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Juvenile growth of hybrid poplars on acidic boreal soil determined by environmental effects of soil preparation, vegetation control, and fertilization

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ABSTRACT

The silviculture of hybrid poplars and other fast-growing tree species is a promising solution to reduce the pressure on natural forests while maintaining wood supplies to industries. However, hybrid poplars are very sensitive to competing vegetation and to inadequate soil conditions and fertility. Possible management tools include mechanical site preparation (MSP), vegetation control (VC), and fertilization. Experimental plantations of hybrid poplars (one clone, *Populus balsamea* x *Populus maximowiczii*) were established at eight formerly forested sites on acidic soil in the southern boreal forest of Quebec, Canada. The objective was to test the response of hybrid poplars to the interaction of several silvicultural tools, which has been rarely done. Four MSP treatments (in decreasing order of intensity: mounding, harrowing, heavy disk trenching, light disk trenching) and a control (unprepared) were all combined with four different frequencies of plant competition control by brushing (from never up to once a year). Fertilization with N or N+P was also tested in three selected MSP treatments. After five years, hybrid poplar tree growth among MSP treatments increased in the following order: unprepared < light disk trenching < heavy disk trenching < harrowing < mounding. MSP was also essential in favouring early tree survival, as illustrated by mortality rates of over 20% in unprepared plots and below 5% in all other MSP treatments. The effect of competition control on hybrid poplar growth was greatest in the less intensive MSP treatments, where competing vegetation was the most abundant. On the contrary, fertilization effect was significant only in the most intensive MSP (mounding). Moreover, neither fertilization nor VC could compensate for inadequate soil preparation. Of all the silvicultural treatments tested, mounding provided the best tree growth despite a nitrogen and carbon impoverished surface soil.

Keywords: hybrid poplar, intensive silviculture, mechanical soil preparation, plant competition, fertilization.

1. Introduction

The use of fast-growing plantations on a small proportion of the landscape is a promising silvicultural solution for reducing the pressure on natural forests (Paquette and Messier, 2010). In the context of the forest zoning management approach (Seymour and Hunter, 1992; Messier and Kneeshaw, 1999; Messier et al., 2009b), it has the potential of expanding protected areas and areas under ecosystem management (Başkent and Yolasığmaz, 2003), while maintaining or even increasing wood supply (Binkley, 1997; Fox, 2000; Messier et al., 2003). In several areas of the world, the fast-growing tree species of choice belong to the genus *Populus* (Pontailler et al., 1999; Christersson, 2006; Rodríguez et al., 2010). *Populus* trees, clones and hybrids are very demanding in terms of nutrients, water and light (Barnéoud et al., 1982; Mitchell et al., 1999; Paré et al., 2001). However, because of the increasing interest in using these trees and the low availability of land, plantations are being established on marginal sites and in less than ideal conditions (Vande Walle et al., 2007), for instance at high latitudes of the northern hemisphere, i.e., in the boreal zone (Christersson, 1996; Larchevêque et al., 2010). This important biome represents 11% of the Earth's terrestrial areas and includes 29% of the world's forests (Weih, 2004).

To date, hybrid poplar plantations in northern latitudes, for example in Sweden (Christersson, 2008, 2010) or in the prairie–boreal forest transition region of central Canada (Block et al., 2009; Pinno and Bélanger, 2009; Pinno et al., 2009; Amichev et al., 2010in press), are all located on agricultural lands; only a few have been tested on recently logged or otherwise formerly forested sites of eastern Canada (Coll et al., 2007; Bona et al., 2008; Guillemette and DesRochers, 2008; Sigouin, 2008). Hybrid poplar plantations established at these sites, as opposed to agricultural lands, pose further challenges in terms of soil fertility and tree nutrition since forest soils do not have long histories of anthropogenic use and fertilizer amendments the way agricultural soils do (Vande Walle et al., 2007) and as such are often less fertile, at least in the boreal zone. Selective tests of hybrid poplar clones adapted to the nutrient-poor, acidic soils and relatively rigorous climate of the boreal forest have given encouraging results (Gagné, 2005, and P. Périnet, personal communication). It seems that even in such harsh conditions for poplar plantations, short rotations (< 20 years) producing large wood volumes are possible. In comparison, the typical rotation for natural stands of trembling aspen (*Populus tremuloides*) is 41-88 years (Pothier and Savard, 1998).

Unsuccessful plantations of fast-growing trees have often been attributed to the selection of inappropriate soil management techniques (Evans, 1999). Mechanical soil preparation (MSP) can produce microsites that are appropriate for tree planting (Sutherland and Foreman, 1995; Knapp et al., 2008), while reducing competing vegetation and generally improving tree growth (Thiffault et al., 2003). In boreal zones, it is particularly beneficial for increasing soil temperature (Örlander, 1987; Sutton, 1993; Landhäusser, 2009), which in turn increases leaf, shoot and root growth (Wan et al., 1999; Landhäusser et al., 2001). The impact of MSP on soil fertility is more variable, sometimes improving nutrient mobilization (Ross and Malcolm, 1982) and on other occasions reducing it (Messier et al., 1995; Yildiz et al., 2010), notably due to soil organic matter removal (Arocena, 2000; Gartzia-Bengoetxea et al., 2009). Given that hybrid poplars have high needs for resources, they are also known to be particularly sensitive to competition (Stanturf et al., 2001; Kabba et al., 2007, 2009). Competition control generally has positive effects on early development of seedlings because the first few years are the most critical for survival (Morris et al., 1993; Löf, 2000; Harrington, 2006). The control of competing vegetation typically proves beneficial to hybrid poplars (Stanturf et al., 2001), although experimental results may diverge, with some pointing towards effectiveness of the removal of aboveground vegetation only (Czapowskyj and Safford, 1993) while others insist on the need to target belowground plant parts (Coll et al., 2007). Fertilization is also frequently used to fulfill nutritional needs and to maximize tree growth (Mitchell et al., 1999; du Toit et al., 2010). It is generally very effective in poplar plantations (Brown and van den Driessche, 2002, 2005; Guillemette and DesRochers, 2008) and has been extensively studied (Coleman et al., 2006; Guillemette and DesRochers, 2008; Lteif et al., 2008; Patterson et al., 2009; Pearson et al., 2010).

Although the aforementioned management tools, i.e., MSP, vegetation control (VC), and fertilization, have been the object of several studies, very few have combined the three of them in a single design looking at multiple interactions (Burgess et al., 1995; South et al., 1995; Allen, 1996). One example of a three-factor study comes from Nilsson and Allen (2003) and was conducted in 18-year-old loblolly pine (*Pinus taeda* L.) plantations. Tree growth benefited greatly from all treatments, but mostly from high intensity MSP. Fertilization and VC interacted with MSP so that their effects on pine growth differed depending on MSP intensity (Nilsson and Allen, 2003). Similar results were obtained in a recent study by Zhao et al. (2009) on 26-year-old stands of slash pine (*Pinus elliottii* Engelm.).

