TIMING AND DURATION OF HERBACEOUS VEGETATION CONTROL AROUND FOUR NORTHERN CONIFEROUS SPECIES

ROBERT G. WAGNER, THOMAS L. NOLAND, and GINA H. MOHAMMED

Ontario Forest Research Institute, Ontario Ministry of Natural Resources,
P.O. Box 969, 1235 Queen Street East, Sault Ste. Marie, Ontario, Canada P6A 5N5

(Received for publication 30 March 1995; revision 7 February 1996)

ABSTRACT

Optimum timing and duration of herbaceous vegetation control during the early development of forest plantations can be assessed using critical-period analysis. Critical periods are being developed for black spruce (*Picea mariana* (Mill.) B.S.P.), jack pine (*Pinus banksiana* Lamb.), eastern white pine (*Pinus strobus* L.), and red pine (*Pinus resinosa* Ait.) seedlings in the Great Lakes/St Lawrence forest type of Ontario, Canada. Six patterns of herbaceous vegetation control were examined: 3 consecutive years, first-year only, first 2 years, second and third years, third-year only, and no control. Third-year survival and height were not affected by herbaceous vegetation for any conifer species. Stem diameter, however, decreased substantially without vegetation control. Third-year diameters for white pine, jack pine, black spruce, and red pine without vegetation control were 55, 56, 61, and 64%, respectively, of that observed for trees under 3 consecutive years of vegetation control. Stem volume of all species without vegetation control was reduced to between 27 and 36% of that observed under 3 consecutive years of control. Height/stem diameter ratios decreased as the degree of vegetation removal increased. Critical-period analysis indicated that herbaceous vegetation control is important immediately after planting for both tolerant and intolerant conifer species. Stem diameter gains also were proportional to the number of years of herbaceous vegetation control.

Keywords: forest vegetation management; critical periods; competition thresholds; interspecific competition; competition tolerance; *Picea mariana*; *Pinus banksiana*; *Pinus strobus*; *Pinus resinosa*.

INTRODUCTION

Most research on the effects of interspecific competition on North American tree species has focused on the influence of vegetation density (Stewart *et al.* 1984; Walstad & Kuch 1987). Relatively little of this work has focused on the temporal effects of interspecific competition during early plantation development. Most efforts to develop competition indices for young trees also have not adequately accounted for the temporal effects of surrounding vegetation (Burton 1993; Wagner 1993). Optimising vegetation management strategies in young forest plantations requires an understanding of how the temporal effects of interspecific competition affect seedling survival and growth. In practical terms, when is the most effective time to reduce vegetative competition in the seedling environment?

The critical-period concept, first developed in agriculture in the late 1960s (Zimdahl 1988), defines the time period during crop development within which weed control must occur to prevent yield loss. Recent work in agriculture has focused on developing critical periods of weed control for a wide range of agricultural crops (Weaver & Tan 1983; Weaver 1984; Zimdahl 1988; Hall *et al.* 1992; van Acker *et al.* 1993; Woolley *et al.* 1993).

The critical period has been identified as an important component of integrated weed management for agriculture (Swanton & Weise 1991). Development of integrated forest vegetation management strategies also will require better identification of the site and vegetation conditions that are likely to benefit most from control measures (Wagner 1994). Identifying the conditions likely to benefit most from treatment is important for minimising vegetation control interventions and more cost-effectively prescribing alternatives to herbicides, which are often more expensive than herbicide applications.

The critical period is composed of two components (Weaver & Tan 1983). The first is the length of time weed control efforts must be maintained to prevent losses in crop yield. The second component is the length of time weeds can remain in a crop before they interfere with crop growth and begin to reduce yield. Critical-period research to date has focused almost exclusively on annual cropping systems. No work specifically examining critical periods for perennial cropping systems or forest stands was found. There have, however, been limited efforts to inadvertently quantify the first (Lanini & Radosevich 1986; Newton & Preest 1988; Lauer *et al.* 1993) and second (Duba *et al.* 1985) components in separate studies with forest trees.

The objective of this study was to identify and compare critical periods of herbaceous vegetation control for planted black spruce, jack pine, eastern white pine, and red pine during the first 5 years after planting. The study, begun in 1992, has completed three growing seasons.

Critical-Period Approach and Hypothetical Models

The critical-period principle for tree seedlings during the first 5 years after planting is demonstrated in Fig. 1. Two curves, following from the two critical-period components, are created. The weed-free curve indicates the number of years that vegetation control efforts must be maintained to prevent growth losses, or the increase in seedling growth that results from increasing years of herbaceous vegetation control. The weed-infested curve indicates the number of years that vegetation can be associated with seedlings before growth is reduced, or the decline in seedling growth associated with increasing years of not receiving vegetation control. The left and right extremes of each curve represent the same condition. For example, zero years weed infested equals 5 years weed free and vice versa. Seedling survival or any measure of tree growth can be used as a response variable in the analysis.

