

# Mounding and Scalping Prior to Reforestation of Hydrologically Sensitive Deep-Peated Sites: Factors behind Scots Pine Regeneration Success

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**Pearson, M., Saarinen, M., Minkkinen, K., Silvan, N. & Laine, J.** 2011. Mounding and scalping prior to reforestation of hydrologically sensitive deep-peated sites: factors behind Scots pine regeneration success. *Silva Fennica* 45(4): 647–667.

Watering up typically ensues after clearcutting forestry-drained peatland forests. Thus, the effectiveness of maintenance drainage and soil preparation procedures becomes paramount for establishing a new generation of commercial forest. Mounding is the primary method of soil preparation applied in regeneration sites lying on deep peat. As raised planting spots, mounds are resistant to waterlogging and assumed to be beneficial for organic matter (OM) decomposition via, e.g., increased soil aeration and temperature, which would also enhance seedling growth. In recent years, however, less intensive and cheaper alternatives like scalping have been sought with some reported cases of success. Our case study investigated the survival and growth of Scots pine outplants in mounds, scalps, and unprepared microsites along a moisture gradient. After three growing seasons, mounding accelerated neither seedling growth nor OM decomposition relative to the unprepared treatment. Survival in mounds was nonetheless superior overall. Scalps behaved as water collecting depressions leading to a catastrophic regeneration result. Based on our findings, water table level (WTL) overrides other growth-controlling factors in excess moisture conditions. To combat watering up coupled with greater than normal rainfall, we recommend reforestation strategies which provide elevated, prepared planting spots (i.e., mounds) or utilize unprepared, higher microforms.

**Keywords** peatland forest regeneration, soil preparation, mound, scalp, Scots pine, OM decomposition, excess moisture

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**Received** 2 May 2011 **Revised** 25 August 2011 **Accepted** 16 September 2011

**Available at** <http://www.metla.fi/silvafennica/full/sf45/sf454647.pdf>

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## 1 Introduction

In silvicultural terms, forest regeneration success is broadly understood as the establishment of a new generation of trees of the preferred species which are adequately spaced, sufficient in density (per ha), and in robust health and therefore capable of further development to meet the goals of timber production. Compared to boreal forests on mineral soils, the regeneration of drained boreal peatland forests is often burdened by more uncertainty in addition to being a financially riskier venture. After harvesting the transpiring tree stand, a distinct rise in the water table level (WTL) typically ensues (e.g., Heikurainen and Päivänen 1970, Roy et al. 1997) in addition to increased throughfall (of precipitation), snow cover depth, and runoff (Heikurainen and Päivänen 1970, Paavilainen and Päivänen 1995). Wetter conditions may encourage changes in ground and field layer vegetation and regression towards natural mire species; for instance, cottongrass (*Eriophorum vaginatum* L.) has been shown to spread aggressively after timber harvesting on nutrient-poor drained peatland sites consequently deterring natural regeneration of pine (Kuusipalo and Vuorinen 1981). Other serious challenges to successful peatland forest regeneration include an overly thick raw humus layer which inhibits conifer seed germination (Kaunisto 1984), abundant suckering and emergence of natural seed-borne pubescent birch (*Betula pubescens* Ehrh.) seedlings (Saarinen 2002), and potassium (K) and phosphorus (P) deficiency in sapling and pole stage stands growing on deep peats (e.g., Kaunisto 1997).

Early on, however, moisture and aeration conditions controlled by the WTL are likely the foremost factors restricting regeneration success in drained peatlands, for the channeling of excess water away from the regeneration site is crucial for root development of tree seedlings (Mannerkoski 1985). To combat this problem, remedial measures of ditch maintenance and soil preparation, often in combination, are commonly applied so as to afford seedlings with a running start on post-greenhouse life. The positive effects of soil preparation on the conditions for seedling growth on peatlands clearly outweigh the negative ones (Kaunisto and Päivänen 1985, Paavilainen and Päivänen 1995). As a method of soil preparation, mounding provides the

answer to the fundamental hydrological question; by creating peat heaps atop the peatland surface, waterlogging of the growing spots is avoided even during periods of copious rainfall complemented by a high WTL. Seedlings thus benefit from the elevated planting position (Lähde et al. 1981). Planting on discontinuous, raised soil heaps instead of continuous plough ridges has also been found to provoke symmetrical rooting thereby reducing lean and windthrow (Savill 1976).

In light of the constraints on stand establishment, other assumed advantages of mounding versus leaving soil undisturbed include uprooting of competing vegetation from planting spots, reduced damage to seedlings caused by crawling insects, improved aeration and local drainage, and warmer soil temperatures in the rooting zone which apparently enhance nutrient mineralization and availability to seedlings by likewise stimulating the organic matter (OM) decomposition process spurred by microbes (Sutton 1993, Londo and Mroz 2001). On peatlands, however, the effects of harvesting and soil preparation on OM decomposition and quality are not well known (Prescott et al. 2000), and the majority of relevant studies have been restricted to undrained wetland soils or those overlain by a thin peat layer (e.g., Trettin et al. 1997). The silvicultural basis for preparing soil is thus to achieve maximum seedling survival and growth, and in forestry managed peatlands (in Finland) these ends are presumably most reliably achieved by mounding prior to planting (Mannerkoski 1975, Kaunisto 1984). Despite the apparent benefits of mounding, it is not a method entirely without fault; desiccation of mounds during prolonged dry periods and the infamously slow rewetting process of *Carex* peat mounds have been noted (Saarinen 1997, 2005).

To determine the capacity of a given site to sustain the next generation of tree growth into maturity, it is also essential to consider the nutrient balance in peatland forest regeneration areas. Though nutrient dynamics of drained peatland forests have been quite thoroughly studied (e.g., Laiho et al. 1999), investigations of the nutrient status in planting spots, least of all of the prepared type, on deep peats are lacking. Soil preparation is believed to accelerate nutrient release from OM (e.g., Kaunisto and Päivänen 1985, Londo and Mroz 2001), which presumably would be beneficial

for seedling growth also on deep peats. The soil carbon-to-nitrogen (C:N) ratio is an often used index of OM quality, and generally the higher the ratio, the more the N released during decomposition is immobilized by soil microbes (e.g., Enríquez et al. 1993). This could lead to N deficiency in seedlings and consequently limit growth.

On low to moderate fertility drained peatlands, planting Scots pine (*Pinus sylvestris* L.) seedlings in mounds after clearcutting is according to Finnish silvicultural recommendations for drained peatlands (Ruotsalainen 2007) the safest and often also the cheapest regeneration solution in the long run due to the variability of weather conditions and the suckering of pubescent birch in regeneration areas. Mounding is the most widely applied method of mechanical soil preparation in drained peatland forest regeneration schemes (Saarinen 1997). Though scalping, which involves the removal of the humus layer and the consequent baring of the underlying peat surface in patches, is also regarded as a feasible but less expensive soil preparation method particularly in connection with natural or artificial seeding of Scots pine on dwarf shrub to lingonberry (*Vaccinium vitis-idaea* L.) type drained peatland sites (Saarinen 2005) (for site type classification see Vasander and Laine 2008), regeneration may be hindered by rainy growing seasons and/or a substandard drainage regime compounded by the poor permeability of *Sphagnum* peat (Paavilainen and Päivänen 1995, Saarinen 1997). Leaving the soil unprepared, however, is not viewed as an acceptable alternative except in certain dwarf shrub type regeneration areas where the *Sphagnum* moss carpet provides a suitable germination and growing medium for seedlings. The comparative examination of pine seedlings planted in various microsite types on drained clearcut peatlands is still in its embryonic stage, although Mannerkoski (1975) already over three decades ago concluded that mounds were superior to unprepared microsites in the survival and growth of Scots pine outplants as did Kaunisto (1984) in succession. However, on a raised bog Hendrick (1984) reported little difference in growth between lodgepole pine (*Pinus contorta* Dougl.) seedlings planted on hand-dug mounds and those directly planted on the bog surface at close drain spacings (10 m), as well as equivalent growth

amongst those planted on plough ridges and the flat beside the ridge. Furthermore, providing a raised planting spot, i.e., a hummock as opposed to a hollow, clearly enhanced planted black spruce (*Picea mariana* (Mill.) BSP) seedling survival and growth in drained forested wetland cutblocks after two post-clearcutting growing seasons (Roy et al. 1999). Thus, careful selection of planting spots could also be a critical determinant of pine regeneration success on forestry-drained clearcut sites where soil has been left unprepared. No record exists of relevant comparisons implemented in excessive moisture conditions on deep peats and how this may potentially affect the viability of the soil preparation methods studied here. In the future, extreme weather phenomena, e.g., flooding, droughts, and storms, are predicted to increase in frequency and/or magnitude in the Northern European boreal forest zone (Intergovernmental Panel on Climate Change 2007), thus creating new challenges for continuing forestry on peatlands.

