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ARTICLE

Crop tree growth response and quality after silvicultural rehabilitation of cutover stands

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Abstract: Rehabilitation of cutover stands is often a management objective of landowners who desire improved stand conditions and increased value from future harvest revenues. We evaluated crop tree growth response and quality following precommercial rehabilitation treatments in mixedwood stands degraded through repeated exploitive cutting in Maine, USA. Treatments included control (no rehabilitation), moderate rehabilitation (crop tree release), and intensive rehabilitation (crop tree release plus timber stand improvement). Paper birch (*Betula papyrifera* Marsh.), red spruce (*Picea rubens* Sarg.), and eastern hemlock (*Tsuga canadensis* (L.) Carriere) crop tree diameter increments 0 to 9 years after treatment were greater following rehabilitation than in the control. Diameter increment did not differ between intensities of rehabilitation for any species. For conifers in the lower strata, crop tree height growth and change in crown length were negatively correlated with basal area in larger trees. The occurrence of epicormic branches on paper birches was greater in the rehabilitation treatments than the control. However, most epicormic branches occurred above the height corresponding to the first sawlog. These findings indicate that rehabilitation of mixedwood stands with similar characteristics can result in improved growth of crop trees without jeopardizing the quality of the lower bole in paper birches.

Key words: crop tree release, timber stand improvement, commercial clearcut, epicormic branches, mixedwood.

Résumé : La réhabilitation des parterres de coupe est souvent un objectif d'aménagement des propriétaires forestiers qui souhaitent améliorer les conditions du peuplement et augmenter les revenus de la récolte future. Nous avons évalué la réaction de croissance et la qualité des arbres d'avenir à la suite de traitements précommerciaux de réhabilitation dans des peuplements mixtes dégradés par des coupes abusives répétées dans le Maine, aux États-Unis. Les traitements comprenaient un témoin (pas de réhabilitation), une réhabilitation modérée (dégagement des arbres d'avenir) et une réhabilitation intensive (dégagement des arbres d'avenir et amélioration du peuplement). L'accroissement en diamètre des tiges d'avenir de bouleau à papier (*Betula papyrifera* Marsh.), d'épinette rouge (*Picea rubens* Sarg.) et de pruche du Canada (*Tsuga canadensis* (L.) Carrière) de 0 à 9 ans était plus grand après la réhabilitation que dans le témoin. L'accroissement en diamètre n'était pas différent selon l'intensité de réhabilitation chez toutes les espèces. Dans le cas des conifères de la strate inférieure, la croissance en hauteur et le changement dans la longueur de la cime des arbres d'avenir étaient négativement corrélés à la surface terrière chez les plus gros arbres. Des gourmands étaient davantage présents sur les bouleaux à papier ayant profité d'un traitement de réhabilitation que dans le témoin. Toutefois, la plupart des gourmands sont apparus au-dessus de la hauteur délimitant l'extrémité de la première bille de sciage. Ces résultats indiquent que les traitements de réhabilitation peuvent améliorer la croissance des arbres d'avenir sans compromettre la qualité de la partie inférieure du tronc des bouleaux à papier dans les peuplements mixtes ayant des caractéristiques similaires. [Traduit par la Rédaction]

Mots-clés : dégagement des arbres d'avenir, amélioration du peuplement, coupe à blanc commerciale, gourmands, peuplement mixte.

Introduction

In the forests of northeastern North America, removal of the most commercially desirable species and trees began during colonial times with the harvesting of large eastern white pine (*Pinus strobus* L.) for ship masts and continued in the 1800s and early 1900s with the extraction of softwood lumber and pulpwood (Kelty and D'Amato 2005). Over time, high-quality hardwoods were also exploitively harvested, often through repeated diameter-limit cutting (Bédard et al. 2014; Kelty and D'Amato 2005; Nyland 1992). Although markets for hardwood pulpwood and small-diameter, low-quality trees have emerged over time, the prices for these materials remain low relative to sawtimber. Also, the recent decline in markets for biomass and softwood pulpwood due to mill closures in some parts of the northeastern North America limits the ability to extract poor-quality trees from stands that require tending (Kingsley 2017). Harvesting of only high-quality sawlog-sized trees within these stands has been shown to lead to degradation of residual stands over time (Kenefic et al. 2005; Nyland 2005; Rogers et al. 2017). As a result, rehabilitation of cutover stands will likely continue to be a challenge for foresters in the future. Strategies for improving species composition and stand structure, as well as individual tree growth and quality, are needed for stands where exploitive cutting has occurred in the past.

In stands that have been degraded through exploitive cutting, silvicultural rehabilitation can be applied to enhance stand structure and desirable species composition, as well as improve growth and quality of individual trees (Kenefic 2014). In degraded mixedwood (i.e., hardwood–softwood) stands, rehabilitation treatments

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such as crop tree release and timber stand improvement have been shown to reduce the relative basal area of undesirable species and poor-quality growing stock, while retaining diverse vertical stand structure (Greene 2014; Kenefic et al. 2014). Timber stand improvement includes treatments applied in stands composed of pole-sized or larger trees to improve composition and quality by harvesting or otherwise killing (e.g., with herbicide) less desirable trees that are not cut for products. Rehabilitation treatments can also increase the survival of suppressed trees in lower strata by reducing overhead shade (MacDonald 1995). While the immediate benefits of silvicultural rehabilitation related to stand-level characteristics have been shown (Bédard et al. 2014; Kenefic et al. 2014; Lussier and Meek 2014), limited research has been done on quantifying individual crop tree growth response and changes in tree quality after rehabilitation treatments (Heitzman and Nyland 1991).

Many studies quantifying tree growth in relation to forest management treatments in northeastern North America have utilized data from stands dominated by conifers (Brissette et al. 1999; Kuehne et al. 2016; Pothier 2002) or hardwoods (Leak and Yamasaki 2012; Ray et al. 2011; Voorhis 1990). Less research has been focused on diameter and height growth and changes in crown attributes of trees in young mixedwood stands (Prévost and Charette 2017). In stratified mixedwood stands, diameter and height growth of shade-tolerant species such as red spruce (*Picea rubens* Sarg.) and eastern hemlock (*Tsuga canadensis* (L.) Carriere) in lower strata can be extremely limited until trees are released following partial disturbances (Seymour 1992). However, these shade-tolerant species can act as "trainer" trees by shading the boles of hardwood trees in upper strata, thereby minimizing epicormic branching. When shade-tolerant conifers are released, the change in their crown length is a function of the relative rates of height growth and crown recession (Garber et al. 2008). If these trees are not crowded by neighbors within the same stratum, crown recession (upward movement of the crown base due to death of branches at the base of the crown) can be limited due to retention of lower branches, thus resulting in trees with longer crowns and greater live crown ratios. In a study on release of spruce from overtopping quaking aspen (*Populus tremuloides* Michx.), for example, spruce crown length, crown width, and live crown ratio increased after treatment, with enhanced crown development in treated areas (Prévost and Charette 2017). While the retention of lower branches in conifers may negatively influence log quality (Weiskittel et al. 2009), there are ecological benefits associated with vertical niche partitioning afforded by long crowns and lower branches such as nesting sites and cover for wildlife species.