The critical period is determined by the linear distance between the points where the weed-infested curve begins to decline and the weed-free curve levels off. In biological terms, it is the time period between the point where vegetation begins to reduce tree growth and the point where additional vegetation control no longer increases tree growth. In the Fig. 1 example the critical period is between 1 and 3 years after planting. No significant yield loss

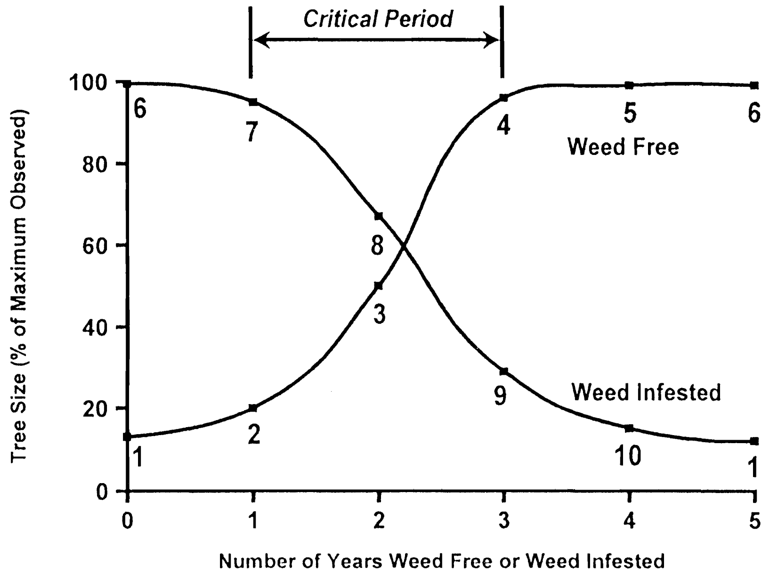

FIG. 1—Two components of critical-period analysis. The weed-free curve indicates the length of time vegetation control efforts must be maintained to prevent growth loss. The weed-infested curve indicates the length of time vegetation can be associated with trees before growth is reduced. Vegetation must be controlled during the critical period (years 1–3) to avoid reductions in growth. Numbers under curves correspond to the treatment number presented in Table 1.

occurs without vegetation control in the year before the critical period, and no additional gain results from vegetation control if it is applied after the critical period because additional years of weed control do not increase growth. So, the critical period defines the time period after planting within which herbaceous vegetation must be controlled to avoid significant growth losses.

These curves can be used to test different hypotheses about the temporal effects of interspecific competition. In Fig. 2 six hypothetical models are depicted, ranging from very wide critical periods (models A and B), to early (C), middle (D), and late (E) periods, to no critical period (F). Each model also has an ecological interpretation. For example, growth losses can be directly proportional to the number of years of exposure to interspecific competition (model A). If trees are highly sensitive to exposure to any interfering vegetation, model B is suggested. Although model B can be derived from potential combinations of weed-free and weed-infested curves, it is probably unlikely to occur in nature because corresponding decreases in the weed-infested curve should result in corresponding increases in the weed-free curve. Early (model C), middle (D), or late (E) critical periods suggest that negative interference is occurring between trees and associated plants at different stages of development. Model F indicates that no significant interference is occurring, possibly due to ecological niche separation between young trees and their neighbours. Various shapes among any of these six archetypical patterns also may be possible, and they may change over time as the stand develops and competitive relationships change.

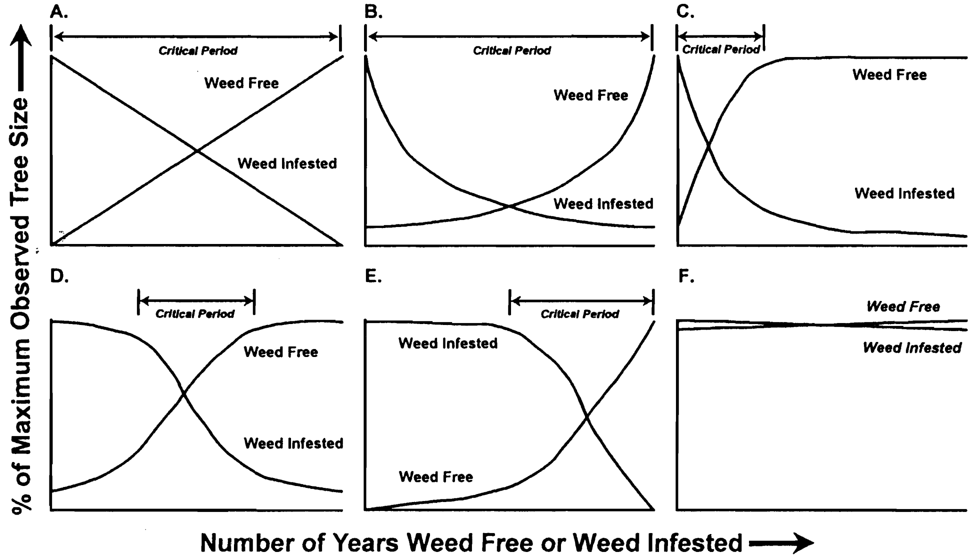

FIG. 2–Six hypothetical models from critical-period analysis. Patterns range from very wide critical periods (A and B), to early (C), middle (D), and late (E) periods, to no critical period (F). Model A indicates that growth losses are proportional to the number of years trees are associated with vegetation. Model B indicates that any association with vegetation substantially reduces tree growth. Models C, D, and E indicate that competitive interactions between trees and surrounding vegetation occur in the early, middle, and late portions, respectively, of the time stand development was studied. Model F indicates that no significant interference has occurred between trees and surrounding vegetation.

METHODS

Study Site

A site 50 km north of Sault Ste. Marie, Ontario, Canada, in the Great Lakes/St Lawrence forest type was selected for the critical-period study. The site, which was flat and had a sandy-textured soil, was clearfelled between 1987 and 1989. In July 1991, the site was prepared for planting with a Donaren disk trencher. The trenches were about 1.5 m wide and 2–3 m apart.