The preceding examples were all concerned with coniferous trees and were mostly conducted in the mild, temperate climate of southeastern USA, with only one being conducted in the boreal forest. Consequently, studies focusing on deciduous fast-growing trees in a boreal context and looking at several silvicultural techniques are currently lacking, which does not bode well considering the growing interest in intensive silviculture in the boreal forest. To ensure the success of these plantations, it is thus imperative to assess which silvicultural tools will provide favourable soil and environmental conditions. The main objective of this unique study was to test the interactions of various MSP techniques, VC frequencies and fertilizer applications within industrial-scale experimental plantations of hybrid poplars established on former boreal forest sites with cold, nutrient-poor, and acidic soils of the Precambrian Shield.

2. Methods

2.1. Sites

Eight formerly forested sites were chosen in the Saguenay–Lac-Saint-Jean region (between 48°08’ and 48°43’ N, and between 71°05’ and 72°52’ W) of the province of Quebec, Canada. These sites are located in the southern boreal forest, and original stands consisted of balsam fir (*Abies balsamea*), trembling aspen (*Populus tremuloides*), black spruce (*Picea mariana*), white spruce (*Picea glauca*), and paper birch (*Betula papyrifera*). Soils are representative of Precambrian Shield settings characterized by coarse acidic soils, and are classified as Orthic ferro-humic Podzols (Canada Soil Survey Comittee, 1992) or Haplorthods (Soil Survey Staff, 1998). Mean annual temperature for this region is 2.2°C and mean annual precipitation is 1000 mm (of which 710 mm is rainfall), while mean summer (June-September) temperature is 15.5°C and mean summer precipitation (rainfall) is 107.5 mm (Environment Canada, 2009).

2.2. Mechanical Soil Preparation (MSP)

Sites were whole-tree harvested in summer 2002; then, soils were mechanically prepared in fall 2003 after the regenerating vegetation had been cleared with a brush saw in late summer. Five techniques were tested, which represent an increasing gradient of soil disturbance intensity at the tree or microsite level: no preparation (control), light disk trenching, heavy disk trenching, harrowing, and mounding. In control plots, no soil preparation was done after harvest and trees were planted directly wherever it was possible to do so. Light disk trenching was done with a TTS Delta disk trencher that involved two hydraulically driven rotating dented disks that were ran in parallel straight rows to remove the surface organic layer (up to 20 cm deep) and expose the mineral soil in which trees were planted. Heavy disk trenching used the same machinery, but three runs of the machinery were done, with the first two runs perpendicular to each other and the last one diagonal to these. Harrowing followed the same three-run pattern, but the equipment involved three rows of five 75-cm diameter disks pulled by a tractor. These disks are larger and can dig much deeper into the soil than those of the disk trencher. The disks were slightly inclined at an angle that varied between disks and rows to ensure that the soil (both the mineral and organic layers) was thoroughly mixed. Mounding is a common treatment in Scandinavia and Canada (Örlander et al., 1990; Sutton, 1993), and here it was done using a mechanical shovel equipped with a 45-cm-wide bucket that dug deep into the soil through the surface organic layer in order to retrieve mineral soil. This mineral soil was then upturned over undisturbed soil to form a mound about 30 cm in height and 50 cm in radius. In this manner, it buried the original organic soil material and crushed the vegetation beneath it. Trees were planted directly in, but slightly on the side of the mound, and given the height of the mound the lower end of a tree barely reached the organic layer. Each of these five treatments covered a 1-ha plot and was repeated at each of the eight sites (its placement relative to other treatments was randomized), hence $n = 8$ over a total of 40 ha of plantations (Fig. 1).

2.3. Tree planting

Bare-root, ~ 1-m-tall hybrid poplar tree cuttings of the 915319 clone *Populus maximowiczii* x *Populus balsamifera* (Périnet et al., 2001) were obtained from a nursery operated by the Ministère des Ressources naturelles et de la Faune du Québec at Grande-Piles, QC, Canada. The cuttings were produced in the spring from parent trees in the nursery plantations, and cultivated over the summer in irrigated, fertilized, and weeded soil. This allowed them to develop a substantial root system, which was subsequently groomed in the fall when the cuttings were dormant, a state in which they were kept until shipping to the field the next spring. The bare-root cuttings were hand-planted with a shovel in April 2004 at a depth of 20-30 cm and in straight rows at a spacing of 3 m x 3 m (density = 1100 trees ha^{-1}). Throughout this text, the year of planting will be considered as year 1.

2.4. Vegetation Control (VC)

Competing herbaceous and woody plants were mechanically removed by brushing (aboveground parts only), during or after the peak of summer biomass production (mid-July to beginning of August). The four VC treatments corresponded to four different frequencies: (*i*) never, (*ii*) at year 3, (*iii*) at years 2 and 4, and (*iv*) at years 2, 3, and 4. These treatments were tested using four 0.25-ha (50 m x 50 m) subplots that were delineated and placed randomly within each 1-ha MSP plot (Fig. 1), for a total of 160 subplots. Three of these subplots were not used in further analyses because of misallocated treatments, leaving 157 subplots. In this text, plots that were never controlled for competition will be commonly referred to as “unweeded”, in contrast to the other VC plots that will be called “weeded”.

2.5. Fertilization

In July of year 5, two doses (0 as control and 400 g tree^{-1}) of fertilizers (N only, as 18-0-0; and N+P, as 18-46-0) were applied at the base of selected trees. Each fertilizer treatment was replicated on five trees chosen randomly in the VC subplot *iii* of two MSP treatments (harrowing and mounding) and the control (unprepared) across all eight sites. Care was taken not to choose adjacent trees, thus they were separated by at least one tree row (i.e., 6 m apart). These trees were located in the buffer zone of the 0.25-ha plots (see section 2.6), so as not to fertilize any tagged trees.

2.6. Growth surveys

Total height, diameter, and annual shoot lengths were measured on 12 trees in each 0.25-ha subplot (see 2.4) in October of years 3 and 5. These 12 tagged trees were chosen randomly within a 20 m x 20 m area in the center of the subplot, leaving a 15-m strip on all sides where no trees were tagged for measurements. This 15-m strip was called the buffer zone. The subset of fertilized and unfertilized trees (located in the buffer zone) was measured in October of years 5 and 6.

2.7. Assessment of competition cover

In 2005, interspecific competition was assessed for six trees chosen randomly among the 12 surveyed trees per 0.25-ha subplot at all the sites in the two VC subplots that did not undergo brushing that year, hence treatments *i* and *ii*. These treatments had never been weeded between site preparation, tree planting and competition surveying. Within a 1-m radius divided in four quadrats around a hybrid poplar tree, the percentage of the area covered by competition was visually evaluated and classified by plant type as tree, shrub, herbaceous or grass. This was done separately for each quadrat and subsequently averaged for the whole tree.