In the following case study, we present a juxtaposition of soil preparation methods (mounding, scalping, unprepared treatments) in clearcut Scots pine forest regeneration areas on drained deep peat soils. Since the hydrological regime of forestry-drained peatland sites varies even within the same site type and site due to, e.g., drainage history and environmental factors, we pragmatically approached the issue by examining the effects of the three treatments in both high and low WTL conditions (relative to soil surface and therefore planting spot position). After all, one of the main defenses for mounding over scalping or leaving soil unprepared is its alleged hydrological superiority, i.e., better local drainage from the standpoint of seedlings.

Our starting point for comparison was the idea that the primary factors determining regeneration success are adequate soil aeration and moisture, substrate quality, and soil temperature. Presumably, soil preparation influences all of these factors. To corroborate this assumption, we contrasted WTL, soil temperature at 5 cm depth (T5), soil C:N, OM decomposition rate, planted pine seedling survival and growth in mounds, scalps, and unprepared microsites. In doing so, we sought to identify a legitimate alternative to mounding by which equivalent pine regeneration success could

be achieved on nutrient-poor drained peatland sites. The hypotheses were:

- 1) Relative to planting spot position, the water table level is highest (and soil aeration consequently lowest and moisture content highest) on average in scalps (scalps > unprepared > mounds).
- 2) Soil temperature is highest on average in mounds (mounds > scalps > unprepared).
- 3) Soil preparation affects the C:N ratio of the soil surface layer.
- 4) The organic matter decomposition rate (and hence nutrient mineralization) is most rapid in mounds compared to scalps and unprepared microsites (mounds > scalps > unprepared).
- 5) Based on the above effects of soil preparation, survival and growth of pine seedlings (regeneration success) in mounds surpass those of seedlings planted in scalps and unprepared microsites (mounds > scalps > unprepared).

## 2 Materials and Methods

### 2.1 Study Sites

The object of our study is a riverside peatland (Joenvarsisuo) situated in Hyytiälä (61°50'41"N, 24°17'19"E), Juupajoki municipality, Central Finland. Spanning an area 6 ha in size, it was initially drained in 1933 followed by ditch maintenance in 1986. The experimental area is divided into Northend and Southend sites which represent a transitional site type between dwarf shrub (*Vatkg*) and *Vaccinium vitis-idaea* (Ptkg II) drained peatland types according to the Finnish classification system (Vasander and Laine 2008). Prior to clearcutting in March 2006, Scots pine forest (155 m<sup>3</sup> ha<sup>-1</sup>, average pine stem volume 0.28 m<sup>3</sup>) covered the sites. The following summer they were cleared of pubescent birch understory. Ditch maintenance, which encompassed cleaning of the main 310 m long ditch (oriented North to South) and digging of a new 45 m long ditch, was carried out concomitantly with soil preparation in December 2006 (Fig. 1). The aim of these ditch maintenance operations was to divert the water from the main ditch via the new shorter one along old uncleaned ditches, which served to filter the surface runoff prior to discharge into the river. Despite ditch

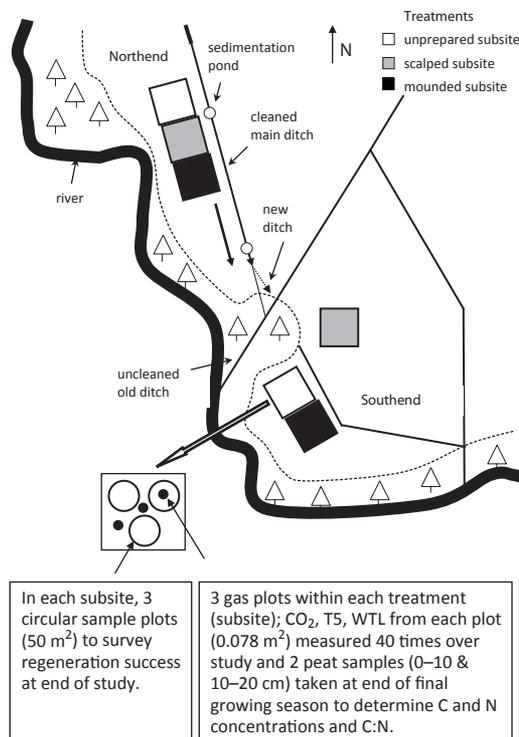


Fig. 1. Experimental design at the Joenvarsisuo peatland.

maintenance, the hydrological regime of the Joenvarsisuo peatland is notably influenced by the watercourse along its western flank. The close proximity of the river combined with minimal site inclination (only at the southern head of the main ditch does the terrain clearly slope) creates wetter conditions overall in the Northend site than the Southend one as witnessed by the prevalence of cottongrass. Thus, these sites provide suitable conditions for examining OM decomposition and regeneration success along a moisture gradient. The thickness of the moderately decomposed (H4–5 on the von Post scale of humification) *Carex-Sphagnum* peat deposit exceeds 1.5 m in the Northend and Southend alike.

### 2.2 Experimental Treatments

On both sites, mechanical soil preparation (mounding and scalping) and control (unprepared) treat-

ments were randomly allocated to 30 m × 30 m subsites; thus, the Northend and Southend sites constituted replicates of the three treatments (Fig. 1). Both methods of soil preparation were applied using the same excavator. During mounding, the digger bucket was thrust into the ground 25–30 cm (the approximate height of mounds), then dragged approximately half a meter simultaneously gathering soil, and finally, by means of its hydraulic flap, flipping over and compacting the peat mound atop unprepared ground next to the excavated pit. This technique left the deeper peat exposed on top of the mound with the original vegetated surface buried underneath. Mound bottoms were thus characterized by a double layer of humus (an excavated layer inverted on an intact one). No shallow ditches were made in mounded subsites. Scalping resulted in 1–1.5 m long, 35 cm wide bare peat strips (discontinuous patches), from which the humus layer and vegetation had been removed. Scalp depth (from the original vegetated surface) amounted to 10 cm. The soil in control subsites was left undisturbed with the exception of logging trails resulting from the clearcutting operation. In May 2007, both sites were stocked with year-old containerized Scots pine (*Pinus sylvestris* L.) seedlings of equal size at a density of 2000 seedlings ha<sup>-1</sup> (irrespective of the presence of naturally regenerated seedlings). Seedlings were planted at the top of mounds and where applicable at the higher end of scalps.

### 2.3 CO<sub>2</sub> Efflux Measurements to Determine Decomposition of Organic Matter

For the purpose of quantifying the decomposition rate of OM, three sample plots per treated subsite within each site for measuring CO<sub>2</sub> emissions were established (18 plots total; 3 mounds, 3 scalps and 3 unprepared microsites in the Northend and likewise in the Southend). Plots on subsites were located so as to harness the variability of the microsite type resulting from a given treatment. Unprepared plots represented the characteristic microform pattern (hummock-high lawn-low lawn) of control subsites.

In order to derive the aerobic decomposition rate of OM alone (expressed as CO<sub>2</sub> efflux in g m<sup>-2</sup> h<sup>-1</sup>), it is first necessary to physically

exclude the autotrophic component (living organs of plants) from the plots. Thus, in June 2007, the sample plots were trenched using a handsaw and thereafter an aluminum collar (d=31.5 cm) with a 25 cm long sleeve (area=0.078 m<sup>2</sup>) was inserted so as to eliminate root respiration and the production of new roots. The superficiality of most of the roots in peatlands (e.g., Finér and Laine 2000) justifies the trenching procedure as a means of suffocating root respiration. In mounds, this meant inserting the collar into the summit, and in scalps into the more or less flat, bare peat surface. To further stifle respiration of an autotrophic source, aboveground parts of ground vegetation (including moss layer) were removed from all the sample plots prior to the start of CO<sub>2</sub> efflux measurements and regularly clipped throughout the measurement campaign. Containerized pine seedlings also had to be removed from gas measurement plots and replanted elsewhere. Moreover, newly deposited litter, though minimal on the clearcut sites, was also picked away before and throughout the measurement campaign. Boardwalks were constructed around the plots to avoid interfering with gas fluxes during measurements. Perforated PVC tubes for determining WTL relative to the soil surface were installed beside each plot.