Herbaceous vegetation, dominated by bracken fern (*Pteridium aquilinum* (L.) Kuhn), false melic grass (*Schizachne purpurascens* (Torrey) Swallen), rough mountain rice grass (*Oryzopsis asperifolia* Michaux), violets (*Viola* spp.), and low sweet blueberry (*Vaccinium angustifolium* Ait.), was established over the entire area. Low densities of trembling aspen (*Populus tremuloides* Michx.) from root suckers also were present.

Experimental Design

Black spruce, jack pine, eastern white pine, and red pine seedlings were planted in a randomised complete block, split-plot design with 10 treatments and four blocks (replications) on the site. Each main plot was 28 × 28 m (0.0784 ha) in size and divided into four 14 × 14-m subplots to which each conifer species was randomly assigned. Thirty trees (five rows of six trees) of each species were planted on a 2 × 2-m spacing in each subplot. A total of 1200 seedlings of each species (4800 total) were planted at the start of the experiment. A 2-m-wide buffer was placed around each subplot.

Planting stock of each species was obtained for the seed zone from local nurseries and planted with shovels in mid-May 1992. The stock types obtained for each species were: jack pine—container, multipot 67 with 57 cc volume (height = 10.7 cm, stem diameter = 3.1 mm); red pine—2+0 medium bareroot (height = 9.2 cm, stem diameter = 4.3 mm); white pine—G+1.5 medium bareroot (height = 9.5 cm, stem diameter = 4.9 mm); and black spruce—G+2 medium bareroot (height = 29.3 cm, stem diameter = 5.2 mm). These stock types are typical of those used for these species when planted on similar sites in Ontario. To ensure maximum association with herbaceous vegetation from the start of the experiment, all trees were planted in the undisturbed areas between trenches, rather than on the inside edge of trenches as is the usual practice.

Vegetation Treatments

Herbaceous vegetation (grasses, ferns, and forbs) was controlled in a sequential pattern for the first 5 years after tree planting to provide tree responses for the two components of the critical-period analysis (Table 1). The 10 vegetation treatments included: no vegetation control; annual vegetation control; 1, 2, 3, and 4 consecutive years of control after planting; and waiting 1, 2, 3, and 4 years after planting before annual control was initiated. The numbers of the vegetation treatments (Table 1) correspond to specific points on the critical-period graph (Fig. 1).

The treatment sequence began immediately after the trees were planted in June 1992. Results from treatment numbers 1, 2, 3, 6, 7, and 8 (Table 1) over three growing seasons (1992–94) are reported in this paper.

Vegetation was controlled using a broadcast application (by backpack sprayer) of glyphosate herbicide (Vision®) at 2 kg a.e./ha in 93 ℓ water/ha. Applications were made at the beginning of each growing season when vegetation had developed sufficient leaf area to receive the herbicide (generally second to third week of June). Because conifers are

TABLE 1–Pattern of vegetation treatment (T = herbicide treated, O = untreated) for 5 years after planting to provide responses for two components of the critical-period analysis.

Vegetation treatment number	Year after planting 1	2	3	4	5
1	O	O	O	O	O
2	T	O	O	O	O
3	T	T	O	O	O
4	T	T	T	O	O
5	T	T	T	T	O
6	T	T	T	T	T
7	O	T	T	T	T
8	O	O	T	T	T
9	O	O	O	T	T
10	O	O	O	O	T

susceptible to injury from glyphosate at this time of year, all trees were protected with paper cups or plastic bags during herbicide application. Since glyphosate is not soil active, vegetation was able to recover in the year after treatment to provide the temporal patterns of vegetation presence desired in the study. All aspen on the plots was removed in 1992 by treating them with the same glyphosate mixture and manually cutting the stems several weeks after treatment.

Variables Measured

In October of each year, the survival and growth (height, ground-line stem diameter, and crown width) of all trees were recorded. Stem volume (stem diameter^2 × height) and height/stem diameter (H:D) ratio were calculated from the height and stem diameter measurements from each tree.

The composition and abundance of all herbaceous vegetation in the 28 × 28-m plots were recorded in late August to early September of each year. Species and percentage cover (visually estimated to the nearest 5%) were recorded for each plant species on six 1-m^2 (0.5 × 2-m) plots that were systematically located with a random start from the corner of each main plot. From the 240 vegetation plots, a subsample of approximately 40 plots (16.6%), representing a range of cover values, were selected for clipping each year. All clipped vegetation was bagged, dried at 70° C for 72 hours, and weighed for biomass estimates. A subsample of foliage collected from about half of the clipped plots was used to calculate a leaf area/dry weight ratio for leaf area index (LAI) estimates. Leaf area for the foliage subsample was determined before drying using a LI-COR 3100 area meter.

Analytical Approach

Mean tree survival and growth were statistically compared for each species among the six treatments using a standard ANOVA and Duncan's multiple-range test at $p \leq 0.05$. Although a split-plot experimental design was available, each species was analysed separately for a randomised complete block design. Survival, stem diameter, and H:D ratio were transformed before the ANOVA using a log transformation to meet assumptions of normality and homogeneous variances. Tree height did not require transformation.

