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Effect of nursery storage and site preparation techniques on field performance of high-elevation *Pinus contorta* seedlings

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ABSTRACT

After five years of growth at high-elevations (~3000 m) in Utah, container lodgepole pine (*Pinus contorta* Dougl. var. *latifolia* Engelm.) seedlings survived well (80–95%) and grew to similar heights regardless of nursery storage method and site preparation technique. Seedlings received one of three storage treatments: (1) spring-sown in the nursery, overwintered in cooler storage and outplanted in July; (2) spring-sown, overwintered in freezer storage, and outplanted in July; or (3) winter-sown, no storage, and hot-planted in late August. We outplanted seedlings at two locations that were clearcut and had received two treatments of surface organic matter (coarse wood, logging slash, and forest floor) removal: surface organic matter (OM) piled with a bulldozer and burned or surface OM remaining *in situ*. Compared to adjacent uncut stands, both site preparation treatments increased total soil bulk density, but retaining surface OM *in situ* maintained soil OM, carbon, and nitrogen levels. After one growing season, seedlings planted where surface OM had been bulldozed were taller and had more biomass, although survival was similar (≥96%) across site preparation treatments. The height growth advantage disappeared after five growing seasons and although overall survival was good, survival was highest where site preparation involved removal of surface OM and freezer-stored seedlings were planted. Total non-structural carbohydrates tended to be higher in roots than in shoots and were also higher in hot-planted seedlings than in stored seedlings. Our results indicate that nursery and forest managers have several options for successful nursery production and outplanting of container lodgepole pine seedlings in the central Rocky Mountains. Using hot-planted seedlings allows for a faster turnaround time (from seed to plantable seedling) and maintaining surface OM may be a cost-effective alternative to dozer piling and burning.

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1. Introduction

Following harvest operations site preparation is often used to create seedbeds for natural regeneration. Lodgepole pine (*Pinus contorta* Dougl. var. *latifolia* Engelm.) is widespread in the coniferous forests of high-elevation sites in the western USA and is often the species of choice for reforestation. Natural regeneration can be delayed on sites that have a poor seed year at time of harvest, have low soil moisture, ectomycorrhizal inoculum, fertility, or temperatures (Bradbury et al., 1998; Fleming et al., 1998), or when seed predation is high (Page-Dumroese et al., 2002). In such cases, artificial regeneration of lodgepole pine may be used, but success of plantings can be highly variable because of effects of container shape, nursery conditions, storage regime, and/or planting site conditions (van den Driessche, 1991; Balisky and Burton, 1997; Jones et al., 2002). Recently, more emphasis has been placed on planting directly into the surface organic matter (coarse wood, logging slash, and forest floor [which includes all surface organic horizons]) remaining on the site to reduce planting costs, reduce erosion, and lessen compaction associated with mechanical treatments (Heineman, 1998; Campbell et al., 2006).

Survival and growth of outplanted conifer seedlings at high elevation is dependent on seedling quality and soil microsite conditions (Balisky and Burton, 1997; Folk and Grossnickle, 1997). Depending on soil surface conditions, temperature extremes can occur for years after harvest, affecting soil biotic and abiotic processes (Balisky and Burton, 1997; Fries et al., 1998). In some areas, microclimate and soil surface properties may be the

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principal factor in determining successful regeneration on many high-elevation sites (Fleming et al., 1998).

Removing the forest floor prior to seedling outplanting has been used extensively (Sutton et al., 1991; Page-Dumroese et al., 1997; Orlander et al., 1998), and is one method used to increase soil temperature in the root zone (Delong et al., 1997), increase available water or nutrients (Radwan, 1992), and decrease herbaceous competition (Simard et al., 2003). These alterations in microsite conditions have been shown to be either favorable (Miller et al., 1989; Fleming et al., 1998; Miller and Anderson, 2002) or, in some cases, limiting (Greacen and Sands, 1980; Powers, 1991) to seedling growth.

In addition to having appropriate microsite conditions, seedling quality also influences seedling survival and growth. As part of traditional nursery production in the northwestern USA, dormant cold-hardy seedlings are stored under refrigeration either in coolers (1–2 °C) or freezers (−1 to −2 °C) to maintain seedling quality until outplanting (reviewed by Camm et al., 1994). On high-elevation sites the planting season is generally short and occurs in summer (June and July) compared to spring planting (March–May) for lower-elevation sites (Revel et al., 1990). Therefore, seedlings harvested at the nursery during the optimum window to preserve seedling quality (December and January; *e.g.*, Ritchie et al., 1985) may need to be stored for 6–7 months if outplanted at high-elevations, instead of 3–4 months for lower elevation sites. During storage, seedlings continue to respire and consume carbohydrates (Wang and Zwiazek, 1999), lose cryoprotectants (Ogren, 1997), can be exposed to detrimental fungi (Sutherland et al., 1989), or suffer other reductions in quality during thawing prior to outplanting (Kooistra and Bakker, 2002, 2005), all of which can reduce overall seedling establishment success (McKay, 1997). Seedlings use total non-structural carbohydrates (TNC) as an energy source during storage. One advantage of a high TNC content is the ability to buffer seedlings from environmental stresses (*e.g.*, low light, cold temperatures) and improve survival (Kobe, 1997). While seedlings may enter cooler- or freezer-storage with 15–20% dry weight TNC, they can lose at least half of their TNC reserves by outplanting. This loss of TNC could negatively affect growth during the first year (Ritchie, 2004).