Soil CO<sub>2</sub> effluxes were measured 3–4 times per month by employing the closed chamber method (Alm et al. 2007). For this, a portable infrared gas analyzer attached via rubber hoses to a soil respiration chamber (h=12.2 cm, d=31.5 cm) was used (EGM-4 Environmental Gas Monitor for CO<sub>2</sub> + modified SRC-1 soil respiration chamber, PP Systems, UK). The metal chamber (the rim of which sealed with rubber innertubing) was placed on the collar groove of sample plots and sealed with water prior to measuring the change in the CO<sub>2</sub> concentration over time (80–120 seconds). EGM-4 automatically monitors the CO<sub>2</sub> concentration increase within the chamber headspace at 1.6 s intervals and calculates an average every 4.8 seconds. The soil CO<sub>2</sub> efflux (g CO<sub>2</sub> m<sup>-2</sup> h<sup>-1</sup>) is thus based on the linear increase over time of the CO<sub>2</sub> concentration in the chamber. Since the automated system lacks a built-in thermometer, efflux readings were corrected afterwards for instantaneous, ambient air temperature using the data supplied by a nearby weather station (see section 2.7). Due to the sensitivity of the temperature

probe (also used to measure soil T and described below) in response to wind exposure and solar radiation in the clearcut experimental area, the weather station air temperature values were preferred over those measured with the probe during gas measurement events. In any case, a one degree temperature error will only lead to an 0.36% error in flux, thus having minimal impact on the results. Often prior to measuring effluxes from scalps, an extension collar had to be placed atop the collar in the ground on account of the plot being inundated with water. In such cases, effluxes were also corrected for chamber headspace air volume (via height). Additionally, supersurface water depth was recorded for scalped plots underwater and this information represented the WTL in these plots on such occasions. Sometimes effluxes had to be recalculated manually due to the negative effects of excessive site moisture on the functioning of the gas analyzer. Using a TES-1312A digital thermometer with K type thermocouple input sensor (TES, Taiwan, R.O.C) and stainless steel temperature probe, soil temperature at 5 cm depth (T5) was measured to the nearest tenth of a °C from the middle of each plot immediately after gas measurement. The manufacturer of the TES thermometer guarantees an accuracy of  $\pm$  (0.1% rdg + 1 °C). In conjunction, the WTL to the nearest cm was registered for each plot by inserting a battery operated, water sensitive rod into the respective PVC tube. The CO<sub>2</sub> efflux measurement campaign commenced in July 2007 and concluded in August 2009. Only data collected during the May-October periods (growing season) is considered in the revelations that follow.

## 2.4 Survey of Regeneration Success

At the end of their third growing season (September 2009) (and upon the culmination of the OM decomposition measurement campaign), the survival and vitality of the 4-year-old planted pine seedlings on all six subsites were assessed by means of circular fixed-area sampling. On each subsite, 3 circular sample plots with a radius of 3.99 m (area = 50 m<sup>2</sup>) were situated within a minimum of 2 m from each other and subsite boundaries. In addition to density of living seedlings (survival rate based on initial planting density

2000 seedlings/ha), the following attributes were surveyed: height, length of current-year terminal leader shoot, vitality based on overall outward appearance, cause and incidence of damage (the last three mentioned were determined for seedlings found dead or alive). Seedling stand density (seedlings/ha), and consequently survival rate, was calculated as the mean of the 3 circular sample plots by subsite, while mean seedling height and length of the current-year terminal shoot were based on the combined total number of living seedlings found in the circular sample plots of a given subsite.

## 2.5 Peat Sampling and Nutrient Analysis

Upon the termination of CO<sub>2</sub> measurements, gravimetric peat soil samples were extracted from the middle of each of the 18 collared sample plots with the aid of a box-shaped peat corer. Two peat samples per plot were conquered, one from 0–10 and the other from 10–20 cm depth below the microsite surface. To characterize the elemental composition (chemical quality) of peat from mechanically prepared and unprepared plots, all 36 samples were analyzed via CEM (HNO<sub>3</sub>+H<sub>2</sub>O<sub>2</sub>) (acid digestion for elemental analysis), ICP and LECO CHN-2000 techniques for nutrient content based on dry mass (mg/g). Since soil C:N ratio is most readily measured and frequently used as a predictor of decomposition rate (Chapin et al. 2002) and may consequently limit N availability to seedlings, it was the focus of our attention here.

## 2.6 Statistical Methods

Based on the characteristics of the experimental design, a general linear mixed model (Mixed procedure in the SPSS 17 statistical software package) with restricted maximum likelihood (REML) estimation method was chosen to test the hypotheses concerned specifically with the effects of treatment, site, time, and peat sample depth (independent variables) and their interactions on the dependent variables. The models were as follows:

$$Y_1 = S + T + M + S * M + T * M + S * T + S * T * M \quad (1)$$

$$Y_2 = S + T + D + S * D + T * D + S * T + S * T * D \quad (2)$$

$$Y_3 = S + T + S * T \quad (3)$$

$Y_1$  = CO<sub>2</sub>, WTL, and T5 with repeated measures in time

$Y_2$  = C and N concentrations and C:N ratio measured at two peat sample depths

$Y_3$  = Seedling survival rate, terminal leader shoot length, and total height

S = Site

T = Soil preparation treatment

M = Time of measurement,

D = Peat soil sample depth

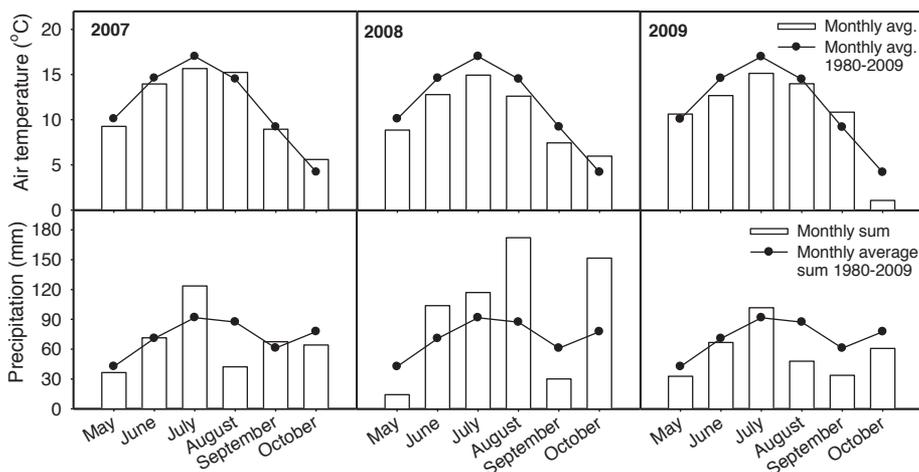
In these models, site (S), treatment (T) and sample depth (D) as well as the interactions S\*M, T\*M, S\*D and T\*D were treated as fixed effects. Site is a block factor dividing the experimental area into two different parts. We were interested in the effects of differing hydrology and nutrient status of the selected sites, and thus site was treated as a fixed factor. We lacked independent replicates of the two types of site, therefore this research is a case study in nature. Because different site-treatment combinations did not have replicates, site\*treatment (S\*T), site\*treatment\*time (S\*T\*M) and site\*treat-

ment\*sample depth (S\*T\*D) interactions were treated as random effects. First-order autoregressive (AR1) covariance structure was assumed for the time correlation in S\*T\*M term and compound symmetry (split-plot structure) for the depth correlation in S\*T\*D term.

The Bonferroni adjustment method was applied to the confidence intervals and significance values to account for multiple comparisons of the estimated marginal means (predicted means of the fitted model). In order to meet the assumptions of the statistical inference procedure, a square root transformation for the dependent variable CO<sub>2</sub> emission was applied.

### 2.7 Weather Conditions during the Study Period (2007–2009)

Since the Joenvarsisuo peatland lacked its own weather station, air temperature and precipitation figures (Fig. 2) presented here for the study period were extrapolated from data provided by the weather station at a nearby peatland, Lakkasuo (3.6 km further south), which was assumed to share similar climatic conditions. In order to compare air temperature and precipitation during the study years with long-term averages, the 30-year average monthly air temperature and rainfall from May to October 1980–2009 was calculated from



**Fig. 2.** Average monthly air temperature and precipitation sum during the study period (2007–2009) relative to long-term averages (1980–2009).

data originating from the Finnish Meteorological Institute's Hyytiälä weather station (1 km from our study sites).