In this study, growth of paper birch (*Betula papyrifera* Marsh.), red maple (*Acer rubrum* L.), and softwood crop trees were evaluated in mixedwood stands degraded through repeated exploitive cutting in Maine, USA. Within the context of rehabilitation silviculture, crop trees are those that are selected to become a component of a future commercial harvest (Helms 1998) rather than those of particular rarity or value. Prior to precommercial rehabilitation treatments, paper birch and red maple were the most common hardwoods in the study. In northeastern North America, release of young hardwoods such as paper birch has been recommended as a silvicultural technique when competitors of less desirable species may hinder crop tree growth over time (Marquis 1969; Sendak and Leak 2008). Depending on regional market conditions, precommercial treatments may be a good economic investment when followed by commercial thinning (Leak and Yamasaki 2012). Across all species utilized for boltwood (i.e., logs of short length commonly used to manufacture turned products such as dowels or toothpicks or peeled veneer) in Maine, paper birch and red maple rank first and sixth, respectively, in average boltwood stumpage price paid to landowners, and sawlog prices are in the middle of the price range for hardwoods (Maine Forest Service 2017).

The goal of this study was to evaluate tree growth response and changes in crown attributes and tree quality 9 years after applying precommercial rehabilitation treatments to degraded mixedwood stands in central Maine, USA. Our objectives were to (*i*) test the influence of rehabilitation treatment (control, moderate, and intensive) on crop tree periodic annual diameter and height increment, crown recession, change in live crown length, and occurrence of epicormic branches (the response variables), and (*ii*) assess the influence of stand attributes (e.g., basal area in trees larger than the subject crop tree) on response variables. We hypothesized that crop tree diameter growth would be greater for the moderate and intensive treatments than for the untreated control. We also hypothesized that height growth of conifer crop trees in lower strata would be greater for the moderate and intensive treatments compared with the control. For these same trees, we hypothesized that crown recession would be minimal and that change in live crown length would be greater for the moderate and intensive treatments compared with the control. Finally, we hypothesized that the probability of epicormic branching in paper birches would be lowest in the control due to higher posttreatment stand densities.

Methods

Study area and experimental design

The study was conducted on the 1619 ha Penobscot Experimental Forest (PEF) located in central Maine, USA (44°52′N, 68°38′W; mean elevation of 43 m). The PEF lies within the Acadian Forest Ecoregion, which is a transitional zone between the eastern North American broadleaf and boreal forests (Halliday 1937). Common tree species include balsam fir (*Abies balsamea* (L.) Mill), red spruce, eastern hemlock, northern white-cedar (*Thuja occidentalis* L.), eastern white pine, maples (*Acer* spp.), birches (*Betula* spp.), and aspens (*Populus* spp.). Mean annual temperature and annual precipitation are 6.1 °C and 107 cm, respectively. Since the 1950s, the U.S. Department of Agriculture Forest Service has maintained studies on the PEF to investigate the influence of silvicultural treatments and exploitive cuttings on stand composition, structure, growth, and yield (Sendak et al. 2003). Soils in the study area are derived from glacial till parent material. Common soils included loamy-skeletal, isotic, frigid Lithic Haplorthods (Thorndike series), coarse-loamy, isotic, frigid Oxyaquic Haplorthods (Plaisted series), and coarse-loamy, isotic, frigid Aquic Haplorthods (Howland series) (Natural Resources Conservation Service 2012).

The present study was conducted in two management units (MUs) that were commercially clearcut twice: in the 1950s and again in the 1980s. In the 1950s, postharvest basal area, tree density, and quadratic mean diameter were, respectively, 14.2 ± 6.4 $m^2 \cdot ha^{-1}$, 1829 ± 1546 trees·ha^{-1}, and 11.4 ± 3.3 cm (mean ± SD) in one MU and 18.0 ± 6.6 $m^2 \cdot ha^{-1}$, 2524 ± 1939 trees·ha^{-1}, and 10.4 ± 1.7 cm in the other MU. In the 1980s, postharvest basal area, tree density, and quadratic mean diameter were, respectively, 3.2 ± 1.7 $m^2 \cdot ha^{-1}$, 1213 ± 746 trees·ha^{-1}, and 5.9 ± 2.1 cm in one MU and 5.7 ± 5.3 $m^2 \cdot ha^{-1}$, 1783 ± 1619 trees·ha^{-1}, and 7.2 ± 2.5 cm (mean ± SD) in the other MU (the preceding statistics were calculated using inventories of trees ≥ 1.3 cm diameter at breast height on permanent plots on soils derived from glacial till). The commercial clearcut treatment removes all merchantable trees, leaving small-diameter and poor-quality trees as residuals (Rogers et al. 2017). This treatment is different from clearcutting (a regeneration method in silviculture) wherein all trees are cut as a means of establishing a new cohort after the harvest. In the MUs of this study, repeated commercial clearcutting resulted in a shift from conifer-dominated stands to mixedwood stands of mostly submerchantable trees. In 2007 when silvicultural rehabilitation was considered, the stands were adequately stocked with desirable sapling and pole-sized trees (Kenefic et al. 2014). Also, while the timing of past harvests within MUs was not synchronized by years

(Sendak et al. 2003), each had similar stand-level attributes in 2007 (Kenefic et al. 2014).

In 2008, three rehabilitation treatments were applied: control (no rehabilitation); moderate rehabilitation (crop tree release); and intensive rehabilitation (crop tree release, timber stand improvement, and red spruce fill planting). The moderate and intensive treatments involved releasing softwood and hardwood trees crop trees ≥ 1.4 m tall on 4.6 m and 7.6 m spacings, respectively. Selection of trees within species groups was done independently, leaving some softwood and hardwood crop trees in close proximity to one another. Crop trees were selected based on species desirability, vigor, crown position, and crown size (Kenefic et al. 2016). Red maple of both seedling and stump-sprout origin were selected as crop trees; the latter were dominant stems originating low on the stump in clumps with tight formation and little decay. Within-clump release of the crop tree (dominant stem) was not attempted. Noncommercial species (e.g., pin cherry (*Prunus pensylvanica* L. f.) and gray birch (*Betula populifolia* Marsh.)) and balsam fir (the preferred host of the eastern spruce budworm (*Choristoneura fumiferana* (Clemens)) and prone to several internal heart-rots (Seymour 1992)) were not selected as crop trees.