Harvesting seedlings at the nursery and shipping them directly to the outplanting site is one way to avoid problems associated with storage. In general, container seedlings can be planted outside the traditional spring planting window (*i.e.*, summer and fall) whenever soil moisture and temperature levels are conducive for survival (Revel et al., 1990; Adams et al., 1991; Fredrickson, 2003; Luoranen et al., 2005), seedlings have at least some level of hardening, and seedling growth specifications are met (Rose et al., 1990; Landis and Dumroese, 2006). This allows nursery managers and foresters greater flexibility in planning reforestation programs, especially on high elevation sites where snow persists into summer, and when budgetary constraints hamper regeneration activities (Barrows, 2006). In Sweden, outplanting date had little effect on either survival or growth of first-year Norway spruce (*Picea abies* L.) container seedlings (Luoranen et al., 2005).

This is the first evaluation of hot-planting seedlings in the western USA, where little is known about lodgepole seedling storage regimes and the importance of retaining residual surface organic matter (OM) for establishment and survival in high-elevation forests. Therefore, we had two objectives: (1) compare the effects of two site preparation techniques (residual surface OM [coarse wood, logging slash, and forest floor] left *in situ* versus residual surface OM piled with a bulldozer and burned) on soil chemical and physical properties compared with an adjacent uncut stand; and (2) compare, after one and five years of growth, subsequent survival and growth of seedlings stored under three regimes and outplanted into different operationally installed site preparation treatments.

2. Methods and materials

2.1. Site description

Our study was located on the Ashley National Forest, Roosevelt Ranger District, in the Unita Mountain Range of northeastern Utah, USA. The first location (Pole Mountain) was at an elevation of 3012 m (longitude −110.038; latitude 40.609) and the second location (Hicks Park) was at an elevation of 2919 (longitude −109.735; latitude 40.745). Both 100-ha locations have similar aspect (north) and soil (loamy-skeletal, mixed, Oxyaquic Cryoboralfs weathered from a quartizite parent material), and had a similar overstory (*Pinus contorta* Dougl. var. *latifolia* Engelm.; 2401 trees ha^{-1}; trees were about 150 yr old, 18 m tall, 31 cm dbh) and understory (*Vaccinium scoparium* Leiberg) vegetation prior to harvest. Soil coarse-fragment content ranges from 10% to 55% with scattered bedrock outcroppings, and the texture of the fine-fraction is fine-loamy (Soil Survey Staff, 2003). Mean annual precipitation is 191 cm with snowfall comprising 81% of the total (Western Regional Climate Center, 2005). Mean air temperature for January is −6 °C and 21 °C in July.

2.2. Study design

On half of each location (50 ha) in August 1994, overstory trees were directionally hand-felled toward a skid trail and moved to a landing with a D-8 Caterpillar® bulldozer, resulting in a clearcut. The remaining adjacent 50 ha served as an uncut control for comparison of site preparation treatments on soil physical and chemical properties. In July 1995, the clearcut portion of each location was randomly divided into two operationally installed site preparation treatments: (1) piling all surface OM using a D-8 Caterpillar® bulldozer; and (2) leaving the surface OM *in situ*. Within each location and site preparation combination (excluding the uncut control) we planted three subplots of seedlings. Each subplot contained 20 rows of seedlings. Each row was comprised of three seedlings from each of three nursery storage methods (described below), systematically clustered down the row on 1 m (within rows) and 2 m (between rows) spacing. Therefore, we planted 540 seedlings per location-site preparation combination.

2.3. Soil sampling

To meet our first objective of comparing the effects of post-harvest site preparation techniques on soil chemical and physical properties, we measured soil bulk density at three randomly selected points within each planting subplot and nine randomly located points within the adjacent control stands. Bulk density was measured to a depth of 30 cm using a foam-excavation technique. This method and the calculation of fine-fraction bulk density are outlined in Page-Dumroese et al. (1999). Soil from the bulk density samples was dried at 105 °C, weighed, passed through a 2-mm sieve, and used for chemical analysis. Soil OM concentration was determined by weight loss after combustion at 375 °C for 16 h (Ball, 1964), and soil carbon (C) and nitrogen (N) concentration measured by inductively coupled furnace (LECO Corp, St. Joseph, MI, USA). Total soil OM, C, and N contents were calculated to a hectare basis using soil fine-fraction bulk density values (Cromack et al., 1999). In the center of one randomly selected subplot of each site preparation technique at each location, we measured soil temperature at the 10 cm soil depth (about half of the seedling plug depth) every 4 h for the first year of the study using a HOBO®

Tidbit (Onset Computer Corp., Bourne, MA, USA). We also placed temperature probes in one subplot in the adjacent uncut control stand.