2.8. Foliar analyses

Leaves were sampled every year from years 3 to 5. In year 3, one leaf from each of the 12 surveyed trees per 0.25-ha subplot was pooled (157 samples). In year 4, leaves were sampled at all sites in August in all four MSP treatments and the control and in two VC treatments, (*i*) never and (*iv*) years 2-3-4. All 12 surveyed trees were individually sampled in each subplot, and five leaves were taken from each tree at regular intervals along the vertical length of the crown. In year 5, sampling was repeated similarly to the previous year, but only in the VC subplot *iv*. Fertilized trees were sampled in August of years 5 and 6, and leaves from trees in a same plot were pooled by treatment (unfertilized, N-fertilized, N+P-fertilized). Foliar samples from all years were oven-dried at 70^{o}C for 48 h. Total N was determined as for the soil samples on a LECO CNS analyzer (LECO Corporation, St. Joseph, MI, USA), while phosphorus was determined following calcination at 500^{o}C and dilution with hydrochloric acid (Miller, 1998). Phosphorus was analyzed by flow injection analysis and ion chromatography (FIA; Lachat Instruments, Milwaukee, WI, USA), and base cations by atomic absorption and emission (Varian, model AA240FS, Palo Alto, CA, USA).

2.9. Soil analyses

2.9.1. General characteristics

In year 2, one mineral soil sample was taken, in the center of each 0.25-ha subplot, at a depth of approximately 15-20 cm, thus reaching into the B-horizon. These mineral soil samples (n = 157) served to describe the plots and sites in a general way and ensure that heterogeneity had been reduced to a minimum when initially choosing sites prior to mechanical soil preparation. These descriptive soil data were thus not used in explaining tree growth responses to the various treatments. Soil pH was analyzed in distilled water and $CaCl_2$ (Hendershot et al., 2007). Exchangeable cations (K, Ca, Mg, Al and Fe) were extracted using unbuffered 0.1 M $BaCl_2$ and determined by atomic absorption and emission (Hendershot et al., 2007). Soil particle size distribution (texture) was determined by the hydrometer method (Gregorich and Beare, 2007) without pre-treatment of the samples due to the low organic matter content, coarse nature of the particles and low level of aggregation of the samples.

In year 4, one soil pit was dug in the VC subplot *iv* of every 1-ha MSP plot ($n = 40$) to characterize vertical soil profiles; horizons were identified and their thickness measured, while a sample was taken from the B-horizon with a cylinder of known volume to later calculate B-horizon bulk density. This sampling served in describing the sites and not in explaining tree growth responses. Site means of the general soil characteristics are presented in Table 1.

2.9.2. Physico-chemical characteristics

Soil penetrability, humidity, and temperature were assessed during year 4, and were subsequently compared to tree growth in trying to explain responses to the various treatments.

In June of year 4, soil penetrability was evaluated at the base of each of the 12 surveyed trees in the harrow and mounding MSP treatments and the unprepared control (288 trees) with a drop-hammer penetrometer (model PEM-1 from Roctest Ltd., Saint-Lambert, QC, Canada), where a weight of 4.5 kg was dropped repeatedly from a height of 46 cm to drive a metal rod into the ground; the depth reached by the rod after 10 hits represented soil penetrability. Since rocks can hamper the efficiency of this method, several trials were done around a tree to ensure adequate representation of soil conditions.

In August of year 4, soil volumetric water content was measured with a TDR-300 soil moisture meter equipped with two 20-cm probes (Spectrum Technologies Inc., Plainfield, IL, USA). A mean value per tree was obtained from four measurements taken around the base of each of the 12 surveyed trees in the harrow and mounding MSP treatments and the control at all sites (288 trees). Repeatability of water content measurements was verified by sampling twice at seven 0.25-ha subplots found across three sites, either before and after a rainy day or over a period of 2 weeks in August of year 4; results of matched-pairs *t*-tests showed these measurements to be satisfyingly similar despite the different conditions in which they were taken.

Soil temperature was measured at the base of each tree with a hand-held, 20-cm electronic thermometer probe. Measurements were taken across all sites between June and August of year 4, and were repeated 2-3 times over the season for each tree, approximately once per month. By doing so, temperature measurements were satisfyingly consistent for individual trees. Data-logging temperature sensors (Maxim Integrated Products, Sunnyvale, CA, USA) were also placed at two sites in two VC subplots (*i* and *iv*) of all four MSP treatments and the control. Soil temperature was measured every 2 h from the beginning of June to the end of October of year 4, at depths of 2, 10 and 20 cm. The sensors' data were compared with the hand-held thermometer probe measurements to further verify data reliability.

2.9.3. N mineralization rates

Tree growth responses to treatments were additionally submitted to the comparison with soil nutrients data, namely the mineralization of N.

Potential N mineralization was assessed by comparing nitrate (NO_3) and ammonium (NH_4) concentrations at the start and at the end of a 6-week (from the beginning of July to mid-August of year 4) closed-top *in situ* incubation with 30-cm-long PVC tubes as described in Brais et al. (2002). Tubes were inserted in the surface soil (0-20 cm) at a distance of 30 cm from the base of three trees per 0.25-ha subplot in two MSP treatments (harrowing and mounding) and the control, and within those only the VC treatments *i* and *iv* were used (144 trees). Ammonium and nitrate ions were extracted with 2M KCl and analyzed by flow injection analysis and ion chromatography (FIA). Total C and N were determined by combustion (1100°C) and infrared detection on a LECO CNS-2000 analyzer (LECO Corporation, St. Joseph, MI, USA).

2.10. Data treatment

In the experimental design, treatments were randomized at each level (MSP, VC, fertilization), but the levels were not complete since fertilization was only done within certain MSP and VC treatments, and some soil variables were only measured in selected treatments. Responses were thus treated separately when appropriate. Mean growth from 12 trees per

0.25-ha subplot was compared across the eight sites by a mixed-effect analysis of variance, using MSP treatments and the control (5 levels), VC treatments (4 levels) and the interaction of MSP and VC as fixed effects, site (n = 8) and plot (n = 40) as random effects (indicative of the hierarchical design), with probability levels resolved by Restricted Maximum Likelihood (REML, see Searle et al., 1992; Wolfinger et al., 1994) and submitted to post hoc Tukey HSD tests where justified. Absolute values of annual growth and the total cumulative 5-year (2004-2008) growth were thus analyzed for tree height and diameter. In addition, to further assess the effects of competition control on growth, the relative growth gain (RGG) was computed as the difference between the cumulative 5-year growth of weeded (the most frequent VC, *iv*) and unweeded subplots (VC *i*) within a same MSP plot, divided by the growth of the unweeded subplot, and expressed as a percentage. It was inspired by the relative growth rate and other measures of relative growth presented by Hunt (1990). The RGG was submitted to an ANOVA and post hoc Tukey HSD tests.

Shoot growth of fertilized trees (N and N+P fertilizations treated either separately or jointly) in years 5 and 6 was compared with that of unfertilized trees (the 12 tagged trees of section 2.6) through a mixed-effects analysis of variance; this was done separately for each selected MSP treatments and the control. Both annual shoot length and proportional height growth (current year's height divided by previous year's height) of fertilized trees were tested, again with mean growth per subplot.

Effects of MSP and VC treatments on soil properties (humidity, temperature, penetrability, chemical content, N mineralization) and foliar nutrition were analyzed through mixed models, similarly to tree growth, and separately for each variable. Sample sizes may have varied between variables (see particular sampling strategies above). Potential N mineralization of NH_4 and NO_3 was estimated as the difference between initial and final concentrations from *in situ* incubation tubes.

