Forty years of spruce–fir stand development following herbicide application and precommercial thinning in central Maine, USA

Matthew G. Olson, Robert G. Wagner, and John C. Brissette

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Abstract: We examined the development of a 33-year experiment in spruce–fir stands that received nine herbicide treatments (applied aerially in 1977), with and without precommercial thinning (PCT) (applied in 1986). We tested two commonly held assumptions about the long-term effects of herbicide and PCT in mixedwood stands managed for softwoods: (*i*) herbicide release produces stands dominated by softwoods and (*ii*) PCT promotes both softwood dominance and merchantable volume. All herbicides were effective at releasing balsam fir (*Abies balsamea* (L.) Mill.) and spruce (*Picea* spp.) from overtopping shrubs and hardwoods that had naturally regenerated following clearcut harvesting in 1970. Glyphosate (Roundup), triclopyr amine (Garlon 3A), 2,4,5-T, and a mixture of 2,4,5-T and 2,4-D herbicide treatments were all effective at shifting long-term species composition to softwood dominance after 30 years, irrespective of the rates applied. Herbicide-treated stands that did not receive PCT were overstocked with softwoods for at least 24 years and produced less than half of the merchantable softwood volume by 40 years than herbicide-treated stands that received PCT. Intolerant hardwoods dominated untreated stands for all 33 years of the experiment. When unsprayed plots received PCT, however, they produced stands at 40 years that were compositionally and structurally indistinguishable from those that had received both herbicide and PCT treatments. Results from this experiment clearly demonstrated that early herbicide application, regardless of type and rate of herbicide, created softwood-dominated mixedwood stands over the long term and that PCT more than doubled merchantable softwood volume within 25 years of application.

Résumé : À partir d'une expérience établie il y a 33 ans, nous avons analysé le développement de peuplements d'épinette et de sapin qui ont reçu neuf traitements d'herbicide (appliqués par voie aérienne en 1977), avec et sans éclaircie précommerciale (EPC) (appliquée en 1986). Nous avons testé deux hypothèses généralement retenues en ce qui concerne les effets à long terme des herbicides et de l'EPC appliqués dans les forêts mixtes aménagées pour les résineux : (*i*) l'application d'herbicide produit des peuplements dominés par les résineux et (*ii*) l'EPC favorise la dominance et le volume marchand des résineux. Tous les herbicides ont été efficaces pour soustraire le sapin baumier (*Abies balsamea* (L.) Mill.) et les épinettes (*Picea* spp.) de la compétition des arbustes et des feuillus dominants qui s'étaient régénérés naturellement à la suite d'une coupe à blanc réalisée en 1970. Les traitements d'herbicide avec le glyphosate (Roundup), le tryclopyr amine (Garlon 3A), le 2,4,5-T et un mélange de 2,4,5-T et de 2,4-D ont tous été efficaces pour amener la composition à long terme des peuplements vers une dominance de résineux après 30 ans, peu importe le taux qui a été appliqué. La densité relative en résineux des peuplements traités avec un herbicide sans EPC a été excessive pendant au moins 24 ans et ces peuplements ont produit moins de la moitié du volume marchand résineux à l'âge de 40 ans comparativement aux peuplements traités avec un herbicide et une EPC. Les feuillus intolérants à l'ombre ont dominé les peuplements non traités pendant les 33 années de l'expérience. Toutefois, les parcelles soumises à une EPC sans épandage d'herbicide ont produit des peuplements dont la composition et la structure à 40 ans ne pouvaient être différenciées de celles des parcelles traitées avec un herbicide et une EPC. Les résultats de cette étude démontrent clairement qu'un épandage hâtif d'herbicide, peu importe le type d'herbicide et son taux d'application, a produit à long terme des peuplements mixtes dominés par les résineux et que l'EPC a plus que doublé le volume marchand résineux en moins de 25 ans avoir été appliquée.

[Traduit par la Rédaction]

Introduction

The spruce–fir forest of the northeastern United States and eastern Canada is periodically infested by the spruce budworm (*Choristonuera fumiferana* Clemens) that severely defoliates stands and causes widespread mortality of balsam fir (*Abies balsamea* (L.) Mill.), and spruce (*Picea* spp.) to a lesser degree (MacLean 1980; Seymour 1992). Even-aged management of spruce–fir stands became common following a severe budworm outbreak in the mid-1970s when the region's entire spruce–fir resource was infested (Seymour 1992). Clearcutting became an important harvesting practice in an attempt to salvage dead and dying trees in infested

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M.G. Olson and R.G. Wagner. School of Forest Resources, University of Maine, Nutting Hall, Orono, ME 04469-5755, USA.
J.C. Brissette. USDA Forest Service, Northern Research Station, 271 Mast Road, Durham, NH 03824, USA.

Corresponding author: Matthew G. Olson (e-mail: matthew.g.olson77@gmail.com).

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stands. Although natural regeneration of spruce and fir can be prolific following clearcutting (Seymour 1995), competition from abundant, fast-growing shrubs and hardwoods presents a formidable management challenge (Newton et al. 1992*b*; Seymour 1995). In addition, spruce and fir often naturally regenerate at very high densities, requiring some form of early stocking control (Seymour 1995).

The principal method used to reduce competing vegetation in regenerating spruce–fir stands has been release treatments using aerial herbicide application (Newton et al. 1992*a*, Seymour 1995). Precommercial thinning (PCT) using brushsaws is generally conducted a few years after herbicide application to space spruce and fir saplings (Seymour 1995). PCT is practiced extensively in the Acadian Forest (Homyack et al. 2007; Cole et al. 2008; Pitt and Lanteigne 2008). An analysis by Wagner et al. (2003) indicated that herbicide and PCT treatments play an important role in Maine's future wood supply and that understanding the long-term compositional and structural responses to these treatments is vital to making accurate predictions of future forest conditions.

Although there has been a substantial research effort quantifying the influence of vegetation control on early stand growth over the past few decades, there are relatively few studies documenting long-term stand dynamics for northern forests (Wagner et al. 2006). Even though the widespread use of PCT is relatively recent in the northeastern United States, a number of studies have documented growth responses from PCT on spruce–fir stands in the region (Piene 1981; Ker 1987; Piene and Anderson 1987; Lavigne and Donelly 1989; Barbour et al. 1992; Briggs and Lemin 1994; Burns et al. 1996; Brissette et al. 1999; Pitt and Lanteigne 2008). Since vegetation management and PCT are generally applied together, however, understanding the combined influence of these treatments on stand development is crucial.

The Austin Pond Study is one of the longest running experiments of its kind in North America. Established in 1977 by the University of Maine's Cooperative Forestry Research Unit, the study was initially designed to examine the efficacy of aerially applied herbicide treatments for managing early successional vegetation. In 1986, a PCT treatment was applied to reduce conifer density and surviving hardwoods on one half of each herbicide plot. The resulting split-plot treatment array represented all combinations of competition release (whole plot) and PCT (split plot) typically used at that time by large, private landowners in spruce–fir stands of the region (McCormack and Lemin 1998).

