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Optimum Vegetation Conditions for Successful Establishment of Planted Eastern White Pine (*Pinus strobus* L.)

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Abstract: The 10th-growing season performance of planted eastern white pine (*Pinus strobus* L.) seedlings was evaluated in response to herbaceous and woody vegetation control treatments within a clearcut and two variants of the uniform shelterwood regeneration system (single vs. multiple future removal cuts). Herbaceous vegetation control involved the suppression of grasses, forbs, ferns and low shrubs for the first 2 or 4 growing seasons after planting. Deciduous woody vegetation control treatments, conducted in combination with the herbaceous treatments within a response-surface design, involved the permanent removal of all tall shrubs and deciduous trees at the time of planting, at the end of the 2nd or 5th growing seasons, or not at all. In general, the average size of planted pine was related positively to the duration of herbaceous vegetation control and negatively to delays in woody control. White pine weevil (*Pissodes strobi* Peck) altered these trends, reducing the height of pine on plots with little or no overtopping deciduous woody vegetation or mature tree cover. Where natural pine regeneration occurred on these plots, growth was similar but subordinate to the planted pine. Data from the three sites indicate that at least 60% of planted pine may be expected to reach an age-10 height target of 2.5 m when overtopping cover (residual overstory + regenerating deciduous) is managed at approximately 65% ± 10%, and total herbaceous cover is suppressed to levels not exceeding 50% in the first five years. On productive sites, this combination may be difficult to achieve in a clearcut, and requires fairly rigorous vegetation management in shelterwood regeneration systems. Currently, synthetic herbicides offer the only affordable and effective means of achieving such vegetation control.

Keywords: eastern white pine (*Pinus strobus* L.); uniform shelterwood; competition; vegetation management; silviculture

1. Introduction

Eastern white pine (*Pinus strobus* L.) was important during the post-colonial development of northeastern North America, providing building materials and generating economic value that fueled development and infrastructure throughout the continent [1,2]. Today, this species continues to retain relatively consistent high lumber values, while garnering significant appreciation for its wildlife, recreational and spiritual values [3].

Unfortunately, difficulties plaguing the regeneration success of white pine have precipitated a significant decline in its abundance and dominance throughout its former range [4,5]. These losses can largely be attributed to damage caused by white pine blister rust (*Cronartium ribicola* J.C. Fisch.) and white pine weevil (*Pissodes strobi* Peck) [6,7], particularly during the latter half of the 20th century when active regeneration efforts were widely discouraged [2,8,9]. By the 1970s, regeneration failures prompted experimentation with the uniform shelterwood system as a means of tailoring white pine management to the ecology of this mid-tolerant species [10,11]. The partially shaded understory environment of the shelterwood is deemed to reduce rust infection potential by lowering humidity levels during spore dispersal, and reduce weevil incidence by lowering ambient temperatures and terminal shoot diameters to levels that disfavor oviposition, larval development and survival [12,13]. More recent research offers increased hope of further diminishing losses through the development of resistance to these pests via genetic improvement in seedlings [14–16] and exposure to foliar endophytic fungi during seedling production [17].

Given that tools may exist to prevent catastrophic losses from blister rust and weevil, attention must be focused on the interacting effects of competing vegetation and these pests on the regeneration performance of white pine, particularly on the productive, fresh-to-moist, highly competitive sites favored by this species [18–21]. The development of vegetation management strategies for various regeneration scenarios is complicated by the fact that young white pine growing with adequate shade to minimize weevil attack experience competition from both overtopping trees and understory vegetation [7,22,23]. There is thus a need to balance residual canopy density and deciduous tree regeneration with understory vegetation control, such that the understory environment remains unfavorable to weevil and blister rust, but offers adequate resources for competitive pine regeneration and growth [24–27]. Previous studies have reported on the separate influences of understory herbaceous and woody competition control on white pine seedling growth beneath partially harvested conifer and hardwood stands [20,21,25,28], but the comparative and interacting influences of these two forms of vegetation on pine seedling survival and growth was previously not well understood.

Within the context of silvicultural practices that are currently used, and with the over-riding objective of maximizing pine productivity, we established three field sites sharing a response surface design. Our specific objective was to identify understory and overstory conditions that favor planted white pine survival and growth. The study sites encompass regeneration conditions following clearcutting (established in 2000, in northeastern Ontario), as well as single and multiple removal-cut variants of the uniform shelterwood system (established in 2001, in central New Brunswick and northeastern Ontario). During the first four growing seasons in the clearcut environment, we found that white pine seedlings experienced strong competition for soil moisture and nutrients from both herbaceous vegetation and regenerating deciduous woody vegetation [29,30]. Since seedlings exposed to full sunlight on the clearcut sustained high incidence of weevil attack, our preliminary recommendations focused on the proactive, early suppression of herbaceous vegetation to reduce competition for soil moisture and nutrients [31]. The two shelterwood environments proved just as competitive as the clearcut, but sunlight was often the most limiting resource, given that the mature overstories intercepted substantial available quantities of light [32]. Our 6th-year recommendations from these shelterwoods emphasized thinning of mature stands from below to allow 50% to 60% of full sunlight into the understory (something that was not being done consistently in operations of the time), followed by the proactive, early suppression of both woody and herbaceous vegetation to maintain optimum light levels and reduce competition for soil moisture and nutrients [33].

In this paper, we use the 10th-season growth performance of the planted white pine in these three sites to:

(1) establish the temporal consistency of the treatment responses beyond our earlier year-6 assessments;
(2) generate a practical growth and survival performance measure from the data; and
(3) integrate data from all three sites to establish overall management guidelines with respect to overstory and understory conditions.

2. Materials and Methods

A detailed description of the study sites and experimental methods can be found in Pitt et al. [31,33]. The following paragraphs provide a summary of these methods for convenience.

2.1. Experimental Design

Our aim in establishing this experiment was to better understand the specific effects of herbaceous and deciduous woody competition on planted white pine performance so that forest managers might develop more consistent and effective vegetation management prescriptions for operational use. Under this goal, references to herbaceous and woody vegetation include, respectively, all life forms that typically make up the low-growing vegetation layer (grasses, forbs, ferns, and low shrubs), and those likely achieve dominance over planted pine seedlings (tall shrub species capable of achieving at least 2 m in height and deciduous tree species). We studied planted pine performance as a response-surface defined by 3 levels of the *duration of herbaceous vegetation control* (*H*; 0 (none), first 2 or first 4 years) and 4 levels of the *timing of woody vegetation control* (*W*; year 0, 2, 5 or none, where year refers to the number of growing seasons since planting) (Figure 1). These 12 treatment combinations may be uniquely coded with 6 characters representing treatments occurring through growing seasons 1 through 6, with "0" = no vegetation control; "*h*" = herbaceous control only, "*w*" = woody control only, and "*b*" = both herbaceous and woody control. For example, four years of herbaceous vegetation suppression, combined with woody vegetation control at the end of the second growing season is denoted by "*hhbbww*". In the response surface treatments, once woody control was imposed, its effects were assumed to persist through the life of the study (i.e., we allowed no woody stem regeneration to occur in these plots). Thus, a 10-digit treatment code describing the full 10 years of the study reported herein would be redundant, as the 6th character would simply be repeated for the last 4 years, regardless of treatment.

The advantage of this experimental approach is that it allows for simultaneous interpolation across the duration of herbaceous vegetation control and the timing of woody control in the optimization of a vegetation management prescription. The objective is to identify vegetation conditions that favor early white pine survival and growth, rather than compare and contrast particular vegetation management tools. Each of the 4 corners and center points on the response grid (Figure 1) were replicated 3 times (total of 20 experimental units or plots) and the entire response grid was blocked on 3 different nominal, initial deciduous woody densities (5000, 10,000 and 15,000 stems per ha (sph)). As comparative benchmarks or references, the experiment also included 3 replicate plots of a continuous complete vegetation control treatment during the ten growing seasons after planting (*bbbbbb*), and 3 replicates at each of the 3 woody densities of a simulated operational "broadcast" release of both woody and herbaceous vegetation after the second growing season (*00b000*). The entire experiment required 72 treatment plots at each site.

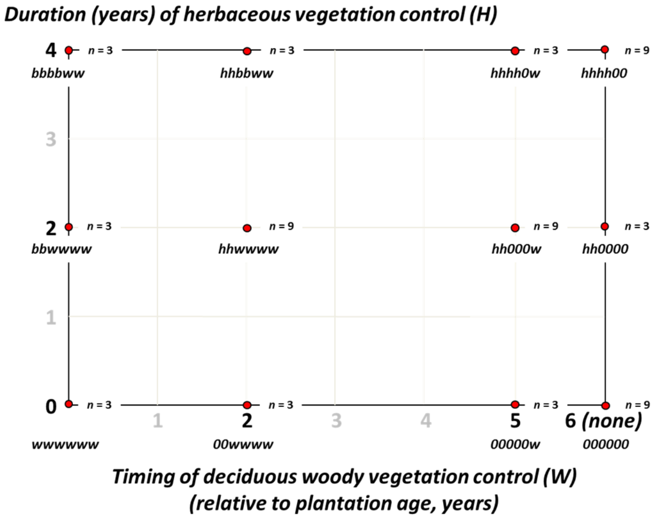

Figure 1. Response-surface design for studying the effects of competition on white pine establishment and growth. The combinations of duration of herbaceous vegetation control (*H*) and timing of deciduous woody vegetation control (*W*) lead to 12 treatments (red circles). These treatments may be coded in terms of "0" no vegetation control, "*w*" woody control, "*h*" herbaceous control, and "*b*" both woody and herbaceous control, with 6 characters representing the first 6 years of the experiment. Each of the 4 corners and center points on the grid were replicated 3 times. The entire response grid was blocked on 3 deciduous woody densities (5000, 10,000, and 15,000 stems/ha), requiring a total of 60 plots (those with woody control in year 0 being common to each density). Reference treatments (not shown) include complete vegetation control (*bbbbbb*, n = 3) and operational broadcast release (*00b000*, $n = 3 \times 3$ densities). The entire experiment at each site required 72 plots.