Survival of trees was recorded as alive (0) or dead (1) for all 1884 trees during the biannual growth surveys. Mortality was further assessed by noting time since death, in years (either 0 (still alive) or dead for 1, 2, 3 or 4 years). Both were individually compared with silvicultural treatments through a generalized linear mixed model (GLMM) fitted with the Laplace method of likelihood approximation (Bolker et al., 2009). Site and plot were added as random effects, as in the growth mixed model above, but here subplot (n = 157) was added as well in order to simulate correlation among trees within the same 0.25-ha subplot. Survival data was best represented with the binomial distribution while time since death was best represented with a Poisson distribution, for which overdispersion ($\hat{c}$, variance divided by the mean) was satisfyingly verified prior to GLMM analysis by fitting a simple linear model without random effects.

Statistical analyses were conducted with the R software (R Development Core Team, 2009), using a significance level of $\alpha = 0.05$. General linear mixed models were constructed with the “nlme” package and GLMMs with “lme4”.

3. Results

Height growth of 5-year-old hybrid poplars was enhanced by mechanical soil preparation (MSP) prior to planting. There was a significant difference between the different MSP treatments and the control (Fig. 2, Table 2). The best growth was obtained in the following order: mounding > harrowing > heavy disk trenching > light disk trenching > unprepared (control). Unprepared plots produced trees significantly shorter than all other MSP treatments (Fig. 2). Growth in diameter at breast height (DBH) responded to MSP treatments very similarly to height growth (Fig. 3 and Table 2). The gradient of the effect of MSP on height and diameter growth was likewise observed on annual growth (data not shown). In early years the difference was most evident when comparing the most intensive treatment with the least intensive, i.e., mounding and unprepared. The first treatment produced annual shoots of at least twice the length of the latter. Intermediate treatments were relatively similar in the first year, and only started differing later on. Any MSP treatment, even the least intensive (light disk trenching), significantly reduced mortality in hybrid poplars (< 5%) compared with the absence of preparation, where mortality rates were over 20% and trees died early after planting (Fig. 5). MSP also reduced the ground cover of competing shrubs and herbaceous plants significantly compared with plots that were not mechanically prepared prior to planting (e.g., herbaceous cover in unprepared plots = 25.4%, SE = 2; in other MSP treatments = 9-15%, SE = 2; $P < 0.05$).

Vegetation control (VC) by removal of aboveground parts of competing herbaceous and woody vegetation increased height and diameter growth of trees (Fig. 2 and 3, Table 2). The different frequencies of VC affected growth in the following order: at years 2, 3 and 4 > at year 3 > at years 2 and 4 > never (Fig. 2 and 3). There was no significant interaction between MSP and VC in the absolute values of tree height and diameter growth (MSP x VC, in Table 2). Nevertheless, the relative gain in height growth due to VC (RGG, which compared the two most extreme VC frequencies, *i* and *iv*) varied significantly depending on

MSP, ranging from 25% with mounding to greater than 200% in unprepared plots (Fig. 4). Diameter RGG, on the other hand, did not vary between MSP treatments.

In the three selected MSP treatments where it was applied, there was no significant difference between N fertilization and N+P fertilization ($P > 0.3$; data not shown). Therefore, all subsequent references to "fertilized trees" combine both types of fertilization. Annual shoot growth of fertilized trees was higher than that of unfertilized trees during the year of fertilizer application (i.e., year 5). However, it was only significant in the mounding treatment ($P = 0.009$; Table 3). During that year, trees on mounds that received fertilizers produced around 31% more shoot length, or grew 32 cm higher, compared with unfertilized trees (Table 3). Proportional height growth (current year height divided by previous year height) of fertilized trees also improved significantly in mounded plots. Harrowed trees also responded, albeit only slightly, to fertilizers when considering the proportional gain in growth ($P = 0.054$). Trees in both mounding and harrowing plots again showed greater annual shoot growth due to fertilization the following year (i.e., year 6). However, mounding was again in year 6 the only treatment to clearly respond in proportional height growth ($P = 0.023$; Table 3). Trees in unprepared plots did not respond favorably the years following fertilization. Despite varying growth results, fertilization significantly enhanced leaf mass and leaf N content in the tested MSP treatments and the control (Table 3).

Effects of MSP showed a tendency to increase soil temperature and penetrability, whereas a decrease in soil water content and total C and N concentrations (although the C/N ratio remained constant) was observed with increasing intensity of soil preparation treatments (Table 4). MSP treatments were relatively similar regarding potential mineralization rates of N (sum of NH_4 and NO_3). Availability of other elements, as well as pH, cation exchange capacity (CEC) and base saturation (BS), did not differ significantly between MSP treatments (data not shown). Mechanical soil preparation also reduced slightly the thickness of the residual, post-treatment organic soil layer (for the four MSP treatments, mean = 7.9 to 8.8 cm; SE = between 0.6 and 1.7; $n = 8$) compared with the undisturbed FH horizon in unprepared plots (mean = 10.1 cm; SE = 1; difference marginally significant at $0.05 < P < 0.1$). Competition control, in contrast, had no significant effect on soil variables (data not shown).

Foliar nutrient content (mg g^{-1} of Ca, K, Mg, N, and P) during summer of all years varied across MSP treatments to different extents depending on the nutrient. Calcium and P foliar contents were similar among treatments, with ranges of 55-75 mg g^{-1} and 13-16 mg g^{-1} (and P values between treatments of 0.12 and 0.40, respectively). Foliar contents of K (84-

123 mg g^{-1}), Mg (14-21 mg g^{-1}) and N (13-15 mg g^{-1}) varied significantly between MSP treatments, and usually with higher values in more intensive treatments producing better growth. Unprepared plots always showed the lowest values.

4. Discussion

The silvicultural treatments tested in this study, particularly MSP, affected several parameters that may in turn impact tree growth, such as above- and belowground competition, soil chemical, physical and biological properties, as well as the distribution of these properties in the soil. Moreover, the treatments interacted in important ways to modify those parameters. This discussion will focus on each silvicultural tool separately, and will also include interactions when appropriate.

Considering the relatively harsh climatic and soil conditions in the region of study, these hybrid poplar plantations performed reasonably well when treated with the best available management tools (i.e., mounding). The highest growth obtained was slightly better than that of other studies on hybrid poplars conducted in forested sites of Quebec (Coll et al., 2007; Guillemette and DesRochers, 2008; Sigouin, 2008), but not as good as in forested sites of Vancouver Island in western Canada (van den Driessche, 1999; Brown and van den Driessche, 2005), and fairly comparable to plantations established on agricultural sites in the transitional zone between the prairies and the boreal forest of central Canada (Pinno and Bélanger, 2009; Pinno et al., 2009).