Herbicide and PCT treatments are generally prescribed under the assumption that they are required to maintain long-term softwood dominance and to more rapidly produce stands of merchantable value than would otherwise be possible. A major limitation to testing these assumptions has been a lack of controlled experiments documenting the long-term (>30 years to rotation age) effectiveness of these treatments alone and in combination (Thompson and Pitt 2003; Wagner et al. 2006). The objective of this study was to twofold. First, we used measurements from the Austin Pond Study collected over a 33-year period from 1977 to 2010 to evaluate the long-term effects of herbicide release and PCT on stand composition and structure. Second, we used these results to test two commonly held assumptions about the long-term effects of herbicide and PCT in mixedwood stands managed for softwoods: (*i*) early herbicide release produces stands dominated by softwoods and (*ii*) PCT promotes both softwood dominance and merchantable volume.

Methods

Study site

The Austin Pond Study is located in central Maine, USA (45.20°N, 69.70°W), 30 km northeast of Bingham. The site is at approximately 400 m elevation on gently sloping outwash with a northeast aspect (Newton et al. 1992*a*). Soils on the site range from Telos to Chesuncook series and from 2 to 4 on the Briggs (1994) soil drainage scale (0–30 cm below soil surface). The stand originated in 1970 following clearcut harvesting during the winter of 1969–1970. An aerial photograph from 1968 showed that the site supported a mature softwood-dominated forest before harvest. Seven years later, when the original study was installed, natural softwood regeneration was abundant but overtopped by high densities of deciduous shrubs and hardwoods (Newton et al. 1992*a*, 1992*b*).

Treatments and experimental design

In the original experiment, seven herbicides were tested in various mixtures and rates, making a total of 12 herbicide treatments plus an untreated and water-only control (i.e., a total of 14 treatments). Eight of these treatments were dominated by phenoxy herbicides (2,4-D or 2,4,5-T), which were the most commonly used herbicides at the time. Glyphosate and triclopyr amine were new materials, having just been registered by the US Environmental Protection Agency, and relatively little was understood about their influence on forest vegetation at the time. The Austin Pond Study includes some of the oldest aerial applications of glyphosate and triclopyr in North American forests and contains the oldest surviving set of forest research plots with these herbicides. A primary motivation for the original study was the need to evaluate these new herbicides at a time when 2,4-D and 2,4,5-T were expected to be no longer available (McCormack and Newton 1980).

Each treatment plot was 1.07 ha (66.4 m × 160.9 m) in size. Each of the original 14 treatments was replicated twice and completely randomized, resulting in 28 treatment plots. Spray treatments (i.e., 12 herbicides plus the water-only) were aerially applied using a Bell 47-G3 helicopter. A conventional boom equipped with D6-46 nozzles that delivered a spray with a median drop size of approximately 400–500 μm was used. The aqueous spray mixtures were delivered at 37.4 L/ha in four swaths per plot with an effective swath width of 16.7 m. Flights were guided by live flaggers on the ground and a spotter flying with the pilot. All treatments were completed during a single morning spray session in early August 1977. There were very few skips in coverage, and the treatments were similar to those occurring in large operational applications at the time (McCormack and Newton 1980).

In autumn 1986, 9 years after the herbicide treatments, each of the original 28 herbicide treatment plots was divided in half (66.4 m × 80.5 m, 0.53 ha) and one half received a PCT treatment that reduced the tree density to approximately 1750/ha. The PCT was conducted using typical contract

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crews with motor-manual brushsaws. The PCT guidelines required the uniform spacing of all spruce and fir that were in a dominant position and removal of all hardwood trees (McCormack and Lemin 1998). The resulting experimental design was a completely randomized (14 herbicide treatments × 2 replicates) split plot with half the plot receiving PCT and the other half left unthinned.

Because the intent of the original experiment at Austin Pond was to evaluate herbicide efficacy within the first few years after application, earlier sampling approaches were not designed to capture long-term responses. In the summer of 1999, four circular 0.021 ha (8.23 m radius) permanent sample plots were systematically placed inside each treatment plot to quantify and track long-term responses to herbicide and PCT treatments. The sample plots were nested near the center of each treatment plot to minimize edge effects. Species and diameter at breast height (DBH = 1.37 m) were recorded for all live tree stems in each sample plot. This information was recorded for individual trees >8.9 cm DBH. For stems less than 8.9 cm DBH, trees were tallied into one of four diameter classes of 1.27, 2.54, 5.08, and 7.62 cm using a gauge. In 1999, a subsample (n = 2700) of live trees for the most abundant species was selected across all DBH classes and total height was measured using an electronic hypsometer (Haglöf, vertex II). These measurements were repeated during the summer of 2010, which included relocating and estimating heights on 1219 of the 2700 live trees measured for height in 1999.

Analytical approach

For this investigation, we selected nine herbicide treatments (Table 1) that included both thinned and unthinned halves to evaluate the stand development that had occurred following herbicide application and PCT. Four herbicide and two application rate treatments plus the unsprayed control (nine whole-plot treatments in total) formed the basis for the herbicide comparisons. Analysis was performed on measurements from four inventories spanning 33 years (summer of 1977 to summer of 2010). The earliest sample was the 1977 inventory conducted 7 years after clearcutting on the original herbicide blocks just before they were treated. This inventory provided an estimate of the vegetation conditions in each randomly assigned herbicide plot prior to treatment. The 1983 inventory was used to represent vegetation development 6 years after herbicide application and 13 years after clearcutting. Since the 1977 and 1983 inventories pre-date the PCT treatment, analysis of these first two inventories was based on nine, twice-replicated herbicide treatments, or 18 experimental units. The inventories from the summers of 1999 and 2010 were conducted 13 and 24 years after PCT, 22 and 33 years after herbicide application, and 29 and 40 years after clearcutting, respectively. For the 1999 and 2010 inventories, analysis was based on 18, twice-replicated herbicide × PCT combinations, or 36 experimental units.

Analysis of stand composition included measurements from all four inventories and represented stand dynamics over the entire 33-year study. Stand composition was expressed using species importance values (IV) to provide a comparable measure of species composition across all inventories. IV is an index of the importance of a plant species within a plant community (Curtis and McIntosh 1951) and is calculated from estimates of a species' relative density, relative frequency, and relative dominance. The estimate of relative frequency was expressed as the number of plots where a species was found divided by the sum of the frequencies of all species, which was then converted to a percentage. Relative density was calculated based on the stem density of each species expressed as a percentage of total density, while relative dominance was estimated for each species based on either percent cover or basal area. Estimates of IV for a species were based on relative dominance (calculated from percent cover) and frequency for the 1977 inventory, relative density and frequency for the 1983 inventory, and relative density, frequency, and dominance (calculated from basal area) for the 1999 and 2010 inventories.

