RESEARCH ARTICLE

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Silvicultural Rehabilitation of Cutover Mixedwood Stands

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We investigated rehabilitation of mixedwood stands degraded by exploitative cutting on the Penobscot Experimental Forest in Maine. Three precommercial rehabilitation treatments were applied: control (no rehabilitation), moderate rehabilitation (crop tree release [CTR]), and intensive rehabilitation (CTR, timber stand improvement [TSI], and red spruce fill planting). Crop trees (primarily red maple, paper birch, spruce, aspen, and eastern hemlock) were selected and released based on their potential for improved growth and value, spacing, and species composition. Rehabilitation reduced sapling basal area, density, and hardwood abundance and increased crop tree diameter increment. Fill planting increased spruce stocking, but many planted seedlings were browsed. Long-term projections suggested that future stand value will repay costs of moderate rehabilitation (CTR); intensive rehabilitation (CTR-TSI-planting) as applied in this study requires greater investment than can be repaid through quality and growth improvements of low-value hardwoods and softwoods. Although simulations suggested no difference in future stand value between treated and untreated stands, improvements in composition, growth, and quality after rehabilitation will facilitate later commercial thinning and shelterwood regeneration in stands which otherwise have few management options.

Keywords: Penobscot Experimental Forest, timber stand improvement, crop tree release, precommercial thinning, northern conifers, red spruce

The forests of the United States and Canada have a history of partial cutting characterized by removal of the most commercially desirable species and trees (e.g., Curtis 1998, Bedard and Majcen 2001, Lieffers et al. 2003, Kelty and D'Amato 2006). This practice began in northeastern forests during colonial times when eastern white pine (*Pinus strobus* L.) trees were high graded for ships' masts (Manning 2000), continued with extraction of softwood lumber and pulpwood in the 1800s and early 1900s (Pinchot 1898, Hosmer 1902, Westveld 1928, 1930, Judd 1989), and has persisted to the present day in exploitation of quality hardwoods (Nyland 1992, Judd et al. 1995, Irland 1999). Although technological advances and the emergence of new markets have increased the utilization of small, low-quality trees (Seymour 1995, Fajvan et al. 1998), ready availability of such material has kept prices low relative to those of sawtimber (Luppold et al. 2002). As a consequence, many partially cut stands on the landscape today have been subjected to some degree of past degradation (Harper and Rettie 1946, Nyland 1992, Whitney 1994, Irland 1999, MacCleery 2002).

In northern New England, the Adirondacks of New York, and adjacent portions of Canada, mixed-species, conifer-dominated (mixedwood) stands are common. A history of repeated partial cutting with removal of valuable species (primarily red spruce, *Picea rubens* Sarg.) has caused shifts in composition and a deterioration of residual growing stock throughout the region (Westveld 1953, Nyland 1992, Seymour 1992). At the dawn of the 21st century, Irland (1999) concluded that cutting in the Northeast was depleting stand quality and value far more than improving it. In Maine, for example, the volume of spruce decreased by approxi-

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mately 50% between the 1980s and early 2000s, whereas red maple (*Acer rubrum* L.) increased and is now one of the most abundant species in the state (McWilliams et al. 2005). Today, average annual removals of spruce exceed net growth, but red maple and balsam fir (*Abies balsamea* [L.] Mill.) growing stock is accumulating (McCaskill et al. 2011). About 95% of the acreage cut annually in Maine in the past 10 years has been partially harvested (Maine Forest Service 2013); many of these cuts removed the best trees (Seymour 2005). These practices have resulted in millions of acres of cutover land and present management challenges to today's forestry practitioners (Kenefic and Nyland 2006). Many are asking "How can we effectively rehabilitate our cutover forests?"

Conceptually, rehabilitation is silviculture applied to restore desired characteristics of stands degraded through past mismanagement. Restoration of some aspects of forest composition or structure may be inherent to rehabilitation, but the outcome is determined by the landowner's objectives rather than a baseline ecological condition. Within the context of the study reported here, rehabilitation is applied to stands degraded in vigor, quality, composition, and value by exploitative harvesting. Treatments are designed not only to improve production potential but also to enhance structure and increase species desired by the landowner, which have been depleted through past harvesting.

The goal of the research reported here is to evaluate alternative approaches to silvicultural rehabilitation in the northern conifer forest. Specifically, we sought to quantify short-term costs and silvicultural outcomes from a range of precommercial rehabilitation treatments in mixedwood stands degraded by commercial clearcutting (removal of all merchantable trees without attention to regeneration or residual stand condition) and to assess longer-term financial and residual stand implications using simulation (i.e., the Northeast Variant of the Forest Vegetation Simulator [FVS-NE]) (Crookston and Dixon 2005). Our approach focused on the intensity of rehabilitation: none, moderate, and intensive (defined below). We hypothesized that outcomes in terms of stand composition, quality, and growth response would differ among treatments such that increasing intensity would result in a more desirable residual stand condition. Whether this benefit would be offset by higher costs as rehabilitation intensity increased was an integral part of our assessment.

Methods

Study Area

This research was conducted in the US Department of Agriculture Forest Service (USDA) Northern Research Station's long-term silviculture experiment on the 3,855-acre Penobscot Experimental Forest (PEF) in the towns of Bradley and Eddington in east-central Maine (44°53′ N and 68°39′ W). This approximately 440-acre experiment was initiated in 1952 to study the outcomes of even- and uneven-aged silviculture and exploitative cutting in the northern conifer (previously called spruce-fir) forest (Sendak et al. 2003). The PEF is located in the southern portion of the Acadian Forest region between the eastern broadleaf and boreal forests (Rowe 1972). The Acadian region stretches from northern New England through southern Quebec to the Atlantic provinces (Braun 1950). Eastern hemlock (*Tsuga canadensis* [L.] Carr.), fir, and red spruce are common and occur in mixture with white pine, northern white-cedar (*Thuja occidentalis* L.), white spruce (*Picea glauca* [Moench] Voss), red maple, birch and aspen species (*Betula* and *Populus* spp.), and pin cherry (*Prunus pensylvanica* L.f.). Northern red oak (*Quercus rubra* L.), American beech (*Fagus grandifolia* Ehrh.), sugar and striped maple (*Acer saccharum* Marsh. and *Acer pensylvanicum* L.), ash species (*Fraxinus* spp.), red pine (*Pinus resinosa* Ait.), black spruce (*Picea mariana* [Mill.] B.S.P.), and larch (*Larix laricina* [Du Roi] K. Koch) are also infrequently found in the study area.