4.1. Mechanical soil preparation

The gradient of increasing height growth across MSP treatments paralleled the gradient of increasing MSP intensity. The slowest growth was obtained at unprepared plots that retained the original, undisturbed soil layers with a relatively thick organic layer. The best growth was found among the strongly disturbed mounds mostly made up of mineral soil with a buried organic horizon, whereas intermediate growth was produced by varying intensities of organic and mineral soil mixing (i.e., harrowing and disk trenching). These results generally agree with previous studies on other tree species that reported greater benefit to growth from intensive MSP treatments (Nilsson and Allen, 2003; Landhäusser, 2009).

Another crucial benefit derived from MSP relates to the establishment and early survival of trees. In plots that were not mechanically prepared prior to planting, mortality of hybrid poplars was as high as 20%, a number also reported by Burgess et al. (1995). Moreover, many of these trees died early, in the first or second year after planting (as suggested by the higher time since death, Fig. 5; and S. Bilodeau-Gauthier, personal observation). In other MSP treatments, mortality was lower than 5% in general, and even absent in mounded plots. In an intensive management perspective, where the production of every single seedling involves substantial resources, MSP is therefore a necessity in Precambrian Shield settings characterized by coarse acidic soils.

The MSP treatments used in this study also had an impact on soil conditions. The more intensive MSP treatments reduced the soil water content, but this was apparently not sufficient to hamper tree growth. MSP created microsites favourable to tree growth and development, as emphasized by the present growth results and as predicted in other studies (Örlander, 1987; Sutton, 1993; Thiffault et al., 2003). These favourable microsites were notably the consequence of improved soil penetrability and temperature. Soil temperature was similar in mounds and harrowed plots but higher than in unprepared plots, as also reported by Sigouin (2008). A higher soil temperature can have positive effects on soil N mineralization (Grenon et al., 2004). Grenon et al. (2005) even suggested that N mineralization rates were more important for tree growth than total soil N reservoirs. Here, mounds produced the same amount of mineralized N compared to other MSP treatments where more organic matter was preserved. In contrast, mounds were mostly composed of mineral soil, and exhibited the lowest total N content of all MSP treatments. Therefore, mounding might have seemed detrimental to tree growth because of this nutrient-poor and drought-prone mineral soil in which the tree is initially planted. Indeed, the removal of nutrient-rich organic matter was shown to cause nutrient deficiencies and limit tree growth (Merino and Edeso, 1999), and Fang et al. (2008) recently highlighted the benefits of nutrient-rich organic material for hybrid poplar growth. Still, mounding created beneficial conditions for soil fertility since N mineralization was equal to that in other MSP treatments. Although this does not yet explain the greater growth yield attributable to mounding, at least it suggests that this MSP technique is possibly on par with others with regards to the N supply.

Because mounding created less compacted and warmer soil conditions than harrowing and the control, root development in early years could have been favored in mounds. This was shown through visual observation of root excavations undertaken within all MSP treatments and the control at the end of the first growing season (data not shown) and as revealed by a series of non-destructive root excavations undertaken during the fourth growing season on 45 trees within the mounding and control plots at all eight sites (Bilodeau-Gauthier et al., submitted for publication). In these excavations, trees growing on mounds systematically had substantially larger root systems than trees from other MSP treatments. The well-developed root system on mounds could also explain the strong height response of the trees to an added nutrient supply. Early root development in mounds has indeed been shown to be a great asset for the subsequent success in height growth (Block et al., 2006; Block et al., 2009). In addition, the surface of mounds, with mineral soil exposed, was generally almost devoid of competing vegetation for a few years after the treatment (Bilodeau-Gauthier et al., personal observations). The upheaval and exposure of the mineral soil seemed to efficiently reduce colonization by competing species, a reduction that is a typical benefit of mounding treatments (Örlander et al., 1990).

Along the same lines, Messier et al. (2009a) observed, in a split-root pot experiment where half of the pot was covered with competing grasses while the other was bare, that fine-root biomass of hybrid poplars was highly sensitive to the presence of competing roots despite adequate supplies of water and nutrients. Also, Platt et al. (2004) observed positive responses in mountain beech (*Nothofagus solandri*) seedlings after root competition removal, with or without fertilizer additions, but no response to fertilization alone. This again suggests that belowground competition for nutrients can be strong and that trees benefit from fertilization the most when competition is low (Kabba et al., 2007).

Furthermore, the underlying – and undisturbed – organic horizon over which the mound was formed might represent a reservoir of nutrients available to the tree once the roots are deep enough. Because former vegetation is buried and possibly destroyed when mineral soil is upturned to form the mound, this potential reservoir is probably relatively devoid of competing roots from other plants. Although the data presented in this paper showed the mound surface soil to be less fertile than in other MSP treatments, further investigation of deeper horizons will possibly reveal yet another benefit of mounding.

4.2. Competition control

Competition control increased the height and diameter growth of hybrid poplars, which is in accordance with previous reports on aboveground vegetation removal for hybrid poplars (Czapowskyj and Safford, 1993; mowing treatments of Pinno and Bélanger, 2009). It should be noted, however, that the competition control treatments used here did not totally eliminate the competing vegetation as opposed to other studies using herbicides or soil cultivation (Coll et al., 2007; Sigouin, 2008; Pinno and Bélanger, 2009). Notably, Coll et al. (2007) reported that 2-year-old hybrid poplars planted at formerly forested sites gained nothing from mechanical removal of aboveground plant parts, while there were great benefits from herbicide applications that targeted competing roots. They thus concluded that competition was strongest for soil nutrients at these sites and that competition control treatments needed to aim at belowground plant parts. Nonetheless, shoot removal certainly also impacts belowground plant parts by killing fine roots (Comas et al., 2000) and by limiting water uptake.

The present study revealed responses of tree growth to aboveground competition control that differed when combined to other silvicultural management tools. Admittedly, this was not apparent when looking at absolute values because the interaction term in the mixed analysis of variance was not significant. However, by comparing relative growth values of trees in weeded and unweeded plots, it appeared that the relative growth gain (RGG) due to VC varied according to MSP treatment, but only for height and not diameter. Indeed, the effect of competition control on hybrid poplar growth was stronger in the less intensive MSP treatments. In unprepared plots, mean height growth of weeded hybrid poplars was more than 2-fold (200%) that of the unweeded trees, while in mounding plots the RGG due to VC was only around 25% (Fig. 4).

A similar conclusion was reached by Burgess et al. (1995) after 7 years in *Pinus strobus* and *Picea glauca* plantations in Ontario, Canada. This emphasizes the idea that MSP itself is an efficient approach to limiting competition for resources (Pehl and Bailey, 1983; Ross and Walstad, 1986). As a result, removing plant competition where it has previously been reduced by MSP has much less impact on the development of target trees. Analogous to that are the results of Pinno and Bélanger (2009), who reported that competition control was less effective on unproductive, nutrient-poor sandy sites where competition for soil resources was naturally low. In a study on pine plantations, Nilsson and Allen (2003) observed that loblolly pine growth was enhanced in early years due to herbicide control of competing vegetation.

Because VC had no significant effect on soils, and because removal of aboveground parts of plant competitors mainly impacts aboveground competition, the effects of VC on tree growth reported in the present study should represent mostly the response of trees to changes in light competition intensity. When competing vegetation is controlled only at year 3, it has similar or slightly greater benefits for hybrid poplars than control at years 2 and 4. This suggests that a silvicultural intervention at that time is not optimal, and that the better results of the third-year brushing treatment would represent a more efficient improvement in light availability from competition removal.