Theeight most common plant species or species groups (henceforth referred to as species) across the inventories were selected to retrace community dynamics using descriptive and multivariate statistics. The eight species used were (1) balsam fir, (2) spruce (red (*Picea rubens* Sarg.), black (*Picea mariana* (Mill.) BSP), and white (*Picea glauca* (Moench) Voss)), (3) aspen (trembling (*Populus tremuloides* Michx.) and bigtooth (*Populus grandidentata* Michx.)), (4) red maple (*Acer rubrum* L.), (5) white birch (white (*Betula papyrifera* Marsh.) and gray (*Betula populifolia* Marsh.)), (6) red cherry (*Prunus pensylvanica* L.f.), (7) other trees (sugar maple (*Acer saccharum* Marsh.), yellow birch (*Betula alleghaniensis* Britt.), willow (*Salix* spp.), eastern white pine (*Pinus strobus* L.), and northern white-cedar (*Thuja occidentalis* L.)), and (8) shrub (raspberry (*Rubus* spp.), beaked hazelnut (*Corylus cornuta* Marsh.), mountain maple (*Acer spicatum* Lam.), and striped maple (*Acer pensylvanicum* L.)). For each species, IV was estimated at the experimental unit level (i.e., n = 18 for 1977 and 1983 and n = 36 for 1999 and 2010) and expressed as the average of the two replicates for both the herbicide (n = 9, 1977 and 1983) and herbicide x PCT treatment combinations (n = 18, 1999 and 2010). Trends in mean IV of individual species for each treatment-averaged unit, either herbicide (pre-PCT) or herbicide × PCT combination (post-PCT), were interpreted over the four inventories using descriptive plots. Since only stems >1.37 m tall were included in the 1983 inventory, low shrubs, like raspberry, were likely underrepresented in 1983; therefore, early trends in shrub importance were interpreted cautiously. Nonmetric multidimensional scaling was used to ordinate the nine herbicide treatments and 18 treatment combinations within a two-dimensional species space derived from just the tree species (i.e., after omitting shrub species from the main matrix). The ordination presented comes from the best of several runs using the "slow and thorough" automated option in PC-ORD 4 and was interpreted as trajectories of tree community dynamics on the Austin Pond Study.

Analysis of variance (ANOVA) was performed using SAS 9 to test for treatment effects on softwood importance and several structural measures based on the 2010 inventory. Estimates of softwood importance and stand structure were run as a completely randomized, split-plot design in which herbicide treatment was the whole-plot factor and PCT was the split-plot factor. All data were kept at the sample plot level and nested within treatment unit for all ANOVA tests. The level of statistical significance (α) was 0.05.

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Table 1. Details of the nine herbicide treatments from the original experiment included in this study.

Herbicide treatment	Application rate (kg/ha)	Rate type	Code
2,4-D + 2,4,5-T (phenoxy)	1.1 + 1.1	Low	DTL
	2.3 + 2.3	High	DTH
2,4,5-T (phenoxy)	2.3	Low	TL
	3.4	High	TH
Triclopyr amine (Garlon 3A)	2.3	Low	TrL
	4.5	High	TrH
Glyphosate (Roundup)	1.7	Low	GL
	3.4	High	GH
Unsprayed (control)	na	na	US

Softwood importance was calculated by summing the IV for softwood species in each sample plot. The softwood species included were balsam fir, spruce, eastern white pine, and northern white-cedar. The estimate of softwood importance was based on relative density and relative dominance, since working at the sample plot level precluded the use of relative frequency. Analysis of stand structure was performed using five structural variables (quadratic mean diameter, stem density, basal area, and total and merchantable volume) calculated for softwoods, hardwoods, and all species combined. Total and merchantable volumes were estimated using species-specific equations developed by Honer (1967) and assumed a stump height of 15 cm. An estimate of height was needed to calculate stem volume for all recorded trees. Height was predicted for trees without field measurements of height using a nonlinear mixed-effects model based on the height–diameter relationship estimated from a subsample of live trees measured for height in 1999 and 2010 across the study. This model was built in R 2.8.1 using measurements from 2700 and 1219 trees from the 1999 and 2010 inventories, respectively, for the most abundant species selected across all DBH classes. Species was included as a random effect, along with inventory and treatment unit, to estimate slope coefficients for each species, which were used to calculate species-specific heights. Merchantable volume was estimated to a minimum top diameter of 10 and 15 cm for softwoods and hardwoods, respectively, which was set to reflect medium merchantability standards for each group. However, analysis of results for hardwood merchantable volume was excluded from this investigation, since transformations were unable to correct for nonhomogeneous variances and lack of normality.

We used 11 linear contrasts to test for differences among individual treatments and groups of treatments for the 2010 inventory. In particular, we were interested in comparisons among the four main treatment combinations of the experiment: (*i*) untreated, plots without herbicide or PCT (i.e., control); (*ii*) PCT only, half of the unsprayed plots treated with PCT; (*iii*) herbicide only, plots treated with herbicide but not PCT; and (*iv*) herbicide plus PCT, half of the herbicide-treated plots treated with PCT. Other comparisons were made among herbicides treatments, application rates, and treatment groupings based on early findings from this study (e.g., triclopyr and glyphosate herbicides versus phenoxy herbicides). The level of significance for linear contrasts was adjusted to correct for multiple comparisons using the Bonferroni method and assessed at 0.005 (i.e., 0.05 (α) divided by 11).