2.4. Seedling storage and outplanting

To meet our second objective, we grew seedlings and stored them using refrigerated storage methods (cooler and freezer), and hot-planting (not stored).

2.4.1. Cooler- and freezer-stored seedlings

On 3 March 1997, we sowed 1000 Ray Leach Cone-tainers™ (66 cm^3, 2.5 cm diameter, 15 cm deep, 1076 cells m^{-2}; Stuewe & Sons Inc., Corvallis, OR, USA) at the University of Idaho Forest Research Nursery greenhouse in Moscow, ID, USA (longitude −116.999; latitude 46.732) with seeds collected from each location before harvesting. Experiment seedlings were surrounded by buffer seedlings and the cultural regime followed standard practices (Wenny and Dumroese, 1987, 1994). During the initial growth phase, seedlings were fertigated with Peters® Professional Conifer Starter™ (7N:40P_2O_5:17K_2O) each time containers weighed 80–85% of field capacity weight; the total irrigation amount for each fertigation was determined gravimetrically according to White and Marstalerz (1966). During the rapid growth phase, we used exponential fertilization (based on Timmer and Aidelbaum, 1996) during fertigation. Using the equation $N_T = N_S\ (e^{rt} - 1)$ where a target N_T (final N content of the seedling) = 30 mg, N_S (initial N content) = 0.5 mg, and t = 34 (2 fertilizer applications each week for the 17 week rapid growth phase), we calculated a relative addition rate (r) of 0.10922. For each fertigation, we used $N_T = N_S\ (e^{rt} - 1) - N_{t-1}$ (where N_T is the amount of N to apply at each of the 34 applications, N_{t-1} is the cumulative amount of N applied, and t goes from 1 to 34) to determine the amount of fertilizer to add to the irrigation water. We fertigated with Peters® Professional Conifer Grower™ (20N:7P_2O_5:19K_2O) during the first application each week and liquid ammonium calcium nitrate (17N:0P_2O_5:0K_2O) during the second application each week, calculating when to fertigated and total volume of solution as described above. During hardening, seedlings were fertigated with an alternating rotation of Peters® Professional Conifer Finisher™ (4N:25P_2O_5:35K_2O) and liquid ammonium calcium nitrate when container weights were 70–75% of field capacity weight. For the 9-month nursery cycle, seedlings received an average of 1.3 mg N per week of fertigation (31 mg N).

In mid-December 1997, seedlings were irrigated to field capacity, pulled from their containers and sealed inside cardboard boxes lined with a 1.5-mm plastic bag (400 seedlings per box). Similar to industry standards, seedlings <7.5 cm tall or <2.3 mm in root-collar diameter (RCD) or with insufficient roots to hold a root plug were culled. Half of the seedlings were placed into cooler storage (1–2 °C) at the University of Idaho nursery, while the remaining half were freezer-stored (−1 to −2 °C) at the nearby USDA Forest Service Coeur d'Alene Nursery, Coeur d'Alene, ID, USA. In July 1998, seedlings were driven to Utah and within 3 days of removal from storage were outplanted within each subplot within the two site preparation treatments (OM retained *in situ*; OM bulldozed). At each location, seedlings were dibble-planted in all subplots on the same day. Locations were planted on consecutive days. After outplanting, seedlings were measured for initial height and RCD.

2.4.2. Non-stored (hot-planted) seedlings

To ensure sufficient growing time and to meet our projected September outplanting date for this stocktype, seeds were sown on 5 January 1998. As in 1997, seedlings were grown with the same seed sources, container type, fertilizers, fertigation techniques, and cultural conditions to achieve a similar target height as the seedlings grown the previous year and already in storage. For the 8-month nursery cycle, seedlings received an average of 1.3 mg N per week of fertigation (26 mg N). One month before outplanting, seedlings were transferred from the greenhouse to a shadehouse for hardening as described above. In August 1998, seedlings were removed from the shadehouse, driven to Utah, and within 3 days of removal from storage were outplanted within each subplot as described above.

2.4.3. Measurements the first spring after outplanting

Just after snow melt in late June 1999, we randomly selected three seedlings of each storage treatment from each combination of location, site preparation, and subplot (n = 36). Seedlings were carefully excavated by hand, placed in a zip-lock-type plastic bag, and transported in a cooler to our laboratory. Stored seedlings were 28 months old (9 months in the nursery, 7 months in storage, 12 months on the site) and hot-planted seedlings were 18 months old (8 months in the nursery, 10 months on the site) when sampled. Before excavating, we evaluated seedling microsite in a 1-m diameter circle around each seedling by estimating the percentage coverage of grass, shrubs (>0.5 m tall), mineral soil exposed, surface rocks, forest floor (all surface organic horizons), and decayed and intact wood. Microsites were evaluated by the same person to maintain consistent estimates. Seedling survival for each combination of location, site preparation, storage technique, and subplot was calculated by dividing the total number of live seedlings by the total number of outplanted seedlings in each subplot.

