Effects of timing of glyphosate application on jack pine, black spruce, and white spruce plantations in northern Manitoba¹

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ABSTRACT

Deferring conifer release treatments is sometimes necessary, but its effects on crop tree performance are not well understood. We investigated the effects of deferring glyphosate applications on jack pine (*Pinus banksiana* Lamb.), black spruce (*Picea mariana* [Mill.] BSP), and white spruce (*Picea glauca* [Moench.] Voss.) plantations established on a dry site with moderate competition and a moist site with heavier competition in The Pas, northern Manitoba. At each site, experimental treatments included no herbicide and one glyphosate (formulated as Vision®) at 1.42 kg acid equivalent glyphosate ha⁻¹ application between one and five years after planting with three replications. Survival, root collar diameter, and height of the three conifers were repeatedly measured for ten consecutive years following planting. Survival of the three conifers was not affected by glyphosate application. For all the three species, root collar diameter and stand volume of crop trees increased significantly in glyphosate-treated plots, compared to control plots. Varying the timing of glyphosate application between year 1 and 5 resulted in a similar conifer dimensions. Glyphosate application significantly improved height growth of black spruce and marginally white spruce, but not jack pine. On these sites, glyphosate reduced the cover of woody species, but grass, forbs and shrubs rapidly captured the newly available growing space. A two variable regression analysis revealed that grass cover negatively affected stand volume of all three conifer species. Cover of tall shrub, forbs, and interaction of cover and height of tall shrubs were the next most important variables to explain jack pine, black spruce, and white spruce volume growth, respectively.

Key words: vegetation management, forest herbicides, survival, growth, stand volume, long-term repeated measurements

RÉSUMÉ

Le report des traitements de dégagement des conifères est parfois nécessaire, mais ses effets sur la performance des arbres à récolter ne sont pas bien connus. Nous avons étudié les effets du report des applications glyphosate dans le cas de plantations de pin gris (*Pinus banksiana* Lamb.), d'épinette noire (*Picea mariana* [Mill.] BSP) et d'épinette blanche (*Picea glauca* [Moench.] Voss.) établies sur station sèche ayant un niveau modéré de compétition et sur station humide avec une compétition plus accentuée dans la région de The Pas dans le nord du Manitoba. Pour chaque station, les traitements expérimentaux comprenaient un témoin et une application de 1,42 kg ha⁻¹ d'agent équivalent de glyphosate (selon la formule Vision®) entre un et cinq ans après plantation, le tout selon trois reproductions. La survie, le diamètre de la racine au collet et le volume du peuplement constitué d'arbres à récolter ont été mesurés pendant dix années consécutives après la plantation. La survie des trois espèces de conifères n'a pas été affectée par l'application de glyphosate. Pour les trois espèces, le diamètre de la racine au collet et le volume du peuplement constitué d'arbres à récolter ont augmenté significativement dans les parcelles traitées au glyphosate, comparativement aux parcelles témoins. La variation dans le moment de l'application de glyphosate entre l'an 1 et l'an 5 a eu pour conséquence des dimensions semblables chez les conifères. L'application de glyphosate a amélioré de façon significative la croissance en hauteur des épinettes noires et de façon marginale celle des épinettes blanches, mais pas celle des pins gris. Sur ces stations, le glyphosate a réduit le couvert des espèces ligneuses, mais les plantes graminées, les plantes herbacées et les arbustes ont rapidement pris possession de l'espace de croissance nouvellement disponible. Une analyse de régression à deux variables a révélé que le couvert herbacé a affecté négativement le volume du peuplement dans le cas des trois espèces de conifères. Le couvert des grands arbustes et des plantes herbacées, ainsi que l'interaction du couvert et de la hauteur des grands arbustes ont été les variables les plus importantes en second lieu pour expliquer la croissance en volume respectivement du pin gris, de l'épinette noire et de l'épinette blanche.

