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Intensive Mechanical Site Preparation to Establish Short Rotation Hybrid Poplar Plantations—A Case-Study in Québec, Canada

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Abstract: Because they generate more wood per area and time, short rotation plantations are likely to play an increasing role in meeting the global increase in the demand for wood fiber. To be successful, high-yield plantations require costly intensive silviculture regimes to ensure the survival and maximize yields. While hybrid poplar (*Populus* spp.) is frequently used in intensive, short rotation forestry, it is particularly sensitive to competition and resource levels. Mechanical site preparation is thus of great importance to create microsites that provide sufficient light levels and adequate soil water and nutrient availability. We conducted an experiment in Québec (Canada) to compare two intensive site preparation treatments commonly used to establish hybrid poplar. We compared the effects of double-blade site preparation (V-blade), mounding and a control on hybrid poplar growth and nutritional status four growing seasons after planting on recently harvested forested sites. We also evaluated the effects of site preparation and planted poplar on inorganic soil N. Our results confirmed general positive effects of site preparation on the early growth of hybrid poplar clones. After four growing seasons, survival was higher in the mounding treatment (99%) than in the V-blade (91%) and the control (48%). Saplings planted in the V-blade and in the mounding treatments had mean diameters that were respectively 91% and 155% larger than saplings planted in the control plots. Saplings were 68% taller in the mounding treatment than the control plots, but differences between the V-blade and controls were not significant. We did not detect significant effects of site preparation or the presence of planted hybrid poplar on soil inorganic N. Sapling foliar nutrient concentrations were not influenced by the site preparation treatments. Based on these results, mounding appears to be a good management approach to establish hybrid poplar plantations under the ecological conditions we have studied, as it is less likely to cause erosion because of the localized nature of the treatment. However, these environmental benefits need to be balanced against economic and social considerations.

Keywords: intensive silviculture; *Populus maximowiczii* × *P. deltoides* × *P. trichocarpa*; fast-growing tree species; severe soil disturbance; foliar nutrition; soil inorganic N

1. Introduction

Fast-growing plantations established using performant plant material and managed over short rotations are increasingly being considered as a solution to meet the global increase in the demand for wood fiber. Moreover, when integrated into functional zoning, high-yield plantations contribute to offsetting timber production losses related to extensive management and conservation areas [1]. They also provide an opportunity to produce wood fiber over shorter periods of time than in natural forests or less intensively-managed plantations, thus reducing the time crop trees are exposed to biotic and abiotic risk factors. The annual increase in area of planted forests worldwide was 1.2% between 2010–2015, which is half of the rate estimated to be needed to meet the six billion cubic meters of the global wood demand in 2050 [2,3].

To be successful and meet their production objectives, high-yield plantations require intensive silviculture regimes to ensure the survival and maximize the growth of planted seedlings. After harvesting of boreal and sub-boreal forest ecosystems, thick soil organic horizons and competition for resources by fast-growing herb and shrub species limit root growth of planted seedlings or cuttings and jeopardize successful establishment [4]. Mechanical site preparation is thus frequently used to create a sufficient number of suitable planting microsites that provide adequate light levels as well as proper soil water and nutrient availability, while limiting waterlogged conditions [5]. Hybrid poplar (*Populus* spp.) is frequently used in intensive, short rotation forestry [6–12]; this species offers fast growth rates and high productivity [13]. However, adequate site preparation is mandatory to ensure survival and promote early growth, as the species is particularly sensitive to competition and resource levels [14,15].

We conducted an experiment in Québec, a Canadian province characterized by the abundance of its forest resources, which extend over 760,000 km^2 and represent 2% of the world's forests. With 40% of the world's certified forest area within its border, Canada has the largest area of third-party independently certified forests in the world [16], and provincial forest acts, including the one in force in Québec, are based on the principles of sustainable forest management [17]. Forestry activities must thus protect ecosystem functions. For example, management activities have to ensure that site productivity is maintained over the long-term with minimal or no impacts on soil and water quality, even under intensive silviculture regimes. Additionally, in Québec, herbicide use is restricted on private lands and prohibited on public lands [18], which creates a further challenge for the establishment of hybrid poplar, a species known to be highly sensitive to root competition [19].