Results and discussion

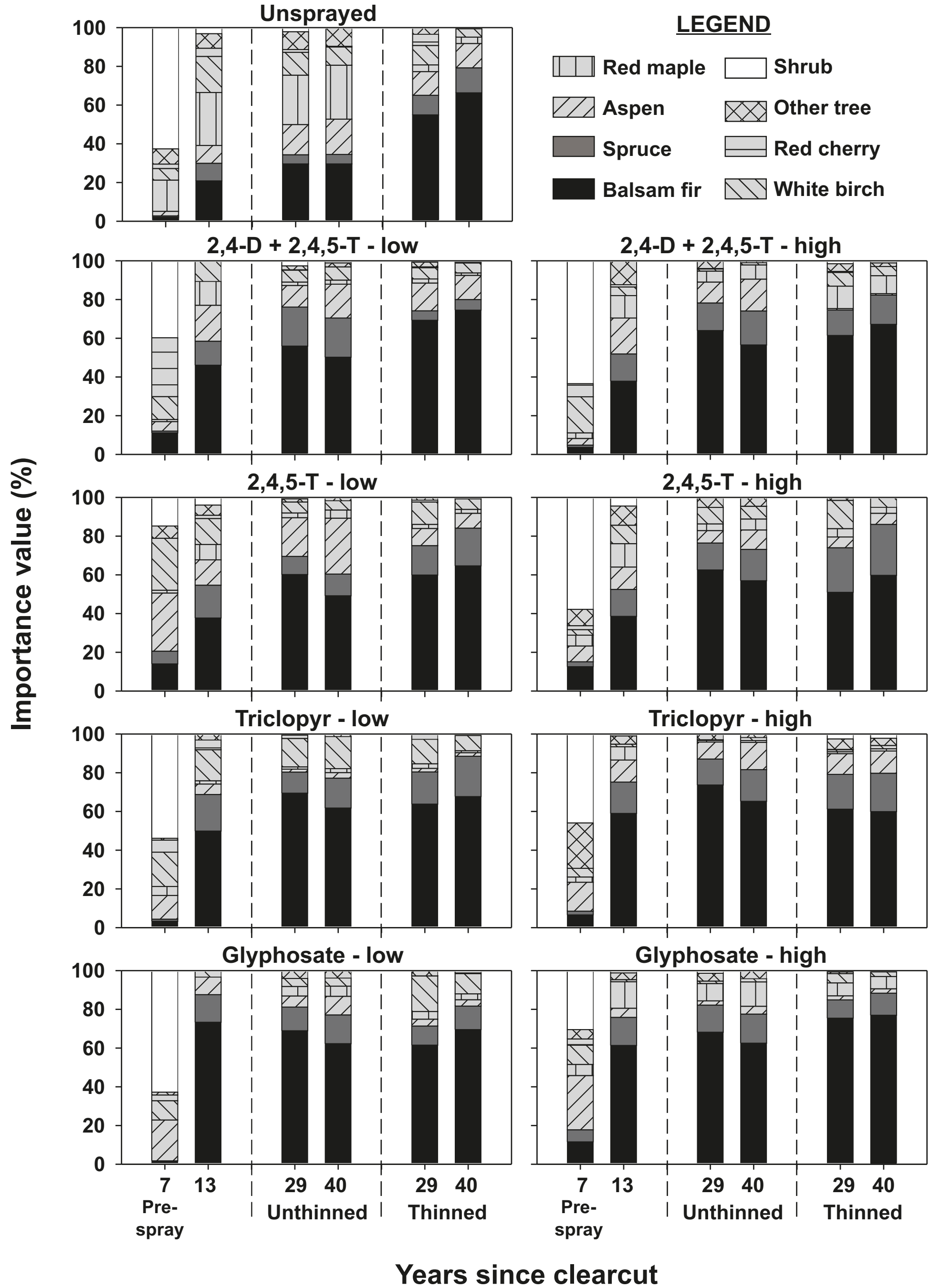
Compositional dynamics: 1977–2010

Clearcutting of mature stands in the Acadian forest typically stimulates the rapid regeneration of deciduous hardwoods and shrubs originating from seed, stumps, and roots along with slower development of softwood regeneration, principally balsam fir and spruce (red, black, and white) from advance regeneration released by harvesting (Westveld 1931; White 1991; Seymour 1995). This pattern of early stand development was clearly evident on the Austin Pond Study 7 years after clearcutting. Hardwoods dominated tree species composition before the site was sprayed in 1977, with balsam fir and spruce having <20% IV in all treatments (Fig. 1). Raspberry was the dominant taxon at the time of herbicide application (Newton et al. 1992*a*) with mean cover of 50% estimated for 60% of plots sampled in 1977 over the full experiment (unpublished data).

Differences in composition among treatments were evident during the first 9 years after herbicide application and revealed that all herbicide treatments were effective at shifting species composition to softwood dominance. Two years after spraying, all herbicide treatments reduced deciduous cover by >50% (McCormack and Newton 1980). Herbicides were particularly effective at controlling raspberry, reducing its cover by >40% in all treatments, with most showing reductions of 70%–90% (McCormack and Newton 1980). By 1983, herbicide treatments increased softwood dominance relative to the unsprayed plots, a pattern reflected by substantial increases in the IV of balsam fir and, to a lesser extent, spruce in herbicide-treated plots, while tree composition in unsprayed plots was dominated by hardwoods (primarily aspen, red maple, and white birch) (Fig. 1). These differences persisted until PCT in 1986 (Newton et al. 1992*a*).

The earliest published findings from the Austin Pond Study (reported in McCormack and Newton 1980) observed lower control of deciduous vegetation in areas treated with phenoxy herbicides (those containing 2,4-D and 2,4,5-T) than those treated with triclopyr or glyphosate and lower rates of herbicides than those treated with higher rates. Findings from Newton et al. (1992*a*) indicated that these differences in efficacy persisted until the PCT treatment in 1986. However, these early differences in control did not translate into long-term differences in softwood dominance among

Fig. 1. Compositonal dynamics of nine herbicide treatments over four inventories spanning 33 years (1977–2010). Years since clearcut corresponded to inventories as follows: 7 (pre-spray), 1977 inventory; 13, 1983 inventory; 29, 1999 inventory; 40, 2010 inventory.



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herbicide treatments. By 2010, there was no difference in softwood importance between unthinned plots treated with phenoxy herbicides and those treated with triclopyr and glyphosate ($p = 0.568$) (Table 2). Also, there were no differences in softwood importance between low and high rates of herbicide treatments ($p > 0.864$). Although early assessments indicated greater efficacy of triclopyr and glyphosate herbicides than of phenoxy herbicides in promoting softwood release and greater control with higher application rates than lower rates, our analysis revealed no difference in the long-term silvicultural effectiveness among herbicide treatments in producing softwood-dominated mixedwood stands.

When unsprayed plots received PCT (i.e., PCT-only plots), however, softwood dominance was promoted. The compositional shift to softwood dominance in the PCT-only treatment contrasted sharply with the maintenance of hardwood dominance in the untreated plots (Fig. 1). Since 1999, balsam fir has been the dominant species for all treatments except the untreated reference with >50% importance (Fig. 1), and there were no differences ($p > 0.144$) (Table 2) in softwood importance among the PCT-only plots and both thinned and unthinned halves of the herbicide treatments in 2010. Although the untreated plots were dominated by hardwoods before PCT, softwoods still accounted for 25% of total importance,

Table 2. *p* values from ANOVA and linear contrasts of 2010 softwood importance value and five stand structure attributes (quadratic mean diameter, density, basal area, total volume, and merchantable volume).