2.2. Study Sites and Treatments

The full 72-plot experiment was replicated on each of 3 sites representing the silvicultural systems typically being used in the regeneration of white pine. The first is located in the Great-Lakes—St. Lawrence forest region, northeast of North Bay, Ontario, in the Nipissing Forest (World Geodetic System (WGS) 84: 46°42′44.3″ N; 79°22′14.4″ W). It represents ecosite G033 [34] and is regionally typical of dry, sandy white and red pine-dominated mixedwood sites. Soils are fine loamy sands (first 10 cm) over deep, medium- to coarse-textured sands, with an effective rooting depth greater than 70 cm and no signs of mottling or gleying. Mean annual, January, and July temperatures are 4.4 °C, −12.2 °C, and 18.8 °C, respectively, with 1574 annual growing degree days and 475.3 mm of annual precipitation during May–September. The area was harvested in spring of 2000 using a full-tree system. Subsequent to this harvest, a 3-ha portion of the cutover was subjected to manual cutting and removal of all remaining residual trees to emulate a true "clearcut" harvest condition. No further site preparation was undertaken. In August of 2000, 72 18-m × 18-m treatment plots were established on this 3-ha site, with 2-m corridors between each. At this time, the plots were regenerating to trembling aspen (*Populus tremuloides* Michx.), bracken fern (*Pteridium aquilinum* L.), low-shrub vegetation dominated by blueberry (*Vaccinium* spp.) and bush honeysuckle (*Diervilla lonicera* Mill.), and a variety of forbs, dominated by spreading dogbane (*Apocynum androsaemifolium* L.), large-leaved aster (*Aster macrophyllus* L.) and wild sarsaparilla (*Aralia nudicaulis* L.). Following visual inspection, the plots were stratified, based on stem density of aspen and other deciduous tree species, into lower, middle, and upper third percentiles. The study's 14 treatments (Figure 1) were then randomly assigned to plots within these density classes.

The second site is located 2.2 km from the first (WGS 84: 46°43′50.7″ N; 79°22′46.1″ W) and differs only with respect to its harvest history. The 100-year-old fire-origin white and red pine (*Pinus resinosa* Sol. Ex Aiton) stand had been subjected to a regeneration cut of the uniform shelterwood system in

1999, leaving a high-quality, mature overstory of white and red pine. However, many subordinate stems of white spruce (*Picea glauca* (Moench) Voss), balsam fir (*Abies balsamea* (L.) Miller), red maple (*Acer rubrum* L.) and trembling aspen, although marked for harvest, were left standing due to market conditions. In the fall of 2000, manual felling and a grapple skidder were used to complete the regeneration cut by thinning the stand from-below (removing, in order, defective trees, undesirable species and the smallest stems until the target basal area was reached), to emulate what would be conducted under an intensive silvicultural regime. Across the experimental site, the original unharvested stand density was reduced, in total, by 66%, to 132 sph, and basal area (BA) by 52%, to 18 m^2/ha [33]. The average diameter at breast height (DBH) of the final residual stand was 40 cm, with several stems exceeding 60 cm. Species composition was 71% white pine and 25% red pine, by BA, all in dominant and codominant trees. This residual stand was deemed suitable for removal in two or more future harvests. For the sake of the experiment, large woody debris and slash were removed from the site to equalize microsite availability for regeneration across the area. The complete area was then chain scarified with two perpendicular passes in the spring of 2001 and 72 18-m × 18-m treatment plots were subsequently established with 3-m corridors between each. The study's treatments were assigned to these plots at random.

The third site is located in the Acadian forest region of central New Brunswick, 20 km west of Doaktown (WGS 84: 46°24′30″ N; 66°04′26″ W). This site falls within the New Brunswick Lowlands geomorphologial region which has 1559 annual growing degree days and 480 mm annual precipitation during May–September. Mean annual, January, and July temperatures are 5.0 °C, −10.5 °C, and 18.9 °C, respectively. Soils are fine, loamy sands (<10 cm) underlain by formations of grey lithic and feldspathic sandstone [35,36]. An operational regeneration harvest took place in the 100-year-old stand in 1998, leaving a relatively low-quality, mature overstory of eastern white pine (previously damaged by white pine weevil), and scattered representatives of red pine, white birch (*Betula papyrifera* Marsh.), and red maple [33]. The original stand density was reduced by 77%, to 100 sph, and BA by 55%, to 17.5 m^2/ha. The average DBH of the residual stand was 45 cm, with several stems exceeding 60 cm and considered to be suitable for removal in a single future harvest. Scarification was conducted in 1999 with light chains in a single pass and seventy-two 18-m × 18-m treatment plots were established and assigned the study's 14 treatments in a fashion identical to the ON shelterwood site.

Across the 3 study sites, plots receiving both deciduous woody and herbaceous vegetation control (*b*) (Figure 1) in advance of the first growing season were treated with a broadcast foliar application of glyphosate during early September 2000 on the clearcut, or 2001 on the two shelterwoods (year 0). A Solo® backpack sprayer was used for these applications, equipped with a 46-cm wand and 8004 nozzle, delivering a 3% solution of Vision® herbicide. Plots receiving herbaceous-only vegetation control (*h*) were similarly treated, but with care taken to avoid any contact with aspen, red maple and other deciduous tree species on the site. Plots receiving initial woody-only vegetation control (*w*) were treated with a basal bark treatment (streamline method) and the herbicide Release® (25% product mixed in mineral oil, applied with very low pressure, directly to the lower 30 cm of target stems with a backpack sprayer equipped with a 46-cm wand and a SS1502 nozzle).

While natural regeneration may be anticipated, particularly in shelterwood systems, planting is frequently used to insure timely regeneration and full stocking, and/or enhance genetic and species diversity. To satisfy the productivity objectives of this experiment and maximize plot-to-plot and site-to-site consistency in timing and stocking, all plots were planted at 2-m spacing in May of year 1 (2001 at the clearcut; 2002 at the shelterwoods). In ON, Multipot 67, 1-0 containerized white pine seedlings were used, averaging 10 cm in height and 2.4 mm in stem diameter, measured 5 cm above ground line (AGL). In NB, similar sized Jiffy 36 seedlings were used.

On complete vegetation control plots and herbaceous-only control plots, vegetation control was maintained during each growing season dictated by the experimental design (Figure 1) via periodic manual clipping and directed foliar applications of glyphosate (2% Vision®) at the end of the preceding growing season (late August/early September). On plots receiving later woody-only control, basal bark treatment was used at the end of the preceding growing season. Once woody control occurred within the response-surface experiment, either through complete vegetation control or woody-only control, woody control was maintained through subsequent years, as needed, via manual clipping. Plots assigned to the simulated operational release treatment (*00b000*) received a broadcast application of glyphosate (2% Vision®) at the end of the second growing season, with no subsequent follow-up treatments or manual clipping.

To avoid potentially critical reductions in white pine sample size due to fatal blister rust infections, all planted pine were treated with a single application of the fungicide Bayleton® (triadimefon) during mid-July of each of the first five growing seasons. The product was mixed with water at a rate of 300 mg active per L; each seedling was sprayed to wet with a Solo® backpack sprayer, equipped with a 46-cm wand and 8004 nozzle.

2.3. Field Measurements

Within each treatment plot, we established a centrally located 10-m × 10-m measurement plot. The 25 planted pine trees within each of these measurement plots (5 trees × 5 trees) were identified with a pin-mounted, numbered aluminum tag. At the end of each of the first 6 and then the 10th growing seasons, surviving trees were measured for total height (ground line to the tip of the tallest bud; cm) and stem diameter (5 cm AGL; mm). At each measurement time, each tree was visually rated for its health class using a 5-class system (1 = vigorous, 2 = healthy, 3 = mediocre, 4= moribund, and 5 = dead) [37]. Trees with terminal leaders that were attacked by white pine weevil were recorded as such.

Cover of vegetation within the measurement plots was estimated from five 2-m × 2-m subplots during peak growing season (mid-August) of each of the first 6 and 10th years. Subplot centers were randomly located within each measurement plot and permanently identified. Cover and cover-weighted height were recorded for deciduous trees, tall shrubs, low shrubs, forbs, ferns, grasses, planted pine, and other conifers (including naturally regenerated pine). Cover assessments were facilitated by placing two 2-m lengths of graduated plastic pipe at right angles to each other over the subplot center, and visually estimating the portion of the subplot ground surface occupied by the vertical projection of the plant crown(s), to the nearest 5%. Trace amounts of cover were assigned a value of 1%.

At the two shelterwood sites, a complete enumeration of the overstory took place at the end the growing season at the time of plot establishment (year 0), and years 1, 5, and 10. DBH was recorded (to the nearest mm with a diameter tape) for every tree on each treatment plot, including the 1.5-m buffer zone around the plot.