In the laboratory, seedlings were measured for total height (cm), RCD (mm), and shoots were separated from roots. Roots were gently washed to remove adhering nursery and native soil, ectomycorrhizal root tips were counted (Harvey et al., 1996), and root volume measured by water displacement (Burdett, 1979). After drying to constant mass at 60 °C, shoots and roots were weighed. Total seedling non-structural carbohydrates (TNC) were analyzed following the procedures outlined in Jones et al. (1977). Glucose concentration was quantified colorimetrically and adjusted to seedling starch concentration (dry matter) using a hydrolysis factor of 0.9 (Volenec, 1986).

2.4.4. Measurements after five shoot elongations

After seedlings completed five shoot elongations on the outplanting locations (late September 2002 and 2003 for stored and hot-planted seedlings, respectively), height and RCD were measured on all remaining seedlings; this was the basis for determining 5-yr survival.

2.5. Data analysis

Data were analyzed using SAS (version 9, SAS, Institute Inc., Cary, NC, USA). We used ANOVA after ensuring homogeneity of variance, to evaluate our predictor variable (site preparation) on seven soil response variables (temperature, OM, C, N, rock-fragment content, and total and fine fraction bulk density). The models evaluated were of the form:

$$\text{Response} = \boldsymbol{L} + T + \boldsymbol{L * T} + \textbf{Subplot}(\boldsymbol{L * T}) + \textbf{Error}$$

where L = location and T = site preparation treatment. Bold terms are random effects in the models.

Soil temperature for each site preparation treatment (uncut, OM bulldozed, OM *in situ)* was summarized by calculating mean monthly temperature. Differences between site preparation

Table 1
Average mineral soil characteristics (0–30 cm depth) of two site preparation treatments and an uncut stand from two lodgepole pine locations in northeastern Utah

Variable	Undisturbed stand	Surface organic matter retained *in situ*	Surface organic matter bulldozed
Organic matter (Mg ha^{-1})	76 (4) a	70 (3) a	64 (5) b
Carbon (Mg ha^{-1})	45 (6) a	38 (5) a	27 (5) b
Nitrogen (kg ha^{-1})	1364 (20) a	1327 (21) a	1246 (30) b
Total bulk density (Mg m^{-3})	1.52 (0.04) a	1.71 (0.05) b	1.94 (0.06) b
Fine fraction bulk density (Mg m^{-3})	1.35 (0.03) a	1.42 (0.02) a	1.83 (0.05) b
Rock-fragment content (%)	30 (5) a	42 (5) b	44 (6) b

Values are an average (S.E. in parentheses) of two study locations. Within rows, soil properties with the same letter are not significantly different ($p \leq 0.05$) by Tukey's studentized range test. *Surface Organic Matter* was comprised of coarse wood, logging slash, and forest floor (all organic horizons).

Table 2
Surface soil cover characteristics after site treatment on two lodgepole pine locations in northeastern Utah

Treatment	(% Soil surface coverage)							
	Forest floor	Intact log	Decayed log	Stump	Grass	Shrub	Mineral soil	Rock
Surface organic matter retained *in situ*	80	5	6	3	21	1	6	15
Surface organic matter bulldozed	36	1	1	1	15	1	54	21

Cover percentages in each site preparation treatment can total more than 100% as variables overlap. *Surface Organic Matter* comprised of coarse wood, logging slash, and forest floor (all organic horizons).

treatments were tested using analysis of variance with repeated measure (ANOVAR).

We used PROC MIXED, after ensuring that the sphericity assumption was met, to perform a split plot analysis of site preparation technique (whole plots) and seedling storage technique (split plots) on seven seedling response variables (height, RCD, root and shoot biomass, root volume, ectomycorrhizae per gram of dry root, and TNC). Seedlings were treated as individual measurements. The models evaluated were of the form:

$$\text{Response} = \boldsymbol{L} + T + \boldsymbol{L} * \boldsymbol{T} + \textbf{Subplot}(\boldsymbol{L} * \boldsymbol{T}) + S + T * S + \textbf{Experimental Error} + \text{Planting Cluster} + \textbf{Seedlings}(\boldsymbol{L} * \boldsymbol{T} * \boldsymbol{S}) + \textbf{Subsampling Error}$$

where L = location, T = site preparation treatment, and S = storage treatment. **Experimental Error** is specified as **L*S + L*T*S**. Bold terms are random effects in the models.

When F-tests were significant at $p \leq 0.05$, we used Tukey's studentized range test to separate the means (Zar, 1999). Except for survival data, no transformations were required.