Mots clés : contrôle de la végétation, herbicides forestiers, survie, croissance, volume du peuplement, mesures répétées à long terme

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Introduction

Clearcutting in boreal forests typically favours the development of opportunistic, fast-growing herbaceous and woody species, which capture available resources at the expense of conifer seedlings (Munson *et al.* 1993, Sutherland and Foreman 2000). Clearcutting of mixedwood forest types on nutrient-rich, mesic soils often promotes vegetative reproduction of deciduous hardwoods such as trembling aspen (*Populus tremuloides* Michx.), balsam poplar (*Populus balsamifera* L.), and white birch (*Betula papyrifera* Marsh.). Once the hardwoods are controlled through the use of herbicides or motor-manual cutting, grasses and forbs can quickly colonize the available growing space (Bell *et al.* 1997). Competition from grasses, forbs, shrubs and deciduous hardwoods reduces the survival and growth of conifer seedlings (Balandier *et al.* 2006).

Competition control typically improves crop tree growth in northern temperate and southern boreal forests and can be accomplished in a number of ways including the use of herbicides (Walstad and Kuch 1987, Munson *et al.* 1995, Thompson and Pitt 2003, Chen *et al.* 2006, Fu *et al.* 2007). Aerial application of herbicides, such as glyphosate (N-[phosphonomethyl] glycine), has been widely used in North America to control competing vegetation with the objective of increasing conifer growth (Walstad and Kuch 1987). Wagner *et al.* (2006) reported gains for several boreal conifers ranging from 0.3 and 8.2 m³ h⁻¹ for white spruce (four studies), 6.2 m³ h⁻¹ for black spruce (one study), and 13.3 m³ h⁻¹ for jack pine (one study) based on 10- to 12-year post-treatment measurements. These results are based on experimental units that were treated annually for up to five years with glyphosate and may represent biological maximums for the species studied. Gains following operational applications of glyphosate are unlikely to be equivalent to those that have been reported in the literature. Glyphosate is typically applied only once during a rotation, mostly in the second post-plant growing season but applications have been deferred to the third or even fifth post-plant season for political, financial, or technical reasons.

The objective of this study was to examine the effects of operational timing of glyphosate applications on jack pine, black spruce, and white spruce plantations in northern Manitoba. We specifically addressed two questions: (1) When is the optimum time to release the conifer crop trees from competition that includes herbaceous plants, woody shrubs, and hardwood trees in northern boreal forests? We used crop tree survival and the growth parameters root collar diameter and height to evaluate crop tree performance at the individual-tree level and stand volume of crop trees at the stand level. (2) Do different conifer species respond differently to year of application? We compared survival and growth performance of the three tree species based on ten years of repeated measurements on two plantations in northern Manitoba.

Materials and Methods

Study area and sites

The study sites were located near The Pas, Manitoba, with the latitude 53° 58' N, longitude 101° 6' W, and average elevation 270.40 m. The Pas has a mean annual temperature of 0.1°C, and mean precipitation is 443 mm, of which 324 mm falls as rain. Average July and August temperatures are 17.7°C and 16.5°C, respectively, with corresponding mean monthly precipitation of 65 mm and 63 mm (Environment Canada

2005). Two plantations were established within the Manitoba Lowland Section (B.15) of the Boreal Forest Region (Rowe 1972), respectively.

Goose Lake research site

The site was located on a generally flat area north of Goose Lake, Manitoba, which is about 40 km north of The Pas. The soil is clay without coarse fragments and strongly calcareous. The site is subject to prolonged spring flooding from snow melt and soil moisture regime is fresh to moist during the growing season, i.e., moist site. The pre-harvest stands were conifer-dominated mixedwoods, consisting of black spruce, trembling aspen, balsam poplar (*Populus balsamifera* L.), white spruce, jack pine, in decreasing order of importance based on stand volume; trembling aspen and balsam poplar contributed approximately 30% of the stand basal area. According to Sims *et al.* (1997) the predominant pre-harvest stands would be classified as a black spruce mixedwood/herb rich (V19). It was clearcut with conventional full-tree harvesting during winter 1988 and mechanically site prepared with a Ripper Tooth Plow in 1989. The Plow was pulled by a tracked Caterpillar tractor, which pushed aside logging debris and created a continuous furrow in which to plant. A Slash Rake was mounted on the front of the tractor and was used to push aside and pile fallen and relatively small standing hardwood trees. Seedlings were planted in the cleared area with no further soil disturbance other than kicking off the duff layer by planters.