### 3 Results

#### 3.1 Factors behind Regeneration Success

##### 3.1.1 Water Table Level

Relative to the soil surface (and hence planting spot position) of each microsite type, the overall effect of treatment on WTL (Fig. 3) was significant (Eq. 1, Table 1). As expected, the WTL was significantly higher in scalps than in mounds ( $p=0.008$ ) and unprepared plots ( $p=0.013$ ). While the mean WTL in scalps hovered around 7 cm below the surface, in unprepared plots and mounds it was situated at 35 and 43 cm depth, respectively. Although the mean WTL was continuously deeper in mounds than in the unprepared plots at both sites (39 vs. 29 in the Northend and 47 vs. 41 in the Southend, respectively), this difference was statistically insignificant at the 5% level ( $p=0.145$ ) likely due to the large variation amongst observations. In unprepared plots this variation was caused by the natural microform pattern (mean calculated based on WTL in low lawns, high lawns, and hummocks) and in mounds by microsite height above the original peatland surface (ranging between 16–28 cm in the Northend and 21–39 cm in the Southend). In addition, the treatment effect depended on the element of time; during drier periods (e.g., June–September 2009) the WTL in mounds extended significantly deeper than in unprepared microsites ( $p \leq 0.100$ )

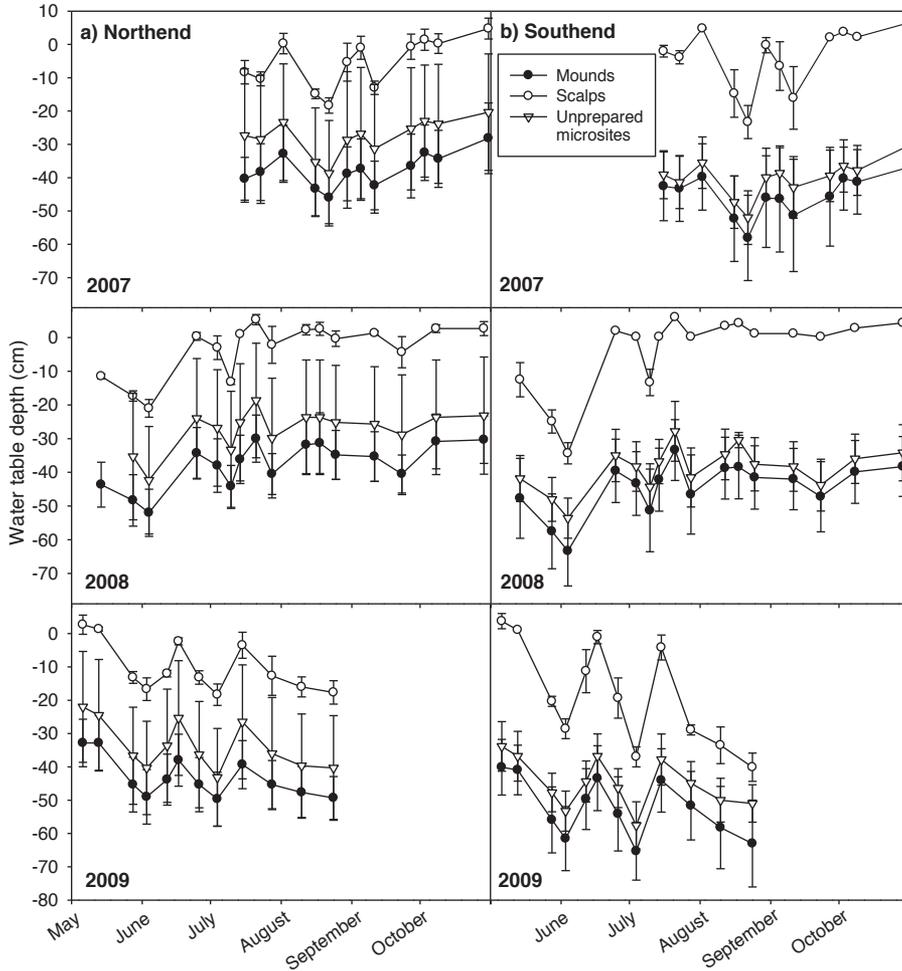
while scalps maintained their elevated WTL on every single occasion of measurement throughout the study. Despite stumbling as a main effect, site also engaged with time to statistically meaningful proportions. Notably, the between site differences in WTL manifested namely during dry, warm intervals. During practically every measurement event in 2009, the Southend WTL overall lay deeper respective to the Northend site, but only once in 2008 during the month of May, which also happened to be drier than normal (Fig. 2). In other words, when WTL reached its deepest levels overall and scalps were least plagued by excessive moisture, the between site differences in WTL became transparent.

##### 3.1.2 Soil Temperature (5 cm Depth)

The differences in soil T5 (Fig. 4) among the three treatments were insignificant (Eq. 1, Table 1). Overall across the time frame of the study, mounds were only 0.6 °C warmer than both scalps and unprepared plots, while no differences between the latter two were found. Scalps were slightly warmer by 0.5 °C than unprepared plots and mounds in the presumably wetter Northend, whereas in the Southend all treatments differed from each other with mounds being the warmest by approximately 1.2 °C over unprepared plots and 1.8 °C over scalps. Southend scalps were thus 0.6 °C cooler than unprepared plots. Additionally, soil temperatures in mounds and unprepared plots were warmer in the Southend by 1.4 °C and 0.2 °C than respective microsites in the Northend, but Southend scalps were nevertheless 0.9 °C cooler than Northend counterparts.

**Table 1.** Results of the two-way ANOVA on the effects of site, soil preparation treatment, and time of measurement on water table level (WTL), soil temperature (T5), and decomposition rate (CO<sub>2</sub>).

Source	df	WTL		T5		CO <sub>2</sub>	
		F	p	F	p	F	p
Site (S)	1	6.4	0.126	0.3	0.631	4.1	0.177
Treatment (T)	2	64.5	0.015	0.5	0.674	5.2	0.156
Time of measurement (M)	37	72.6	0.000	123.4	0.000	9.5	0.000
S*M	37	2.9	0.005	7.0	0.000	1.6	0.018
T*M	74	2.4	0.011	1.2	0.277	2.2	0.000

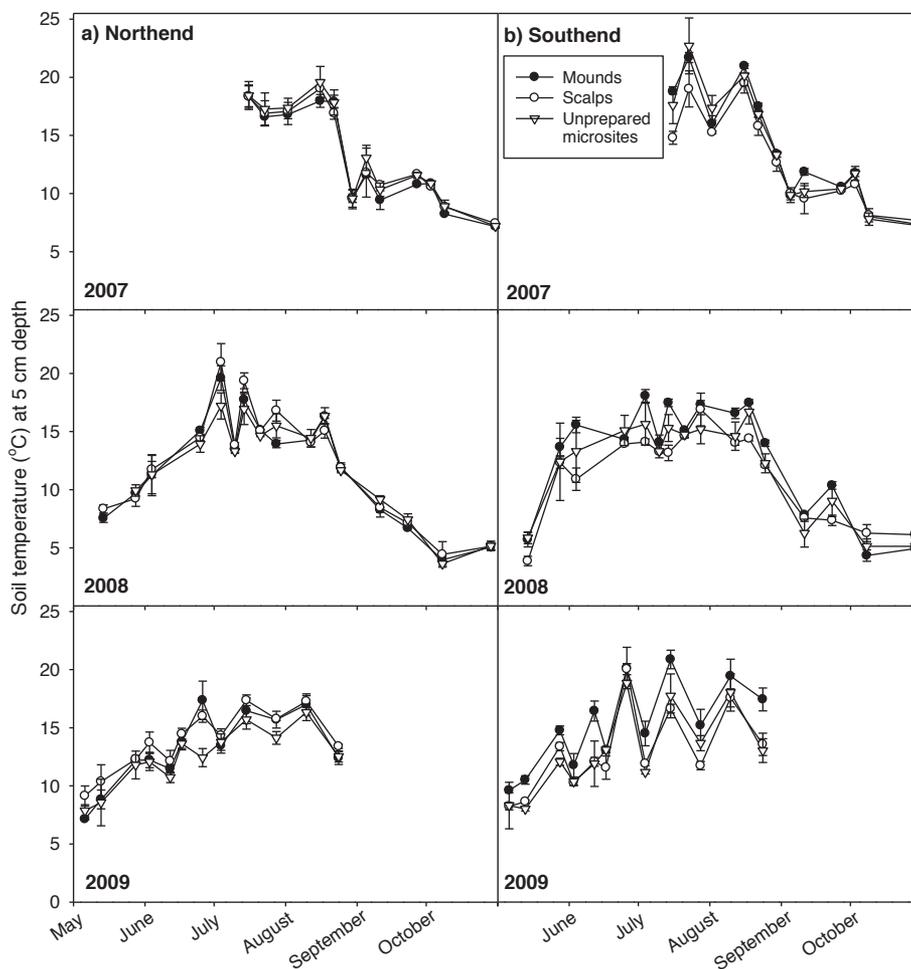


**Fig. 3.** Water table depth (WTL) according to site, treatment, and date. Each point is the mean  $\pm$  SD of three measurements. Positive values indicate that corresponding microsites were underwater at the time of measurement.

Despite the statistically inferred similarity between treatments, significant interaction between site and time of measurement was nonetheless detected. This can primarily be attributed to the Northend-Southend variation which emerged in response to the rainy and cool 2008 summer versus the drier and warmer 2009 summer. Recorded soil temperatures rose higher in the wet Northend during the cool 2008 summer, whereas in the warm 2009 summer the soil temperatures in the dry Southend rose above those observed in the Northend.