RESULTS

Vegetation Abundance

Six of the 10 treatments were complete by the end of the third year (1994): 3 consecutive years of vegetation control (TTT), first-year only (TOO), first 2 years (TTO), second and third years (OTT), third year only (OOT), and no vegetation control (OOO). Untreated plots had from 50 to 80% vegetation cover (Fig. 3), corresponding to between 1300 and 3000 kg dry vegetation biomass/ha and a LAI from 1.3 to 2.5. Herbicide applications reduced cover to between 8 and 30%, having from 100 to 800 kg dry biomass/ha with a LAI from 0.1 to 0.75. Because glyphosate is not soil active, subsequent vegetation recovery achieved levels of abundance similar to that of untreated plots within 1 year after treatment. Herbicide applications in successive years reduced cover to lower levels each year. Total vegetation abundance around the seedlings may be similar over the 3 years, but the patterns of exposure to that abundance were controlled by the treatment sequence.

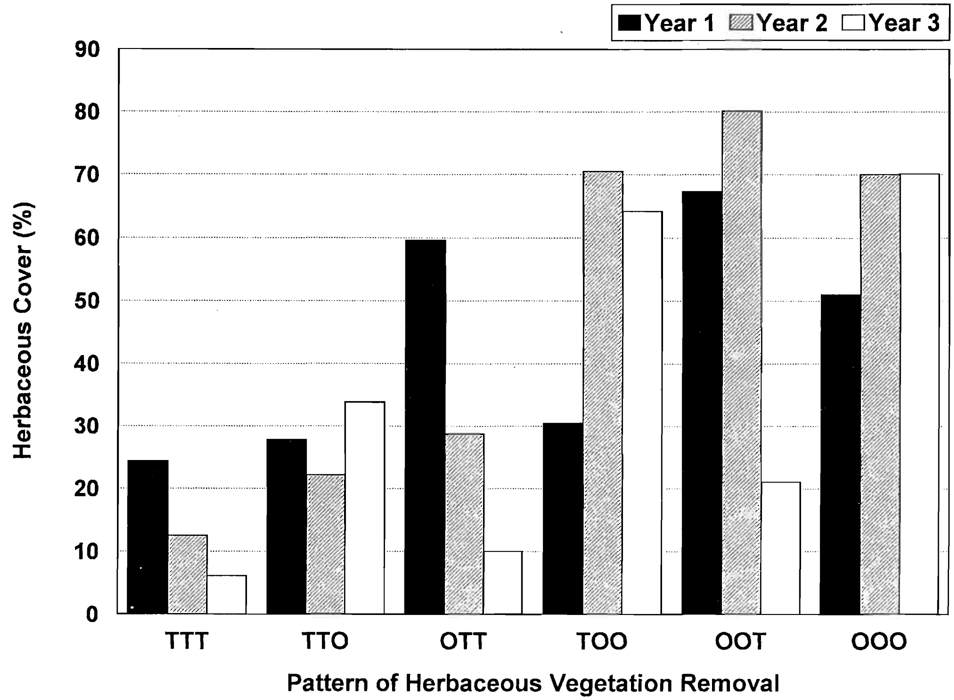

FIG. 3–Percentage cover of herbaceous vegetation resulting from six patterns of removal over 3 years. Sequence of herbaceous vegetation removal each year coded as T = herbicide treated, O = untreated.

Tree Survival and Growth

No difference in the survival of jack pine ($p = 0.49$), red pine ($p = 0.17$), white pine ($p = 0.63$), or black spruce ($p = 0.44$) occurred among treatments by the end of the third year (Table 2). Survival ranged from 59 to 97% among the species and treatments. Survival among species was 70, 78, 89, and 92% for red pine, jack pine, white pine, and black spruce, respectively .

Significant differences ($p < 0.0001$) among treatments for third-year height were found for all species except white pine ($p = 0.24$) (Table 2). The differences, however, were unrelated to the pattern of vegetation control. Jack pine and spruce were tallest by the end of the third year, averaging about 67 cm. White and red pine were substantially shorter, averaging about 38 cm. The differences appear related to seedling height at the time of planting, as white and red pine were shorter than spruce and jack pine.

Substantial differences ($p < 0.0001$) in stem diameter were found among vegetation treatments for all species (Table 2). Association with herbaceous vegetation for 3 years (OOO) reduced stem diameter of white pine, jack pine, black spruce, and red pine to 55, 56, 61, and 64%, respectively, of that for plots with 3 consecutive years of vegetation control (TTT).

Stem diameter increased with increasing years (duration) of vegetation control. Seedlings of all species treated for 2 years (TTO, OTT) were generally larger ($p \leq 0.05$) than those

TABLE 2–Mean survival, height, stem diameter, height/diameter ratio, and stem volume for jack pine, black spruce, white pine, and red pine 3 years after planting under six patterns of herbaceous vegetation removal. Sequence of herbaceous vegetation removal each year coded as T = herbicide treated, O = untreated. Different letters next to each mean within a species and variable indicate a significant difference ($p \leq 0.05$) between treatments.