In the moderate and intensive treatments, trees within 2.5 to 3.7 m of a crop tree and of the same height or taller were cut, using brushsaws or chainsaws, or treated with a basal spray of triclopyr as Garlon 4 Ultra (Dow AgroSciences, Indianapolis, Indiana, USA) in Bark Oil Blue (Aquamix Inc., Cloverdale, Virginia, USA). Outside that radius, trees with crowns that were overtopped or could cause abrasion of the crop tree's branches were also cut or treated with herbicide, unless they were paper birch, northern red oak (*Quercus rubra* L.), spruces (*Picea* spp.), eastern white pine, eastern hemlock, northern white-cedar, or acceptable growing stock red maple. Trees of those species were retained even if competing with the subject crop tree. Hardwood crop trees were typically in the upper strata and taller than softwood crop trees; these were not cut or treated with herbicide if overtopping a softwood crop tree. Additional details on crop tree selection can be found in Kenefic et al. (2016).

The intensive treatment also involved timber stand improvement, which included cutting or applying herbicide to all unacceptable growing stock (i.e., trees that were not expected to increase in value due to decay or form), poor vigor trees, cull trees, and noncommercial tree species not already designated for removal in crop tree release. Because many trees were pole-sized at the time of rehabilitation, we use the term timber stand improvement rather than cleanings, which are conducted in stands not past the sapling stage. Crop tree release and timber stand improvement were conducted from July to October 2008. Survival and quality of planted red spruces were not evaluated 9 years after treatment; earlier assessments showed high mortality due to browsing (Kenefic et al. 2014).

Treatments were randomly assigned to 0.4 ha (61 × 61 m) experimental units (EUs) within MUs, though one MU only had control and moderate rehabilitation treatments due to administrative constraints (Kenefic et al. 2016). Thus, one MU had three replicates each of control and moderate treatments and the other had four replicates each of control, moderate, and intensive treatments. This resulted in an unbalanced randomized block design, with MUs serving as blocks. While Puhlick et al. (2016) found that soil properties were similar between the MUs of this study, soil sample collection and analysis were not conducted in each EU. Hence, soil physical and chemical properties could not be used to explain potential within-MU variation in crop growth response.

Data collection

Within each EU, trees ≥ 11.4 cm diameter at breast height (dbh) were measured on a 0.2 ha (45.7 × 45.7 m) permanent overstory plot. Trees that were 1.3 to <11.4 cm dbh were measured on five 0.006 ha (7.6 × 7.6 m) permanent sapling plots nested within each overstory plot. In June 2008 (prior to rehabilitation), species, dbh, total height, and height to the lowest live branch were measured on all crop trees within overstory plots, regardless of dbh. In June 2017 (9 years after treatment), these measurements were repeated. In 2017, the height from the base of the tree to the first epicormic sprout (diameter < 1.3 cm) and epicormic branch (larger branches, tending to have lighter colored bark and less lichen cover than primary branches) were measured on paper birch crop trees only. The number of epicormic sprouts and branches below the base of the crown (defined by the presence of primary branches) and the presence of a trainer tree and strong competitor were also recorded. A trainer tree was defined as a shade-tolerant conifer (e.g., balsam fir or spruce) in the lower strata with a crown projection area intersecting that of the crop tree. Strong competitors were defined as shade-tolerant conifers or hardwoods (e.g., red maples) occurring in the same stratum with a crown projection area intersecting that of the crop tree. Specific defects and form class, which could potentially affect future log quality, were not measured. For all trees, species and dbh to the nearest 2.5 cm class were measured on overstory and sapling plots in June 2008 and June 2009. In June 2017, these measurements were repeated to the nearest 0.1 cm.

Data analysis

Mixed-effects modeling was used to evaluate the influence of rehabilitation treatment on crop tree periodic annual diameter and height increment, crown recession (defined as the difference between the height to the crown base in 2017 and 2008, with positive values indicating a rise in the live crown), change in live crown length, presence and number of epicormic sprouts and epicormic branches, and height from the tree base to the first epicormic sprout and epicormic branch. Diameter and height increment were calculated as average annual growth from June 2008 to June 2017 (0 to 9 years after treatment), and crown recession and change in crown length were determined for the same time period. Separate models were developed for each of the most common crop tree species: paper birch, red maple (the dominant stem within a clump), red spruce, white spruce (*Picea glauca* (Moench) Voss), eastern white pine, and eastern hemlock. Single-stem red maple crop trees and crop trees of other species were uncommon and thus are not included in the analysis (a full list of crop tree species can be found in Kenefic et al. (2014)). In models of diameter increment, pretreatment dbh was used as a fixed effect to account for size differences among crop trees of the same species. Likewise, pretreatment total height was used as a covariate in models of height increment. Separate models were also developed with the following explanatory variables correlated with rehabilitation treatment: basal area of trees larger than the subject tree, 1- and 9-year posttreatment basal area, the percentage of pretreatment basal area in trees that were cut or treated with herbicide during treatments, and the absolute basal area of trees cut or treated with herbicide during treatments. Crown recession and periodic annual height increment were evaluated as potential explanatory variables in models of change in crown length. Likewise, change in crown length and height increment were evaluated in models of crown recession. The numbers of epicormic sprouts and epicormic branches on paper birch crop trees were predicted using a two-part or hurdle model approach in which (*i*) a binomial model was used to model the probability that a zero value is observed and (*ii*) the nonzero observations were modeled with a truncated Poisson (epicormic sprouts) or truncated negative binomial model (epicormic branches). This approach allows different covariates to be used in each model. Correlated explanatory variables were not used in the same model, and collinearity was assessed through bivariate plots, correlation coefficients, and variance inflation factors. Experimental unit within MU and MU were used as random effects to account for the nested structure of the data. While the intensive treatment was only applied in one of

Table 1. Mean (standard deviation) and range of pretreatment diameter at breast height (dbh; cm) and total height (m), periodic annual height increment (m·year^{-1}; 0 to 9 years after treatment), crown recession (m; 0 to 9 years after treatment), change in crown length (m; 0 to 9 years after treatment), and basal area of trees larger than the subject tree (BAL; m^2·ha^{-1}) associated with crop trees by species.