		Quadratic mean diameter		Density			Basal area			Total volume			Merchantable volume	
Source of variation	SWiv	SW	HW	SW	HW	TL	SW	HW	TL	SW	HW	TL	SW	TL
Herbicide (H)	0.400	0.277	0.212	0.396	0.230	0.333	0.164	0.008	0.382	0.054	0.079	0.348	0.134	0.201
PCT (P)	0.009	<0.001	<0.001	<0.001	0.249	<0.001	0.114	<0.001	0.002	0.034	<0.001	<0.001	<0.001	<0.001
H x P	<0.001	0.001	0.049	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Contrast														
PL-U vs. PH-U	0.864	0.922	0.939	0.383	0.733	0.844	0.333	0.226	0.941	0.532	0.087	0.937	0.902	0.962
TL-U vs. TH-U	0.957	0.949	0.933	0.932	0.890	0.938	0.921	0.893	0.894	0.961	0.889	0.921	0.960	0.951
GL-U vs. GH-U	0.911	0.971	0.954	0.910	0.951	0.775	0.949	0.925	0.877	0.945	0.910	0.900	0.947	0.930
T-U vs. G-U	0.747	0.588	0.713	0.749	0.586	0.817	0.256	0.554	0.301	0.373	0.584	0.593	0.504	0.818
TG-U vs. P-U	0.568	0.283	0.812	0.124	<0.001	0.002	0.045	<0.001	0.275	0.023	<0.001	0.745	0.195	0.183
US-T vs. US-U	<0.001	<0.001	<0.001	0.001	0.088	0.074	<0.001	<0.001	0.020	<0.001	<0.001	<0.001	<0.001	<0.001
S-U vs. US-U	<0.001	0.577	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.641	<0.001	<0.001	0.183	0.084	0.973
S-T vs. US-U	<0.001	<0.001	<0.001	0.969	<0.001	0.122	<0.001	<0.001	0.036	<0.001	<0.001	<0.001	<0.001	0.014
S-U vs. US-T	0.922	0.002	0.001	<0.001	0.863	<0.001	0.932	0.063	0.012	0.622	0.021	0.254	<0.001	0.045
S-T vs. US-T	0.978	0.511	0.813	0.474	0.201	0.166	0.910	0.792	0.864	0.876	0.942	0.989	0.433	0.389
S-T vs. S-U	0.144	<0.001	<0.001	<0.001	0.058	<0.001	0.867	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001

Note: Columns headings: SWiv, softwood importance value; SW, softwood; HW, hardwood; TL, total or all species. Contrasts: US, unsprayed (control); S, sprayed (average of all herbicide treatments); PL, phenoxy low rate (average of low-rate treatments); PH, phenoxy high rate (average of high-rate treatments); TL, triclopyr low rate; TH, triclopyr high rate; GL, glyphosate low rate; GH, glyphosate high rate; P, phenoxy (average of all phenoxy treatments); T, triclopyr (average of all triclopyr treatments): G, glyphosate (average of all glyphosate treatments); TG, triclopyr–glyphosate (average of all triclopyr and glyphosate treatments); U, unthinned; T, thinned (PCT).

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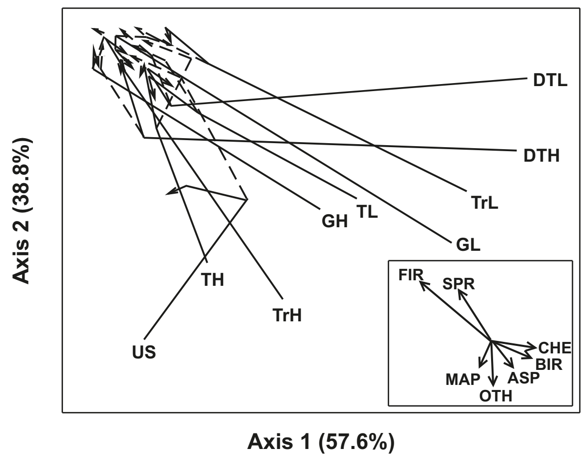
which was apparently sufficient to successfully dominate the PCT-only plots and maintain dominance through 2010. This pattern was reflected in the compositional trajectory of the PCT-only treatment in nonmetric multidimensional scaling space, which diverged from the untreated reference and converged with herbicide treatments onto a portion of the ordination correlated with higher balsam fir and spruce importance (Fig. 2). Thus, PCT treatment, which also targeted the cutting of hardwoods, was just as effective as herbicides in shifting long-term stand composition toward softwoods.

Differences in early herbicide selectivity reported by McCormack and Newton (1980), however, did have a long-term influence on hardwood species composition at 29 and 40 years of stand development. Glyphosate treatments provided >90% control of aspen compared with 70%–90% for triclopyr within 2 years of treatment. The opposite was true for red maple. Triclopyr controlled >90% of red maple and glyphosate only 70%–90%. These differences were reflected in aspen and red maple importance 22 and 33 years after spraying (1999 and 2010, respectively) for the high rates of glyphosate- and triclopyr-only plots. By 2010, red maple accounted for <5% of composition in high-triclopyr-only plots compared with 10%–16% in high-glyphosate-only plots, while aspen accounted for <5% in high-glyphosate-only plots compared with 9%–14% in high-triclopyr-only plots (Fig. 1).

Fig. 2. Compositional trajectories of unthinned (solid lines) and thinned (broken lines) herbicide treatments in nonmetric multidimensional scaling (NMS) space from 1977 to 2010. Letters in the larger image are treatment codes (see Table 1) and their locations in NMS space represent pre-treatment composition. The point at which the broken lines branch off from solid lines represents 1983 composition just before PCT and arrows represent 2010 composition. Vectors within the inset image depict Pearson correlations of tree species variables with NMS axes. Species variables: FIR, balsam fir; SPR, spruce species; MAP, red maple; ASP, aspen species; BIR, white birch; CHE, red cherry; OTH, other tree species (see Methods for details of species groupings).