In this context, we compared two intensive mechanical site preparation treatments commonly used to establish hybrid poplar in Québec, namely double-blade site preparation and mounding. Blading creates series of ~3 m-wide furrows oriented parallel to each other, in which the mineral soil is entirely exposed. This technique displaces a large volume of soil and reduces competing vegetation but might negatively affect soil physical and microbial characteristics [20] and favor N leaching from the site. Mounding, on the other hand, creates ~0.7 m^3 mounds composed of bare mineral soil deposited on top of inverted organic material; mounds are dispersed on the site, approx. 3 m from each other. This technique generates greater cost than blading (~1500 CAN$ ha^{-1} for mounding vs. ~1200 CAN$ ha^{-1} for blading), because it requires more costly equipment and more machine time. Mounding is generally effective in enhancing soil drainage and aeration and in increasing soil temperature, thus favoring high survival and early growth of planted seedlings [21,22], including for fast growing species like hybrid poplar [19]. Although both blading and mounding create a severe soil disturbance at the microsite scale, blading results in greater site disturbance when considered at the stand scale [23–25]. The use of this technique is thus raising concerns as it can promote soil erosion, especially at the early stages of plantation establishment [26]. However, because of its fast growth rates and high nutritional needs, hybrid poplar can significantly influence soil nutrient dynamics [27] and potentially act as a buffer of site preparation effects on soils.

Our objective was to compare the effects of two site preparation treatments (plus a control) on hybrid poplar growth and nutritional status four growing seasons after planting on recently harvested forested sites. We also compared site preparation and planted poplar effects on inorganic soil N as an indicator of site potential productivity. We predicted that sapling height and diameter at breast height would be greater in site prepared plots compared to control conditions, but that blading and mounding would result in similar sapling dimensions. We however posited that blading would result in lower concentrations of soil inorganic N, compared to the other treatments, with correspondingly lower foliar macronutrient concentrations in saplings planted in these plots than in the other treatments. Finally, we also tested the effect planting hybrid poplar on soil inorganic N, and expected that the presence of hybrid poplars would have a positive effect on soil inorganic N by buffering out the negative site preparation impact (significant site preparation × plantation interaction).

2. Materials and Methods

2.1. Study Site and Experimental Design

The experiment was implemented between September 2012 and June 2013 at four sites located approximately 11 km east of the municipality of Saint-Pascal, Québec (Canada) and 4 km south of the municipality of Rivière-Bleue, Québec (Canada). More specifically, the four sites were located at 47°5048200 N, 69°6610600 W; 47°4801800 N, 69°6539300 W; 47°4714900 N, 69°0555400 W; and 47°4728400 N, 69°0535300 W, respectively. The study sites are within the balsam fir (*Abies balsamea* L. [Mill])–yellow birch (*Betula alleghaniensis* Britt.) bioclimatic domain as described in the Québec ecological classification system [28]. In this region, climate is humid-continental with a mean annual temperature of 3.1 °C (± 0.9 °C) and total annual precipitation of 1012 mm (28% fall as snow) [29]. The altitude varies between 240–360 m above sea level. Based on the Canadian System of Soil Classification [30], soils are Gleysolic Podzols and were formed from a moderate (0.5–1 m) to deep (>1 m) coarse glacial till deposit (47% sand, 34% silt, 19% clay; pH = 5.2). After harvesting, mesic sites in this region are typically invaded by fast growing, light demanding shrub and tree species such as *Rubus idaeus* L., *Prunus pensylvanica* L., *Acer spicatum* Lam., and *Populus tremuloides* Michx [31].

We established a complete block 3 × 2 split-plot design with four replicated blocks (one block per site). Each block was divided into three main plots of approx. 700 m^2, each of which was randomly selected to receive one of three site preparation treatments: Two mechanical site preparation treatments plus a control. The first treatment, performed between September and November 2012, was a double-blade scarification as described and illustrated in Hébert et al. [24]: A first scarification pass was executed by a "V-blade" attached in front of a bulldozer that created a 2.7 m wide × 0.47 m deep furrow that exposed the mineral soil. Then, a second pass with a smaller "V-blade" (back hoe) mounted on the back of the same bulldozer was done to increase furrow depth at its center. Furrows were laid out in parallel strips within the plots (Figure 1a). The second treatment was mounding site preparation performed with a 0.8 m^3 bucket mounted on an excavator that dug the soil to collect the mineral layers. Afterwards, the content of the bucket was inverted next to the hole, and created a 0.3 m high × 1.5 m wide × 1.5 m long mound (Figure 1b). Mounds were positioned at about 3 m from each other within each treated main plot. The third main plot of each block was left unprepared to serve as a control (Figure 1c).