	Species					
Attribute	Paper birch	Red maple	Red spruce	White spruce	Eastern white pine	Eastern hemlock
Pretreatment dbh	6.9 (2.1)	8.1 (1.6)	5.8 (3.1)	5.7 (3.4)	8.5 (2.3)	6.0 (2.8)
	2.8–16.0	4.6–11.7	1.0–16.8	0.3–16.5	5.3–13.5	2.0–13.0
Pretreatment height	9.1 (1.7)	11.4 (1.5)	5.0 (2.0)	4.9 (2.4)	6.3 (1.1)	5.2 (1.3)
	5.1–14.9	7.1–14.5	1.7–11.1	1.4–12.1	3.9–9.2	2.9–8.2
Height increment	0.3 (0.1)	0.3 (0.1)	0.2 (0.1)	0.3 (0.1)	0.4 (0.1)	0.3 (0.1)
	<0.1–0.8	<0.1–0.6	<0.1–0.5	<0.1–0.6	0.2–0.7	<0.1–0.8
Crown recession	NA	NA	0.8 (1.0)	1.2 (1.2)	1.4 (1.6)	0.8 (0.8)
			0–6.6	0–5.0	0–8.0	0–3.7
Change in crown length	NA	NA	1.3 (1.2)	1.5 (1.5)	2.3 (1.9)	1.6 (1.3)
			–2.9–4.1	–1.6–4.2	–4.9–4.8	–1.6–4.8
BAL	14.2 (6.2)	11.2 (5.4)	16.7 (7.0)	14.4 (5.1)	6.4 (5.9)	17.9 (8.9)
	1.0–29.3	2.3–26.5	4.0–31.2	3.8–26.9	0.2–19.3	1.3–30.8

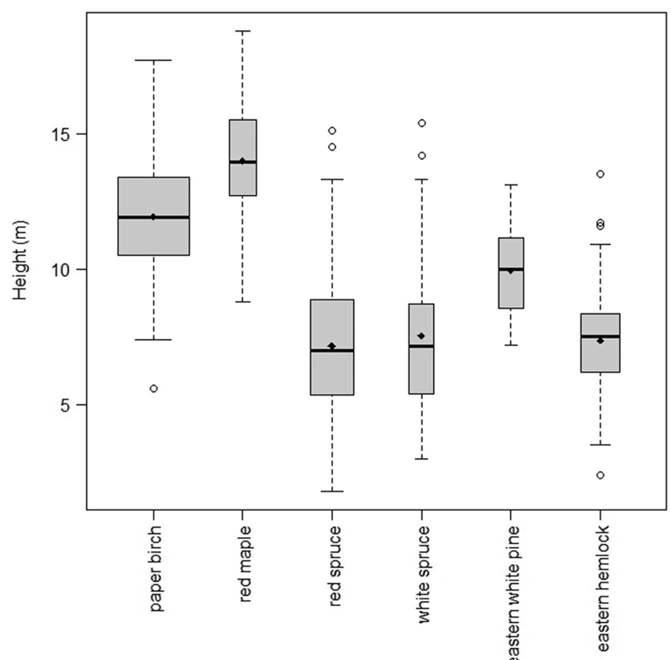
Note: NA, crown recession and change in crown length were not evaluated in hardwoods.

Table 2. Mean (standard deviation) and range of pretreatment and posttreatment stand basal area (BA; m^2·ha^{-1}), stand density (trees·ha^{-1}), and quadratic mean diameter (QMD; cm) associated with experimental units by treatment.

	Treatment		
Attribute	Control (N = 7)	Moderate (N = 7)	Intensive (N = 4)
Pretreatment BA	25.9 (4.8)	24.0 (5.8)	19.8 (1.7)
	19.0–33.9	15.8–31.9	17.5–21.8
1 year posttreatment BA	NA	14.9 (3.2)	10.9 (2.0)
		10.4–20.8	8.0–13.0
9 years posttreatment BA	28.8 (5.0)	21.8 (2.2)	17.8 (4.7)
	19.9–38.4	18.7–24.9	10.4–21.2
9 years posttreatment stand density	5033 (2038)	4237 (847)	3701 (1435)
	3045–9952	2830–5246	1688–5301
9 years posttreatment QMD	8.8 (1.1)	8.2 (0.6)	8.1 (0.8)
	7.0–10.7	7.3–9.2	7.0–9.1

Note: Data are from measurements of trees ≥ 1.3 cm diameter at breast height. NA, trees in the control experimental units were not measured 1 year after treatment.

Fig. 1. Height of crop trees 9 years after treatment for the most common species across all experimental units. The horizontal line and black dot in each box are the median and mean, respectively. The boxes define the hinge (25%–75% quartile, and the line is 1.5 × the hinge), and points outside the hinge are represented as dots. The size of the box is proportional to the squared root of the sample sizes.



the MUs, we felt that it was important to quantify the relative importance of the MU random effect. Statistical comparisons can be made with such unbalanced designs (Ott and Longnecker 2001). Models with and without MU were compared and differed slightly in magnitude, but not direction, of parameter estimates. Likelihood ratio tests were used to determine the optimal models in terms of fixed effects. The lme and glmmadmb functions in the nlme and glmmADMB packages (Bolker et al. 2012; Pinheiro et al. 2014) in R (R Core Team 2014) were used to fit the linear mixed-effects models. Least-squares (LS) means and pairwise comparisons were calculated using the lsmeans and cld functions in the lsmeans (Lenth 2014) and multcompView (Graves et al. 2012) packages, respectively, in R (R Core Team 2014). For the pairwise comparisons, differences between increment LS means were considered significant if P < 0.05 after applying a Tukey's honest significant difference multiplicity adjustment.

Results

Across all EUs, crop tree pretreatment dbh was 6.7 ± 2.7 cm (mean ± SD), but varied by species (Table 1). Pretreatment stand basal area of trees ≥ 1.3 cm dbh was 23.8 ± 5.3 m^2·ha^{-1}. Nine years after rehabilitation treatments, average basal area and tree density were greater in the control EUs than in the moderate and intensive rehabilitation EUs (Table 2). Across all EUs, the most common tree species in order of relative importance based on basal area (highest to lowest; including all trees) were balsam fir, red maple, paper birch, eastern hemlock, gray birch, quaking aspen, eastern white pine, bigtooth aspen (*Populus grandidentata* Michx.), red spruce, white spruce, and northern white-cedar. Conifers generally occupied lower strata, while hardwoods generally occupied upper strata (Fig. 1).

Crop tree periodic annual diameter increment varied by species and treatment (Table 3). In models of diameter increment, rehabilitation treatment and pretreatment dbh were statistically significant fixed effects (P < 0.05) for crop trees of most species, explaining between 24% and 66% of the variation in diameter increment (model parameters are provided in Table 4). For soft-

Table 3. Mean (standard deviation) and range of periodic annual diameter increment (cm·year^{-1}; 0 to 9 years after treatment) associated with crop trees by species and treatment.