2.4. Statistical Analyses

2.4.1. Planted Pine Response to Treatments

Measures of planted pine performance were derived from the 25 planted pines in each treatment plot. Treatment plot averages were calculated for surviving-tree stem diameter, total height and health class. Treatment plot values were calculated for mortality (%), and weevil incidence (%). Height growth increment at age 10 was calculated by fitting a second-order polynomial to the time-series height values for each treatment plot and then evaluating the first derivative of the resulting function at age 10 [38].

To generate a practical performance measure that integrates growth and survival, we calculated the proportion of original 25 planted trees achieving a target of 250 cm in total height after 10 growing seasons (P250). This height threshold was chosen as a productivity benchmark for placing these stands on an "intensive" yield curve [39].

Preliminary analyses of planted pine performance associated with the study's 14 treatments were conducted using analyses of variance, treating initial woody stem density as a blocking variable and each site as a separate experiment. The statistical program *R* [40] was used with the package "lsmeans" for these analyses. Residuals were examined for compliance with normality and equality of variance assumptions; transformations were not necessary. For general means comparison outside of the treatment structure provided by the experimental design, we calculated the least significant difference (LSD; $\alpha = 0.05$) for Tukey's Studentized Range Test, based on a harmonic mean of the sample sizes in each treatment [41].

Consistent with the year-6 analyses previously reported, response surfaces were updated for year-10 total height and stem diameter, and introduced for P250. For each site and response variable, a second-order polynomial model [42] was fit to the $n = 60$ treatment plot means in *R*, using the package "rsm". These analyses quantified the 10th-year planted pine responses to herbaceous vegetation control and timing of woody control. The full model (1) was reduced to contain only statistically significant factors ($\alpha = 0.10$), using a process of backward elimination:

$$Y = \beta_0 + \beta_1 W + \beta_2 W^2 + \beta_3 H + \beta_4 H^2 + \beta_5 WH + \varepsilon \quad (1)$$

where Y is treatment plot mean for 10th-year pine response, $\beta_0 \ldots \beta_5$ are parameters to be estimated, W and H are as previously defined, and ε represents random errors. Repeat observations on the response surface (Figure 1) were used to test model (1) for lack of fit [42]. In each case, model residuals were examined for compliance with normality and equality of variance assumptions; transformations were not necessary. As found in our previous response-surface analyses, regenerating woody stem density did not substantively contribute to these models as a covariate ($\alpha = 0.10$) and was not included.

2.4.2. Planted Pine Response to Growing Conditions

Collectively, the 14 treatments that were applied to the 3 different sites in this experiment produced a wide array of early competition environments that could potentially be associated with 10th-year crop outcomes. We hypothesized that 10th-year planted pine performance may be related to competition levels during the first five growing seasons, such that forest managers might identify threshold tolerances for meeting minimum performance levels. Such thresholds would represent valuable targets for vegetation management treatments in the sustainable production of white pine. To test this hypothesis, we calculated the mean treatment-plot cover values for each year and life form. From these values, we generated a total for herbaceous cover (%), by year, by summing the low shrub, forb, fern, and grass covers. Similarly, we summed the regenerating deciduous tree, tall shrub, and residual overstory cover values to obtain a cover value for vegetation with potential to overtop the planted pine (%). However, since the mature residual overstory was measured in basal area (BA, m^2/ha), we had to convert these plot-level values to cover (%) using the equation established by Parker [27] prior to calculating this sum:

$$\mathit{Overstory}\ \ \mathit{cover}\ (\text{or crown closure})\ (\%) = 88.94(1 - \mathit{exp}(-0.0645 \times \mathit{BA})) \quad (2)$$

We then combined the data from the three sites and studied the measures of planted pine performance in year-10 as a function of early herbaceous and overtopping cover levels during the first five years.

3. Results

3.1. Temporal Consistency of Treatment Responses

3.1.1. Planted Pine Stem Diameter

The treatment-related patterns in stem diameter observed at the end of the 6th growing season in these studies [31,33] were clearly echoed by the 10th-year data. At the end of the 10th growing season, stem diameters were still strongly associated with the earlier vegetation control treatments ($p < 0.001$), averaging just over 55 mm at the clearcut and NB shelterwood sites, and 45 mm at the ON shelterwood site (Table 1). Above-average diameters were observed in all plots receiving early herbaceous and woody vegetation control and those plots receiving aggressive herbaceous control, coupled with late woody release (*hhhh0w*, and *hh000w*). Plots that did not receive herbaceous vegetation control supported the smallest diameter trees on all sites, particularly if woody vegetation control was delayed or not done. The smallest age-10 stem diameters were consistently found in the untreated control plots, ranging from 22 mm at the ON shelterwood, to about 30 mm at the other two sites, statistically ($p \leq 0.05$) below the site averages.

Response-surface analyses allow the data in Table 1 to be interpreted within the context of the experimental design (Figure 2; Table 2) and, like the statistics presented above, only substantively differ from the year-6 surfaces [31,33] in scale. Planted pine diameters increased with both the duration of herbaceous vegetation control and early woody vegetation removal at all three sites (Figure 2; Table 2). Maximum diameter response consistently occurred with 2–4 years of herbaceous vegetation control and early removal of woody vegetation cover. The shapes of the response surfaces of the clearcut and the NB shelterwood (Figure 2a,b) are such that the benefits of herbaceous vegetation control appear increasingly susceptible to delays in woody vegetation control as herbaceous vegetation control duration is increased. In other words, delays in the removal of woody vegetation had less influence on pine diameter growth under herbaceous competition than when the herbaceous vegetation was controlled. In contrast, planted pine stem diameters in the ON shelterwood (Figure 2c) appeared to be equally responsive to herbaceous vegetation control and the timeliness of woody vegetation control; both herbaceous vegetation suppression and early woody vegetation control were necessary to increase stem diameters. For example, the diameter growth losses associated with leaving woody vegetation intact for 10 growing seasons on trees that received 2 years of herbaceous vegetation suppression amounted to 19 mm on the clearcut, 20 mm on the NB shelterwood, and 30 mm on the ON shelterwood. On the clearcut and NB shelterwood sites, these losses amount to less than the gains derived through herbaceous vegetation control alone, whereas at the ON shelterwood, these losses are nearly double the gains provided by the herbaceous vegetation control.

Table 1. Treatment mean responses for planted pine at age 10.

Variable	Site	*bbbbbb*	*bbbbww*	*bbwwww*	*hhbbww*	*hhwwww*	*00b000*	*hhhh0w*	*hh000w*	*hhhh00*	*hh0000*	*wwwwww*	*00wwww*	*00000w*	*000000*	Mean	RMSE [1]	LSD [2]	*P* > *F*
Stem dia. 5 cm AGL [3] (mm)	CCON	83	82	66	75	66	56	71	64	52	44	37	36	36	30	**55.7**	8.2	20.4	<0.001
	SWNB	85	74	72	69	76	60	70	67	50	50	42	44	37	29	**57.8**	9.0	22.4	<0.001
	SWON	48	71	53	60	62	54	48	46	29	28	43	43	36	22	**44.6**	8.6	21.4	<0.001
Total height (cm)	CCON	204	215	176	208	181	146	204	215	243	220	115	120	129	171	**185.9**	27.7	69.1	<0.001
	SWNB	363	345	350	354	347	315	338	331	297	296	228	234	210	195	**298.9**	40.0	99.8	<0.001
	SWON	288	366	351	348	324	307	261	290	227	228	274	269	231	197	**277.0**	37.9	94.5	<0.001
Height increment (cm/year)	CCON	25	26	20	24	20	17	23	23	26	25	12	12	13	25	**21.6**	3.9	9.8	<0.001
	SWNB	61	57	57	64	56	55	49	54	45	45	32	33	31	23	**47.2**	7.6	19.0	<0.001
	SWON	41	49	50	52	44	49	38	39	24	24	38	37	32	21	**37.3**	6.9	17.1	<0.001
Health class of live trees	CCON	2.6	2.6	2.9	2.8	2.8	2.8	2.7	2.6	2.4	2.2	2.8	2.7	2.7	2.0	**2.6**	0.2	0.5	<0.001
	SWNB	1.9	1.8	1.6	1.6	1.9	1.6	1.9	1.6	2.0	1.9	2.2	2.0	2.0	2.4	**1.9**	0.3	0.8	0.003
	SWON	1.6	2.1	1.7	1.7	1.8	1.7	1.6	1.6	2.0	2.0	1.5	1.6	1.5	1.9	**1.8**	0.3	0.7	0.012
Trees affected by weevil (%)	CCON	68	75	54	66	56	51	48	47	34	36	24	32	25	21	**44.0**	16.6	41.4	<0.001
	SWNB	3	2	14	8	2	4	6	4	3	0	4	3	0	0	**3.2**	5.5	13.7	0.151
	SWON	4	25	3	11	14	10	11	3	0	0	0	7	0	0	**6.0**	9.0	22.4	0.003
Mortality (%)	CCON	11	16	12	5	11	16	11	3	13	29	19	17	5	8	**11.6**	7.9	19.8	0.002
	SWNB	9	15	13	12	13	7	9	12	16	9	17	31	13	14	**13.3**	8.7	21.6	0.116
	SWON	1	3	7	1	5	13	3	7	6	4	7	0	13	2	**5.7**	7.2	17.8	0.087
Trees > 2.5 m in height (%)	CCON	15	21	13	19	8	2	12	27	36	21	0	0	1	5	**14.2**	13.9	34.7	<0.001
	SWNB	76	73	79	80	79	70	80	71	59	63	36	32	25	21	**60.1**	14.0	34.9	<0.001
	SWON	72	97	93	85	81	70	51	67	31	31	59	60	36	20	**57.8**	18.4	46.0	<0.001
n		3	3	3	3	9	9	3	9	9	3	3	3	3	9				

Values are derived from 25 trees in each of *n* treatment plots at each site. See Figure 1 for a full description of treatment codes (in short, 6 characters represent years 1 through 6, respectively: "0" = no vegetation control; "*w*" = woody control; "*h*" = herbaceous control, and "*b*" = both woody and herbaceous control); sites are clearcut (CCON) and shelterwood (SWNB and SWON). [1] Root Mean Square Error; [2] Least Significant Difference (α = 0.05) for Tukey's Studentized Range Test, based on harmonic mean of sample sizes (n_h = 3.9375); [3] Above Ground Line.

