for any site or treatment (Figure 6). The average number of stems per transplant across all sites and treatments equalled 2, 3.4, 6.7 and 11.4 after 1, 2, 3 and 4 seasons of growth, respectively.

Mosses, both *Sphagnum* spp. and *P. strictum*, survived only in mulched plots, with no survival found in any unmulched plots. Total moss cover in mulched plots ranged from ~5% in Chattanooga Fen up to ~40% in Cement Creek Fen (Figure 7). *Sphagnum* mosses had a greater cover than *P. strictum* at Cement Creek, but was rare in the other sites. Of the three *Sphagnum* species planted, only *S. russowii* was found during sampling in the fourth year.

Table 4. Results of repeated measures ANOVA designed to test the singular and interactive effect of mulch and site on number of sedge stems.

Effect	Num DF	Den DF	F	P
mulch	1	137	1.25	0.265
site	2	37.6	9.39	0.005
mulch*site	2	137	0.09	0.914

DISCUSSION

This study confirms the usefulness of mulch in peatland restoration. Mulch acts as a thermal barrier keeping the surface soils cooler in the day and warmer at night (Price *et al*. 2003, Petrone *et al*. 2004). In addition to keeping daytime soils cooler, mulch also improves growing conditions for plants by increasing humidity under the mulch (Groeneveld *et al*. 2007). In this study, no mosses survived in any unmulched plots, probably due more to desiccation than to frost heave. This is in line with a large body of work on *Sphagnum* restoration on cutover peatlands (Rochefort *et al*. 2003).

Sphagnum fuscum has been found to have the best survival of *Sphagnum* moss species tested when restoring cutover bogs (Waddington *et al*. 2003, Chirino *et al*. 2006). However, in this study only *S. russowii* was found still surviving at the end of the study. Despite the similarities of both having low pH, key differences exist between iron fens and bogs. Iron fens are very minerotrophic with high Ca^{+2}, Mg^{+2}, Na^{+} and Fe^{+3} concentrations (Chimner *et al*. 2010) that seem to favour the growth of *S. russowii* (a minerotrophic species) over *S. fuscum* (an ombrotrophic species). This is seen in undisturbed iron fens in the San Juan Mountains as *S. russowii* is the most common moss and is the dominant hummock and lawn forming species, whereas *S. fuscum* is rarer and found only on high hummocks (Chimner *et al*. 2010).