	Treatment		
Species	Control	Moderate	Intensive
Paper birch	0.26 (0.15)	0.35 (0.16)	0.39 (0.15)
	0–0.70	0.06–0.79	0.14–0.88
Red maple	0.31 (0.17)	0.35 (0.13)	0.36 (0.14)
	0.11–0.90	0.17–0.57	0.08–0.57
Red spruce	0.19 (0.10)	0.41 (0.14)	0.42 (0.21)
	0–0.40	0.13–0.82	0.18–0.96
White spruce	0.19 (0.10)	0.45 (0.20)	0.46 (0.14)
	0.02–0.33	0.08–0.73	0.24–0.73
Eastern white pine	0.50 (0.22)	0.74 (0.23)	0.95 (0.18)
	0.20–0.84	0.28–1.13	0.57–1.12
Eastern hemlock	0.23 (0.12)	0.65 (0.20)	NA
	0–0.48	0.22–1.01	

Note: NA, eastern hemlock not evaluated in intensive treatment.

woods, variation in diameter increment between MUs and among EUs in the same MU accounted for between 0% and 5% and 34% and 67%, respectively, of the components of variance. For paper birch, variation in diameter increment between MUs and among EUs in the same MU accounted for 11% and 5%, respectively, of the components of variance (Table 4). For red spruce, white spruce, and eastern hemlock, the correlation between observations from the same EU was highest in the control EUs. Pairwise comparisons indicated that paper birch and red spruce crop trees in the moderate and intensive rehabilitation treatments had greater diameter growth, on average, than in the control ($P < 0.05$), and diameter growth was similar between the moderate and intensive rehabilitation treatments (Table 5). Pairwise comparisons also indicated that in the moderate rehabilitation treatments, eastern hemlock crop trees had greater diameter growth, on average, than in the control ($P < 0.05$); there were no eastern hemlock crop trees in the intensive rehabilitation treatment. For red maple crop trees within sprout clumps, there were no significant differences in periodic annual diameter increment among control, moderate, and intensive treatments. For white spruce and eastern white pine, average diameter growth in the moderate treatment did not differ from that in the control or intensive treatment (Table 5). For most crop tree species, models that included the basal area of trees larger than the subject tree explained more variation in diameter growth than models that included diameter and treatment (model parameters are provided in Table 6).

Across all EUs, crop tree periodic annual height increment was 0.3 ± 0.1 m and was similar among species (Table 1). For all species except paper birch, there were no significant differences in crop tree height growth among treatments. Pairwise comparisons indicated that height growth of paper birch in the control was greater than in the moderate rehabilitation treatment ($P < 0.05$), and height growth was similar among the control and intensive rehabilitation treatment. For all species, the best models of crop tree height increment included basal area of trees larger than the subject tree as a statistically significant fixed effect ($P < 0.05$) (Table 6); basal area of larger trees was negatively correlated with crop tree height increment. For red spruce, white spruce, and eastern hemlock, the models explained between 35% and 39% of the variation in height increment (Table 6). For all of the species other than eastern white pine, variation in crop tree height increment between MUs and among EUs in the same MU accounted for between 0% and 6% and 11% and 21%, respectively, of the components of variance (Table 6).

For softwood species, there were no significant differences in change in crop tree crown length or crown recession among rehabilitation treatments. The best models of change in crown length included basal area of larger trees and crown recession as statistically significant fixed effects ($P < 0.05$) (Table 6). Both explanatory variables were negatively correlated with change in crown length. The overall models explained between 56% and 76% of the variation in change in crown length, while variation in change in crown length between MUs and among EUs in the same MU accounted for between 0% and 11% and 19% and 27%, respectively, of the components of variance (Table 6). The best models of crown recession included basal area of larger trees and change in crown length as statistically significant fixed effects ($P < 0.05$), explaining between 47% and 74% of the variation in crown recession. For red spruce, white spruce, eastern white pine, and eastern hemlock, change in crown length was linearly correlated with change in live crown ratio ($r = 0.68$, 0.69, 0.90, and 0.77, respectively), and basal area in larger trees was linearly correlated with height increment ($r = -0.63$, −0.61, −0.44, and −0.51, respectively). For all softwood species, basal area in larger trees had a stronger linear correlation with change in crop tree crown length and crown recession than height increment.

Crop tree diameter and rehabilitation treatment were statistically significant fixed effects ($P < 0.05$) in models of observed probability (presence or absence) of epicormic sprouts and epicormic branches on paper birch crop trees (Table 4). In both models, the occurrence of at least one epicormic sprout or branch on a crop tree decreased with increasing diameter. The presence of a strong competitor also decreased the probability of epicormic branching. Pairwise comparisons indicated there was a greater occurrence of epicormic branches on paper birch crop trees in the moderate and intensive rehabilitation treatments than in the control ($P < 0.05$), and the occurrence of epicormic branches was similar among moderate and intensive treatments (Table 5).

For paper birch crop trees with a least one epicormic sprout, number of epicormic sprouts per tree was similar among rehabilitation treatments (Table 7). Crop tree diameter and the presence or absence of a trainer tree were statistically significant fixed effects ($P < 0.05$) in zero-truncated models of the number of epicormic sprouts and epicormic branches on paper birch crop trees (Table 8). A two-part or hurdle approach, which uses parameter estimates from both the binomial and zero-truncated models (Zuur et al. 2009), was used to predict the number of epicormic sprouts and epicormic branches on paper birch crop trees that could be expected in stands similar to those of this study (Fig. 2). In regards to this approach, the predictor variables from both the binomial and zero-truncated models have an influence on the predicted number of epicormic sprouts and epicormic branches.

For paper birches with epicormic branches, height from the base of the tree to the first epicormic branch was a function of dbh and rehabilitation treatment (Table 4). Pairwise comparisons indicated that average height to the first epicormic branch was less in the moderate and intensive rehabilitation treatments than in the control ($P < 0.05$), though not differentiated between intensities of rehabilitation (Table 5). The presence of a trainer tree had a significant influence on the height to the first epicormic sprout ($P < 0.05$), but other explanatory variables were not influential. On average, the height to the first epicormic sprout was 4.3 m when a trainer tree was not present and 5.0 m when a trainer tree was present. Across all treatments, conifers that functioned as trainer trees were associated with 38% of paper birch crop trees; conifers with the potential to become trainers in the future (i.e., trees with a crown projection area intersecting that of the crop tree but enough height or crown growth to cast shade on the boles of crop trees not yet developed) were associated with another 26% of paper birch crop trees. Strong competitors were associated with 38%, 24%, and 18% of paper birch crop trees in the control, moderate, and intensive treatments, respectively.