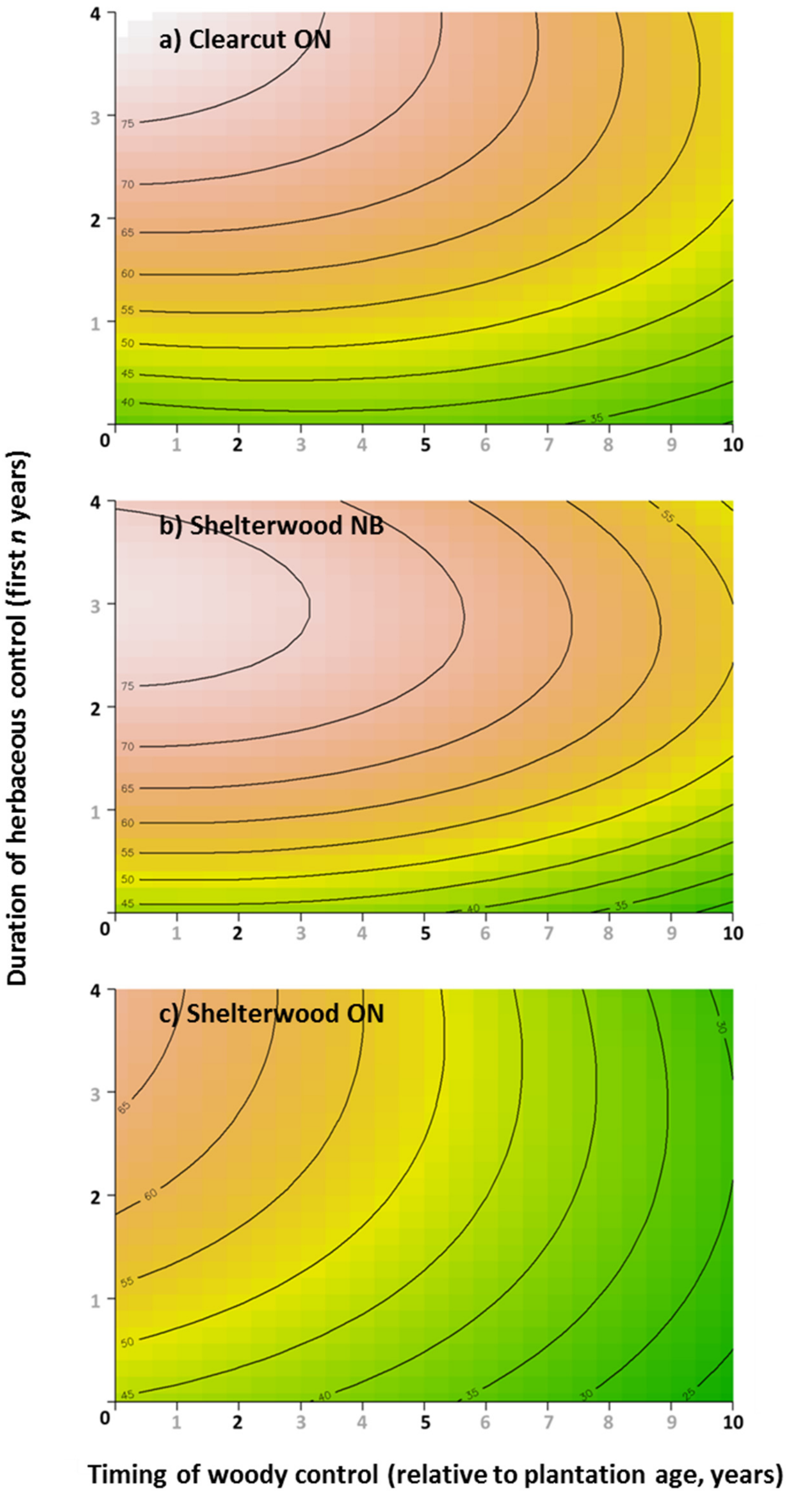

Figure 2. Two-dimensional representations (contour plots) of the response surfaces for age-10 planted pine stem diameter (mm) for the clearcut (**a**) and shelterwood NB (**b**) and ON (**c**) sites (n = 60 observations for each). Colour tones move from largest (white) to smallest (green) diameters. See Table 2 for model statistics.

Table 2. Parameter estimates and fit statistics for age-10 response surfaces (model (1)) based on duration of herbaceous vegetation contol (H, years) and timing of woody vegetation control (W, year).

Parameter	Stem Diameter (mm)			Height (cm)			P250 (%)		
	CCON	SWNB	SWON	CCON	SWNB	SWON	CCON	SWNB	SWON
Intercept	37.74	46.08	42.70	115.26	234.63	278.84	4.72	34.90	69.85
H	20.01	21.23	10.38	43.43	83.17	46.24	3.05	32.17	18.03
H^2	−2.26	−3.73	−1.05	−5.86	−13.80	−6.29	-	−5.40	−3.34
W	-	-	-	5.00	-	−8.36	-	-	−5.61
W^2	−0.08	−0.20	−0.20	-	−0.46	-	-	−0.16	-
$H \times W$	−0.53	-	−0.48	-	-	−1.46	0.49	-	-
p (LOF)	0.844	0.770	0.335	0.631	0.827	0.899	0.358	0.883	0.888
R^2	0.820	0.802	0.762	0.642	0.723	0.683	0.343	0.7314	0.6481
p (>F)	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
RMSE	7.8	8.5	8.5	28.2	37.3	37.5	14.99	13.77	19.16
mean	55.7	57.8	44.6	185.9	298.9	277.0	14.2	60.1	57.8
CV%	14.0	14.7	19.0	15.2	12.5	13.5	105.6	22.9	33.1

All parameter estimates are significant at $\alpha = 0.10$. Sites are clearcut (CCON) and shelterwood (SWNB and SWON). P250 = the percentage of planted pine meeting or exceeding a target height of 250 cm; LOF = lack of fit; RMSE = root mean square error; CV = coefficient of variation.

3.1.2. Planted Pine Height

Planted white pine stem heights were strongly affected by the treatments applied ($p < 0.001$), averaging 186 cm on the clearcut site and 277 and 299 cm on the ON and NB shelterwood sites, respectively, at the end of the 10th growing season (Table 1). As was already evident in the earlier years of the study, woody cover, in combination with herbaceous vegetation control, resulted in the tallest trees at the clearcut (>215 cm), while both early woody and herbaceous vegetation control were associated with the tallest trees at the two shelterwood sites (>300 cm). An exception to this latter trend was provided by two plots receiving complete vegetation control (*bbbbbb*) at the ON shelterwood, where heights averaged just 255 and 273 cm, compared to 336 cm in the third replicate.

The shortest trees in the study were observed at the clearcut site in plots where the woody cover was removed early, particularly with little or no herbaceous vegetation control. For example, the *wwwwww* treatment resulted in trees that were the smallest, statistically shorter than the site mean ($p = 0.05$; Table 1). At the two shelterwood sites, the shortest planted pine were found in plots where woody vegetation control was delayed or not conducted (e.g., the untreated control plots (*000000*) produced trees that averaged 195–197 cm in height; statistically shorter than the respective site means).

In response-surface analyses, planted pine stem heights at the clearcut (Table 2) responded positively to herbaceous vegetation control, with diminishing gains as the duration of control increased ($43 \times H$–$5.86 \times H^2$ cm), and positively to delays in woody vegetation control (an increase of 5 cm for every year of delay). At the two shelterwoods, planted pine heights also responded positively to herbaceous vegetation control, but negatively to any delays in woody vegetation control. In NB, where overstory canopy transmittance was approximately 10% higher and considerably more variable than in ON [43], pine heights were somewhat less sensitive to delays in woody vegetation control than they were in ON. In other words, positive height responses at the ON shelterwood were dependent on both herbaceous vegetation suppression and timely woody vegetation removal, whereas positive responses at the NB site were mostly associated with herbaceous vegetation suppression. For example, in the absence of herbaceous vegetation control, NB shelterwood trees were 46 cm shorter without any woody vegetation control than those released from woody vegetation at the time of planting (-0.46×10^2; Table 2), compared to a difference of nearly 84 cm (-8.36×10) at the ON site. When these same groups of trees were subjected to 2 years of herbaceous vegetation suppression, the presence of woody vegetation amounted to little difference in height loss at the NB site (46 cm), compared to losses of over 110 cm at the ON site. Pine height appears to have been maximized with about 3 years of herbaceous vegetation control. Again, these outcomes are consistent with those observed at the end of the 6th growing season.