Commercial clearcutting was included in the Forest Service's experiment to represent poor cutting practice (Harper and Rettie 1946, McLintock 1953). Unlike silvicultural clearcutting, which removes all trees for the purpose of establishing a new cohort (Smith et al. 1997, p. 302, Helms 1998), commercial clearcutting (also called unregulated harvesting) (Brissette and Kenefic 2014) removes all merchantable trees without attention to regeneration or residual stocking. The PEF commercial clearcuts were applied to two management units (MUs) in the 1950s and 1980s. Although these are replicates in the underlying study, they were treated in different years and had different lapse times since cutting when the present study was initiated in 2008 (20 years in MU22 and 26 years in MU8). MUs are blocks in the present study, with rehabilitation treatments replicated within each. Because administrative constraints limited the number of replicates and treatments in MU8, findings reported here are from MU22.

Before the PEF was established in 1950, the forest had been repeatedly partially cut (Safford et al. 1969). Although records of land-use history are incomplete, inventories from the early 1900s suggest that the forest was irregularly uneven-aged, aggrading second growth. A 1956 inventory of MU22 found 1,703 ft^3 $acre^{-1}$ (≥4.5 in. dbh). Basal area (BA) (≥0.5 in. dbh) was 142 ft^2 $acre^{-1}$:

Management and Policy Implications

Widespread exploitative cutting in the United States and Canada has resulted in forests degraded in many aspects of composition, structure, and quality. In many places, foresters are uncertain about how to proceed in stands with limited management potential. Through experimentation, we observed short-term outcomes and simulated long-term trajectories of stands treated with different precommercial rehabilitation options. Moderate rehabilitation (crop tree release) resulted in short-term improvements in composition and growth of released trees, and treatment cost was likely to be offset by future stand value. Intensive rehabilitation (crop tree release, timber stand improvement, and fill planting) was more costly but may have longer-lasting effects on stand-level composition. Treatment constraints included lack of acceptable growing stock and seed sources and regeneration of desired species. These factors, which limit the potential success of rehabilitation, and the high cost of treatment application underscore the importance of maintaining adequate residual growing stock of desired species and good quality in partially harvested stands. In stands already degraded, some combination of treatments presented here coupled with efforts to reduce costs or increase revenues (e.g., applying for subsidies and delaying thinning until trees are merchantable) may prove feasible. Although financial benefits are not realized in the short-term, precommercial rehabilitation can be used to create stand conditions that facilitate sustainable long-term management.

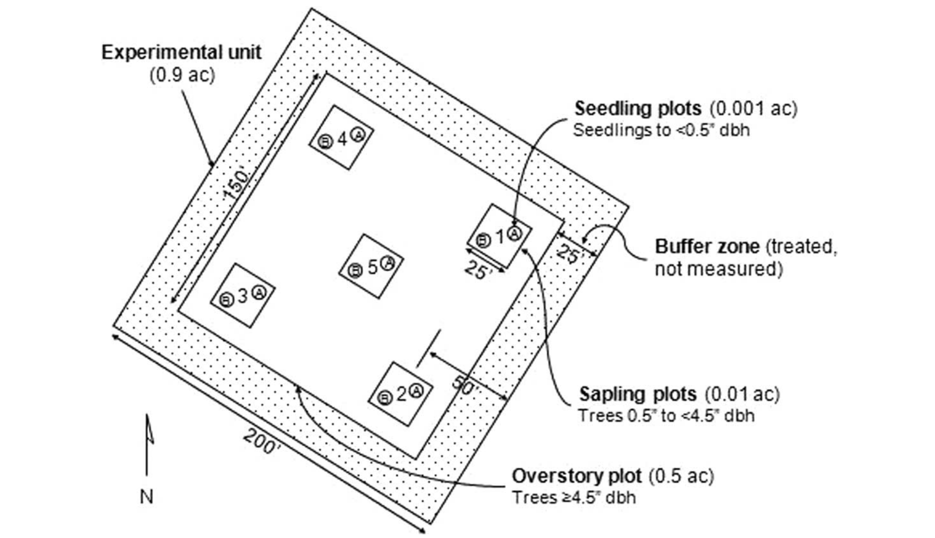

Figure 1. Layout of sample plots within experimental units in the PEF rehabilitation study.

80% softwood (33% fir, 19% cedar, 12% spruce spp., 12% hemlock, and 3% pine) and 20% hardwood (10% red maple, 5% paper birch, and 5% other not identified to species). The first commercial clearcut in 1957 removed 843 ft^3 $acre^{-1}$ and the second in 1988 removed 1,591 ft^3 $acre^{-1}$ (greater harvest volume at that time reflects lower merchantability standards). The last stand-level inventory before the rehabilitation experiment was in 2004. At that time, MU22 had 401 ft^3 $acre^{-1}$ and BA was 92 ft^2 $acre^{-1}$: 58% softwood (37% fir, 11% cedar, 7% spruce spp., 2% hemlock, 1% pine, and <1% larch) and 42% hardwood (20% red maple, 12% aspen spp., 5% paper birch, 3% noncommercial spp. [gray birch and pin cherry], and 1% ash spp.).

Experimental Design

A 14.7-acre area of MU22 was designated for the rehabilitation experiment. Soils there are of glacial till origin and well drained to somewhat poorly drained stony loams, stony silt loams, and stony fine sandy loams on 0–15% slopes (US Department of Agriculture, Soil Conservation Service 1963). Sixteen 0.9-acre (200 × 200 ft) experimental units (EUs) were established; four were later excluded due to atypical conditions (e.g., roads and wet areas). Three treatments (control, moderate, and intensive rehabilitation) were randomly assigned to the remaining EUs such that each was replicated four times, resulting in a completely randomized design. Within each EU, we established a 0.5-acre (150 × 150 ft) overstory permanent sample plot (trees ≥4.5 in. dbh), 5 nested 0.01-acre (25 × 25 ft) sapling plots (trees 0.5–<4.5 in. dbh), and 10 nested 0.001-acre (3.7-ft radius) regeneration plots (trees <0.5 in. dbh) (Figure 1).