### 3.1.3 Carbon and Nitrogen Concentrations and C:N Ratio

The effect of treatment on soil C and N concentrations (Table 3) and C:N ratio (Fig. 5a–b) was highly dependent on sample depth (Eq. 2, Table 2). In the surface layers combined (0–20 cm), the C concentration significantly increased in the order of unprepared microsites, scalps, and mounds (unprepared < mounds  $p < 0.001$  and scalps  $p = 0.007$ , scalps < mounds  $p = 0.026$ ). Mounds had the lowest N concentrations over-



**Fig. 4.** Soil temperature at 5 cm depth (T5) according to site, treatment, and date. Each point is the mean  $\pm$  SD of three measurements.

**Table 2.** Results of the two-way ANOVA on the effects of site, soil preparation treatment, and sample depth on C and N concentrations and C:N ratio of OM.

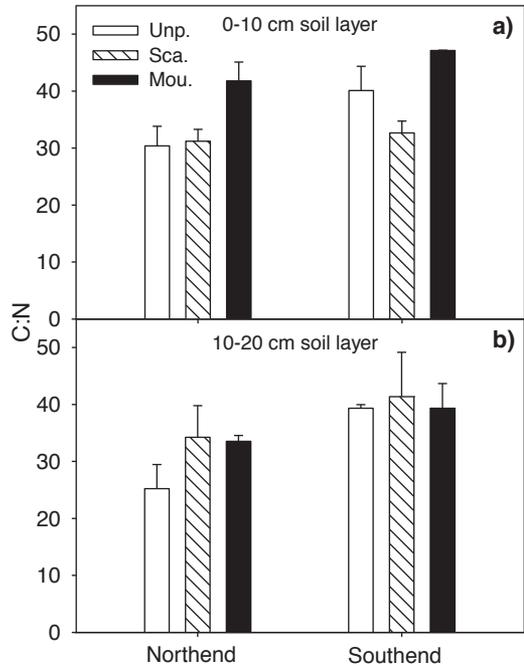
Source	df	C:N		C		N	
		F	p	F	p	F	p
Site (S)	1	9.5	0.091	1.3	0.276	4.3	0.173
Treatment (T)	2	3.1	0.244	15.9	0.000	0.8	0.548
Sample depth (D)	1	2.2	0.161	68.8	0.000	6.6	0.022
S * D	1	2.4	0.147	2.0	0.182	4.3	0.056
T * D	2	12.5	0.001	125.7	0.000	4.2	0.038

**Table 3.** Gravimetric concentrations (mg/g dry matter) of C and N in soil OM of microsites respective to subsite and sample depth (relative to microsite surface). Each mean  $\pm$  SD was calculated from three soil samples.

Subsite	C		N	
	0–10/10–20 cm	0–10/10–20 cm	0–10/10–20 cm	0–10/10–20 cm
N, unprepared	Mean	507.3/566.7	16.9/22.8	
	SD	$\pm 19.3/\pm 18.2$	$\pm 2.7/\pm 3.1$	
N, scalped	Mean	522.3/580.3	16.8/17.2	
	SD	$\pm 11.1/\pm 14.0$	$\pm 0.8/\pm 2.3$	
N, mounded	Mean	596.7/558.7	14.3/16.7	
	SD	$\pm 4.7/\pm 18.6$	$\pm 1.2/\pm 0.8$	
S, unprepared	Mean	517.0/561.3	13.0/14.3	
	SD	$\pm 9.8/\pm 10.8$	$\pm 1.4/\pm 0.1$	
S, scalped	Mean	543.3/594.3	16.7/14.7	
	SD	$\pm 13.7/\pm 12.5$	$\pm 0.7/\pm 2.7$	
S, mounded	Mean	597.0/558.0	12.7/14.3	
	SD	$\pm 2.6/\pm 16.5$	$\pm 0.1/\pm 1.2$	

all (14.5 mg/g) relative to scalps (16.3 mg/g) and unprepared microsites (16.7 mg/g) in the (0–20 cm), but the main effect of treatment was insignificant. Interestingly, the N concentration was likewise smallest in mounds at both sample depths though pairwise comparisons failed to reveal significant differences between treatments. Rather, significant within treatment differences between sample depth N concentrations were apparent; within the unprepared treatment, the deeper soil samples (10–20 cm) were significantly richer in N than the shallower ones (0–10 cm) ( $p=0.005$ ), while a similar trend was perceivable in mounds though not quite as significant ( $p=0.089$ ). Remarkably, the N concentration in mounds increased from top to bottom (most decomposed to least decomposed portion).

At sample depth 0–10 cm, the significantly greatest C concentration (> scalps and unprepared,  $p<0.001$  in both cases) as well as C:N ratio (> scalps  $p=0.029$  and unprepared  $p=0.063$ ) was held by mounds. This finding conforms to logic since this was the most decomposed portion of mounds while in other microsites the least decomposed layer. As for the 10–20 cm deep soil samples, the between treatment differences vanished with respect to C:N and N concentra-



**Fig. 5.** Soil C:N (a-b) ratios corresponding to site, treatment, and sample depth. Each bar represents the mean  $\pm$  SD of three soil samples.

tion while the C concentration of scalps did significantly exceed that of mounds ( $p=0.001$ ) and unprepared microsites ( $p=0.007$ ). Consequently, the C:N ratio also climbed highest in scalps albeit insignificantly at this depth.

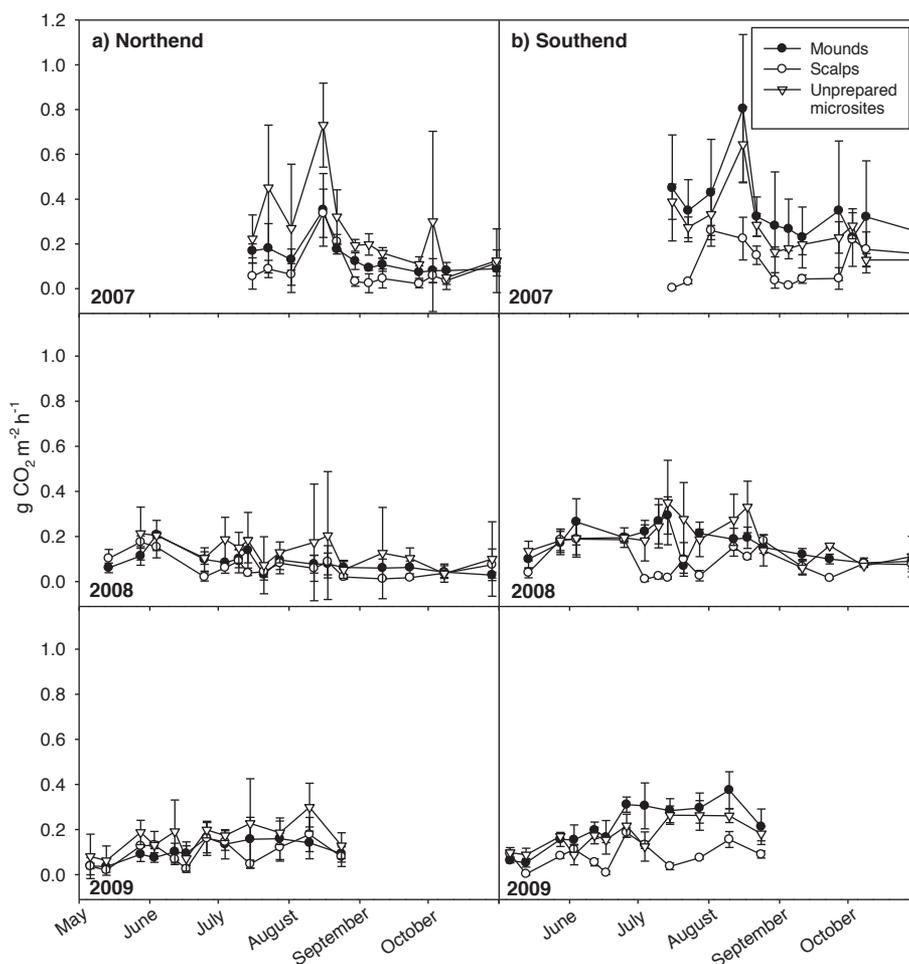
On account of lower N concentrations in mounds and unprepared microsites in the Southend compared to the Northend (mounds: 13.5 vs. 15.5 mg/g; unprepared: 13.6 vs. 19.9 mg/g; scalps: 15.7 vs. 17 mg/g), the overall C:N ratio (0–20 cm) in the Southend also surpassed that in the Northend despite falling short of significance at the 5% level ( $p=0.091$ ). Significant site and sample depth interaction for N concentration further bolstered this point; whereas sample depth negligibly influenced N concentrations in the Southend ( $p=0.738$ ), in the Northend the deeper samples held distinctly more N than the 0–10 cm ones ( $p=0.005$ ). Furthermore, Northend concentrations of N were greater than Southend counterparts at both sample depths, with the 10–20 cm layer differing most clearly ( $p=0.082$ ).