After site preparation, each main plot was divided into two sub-plots, each of which was randomly selected to be either planted with a hybrid poplar clone or left unplanted. Following provincial guidelines, we selected a clone of *Populus maximowiczii* × *P. deltoides* × *P. trichocarpa* [32] for plantation in the selected sub-plots. Planting was performed in May 2013, as described by Hébert et al. [24]. In summary, we planted one-year-old unrooted cuttings of approximately 100 cm in height, 30 cm deep in the soil at a spacing of approx. 4 m × 3 m (~833 stems ha^{-1}) using a metallic rod to create a planting hole. In the double-blade scarification treatment, the cuttings were planted at the hinge position of the scarification furrows [24]. In the mounding treatment, we planted cuttings at the top of the mound. Based on operational practices in this region, we fertilized all planted cuttings in May 2014 with 460 g of a 15–30–5 NH_4–NO_3 granular fertilizer, within a radius of 50 cm around the cutting base.

Granular fertilizer was also applied in the unplanted sub-plots so that the presence of hybrid poplars was the only factor differentiating the planted from the unplanted treatment. The resulting design was a 3 × 2 split-plot with three levels of site preparation (V-blade, Mounding, Control), and two levels of plantation (with plantation, without plantation), replicated four times (i.e., on four different sites).

(a) (b)

(c)

Figure 1. Example of main plots with the site preparation treatments that were tested in the study. The "V-blade" treatment resulted in 2.7 m wide × 0.47 m deep furrows that exposed the mineral soil (**a**). Mounding site preparation consisted in 0.3 m high × 1.5 m wide × 1.5 m long inverted mounds adjacent to the holes created by the excavator (**b**). Control plots consisted in unprepared soil conditions (**c**).

2.2. Sapling Measurements

Cuttings were identified and mapped following planting. In September 2016, we measured diameter at breast height (DBH, at 1.3 m) of all saplings, and measured total height on trees selected for foliar analyses (see below). We assessed tree survival based on initial measurements.

2.3. Foliar and Soil Nutrients

In each planted sub-plot of every block, we selected five planted trees for foliar sampling in September 2016 (end of the fourth growing season since planting). The selected trees were located in the four corners and near the centre of the sub-plot, respecting a buffer of one planted tree from the sub-plot borders. On each selected tree, we collected 10 leaves that we grouped to form one composite sample per tree. Leaves were collected randomly from the base of the tree crown up to a maximum height of about 2 m. Samples were kept cold until further analyzes. They were then oven-dried at 60 °C and ground to pass a 0.5 mm mesh. Using 200 mg sub-samples, we analyzed concentration of total N through direct combustion at 1350 °C and analysis using a TruMac CN Elemental Analyzer (LECO Corporation, St-Joseph, MI, USA). We used sub-samples of 90–110 mg for H_2SO_4–H_2O_2 digestion [33] (6 mL 18 M H_2SO_4; 4 mL 9.8 M H_2O_2), and measured P, K, Ca, and Mg concentrations by inductively coupled plasma analysis (Thermo Jarrel-Ash-ICAP 61E, Thermo Fisher Scientific, Waltham, MA, USA).

In each sub-plot, we collected four soil cores at the end of the 2016 growing season using a 4.8 cm diameter metal cylinder inserted down to the first 15 cm of mineral soil. In planted sub-plots, sampling spots were located at the base of the four corner-saplings that were sampled for foliar analyses. In unplanted sub-plots, we collected samples in the four corners in microsites that would have been adequate for planting. Soil samples were dried to 5% mass based moisture content and sieved at 2 mm. Five grams of soil (±0.02 g) were extracted with 50 mL 2M KCl solution [34] and inorganic N (NH_4–N and NO_3–N) was analysed by spectrophotometry (QuikChem R8500 Series 2, Lachat Instruments, Milwaukee, WI, USA) after 30 min. agitation and filtration.