Rehabilitation Treatments

Objectives of the treatments were to improve the growth of acceptable growing stock (AGS), increase the proportion of desirable species, and increase stand value. Specifically, we intended to reduce proportions of unmerchantable trees and noncommercial species, improve growing space occupancy, and accelerate growth of acceptable softwoods and hardwoods to facilitate later commercial thinning and, ultimately, regeneration with the irregular shelterwood method (Raymond et al. 2009). Because of insufficient stocking of merchantable trees, silvicultural treatments used elsewhere in northern conifers, e.g., variants of selection and shelterwood cutting (Sendak et al. 2003, Saunders and Arsenault 2013) and commercial thinning (Seymour et al. 2014), were not feasible in our study area. Clearing with planting is a viable option on badly degraded sites when biomass markets are available (Nyland 2006), but 20 years after harvest, the study stands had vertical structure, species diversity, and crop trees that we wanted to retain. For these reasons, our experiment focused on the potential of precommercial treatments for stand improvement.

Three treatments were applied: control (no rehabilitation), moderate rehabilitation (crop tree release [CTR]), and intensive rehabilitation (CTR, timber stand improvement [TSI], and fill planting). In both moderate and intensive rehabilitation, promising softwood and hardwood trees ≥4.5 ft in height were identified as crop trees and released on 15- and 25-ft spacings, respectively. Crop trees were AGS (low risk and free of defects such as forks, broken tops, damage, and decay) with potential to increase in volume and value. Red maple stump sprouts free of decay, of low origin, and with a tight formation were eligible for release as a clump (Figure 2); within-clump release was not attempted. Species previously more abundant on the site but diminished through past cutting (e.g., spruce, hemlock, and cedar) were favored when possible. Species infrequently found in the study area (e.g., oak, pine, and ash) were also released to maintain seed sources and biodiversity. Noncommercial species and fir were not selected as crop trees; the latter dominates the residuals and regeneration, is the preferred host of the spruce budworm *(Choristoneura fumiferana),* and has short pathological longevity (70–90 years) (Frank and Bjorkbom 1973, Basham 1991). Because hardwoods were generally stratified above softwoods, hardwood and softwood crop trees were selected independently of one another; this resulted in some crop trees being in close proximity to one another. Release was accomplished mechanically with brushsaws or chainsaws or chemically with a basal spray of Garlon 4 Ultra (triclopyr and oil); the latter was used to kill red maple sprout clumps.

Technicians were instructed to kill trees with stems within 8–12 ft of a crop tree with a crown at the same level or above, trees outside that radius with crowns overtopping, crown-touching, or abrading that of a crop tree, and overstory residuals (except spruce, hemlock, cedar, pine, oak, or AGS red maple or paper birch) competing with a crop tree. They were told not to kill crop trees (even if competing with another crop tree), trees within 8–12 ft of a crop tree but with a crown below that of the crop tree, trees not affecting the crown of a crop tree, or any spruce, pine, or oak if the crop tree was already released on three sides. This resulted in incomplete release of some crop trees, for the sake of retaining AGS and seed sources of desirable species.

The intensive treatment included CTR as described above, as well as TSI (removal of noncommercial species and unacceptable growing stock [UGS]: cull, poor vigor, and high-risk trees). In addition, red spruce seed-

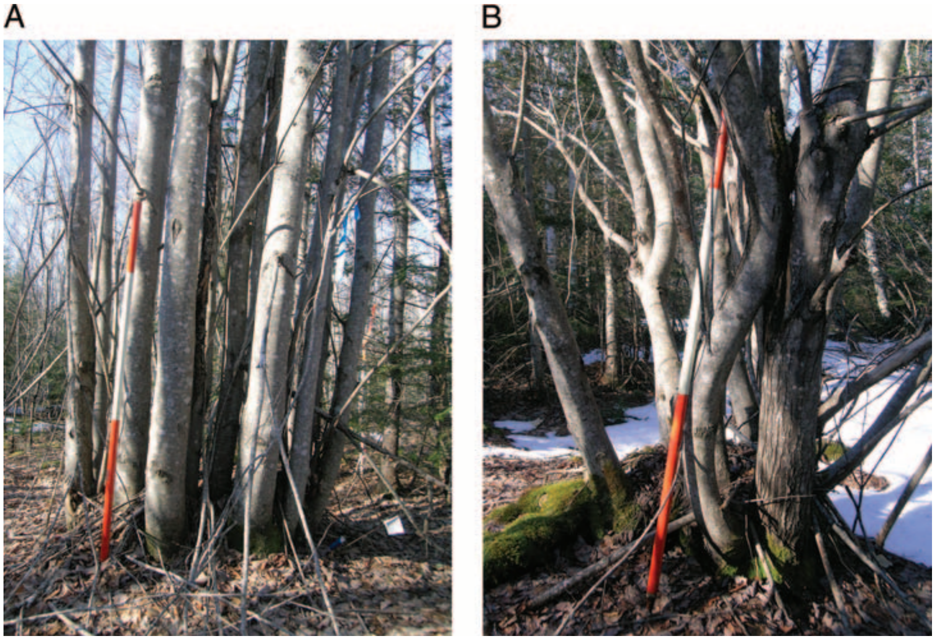

Figure 2. Examples of red maple stump sprout AGS (left: low attachment, free of decay, tight cluster, good form) and UGS (right: high or other poor attachment to decayed stump, wide cluster, poor form).

lings were fill planted at a 7-ft spacing in each intensively treated EU. In all treatments, conifer thickets without crop trees and free of cull and UGS were left intact and not planted, as these were not deemed to need rehabilitation.

Crop tree release and TSI were conducted in June–July 2008. Planting was done in June 2009 using 2-0 container stock; 18-in. sleeves of netting were placed over each planted seedling to reduce browsing. Amounts of fuel and chemicals used and time spent on CTR, TSI, and planting were recorded for each EU. The same technicians conducted all work in a given year. Technicians were students in the University of Maine, School of Forest Resources, and worked under the supervision of a Forest Service Forester; the latter is a licensed herbicide applicator and applied that portion of the treatment.

Data Collection

Crop Trees. Before rehabilitation in 2008, each crop tree (and each stem within red maple sprout clumps) was given a unique number, and species and dbh to the nearest 0.1-in. was recorded. Measurements were repeated in May–June 2012.

Overstory Trees and Saplings. Species and dbh to the nearest 1-in. were recorded for trees on the overstory and sapling plots before rehabilitation in 2008. Merchantability status (merchantable or cull: $<$50% merchantable by volume) was recorded for overstory trees. Overstory inventory was repeated in June 2009 and June 2011; sapling inventory was repeated in June 2009.

Regeneration. Number and species of stems 0.5 ft tall to $<$0.5 in. dbh were recorded on regeneration plots before rehabilitation in 2008; seedlings $<$0.5 ft were recorded as present or absent by species. Regeneration inventory was repeated in June 2009. A 100% inventory of planted seedlings was made in the intensively treated EUs in May–June of each year, starting 1 year after planting (i.e., 2010, 2011, and 2012). Status (living or dead) and evidence of browsing were recorded.