### 3.1.4 CO<sub>2</sub> Efflux Resulting from Decomposition of Organic Matter

Both the site and treatment effects on decomposition of OM interacted significantly with time (Eq. 1, Table 1, Fig. 6). Overall, scalps released the least CO<sub>2</sub> (0.09 g CO<sub>2</sub> m<sup>-2</sup> h<sup>-1</sup>) compared to mounds (0.17 g CO<sub>2</sub> m<sup>-2</sup> h<sup>-1</sup>) and unprepared microsites (0.20 g CO<sub>2</sub> m<sup>-2</sup> h<sup>-1</sup>). Scalps differed from mounds and unprepared microsites chiefly during the rainiest periods (e.g., in 2007 and 2008); consequently, the effect of treatment became evident only when coupled with time and not as a main effect. Likewise, the site effect

was insignificant alone but significant over time. The difference between sites arose especially on those occasions when between treatment differences were smallest and insignificant. On those dates, decomposition was considerably slower in the wetter Northend (0.12 g CO<sub>2</sub> m<sup>-2</sup> h<sup>-1</sup>) than the Southend (0.18 g CO<sub>2</sub> m<sup>-2</sup> h<sup>-1</sup>).

In the Northend, decomposition was fastest in unprepared plots (0.18 g CO<sub>2</sub> m<sup>-2</sup> h<sup>-1</sup>), followed by mounds (0.11 g CO<sub>2</sub> m<sup>-2</sup> h<sup>-1</sup>) and then scalps (0.08 g CO<sub>2</sub> m<sup>-2</sup> h<sup>-1</sup>). As for the Southend, scalps emitted comparatively less CO<sub>2</sub> (0.10 g CO<sub>2</sub> m<sup>-2</sup> h<sup>-1</sup>) than did unprepared plots (0.21 g CO<sub>2</sub> m<sup>-2</sup> h<sup>-1</sup>) and mounds (0.24 g CO<sub>2</sub> m<sup>-2</sup> h<sup>-1</sup>).



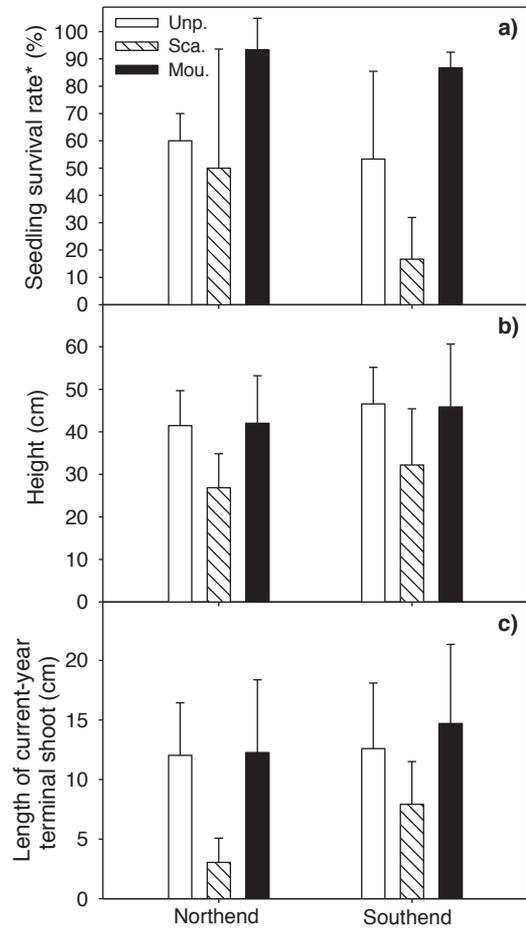
**Fig. 6.** CO<sub>2</sub> efflux resulting from OM decomposition according to site, treatment, and date. Each point is the mean ± SD of three measurements.

For the unprepared and mounding treatments, Southend emissions were higher than Northend ones. In fact, Southend mounds more than doubled the rate of decomposition in Northend mounds. Furthermore, the potential three-way interaction between treatment, site, and time of measurement, which could not be tested in this study, reflects the variability of effluxes in all treatments and sites over time due to changes in weather conditions, i.e., air temperature, precipitation, soil moisture, solar radiation at and prior to measurement. For instance, the differences between treatments (scalps emitted less than others) were equally apparent in the first study year 2007, but in 2008, the rainiest of study years, these differences were mostly indistinguishable in the Northend whereas in the Southend they continued to be commonplace particularly during the July-August period. In 2009, the trend persisted wherein between treatment differences were more apparent in the Southend.

### 3.2 Regeneration Success

#### 3.2.1 Seedling Survival Rate

The effect of treatment on seedling survival rate proved significant (Eq. 3, Table 4, Fig. 7a). Seedlings planted in mounds survived considerably better (90%) than those in the unprepared plots (57%) and scalps (33%) ( $p=0.026$  and  $p=0.001$  in the order given). No significant differences were found between scalps and unprepared microsites ( $p=0.104$ ). Respective to the planting density (2000 seedlings/ha), the indubitably low survival and large SD for outplants in scalps, in particular, can be interpreted as utterly patchy and unsatisfactory regeneration.



**Fig. 7.** Planted Scots pine (*Pinus sylvestris* L.) seedling a) survival rate, b) height, and c) length of current-year terminal leader shoot according to site and treatment. \*Survival rate based on initial planting density of 2000 seedlings ha<sup>-1</sup>.

**Table 4.** Results of the one-way ANOVA on the effects of site and soil preparation treatment on seedling survival rate (SSur), seedling height (SH), and current-year terminal leader shoot length (TSL).

Source	df	SSur		SH		TSL	
		F	p	F	p	F	p
Site (S)	1	2.0	0.178	1.6	0.203	4.1	0.044
Treatment (T)	2	9.0	0.003	6.2	0.002	18.7	0.000

### 3.2.2 Seedling Height

Seedlings planted in scalps were significantly shorter (29.5 cm) than those planted in mounds (43.9 cm) and unprepared spots (44.0 cm) ( $p=0.002$  in both cases) (Eq. 3, Table 4, Fig. 7b). The difference in seedling height between mounds and unprepared planting spots was unimportant ( $p=0.988$ ). Given that the height trend repeated itself in the Northend and Southend alike (Southend seedlings just under 5 cm taller), the site effect remained insignificant at the 5% level.

### 3.2.3 Length of Current-Year Terminal Leader Shoot

Outplants in scalps were characterized by significantly shorter current-year terminal leader shoots (5.5 cm) than those in mounds (13.5 cm) and unprepared spots (12.3 cm) ( $p<0.001$  in both cases), which were akin to each other ( $p=0.349$ ) (Eq. 3, Table 4, Fig. 7c). Also, the differences in terminal shoot length between sites elicited significance at the 5% level. Overall, terminal leader shoots were significantly longer in the Southend (11.7 cm) as opposed to the Northend (9.1 cm).

### 3.2.4 Seedling Vitality and Incidence of Damage

Of the planted seedlings found (*dead or alive*)

within circular sample plots, the vitality displayed by those in scalps was silviculturally unsatisfactory. In Northend scalps, the seedlings were diagnosed as follows: 14% weakened, 54% stunted (with a developmentally impaired future), and 32% dead (none were classified as healthy or slightly damaged). The situation in Southend scalps was equally distressing, with only 6% healthy (i.e., impact of damage undetectable), 12% weakened, 12% stunted, and a death toll of 70% (none were classified as slightly damaged). Root suffocation due to waterlogged soil combined with foraging by the European pine weevil (*Hylobius abietis* L.) caused the distress and death in seedlings growing in scalps (Table 5). It is worth noting that none of the outplants encountered in scalps had avoided damage, whether the impact was detectable or not. The vitality of seedlings planted in unprepared spots was primarily threatened by the pine weevil, but overall most of the seedlings found were in reasonably good health (Northend: 61% healthy, 17% slightly damaged, and 22% weakened; Southend: 39% healthy, 39% slightly damaged, 11% weakened and 11% dead). In our study mounding seemingly reduced pine weevil damage on peat soil relative to other treatments though it did not eradicate the problem. Seedlings in mounds often had undergone damage of an unknown source which resulted in terminal leader replacement or multiple leaders. In any case, seedlings growing in mounds typically appeared vibrant and healthy at this stage in their lives (Northend: 31% healthy, 35% slightly dam-

**Table 5.** Incidence of damage in seedlings found (dead or alive) according to cause (% of seedlings affected<sup>a)</sup>) and subsite.