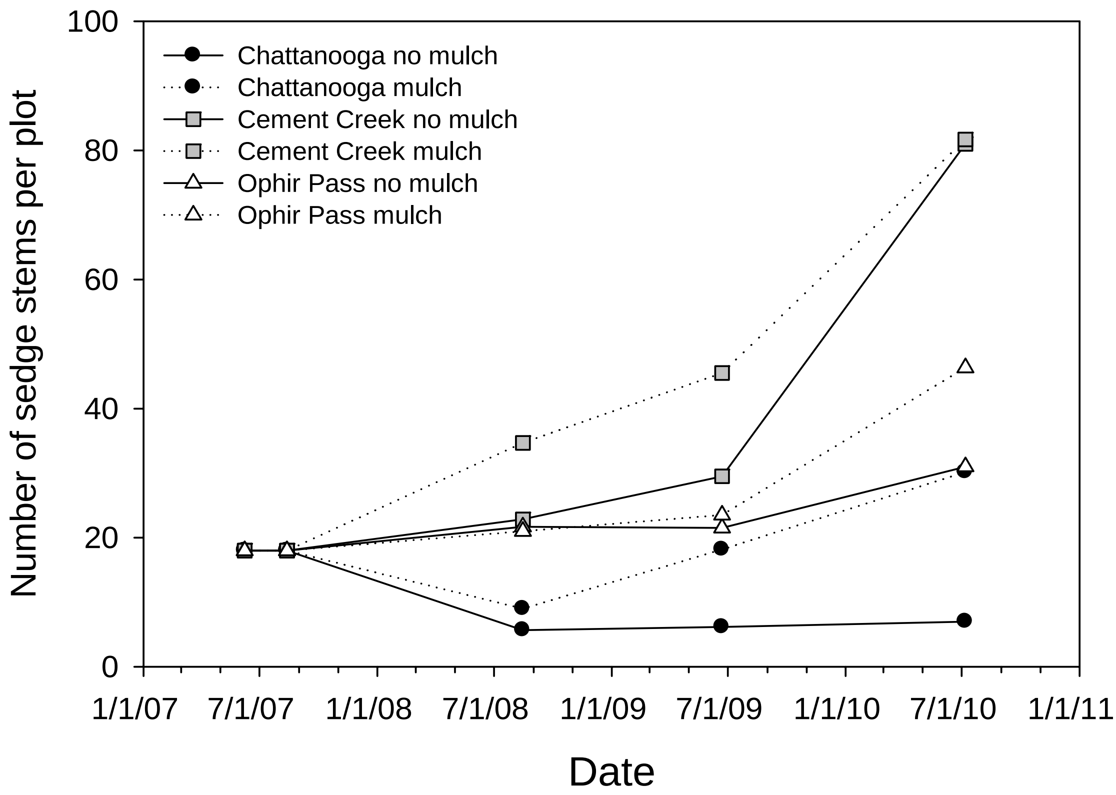

Figure 6. Number of sedge stems per plot through time.

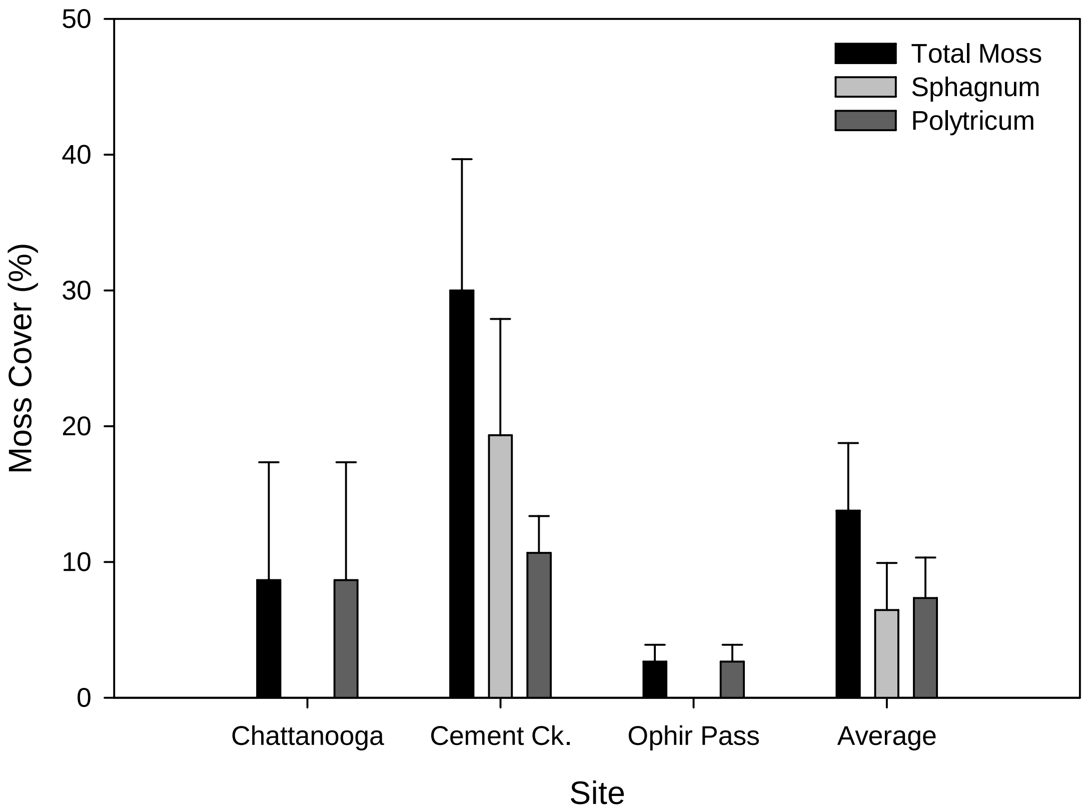

Figure 7. Moss cover by site and species within the mulch treatments. There was no moss survival without mulch.