2.4. Statistical Analyses

Data regarding DBH, height and foliar nutrients were analyzed using linear mixed models with site preparation as a fixed effect and the block as a random effect following a fully randomized block design. Results regarding inorganic soil N were analyzed using a linear mixed model with site preparation, plantation, and site preparation × plantation interaction as fixed effects and the block as a random effect following a split-plot design. An α threshold of 0.05 was used to identify significant effects. Normality and homoscedasticity were verified for all data using visual distribution of data and by analysis of residues. Natural logarithmic transformations were made when necessary. Comparisons between site preparation treatments were assessed with Tukey's a posteriori mean comparison tests. All statistical analyses were performed with the *nlme* and *emmeans* packages of R, version 3.5.3 [35–37].

3. Results

We found a significant effect of treatments on height and DBH as measured 4 growing seasons after planting ($p \leq 0.006$; Figure 2). Saplings were 68% taller in the mounding treatment than the control plots ($p = 0.005$), but height in V-blade treated plots was not different from height in control conditions ($p = 0.116$; Figure 2a). Sapling height was statistically equivalent in plots treated with mounding and V-blade ($p = 0.065$). Saplings in the V-blade and in the mounding treated plots had a DBH that was respectively 91% and 155% larger than saplings planted in the control plots ($p \leq 0.021$; Figure 2b). DBH was equivalent between the mounding and V-blade treatments ($p = 0.195$). Survival was higher in the mounding (99%), compared to 91% in the V-blade and 48% in the control treatments.

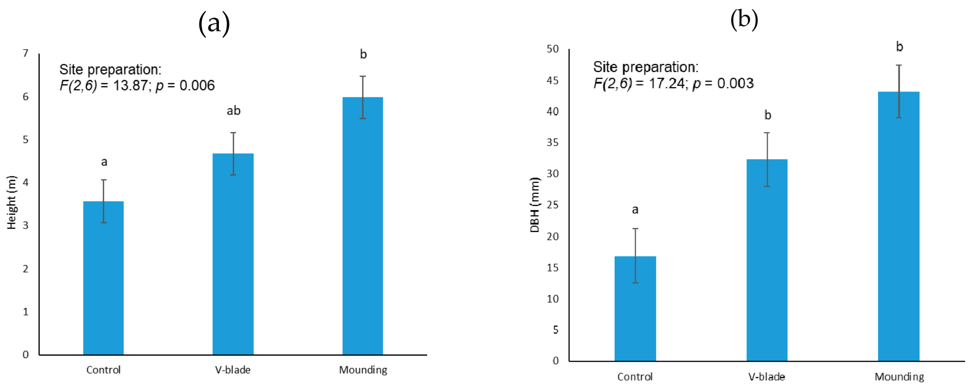

Figure 2. Effects of mechanical site preparation treatments on hybrid poplar sapling height (**a**) and diameter at breast height (DBH) (**b**) after four growing seasons, along with results from the linear mixed models (values in parentheses are the numerator and denominator degrees of freedom). *p*-value for the random block effect was <0.001 for both variables. For a given variable, values with similar letters are not significantly different at $\alpha = 0.05$ based on Tukey HSD pairwise comparisons. Data are presented as means ± standard error.

None of the foliar nutrient concentrations differed between site preparation treatments four growing seasons after planting (Table 1). Soil inorganic N was equivalent between site preparation treatments and was not influenced by the presence/absence of planted hybrid poplars (Table 1).

Table 1. Synthesis of the linear mixed model results for hybrid poplar foliar nutrition and soil inorganic N, as measured four growing seasons after planting.

Variable	Mean (SE)	Site Preparation (SP)		Plantation (P)		SP × P	
		F (2,6) [a]	*p*-Value [b]	*F* (1,9) [a]	*p*-Value [b]	*F* (2,9) [a]	*p*-Value [b]
Foliar N ($g{\cdot}kg^{-1}$)	12.4 ± 0.7	3.2	0.112	–	–	–	–
Foliar P ($g{\cdot}kg^{-1}$)	2.0 ± 0.2	4.7	0.058	–	–	–	–
Foliar K ($g{\cdot}kg^{-1}$)	15.3 ± 10.3	0.0	0.993	–	–	–	–
Foliar Ca ($g{\cdot}kg^{-1}$)	14.0 ± 2.3	2.3	0.183	–	–	–	–
Foliar Mg ($g{\cdot}kg^{-1}$)	2.2 ± 0.4	0.2	0.815	–	–	–	–
Soil inorganic N ($mg{\cdot}kg^{-1}$)	3.1 ± 0.2	2.6	0.155	3.9	0.080	2.6	0.132

[a] Presented as *F (numerator degrees of freedom, denominator degrees of freedom)*. [b] *p*-values for the random block effect varied from < 0.001 to 0.048, depending on variables.