Herbaceous vegetation control treatment	Survival (%)	Height (cm)	Stem diameter (mm)	Height/ diameter ratio	Stem volume (cm^3)
Jack pine					
TTT	85.8 a	70.9 b	22.6 a	31.6 e	402.3 a
TTO	68.6 a	75.6 a	23.3 a	33.7 d	484.5 a
OTT	68.1 a	65.4 c	18.5 b	36.1 c	262.8 b
TOO	87.4 a	79.2 a	16.7 c	49.6 b	273.9 b
OOT	77.5 a	63.2 c	13.1 d	50.0 b	134.1 c
OOO	80.0 a	71.1 b	13.1 d	56.4 a	155.5 c
Black spruce					
TTT	96.7 a	66.7 a	17.2 a	40.6 d	232.5 a
TTO	91.7 a	67.2 a	14.8 b	47.1 c	176.5 b
OTT	90.0 a	60.9 b	14.8 b	43.1 d	162.2 b
TOO	91.7 a	67.1 a	12.2 c	57.1 a	113.8 c
OOT	89.2 a	57.9 b	11.1 d	53.5 b	85.7 d
OOO	94.2 a	59.7 b	10.4 d	58.9 a	73.4 d
White pine					
TTT	92.5 a	40.4 a	15.2 a	26.8 c	109.3 a
TTO	93.3 a	40.7 a	13.3 b	30.5 b	90.6 b
OTT	92.5 a	38.0 a	12.1 c	31.3 b	76.4 bc
TOO	87.5 a	37.0 a	11.2 c	33.3 b	55.9 cd
OOT	85.0 a	38.0 a	9.5 d	40.4 a	41.4 de
OOO	84.7 a	35.4 a	8.4 e	42.2 a	29.3 e
Red pine					
TTT	65.8 a	36.3 b	12.8 a	28.7 d	80.9 ab
TTO	79.2 a	42.0 a	13.1 a	32.8 c	93.6 a
OTT	67.2 a	38.1 ab	11.4 b	33.8 c	66.2 bc
TOO	77.5 a	39.6 ab	10.0 c	39.5 b	49.4 cd
OOT	70.8 a	35.7 b	9.3 cd	38.4 b	39.8 de
OOO	59.2 a	36.5 b	8.4 d	42.7 a	33.5 e

treated for 1 year (TOO, OOT). Black spruce and white pine treated for 3 years (TTT) had larger ($p \leq 0.05$) stem diameters than those treated for 2 years (TTO, OTT). Jack pine and red pine treated for 3 years (TTT) were larger ($p \leq 0.05$) than when treated in the second and third years (OTT), but not ($p > 0.05$) when treated in the first and second years (TTO).

Early timing of vegetation control also was important. One year of control in the first year (TOO) produced larger ($p \leq 0.05$) stem diameters than untreated plots (OOO), but generally not ($p \leq 0.05$) when the 1 year of control was initiated in the third year (OOT). Stem diameters also were generally larger ($p \leq 0.05$) for all species when the 1 or 2 years of control were applied earlier (TOO, TTO) than later (OOT, OTT).

Results for the stem volume comparisons among treatments were similar to those for stem diameter (Table 2). Stem volume, however, was reduced ($p < 0.0001$) substantially more than stem diameter under the influence of herbaceous vegetation. Untreated vegetation (OOO) reduced white pine, black spruce, jack pine, and red pine stem volume to 27, 32, 32, and 36%, respectively, of that for plots with 3 consecutive years of vegetation control (TTT).

The H:D ratio decreased ($p < 0.0001$) with increasing amounts of vegetation control for all species (Table 2). The H:D ratio after 3 consecutive years of vegetation control (TTT) was 27, 29, 32, and 41 for white pine, red pine, jack pine, and black spruce, respectively. Under untreated conditions (OOO), the H:D ratio increased to 42, 43, 56, and 59 for white pine, red pine, jack pine, and black spruce, respectively. Differences among treatments for H:D ratio were similar to that for stem diameter.

Critical-Period Curves

Critical-period graphs were developed from the six treatments (Fig. 4). Stem diameter was used as the dependent variable because it was most sensitive to the effect of herbaceous vegetation, and the principal variable driving differences in stem volume and H:D ratio. The percentage of maximum observed stem diameter in the third year was used so that curves could be compared among species.

The general shape of the critical-period curves was similar for all conifer species (Fig. 4). Stem diameter increased with increasing years of vegetation control, as can be seen from the weed-free curves. While the trends were nearly linear for white pine and black spruce, curves