4.3. Fertilization

Fertilization can provide a substantial improvement in short-term growth, as suggested by the ~30% improvement in height growth observed in fertilized trees during the application year (Table 3). This is similar to other reports of hybrid poplar production gains from fertilization of 21% (Heilman and Xie, 1993; Brown and van den Driessche, 2002), 40% (Coleman et al., 2006), or even 62% (Czapowskyj and Safford, 1993). Yet, in some very nutrient-limited plantations, gains as high as 200% in tree biomass were obtained (Coyle and Coleman, 2005). Nonetheless, it does not seem to be universally effective since in this study the improvement was significant only on mounds. Some explanations for this include (1) the advantage of a larger root system in mounds (see discussion below) that could allow quick and efficient absorption of the nutrient input, and (2) the uptake of N and P by competing herbaceous plants in the other MSP treatments or unprepared plots (see herbaceous cover data in the results section). Overall, the results suggest that fertilization may not be sufficient to compensate for inadequate soil preparation. This was also proposed by Nilsson and Allen (2003), who observed no effect of fertilization (at planting) in low intensity MSP treatments, while in intensive MSP treatments it positively influenced tree growth in later years, after crown closure. Shiver et al. (1990) compared silvicultural treatments on Spodosols (Podzols) with more fertile soil types, and concluded that fertilization and competition control had more lasting effects on the cold, acidic, nutrient-poor Spodosols.

In the present study, combining N with P fertilizer additions did not result in greater growth, despite the fact that P was found to be important in certain ecosystems (Abel et al., 2002; Trichet et al., 2009). There has also been reports on the benefits of combining N and P in other, possibly more nutrient-deficient stands (Blevins et al., 2006), notably some aspen (*Populus tremuloides*) plantations in western Canada (van den Driessche et al., 2005) and cottonwood clones in Washington State, USA (DeBell et al., 1990). In a study that combined competition control and fertilization, Borders et al. (2004) observed increased growth due to competition control in the early years, while fertilization had lasting effects on growth enhancement. In their fertilization trial, Amateis et al. (2000) measured only the height of dominant trees and, as a result, they could not observe fertilizer effects on less than optimally developed trees, as we managed to do here with trees in unprepared plots. Higher leaf mass and N content after fertilization are in accordance with previous studies (Zhang and Allen, 1996; Zhang et al., 1997; Coleman et al., 2006).

5. Conclusion

The results of this study have important implications for future management strategies of hybrid poplar plantations in boreal regions. The different techniques and management tools used here interacted, with varying effects depending on the site conditions induced by the treatments, in ways that can influence the decision of using those techniques or not. Still, other considerations (e.g., socio-economical) might further influence the decision process.

Based on our results, we propose that forest managers prioritize their management interventions as follows: mechanical soil preparation > aboveground vegetation control > fertilization. We suggest this sequence because MSP has the greatest impact in creating favourable soil microsites for planting, in reducing competing vegetation previously on site, and in promoting tree establishment, survival and growth. VC and fertilization, as applied in this study, could not compensate for inadequate MSP. When both of these treatments were undertaken at unprepared sites, trees were about half the height of those on mounds with neither VC nor fertilization.

The present results and suggestions are in line with the few other studies that encompassed similar ranges of interacting tools, albeit with different tree species in different environments (Nilsson and Allen, 2003; Carter and Foster, 2006; Zhao et al., 2009). Among the MSP treatments, mounding appears to offer better early results due to rapid root development, high seedling survival, and substantial N mineralization. In addition, its effects were still observable after several years. The high sensitivity of hybrid poplar roots to belowground competition may explain why MSP is so critical to this species. In conditions where some VC is considered necessary, it could be done only during the second year after planting to minimize the cost and maximize the results. Finally, fertilization should be considered only if intensive MSP is also done.

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LIST OF FIGURES

Fig. 1. Example site (*n* = 8) of treatment plots in the experimental hybrid poplar plantations. Each of the four mechanical soil preparation (MSP) treatments and the control covers 1 ha, and treatments are randomized within a site. The four vegetation control (VC) subplots (randomized within each MSP plot) are: (*i*) never, (*ii*) once a year at year 2, (*iii*) once a year at years 1 and 3, and (*iv*) once a year at years 1, 2 and 3.

Fig. 2. Effect of mechanical soil preparation (MSP) and vegetation control (VC) on height growth (cumulative 5-year height growth) of hybrid poplars across four different MSP treatments and the control (unprepared). Values are means of trees from 8 sites, error bars are SE. MSP treatments and the control were all compared to each other through a post hoc Tukey HSD, and different letters thus represent significantly different means at $\alpha = 0.05$. The two most extreme VC treatments (at years 1-2-3, and never) are significantly different within each treatment.

Fig. 4. Effects of vegetation control (VC) on the relative growth gain (RGG, the difference between the cumulative 5-year growth of weeded and unweeded subplots within a same MSP plot, divided by the growth of the unweeded subplot, and expressed as a percentage).

Fig. 5. Mortality rate (%) and time since death (TSD; in years) per mechanical soil preparation (MSP) treatment and the control (unprepared). A higher value of TSD implies that a tree died early. Values are means of trees from 8 sites, error bars are SE. MSP treatments and the control were all compared to each other through a post hoc Tukey HSD, and different letters thus represent significantly different means at $\alpha = 0.05$ (letters apply to both mortality rate and TSD, which vary equally along the MSP gradient); a letter in parentheses implies a marginal difference ($0.05 < P < 0.1$).

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Table 1

General soil characteristics of the mineral B-horizon (sampled at a depth of 15-20 cm). Values are means for eight sites, with standard deviation.

Table 2

Detailed results of the mixed ANOVA comparing hybrid poplar height and diameter growth with treatments of mechanical soil preparation (MSP) and vegetation control (VC) in a 3-level hierarchical design of site/plot/subplot. Subplot had no variance assigned to it because growth of individual trees was averaged within 0.25-ha subplots. %variance is the proportion of total variance provided by a given source of variation.

Table 3

Effect of fertilization (N and N+P combined) on annual (2008 and 2009) shoot growth and proportional growth (current year height divided by previous year height) of hybrid poplars in two mechanical soil preparation (MSP) treatments and the control (unprepared). Values are means from all eight sites, with SE in parentheses. Probability that the growth of fertilized trees is higher than that of unfertilized trees is the result of an analysis of variance.