4. Discussion

Our results confirm the global positive effects of site preparation on the survival and the early growth of hybrid poplar clones, a fast growing species that is sensitive to nutrient deficiencies and competition by vegetation after planting, especially on forested sites [15,18]. Previous studies in temperate and boreal regions have reported positive effects of mechanical site preparation on species like *Populus* spp., *Pine* spp., and *Picea* spp. [38–41]. The objective of mechanical site preparation is to create adequate microsites for seedling rooting and early growth. Soil disturbance affects substrate temperature, moisture and density (porosity), and ultimately nutrient availability and light exposure ([20] and references therein). The advantages of mounding over blading might be related to the microtopography created by the treatment. Mounding is not recommended on drought-prone sites because mounds are susceptible to drying, which might compromise cutting survival, particularly during the first season after planting. However, soil elevation creates a well-drained, aerated and uncompact substrate that provides better rooting conditions, an advantage given the high annual precipitation regime in our study region (1012 mm). On the other hand, cuttings planted in furrows created by blading might suffer from soil water saturation and root hypoxia, particularly if the water table is high [39,42]. Site preparation can indeed modify rooting patterns; root distribution is more even on mounds than in furrows created by disc trenching [43].

Site preparation such as soil inversion or ploughing has been reported to increase [18,44] or decrease [45,46] soil N pool or mineralized N concentration. In our study, conducted on relatively rich boreal mixedwood sites of Eastern Canada, we did not measure any significant effect of site preparation on soil inorganic N. Similarly, sapling foliar nutrient concentrations were not influenced by the treatments either, although foliar nutrient concentrations suggest that N is below the optimum range while other nutrients appeared to be near the optimum [47]. The effects of site preparation are highly dependent on soil characteristics, including management history, surficial deposit and climate. Benefits from site preparation on nutrient availability and subsequently, on planted cutting nutritional status, are less likely to occur on sites with thin humus relative to boreal forest sites with thick humus layers [48,49]. We expected that the presence of hybrid poplar would, by itself, influence soil inorganic N. Indeed, because of the quality of its litter, the presence of *Populus tremuloides* in boreal stands has been shown to improve cation exchangeable capacity and pH of the forest floor [50]. We posit that we have not detected these effects on the sites we have studied because litter input is still too low to influence soil physical and chemical properties and because tree growth appears to be mainly N limited. Longer-term monitoring of the planted/unplanted plots of this experiment will allow testing the impacts of hybrid poplar on soil properties and disentangle them from those of site preparation.

5. Conclusions

Both of the mechanical site preparation treatments we have tested in this study significantly increased the radial growth of planted hybrid poplar, but only mounding had a significant effect on sapling height growth relative to control conditions. These effects could not be explained by improved soil nutrient availability or foliar nutritional status and might be the results of improved root growth, water status or abiotic or biotic interactions not studied here. Based on these results, mounding, with a higher survival rate, appears as a good management approach to establish hybrid poplar plantations under the ecological conditions studied here. Although the differences with V-blading were small in terms of sapling growth, mounding is less likely to cause erosion and nutrient lixiviation than blading because of the localized nature of the treatment. These environmental benefits need, however, to be balanced against economic and social considerations in the context of sustainable forest management. For example, apart for being more costly, the mounding treatment creates a rough microtopography that can be a challenge for vegetation management operations using motor-manual brushsaws as an alternative to chemical herbicides [51], contrary to V-blading that creates regular corridors in which workers can easily circulate.