Seedling survival was analyzed using a multiple nominal logistic regression model that addresses the binomial distribution of the errors by applying a logit transformation (Trexler and Travis, 1993). The response variable for survival was the percentage of all planted seedlings alive at the end of year 1 and 5.

3. Results

Location had no effect on soil properties. Total bulk density values did not differ between the two site preparation treatments (piling surface OM [coarse wood, logging slash, and forest floor] using a bulldozer and burning or leaving it *in situ*). These site preparation treatments did, however, result in significantly higher (22% and 12%, respectively) bulk densities than the adjacent uncut stands (Table 1). Similar results were observed for rock fragment content (Table 1). The bulldozer reduced surface OM after timber harvesting, resulting in more microsites devoid of surface OM (Table 2). Reduction of surface OM did cause significant declines in mineral soil OM, C, and N contents (Tables 1 and 2), but leaving organic materials *in situ* maintained soil C, N, and OM levels at levels similar to the adjacent uncut stands. Neither site preparation treatment had an affect on soil temperature at the 10-cm depth (about midpoint of the seedling plugs) the first year following outplanting, nor were the treatments significantly different ($p \geq 0.1$) from the uncut (control) stands (Fig. 1).

The average seedling heights and RCDs of all three nursery treatments were similar ($p = 0.17$) when outplanted (height = 9.6 cm, RCD = 2.50 mm). Location had no effect on seedling parameters the spring following outplanting or after five growing seasons (Table 3). Site preparation, however, did significantly influence seedling height, shoot biomass, and TNC the spring following outplanting, whereas survival, RCD, root biomass, root volume, and ectomycorrhizae were unaffected (Table 3). Seedlings growing where surface OM was bulldozed were about 8% taller, had about 20% more total biomass (Table 4), and contained about 15% more shoot TNC and 39% less root TNC (Fig. 2) than their cohorts growing with *in situ* surface OM. After five growing seasons, heights (OM *in situ* = 33.1 cm; OM bulldozed = 33.7 cm) and RCDs (OM *in situ* = 11.8 mm; OM bulldozed = 13.8 mm) of seedlings were similar regardless of site preparation treatment (Table 3). Storage treatment significantly affected every seedling parameter except survival and ectomycor-

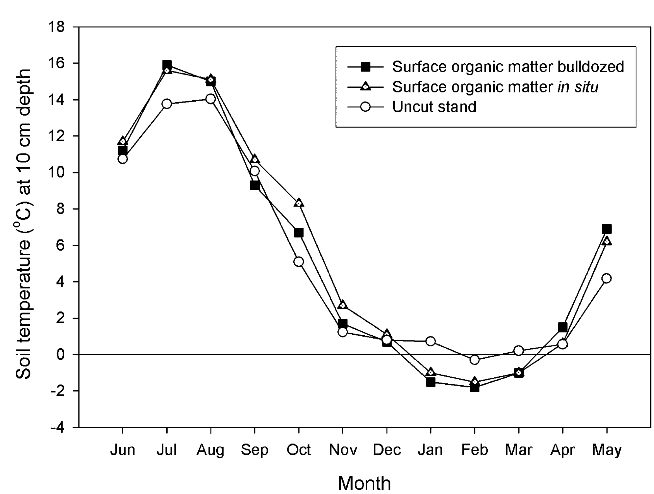

Fig. 1. Average monthly temperature at the 10 cm soil depth for each site preparation treatment and the uncut stand during the first growing season (1998). *Surface Organic Matter* comprised of coarse wood, logging slash, and forest floor (all organic horizons).

Table 3
Summary statistics for the main effects and interactions of study location (L), site preparation treatment (T), and nursery storage treatment (S) on seedling morphological characteristics

Source	Height		RCD		Survival		TNC		Root weight	Root volume	Shoot weight	Ectomycorrhizae g^{-1} dry root
	1 yr	5 yr	1 yr	5 yr	1 yr	5 yr	Shoots	Roots				
L	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
T	*	ns	ns	ns	ns	*	*	*	ns	ns	*	ns
L × T	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
S	**	ns	**	ns	ns	**	**	**	**	**	**	ns
T × S	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns

Height and RCD were collected 1 and 5 yrs after outplanting. Treatment means for main effects of height increment and RCD are shown in Fig. 2. *Significant at $\alpha = 0.10$; **significant at $\alpha = 0.05$; ns, not significant at $\alpha = 0.10$.