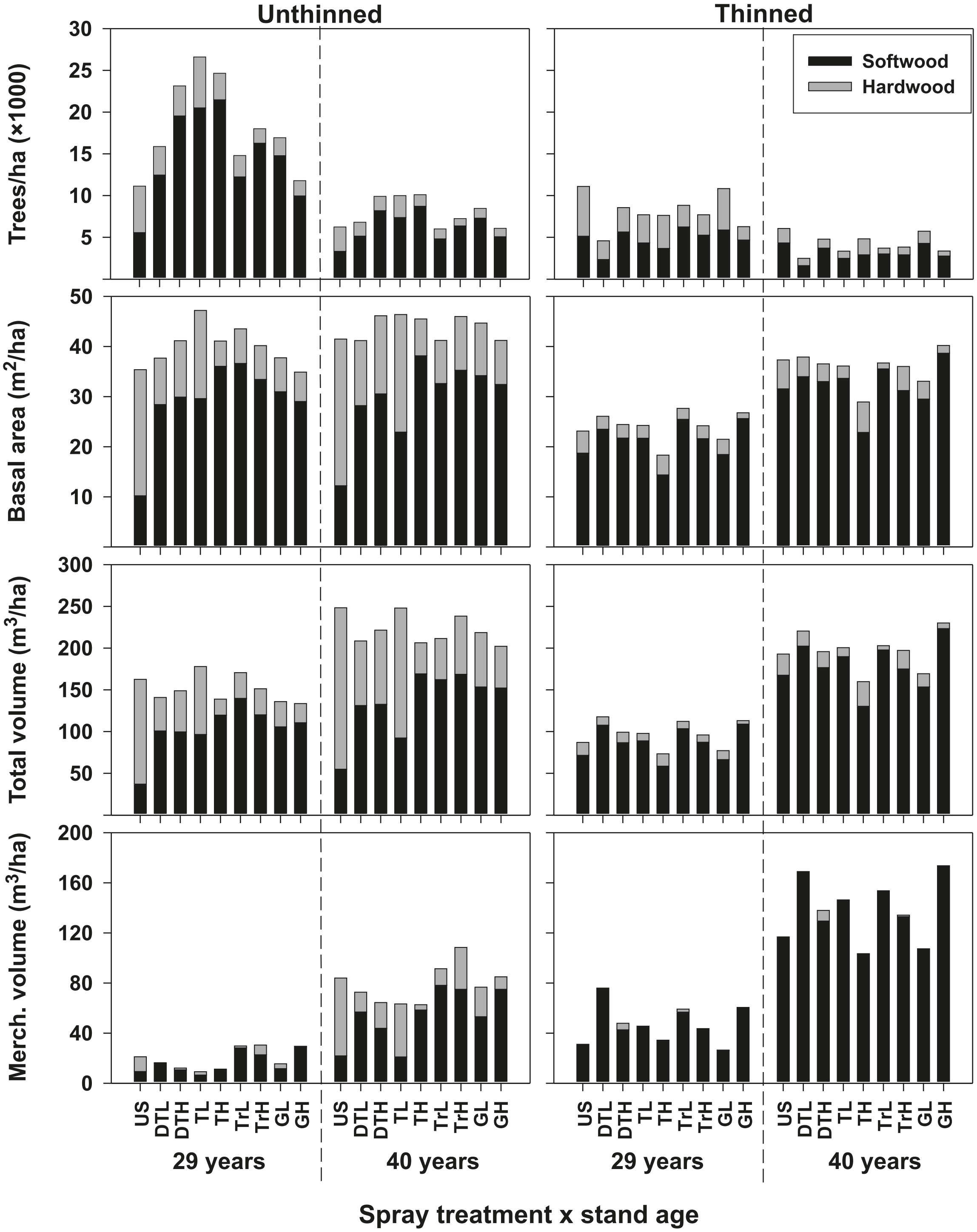
Structural dynamics: 1985–2010

In the season before PCT (1985), softwood regeneration in the herbicide-treated plots was assessed to be overstocked (Newton et al. 1992*b*). At that time, mean density for both fir and spruce combined was nearly four times greater in herbicide-treated plots than in the untreated plots (21 142 and 5766 trees/ha, respectively) and free-to-grow softwood crop trees (balsam fir or spruce ≥1.37 m tall) were over three times more abundant (1398 and 432 trees/ha, respectively; Newton et al. 1992*b*). Young balsam fir stands in the northeastern United States and eastern Canada are often overstocked (Lavigne and Donelly 1989; Seymour 1995). Newton et al. (1992*b*) concluded that overstocking in herbicide-treated plots in 1985 resulted from the release of an abundant softwood regeneration pool triggered by all herbicides without a substantial reduction in softwood stocking over the 9 years since spraying. By 1985, these high-density softwood stands (i.e., the sprayed treatments) were candidates for PCT to reduce overall density and space softwoods (Newton et al. 1992*b*).

With softwood densities ranging from 10 058 to 22 723 trees/ha (Fig. 3) in 1999, composed mainly of balsam fir, herbicide-only treatments had developed into classic "balsam fir thickets" (sensu Westveld 1953). In contrast, stands treated with herbicide and PCT supported substantially lower softwood densities than their unthinned counterparts (5089 and 16 441 trees/ha, respectively), a difference that was significant 24 years after PCT ($p < 0.005$) (Table 2). Consequently, the softwoods were smaller ($p < 0.005$) in diameter in the herbicide-only plots (quadratic mean diameter = 8.2 cm) than in the herbicide plus PCT treatments (13.2 cm) by 2010. Overstocked single-cohort stands of shade-tolerant species, particularly softwoods, can maintain high densities, since overtopped trees can survive long periods of suppression (Oliver and Larson 1996). Interestingly, hardwood densities in both the thinned and unthinned portions of the herbicide treatments were similar in 1999 (2587 and 2763 trees/ha, respectively). However, there was a substantial reduction in hardwood density in the PCT half from 1999 to 2010 (Fig. 3). Daggett (2003) observed high densities of sprout-origin hardwoods suppressed beneath the spaced softwoods of the herbicide plus PCT treatments in 1999, which he concluded had likely developed from stumps and roots of trees cut during PCT. The reduction in hardwood density in these stands was likely the result of suppression of these subordinate sprout-origin hardwoods by released fir and spruce between 1999 and 2010.

There also was a substantial decline in softwood density, and therefore total density, within herbicide-only plots from 1999 to 2010 (Fig. 3). It is likely that this precipitous decline in density was driven by self-thinning among balsam fir as was observed in another long-term spacing study in New Brunswick, Canada (Pitt and Lanteigne 2008). Daggett (2003) observed many standing-dead softwood stems in the herbicide-only treatments, indicating a pattern of self-thinning, yet stand density remained high in 1999 (i.e., stand age 29). During the following 11 years, declines in softwood density in herbicide-only treatments ranged from 50% to 60%. During the 2010 inventory, most sample plots in the herbicide-only treatments contained abundant standing-dead balsam fir <9 cm DBH (M.G. Olson, personal observation). There also was occasional blowdown in small patches within the unthinned herbicide treatments in 2010, which was caused by an intense, wet snowfall accompanied by strong winds early in the winter of 2005–2006. However, the blowdown was largely localized, affecting small, self-supporting groups of softwoods (M.G. Olson, personal observation) and

Fig. 3. Mean density, basal area, and total and merchantable volume of 18 herbicide × PCT treatment combinations (i.e., nine herbicide treatments with and without PCT) in 1999 and 2010 (stand ages 29 and 40, respectively). See Table 1 for herbicide treatment codes.



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patches of blowdown were noted to have affected only 15 of 108 sample plots in herbicide-only treatments (unpublished data). Although these small-scale disturbances have influenced these stands, density-dependent mortality was likely the primary driver of stand dynamics in the herbicide-only treatments, indicating that the period spanning stand ages 29–40 years was a time of rapid self-thinning.

The increase in basal area of the herbicide-only treatments between 1999 and 2010 was the result of increasing hardwood basal area, which by 2010 was substantially greater ($p < 0.005$) (Table 2) in the phenoxy-only treatments (15 m^2/ha) than in those treated with triclopyr and glyphosate (10 m^2/ha) (Fig. 3). A similar pattern was reflected in the differences in 2010 hardwood total volume (90 versus 58 m^3/ha, respectively). In 2010, hardwoods in the herbicide-only treatments were largely stratified above the dense softwood stratum and, in the case of the phenoxy-only treatments, formed a relatively continuous upper stratum across these treatments

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(M.G. Olson, personal observation). These increases in hardwood basal area and total volume observed between 1999 and 2010 in phenoxy-only treatments were likely associated with development of this hardwood stratum over the 11-year period.

In 1999, stands treated with both herbicide and PCT supported lower basal areas and total volumes of softwoods and all species compared with those treated with just herbicide. By 2010, softwood basal area on the herbicide plus PCT treatments caught up to that of herbicide-only plots (32 versus 32 m^2/ha, respectively) (Fig. 3). Although total volume for all trees was still greater on the herbicide-only half in 2010 ($p < 0.005$) (Table 2), softwood total volume on the thinned half (181 m^3/ha) had overtaken that on the unthinned portion (145 m^3/ha) during the 11 years between 1999 and 2010. This trend was associated with declines in softwood density in the herbicide-only treatments driven by intense self-thinning along with a concurrent increase in total volume of the spaced softwood stands on the thinned half of the herbicide treatments. From 1999 to 2010, softwood total volume of the herbicide plus PCT treatment had doubled, while merchantable volume had increased nearly threefold.