Table 4

Effects of mechanical soil preparation (MSP) on soil physical and chemical characteristics. Measures were taken in the first 20 cm of surface soil. Values are means across all eight sites, with SE in parentheses. For each soil characteristic, MSP treatments and the control were all compared to each other through a post hoc Tukey HSD, and different letters thus represent significantly different means at $\alpha = 0.05$

Figure 1

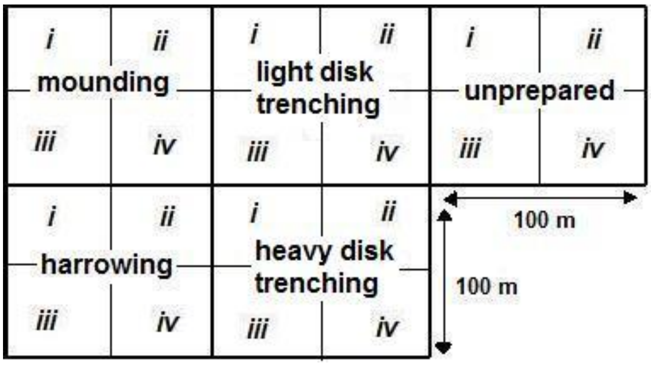

i
ii
mounding
iii
iv
i
ii
light disk trenching
iii
iv
i
ii
unprepared
iii
iv
i
ii
harrowing
iii
iv
i
ii
heavy disk trenching
iii
iv
100 m
100 m

Figure 2

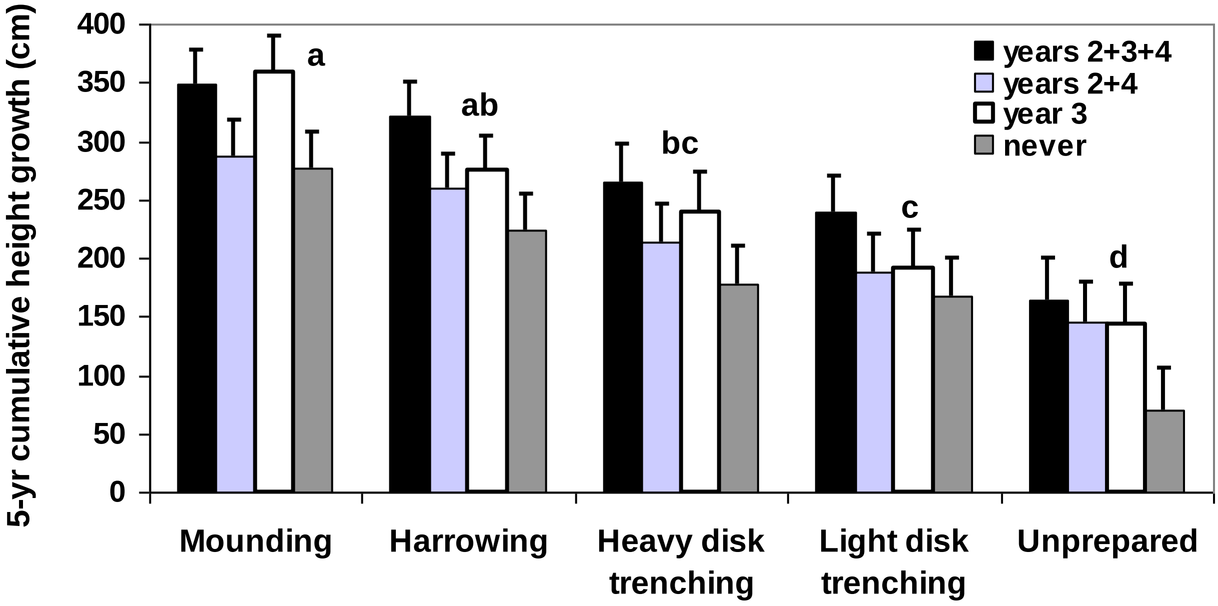

5-yr cumulative height growth (cm)
400
350
300
250
200
150
100
50
0
a
ab
bc
c
d
years 2+3+4
years 2+4
year 3
never
Mounding
Harrowing
Heavy disk trenching
Light disk trenching
Unprepared

Figure 3

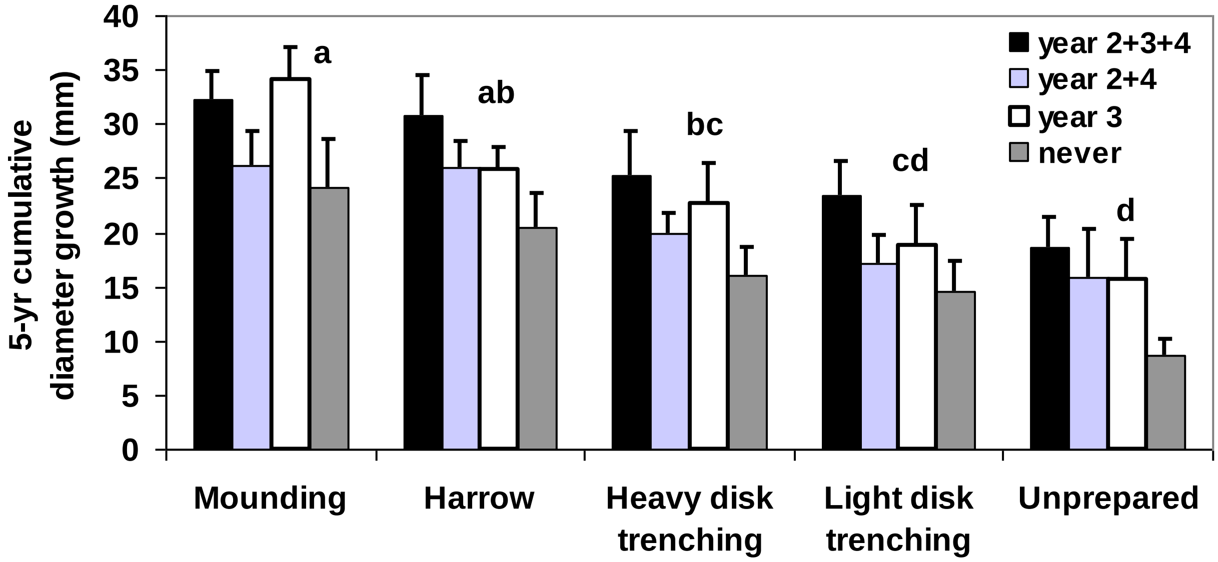

5-yr cumulative diameter growth (mm)
0
5
10
15
20
25
30
35
40
a
ab
bc
cd
d
■ year 2+3+4
▨ year 2+4
☐ year 3
▩ never
Mounding
Harrow
Heavy disk trenching
Light disk trenching
Unprepared