Root Lake research site

The site is located about 20 km northwest of The Pas. The gently rolling loamy soils in this area contain moderate coarse fragments. The site is subject to spring flooding as a result of frozen soils retaining water from melted snow, but it is generally dry during the growing season, i.e., dry site. According to Sims *et al.* (1997) the predominant pre-harvest stands would be classified as a black spruce/feather moss (V33). The site was clearcut with conventional full-tree harvesting in the spring and summer of 1986 and 1987 and mechanically prepared in summer and fall of 1986 and 1989. The Root Lake site was site prepared with a Bracke Patch Scarifier, pulled behind a rubber-tired skidder, to create two rows of intermittent planting patches spaced approximately 2 m apart.

Experiment

A completely randomized block design with two blocks (study sites), six treatments and three replications was used. Within each of the two blocks, 18 treatment plots (90 m × 170 m) were established and randomly assigned to one of the six proposed treatments: no glyphosate, aerial chemical release with Vision^R at a rate of 4 L ha⁻¹ (1.42 kg acid equivalent [a.e.] glyphosate ha⁻¹) applied one, two, three, four, or five years after the conifers were planted. The location of treatment plots was planned to avoid excessively wet or dry microsites.

Buffers surrounding rectangular treatment plots were established to prevent influence from adjacent residual stands and by off-target deposits of glyphosate. Sample plots were located a sufficient distance from the edge of the treatment block to ensure complete treatment coverage. Each sample plot was subdivided into three subplots that were randomly selected to be planted with black spruce, jack pine, or white spruce in late spring 1990. Four hundred container seedlings grown from local seed were planted in each subplot at a 2-m

spacing (Delaney 1992). The average height and root calliper diameter were 15 cm and 2.1 mm for black spruce, 10 cm and 2.3 mm for jack pine, and 16 cm and 2.3 mm for white spruce, respectively.

Glyphosate applications were conducted in mid- August between 1991 and 1995 and spray cards were used to confirm the delivery and droplet size of glyphosate within each the treatment block. A Cessna Ag Truck was used to apply the 4 L ha⁻¹ of glyphosate mixed with 45 L ha⁻¹ of water at an average speed of approximately 175 km/h. The delivery system employed D10-46 nozzles and operated at a pressure of 21 P.S.I. Six passes were made over each treatment block with each swath being approximately 20 m wide.

Conifer field measurements and analysis

Within each subplot, a randomly located 100-m² sample plot was established to provide 25 planted conifer seedlings for measurements. All 25 seedlings within each sample plot were measured annually in August from 1990 to 1999. During each measurement, survival, root collar diameter (cm), and height (m) were assessed.

Survival was calculated for each plot at each measurement year as a ratio of surviving trees to total number of trees planted. Individual tree stem volume (*V*), assumed to be conical (*sensu* Pitt *et al.* 2004), was calculated from root collar diameter and height using the follow function (Eq. 1):

$$[1] \quad V = \frac{1}{3} \pi \left(\frac{RCD}{2} \right)^2 \times H$$

where *RCD* = root collar diameter (cm) and *H* = tree height (cm). All individual tree volumes were summed to subplot level and then scaled to per hectare to provide stand volume estimates.

For each planted species, we tested the effects of timing of treatment application using the following General Linear Model (Eq. 2) (Hicks 1993):

$$[2] \quad \begin{array}{c} \text{between subjects} \\ Y_{ijklm} = \mu + S_i + T_j + ST_{ij} + P_{k(ij)} \\ \text{within subjects} \\ + Y_l + SY_{il} + TY_{jl} + STY_{ijl} + \epsilon_{mlk(ij)} \end{array}$$

where *Y_{ijkl}* = the dependent variable of interest including survival, mean *RCD*, height, and stand volume of crop trees, respectively; *μ* = overall mean; *S_i* = sites (*i* = 1, 2); *T_j* = timing of glyphosate application (*j* = 1, 2, 3, 4, 5, 6), *P_{k(ij)}* = experimental plot within each site (*k* = 1, 2, ...18) and the error term for effects between subjects; *Y_l* = year of measurement (*l* = 1, 2,...10), and *ε_{mlk(ij)}* is the random error within subjects (Hicks 1993).