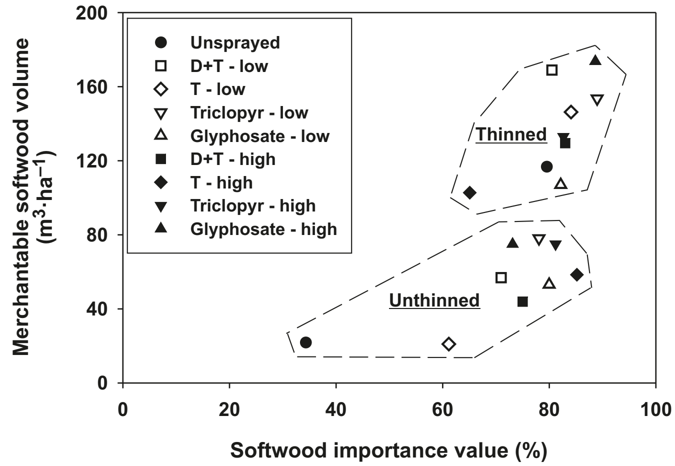
Thirteen years after PCT (1999), the densities of softwoods and hardwoods in PCT-only plots were similar to those in untreated plots; however, basal area, total volume, and merchantable volume of softwoods were greater in the PCT-only treatment, and by 2010, all softwood structural variables were greater ($p < 0.005$) (Table 2). The average diameter of softwoods in 2010 was greater ($p < 0.005$) in the PCT-only plots (quadratic mean diameter = 11.4 cm) compared with untreated stands (5.6 cm). By 2010, the PCT-only treatments were structurally indistinguishable from the herbicide plus PCT treatments. Newton et al. (1992*b*) reported >5700 trees/ha of both fir and spruce, but mainly fir was available for release in unsprayed plots in 1985 and included nearly 500 free-to-grow softwood crop trees/ha (balsam fir or spruce ≥1.37 m tall). Although the majority of softwoods were overtopped in the unsprayed treatment in the season before PCT, there were clearly enough softwood trees available for release at the time of PCT to develop into a spaced softwood stand.

Long-term effects of herbicide and PCT

The principal objectives of herbicide and PCT treatments are to shift overall stand composition toward desired species and to increase growth on the best individual trees. One or both of these objectives were accomplished over 33 years of stand development at the Austin Pond Study depending on the treatment combination.

Thirty-three years after spraying, all herbicide-only treatments, regardless of herbicide type and application rate, were dominated by softwoods (Fig. 4), while no intervention, represented by untreated plots, produced stands dominated by hardwood species with a suppressed understory of scattered softwoods. MacLean and Morgan (1983) found that the total stem volume of balsam fir was nearly 300% greater in plots treated with phenoxy herbicides than in untreated control plots 28 years following herbicide release in northern New Brunswick, Canada. In our study, long-term softwood dominance was promoted by all herbicide treatments despite some early differences in efficacy among herbicide types (i.e., phenoxy herbicides versus triclopyr and glyphosate). Therefore, results from this study support the commonly held assumption that herbicide treatments will produce stands dominated by softwoods over the long term. However, it also is important to note that all herbicide treatments produced softwood-dominated mixedwoods at 40 years and did not produce softwood monocultures as is commonly assumed. Similarly, softwood monocultures did not develop following herbicide release of black spruce in boreal Canada (Dampier et al. 2007) and loblolly pine (*Pinus taeda* L.) in Virginia, USA (Quicke et al. 1996).

Fig. 4. Scatterplot representing 2010 locations of 18 herbicide × PCT treatment combinations displayed in two-dimensional space defined by softwood importance value and merchantable volume.



Based on results reported by Newton et al. (1992*b*), the herbicide treatments in this study favored the development of overstocked softwoods (first observed in 1985), which set the stands up for PCT within 10 years of herbicide treatment. Without PCT, this overstocked condition has persisted for at least 24 years and produced a long period of intense self-thinning. Overstocking usually results in slow growth, high mortality, long rotations, and high harvesting costs (Zhang et al. 2009). The high densities, smaller stem diameters, and resulting low merchantable volumes in these treatments revealed the continuing negative influence of overstocking on stand development unless PCT is coupled with an earlier herbicide application.

PCT was a significant factor in most ANOVA models ($p < 0.05$) (Table 2), including models of softwood IV and merchantable volume, indicating that PCT had a strong influence on long-term stand composition and structure in the Austin Pond Study. In the case of the PCT-only treatment, PCT alone shifted the composition to softwoods and produced spaced softwood stands that were structurally similar to the thinned halves of all herbicide treatments, which largely accounts for the significant herbicide × PCT interaction found in the ANOVA models. It also was observed at the time of PCT that the unsprayed plots were more difficult and time consuming to thin than the sprayed plots due to the high hardwood densities (M. McCormack, personal communication). In herbicide-treated plots, PCT further reduced hardwood abundance and assured near complete domination by softwoods. By 2010, PCT-treated plots also supported two or more times the merchantable softwood volume than their unthinned counterparts (Fig. 4). Therefore, the results from this study also support the commonly held assumption that PCT, when applied to favor softwoods in mixedwood stands, promotes both long-term dominance and merchantable volume of softwoods. Brissette et al. (1999) also reported more spruce–fir merchantable volume in plots spaced at 2.4 m than in unspaced plots 18 years after PCT. Spacing in this study was approximately 2.4 m (1750 trees/ha), which was somewhat wider than is commonly practiced today (2200–2500 trees/ha). In the longest running spacing study in the Acadian Forest, Pitt and Lanteigne (2008) also demonstrated the dramatic influence that early PCT can have on the development of spruce–fir stands through the entire rotation.

Results from this experiment clearly demonstrated that early herbicide application, regardless of type and rate of herbicide, created softwood-dominated mixedwood stands over the long-term and that PCT more than doubled merchantable softwood volume within 25 years of application.

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References

Barbour, R.J., Bailey, R.E., and Cook, J.A. 1992. Evaluation of relative density, diameter growth, and stem form in a red spruce (*Picea rubens*) stand 15 years after precommercial thinning. Can. J. For. Res. **22**(2): 229–238. doi:10.1139/x92-030.

Briggs, R.D. 1994. Site classification field guide. Misc. Publ. 724. Maine Agricultural and Forest Experiment Station, University of Maine, Orono, Me.

Briggs, R.D., and Lemin, R.C., Jr. 1994. Soil drainage class effects on early response of balsam fir to precommercial thinning. Soil Sci. Soc. Am. J. **58**(4): 1231–1239. doi:10.2136/sssaj1994.03615995005800040034x.