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References

1. Paquette, A.; Messier, C. The role of plantations in managing the world's forests in the Anthropocene. *Front. Ecol. Environ.* **2010**, *8*, 27–34. [CrossRef]
2. Barua, S.K.; Lehtonen, P.; Pahkasalo, T. Plantation vision: Potentials, challenges and policy options for global industrial forest plantation development. *Int. For. Rev.* **2014**, *16*, 117–127. [CrossRef]
3. Payn, T.; Carnus, J.-M.; Freer-Smith, P.; Kimberley, M.; Kollert, W.; Liu, S.; Orazio, C.; Rodriguez, L.; Silva, L.N.; Wingfield, M.J. Changes in planted forests and future global implications. *For. Ecol. Manag.* **2015**, *352*, 57–67. [CrossRef]
4. Balandier, P.; Collet, C.; Miller, J.H.; Reynolds, P.E.; Zedaker, S.M. Designing forest vegetation management strategies based on the mechanisms and dynamics of crop tree competition by neighbouring vegetation. *Forestry* **2006**, *79*, 3–27. [CrossRef]
5. Thiffault, N.; Jobidon, R.; Munson, A.D. Comparing large containerized and bareroot conifer stock on sites of contrasting vegetation composition in a non-herbicide scenario. *New For.* **2014**, *45*, 875–891. [CrossRef]
6. Goehing, J.; Henkel-Johnson, D.; Macdonald, S.E.; Bork, E.W.; Thomas, B.R. Spatial partitioning of competitive effects from neighbouring herbaceous vegetation on establishing hybrid poplars in plantations. *Can. J. For. Res.* **2019**, *49*, 595–605. [CrossRef]
7. Fortier, J.; Truax, B.; Gagnon, D.; Lambert, F. Abiotic and biotic factors controlling fine root biomass, carbon and nutrients in closed-canopy hybrid poplar stands on post-agricultural land. *Sci. Rep.* **2019**, *9*, 6296. [CrossRef]
8. Thomas, B.R.; Schreiber, S.G.; Kamelchuk, D.P. Impact of planting container type on growth and survival of three hybrid poplar clones in central Alberta, Canada. *New For.* **2016**, *47*, 815–827. [CrossRef]
9. Grenke, J.S.J.; Macdonald, S.E.; Thomas, B.R.; Moore, C.A.; Bork, E.W. Relationships between understory vegetation and hybrid poplar growth and size in an operational plantation. *For. Chron.* **2016**, *92*, 469–476. [CrossRef]
10. Mamashita, T.; Larocque, G.R.; DesRochers, A.; Beaulieu, J.; Thomas, B.R.; Mosseler, A.; Major, J.; Sidders, D. Short-term growth and morphological responses to nitrogen availability and plant density in hybrid poplars and willows. *Biomass Bioenerg.* **2015**, *81*, 88–97. [CrossRef]