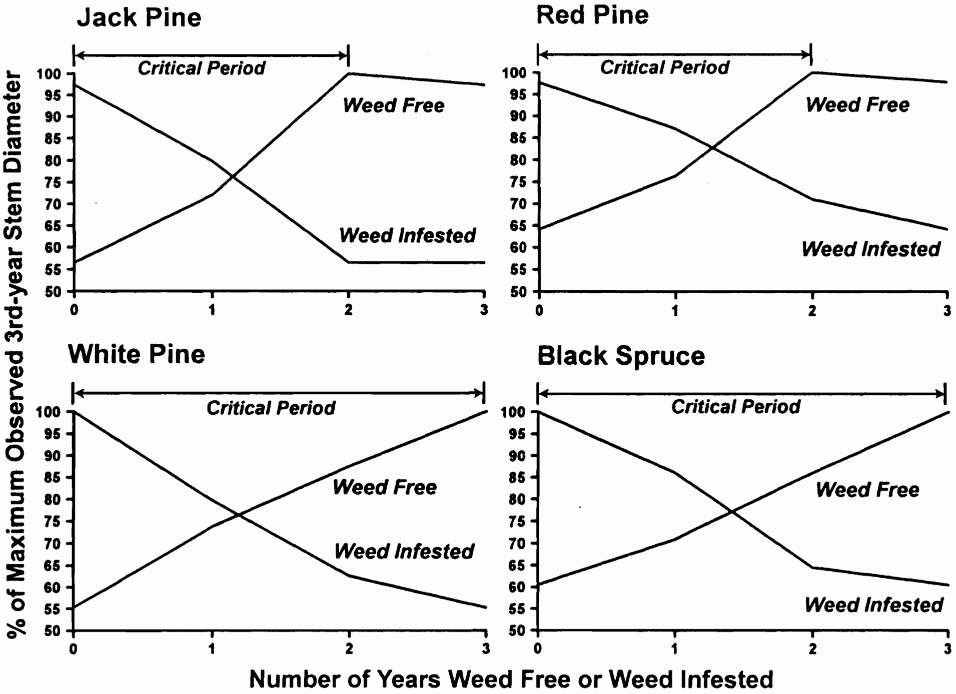

FIG. 4—Critical-period graphs for jack pine, red pine, white pine, and black spruce based on percentage of maximum observed stem diameter in the third year after planting. Preliminary critical periods are graphically identified for each species.

for jack and red pine reached a maximum after 2 years of control. Stem diameter decreased (*see* weed-infested curves) 13, 14, 20, and 21% for red pine, black spruce, white pine, and jack pine respectively, after only 1 year of association with herbaceous vegetation. All weed-infested curves continued to decline through year 3, but there was indication that the rate of decline was levelling off between years 2 and 3, especially for jack pine.

Based on the weed-free and weed-infested curves, critical periods were graphically determined for each species (Fig. 4). Jack pine and red pine critical periods occurred from 0 to 2 years after planting. Critical periods for white pine and black spruce spanned the whole 3-year period.

DISCUSSION

Stem diameter, stem volume, and H:D ratio were strongly affected in the first 3 years after planting by the duration and timing of herbaceous vegetation control. Survival and height growth, however, were not affected. The insensitivity of height growth relative to diameter growth has been generally observed in vegetation management studies (Zedaker *et al.* 1987). Increases in stem diameter with decreasing vegetation abundance, and the insensitivity of height growth relative to diameter, have been documented in other Ontario studies with these tree species (Morris *et al.* 1990; Brand 1991; MacDonald & Weetman 1993). Decreases in diameter growth associated with herbaceous vegetation are likely to be related to competition for light, soil water, and nutrients (Radosevich & Osteryoung 1987; Brand 1991) and/or allelopathic influences (Horsley 1977; Mallik 1987; Fisher 1987). Increased soil temperature also is a possible factor (Brand 1991).

The H:D ratio was a good indicator of competitive stress for all species, decreasing as the intensity of vegetation control increased. A similar range of H:D values was obtained for all four conifer species. The advantage of this ratio as an indicator of interspecific competition is that it can be used for trees of a wide range of sizes. The H:D ratio has generally been found to increase when tree seedlings are shaded by neighbouring plants (Cole & Newton 1987; Lieffers & Stadt 1994).

Light measurements from the same herbaceous vegetation in an adjacent study on the same site (unpubl. data) indicated that PAR decreased substantially below heights of 60 cm above the ground. By the third year, the average height of all four conifer species was near or below 60 cm (Table 2). Measurements of shoot water potential from the adjacent study using the same tree species (unpubl. data) suggested that moisture stress may not be important in these environments, as precipitation occurs regularly throughout the growing season. Nutrient availability is currently being studied. It is unclear, therefore, the degree to which above- and/or below-ground environmental resources determine the conifer responses observed in this study.

The critical-period analysis indicated that both timing and duration of herbaceous vegetation control are important to the growth of northern conifers. The weed-infested curves indicated that herbaceous vegetation can substantially decrease seedling diameter growth in the first year after planting. No period was identified on the weed-infested curves where herbaceous vegetation did not reduce stem diameter. Early vegetation control, therefore, appears important in preventing early growth losses. Wood & von Althen (1993) also found that controlling vegetation in the year of planting enhanced diameter growth of white and black spruce more than waiting until the year after planting. A study with Norway spruce (*Picea abies* L.) found greatest growth when vegetation was controlled during site preparation, with substantial decreases occurring as the interval between planting and competition release increased (Lund-Høie 1984).

The weed-free curves revealed that the number of years (duration) of vegetation control also is important. We found consistent increases in stem diameter associated with increasing years of vegetation control for at least the first 2 years. Our weed-free curves for white pine and spruce were similar to those for herbaceous vegetation control around Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), a species also of intermediate tolerance (Newton & Preest 1988). Early differences produced by additional years of herbaceous vegetation control can have significant long-term consequences on stand development. Lauer *et al.* (1993) found that herbaceous vegetation control applied in the first and second year after planting nearly doubled wood volume gains in loblolly pine (*Pinus taeda* L.) at age 9 relative to trees that had received vegetation control only in the first year. This effect was consistent over a range of sites in the southern United States.

The conifer species in this study were selected based on their range of tolerance. Tolerance is defined as the relative capacity of a tree species to compete under low light and high root competition (Daniel *et al.* 1979). Jack pine, red pine, eastern white pine, and black spruce are rated as very intolerant, intolerant, intermediate, and tolerant, respectively. From the tolerance rating of each species, we expected the intolerant species to be more sensitive to the increased resources made available by an increased duration of vegetation control, but found the opposite. The weed-free curves for the intolerant species (jack and red pine) levelled off after 2 years, while the intermediate and tolerant species (white pine and black spruce) continued to linearly increase through the third year. Greater tolerance to competition also suggests that the weed-infested curves of intermediate and tolerant species should be less steep than those of the intolerant species. There was, however, little difference in the steepness of the weed-infested curves among the four species, and no apparent pattern related to tolerance.