Table 4. Model parameter estimates and fit statistics for mixed-effects models of periodic annual diameter and height increment (cm·year^{-1} and m·year^{-1}, respectively; 0 to 9 years after treatment) that included treatment, pretreatment diameter at breast height (dbh; cm), and pretreatment height (HT; m) as fixed effects and management unit and experimental unit within management unit as random effects (b_k and $b_{j|k}$, respectively). Also, shown are models of observed probability (presence or absence) of epicormic sprouts and branches, as well as height from the base of the tree to the first epicormic branch (m) that included treatment and dbh and the presence of a strong competitor (COMP; 0 if absent, 1 if present) 9 years after treatment as fixed effects.

	a_i (SE)				
Species	Control	Moderate	Intensive	c (SE)	d (SE)
Diameter increment					
Paper birch	0.046 (0.048)	0.153 (0.026)	0.176 (0.031)	0.029 (0.004)	NA
Red spruce	0.150 (0.039)	0.347 (0.044)	0.377 (0.073)	0.009 (0.003)	NA
White spruce	0.036 (0.081)	0.338 (0.095)	0.406 (0.090)	0.016 (0.007)	NA
Eastern white pine	0.219 (0.143)	0.422 (0.110)	0.629 (0.121)	0.036 (0.015)	NA
Eastern hemlock	0.183 (0.050)	0.567 (0.053)	NA	0.014 (0.006)	NA
Height increment					
Paper birch	0.425 (0.062)	0.351 (0.019)	0.369 (0.022)	0.009 (0.005)	NA
Probability of epicormic sprouts					
Paper birch	1.519 (0.686)	2.841 (0.478)	2.328 (0.548)	0.391 (0.075)	NA
Probability of epicormic branches					
Paper birch	−0.318 (0.695)	1.925 (0.583)	1.539 (0.669)	0.140 (0.055)	0.810 (0.354)
Height to first epicormic branch					
Paper birch	5.468 (0.703)	3.861 (0.428)	3.991 (0.509)	0.103 (0.049)	NA

Marginal R^2	Conditional R^2	Residual SE	b_k SE	$b_{j\|k}$ SE
0.236	0.327	0.134	0.048	0.033
0.401	0.548	0.075	0.021	0.067
0.334	0.493	0.055	<0.001	0.055
0.494	0.704	0.167	<0.001	0.119
0.656	0.730	0.105	<0.001	0.065
0.061	0.126	0.136	0.052	<0.001
NA	NA	NA	0.001	0.511
NA	NA	NA	0.001	0.824
0.170	0.320	1.238	0.635	0.362

Note: Models of diameter increment and height to the first epicormic branch: $a_i + c(\text{dbh}) + b_k + b_{j|k}$. Model of height increment: $a_i - c(\text{HT}) + b_k + b_{j|k}$. ln(probability of epicormic sprouts or branches) = $a_i - c(\text{dbh}) - d(\text{COMP}) + b_k + b_{j|k}$. SE, standard error. NA, not applicable.

Table 5. Least-squares (LS) mean (standard error) periodic annual diameter and height increment (cm·year^{-1} and m·year^{-1}, respectively; 0 to 9 years after treatment) at the mean pretreatment diameter at breast height (dbh, cm) and height (m), respectively, as well as, 9 years after treatment, observed probability of epicormic sprouts and branches (0–1) and height from the base of the tree to the first epicormic branch (m) at the mean dbh.

	Treatment		
Species	Control	Moderate	Intensive
Diameter increment			
Paper birch	0.243 (0.038)a	0.351 (0.038)b	0.373 (0.043)b
Red spruce	0.202 (0.033)a	0.399 (0.036)b	0.429 (0.068)b
White spruce	0.125 (0.064)a	0.426 (0.072)ab	0.495 (0.061)b
Eastern white pine	0.523 (0.082)a	0.726 (0.072)ab	0.933 (0.088)b
Eastern hemlock	0.268 (0.033)a	0.652 (0.041)b	NA
Height increment			
Paper birch	0.347 (0.039)b	0.273 (0.039)a	0.291 (0.041)ab
Epicormic sprouts			
Paper birch	0.086 (0.771)a	0.261 (0.775)b	0.174 (0.781)ab
Epicormic branches*			
Paper birch	0.108 (0.717)a	0.532 (0.743)b	0.436 (0.751)b
First epicormic branch			
Paper birch	6.5 (0.6)b	4.8 (0.5)a	5.0 (0.6)a

Note: Different letters indicate significant differences between LS means among treatments at $P < 0.05$. NA, eastern hemlock not evaluated in intensive treatment.

*Average of values obtained when considering the presence or absence of a strong competitor.

Discussion

This study shows that rehabilitation silviculture can influence crop tree growth, the presence or absence and the number of epicormics, as well as their location along the boles of paper birches, and the change in crown metrics of conifers in stands degraded through repeated exploitive cutting. The mixedwood stands of this study were dominated by submerchantable trees prior to rehabilitation; however, they had sufficient stocking of desirable sapling and pole-sized trees to allow intermediate treatments (i.e., not intended to regenerate the stand). As a result, paper birch and red spruce periodic annual diameter increments 0 to 9 years after treatment were greater than in the control and similar between the moderate and intensive rehabilitation treatments. This finding is in agreement with that of Voorhis (1990), who observed similar diameter growth of paper birch in light and heavy precommercial thinning treatments in mixed northern hardwood stands. These findings suggest that limiting rehabilitation to crop tree release alone may satisfy diameter growth objectives for these species. Additional reductions in stand-level density from removal of noncommercial species and unacceptable growing stock not competing with crop trees (largely pin cherry, gray birch, and red maple sprout clumps in the present study; data not shown) did not confer a growth advantage to crop trees relative to crop tree release only. Also, a moderate treatment as applied in the current study has the benefit of being less costly than more intensive treatments including removal of noncommercial species and unacceptable growing stock (Greene 2014; Kenefic et al. 2014). Because the moderate rehabilitation treatment leaves some unacceptable growing stock trees that do not interfere with crop tree growth, the associated greater stand den-

Table 6. Model fit statistics for mixed-effects models of periodic annual diameter and height increment and change in crown length (cm·year⁻¹, m·year⁻¹, and m, respectively; 0 to 9 years after treatment) that contained the basal area of trees larger than the subject tree (BAL; $m^2 \cdot ha^{-1}$) and crown recession (CR; m) as fixed effects, as well as a random intercept based on management unit and experimental unit within management unit (b_{k1} and $b_{j|k1}$, respectively) and a random slope based on management unit and experimental unit within management unit (b_{k2} and $b_{j|k2}$, respectively).