Cause	Northend			Southend		
	Unprepared	Scalped	Mounded	Unprepared	Scalped	Mounded
No sign of damage	28		21	17		15
Unknown <sup>b)</sup>	11	9	38	56	12	33
Insect damage, general			3			
<i>Hylobius abietis</i> L.	56	50	31	72	76	44
<i>Retinia resinella</i> L.			3			11
Waterlogged soil	6	86			82	
Frost heaving		5	14			4
Poorly planted						22
<i>Alces alces</i> L.						11

<sup>a)</sup> In some cases, two equally damaging causes, thus the percent sum for each subsite does not equal 100.

<sup>b)</sup> Terminal leader replaced or multiple leaders prevalent in seedlings but the cause could not be determined with certainty.

aged, 17% weakened, 14% stunted, and 3% dead; Southend: 48% healthy, 26% slightly damaged, 22% weakened and 4% dead). Overall only a small minority (14%) of all the planted seedlings surveyed had evaded damage during their three years in the field; this epitomizes the challenge faced by reforestation efforts.

## 4 Discussion

### 4.1 Soil Preparation Creates Varying Hydrological Conditions

Though in theory the soil preparation methods applied in this study neither decrease nor increase the WTL as such, but rather alter the distance between the intended planting spot and WTL, they nonetheless led to a wide range of soil moisture conditions. In accordance with the first hypothesis, scalped microsites maintained a unanimously higher WTL compared to other microsite types. Given that the surface of scalps was situated approximately 10 cm below the original surface (from which they were peeled off) of the drained peatland, their ability to disperse and/or percolate surplus water was limited and slow compared to other microsite types during periods of excess rainfall and high WTLs. Especially after recent rainfall events, the WTL represented by supersurface water accumulation was normally not linked to the WTL in peat (measured from perforated tubes) at the time of measurement. In this way scalps were often sandwiched between two separate layers of water which fortified the poor aerative environment. Considering that the *Carex-Sphagnum* peat was moderately decomposed, its hydraulic conductivity was fairly slow and water retention capacity rather high (Päivänen 1982). Furthermore, the technical operation of scalping does not aim to create microsites from natural hummocks, but rather naturally flat lawn surfaces; this in itself predisposes scalps to excessive moisture risk. Thus, the assumed benefits of scalping for seedlings, such as sufficient moisture regime, reduced competition with other plants, and stable soil temperatures were undermined by wet growing seasons (Fig. 2). Even in the relatively drier 2009 growing season, WTL fluctua-

tions toward zero were still evident in both Northend and Southend scalps, which is indicative of their hydrological sensitivity. If the range of potential maintenance drainage procedures is restricted by water quality concerns associated with nearby watercourses, as in this study, then the credibility of the scalping method inevitably suffers in association with clearcutting. Higher than average rainfall only compounds the potential for regenerative failure in scalps. This finding, however, is not to discredit the suitability of the scalping method on well-drained peatland sites (Saarinen 2005).

Consistent with, e.g., Kaunisto and Päivänen (1985) and Sutton (1993), the higher position of seedlings growing in mounds provided them with favorable moisture conditions. They were unaffected by the raininess of 2008 which proved insurmountable for seedlings growing in scalps. Somewhat surprisingly, seedlings in unprepared planting spots fared tolerably despite overabundant rainfall. The elevation of unprepared planting spots (Roy et al. 1999) together with surrounding transpiring vegetation (e.g., Verry 1988) may have determined whether WTL became a survival and/or growth inhibiting factor or not in the unprepared treatment. Astonishingly, statistical testing revealed significant between site differences in WTL largely in the last summer. The main effect of site was apparently made insignificant by the raininess of the first two growing seasons, particularly 2008, the inherent WTL variation in mounds and unprepared microsites due to their variable height, and the unforeseen similarity of scalped subsites (both strikingly wet).

### 4.2 Effects on Soil Temperature

In violation of the second hypothesis, mounds were only warmest in the dry Southend, while the mean soil temperature in scalps exceeded that of both mounds and unprepared plots in the wet Northend as well as Southend scalps. However, statistical testing deemed the treatment effect trivial. The abundant moisture in scalps likely stabilized soil temperature overall (Päivänen 1982, Paavilainen and Päivänen 1995); the peat substrate neither cooled down nor heated up rapidly and soil temperatures at 5 and 30 cm (data not

shown) were typically identical on these occasions. Moisture in fact had an important role in the significant interaction between site and time of measurement for T5. Particularly during the cool and wet summer of 2008, rainy periods likely led to effective heat storage in Northend microsites, namely scalps and unprepared ones, where the WTL was always higher (though the differences lacked significance in 2008) than in the Southend.

The warming of peat soil associated with mounding was far from conclusive here. While cool dismal summer weather influenced these results, soil heat capacity and thermal conductivity do vary depending on the microsite in question (e.g., Balisky and Burton 1995, Paavilainen and Päivänen 1995), hence the response of soil T5 to the concurrent air temperature (and weather) at the time of measurement was not necessarily immediate but rather delayed. Certainly, antecedent weather conditions played an important role. On a cautionary note, the significant two-way interaction between site and time of measurement may in part be due to logistical constraints. On every other occasion of measurement, the Northend plots were measured in the morning and Southend ones in the early afternoon, and vice versa. T5 results are thus slightly biased regarding the time factor for morning and afternoon air temperatures do influence soil T5 particularly during the June–August period on clear days (e.g., the Southend significantly warmer every other measurement day when measured in the afternoon), although the specific dynamics of this relationship will depend on individual microsite properties.

On a further note, we must draw attention to an issue related to the margin of error of the soil temperature measuring device. Despite the significance of differences in soil temperature found through statistical testing (site \* time), these differences nonetheless lie within the device's margin of error. Since the error involved is random, it will decrease as the number of temperature observations increase. Every plot was measured 40 times, which altogether means 720 soil temperature observations over the duration of the study. We believe this to be sufficient. Moreover, the lack of significant differences between treatments may likewise be indicative of the overriding effect of soil moisture over soil temperature during the

study; soil moisture level, not soil temperature, was the decisive factor for both the regeneration success and OM decomposition observed in the various microsite types.

### 4.3 Effects on Carbon-to-Nitrogen Ratio

In congruence with the third hypothesis, soil preparation did indeed affect the C:N ratio of the soil surface layer (0–20 cm). Relative to the C:N ratio of the soil in the unprepared treatment, however, the benefits of mounding and scalping remained truly ambiguous. For instance, on the whole mounding succeeded in reducing the N concentration in the surface peat and increasing the C:N ratio, which contradicts previously presented inferences on the subject (Kaunisto and Päivänen 1985, Sutton 1993). N concentrations generally increase towards deeper peat layers and with the degree of decomposition on oligo-ombrotrophic sites (e.g., Kaunisto 1982, Laiho et al. 1999), and this should have brought higher concentrations on the top of mounds. On the other hand, Laiho et al. (1999) also showed the difference in N concentration between the topmost and deeper peat layers to decline as the time since (initial) drainage increased on oligo-ombrotrophic sites. In their study the oldest drainage age class was between 41–55 years, whereas our sites were considerably older having been drained already 78 years ago. Thus, the declining trend they observed may have been even more apparent here, shown as the N enrichment of the topmost peat (now upturned). Depending on the effectiveness of drainage in different parts of the peatland, peat subsidence and hence the thickness of the N enriched layer may also vary (Laiho et al. 1999). Overall, the effect of soil C:N on regeneration success in this study was negligible. Since the pine seedlings were just 4 years old when surveyed, their nutritional demands had likely yet to be challenged by the scarcity of available nitrogen in their growing spots, whether prepared or not.

### 4.4 Effects on Decomposition Rates

Though the experimental design of our case study precluded any testing of interplay between site

and treatment, the response of OM decomposition to mounding after clearcutting was nevertheless slower than (Northend) or equal to (Southend) the unprepared treatment. Contrary to the fourth hypothesis, mounding thus failed to accelerate OM decomposition relative to the unprepared treatment, which is congruent with the findings of Mojeremane (2009) from afforestation sites on peaty gley soils. Primarily due to the adverse effects of waterlogging in scalps, microbial respiration was hindered and thus CO<sub>2</sub> emissions were comparatively lowest. This in spite of scalps being the warmest microsites in the Northend. Anoxic conditions have been found to result already after 3–5 days of water saturation (Mausbach and Richardson 1994), although Zak and Gelbrecht (2007) observed that the lowering of the redox potential of peat resulted in anoxia only after 10–20 weeks in waterlogged conditions associated with fen rewetting. In any case, excess moisture apparently nulled any positive effect of increasing soil temperature on OM decomposition, and this observation agrees with Hogg et al. (1992) who found higher temperatures to have a negligible effect on decomposition of continuously flooded peat samples. Water tables have also been shown to control the emission of CO<sub>2</sub> by regulating the O<sub>2</sub> supply to decomposer microflora in soils with thick organic layers at high latitudes (e.g., Moore and Dalva 1993, Davidson et al. 1998). On the same site types as ours, Mäkiranta et al. (2010) similarly concluded that clearcutting reduced the decomposition rate of peat soil due to a rise in the WTL, which also offset the clearcutting-induced increase in mean soil temperature.