Table 4
Average morphological characteristics and survival of lodgepole pine seedlings planted on high-elevation locations in northeastern Utah in late June or late August 1998 and remeasured in June 1999

Treatment	Height (cm)	Root-collar diameter (mm)	Root weight (g)	Root volume (ml)	Shoot weight (g)	Ectomycorrhizae g^{-1} dry root	Survival (%)
Surface organic matter *in situ*							
Cooler-stored	12.9 (1.1) a	4.7 (0.5) a	1.6 (0.03) a	6.6 (0.4) a	3.3 (0.2) a	0.68 (0.01) a	97 (0.2) a
Freezer-stored	14.3 (1.0) a	4.8 (0.6) a	1.7 (0.02) a	7.0 (0.6) a	3.0 (0.3) a	0.74 (0.01) a	96 (0.2) a
Hot-planted	11.2 (1.2) b	3.4 (0.6) b	1.1 (0.01) b	4.7 (0.2) b	1.5 (0.1) b	0.51 (0.01) a	95 (0.2) a
Overall mean	12.8 A	4.3 A	1.5 A	6.1 A	2.5 A	0.65 A	96 A
Surface organic matter bulldozed							
Cooler-stored	13.9 (1.0) x	4.8 (0.5)x	1.8 (0.02) x	7.2 (0.5) x	3.5 (0.2) x	0.76 (0.01) x	96 (0.1) a
Freezer-stored	15.7 (0.9) y	6.3 (0.5) y	2.2 (0.01) x	8.2 (0.7) x	4.1 (0.3) x	0.84 (0.02) x	96 (0.1) a
Hot-planted	11.9 (1.2) z	3.4 (0.5) z	1.3 (0.02) y	5.3 (0.5) x	1.8 (0.2) y	1.17 (0.01) x	98 (0.1) a
Overall mean	13.8 B	4.9 A	1.8 A	6.9 A	3.2 B	0.92 A	97 A

Values are an average (S.E. in parentheses). Within site preparation treatment, storage treatments with the same letter are not significantly different ($\alpha < 0.05$) by Tukey's studentized range test. Among site preparation treatments, overall means with the same letter are not significantly different ($\alpha < 0.05$) by Tukey's studentized range test. Seedlings cooler- and freezer-stored were outplanted in late June 1998. Non-stored (hot-planted) seedlings were outplanted in late August 1998. *Surface Organic Matter* comprised of coarse wood, logging slash, and forest floor (all organic horizons).

rhizae when seedlings were measured the spring following outplanting. In general, the older cooler- or freezer-stored seedlings were larger than their younger hot-planted cohorts (Table 3), but hot-planted seedlings had more TNC in their root systems (Fig. 2). After five growing seasons, site preparation and seedling storage affected seedling survival; survival of stored seedlings was 92% compared with 84% for hot-planted stock (Fig. 3), and seedlings growing where surface OM was bulldozed had 93% survival compared with 88% survival for those growing with *in situ* surface OM (Fig. 3).

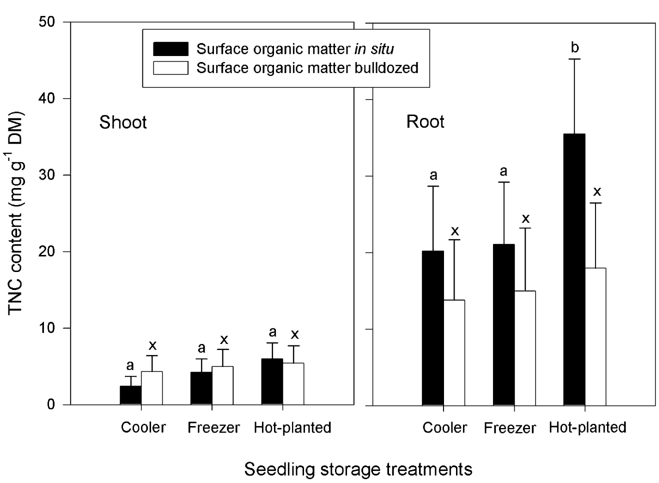

Fig. 2. Total non-structural carbohydrate (TNC) content in seedling shoots and seedling roots (mean + S.E.) at the end of the first growing season (1998). Stored trees had a full growing season on site (July–September); hot-planted seedlings had only 1 month (September). Within each site preparation treatment, storage treatments with the same letter are not significantly different ($p \leq 0.05$). *Surface Organic Matter* comprised of coarse wood, logging slash, and forest floor (all organic horizons).

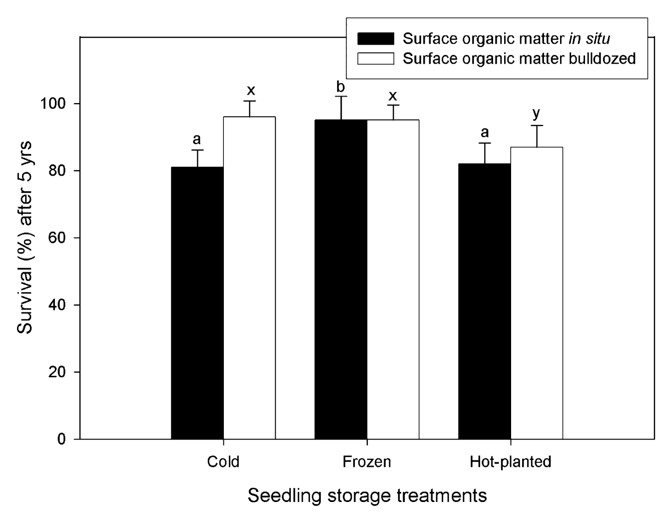

Fig. 3. Seedling survival 5 yrs after outplanting (mean + S.E.). Within each site preparation treatment, storage treatments with the same letter are not significantly different ($p \leq 0.05$). *Surface Organic Matter* comprised of coarse wood, logging slash, and forest floor (all organic horizons).