Overall differences in the critical-period curves among the four species (Fig. 4) were relatively minor, indicating that both tolerant and intolerant conifers were responding similarly to the presence of herbaceous vegetation. Relative stem volume losses were similar for all species, even though they were of different absolute sizes by the third year. Several more years are required for the critical-period curves to be more fully expressed and capable of adequately addressing potential differences related to species tolerance. The patterns observed so far, however, raise interesting questions about definitions of conifer tolerance as it relates to competitiveness with early seral vegetation.

The emerging critical-period patterns in this study are somewhat different from those developed in other studies. Our critical periods are relatively earlier and wider than those found for agricultural crops. Critical periods for agricultural crops have generally been confined to the middle of a particular growing season, with a period of time early in the season where weeds can be associated with the crop without reducing yield, and a period toward the end of the growing season where no yield gains result from additional vegetation control (Weaver & Tan 1983; Weaver 1984; Hall *et al.* 1992; van Acker *et al.* 1993; Woolley *et al.* 1993). In contrast, our critical periods indicate that there is no early period during the first few years after planting where seedling growth is not reduced by the presence of herbaceous vegetation. Our critical periods also span most of the period studied. The difference appears to be related to developing critical periods for vegetation control over several years rather than within a single growing season. The pattern may not depend on whether the crop is perennial or annual in nature, as critical periods similar to those for annual agricultural crops for within-season vegetation control have been found for oil palm (*Elaeis guinensis* Jacq.) (Iremiren 1986), rubber (*Hevea brasiliensis*) (Suryaningtyas & Terry 1993), and eastern white pine (Irvine *et al.* 1995) trees in nursery beds.

Of the six hypothetical critical-period models presented, models A and C (Fig. 2) are emerging as dominant forms describing the response of stem diameter. Jack pine and red pine patterns follow model C, while white pine and black spruce patterns are most similar to model A. Characteristics of models A and C, however, can be found in the critical-period graphs for all four species. From these patterns, therefore, it can be concluded that herbaceous vegetation control is most important in the first years after planting, and that stem diameter losses from herbaceous competition are proportional to the number of years without vegetation control. It should be noted that these results apply to the specific conditions encountered on our study site. Responses in other situations may vary depending on the temporal pattern of invasion by herbaceous vegetation after logging and site-preparation, as well as any site differences that can alter competitive interactions between conifers and herbaceous vegetation.

Because height and survival were generally unresponsive to herbaceous vegetation control through year 3, no critical period was identified, suggesting that model F (Fig. 2) best describes the critical-period pattern for these variables. Increases in height growth, however, often can be delayed for several years after increases in stem diameter growth are observed (Wood & Mitchell 1995). Therefore, a different critical-period pattern for height growth may emerge with time.

The critical-period approach provides an analytical method for quantifying the optimum timing and duration of vegetation management in young forest plantations, as well as for examining the temporal effects of plant interference. Results from this study over the next several years will help refine critical-period methodology for perennial vegetation, and confirm whether the patterns reported here are maintained or change over time.

ACKNOWLEDGMENTS

This research was supported by the Vegetation Management Alternatives Program (VMAP) under the Ontario Ministry of Natural Resources Sustainable Forestry Initiative. John Winters and Ago Lehela provided vital field support. Din Chen conducted the statistical analysis. Bruce Zutter and two anonymous reviewers provided useful comments.

REFERENCES

BRAND, D.G. 1991: The establishment of boreal and sub-boreal conifer plantations: An integrated analysis of environmental conditions and seedling growth. *Forest Science 37*: 68–100.

BURTON, P.J. 1993: Some limitations inherent to static indices of plant competition. *Canadian Journal of Forest Research 23*: 2141–52.

COLE, E.C.; NEWTON, M. 1987: Fifth-year response of Douglas-fir to crowding and nonconiferous competition. *Canadian Journal of Forest Research 17*: 181–6.

DANIEL, T.W.; HELMS, J.A.; BAKER, F.S. 1979: "Principles of Silviculture". McGraw-Hill Book Co., New York. 500 p.

DUBA, S.E.; NELSON, L.R.; GJERSTAD, D.H. 1985: Interaction of genotype and vegetation control on loblolly pine seedling performance. Pp.305–8 *in* Shoulders, E. (Ed.) Proceedings of the Third Biennial Southern Silviculture Research Conference, 7–8 November 1984, Atlanta, Georgia. *USDA Forest Service, Southern Forest Experiment Station, General Technical Report SO-54.*

FISHER, R.F. 1987: Allelopathy: a potential cause of forest regeneration failure. Pp.176–84 *in* Waller, G.R. (Ed.) "Allelochemicals: Role in Agriculture and Forestry". American Chemical Society, Washington, D.C.

HALL, M.R.; SWANTON, C.J.; ANDERSON, G.W. 1992: The critical period of weed control in grain corn (*Zea mays*). *Weed Science 40*: 441–7.

HORSLEY, S.B. 1977: Allelopathic inhibition of black cherry by fern, grass, goldenrod and aster. *Canadian Journal of Forest Research 7*: 205–16.