3.1.3. Planted Pine Height Increment

Height growth rates at age 10 generally followed treatment-related trends that were consistent with average height (Table 1). However, at the clearcut site, trees in some of the plots with early woody and herbaceous vegetation control (e.g., *bbbbbb*, *bbbbww*, and *hhbbww*) were exhibiting above-average height growth (>22 cm/year), on par with those trees in plots that retained woody cover in the presence of early herbaceous vegetation control (*hhhh0w*, *hh000w*, *hhhh00*, *hh0000*). Like total height, the slowest rates of height growth were found at the clearcut site (12–13 cm/year) in plots that received woody vegetation control and no herbaceous control (*wwwwww*, *00wwww*, and *00000w*). These trees were growing less than half as fast as trees in fully untreated plots (*000000*), which averaged at 25 cm/year.

The fastest growing trees were observed in shelterwood plots that received both early woody and herbaceous vegetation control (≥55 cm/year in NB; ≥44 cm/year in ON); the slowest growing trees, in contrast to the clearcut, were consistently found in the untreated plots (21–23 cm/year). However, the two shelterwoods differed in terms of the treatments producing the slowest growing trees. In the NB shelterwood, like the clearcut, these trees were found in the plots receiving woody vegetation control only (31–33 cm/year). At the ON shelterwood, herbaceous vegetation control in the absence of woody control (*hhhh00*, *hh0000*) produced the slowest growing of the treated plots. These differences are likely a reflection of the different light regimes at the two sites, as mentioned above.

3.1.4. Planted Pine Stem Health

Pine at the clearcut site averaged a "mediocre" health class rating (2.6, Table 1), consistent with the very high incidences of weevil attack observed across this site (average of 44%, Table 1). Continued weevil attack through the 10th growing season has created very poor stem form on a high percentage of the trees across this site, particularly on plots where the woody vegetation has been controlled. Interestingly, if the three treatments where woody vegetation remains on the site are ignored (Figure 3), there is a strong positive relationship between the height growth rate observed on these plots, and weevil incidence; likely a reflection of weevil preference for thicker leaders for oviposition and feeding [12]. In contrast to the open conditions at the clearcut site, weevil incidence was relatively low at the two shelterwood sites and trees were generally rated as "healthy". At the NB site, weevil incidence averaged just 3.2 percent and was invariant to the vegetation control treatments ($p = 0.151$). Trees with the poorest health class ratings tended to be found in plots that did not have herbaceous vegetation control (*wwwwww*, *00wwww*, *00000w*, *000000*). At the ON shelterwood, a July windstorm occurring during the 5th growing season (2006) resulted in significant overstory BA reductions of 4.2 to 25.5 m^2/ha on as many as 10 plots in the study. These plots were largely responsible for the elevated incidence of weevil observed on the site by year 10, with an average incidence of 20% and occurring as high as 57%. At this site, variability in health class ratings across the treatments was fairly narrow, though still statistically significant ($p = 0.012$). In some cases, poorer than average ratings could be linked to high weevil incidence (e.g., *bbbbww*); in other cases, poor health appeared to be associated with suppression in plots not subjected to woody vegetation control (*hhhh00*, *hh0000*, *000000*).

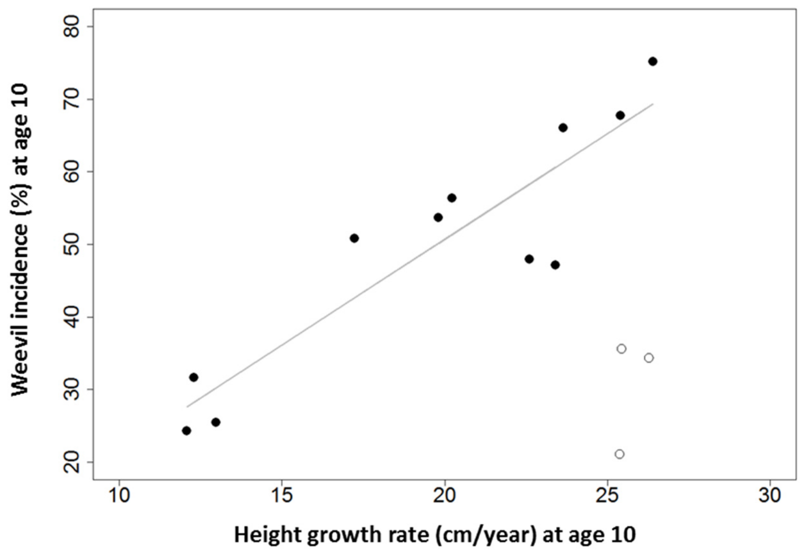

Figure 3. Relationship between treatment means for weevil incidence (%) and planted pine height growth rate (cm/year) at age 10 (r = 0.91), observed at the ON clearcut site for treatments where the woody cover has been removed (solid circles). Treatments with woody cover still in place (*hhhh00*, *hh0000*, and *000000*; Figure 1) are not included in the correlation (hollow circles).

3.1.5. Planted Pine Stem Mortality

Cumulative 10th-year mortality was highest in the NB shelterwood (13.3%) and not associated with the vegetation control treatments (Table 1, p = 0.116). This average is only up 2 percentage points from the 6th-year assessment [33]. The ON shelterwood exhibited the lowest mortality at 5.7% (p = 0.087), up from just 4% in year 6. Of the three sites, the clearcut exhibited the widest range in mortality and the largest increase in mortality since year 6. There, values ranged from 3% in the *hh000w* treatment, to 29% in the *hh0000* treatment, averaging 11.6%, and up from 1% to 9% in the 6th year. Though differences between some of the treatments existed at the clearcut (p = 0.002), patterns were not obvious. Although we did not evaluate specific causes of mortality, we did observe evidence of root rot in many cases.

3.2. Growth and Survival as a Performance Measure

The percentage of trees meeting or exceeding an age-10 target height of 2.5 m (P250) is a performance measure that integrates planted pine growth and survival. Only treatments in the shelterwoods were capable of exceeding P250 values of 50% and there, treatments involving both woody and herbaceous vegetation control were the most successful and consistent, with values averaging 77%. Treatments that removed only the woody vegetation tended to produce below-average P250 values, and no vegetation control produced the lowest values (20%–21%). At the clearcut, the best results (27% to 36%) were observed where early herbaceous vegetation control was conducted and woody cover was retained for at least the first 5 growing seasons (*hh000w* and *hhhh00*).

Response surface analyses of the P250 values (Figure 4; Table 2) generated patterns similar to those of total height growth at the three sites. Responses to herbaceous vegetation control were consistently positive; strongest at the NB site and weakest at the clearcut. For example, 2 years of herbaceous vegetation control increased P250 by nearly 43% in the NB shelterwood plots (32.17 × 2–5.40 × 22); 23% in the ON shelterwood plots (18.03 × 2–3.34 × 22); and just 6% in clearcut plots (3.05 × 2). Responses to delays in woody vegetation control were negative at the shelterwood sites, and most dramatic in ON, where a 5-year delay resulted in a 28% reduction in P250 (−5.61 × 5). A similar delay at the NB site resulted in just a 4% reduction (−0.16 × 52). At the clearcut, positive increases in P250 were only realized through herbaceous vegetation control and delayed woody control.