4. Discussion

Harvesting trees and subsequent site preparation increased total bulk density and exposed more subsurface rocks, which resulted in a higher rock fragment content of the soil. According to

USDA Forest Service Region 4 soil quality standards and guidelines (Powers et al., 2004), any 15% increase in bulk density above the non-harvested condition is considered detrimental to site productivity. In our study, retaining surface organic matter kept bulk densities below that detrimental threshold, whereas bulldozing surface OM resulted in values exceeding the standard. Moreover, and as expected, the higher total bulk density was also reflected in a higher fine fraction bulk density. Although compaction of the fine fraction can decrease total porosity and limit water availability, and thereby reduce root growth (Greacen and Sands, 1980; Gomez et al., 2002; Miller et al., 2005), seedlings growing in the treatment with bulldozed surface OM (with bulk density nearly 18% higher than the *in situ* surface OM treatment) were significantly taller and had the most biomass the spring following outplanting. In the North American Long-Term Soil Productivity study site network, removal of *in situ* surface OM or soil compaction often increased seedling survival, but the combination of these treatments did not provide any additional benefits and sometimes reduced growth after five years; the additive affect of two types of soil disturbance did not provide supplementary benefits (Fleming et al., 2006). Soil texture is also important for determining the influence of compaction on seedling growth. Compaction-caused reductions in total porosity on these relatively fine-textured soils may have resulted in little change in soil moisture retention properties (Sands et al., 1979; Page-Dumroese et al., 2006). Moreover, although removal of surface OM can deplete soil N and C reserves and reduce stand productivity on some sites (Jurgensen et al., 1997; Page-Dumroese and Jurgensen, 2006), after five years of growth seedling heights and RCDs were similar across our site preparation treatments. In addition, survival, which was excellent regardless of site preparation, was slightly higher after five growing seasons where surface OM was bulldozed.

Management of surface OM can also affect soil temperature, which in turn can affect root regeneration. Root growth during the first year is an important variable in determining conifer seedling survival after outplanting (Stone, 1955; Lopushinsky and Beebe, 1976), but root growth of newly planted seedlings is often hampered by low soil temperatures (Lopushinsky and Kaufmann, 1984; Grossnickle, 2005). Fleming et al. (1998) attributed higher soil temperatures to clearcutting and piling surface OM on high-elevation sites, and deemed this an advantage. Several studies have reported greater root, stem, foliage, and total biomass of outplanted lodgepole pine after one growing season in Washington state, USA and British Columbia, Canada where soil temperatures were warmer (Dobbs and McMinn, 1977; Lopushinsky and Max, 1990; Coates et al., 1991; Balisky and Burton, 1997). Campbell et al. (2006) found that after two years, lodgepole pine seedlings planted into areas with surface OM removed had 6% larger stems than those planted directly into the forest floor; whereas seedlings planted in areas with *in situ* surface OM produced 11% more new emergent roots. Moreover, the process of removing surface OM can also decrease subsequent competition (Powers et al., 2004), thereby promoting seedling growth. One drawback of warmer temperatures, however, could be increased surface OM decomposition rates in both site preparation treatments, thereby lowering soil C, OM, and N pools (Prescott et al., 2000).

We failed to see an appreciable increase in soil temperature at the 10-cm level during the first year as a result of bulldozer removal of surface OM. Overall, soil temperatures were $<10\ ^{\circ}C$ for most of the year, but root temperatures ($\sim 15\ ^{\circ}C$) during the active growing season (July and August) were approaching those found optimum for another conifer species (Jacobs et al., 2008). Although 15–20 °C is considered the optimum soil temperature for root growth, roots of lodgepole pine seedlings will continue to grow at temperatures just above freezing (Lopushinsky and Max, 1990). Although soil temperatures at our sites were similar in both site preparation treatments, seedlings in the bulldozed surface OM treatment grew 20% more root biomass, perhaps because of increased soil surface temperatures or decreased competition.