Brissette, J.C., Frank, R.M., Jr, Stone, T.L., and Skratt, T.A. 1999. Precommercial thinning in a northern conifer stand: 18-year results. For. Chron. **75**(6): 967–972.

Burns, J., Puettmann, K.H., and Perala, D. 1996. Strip thinning and spacing increases tree growth of young black spruce. North. J. Appl. For. **13**(2): 68–72.

Cole, H.A., Newmaster, S.G., Lanteigne, L., and Pitt, D.G. 2008. Long-term outcome of precommerical thinning on floristic diversity in northwestern New Brunswick, Canada. iForests, **1**: 145–156.

Curtis, J.T., and McIntosh, R.P. 1951. An upland forest continuum in the prarie–forest border region of Wisconsin. Ecology, **32**(3): 476–496. doi:10.2307/1931725.

Daggett, R.H. 2003. Long-term effects of herbicide and precommercial thinning treatments on species composition, stand structure, and net present value in spruce–fir stands in Maine. Master's thesis, University of Maine, Orono, Me.

Dampier, J.E.E., Luckai, N., Bell, F.W., and Towill, W.D. 2007. Do tree-level monocultures develop following Canadian boreal silviculture? Tree-level diversity tested using a new method. Biodivers. Conserv. **16**(10): 2933–2948. doi:10.1007/s10531-007-9151-0.

Homyack, J.A., Harrison, D.J., and Krohn, W.B. 2007. Effects of precommercial thinning on snowshoe hares in Maine. J. Wildl. Manage. **71**(1): 4–13. doi:10.2193/2005-481.

Honer, T.G. 1967. Standard volume tables and merchantable conversion factors for the commercial tree species of central and eastern Canada. Inf. Rep. FMR-X-5. Forest Management Research and Services Institute, Ottawa, Ont.

Ker, M.F. 1987. Effects of spacing balsam fir: 25 year results from the Green River spacing trials. *In* Proceedings of the Precommercial Thinning Workshop. *Edited by* T.S. Murray and M.D. Cameron. Canadian Forest Service, Fredericton, N.B. pp. 58–75.

Lavigne, M.B., and Donelly, J.G. 1989. Early results of a spacing trial in a pre-commercially thinned balsam fir stand in western Newfoundland. Inf. Rep. N-X-269. Forestry Canada, Newfoundland and Labrador Region.

MacLean, D.A. 1980. Vulnerability of fir-spruce stands during uncontrolled spruce budworm outbreaks: a review and discussion. For. Chron. **56**: 213–221.

MacLean, D.A., and Morgan, M.G. 1983. Long-term growth and yield response of young fir to manual and chemical release from shrub competition. For. Chron. **59**: 177–183.

McCormack, M.L., and Lemin, R.C., Jr. 1998. Crop tree conditions after one herbicide release and precommercial thinning of natural spruce–fir regeneration in northwestern Maine, USA. *In* Third International Conference on Forest Vegetation Management: Popular Summaries. *Edited by* R.G. Wagner and D.G. Thompson. Inf. Pap. No. 141. Ontario Ministry of Natural Resources, Ontario Forest Research Institute, Sault Ste. Marie, Ont.

McCormack, M.L., and Newton, M. 1980. Aerial applications of triclopyr, phenoxys, picloram, and glyphosate for conifer release in spruce–fir forests of Maine. Weed Sci. Soc. Am. **20**: 47–48. (Abstr.)

Newton, M., Cole, E.C., White, D.E., and McCormack, M.L., Jr. 1992*a*. Young spruce–fir forests released by herbicides. I. Response of hardwoods and shrubs. North. J. Appl. For. **9**(4): 126–130.

Newton, M., Cole, E.C., McCormack, M.L., Jr, and White, D.E. 1992*b*. Young spruce-fir forests released by herbicides. II. Conifer response to residual hardwoods and overstocking. North. J. Appl. For. **9**(4): 126–130.

Oliver, C.D., and Larson, B.C. 1996. Forest stand dynamics. Updated edition. John Wiley & Sons, Inc., New York.

Piene, H. 1981. Early growth responses to operational spacing in young balsam fir stands on the Cape Breton Highlands, Nova Scotia. Info. Rep. M-X-125. Canadian Forest Service, Maritime Research Centre, Fredericton, N.B.

Piene, H., and Anderson, W.F.A. 1987. Ten–year growth response to spacing in young balsam fir stands, Cape Breton Highlands, Nova Scotia. *In* Precommercial Thinning Workshop. *Edited by* T.S. Murray and M.D. Cameron. Canadian Forest Service, Maritime Research Centre, Fredericton, N.B. pp. 76–85.

Pitt, D.G., and Lanteigne, L. 2008. Long-term outcome of precommercial thinning in northwestern New Brunswick: growth and yield of balsam fir and red spruce. Can. J. For. Res. **38**(3): 592–610. doi:10.1139/X07-132.

Quicke, H.E., Glover, G.R., and Lauer, D.K. 1996. Growth responses following herbicide release of loblolly pine from competing hardwoods in the Virginia Piedmont. South. J. Appl. For. **20**(4): 177–181.

Seymour, R.S. 1992. The red spruce and balsam fir forest of Maine: evolution of silvicultural practices in response to stand development patterns and disturbances. *In* The ecology and silviculture of

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mixed-species forests. *Edited by* M.J. Kelty, B.C. Larson, and C.D. Oliver. Kluwer Academic Publishers, Boston, Mass. pp. 217–244.

Seymour, R.S. 1995. The northeastern region. *In* Regional silviculture of the United States. 3rd ed. *Edited by* J.W. Barrett. John Wiley & Sons, Inc., New York. pp. 13–79.

Thompson, D.G., and Pitt, D.G. 2003. A review of Canadian forest vegetation management research and practice. Ann. For. Sci. **60**(7): 559–572. doi:10.1051/forest:2003060.

Wagner, R.G., Bowling, E.H., and Seymour, R.S. 2003. Assessing silviculture research priorities for Maine using a wood supply analysis. Tech. Bull. 186. Maine Forest and Agriculture Experiment Station, Orono, Me.

Wagner, R.G., Little, K.M., Richardson, B., and McNabb, K. 2006. The role of vegetation management for enhancing productivity of the world's forests. Forestry, **79**(1): 57–79. doi:10.1093/forestry/cpi057.

Westveld, M. 1931. Reproduction on the pulpwood lands in the northeast. Tech. Bull. 223. U.S. Department of Agriculture, Forest Service, Washington, D.C.

Westveld, M. 1953. Ecology and silviculture of the spruce–fir forests of eastern North America. J. For. **51**: 422–430.

White, A.S. 1991. The importance of different forms of regeneration to secondary succession in a Maine hardwood forest. Bull. Torrey Bot. Club, **118**(3): 303–311. doi:10.2307/2996645.

Zhang, S., Chauret, G., and Tong, Q. 2009. Impact of precommercial thinning tree growth, lumber recovery and lumber quality in *Abies balsamea*. Scand. J. For. Res. **24**(5): 425–433. doi:10.1080/02827580903124392.

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