	Parameter									
Species	*a*	*c*	*d*	Marginal R^2	Conditional R^2	Residual SE	b_{k1} SE	b_{k2} SE	$b_{j\|k1}$ SE	$b_{j\|k2}$ SE
Diameter increment										
Paper birch	0.3191 (0.0189)	–0.0234 (0.0025)	NA	0.5061	0.6961	0.0930	<0.0001	<0.0001	0.0738	0.0092
Red maple	0.3403 (0.0277)	–0.0211 (0.0035)	NA	0.3420	0.6635	0.0972	<0.0001	NA	0.0798	NA
Red spruce	0.3208 (0.0205)	–0.0137 (0.0019)	NA	0.4712	0.6486	0.1088	<0.0001	NA	0.0675	NA
White spruce	0.3885 (0.0350)	–0.0215 (0.0042)	NA	0.4659	0.6755	0.1168	<0.0001	NA	0.0807	NA
Eastern white pine	0.7417 (0.0221)	–0.0403 (0.0036)	NA	0.8058	0.8265	0.1169	<0.0001	NA	0.0312	NA
Eastern hemlock	0.3986 (0.0315)	–0.0195 (0.0055)	NA	0.6300	0.8490	0.1084	0.0197	0.0066	0.0819	0.0085
Height increment										
Paper birch	0.3112 (0.0279)	–0.0064 (0.0016)	NA	0.0183	0.2025	0.1324	0.0332	NA	0.0509	NA
Red maple	0.2965 (0.0231)	–0.0106 (0.0038)	NA	0.1339	0.2856	0.1209	<0.0001	NA	0.0433	NA
Red spruce	0.2327 (0.0200)	–0.0104 (0.0015)	NA	0.3878	0.5191	0.0881	0.0213	NA	0.0370	NA
White spruce	0.3011 (0.0253)	–0.0154 (0.0036)	NA	0.3742	0.5471	0.1009	<0.0001	NA	0.0508	NA
Eastern white pine	0.4095 (0.0173)	–0.0085 (0.0029)	NA	0.2027	0.2027	0.0991	<0.0001	NA	<0.0001	NA
Eastern hemlock	0.2677 (0.0315)	–0.0099 (0.0012)	NA	0.3532	0.4888	0.1007	0.0379	NA	0.0540	NA
Change in crown length										
Red spruce	3.2226 (0.3134)	0.7271 (0.0750)	0.0819 (0.0133)	0.5605	0.6781	0.7430	0.2155	NA	0.3661	NA
White spruce	4.2425 (0.5975)	0.7843 (0.1477)	0.1245 (0.0333)	0.5669	0.6817	0.8934	<0.0001	NA	0.4458	NA
Eastern white pine	4.2692 (0.3476)	1.0405 (0.1048)	0.0837 (0.0307)	0.7621	0.8379	0.8356	<0.0001	NA	0.4971	NA
Eastern hemlock	3.4740 (0.3318)	0.7818 (0.0547)	0.0789 (0.0103)	0.5576	0.6491	0.8778	0.3378	NA	0.4506	NA

Note: Models of diameter and height increment: $a + (c + b_{k2} + b_{j|k2})\,(\text{BAL}) + b_{k1} + b_{j|k1}$. Models of change in crown length: $a - c(\text{CR}) - d(\text{BAL}) + b_{k1} + b_{j|k1}$. SE, standard error. NA, not applicable (no random slope).

Table 7. Mean (standard deviation) and range of epicormic sprouts (number·tree⁻¹) and height to first epicormic sprout (m) of paper birch crop trees with epicormic sprouts.

	Treatment		
Attribute	Control	Moderate	Intensive
Epicormic sprouts	2.1 (1.3) 1–6	2.9 (3.1) 1–17	2.2 (1.6) 1–6
Height to first epicormic sprout	5.2 (1.4) 3.1–8.1	4.4 (1.6) 0.6–6.9	4.3 (1.5) 1.5–7.7
Epicormic branches	1.9 (1.2) 1–5	2.6 (1.7) 1–8	2.5 (1.7) 1–9
Height to first epicormic branch	6.4 (1.7) 3.1–9.5	4.8 (1.4) 0.9–7.8	4.6 (1.1) 1.7–6.7
dbh	9.6 (3.0) 5.1–21.1	10.1 (3.2) 4.8–22.6	10.0 (2.9) 5.1–21.1

Note: Statistics for paper birch crop trees with epicormic branches are also shown. Diameter at breast height (dbh; cm) is for all paper birch crop trees, regardless of the presence of epicormics. These descriptive statistics were derived using data 9 years after treatment.

sities may reduce wind speeds and allow trees to support each other when covered by snow (Greene 2014). These effects may reduce the bending and breaking of residual tree stems.

Though not as shade tolerant as other conifers in our study, eastern white pine persisted in shade cast by upper-strata hardwoods in the control treatment. We detected no mortality of eastern white pine crop trees, although diameter growth was greater in the intensive rehabilitation treatment than in the control. Diameter growth in the moderate treatment was not statistically different than growth in the control or in the intensive treatment. With regard to red maple crop trees, our finding of no statistically significant difference in diameter growth among treatments suggests that other stems in the same sprout clump may be the primary competitors of sprout-origin red maple crop trees. Stems of poor form and high position on stumps could be cut to encourage diameter growth of the favored stems (Trimble 1974).

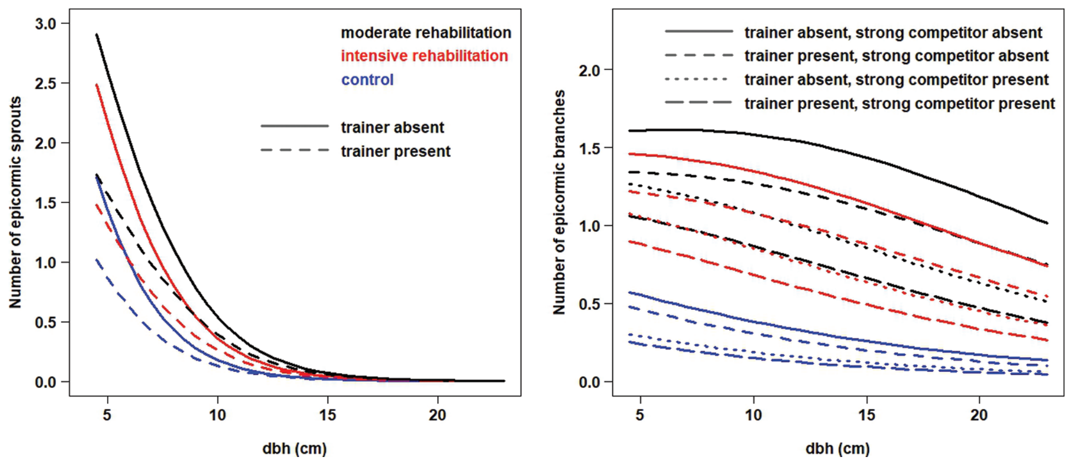
While comparisons of crop tree growth among rehabilitation treatments provided useful insights into growth dynamics, stand metrics explained more of the variation in diameter and height growth of crop trees compared with models that included reha-