Analysis

Statistical Analyses. Treatment differences in structural and compositional attributes of the overstory, saplings, and regeneration were examined using analysis of variance (ANOVA) with a significance level of 0.05. The analysis was conducted on the basis of a completely randomized design with treatments as fixed effects using SAS 9.3 (SAS Institute, Inc. 2000). When significant effects were found, Tukey's mean separation procedure was used to determine significant differences between treatments. The analysis was conducted for all species, softwood component, and hardwood component separately. Basal area increment was calculated as the difference in overstory BA (trees $\geq$4.5 in. dbh) between posttreatment and 2011 conditions and assessed for statistical differences using ANOVA.

Crop-tree growth was calculated as the periodic diameter increment between pretreatment and 2012 inventories. A linear mixed-effects model was used to examine the fixed effect of treatments on individual crop tree diameters. The correlation structure resulting from the grouping of crop trees by EUs was modeled as a random effect. Effects of initial tree diameter and species were incorporated as fixed effects in the model. For each of the most abundant species (i.e., hemlock, paper birch, aspen, red maple sprout clumps, red spruce, white pine, and white spruce), the same model structure was used to test for treatment effects while accounting for the initial diameter of crop trees.

Projections and Financial Analysis. We used FVS-NE to project the 2008–2009 inventory data for 50 years to do a preliminary assessment of stand composition and financial outcomes of the treatments. Projections were made using tallies of trees $\geq$0.5-in. dbh by species as well as posttreatment regeneration data, including planted seedlings. The effect of moderate and intensive rehabilitation relative to the control was determined by comparing differences between projected future composition (percent softwood and hardwood BA) at 10-year intervals. Projected future stand value was calculated with a real price increase of 0.75% year^{-1} (Haynes et al. 2007), and the cost of the treatments was compounded at a 4% real interest rate. Costs in 2008 were calculated using time spent on treatment application in each EU and amounts of fuel and herbicide consumed, multiplied by average prices paid ($12 hour^{-1} for labor, $2.69 gallon^{-1} for fuel, and $100 gallon^{-1} for herbicide). Stand value was calculated from initial and projected FVS tree lists at the end of each 10-year projection cycle. Prices and product values were obtained from operational 2-year averages for species, size, and quality classes that have been developed and used by the University of Maine, School of Forest Resources, University Forest Office. Any trees identified as cull in the initial measurement were not included in stand value calculations; tree quality was not otherwise accounted for in projections or associated value calculations.

Table 1. Species composition of crop trees in control, moderate, and intensive rehabilitation pretreatment (2008) and 4 years posttreatment (2012).

	Proportion of BA (SE)					
	Pretreatment			4 Years posttreatment		
	Control	Moderate	Intensive	Control	Moderate	Intensive
Eastern hemlock	0.07 (0.03)	0.08 (0.03)	T*	0.07 (0.03)	0.08 (0.03)	T*
Red spruce	0.09 (0.06)	0.16 (0.10)	0.01 (0.01)	0.08 (0.05)	0.14 (0.09)	0.02 (0.01)
White spruce	0.02 (0.02)	0.01 (0.01)	0.04 (0.02)	0.02 (0.02)	0.01 (0.01)	0.04 (0.02)
Eastern white pine	0.03 (0.01)	0.06 (0.03)	0.12 (0.07)	0.03 (0.02)	0.07 (0.03)	0.14 (0.08)
Red pine	T*	0	T*	T*	0	T*
Eastern larch	0	0	0.01 (0.01)	0	0	0.01 (0.01)
All softwoods	0.21 (0.08)	0.30 (0.1)	0.18 (0.08)	0.20 (0.08)	0.30 (0.1)	0.22 (0.1)
Paper birch	0.30 (0.09)	0.20 (0.04)	0.36 (0.06)	0.31 (0.08)	0.22 (0.04)	0.35 (0.05)
Red maple	0.43 (0.13)	0.33 (0.13)	0.28 (0.10)	0.43 (0.13)	0.31 (0.13)	0.25 (0.09)
Quaking aspen	0.03 (0.02)	0.09 (0.05)	0.09 (0.04)	0.03 (0.02)	0.09 (0.05)	0.08 (0.03)
Bigtooth aspen	0.02 (0.02)	0.06 (0.04)	0.03 (0.02)	0.02 (0.02)	0.07 (0.05)	0.03 (0.02)
Northern red oak	0	0.01 (0.01)	0.01 (0.01)	0	0.01 (0.01)	0.01 (0.01)
White ash	0	T*	0.06 (0.06)	0	T*	0.06 (0.06)
All hardwoods	0.79 (0.08)	0.70 (0.1)	0.82 (0.08)	0.80 (0.08)	0.70 (0.1)	0.78 (0.1)

*T (trace), indicates proportion <0.01 but >0.

Results

Treatments

On average, 77.1 ± 4.9 (mean ± SE) crop trees acre^{-1} were selected across the EUs. Crop tree species composition, in terms of BA, was predominantly hardwood; the most frequent species were paper birch and red maple, though aspen spp., spruce spp., pine spp., and hemlock were also common (Table 1). Overall, 90% of red maple crop trees were sprout clumps with an average of 11.1 ± 1.0 stems each; these contributed more than one-third of the total crop tree BA. Average dbh of crop trees was 2.5 ± 0.1 in. for softwoods, 2.7 ± 0.1 in. for single-stem hardwoods, and 2.2 ± 0.1 in. for red maple sprout clumps.

Before rehabilitation, sapling and overstory BA averaged 75.5 ± 4.0 and 22.1 ± 4.0 ft^2 acre^{-1}, respectively; 5% of overstory BA was cull. Hardwoods comprised about 70% of sapling and 50% of overstory BA (Table 2); 12% of sapling BA was noncommercial species. Neither amount of BA nor stem density (trees acre^{-1} [TPA]) differed among EUs before rehabilitation ($P = 0.44$ to 0.68) (Table 3), although sapling BA was highly variable (Figure 3). On average, moderate rehabilitation reduced sapling and overstory BA by 25.0 ± 3.7 ft^2 acre^{-1} (33%) and 5.8 ± 3.6 ft^2 acre^{-1} (26%), respectively; intensive rehabilitation reduced sapling and overstory BA by 33.1 ± 3.4 ft^2 acre^{-1} (44%) and 4.7 ± 1.8 ft^2 acre^{-1} (21%).