To simplify analysis, we also tested if herbicide timing resulted in different responses of crop trees by using the tenth year data only. The following model was used (Eq. 3):

$$[3] \quad Y_{ijk} = \mu + S_i + T_j + \epsilon_{k(ij)}$$

where *Y_{ijk}*, *μ*, *S_i* and *T_j* are same as described in Eq. 2. Tukey's post hoc multiple comparisons were performed when effects were significant (*α* = 0.05). Normality and homogeneity of variances were confirmed following the procedure described

in Neter *et al.* (1996). Stand volume was log transformed to meet the homogeneity assumption. Since Eq. 2 and Eq. 3 resulted in similar trends, we reported only the statistical results from Eq. 3. All statistical tests were performed using SYSTAT 10 (Systat Software Inc., San Jose, California).

Non-crop vegetation field measurements

Visual estimates of foliar cover projected onto ground level of individual fern, grass, forb, shrub and tree species were estimated to the nearest 5% by sampling four systematically located, crop-centred, 4-m² (1.13-m radius) non-overlapping circular quadrates per treatment plot. At the same time competitor height was measured to the nearest 5 cm using a height pole or a yard stick for competitors taller or shorter than 2 m, respectively. Assessments were made annually in August from 1990 to 1999. Average cover by broad vegetation category was calculated for each treatment through three steps. First, individual species were categorized into one of seven broad classes (i.e., fern, grass, forb, low shrub, tall shrub, hardwood, and conifer). Second, the cover of each species within a category was summed for each 4-m² sample plot. Average heights were determined in the same manner. Third, sample plot totals were summed by treatment and averaged. Since cover is additive, total sums may exceed 100%.

Regression analysis of gross total volume with non-crop vegetation

The effect of competing vegetation on volume growth of crop trees was examined using regression analyses. Stand volume of crop trees of the tenth year measurements (1999) was regressed against cover, height, and cover × height interactions of each competing vegetation category (i.e., fern, grass, forb, low shrub, tall shrub, hardwood, and softwood) using backward stepwise regression.

Results

Conifer responses

Survival did not differ significantly with glyphosate treatment, but did with site (Table 1). Survival averaged 81%

Table 1. Significance of site and treatment on survival, average root collar diameter (RCD, cm), average height (Ht, m), and stand volume of crop trees (SV, m³/ha)

Source ^a	Df	Survival	RCD	Ht	SV
Jack pine					
<i>S_i</i>	1	< 0.001	< 0.001	0.004	< 0.001
<i>T_j</i>	5	0.627	0.002	0.968	0.049
<i>ε_{k(ij)}</i>	29				
Black spruce					
<i>S_i</i>	1	0.037	< 0.001	< 0.001	< 0.001
<i>T_j</i>	5	0.824	< 0.001	0.034	0.028
<i>ε_{k(ij)}</i>	29				
White spruce					
<i>S_i</i>	1	0.373	0.094	0.023	0.075
<i>T_j</i>	5	0.405	0.016	0.091	0.019
<i>ε_{k(ij)}</i>	29				

^a*S_i* = site (*i* = 1, 2), *T_j* = glyphosate treatment (*j* = 1, 2, 3, 4, 5, 6).

across sites, species and treatments in the tenth growing season. At the end of tenth growing season, survival was 76% and 92% for jack pine, 79% and 90% for black spruce, and 72% and 76% for white spruce at Goose Lake and Root Lake, respectively.

Glyphosate applications significantly affected the RCDs for all three species (Table 1; Fig. 1), but the significant differences only occurred between controlled and treated plots while timing of glyphosate application between Yr 1 and Yr 5 resulted in similar RCDs (Fig. 1). Average root collar diameters (RCD) in the tenth growing season were 5.0, 2.6, and 2.3 cm for jack pine, black spruce and white spruce, respectively.