Polytrichum has been tested for use as a nurse plant for regenerating *Sphagnum* in frost heave areas (Groeneveld *et al*. 2007). Intact carpets of *Polytrichum* were found to minimise frost heave, with newly reintroduced fragments not as efficient during its establishing phase (Groeneveld & Rochefort 2005). In this study, *Polytrichum* grew from fragments under the mulch and appeared to do better than *Sphagnum* in slightly drier areas. For example, at Chattanooga Fen, where the water table ranged between 20 and 40 cm below the soil surface, only *Polytrichum* survived, whereas in the wetter Cement Creek, more *Sphagnum* survived. Chirino *et al*. (2006) also found that *Sphagnum* moss diaspores grew better in south-eastern Canada when soil moisture was favourable (wet years) than in dry years. Fen *Sphagnum* species (*S. warnstorfii, S. centrale* and *S. fallax)* were also found to regenerate better at higher water table levels, with an optimum water table level just at or below the soil surface (Graf & Rochefort 2010).

Straw mulch is the recommended choice for restoring extracted peatlands in North America (Quinty & Rochefort 2003, Groeneveld & Rochefort 2005). This is because it lasts long enough to protect the newly scattered diaspores (3–5 years, Waddington *et al*. 2003), and is cheap enough for use on the large areas that need to be restored after peat mining. However, straw mulch did not work well in the San Juan Mountains of Colorado because of the extremely high snow packs (> 10 m). After the first winter, the straw mulch had been completely compressed into the peat with little to no loft (trapped air) left. Conversely, Excelsior mulch held up very well under the deep snowpack and retained much of its original loft after several winters. The Excelsior mulch did not appear to inhibit mosses growing underneath it.

In addition to mulch, the water content of the peat was found to influence frost heaving. It is generally assumed that increasing soil water content increases frost heave (Graf & Rochefort 2008 and citations within). However, in this study the greatest frost heaving occurred at soil moisture contents of 70–80% (water table 10–20 cm below the soil surface), with very little frost heaving occurring when the water table was near the soil surface. It appears that if fens are saturated, frost heave is minimised because there is too much water to freeze during one night. If the peat is too dry, there is not enough water in the soils to form needle ice (Graf & Rochefort 2008). Observations from a nearby large fen restoration project (near Telluride, Colorado) supports this suggestion, as frost heave was not observed in restored fens that had groundwater levels near the soil surface (D.J. Cooper, personal communication). Higher water table levels have also been found to increase sedge survival. For example, Cooper & MacDonald (2000) found that *Carex aquatilis* transplants survived better at higher water table levels in a mined-over fen in another part of Colorado.

Sedge transplants appear to be a reliable way to revegetate small fens. Sedges grown in greenhouses, from seed collected from local sources, have been planted successfully in many mountain fen restoration projects (D.J. Cooper, unpublished data). However, transplants are cheaper than greenhouse-grown sedges, although transplants grow more slowly initially and may require more plants per unit area to obtain desirable coverage.

In summary, mulch was found to be useful for restoring bare peatlands by reducing temperature extremes, increasing humidity under the mulch, and reducing frost heave. Mulch was absolutely required to regenerate moss fragments and was helpful in establishing sedges from transplants. *Sphagnum russowii* and *Polytrichum strictum* were the most promising moss species for restoration into iron fens.

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