IREMIREN, G.O. 1986: Effects of time and frequencies of weeding on the growth of polybag oil palm (*Elaeis guinensis* Jacq.) seedlings. *Weed Research 26*: 127–32.

IRVINE, M.T.; WAGNER, R.G.; SWANTON, C.J. 1995: The critical period of weed removal in eastern white pine bare-root nursery stock. *Proceedings of the Weed Science Society of America Abstracts 35*: 28.

LANINI, W.T.; RADOSEVICH, S.R. 1986: Response of three conifer species to site preparation and shrub control. *Forest Science 32*: 61–77.

LAUER, D.K.; GLOVER, G.R.; GJERSTAD, D.H. 1993: Comparison of duration and method of herbaceous weed control on loblolly pine response through midrotation. *Canadian Journal of Forest Research 23*: :2116–25.

LIEFFERS, V.J.; STADT, K.J. 1994: Growth of understory *Picea glauca*, *Calamagrostis canadensis*, and *Epilobium angustifolium* in relation to overstory light transmission. *Canadian Journal of Forest Research 24*: 1193–8.

LUND-HØIE, K. 1984: Growth responses of Norway spruce (*Picea abies* L.) to different vegetation management programmes—preliminary results. *Aspects of Applied Biology 5*: 127–33.

MacDONALD, G.B.; WEETMAN, G.F. 1993: Functional growth analysis of conifer seedling responses to competing vegetation. *Forestry Chronicle 69*: 64–8.

MALLIK, A.U. 1987: Allelopathic potential of *Kalmia angustifolia* to black spruce (*Picea mariana*). *Forest Ecology and Management 20*: 43–51.

MORRIS, D.M.; MacDONALD, B.; McCLAIN, K.M. 1990: Evaluation of morphological attributes as response variables to perennial competition for 4-year-old black spruce and jack pine seedlings. *Canadian Journal of Forest Research 20*: 1696–703.

NEWTON, M.; PREEST, D.S. 1988: Growth and water relations of Douglas-fir (*Pseudotsuga menziesii*) seedlings under different weed control regimes. *Weed Science 36*: 653–62.

RADOSEVICH, S.R.; OSTERYOUNG, K. 1987: Principles governing plant-environment interactions. Pp.105–56 *in* Walstad, J.D.; Kuch, P.J. (Ed.) "Forest Vegetation Management for Conifer Production". John Wiley and Sons, Inc.

STEWART, R.E.; GROSS, L.L.; HONKALA, B.H. 1984: Effects of competing vegetation on forest trees: A bibliography with abstracts. *USDA Forest Service General Technical Report WO-43.*

SURYANINGTYAS, H.; TERRY, P.J. 1993: Critical period of weed competition in rubber seedlings. Pp.1177–81 *in* Proceedings Vol. 3 of the Brighton Crop Protection Conference "Weeds—1993", 22–25 November, Brighton, England.

SWANTON, C.J. ; WEISE, S.F. 1991: Integrated weed management: The rationale and approach. *Weed Technology 5*: 657–63.

van ACKER, R.C.; SWANTON, C.J.; WEISE, S.F. 1993: The critical period of weed control in soybean [*Glycine max*. (L.) Merr.]. *Weed Science 41*: 194–200.

WAGNER, R.G. 1993: Research directions to advance forest vegetation management in North America. *Canadian Journal of Forest Research 23*: 2317–27.

——1994: Toward integrated forest vegetation management. *Journal of Forestry 92(11)*: 26–30.

WALSTAD, J.D.; KUCH, P.J. (Ed.) 1987: "Vegetation Management for Conifer Production". John Wiley and Sons Inc. 523 p.

WEAVER, S.E. 1984: Critical period of weed competition in three vegetable crops in relation to management practices. *Weed Research 24*: 317–25.

WEAVER, S.E.; TAN, C.S. 1983: Critical period of weed interference in transplanted tomatoes (*Lycopersicon esculentum*): growth analysis. *Weed Science 31*: 476–81.

WOOD, J.E.; MITCHELL, E.G. 1995: Silvicultural treatments for black spruce establishment in boreal Ontario: Effect of weed control, stock type, and planting season. *Natural Resources Canada, Canadian Forest Service, Sault Ste. Marie, Ontario, Northern Ontario Development Agreement's Northern Forestry Program Technical Report TR-10.* 19 p.

WOOD, J.E.; von ALTHEN, F.W. 1993: Establishment of white spruce and black spruce in boreal Ontario: Effects of chemical site-preparation and post-planting weed control. *Forestry Chronicle 69*: 554–60.

WOOLLEY, B.L.; MICHAELS, T.E.; HALL, M.R.; SWANTON, C.J. 1993: The critical period of weed control in white beans (*Phaseolus vulgaris*). *Weed Science 41*: 180–4.

ZIMDAHL, R.L. 1988: Pp.145–55 *in* Altieri, M.A.; Liebman, M. (Ed.) "Weed Management in Agroecosytems: Ecological Approaches". CRC Press Inc., Boca Raton, Florida.

ZEDAKER, S.M.; BURKHART, H.E.; STAGE, A.R. 1987: General principles and patterns of conifer growth and yield. Pp.203–41 *in* Walstad, J.D.; Kuch, P.J. (Ed.) "Forest Vegetation Management for Conifer Production". John Wiley and Sons Inc.