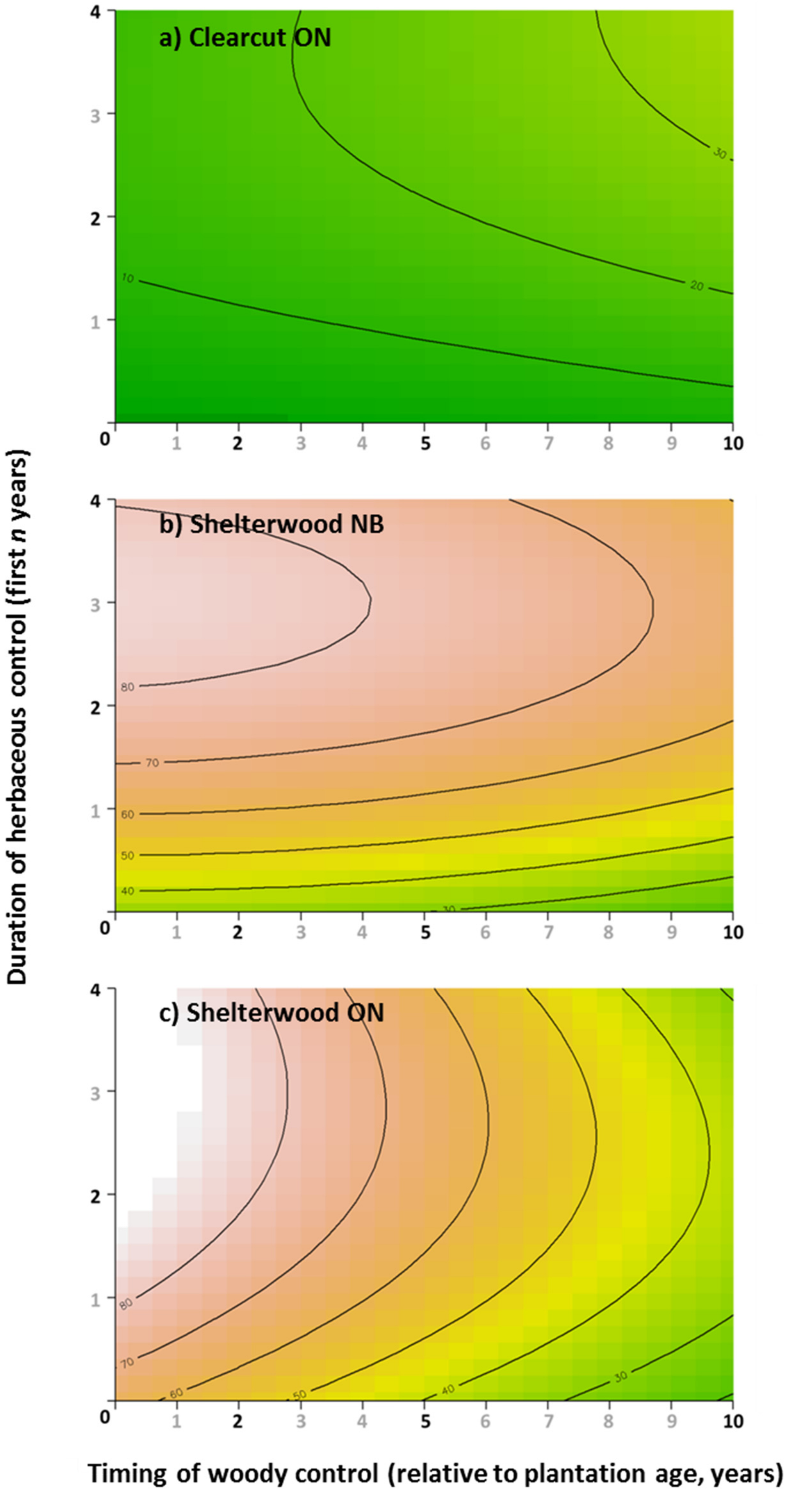

Figure 4. Two-dimensional representations (contour plots) of the response surfaces for age-10 planted pine P250 (percentage of trees meeting or exceeding an age-10 height target of 250 cm) for the clearcut (**a**) and shelterwood NB (**b**) and ON (**c**) sites (n = 60 observations for each). Colour tones move from highest (white) to lowest (green) P250. See Table 2 for model statistics.

3.3. Response to Overstory and Understory Growing Conditions

The response surfaces generated for the year-10 planted pine (Figures 2 and 4; Table 2) confirm that optimum vegetation management for white pine regeneration should aim to strike a balance between maintaining just enough overtopping cover to minimize weevil incidence without sacrificing height growth, while suppressing herbaceous ground cover to maximize stem diameter growth. Collectively, the three study sites offer a wide gradient of early vegetation conditions that may be correlated to age-10 planted pine performance. While a range of different predictive combinations were explored, the *maximum herbaceous cover level* reached during the first five years (calculated from the sum of grass, forb, fern and low shrub cover values) and the *average overtopping cover* (sum of regenerating deciduous tree, tall shrub, and mature residual overstory) during this same period (Table 3) provided good correlations with 10th-year pine performance, while also having potential practical value as thresholds in prescription development. With the percentage of trees reaching a target height of 250 cm in 10 years (P250) being used as a performance measure, the combined data from all three studies (n = 216) define the relationship as (Figure 5):

$$\text{P250} = 12.680 - 0.001(HC^2) + 1.832(OC) - 0.014(OC^2) - 0.002(HC \times OC) \tag{3}$$

where HC is the maximum total herbaceous cover reached during the first 5 growing seasons (%) and OC is the average cover overtopping pine during the first 5 growing seasons (%); all parameters being significant ($p \leq 0.10$). This model explains 51% of the plot-to-plot variation observed in P250, with a root-mean-square-error (RMSE) of 22.9%. While this may not be considered to be an extremely precise model, the overall trends (Figure 5) suggest important threshold targets for vegetation management in the regeneration of white pine. For example, if a target performance of P250 $\geq$ 60% is desired (i.e., at least 1500 high-performing stems per ha), one should aim to allow no more than 50% total herbaceous ground cover to occur during the first 5 growing seasons, while maintaining about 65% $\pm$ 10% overhead cover during this same period. We note that changes in the height-performance threshold (i.e., P200 or P300) simply result in changes to the values of the response-surface contours (percentage success) and not the shape of the response surface itself (i.e., the zone of maximization).

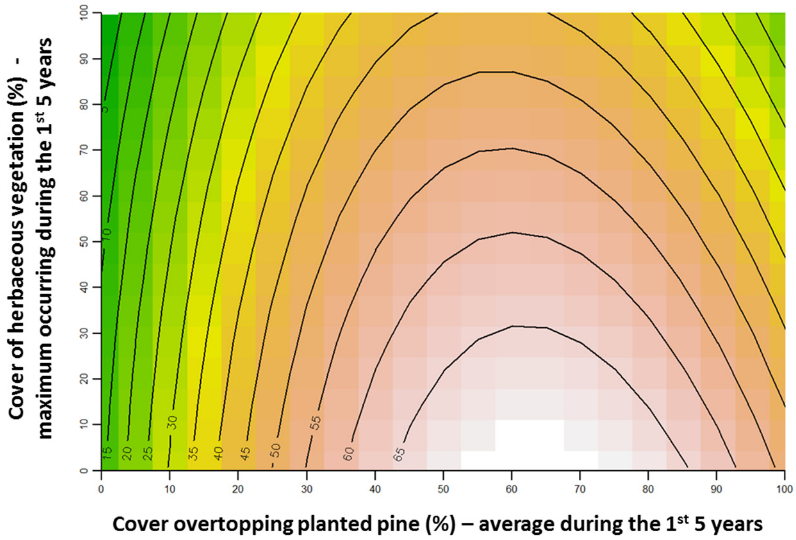

Figure 5. Two-dimensional representation (contour plot) of the response surface for age-10 planted pine P250 (percentage of trees meeting or exceeding an age-10 height target of 250 cm), as a function of maximum herbaceous vegetation cover occurring during the first 5 growing seasons and average overtopping cover during the same period. Herbaceous and overtopping cover are the sum of grass, forb, ferns, and low shrub cover, and deciduous tree, tall shrub, and overstory tree cover, respectively. Colour tones range from highest (white) to lowest (green) P250.

Table 3. Treatment mean non-crop cover values used to produce model (3) (Figure 5).

Site	Variable	*bbbbbb*	*bbbbww*	*bbwwww*	*hhbbww*	*hhwwww*	*00b000*	*hhhh0w*	*hh000w*	*hhhh00*	*hh0000*	*wwwwww*	*00wwww*	*00000w*	*000000*
CCON	∑ herbaceous	5	40	55	15	69	99	20	50	12	60	124	133	139	136
	∑ overtopping	0	0	0	6	4	3	43	33	38	37	2	4	21	19
	Overstory cover (BA, m^2/ha)	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		(0)	(0)	(0)	(0)	(0)	(0)	(0)	(0)	(0)	(0)	(0)	(0)	(0)	(0)
	P250	15	21	13	19	8	2	12	27	36	21	0	0	1	5
SWNB	∑ herbaceous	4	12	11	1	20	58	6	8	6	4	114	117	117	88
	∑ overtopping	67	56	44	69	59	65	62	76	72	79	36	36	73	69
	Overstory cover (BA, m^2/ha)	67	56	43	68	56	61	44	60	57	60	35	31	60	53
		(28)	(18)	(13)	(25)	(18)	(19)	(15)	(19)	(17)	(18)	(10)	(8)	(21)	(17)
	P250	76	73	79	80	79	70	80	71	59	63	36	32	25	21
SWON	∑ herbaceous	2	3	16	3	27	79	3	16	4	13	128	127	104	96
	∑ overtopping	63	54	62	70	58	67	86	97	96	99	61	54	84	91
	Overstory cover (BA, m^2/ha)	63	54	62	63	52	58	55	61	63	66	60	47	57	61
		(21)	(16)	(19)	(19)	(15)	(18)	(17)	(19)	(20)	(21)	(18)	(12)	(16)	(19)
	P250	72	97	93	85	81	70	51	67	31	31	59	60	36	20
	n	3	3	3	3	9	9	3	9	9	3	3	3	3	9

∑ herbaceous is the sum of grass, forb, fern and low shrub cover (%) occurring as a maximum during the first five growing seasons. ∑ overtopping is the sum of regenerating deciduous tree, tall shrub, and mature residual overstory cover (%) averaged over the first 5 growing seasons. The portion of the latter contributed by the mature residual overstory is given in cover (%) and basal area (m^2/ha). Values are derived from 25 trees in each of *n* treatment plots. See Figure 1 for a description of treatment codes (in short, 6 characters represent years 1 through 6, respectively: "0" = no vegetation control; "*w*" = woody control; "*h*" = herbaceous control, and "*b*" = both woody and herbaceous control); sites are clearcut (CCON) and shelterwood (SWNB and SWON).