Overstory TPA and BA did not differ among treatments after rehabilitation ($P =$ 0.29 and 0.38). Three years after treatment, however, overstory TPA was lower in the intensively rehabilitated treatment than in the control ($P = 0.04$). No other differences in overstory stocking were found, though percent cull was lower in the moderate and intensive treatments (1 and 0% of BA, respectively) than in the control (4%).

After rehabilitation, sapling BA and TPA were lower in both rehabilitation treatments than in the control ($P < 0.01$) (Table 3). This was the result of fewer hardwoods; TPA and BA of hardwoods (including noncommercial species) were lower in the moderate and intensive treatments than in the control ($P < 0.01$). The amount of softwoods in the saplings and the amount of hardwoods and softwoods in the overstory did not differ among treatments ($P = 0.18$–0.91).

Density of seedlings before treatment was 4,050 ± 420 acre^{-1}: 43% softwood (40% fir, 2% white-cedar, and <1% each hemlock and pine) and 57% hardwood (20% red maple, 18% noncommercial species, 12% paper birch, 7% ash spp., and <1% oak) (Table 4). Pretreatment regeneration stocking (percentage of plots with at least one seedling ≥0.5 ft tall) averaged 56% for hardwoods and 49% for softwoods. There were no differences in regeneration density or stocking among treatments before rehabilitation ($P = 0.21$–0.95). We planted 176.4 ± 3.7 (range 150.3–214.5) spruce seedlings acre^{-1} in the intensively treated EUs; rehabilitation did not otherwise deliberately alter regeneration. Density and stocking of hardwood and softwood regeneration did not differ significantly among treatments after rehabilitation ($P = 0.29$–0.76). Stocking of spruce increased from 0 to 23% as a result of planting in the intensively treated EUs; there were no other species differences ($P > 0.05$). Planted seedlings were heavily browsed by hare and rodents; mortality over the first 3 years was 34%. Density of survivors at the beginning of the 2012 growing season was 118.2 ± 16.5 seedlings acre^{-1} (range 70.8–142.7); 87% of those had been browsed.

Growth Response

We observed no difference among treatments in stand-level BA increment of the overstory ($P = 0.24$), which averaged 3.4 ± 0.4 ft^2 acre^{-1} year^{-1} over the first 2 years after treatment. Periodic crop tree growth (diameter increment), however, was greater in the moderate and intensive treatments than in the control ($P < 0.01$) but did not differ significantly between the two rehabilitation treatments ($P =$ 0.21). Four-year crop tree growth averaged 0.8 ± 0.05 and 0.9 ± 0.05 in. in the moderate and intensive treatments, respectively, and 0.6 ± 0.05 in. in the control. This difference was primarily driven by faster growth of hemlock ($P = 0.02$), paper birch ($P = 0.02$), and white spruce ($P <$ 0.01) in the rehabilitation treatments relative to that in the control; other species did

Table 2. Species composition in control, moderate, and intensive rehabilitation pretreatment (2008), 1 year posttreatment (2009), and 3 years posttreatment (2011, overstory only).

	Mean proportion of BA (SE)							
	Pretreatment and 1 year posttreatment: control*	Pretreatment		1 Year posttreatment		3 Years posttreatment		
		Moderate	Intensive	Moderate	Intensive	Control	Moderate	Intensive
Saplings (0.5–<4.5 in. dbh)								
Balsam fir	0.28 (0.06)	0.32 (0.07)	0.21 (0.04)	0.35 (0.07)	0.31 (0.07)			
Total softwood†	0.31 (0.06)	0.38 (0.07)	0.24 (0.05)	0.43 (0.07)	0.36 (0.07)			
Aspen spp.	0.11 (0.04)	0.20 (0.07)	0.19 (0.06)	0.20 (0.07)	0.17 (0.06)			
Paper birch	0.13 (0.03)	0.16 (0.05)	0.12 (0.02)	0.16 (0.04)	0.13 (0.03)			
Red maple	0.30 (0.06)	0.19 (0.06)	0.30 (0.04)	0.14 (0.06)	0.26 (0.06)			
Noncommercial spp.‡	0.15 (0.04)	0.07 (0.02)	0.13 (0.03)	0.06 (0.02)	0.02 (0.01)			
Total hardwood†	0.69 (0.06)	0.62 (0.07)	0.76 (0.05)	0.57 (0.07)	0.64 (0.07)			
Overstory (≥4.5 in. dbh)								
Balsam fir	0.29 (0.09)	0.32 (0.08)	0.27 (0.07)	0.31 (0.08)	0.27 (0.07)	0.29 (0.07)	0.28 (0.07)	0.28 (0.07)
Eastern hemlock	0.09 (0.03)	0.04 (0.02)	0.02 (0.02)	0.04 (0.02)	0.03 (0.03)	0.08 (0.03)	0.06 (0.02)	0.03 (0.03)
Eastern white pine	0.05 (0.03)	0.03 (0.03)	0.03 (0.02)	0.06 (0.03)	0.01 (0.01)	0.04 (0.03)	0.06 (0.02)	0.07 (0.04)
Spruce spp.	0.06 (0.04)	0.06 (0.03)	0.08 (0.04)	0.08 (0.03)	0.12 (0.06)	0.02 (0.01)	0.08 (0.03)	0.09 (0.04)
Northern white-cedar	0.14 (0.09)	0.09 (0.07)	0.02 (0.02)	0.10 (0.07)	0.03 (0.02)	0.12 (0.07)	0.07 (0.04)	0.03 (0.02)
Eastern larch	0	0	0.01 (0.01)	0	0.01 (0.01)	0	0	0.01 (0.10)
Total softwood†	0.63 (0.13)	0.55 (0.05)	0.44 (0.11)	0.59 (0.05)	0.47 (0.11)	0.55 (0.10)	0.56 (0.09)	0.50 (0.10)
Ash spp.	0.03 (0.03)	0	0	0	0	0.01 (0.01)	0	0
Aspen spp.	0.07 (0.05)	0.12 (0.05)	0.15 (0.07)	0.14 (0.06)	0.19 (0.09)	0.16 (0.10)	0.19 (0.08)	0.20 (0.12)
Paper birch	0.03 (0.02)	0.01 (0.01)	0.02 (0.01)	0.01 (0.01)	0.01 (0.01)	0.04 (0.02)	0.03 (0.01)	0.04 (0.01)
Red maple	0.22 (0.09)	0.28 (0.05)	0.35 (0.08)	0.23 (0.03)	0.33 (0.13)	0.22 (0.05)	0.20 (0.03)	0.26 (0.11)
Noncommercial spp.‡	0.01 (0.00)	0	0.05 (0.04)	0.01 (0.01)	0	0.01 (0.01)	0.01 (0.00)	0
Total hardwood†	0.37 (0.13)	0.45 (0.05)	0.56 (0.11)	0.41 (0.05)	0.53 (0.11)	0.45 (0.10)	0.44 (0.09)	0.50 (0.10)

*Pretreatment and 1 year posttreatment inventories are the same for the control because it was not treated.
†Other softwoods and hardwoods included in the total were found on ≤0.03 but >0 of the plots in any inventory: eastern hemlock, spruce spp., northern white-cedar, larch, American beech, ash spp., and northern red oak in the understory, and American beech and northern red oak in the overstory.
‡Noncommercial species include gray birch and pin cherry.