Height did not differ significantly with treatment for jack pine, but did significantly for black spruce ($P = 0.034$) and marginally for white spruce ($P = 0.091$) (Table 1; Fig. 2). Similar to RCD, the significant differences only occurred between controlled and treated plots while timing of glyphosate application between Yr 1 and Yr 5 resulted in similar heights (Fig. 2). Average heights of surviving seedlings in the tenth growing season were 2.39, 1.29, and 0.94, m for jack pine, black spruce, and white spruce, respectively (Fig. 2).

Glyphosate treatments significantly increased stand volume of crop trees (Table 1; Fig. 3). Similar to RCD and height growth, timing of glyphosate application between Yr. 1 and Yr. 5 did not lead to significant differences in stand volume. In the tenth growing season, stand volume was 3.0, 0.9 and 0.5 $\text{m}^3 \text{ha}^{-1}$ for jack pine black spruce, and white spruce, respectively (Fig. 3).

Vegetation responses

Vegetation cover was higher at Goose Lake than Root Lake at the beginning of the study and remained higher throughout the study period (Fig. 4). This vegetation was well established prior to implementing the treatments. Average total cover was 66% and 29% at Goose Lake and Root Lake, respectively, in 1990. In subsequent years, the average total cover continued to increase in control plots and reached a maximum of 146% and 83% at Goose Lake and Root Lake, respectively, in the eighth year of the study. In treated plots, total vegetation cover decreased the year after treatment and sharply increased typically to pre-treatment levels within a year to three years post-treatment (Fig. 4).

Fig. 1. Effects of glyphosate application (C = no treatment, Y1 = release first year after planting, Y2 = release second year after planting, and so on) on root collar diameter (RCD) of three conifer species at two study sites in northern Manitoba. Error bars are 1 SE.

Although the composition of the post-treatment vegetation differed from the controls, the glyphosate applications in Yr 1 and 5 did not reduce broadleaf cover in the same manner as applications in Yr 2 and 3 (Fig. 4). In general, shrub and hardwood cover was substantially reduced by glyphosate treatments while forb cover increased and grass and fern cover remained relatively unaffected (Fig. 4).

Stand volume and weed cover

Stepwise regression analysis showed that percent cover of grass was the most important variable that negatively affected stand volume of crop trees for all study species (Table 2). The coefficient of determination (R^2) of the fitted regressions varied with species with the highest for jack pine ($R^2 = 0.625$, $MSE = 0.733$) and lowest for white spruce ($R^2 = 0.325$, $MSE = 0.040$).

For two-variable models, the first variable was the same (grass cover) for all species, but the second variable differed by species. Percent cover of tall shrub, percent cover of forbs, and percent cover $\times$ height of tall shrubs were the second variables in two-variable models for jack pine, black spruce,

and white spruce, respectively. The coefficient corresponding to the second variable was negative for jack pine and black spruce and positive for white spruce (Table 2).

With more than two variables, the independent variables that entered during the stepwise regressions were not consistent across species. The order of regressor variables in the model also changed in the stepwise regression as a result of multi-collinearity among independent variables.

Discussion

We observed that aerial application of glyphosate did not improve 10th-year survival of crop trees of jack pine, black spruce, or white spruce. Our finding is consistent with previous vegetation control studies (e.g., Bell *et al.* 2000, Fu *et al.* 2007). The trade-off between reduced competition and exposure to suddenly increased radiation and greater variation in temperature and humidity may explain insignificant effects of vegetation control on crop tree survival. Alternatively, increased growth resulting from less competition may lead to less defensive investments and consequently, to lower survival rates. For shade-tolerant tree species, survival is generally

Fig. 2. Effects of glyphosate application (C = no treatment, Y1 = release first year after planting, Y2 = release second year after planting, and so on) on stem height of three conifer species at two study sites in northern Manitoba. Error bars are 1 SE.