One explanation for the unexpected observed rates of OM decomposition in mounds and unprepared plots may be the difference in their C:N ratios (e.g., Enríquez et al. 1993). Higher C:N ratios are generally understood to limit decomposition due to a shortage in available nitrogen and an abundance of recalcitrant material. In this study, the smallest C:N ratio (and greatest N concentration) was in fact linked to the fastest rate of decomposition in the Northend (unprepared microsites), and similar C:N ratios (and N concentrations) led to equal rates of decomposition in the Southend (unprepared microsites and mounds). However, when dealing with recalcitrant OM, carbon quality has been shown to be an important

determinant of decomposition rate (e.g., Melillo et al. 1982, Prescott et al. 2000) and in some cases the lignin concentration or lignin:N ratio may be a better predictor than N concentration or C:N ratio (e.g., Melillo et al. 1982).

Another potential explanation has to do with the location of the most readily decomposable OM relative to the WTL from the aspect of aerobic fungi and bacteria. In pure, unmixed peat mounds, the best quality substrate for microbial decomposition is buried underneath. Conversely, the upper portion of mounds consists of more decomposed OM, i.e., old recalcitrant carbon. Hogg et al. (1992) found that old, deeper peats are resistant to decay despite exposure to warmer, aerobic conditions; this would also appear to be the case in the mounds studied here. Additionally, burying of the newer carbon into a low oxygen environment close to the water table at the bottom of mounds may explain why mounding did not accelerate decomposition relative to the unprepared treatment; the newer carbon in unprepared plots enjoyed better soil aeration. Mojeremane (2009) previously identified a low oxygen situation at the bottom of mounds which restricted decomposition. Furthermore, Smith et al. (2003) stressed the importance of soil aeration and water content in controlling the diffusion of CO<sub>2</sub> through soil into the atmosphere. In our case, CO<sub>2</sub> had to travel from the poorly aerated mound bottom through the denser, recalcitrant peat summit. Hence, the conditions for gas diffusion were less than ideal. Considering that the sleeved collars were inserted into the ground just one month before the start of the measurement campaign, cut, dying roots may partially account for the magnitude of CO<sub>2</sub> effluxes in 2007 (Minkinen et al. 2007). On the other hand, the fast decrease in peak effluxes in 2007 (Fig. 6) which occurred in all treatments and sites could indicate that the readily processable OM had been quickly consumed by microbes (Prescott et al. 2000).

The unique hydrological behavior of our study sites was also reflected in the special manner by which treatment or site interacted with the temporal element. Whenever between treatment differences in OM decomposition became significant, i.e., scalps emitted the least CO<sub>2</sub>, which typically occurred during wet and cool periods, site interaction with time was accordingly indistinguishable.

Oppositely, whenever drier spells materialized (e.g., in 2009), site and time together displaced the combined treatment-time effect on OM decomposition. Consequently, Southend emissions clearly exceeded those from the Northend while between treatment differences disappeared. Interestingly, the nature of this interactive effect of site\*time for CO<sub>2</sub> was equally matched by that for WTL – dry, warm weather emphasized the role of site. Hence, based on the results of this study, the importance of considering WTL when quantifying the rate of OM decomposition, even in drained sites, should not be forgotten.

Regarding the method we used for determining CO<sub>2</sub> emission, one drawback of the chamber technique is that any coupling or priming effect of vegetation on OM decomposition is lost (Kuz'yakov 2002) due to the necessary removal of the autotrophic component. However, this methodological shortcoming for determining heterotrophic soil respiration has yet to be resolved, and in the absence of a less intrusive method, we must rely on the results produced employing the dominant technique of the day.

#### 4.5 Seedling Survival, Growth, and Vitality

Contrary to the fifth and final hypothesis, the benefits of mounding at this life stage of the pine seedlings were restricted to better survival compared to those growing in unprepared spots. Furthermore, outplants in scalps underachieved on all scales even compared to the unprepared treatment. Thus, the widely held presumption (i.e., the motive for applying mounding) in peatland forestry, at least in Finland, that mounding accelerates (pine) seedling growth compared to leaving soil unprepared (Mannerkoski 1975, Kaunisto 1984) was impugned at least by this study. Though their studies were carried out on similar site types, the pine seedlings they used were slightly older when planted (2–3 years old) and thus also upon surveying (5–7 years old) than those in our study (1 year old when planted, 4 years old when surveyed).

Although the benefits of soil preparation in reducing pine weevil damage to tree seedlings have been recognized namely on mineral soils (von Sydow 1997, Hånell 1993, Heiskanen

and Viiri 2005), soil preparation in the form of mounding reduced the risk of damage to planted seedlings caused by the European pine weevil on (wet) organic soil in our study. Despite the lower survival rate compared to seedlings in mounds, the regeneration situation did not present itself as being troublesome in the unprepared treatment since seedlings of both natural and artificial origin complemented each other. In fact, the lack of differences in height, terminal leader shoot length, and vitality between seedlings growing in mounds and unprepared spots would seem to indicate relatively equal growing conditions. Careful consideration of microrelief, peat characteristics, species, and local climate prior to planting may improve the survival rate in unprepared peatland forest regeneration sites as suggested by Roy et al. (1999). On the other hand, *Hylobius abietis* heavily taxed seedling survival in the unprepared treatment (Table 5) and this is indubitably of concern when evaluating the success of regeneration.

In scalps, the worst case regeneration scenario became concretized. Excess moisture in scalps particularly in 2008 proved fatal to seedlings. The few survivors left at the time of the survey remained stunted. In the same way as with overall height, excess moisture stress led to significantly shorter terminal shoots in seedlings growing in scalps compared to mounds and unprepared spots. Given the young age (and small size) of the seedlings and the limitations of the drainage network, the timing of the surplus rainfall (2008 growing season) could not have been any worse; as seedlings grow, their demand for water and transpiration increase, gradually becoming less sensitive to intermittent standing water. Here, however, the seedlings in scalps had barely expanded their root system from the peat pot when forced to surrender. The results of this study confirm the dangers associated with insufficient drainage in clearcut peatland forest regeneration areas; in such circumstances, soil C:N ratio, temperature, and decomposition rate are simply secondary factors. As seen here, soil preparation to promote stand regeneration is far from cost-effective if surplus water cannot be expelled, thus identification of vulnerable sites is an absolute necessity if the intention is to continue practicing forestry in deep-peated forest regeneration areas in the future.

## 4.6 Conclusions

In this case study, excess moisture dictated the results on regeneration success of planted Scots pine. Despite ditch maintenance and soil preparation, exceptionally wet post-clearcutting growing seasons can exacerbate the regeneration situation in hydrologically sensitive, ditched clearcut sites on deep peats. Mounding only led to a superior outplant survival rate, whereas early seedling growth was not better in mounds compared to unprepared spots which is contrary to what was hypothesized. Scalping could not provide seedlings with the basic requirement for survival in deep peat soils, i.e., well-aerated growing spots. Therefore, scalping should not be applied at least in such sites as these characterized by excessive moisture risk, and definitely not before ensuring an adequate degree of drainage in a given peatland forest regeneration site. Furthermore, as a soil preparation method scalping clearly needs further development aimed at reducing susceptibility to “watering up”. By adjusting scalp depth and inclination (and planting position), for instance, it may be possible to prevent scalps from becoming seedling swallowing reservoirs. WTL certainly appears to be the single most important regulating factor during the early development of pine outplants in hydrologically sensitive peatland forest regeneration areas. Finally, our results indicate that the soil preparation methods employed here on these types of deep-peated sites do not intensify CO<sub>2</sub> emissions from soil OM to the atmosphere compared to leaving soil unprepared. This observation radically conflicts with earlier conceptions of the matter, but further research is necessary to dissect the processes behind this phenomenon and reveal the underlying causes.

## Acknowledgements

Funding for this study was generously provided by the Finnish Cultural Foundation, Research Foundation of the University of Helsinki, Maj and Tor Nessling Foundation, and GSForest - Graduate School in Forest Sciences. We are also grateful to Janne Levula and Silja Pirttijärvi at Hyytiälä Forestry Field Station for their operational assistance.

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