Residual overstory basal areas in the range of 15 to about 26 m^2/ha appear to achieve the desired target overhead cover (Figure 6; Table 3), without introducing much additional cover from regenerating deciduous trees and tall shrubs. When this latter cover was added to residual overstory cover at the shelterwood sites, just under half of the plots in NB exceeded 75% overtopping cover, while more than half the plots at the ON site exceeded this level (Figure 6), placing them outside of the optimal range. In the absence of mature overstory (i.e., on a clearcut), the data suggest that relatively high densities of deciduous regeneration are required to place overtopping cover into the optimal zone (Figure 6; Table 3).

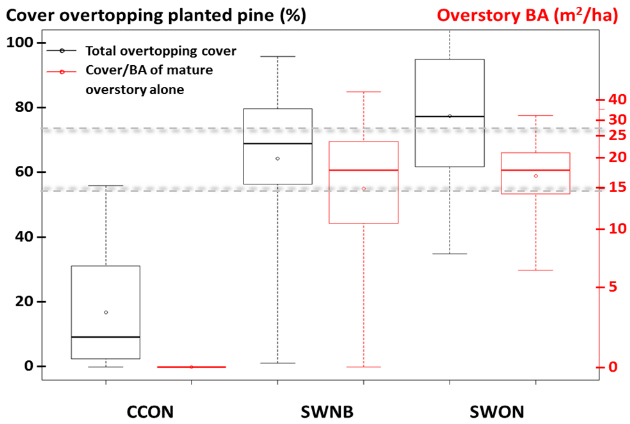

Figure 6. Distribution of overtopping cover (in black; sum of deciduous tree, tall shrub, and overstory covers) and mature tree basal area (in red; m^2/ha) across the 72 plots at each site. Whiskers reflect maximum and minimum observations; boxes encompass the 25th and 75th quantiles; solid lines reflect the medians; and hollow circles the means. Zone between horizontal dashed lines reflects the overtopping cover range associated with maximum planted pine performance (see Figure 5). Sites are clearcut (CCON) and shelterwood (SWNB and SWON).

The results of these analyses suggest that good white pine regeneration performance may require fairly rigorous management of both overtopping and early herbaceous vegetation. The percentage frequency of the various treatments that occur within the P250 = 60% contour of Figure 5 indicate that the most consistent treatments ($\geq$90%) are those in the shelterwoods where early (0–2 years) woody release was coupled with 2 to 4 years of herbaceous vegetation suppression (Figure 7). The benchmark complete removal treatment (*bbbbbb*) appears to exhibit some inconsistency with this generality, offering only 65% success at the ON shelterwood. Historically, both planted and natural pine performance on 2 of the 3 replicates of this treatment in ON was lower than expected, apparently due to random chance. Simulated operational release (*00b000*) in the shelterwoods provided at least 70% consistency in achieving P250 $\geq$ 60%. Early herbaceous vegetation control beneath deciduous cover was necessary at the clearcut site to achieve the same degree of success; however, consistency was less than 20%.

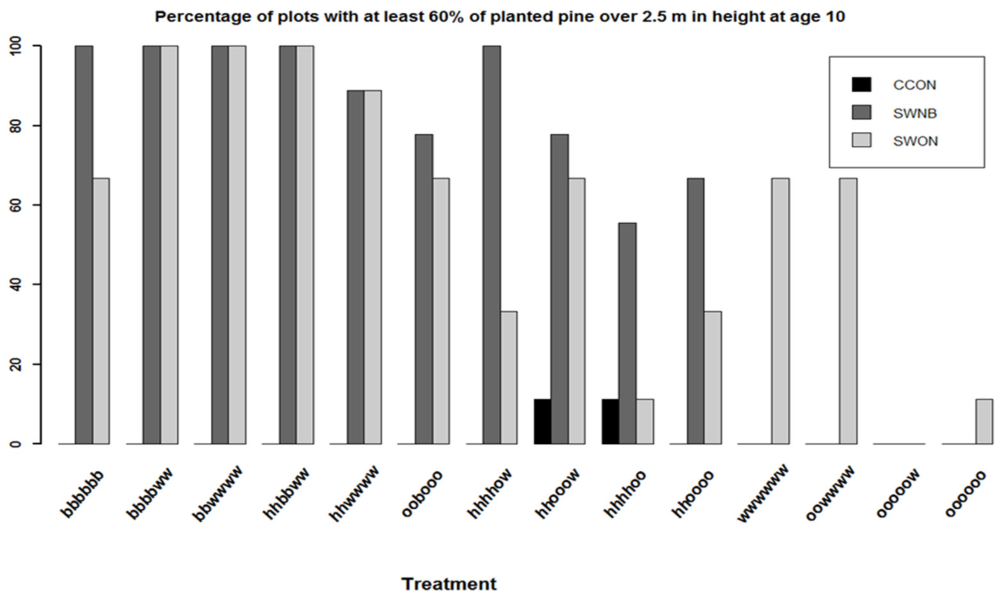

Figure 7. Treatment consistency (%) in reaching an age-10 planted pine height target of 250 cm (P250) at least 60% of the time (i.e., area inside the 60% contour of Figure 5). See Figure 1 for treatment code definitions codes (in short, 6 characters represent years 1 through 6, respectively: "*0*" = no vegetation control; "*w*" = woody control; "*h*" = herbaceous control, and "*b*" = both woody and herbaceous control). Sites are clearcut (CCON) and shelterwood (SWNB and SWON).

4. Discussion

4.1. Looking Back

The planted white pine response surfaces generated after the 10th-growing season (Figures 2 and 4; Table 2) bear strong resemblance to those derived following the 6th growing season [31,33], confirming clear temporal consistency of the early vegetation management treatments. With a few minor exceptions, model parameters that were significant after year-6 were essentially the same as those selected through backward elimination with the 10th-year data. Model precision, as reflected by the coefficients of variation (RMSE expressed as a percentage of the mean), generally stayed the same or increased slightly when the older trees were modelled. With the exception of stem diameter predictions on the clearcut, the range of responses to the treatments were proportionally larger with the older trees; trees in the NB shelterwood showed the largest range increase of about 35% for both total height and stem diameter predictions; trees at the clearcut, the smallest (7% for height predictions and −29% for diameter predictions). Response ranges for 10th-year height and diameter at the ON shelterwood increased by about 20% over 6th-year measures.

The fact that the decade-long growth responses of planted pine in these studies reflect vegetation management treatments that took place during the first few years of establishment is a strong indication that these treatments will have rotation-length influences on the structure, composition, and productivity of these stands. This finding is consistent with other long-term vegetation management studies in the literature [44] and is important because vegetation management treatments are often dismissed by inexperienced managers as having only "temporary, short-term effects" [45]. Instead, the temporal consistency of the data in this study foretells their usefulness in prescription development.

4.2. The Three Sites in Perspective

Our goal was to conduct this experiment within representative examples of the silvicultural systems being used to regenerate white pine, on sites that were as similar as possible in terms of soil type and site quality. Comparisons of the silvicultural systems themselves were not intended and we caution that such would be confounded with site-to-site differences. Moreover, the results attained in this study pertain to the relatively narrow range of site conditions encompassed by the three sites involved; one cannot necessarily expect the treatments to perform the same on the wider range of possible site conditions that white pine might be managed on.

Past studies of the effects of competition on tree growth have shown crop-tree stem diameter to be the best allometric indicator of competition for growing resources, with stem height and mortality being comparatively invariant in all but the more extreme competition levels [45]. In this study, planted pine stem diameters responded strongly and positively to the increased light, soil moisture and nutrient availability associated with both herbaceous and woody vegetation control (Figure 2; [29,30,32]). Close examination of the stem diameter response surfaces reveals clear similarities between the clearcut (Figure 2a) and the NB shelterwood (Figure 2b), suggesting comparative competitive environments at these sites, despite large differences in overtopping residual cover (Figure 6). Delays in the removal of woody vegetation appear to have had less influence on planted pine diameter growth in the presence of herbaceous competition than when the herbaceous vegetation was controlled, perhaps indicating that competition for soil moisture and nutrients might be greater than for light at these sites.

In contrast, planted pine stem diameters at the ON shelterwood (Figure 2c) were equally responsive to herbaceous vegetation control and the timeliness of woody vegetation control. In other words, both herbaceous vegetation suppression and early woody vegetation control were necessary to increase planted pine stem diameters. While this might indicate increased competition for light at this site (overtopping cover was higher at the ON shelterwood than the other two sites; Figure 6), this difference alone does not seem adequate to explain the much steeper gradient to the treatment response-surface observed there (Figure 2c). Naturally regenerating pine, most prolific at the ON shelterwood site, are exerting intraspecific competition on the planted pine, contributing to reductions in their diameter growth. By the end of the 10th growing season at the ON shelterwood, conifer natural regeneration dominated by white and red pine averaged 27,320 sph, 121 cm in height with 99% stocking, compared to 20,430 sph (90 cm × 97% stocking) at the NB shelterwood and just under 740 sph (36 cm × 18% stocking) at the clearcut. Scarification and seed availability explain the large regeneration differences between the shelterwoods and clearcut. An imbalance of natural regeneration across plots and sites precluded the inclusion of natural pine responses in this paper, but we note that, where present, these trees generally mirrored the planted pine, suggesting that our results may apply equally well to natural regeneration scenarios [33].