Fig. 3. Effects of glyphosate application (C = no treatment, Y1 = release first year after planting, Y2 = release second year after planting, and so on) on stand volume of three conifer species at two study sites in northern Manitoba. Error bars are 1 SE.

independent of resource limitation from competition (Sipe and Bazzaz 1995, Chen 1997, Chen and Klinka 1998).

Glyphosate application increased crop tree RCD and stand volumes. Our findings from the northern boreal plantations are consistent with previous studies from southern boreal plantations (e.g., Chen *et al.* 2006, Fu *et al.* 2007). Compared with diameter growth, height growth of conifers is much less responsive to vegetation control (Morris *et al.* 1990, Brand 1991, Chen *et al.* 2006). The different responses between height and root collar diameter to brush control in jack pine and white spruce suggest that carbon allocation differs with level of competition (Chen *et al.* 1996).

Timing of glyphosate applications between years 1 to 5 had similar effects on crop tree growth. This suggests that delay in glyphosate applications within the first five years of plantation establishment would not have a negative effect on crop trees in the northern boreal forest. We explain the differences between our findings and those of Wagner *et al.* (1999) and Wagner and Robinson (2006) with (1) the use of

repeated glyphosate applications, and (2) the composition of the competitive vegetation complex. Competition effects differ greatly between herbaceous plants and woody species (Bell *et al.* 2000, Willoughby *et al.* 2006) as the latter have more pronounced long-term effects. Recent experiments from across North America suggest that woody vegetation alone captures about 20% to 30% of the early volume growth potential of crop trees. Achieving the remaining 70% to 80% of the growth potential of a site requires effective control of herbaceous vegetation (Wagner 2000). To maximize the growth of young conifer plantations, it may be necessary to reduce cover of grasses and forbs below a threshold of approximately 20% during the early years of plantation development (Wagner 2000). In our study, the treatments did not maintain competition below this threshold for more than a single growing season (Fig. 4). The fact that grass cover was the primary factor reducing conifer growth suggests that grasses need to be more aggressively controlled with more than a single application of glyphosate. Multiple applications,

Fig. 4. Effects of glyphosate application (C = no treatment, Y1 = release first year after planting, Y2 = release second year after planting, and so on) on competitive vegetation at two study sites in northern Manitoba.

Table 2. Estimated coefficients and fit characteristics for one and two variable(s) models for jack pine, black spruce, and white spruce stand volume of crop trees (one variable model is: Stand volume = $a_0 + a_1x$ and two variable model is: Stand volume = $a_0 + a_1x + a_2y$ where x and y are first and second regressor variables, respectively).

Species	Variables	a_0	a_1	a_2	R^2	MSE
Jack pine	Grass	4.5956	-0.1953	—	0.625	0.733
	Grass, tall shrub	4.8931	-0.1492	-0.1210	0.777	0.456
Black spruce	Grass	1.4214	-0.0748	—	0.483	0.163
	Grass, forb	1.9114	-0.0590	-0.0204	0.605	0.1316
White spruce	Grass	0.6897	-0.0272	—	0.325	0.0404
	Grass, TSh ¥ TSc	0.6364	-0.0328	0.0298	0.4388	0.0357

Note: TSh and TSc are height and cover of tall shrubs, respectively. All other variables are percent covers.

as recommended by Wagner and Robinson (2006) for control of vegetation on coarse sandy soils, may have been necessary on richer clay soils for maximum conifer growth potential to be expressed.

Conclusions

We described the effect of the timing of glyphosate application on survival and growth of jack pine, black spruce, and white spruce in the northern boreal forest. Glyphosate application did not affect survival, but increased root collar diameter and stand volume of crop trees for all the studied species. The effect of glyphosate application on height growth varied among species. The timing of glyphosate application between year 1 and year 5 did not result in a significant difference in crop tree growth. On these site conditions, a single application of glyphosate provided only temporary reductions in competition and did not reduce competition levels below the threshold needed to maximize conifer growth. Repeated glyphosate applications, as shown by Wagner and Robinson (2006), are probably necessary if the objective is to maximize conifer growth. Further research, including a follow-up measurement of this study at age 20 or later, is recommended to determine long-term effects of glyphosate treatments on boreal crop tree growth in the northern boreal forest.

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