Table 8. Model fit statistics for zero-truncated mixed-effects models of number of epicormic sprouts and epicormic branches on paper birch crop trees (9 years after treatment) that included diameter at breast height (dbh; cm) and the presence or absence of a trainer tree as fixed effects and management unit and experimental unit within management unit as random effects (b_k and $b_{j|k}$, respectively).

	a_i (SE)				
Model	Trainer absent	Trainer present	c (SE)	b_k SE	$b_{j\|k}$ SE
No. of epicormic sprouts	1.974 (0.497)	1.332 (0.208)	−0.142 (0.059)	0.001	0.390
No. of epicormic branches	0.253 (0.312)	−0.078 (0.158)	0.0562 (0.027)	<0.001	0.217

Note: ln(number of epicormic sprouts or epicormic branches) = $a_i + c(\text{dbh}) + b_k + b_{j|k}$. SE, standard error.

Fig. 2. Predicted number of epicormic sprouts and epicormic branches on paper birch crop trees using equations in Tables 4 and 8 in which values from the binomial model were divided by (1 – exp(–truncated Poisson or truncated negative binomial model values)) and then multiplied by values from the truncated Poisson or truncated negative binomial model. Large-size crop trees (based on diameter at breast height (dbh)), the presence of a strong competitor (i.e., a shade-tolerant conifer or hardwood occurring in the same stratum that has a crown projection area intersecting that of the crop tree), and the presence of a trainer tree (i.e., a shade-tolerant conifer in lower strata that has a crown projection area intersecting that of the crop tree) are correlated with a lower number of epicormic branches. [Colour online.]



bilitation treatment. Specifically, basal area in trees larger than the subject crop tree was negatively correlated with crop tree diameter and height growth. While this suggests that competition for resources influenced crop tree growth, previous work in this and other degraded stands has documented high variability in stand structures (Kenefic et al. 2014; Leak et al. 2014; Lussier and Meek 2014). Our estimate of basal area in larger trees was calculated at the experimental-unit level, so it may not reflect the local environment of an individual crop tree. With this caution in mind, the finding that stand metrics were correlated with crop tree growth suggests that these models can be used to predict crop tree growth over a range of treatment intensities in stands of similar species composition and structure.

For all of the species examined in this study, we found high within-MU variation in diameter growth, but relatively low variation in diameter growth between MUs. This is an indication that the blocking variable (i.e., MU in the experimental design) had a relatively small influence on crop tree diameter growth. The high degree of within-MU variation might reflect differences in soils (e.g., chemical and physical properties of the various soil series), which are variable across EUs. These trends were similar for height growth, except that within-MU variation was less pronounced for all species except white pine. For softwoods, there was more variability in diameter growth within the moderate and intensive rehabilitation EUs than the control EUs. This within-EU variation in softwood diameter growth was likely due to differences in the proximity of softwood crop trees to hardwood crop trees and the resulting variability in amounts of overhead shade.

We found no statistically significant differences in change of conifer crop tree crown length among treatments. Basal area in trees larger than the subject crop tree and crown recession were negatively correlated with change in crown length. Overall, the greatest positive change in crown length occurred in trees with less competition. This suggests that releasing conifers from competition from above and on the sides will result in wider and longer crowns. Over the long term, such increases in branch size and longevity can increase frequency and size of knots on the lower bole (Benjamin et al. 2009), negatively affecting wood quality; however, past studies of red spruce released through precommercial thinning revealed limited effects on log grade (Weiskittel et al. 2009), supporting the application of release treatments such as ours in similar stands.

We observed a greater occurrence of epicormic branches on paper birch crop trees in the moderate and intensive rehabilitation treatments than in the untreated control. However, the height from the base of the tree to the first epicormic branch averaged 4.8 and 4.6 m in the moderate and intensive treatments, respectively. Hence, the portion of the tree corresponding to the first sawlog (2.4–3.7 m lengths plus trim) tended to be free of epicormic branches. Across treatments, the height to the first epicormic sprout averaged 4.6 m and was greater when a trainer tree was present (5.0 m). These outcomes differ from those of earlier studies of crop tree release in northern hardwood stands, e.g., Heitzman and Nyland (1991). This difference is likely due to the presence of lower-stratum conifers in our mixedwood stands. As suggested by our modeling of epicormic sprout and epicormic branch numbers, these trainer trees cast shade on the lower boles of paper birch crop trees, preventing epicormics from occurring. While we did not record the height from the base of the tree to each epicormic or its location along the sides of the bole, epicormics occurring on more than one side (or "face" when considering log grades) within the same log length could decrease log grade and economic value. Wood et al. (1996) found that removal of competing trees within 3 m of the boles of yellow birch (*Betula* *alleghaniensis* Britton) crop trees provided a good balance between increasing diameter growth and limiting the probability of epicormic sprouts. This radius was similar to the one used in our study (2.5 to 3.7 m).

Conclusion

This study indicates that rehabilitation treatments can improve the growth of crop trees in mixedwood stands degraded by exploitive cutting. Diameter growth rates of hardwood and softwood crop trees were similar between intensities of rehabilitation, suggesting that less intensive rehabilitation (crop tree release only) may be sufficient for meeting the objectives of increased crop tree diameter growth, at least during the first decade after treatment. We also observed that, independent of treatment, basal area of larger trees was negatively correlated with crop tree diameter and height growth. This finding suggests that local competition has a greater influence on growth response than stand-level treatment alone, likely due to high spatial variability of structure in these previously exploited stands. Release treatments also resulted in greater conifer crown length and a greater occurrence of epicormic branches on paper birch; however, epicormics tended to occur above the portion of the tree that would yield the first sawlog in future cuttings, likely due to lower-bole shading from lower-stratum conifers in these stratified mixedwood stands. Furthermore, the presence of a trainer tree in association with a paper birch crop tree was correlated with a lower number of epicormics. These findings suggest release outcomes that differ from those of pure hardwood stands and contribute to the growing body of knowledge about benefits of mixedwood management (e.g., Kabrick et al. 2017). Results are applicable to mixedwood stands that are dominated by submerchantable growing stock and adequately stocked with desirable species of good form and quality to support crop tree release.

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