Tree height growth typically takes priority over diameter growth in photosynthate allocation [46], and so competition-induced suppression of height can be a sign of substantial stress often found under reduced light conditions [45,47]. That the two shelterwood sites exhibited fairly strong height-response gradients to herbaceous and woody vegetation control (Table 2) is an indication of serious competition for resources at these sites. If not for the presence of white pine weevil at the clearcut site, we suspect that the pattern of response there would be similar to that of the shelterwoods. Instead, planted pine in the clearcut scarcely avoided attack when they were beneath dense aspen cover, and only achieved reasonable height growth when competition for soil moisture and nutrients was reduced through herbaceous vegetation control. Still, maximal heights on the clearcut (~240 cm) were consistent only with the more marginal responses in the shelterwoods, likely due to reduced light availability and mechanical interference associated with the overtopping aspen regeneration (again, ignoring any subtle differences in site quality that might exist among sites).

At the clearcut site, weevil incidence and severity have been and continue to be highest in plots receiving both herbaceous vegetation control and timely woody control (Table 1). Although these treatments currently support the highest height growth rates at that site (Figure 3), leader diameters are obviously quite favorable to weevils and these trees seem to be destined for downwardly spiraling stem form and quality. Consequently, our results confirm operational experience that a clearcut environment may not be appropriate for white pine regeneration unless fairly high pine densities are managed with dense overtopping deciduous cover [12,48]. Then, the need for herbaceous vegetation control and measures to mitigate subsequent mechanical interference between the pine and hardwoods would likely make this strategy cost prohibitive.

During the first 10 growing seasons, treatment-related patterns in planted pine mortality have not emerged; an observation that is not surprising given the shade tolerance of white pine [45]. We have also not observed significant white pine blister rust incidence in any of the test plantations. The seasonal Bayleton® treatments provided for the first five growing seasons could provide an explanation for this, as there is known to be a degree of residual control afforded by triadimefon [49]. However, the current lack of availability of this or any other fungicide for prophylactic control of blister rust means that forest managers must rely on cultural practices that modify humidity [12], while waiting for research results from other studies that indicate positive resistance through genetic selection, hybrids and/or the use of foliar endophytic fungi [15,17].

4.3. Applying What We've Learned

The ultimate goal of this study was to elucidate the understory and overstory vegetation conditions that favor planted white pine survival and growth so that forest managers might develop more consistent, effective and scientifically based vegetation management prescriptions for the regeneration of this important species. Rather than comparing and contrasting vegetation management tools, we aimed to identify threshold competition levels to be observed using one or more of the tools available within the framework of local guidelines and regulations.

In previous reporting of this study [31,33], we discussed several practical management options for emulating the study's outcomes. Importantly, the 10th-year data reported herein do not prompt us to retract any of these recommendations. Rather, these longer-term data allow us to generalize prescriptions around managing overhead cover and minimizing early herbaceous cover, with the aim of balancing light, for maximum growth and minimum weevil preference, while minimizing competition for soil moisture and nutrients (Figure 5). The successful restoration of white pine following clearcutting requires a potentially expensive strategy involving herbaceous and woody vegetation control that maintains high densities of white pine (in excess of 2500 sph) overtopped by a dense nurse crop. More consistent and affordable regeneration success may be realized through shelterwood systems, wherever uniform canopies of mature pine exist. Current guidelines call for the retention of 10 to 18 m^2/ha of residual overstory basal area (40% to 60% crown closure) during the regeneration cut, depending on whether a single or multiple future removal cuts are planned [27,48]. This target range appears consistent with the optimum overhead cover levels for regenerating white pine height growth and survival suggested by this study (Figure 6), but imply that there is very low tolerance for the ingress of regenerating deciduous woody cover or understory light levels may become limiting [50,51]. This need for woody vegetation control, coupled with the need to retain herbaceous covers below about 50% during the first five years, confirms that fairly rigorous vegetation management is required to successfully regenerate white pine on productive white pine sites [20,21,48].

The forest manager's task lies in the selection of tools to effectively and efficiently achieve both woody and herbaceous vegetation control, subject to jurisdictional constraints around social and legal acceptance. Prescribed fire, where permitted, has been shown to be an effective site preparation tool shortly following the regeneration cut [48,52], but liability and very exact site, stand and weather requirements significantly reduce its affordability. Mechanical site preparation or scarification may serve to minimize the regeneration of competing vegetation, particularly if undertaken in early to mid-July when carbohydrate reserves in non-crop root systems are lowest [53], but will not likely prevent regrowth and production from seedbanks on fertile sites [54,55]. Manual cutting offers a degree of woody vegetation control, but often serves to exacerbate herbaceous competition (analogous to the poorly performing *wwwwww*, *00wwww* and *00000w* treatments in this study). Alternatively, the use of grazing animals for vegetation control has largely been demonstrated as impractical [56,57].

Now and into the foreseeable future, the only practical and affordable means of achieving both woody and herbaceous vegetation control on productive sites within the range of eastern white pine involves the use of synthetic herbicides [58]. Except in Quebec, where public land herbicide use has been banned since 2001, glyphosate-based herbicides are the only federally registered products available in northeastern Canada that will provide the broad-spectrum control needed. Glyphosate is strictly absorbed by green foliage and may be used immediately following harvest to reduce woody and herbaceous competition during site preparation, or as a release treatment following the establishment of regeneration. In our study, a single broadcast application of glyphosate at the end of the second growing season following planting in the shelterwood scenarios was almost as successful as some of the more rigorous site preparation treatments tested. Operationally, such applications are most effectively made using aircraft equipped with nozzles that deliver consistent-sized droplets in the 500 μm range, such as the Accu-Flo™, with relatively high application volumes (40 to 50 L per ha). In the northeastern United States, a much wider array of herbicide options exist, including products that have a degree of residual control through root uptake, such as sulfometuron methyl for herbaceous control, and imazapyr and metsulfuron methyl for deciduous woody control.

4.4. Looking Forward

The three study sites reported herein were designed for long-term monitoring. Consistent with the need to manage overtopping cover, a series of treatments have been implemented at each site since the 10th-growing season data collection reported herein. At the clearcut, deciduous woody vegetation (largely aspen) remaining on *hhhh00* and *000000* plots were pre-commercially thinned to 3 different densities: 700, 1300, and 2500 sph (n = 6 plots for each level); plots assigned the *hh0000* treatment (n = 3) were left as unthinned controls. These overlay treatments will allow the manipulation of the light levels over plots that, to date, have some of the best planted pine height growth on the clearcut site.

At the ON shelterwood, moderated 10th-year planted pine height response (Figure 4c) and understory light measurements [43] suggested the need to execute a first-entry removal cut to reduce overstory BA. Across the entire research site, a total of 5.4 m^2/ha of BA was removed using manual falling, delimbing and bucking in late November 2012. A Fabtek 548B forwarder was used within the corridors between the plots to remove 62 m^3/ha (25%) of gross merchantable volume. Tree marking focused on corridor trees, unhealthy/damaged trees, suppressed trees, and those that would result in uniform residual overstory crown closure, ultimately reducing BA by 26%, crown closure by 27%, and stem density by 33%. This harvest left the current overstory stand with 81 sph, DBH averaging 48.4 cm, and BA totaling 15.4 m^2/ha, increasing average beneath-canopy light levels to about 65% (W. Parker, unpublished data). Damage to planted and natural regeneration was very minimal. A second removal harvest is scheduled for this site sometime just before or after the year-20 assessments. A single removal harvest at the NB shelterwood is being planned shortly following the scheduled year-15 assessments.

At the end of the growing season in year 12 (NB) and 13 (ON), both shelterwood sites received a broadcast aerial application of glyphosate as an overlay treatment across all plots. The specific aim of this treatment was to release planted pine languishing in the shade of the deciduous woody layer remaining on the *hhhh00*, *hh0000* and *000000* plots. Treatments were made using a helicopter equipped with Accu-Flo™ 0.016 nozzles applying 4.5 L of Forza® (glyphosate) in a total solution of 50 L per ha. The pine saplings in many of these plots represent relatively low establishment costs, as compared to plots receiving more aggressive early vegetation control. Pre-commercial thinning will likely be required sometime after the year-15 assessments at these shelterwood sites to reduce intra-specific competition amongst the pine. We expect that by year 20, the wide array of different regeneration strategies offered by this suite of long-term studies will provide data for thorough cost-benefit analyses within the context of maintaining social, environmental, and economic values.

5. Conclusions

Early vegetation management treatments aimed at reducing the abundance of herbaceous and woody vegetation strongly promoted the size of white pine at least a decade after planting. Subject to the scope of productive, well-drained sites studied, installations of the same response-surface design in a clearcut and two variants of the uniform shelterwood regeneration system (single vs. multiple future removal cuts) indicate that the 10th-year performance of planted eastern white pine is dependent on careful management of overtopping vegetation to achieve 65% ± 10% cover through the first 5 years, and the suppression of herbaceous vegetation cover to totals not exceeding 50% during this same period. Such conditions may be difficult to achieve using practical tools in clearcut scenarios, and the results of this experiment generally do not support the use of this regeneration system for white pine. Typical uniform shelterwood systems that aim to leave 40% to 60% mature residual canopy cover, place overtopping cover near the desirable range; however, tolerance for regenerating deciduous cover must be low. The need to control overtopping regenerating deciduous cover and understory herbaceous cover for maximum growth of regenerating pine translates to fairly rigorous vegetation management, unlikely to be attained without herbicide use on productive sites. Naturally regenerating pine present in this study mirrored the responses of planted pine, suggesting that these results also apply to natural regeneration scenarios. In the years to come, this study should offer data that support cost:benefit analyses within the context of social, environmental, and economic values.

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