Figure 4

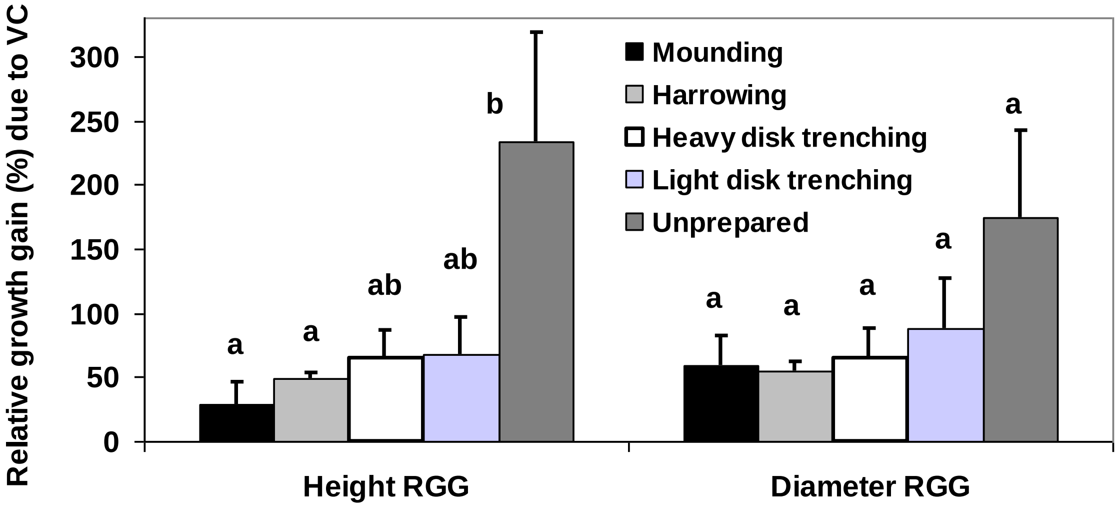
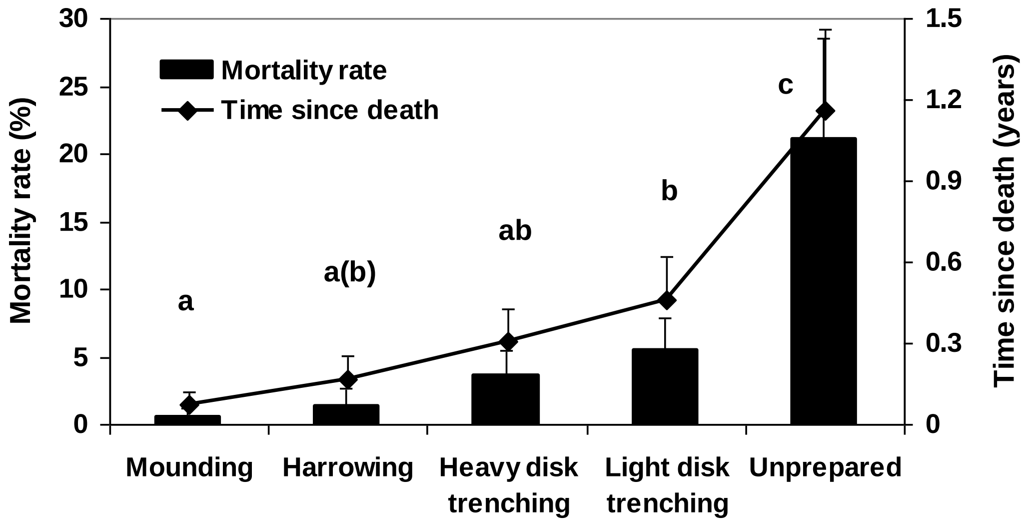

Relative growth gain (%) due to VC
300
250
200
150
100
50
0
Mounding
Harrowing
Heavy disk trenching
Light disk trenching
Unprepared
a
a
ab
ab
b
a
a
a
a
a
Height RGG
Diameter RGG

Figure 5



Mortality rate
Time since death
Mortality rate (%)
Time since death (years)
30
25
20
15
10
5
0
1.5
1.2
0.9
0.6
0.3
0
a
a(b)
ab
b
c
Mounding
Harrowing
Heavy disk trenching
Light disk trenching
Unprepared

Table 1

Soil variable	Site mean	SD
Texture		
Clay, %	5.0	1.2
Silt, %	24.7	4.9
Sand, %	70.3	4.8
CEC, $\mathrm{cmol_c\ kg^{-1}}$	2.27	2.4
pH	4.13	0.17
BS, %	53.3	16.1
Bulk density, $\mathrm{g\ cm^{-3}}$	1.05	0.16

Table 2

Source of variation	df	SSE	MSE	%variance	F-value	P-value
Height growth						
Fixed effects						
Mechanical soil preparation (MSP)	4	62,8326	157,081	72.8	19.4	< 0.0001
Vegetation control (VC)	3	146,272	48,757	22.6	6.02	0.000696
MSP x VC	12	23,840	1,987	0.9	0.245	0.995
Random effects						
Block	7	15,582	2,226	1.0		
Plot	28	67,620	2,415	1.1		
Residuals	102	345,931	3,391	1.6		
Total	156					
Diameter growth						
Fixed effects						
Mechanical soil preparation (MSP)	4	4,126	1,032	59.7	13.1	< 0.0001
Vegetation control (VC)	3	1,798	599	34.6	7.58	< 0.0001
MSP x VC	12	242	20	1.2	0.256	0.995
Random effects						
Block	7	190	27.1	1.6		
Plot	28	1,243	44.4	2.6		
Residuals	102	746	7.31	0.4		
Total	156					

Table 3

MSP	Shoot growth (cm)		Prob [Fert > Non-Fert]	Proportional growth		Prob [Fert > Non-Fert]
	Fertilized	Unfertilized		Fertilized	Unfertilized	
Year 5						
Mounding	136.8 (10.5)	104.1 (9.1)	0.0094	1.53 (0.02)	1.38 (0.02)	0.0005
Harrowing	106.1 (11.8)	92.4 (12.4)	0.47	1.43 (0.03)	1.32 (0.04)	0.054
Control	67.2 (15.9)	58.4 (16.4)	0.68	1.43 (0.04)	1.36 (0.03)	0.28
Year 6						
Mounding	105.7 (5.9)	77.0 (10.4)	0.036	1.28 (0.02)	1.22 (0.01)	0.023
Harrowing	84.9 (5.7)	61.2 (7.1)	0.031	1.26 (0.02)	1.22 (0.02)	0.14
Control	67.4 (15.2)	91.1 (13.0)	0.22	1.31 (0.04)	1.27 (0.03)	0.40
Year 5	Leaf mass (g leaf $^{-1}$)			Leaf N (mg g^{-1})		
Mounding	0.62 (0.03)	0.40 (0.01)	< 0.0001	23.3 (1.3)	18.3 (1.0)	0.0081
Harrowing	0.54 (0.04)	0.42 (0.03)	0.033	22.3 (0.9)	17.4 (0.9)	0.0019
Control	0.46 (0.04)	0.34 (0.03)	0.027	22.0 (0.5)	17.6 (0.8)	0.0006

Table 4

	Mechanical soil preparation		
Soil variable	Mounding	Harrowing	Unprepared
Temperature, °C	14.8 (0.9) a	14.3 (0.6) ab	13.8 (0.5) b
Humidity, % vol. water	13.9 (1) a	21.5 (2) b	26.1 (2) b
Penetrability, cm	28.5 (2) a	21.1 (1) b	23.8 (2) ab
Total C, mg g^{-1}	15.4 (3) a	46.0 (6) b	80.1 (15) c
Total N, mg g^{-1}	0.797 (0.2) a	2.02 (0.3) b	3.44 (0.6) c
C/N	23.3 (3) a	23.3 (1) a	22.6 (0.9) a
Mineralized N, mg g^{-1}	0.0518 (0.02) a	0.0293 (0.01) a	0.0455 (0.02) a