Although Harvey et al. (1996) found that surface OM left *in situ* is where ectomycorrhizae flourish, they also found the greatest number of ectomycorrhizal tips occurred in the harshest environments (bulldozed surface OM treatment). To take advantage of ectomycorrhizal inoculum, Balisky and Burton (1997) recommend outplanting seedlings in close proximity to surface OM, where access to higher levels of nutrients is also greater (Page-Dumroese et al., 1989). The spring following outplanting, however, we observed no difference in the number of ectomycorrhizae g^{-1} of dry root in our site preparation treatments. Our observed values (0.5–1.2 ectomycorrhizae g^{-1}) are relatively low compared to other conifer species growing at lower elevations in Idaho (3–18 ectomycorrhizae g^{-1}; Harvey et al., 1996). This lack of infection may be due to any number of factors that affect seedling root growth, the ability of a seedling to defend against ectomycorrhizal infection, or low nutrient status of the soil (Harvey et al., 1997).

At the end of the first growing season (October 1998), hot-planted seedlings tended to have more TNC than stored seedlings (Fig. 2), especially in their roots. This may be a reflection of TNC not being replenished after the long storage duration for the cooler- and freezer-stored seedlings, higher residual TNC in hot-planted seedlings recently shipped from optimum conditions within the nursery, or because TNC content naturally decreases as seedlings become acclimated to site conditions (Tinus et al., 2000). After outplanting, container seedlings have limited carbohydrate reserves and must quickly assimilate carbon in order to grow new tissue (van den Driessche, 1987; Campbell et al., 2006). When lifted properly at the appropriate time, seedlings, including high-elevation sources (Tung et al., 1986), freezer-stored for 6–7 months can survive and grow as well as those frozen for shorter durations (Ritchie et al., 1985). Although cooler-stored seedlings lose carbohydrate reserves faster than freezer-stored seedlings (Ritchie, 1982), the primary reason for restricting long-term cooler storage (>2 months) is increased potential for losses due to disease (Ritchie, 2004).

Comparing stocktypes, which by definition are inherently different, often provides a conundrum. In our study, we outplanted stocktypes (storage was the difference in stocktype) that we expected would elongate shoots from their buds (cooler- or freezer-stored) prior to the first winter on the site and a stocktype we expected would not (hot-planted). Because, on these sites, forest managers typically make their first assessment of previous year plantings following snow melt, we evaluated seedlings then even though stored seedlings experienced a complete growing season (July–September) that allowed bud break, shoot elongation, and stem diameter growth, whereas hot-planted seedlings did not initiate height growth immediately after outplanting and had less time (September only) for stem diameter growth. We realized, however, that our non-traditional stocktype (hot-planted seedlings) would be inappropriately penalized for "poorer growth", as was demonstrated by Marion and Alm (1986), so we also chose to analyze height data after allowing seedlings five shoot elongations on the site, even though this required measurements in two successive years, to ensure a fair comparison of long term growth potential.

As expected, therefore, the following spring (June 1999) before resumption of terminal shoot growth, hot-planted seedlings were shorter and had less RCD, dry root and shoot biomass, and root volume than cooler- and freezer-stored seedlings (Table 4). Although hot-planted seedlings had higher root TNC going into winter, we detected no resulting advantage—survival was ≥96% regardless of seedling storage technique (Table 4).

After five complete growing seasons (2002 for stored seedlings; 2003 for hot-planted), seedling heights and RCDs were similar regardless of site preparation treatment. However, site preparation that retained surface OM reduced survival of cooler stored (81%) and hot-planted (82%) seedlings compared to their cohorts planted on sites where such surface OM had been removed (96% and 87%, respectively; Fig. 3), although these reduced survival rates were still considered excellent by managers of these sites. Freezer-stored seedlings survived well (95%) regardless of site preparation treatment.

In the Unitas, precipitation is largely absent from snow melt until summer rains occur in late July or early August. We believe that hot-planted seedlings were successful because we strived to match outplanting with resumption of normal precipitation, and matching the target seedling with optimum planting windows (in this case, after resumption of rainfall in late summer) should improve stock performance (Landis and Dumroese, 2006).

5. Management implications

Our results from northeastern Utah indicate that forest managers may have several choices when reforesting high-elevation (~3000 m) sites with lodgepole pine seedlings. Acceptable seedling survival and growth was achieved through traditional container nursery production and outplanting (*i.e.*, spring sown seeds, over-winter refrigerated storage, and spring outplanting). After five shoot elongations, however, hot-planted seedlings were of similar size as their stored, spring-planted cohorts. Hot-planting seedlings in concert with expected summer rainfall would appear to provide acceptable artificial regeneration results. In northern Utah, the reforestation cycle can be shortened by nearly a year through use of winter-sown seeds in greenhouses and late-summer hot-planting seedlings during expected summer rains, thereby avoiding potential scheduling conflicts associated with unpredictable spring snow melt and budgets. In addition, planting through the surface OM provided favorable microsite conditions for seedling survival and growth, and did not alter soil bulk density. Because it can cost significantly more to remove coarse wood, logging slash, and forest floor materials and could increase soil compaction, planting directly into residual surface OM should be considered a viable outplanting method. Planting through logging slash, coarse wood, and forest floor alleviates the concerns of detrimental compaction and the potential for decreased site productivity, while achieving adequate stocking levels with fewer resources.

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