11. Masse, S.; Marchand, P.P.; Bernier-Cardou, M. Forecasting the deployment of short-rotation intensive culture of willow or hybrid poplar: Insights from a Delphi study. *Can. J. For. Res.* **2014**, *44*, 422–431. [CrossRef]
12. Larocque, G.R.; DesRochers, A.; Larchevêque, M.; Tremblay, F.; Beaulieu, J.; Mosseler, A.; Major, J.E.; Gaussiran, S.; Thomas, B.R.; Sidders, D.; et al. Research on hybrid poplars and willow species for fast-growing tree plantations: Its importance for growth and yield, silviculture, policy-making and commercial applications. *For. Chron.* **2013**, *89*, 32–41. [CrossRef]
13. Stanturf, J.A.; van Oosten, C. Operational poplar and willow culture. In *Poplars and Willow: Trees for Society and the Environment*; Isebrands, J.G., Richardson, J., Eds.; FAO: Rome, Italy, 2014; pp. 200–257.
14. Bilodeau-Gauthier, S.; Paré, D.; Messier, C.; Bélanger, N. Juvenile growth of hybrid poplars on acidic boreal soil determined by environmental effects of soil preparation, vegetation control, and fertilization. *For. Ecol. Manag.* **2011**, *261*, 620–629. [CrossRef]
15. McCarthy, R.; Rytter, L.; Hjelm, K. Effects of soil preparation methods and plant types on the establishment of poplars on forest land. *Ann. For. Sci.* **2017**, *74*, 1–12.
16. Forest Products Association of Canada. *Forest Certification in Canada. The Programs, Similarities and Achievements*; Forest Products Association of Canada (FPAC): Ottawa, ON, Canada, 2011.
17. Québec, Sustainable Forest Development Act. Chapter A-18.1. In Les Publications du Québec: Québec, QC, Canada. 2020. Available online: http://legisquebec.gouv.qc.ca/en/ShowDoc/cs/A-18.1 (accessed on 10 June 2020).
18. Bilodeau-Gauthier, S.; Paré, D.; Messier, C.; Bélanger, N. Root production of hybrid poplars and nitrogen mineralization improve following mounding of boreal Podzols. *Can. J. For. Res.* **2013**, *43*, 1092–1103. [CrossRef]
19. Messier, C.; Coll, L.; Poitras-Larivière, A.; Bélanger, N.; Brisson, J. Resource and non-resource root competition effects of grasses on early- versus late-successional trees. *J. Ecol.* **2009**, *97*, 548–554. [CrossRef]
20. Löf, M.; Dey, D.C.; Navarro, R.M.; Jacobs, D.F. Mechanical site preparation for forest restoration. *New For.* **2012**, *43*, 825–848. [CrossRef]
21. Pennanen, T.; Heiskanen, J.; Korkama, T. Dynamics of ectomycorrhizal fungi and growth of Norway spruce seedlings after planting on a mounded forest clearcut. *For. Ecol. Manag.* **2005**, *213*, 243–252.
22. Bolte, A.; Löf, M. Root spatial distribution and biomass partitioning in *Quercus robur* L. seedlings: The effects of mounding site preparation in oak plantations. *Eur. J. For. Res.* **2010**, *129*, 603–612. [CrossRef]
23. Buitrago, M.; Paquette, A.; Thiffault, N.; Bélanger, N.; Messier, C. Early performance of planted hybrid larch: Effects of mechanical site preparation and planting depth. *New For.* **2015**, *46*, 319–337.
24. Hébert, F.; Bachand, M.; Thiffault, N.; Paré, D.; Gagné, P. Recovery of plant community functional traits following severe soil perturbation in plantations: A case-study. *Int. J. Biodiv. Sci. Ecosyst. Serv. Manag.* **2016**, *12*, 116–127. [CrossRef]
25. Sutton, R.F. Mounding site preparation: A review of European and North American experience. *New For.* **1993**, *7*, 151–192. [CrossRef]
26. Figueiredo, T.; Fonseca, F.; Martins, A. Soil loss and run-off in young forest stands as affected by site preparation technique: A study in NE Portugal. *Eur. J. For. Res.* **2011**, *131*, 1747–1760. [CrossRef]
27. Truax, B.; Gagnon, D.; Lambert, F.; Fortier, J. Riparian buffer growth and soil nitrate supply are affected by tree species selection and black plastic mulching. *Ecol. Eng.* **2017**, *106*, 82–93. [CrossRef]
28. Saucier, J.P.; Robitaille, A.; Grondin, P. Cadre bioclimatique du Québec. In *Manuel de Foresterie*, 2nd ed.; Doucet, R., Côté, M., Eds.; Ordre des Ingénieurs Forestiers du Québec, Éditions Multimondes: Québec, QC, Canada, 2009; pp. 186–205.
29. Environment Canada Canadian Climate Normals 1981–2010 Station Data. Available online: http://climate.weather.gc.ca/climate_normals/index_e.html (accessed on 10 June 2020).
30. Soil Classification Working Group. *The Canadian System of Soil Classification*, 3rd ed.; 1646; Agriculture and Agri-Food Canada: Ottawa, ON, Canada, 1998; p. 187.
31. Jobidon, R. *Autécologie de Quelques Espèces deCcompétition d'Importance pour la Régénération Forestière au Québec. Revue de Littérature 117*; Ministère des Ressources Naturelles, Direction de la Recherche Forestière: Québec. QC, Canada, 1995; p. 180.
32. Réseau Ligniculture Québec. *Le Guide de Populiculture au Québec*; Réseau Ligniculture Québec: Québec, QC, Canada, 2011; p. 124.
33. Thomas, R.R.; Sheard, R.W.; Moyer, J.R. Comparison of conventional and automated procedures for nitrogen, phosphorus and potassium, analysis of plant material using a single digestion. *Agron. J.* **1967**, *59*, 240–243. [CrossRef]