Table 3. BA and TPA in control, moderate, and intensive rehabilitation pretreatment (2008), 1 year posttreatment (2009), and 3 years posttreatment (2011, overstory only).

	Pretreatment and 1 year posttreatment: control*	Pretreatment		1 Year posttreatment		3 Years posttreatment		
		Moderate	Intensive	Moderate	Intensive	Control	Moderate	Intensive
Softwood BA $acre^{-1}$								
0.5 to <4.5 in. dbh	26.8a (10.5)	29.0a (7.2)	16.5a (4.7)	21.6a (5.1)	12.3a (3.2)			
≥4.5 in. dbh	15.6a (4.9)	15.2a (7.1)	7.5a (2.3)	12.3a (4.2)	5.6a (1.6)	17.9a (4.6)	15.7a (4.5)	7.7a (1.3)
Total	42.4 (13.9)	44.2 (13.5)	24.0 (2.8)	33.9 (8.5)	17.9 (1.9)			
Softwood TPA								
0.5 to <4.5 in. dbh	1,268.5a (644.9)	1,278.9a (276.6)	860.8a (231.8)	958.3a (245.5)	648.2a (152.7)			
≥4.5 in. dbh	60.0a (17.8)	63.4a (27.4)	33.4a (8.1)	50.3a (14.0)	23.2a (3.1)	71.2a (14.7)	71.2a (15.7)	34.4a (5.4)
Total	1,328.5 (656.8)	1,342.3 (300.5)	894.1 (229.5)	1,008.7 (258.6)	671.4 (151.5)			
Hardwood BA $acre^{-1}$								
0.5 to <4.5 in. dbh	55.4a (2.5)	45.9a (11.9)	53.0a (3.4)	27.7b (7.9)	24.0b (4.3)			
≥4.5 in. dbh	7.5a (1.9)	10.9a (3.2)	9.5a (3.9)	8.4a (2.4)	6.9a (3.0)	13.1a (1.5)	12.8a (3.4)	9.5a (4.2)
Total	62.9 (3.2)	56.8 (12.1)	62.5 (6.0)	36.0 (8.1)	30.9 (6.4)			
Hardwood TPA								
0.5 to <4.5 in. dbh	2,920.3a (262.2)	2,310.4a (266.9)	2,613.6a (203.2)	1,223.2b (198.4)	1,090.7b (230.3)			
≥4.5 in. dbh	31.9a (9.3)	53.7a (12.8)	46.0a (13.8)	40.2a (9.5)	32.9a (8.8)	71.2a (13.8)	63.9a (15.0)	47.9a (14.7)
Total	2,952.2 (261.1)	2,364.1 (259.6)	2,659.6 (209.5)	1,263.3 (196.1)	1,123.6 (236.1)			
All species BA $acre^{-1}$								
0.5 to <4.5 in. dbh	82.2a (10.4)	74.9a (8.0)	69.4a (5.3)	49.3b (4.1)	36.3b (5.2)			
≥4.5 in. dbh	23.1 (5.1)	26.1 (10.1)	17.0 (5.7)	20.7 (6.5)	12.5 (4.2)	31.1a (3.3)	28.6a (7.2)	17.2a (4.9)
Total	105.3 (14.4)	101.0 (14.9)	86.4 (4.1)	69.9 (7.9)	48.8 (5.1)			
All species TPA								
0.5 to <4.5 in. dbh	4,188.7a (582.3)	3,589.3a (99.0)	3,474.3a (384.3)	2,181.5b (140.4)	1,738.9b (274.1)			
≥4.5 in. dbh	92.0a (17.3)	117.1a (38.9)	79.4a (18.6)	90.5a (21.9)	56.1a (9.2)	142.3a (4.0)	135.0ab (22.2)	82.3b (13.0)
Total	4,280.7 (594.9)	3,706.5 (108.5)	3,553.7 (383.1)	2,272.0 (152.9)	1,795.1 (272.8)			

Data are means (standard error). Within each row, means with different letters in the same inventory are significantly different ($P < 0.05$).
*Pretreatment and 1 year posttreatment inventories are the same for the control because it was not treated.

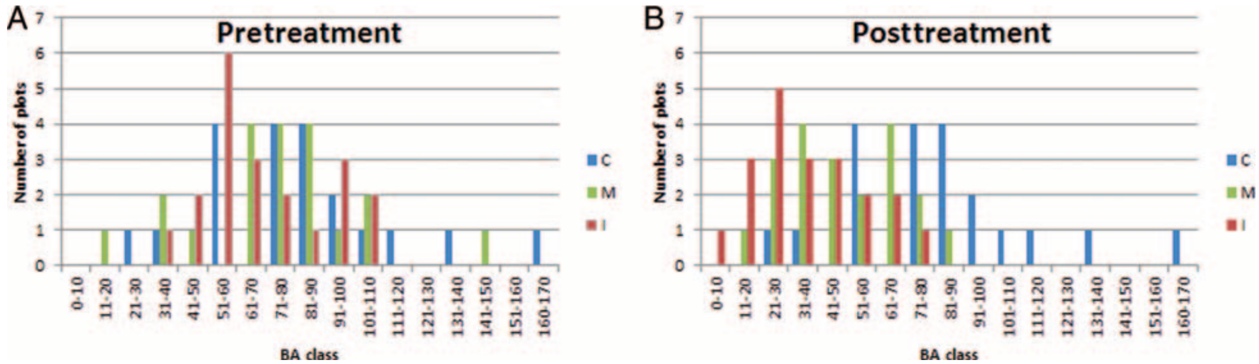

Figure 3. Frequency distribution of sapling plots by BA (ft² acre^{-1}) class for rehabilitation treatments: control (C), moderate (M), and intensive (I), pretreatment (2008; left) and posttreatment (2009; right).

Table 4. Seedling (0.5 ft tall to <4.5 in. dbh) density for softwoods and hardwoods and stocking by species in control, moderate, and intensive rehabilitation pretreatment (2008) and 1 year posttreatment (2009).

	Pretreatment/1 year posttreatment: control*	Pretreatment		1 Year posttreatment	
		Moderate	Intensive	Moderate	Intensive
Seedling density (no. of stems acre^{-1})					
Softwoods	1,775.0 (394.5)	2,150.0 (755.5)	1,350.0 (417.3)	1,125.0 (383.8)	1,250.0 (221.7)
Hardwoods	2,050.0 (533.1)	2,100.0 (393.7)	2,725.0 (363.7)	2,525.0 (981.0)	1,575.0 (388.1)
Total	3,825.0 (909.6)	4,250.0 (956.1)	4,075.0 (411.1)	3,650.0 (920.6)	2,825.0 (444.2)
Seedling stocking (proportion of plots with ≥1 stem)					
Balsam fir	0.61 (0.08)	0.47 (0.11)	0.45 (0.06)	0.40 (0.11)	0.45 (0.05)
Eastern hemlock	0.08 (0.05)	0.08 (0.05)	0	0	0
Eastern white pine	0.06 (0.06)	0	0.03 (0.03)	0	0.03 (0.03)
Spruce spp.	0	0	0	0	0.23 (0.03)
Northern white-cedar	0.10 (0.07)	0.05 (0.05)	0.05 (0.03)	0.05 (0.05)	0.03 (0.03)
Softwood	0.64 (0.10)	0.50 (0.10)	0.50 (0.04)	0.45 (0.10)	0.58 (0.03)
Ash spp.	0	0.03 (0.03)	0.23 (0.13)	0.03 (0.03)	0.13 (0.08)
Aspen spp.	0	0	0	0	0.03 (0.03)
Northern red oak	0	0	0.08 (0.05)	0	0.03 (0.03)
Paper birch	0.24 (0.08)	0.31 (0.06)	0.18 (0.05)	0.28 (0.13)	0.08 (0.03)
Red maple	0.45 (0.09)	0.46 (0.06)	0.33 (0.05)	0.30 (0.17)	0.28 (0.08)
Noncommercial spp.†	0.21 (0.07)	0.18 (0.07)	0.33 (0.13)	0.25 (0.09)	0.13 (0.03)
Hardwood	0.55 (0.04)	0.62 (0.07)	0.58 (0.13)	0.48 (0.15)	0.40 (0.07)

Data are means (standard error).
*Pretreatment and 1 year posttreatment inventories are the same for the control because it was not treated.
†Noncommercial species include gray birch and pin cherry.

not differ significantly among treatments ($P > 0.05$).

Projections and Financial Analysis

Most of the time invested in rehabilitation was spent on mechanical release; this took 17.8 and 40.1 hours acre^{-1} in the moderate and intensive treatments, respectively. Herbicide application took 1.3–1.4 hours acre^{-1} in both treatments, and planting added 8.8 hours acre^{-1} to the intensive treatment. On average, we spent 19.2 ± 4.8 and 50.2 ± 5.8 hours acre^{-1} applying the moderate and intensive treatments, respectively. This is reflected in the costs: labor was \$231 acre^{-1} in the moderate treatment and \$603 ac^{-1} in the intensive treatment. Total cost, including herbicide and fuel, was \$380 acre^{-1} in the moderate treatment and \$795 acre^{-1} in the intensive treatment.

Future value calculated from FVS-NE projections did not differ between treated and untreated stands and is greater than the compounded cost of moderate but not intensive rehabilitation (Figure 4). FVS-NE projections also suggested potential outcomes of rehabilitation with regard to softwood and hardwood composition (Figure 5). Both intensities of rehabilitation were projected to have a slightly greater proportion (i.e., about 5%) of softwoods than the control; this difference lasts about two decades after moderate rehabilitation but persists for the long-term after intensive rehabilitation.

Discussion

The negative effects of exploitative cutting, such as diameter-limit cutting or commercial clearcutting, have been established for a number of forest types through simulation (Nyland et al. 1993, Maguire 2005, Nyland 2005, Bohn et al. 2011), observation (Fajvan et al. 1998, Archambault et al. 2006), and experimentation (Hart 1964, Kenefic et al. 2005). These studies have shown that repeated applications of exploitative cutting result in stands dominated by poor-quality and low-vigor trees; such stands undergo compositional shifts toward less desirable and noncommercial species and are characterized by clumps and voids of vegetation resulting from the juxtaposition of under- and overstocked areas (Nyland 2006). Over the long-term, tree and stand commodity value is diminished relative to that of well-managed stands, and sustainability of production is jeopardized (Kenefic et al. 2005, Nyland 2005). Commercial operations may not be feasible for many years without steps to restore production potential (Kenefic and Nyland 2005, Nyland 2006).

The composition and structure of the area used for our rehabilitation experiment were characteristic of those described in earlier studies of degraded stands. Although MU22 had been a well-stocked, softwood-dominated stand in the 1950s, the study area predominantly comprised submerchantable hardwoods and fir in 2008. This finding is consistent with recent forest inventory data for the state of Maine (McCaskill et al. 2011), which show fir and red maple as two of the most abundant species statewide in terms of density of growing stock trees. Before our rehabilitation experiment, 12% of sapling BA was noncommercial species and 5% of overstory BA was cull. Most of the red maple were sprout origin and had been cut multiple times, resulting in clumps of poorly formed trees (Figure 2). Stocking of desirable regeneration was poor (e.g., 0% for spruce spp., 3% for pine spp., and 5% for hemlock). We also observed high variability in sapling plot-level BA, consistent with the under- and overstocked areas observed within exploitatively cut stands (Nyland 2006).