34. Carter, M.; Gregorich, E. *Soil Sampling and Methods of Analysis*, 2nd ed.; CRC Press: Boca Raton, FL, USA, 1993; p. 1262.
35. Pinheiro, J.; Bates, D.; DebRoy, S.; Sarkar, D. R Core Team nlme: Linear and Nonlinear Mixed Effects Models R package version 3.1-140. 2019. Available online: https://cran.r-project.org/package=nlme (accessed on 10 June 2020).
36. R Core Team. *R: A Language and Environment for Statistical Computing*; R Foundation for Statistical Computing: Vienna, Austria, 2017; Available online: https://www.r-project.org/ (accessed on 10 June 2020).
37. Lenth, R. Emmeans: Estimated Marginal Means, aka Least-Squares Means. R package version 1.3.5.1. 2019. Available online: https://CRAN.R-project.org/package=emmeans (accessed on 10 June 2020).
38. Fraser, E.C.; Landhäusser, S.M.; Lieffers, V.J. The effects of mechanical site preparation and subsequent wildfire on trembling aspen (*Populus tremuloides* Michx.) regeneration in central Alberta, Canada. *New For.* **2003**, *25*, 67–81. [CrossRef]
39. Simard, M.; Lecomte, N.; Bergeron, Y.; Bernier, P.Y.; Paré, D. Forest productivity decline caused by successional paludification of boreal soils. *Ecol. Appl.* **2007**, *17*, 1619–1637. [CrossRef]
40. Hébert, F.; Boucher, J.-F.; Walsh, D.; Tremblay, P.; Côté, D.; Lord, D. Black spruce growth and survival in boreal open woodlands 10 years following mechanical site preparation and planting. *Forestry* **2014**, *87*, 277–286. [CrossRef]
41. Henneb, M.; Valeria, O.; Thiffault, N.; Fenton, N.J.; Bergeron, Y. Effects of mechanical site preparation on microsite availability and growth of planted black spruce in Canadian paludified forests. *Forests* **2019**, *10*, 670. [CrossRef]
42. Sikström, U.; Hökkä, H. Interactions between soil water conditions and forest stands in boreal forests with implications for ditch network maintenance. *Silva Fenn.* **2016**, *50*, 1416. [CrossRef]
43. Celma, S.; Blate, K.; Lazdiņa, D.; Dūmiņš, K.; Neimane, S.; Štāls, T.A.; Štikāne, K. Effect of soil preparation method on root development of P. sylvestris and P. abies saplings in commercial forest stands. *New For.* **2018**, *50*, 283–290. [CrossRef]
44. Ryan, D.F.; Huntington, T.G.; Martin, C.W. Redistribution of soil nitrogen, carbon and organic matter by mechanical disturbance during whole-tree harvesting in northern hardwoods. *For. Ecol. Manag.* **1992**, *49*, 87–99. [CrossRef]
45. Sutinen, R.; Gustavsson, N.; Hänninen, P.; Middleton, M.; Räisänen, M.L. Impact of mechanical site preparation on soil properties at clear-cut Norway spruce sites on mafic rocks of the Lapland Greenstone Belt. *Soil Tillage Res.* **2019**, *186*, 52–63. [CrossRef]
46. Aleksandrowicz-Trzcińska, M.; Drozdowski, S.; Studnicki, M.; Żybura, H. Effects of site preparation methods on the establishment and natural-regeneration traits of scots pines (*Pinus sylvestris* L.) in northeastern Poland. *Forests* **2018**, *9*, 717. [CrossRef]
47. Lteif, A.; Whalen, J.K.; Bradley, R.L.; Camiré, C. Diagnostic tools to evaluate the foliar nutrition and growth of hybrid poplars. *Can. J. For. Res.* **2008**, *38*, 2138–2147. [CrossRef]
48. Thiffault, N.; Jobidon, R. How to shift unproductive *Kalmia angustifolia-Rhododendron groenlandicum* heath to productive conifer plantation. *Can. J. For. Res.* **2006**, *36*, 2364–2376. [CrossRef]
49. Thiffault, N.; Jobidon, R.; Munson, A.D. Performance and physiology of large containerized and bare-root spruce seedlings in relation to scarification and competition in Québec (Canada). *Ann. For. Sci.* **2003**, *60*, 645–655. [CrossRef]
50. Légaré, S.; Paré, D.; Bergeron, Y. Influence of aspen on forest floor properties in black spruce-dominated stands. *Plant Soil* **2005**, *275*, 207–220. [CrossRef]
51. Thiffault, N.; Roy, V. Living without herbicides in Québec (Canada): Historical context, current strategy, research and challenges in forest vegetation management. *Eur. J. For. Res.* **2011**, *130*, 117–133. [CrossRef]