Variability in stand condition and limited potential of the growing stock constrained rehabilitation. There was insufficient volume for a merchantable harvest; treatments only reduced overstory BA by about 5 ft^2 $acre^{-1}$ (1 cord $acre^{-1}$). Crop tree release and TSI were primarily in the submerchantable classes, reducing sapling BA by 26–33%. A key characteristic of the treatments was within-stand variability per the heterogeneity of stand composition and structure (Figure 3). Release work, removal of UGS and noncommercial species, and fill planting were applied as needed within EUs, using a multiple treatment approach (e.g., Meek and Lussier 2008). Ideally, we would have selected softwood and hardwood crop trees at 15- and 25-ft spacing, respectively. Because the less shade-tolerant hardwoods were generally stratified above the slower-growing, more shade-tolerant softwoods, we did not constrain the location of crop trees in either species group by the other. This would have resulted in 190 and 70 softwood and hardwood crop trees $acre^{-1}$, respectively. However, because of the irregular spacing of potential crop trees, we averaged 27 and 56 softwood and hardwood crop trees $acre^{-1}$. This result reflects the patchy distribution of AGS in the study area. In addition, the need to include red maple sprout clumps among crop trees provides evidence of the constraints resulting from past exploitation of this previously softwood-dominated site. It suggests that rehabilitation may require retaining and releasing trees that would not normally be considered crop trees; this is consistent with recommendations by Nyland (2006) and Kenefic and Nyland (2005), who suggest that during rehabilitation of heavily cutover stands, managers may need to leave some marginal trees to provide intermediate revenues until better quality growing stock support more traditional treatments.

The need for rehabilitation treatments of this sort is not new but is rarely addressed explicitly in the literature. Much of the early Forest Service research in the Northeast addressed release of softwoods from overtopping hardwoods, as well as removal of cull trees and noncommercial species from cutover stands (Westveld 1928, 1930, 1933, 1937, Curry and Rushmore 1955, Rushmore 1956a, 1956b). The widely used regional northern hardwood silviculture guide includes general recommendations for managing understocked stands (Leak et al. 1987). However, there is merit in explicitly

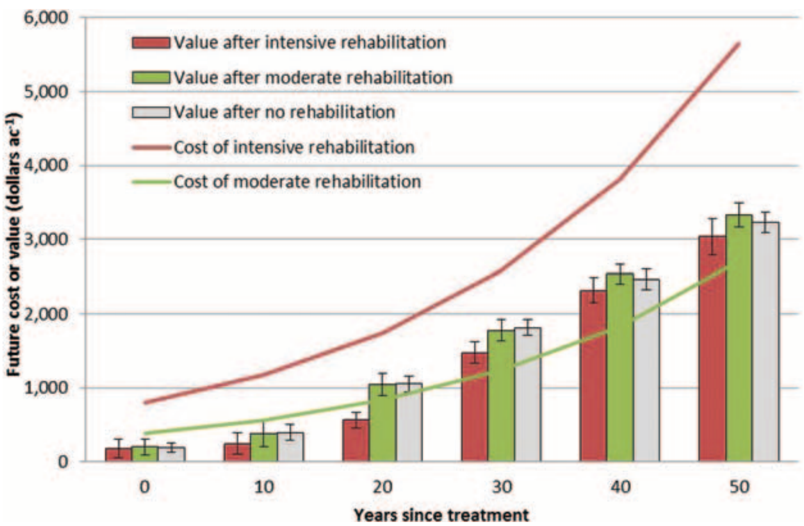

Figure 4. Values (0.75% real price increase) of projected stands following no, moderate, and intensive rehabilitation relative to compounded costs of treatments (4% real interest rate).

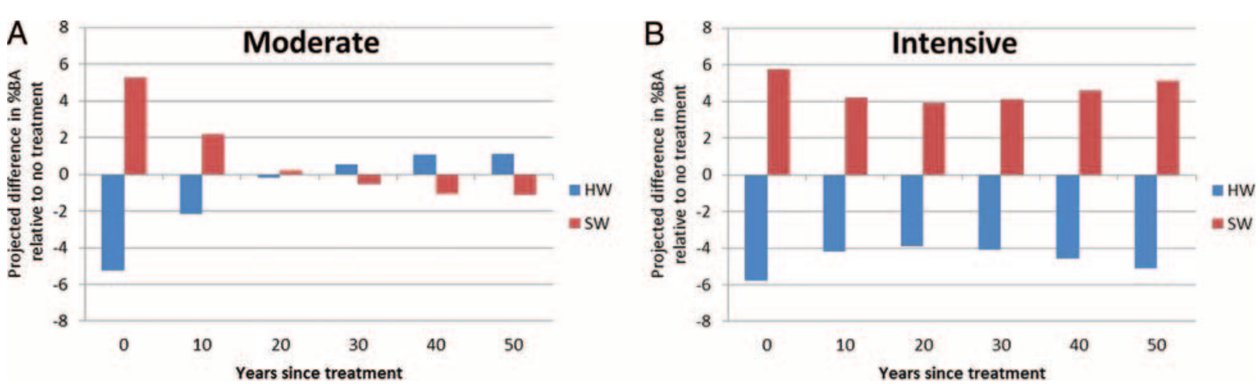

Figure 5. Projected future composition of the moderate (left) and intensive (right) rehabilitation treatments, expressed as the difference in percentage of softwood (SW) and hardwood (HW) basal area (BA, trees ≥0.5 in. dbh) between treated and untreated conditions.

recognizing rehabilitation as distinct from traditionally applied silviculture. Such treatments often require that the landowner invest in or accept no profit in the short-term and recognize that present harvest volumes will be low and of poor quality, and prescriptions must include options that differ from place to place within stands (e.g., Meek and Lussier 2008). Cutover stands like ours may not normally be considered operable, but their impoverished nature and the potential future benefit from intervention deserve consideration when one is determining whether or not and how to apply treatments (Kenefic and Nyland 2005, Nyland 2006).

Past cutting had depleted merchantable growing stock from our stands, necessitating investments without reimbursement from concurrent sale revenue. The objectives were to improve growth of AGS (crop trees) and increase the proportion of desirable species and stand value. Comparison of stand attributes after treatment confirm the short-term positive effects of rehabilitation on composition, crop tree growth, and quality. Relative to the control, rehabilitation resulted in less hardwood BA and fewer hardwood TPA among the saplings, lower amounts of noncommercial species, and lower proportions of cull. Simulations suggest slight long-term improvements in softwood to hardwood composition relative to that of the control; these are projected to last longer after intensive than moderate rehabilitation, probably because of the greater reduction in hardwood saplings in the former.

Rehabilitation had little effect on regeneration in the short-term. Spruce seedling stocking was higher in the intensive treatment because of fill planting, but more than one-third of planted seedlings died over the first 3 years and almost 90% of survivors were browsed. Browsing of spruce seedlings is common on the PEF and in nearby parts of Maine. A recent study found that 37% of spruce seedlings (from new germinants to $<$0.5 in. dbh) across the long-term silvicultural study on the PEF had been browsed (Berven 2011). This presents a challenge when objectives include increasing the abundance of desirable conifers, especially spruce, over the long-term. The planted seedlings may have been especially attractive as a food source because of supplemental fertilization in the nursery and the relative rarity of spruce in the regeneration stratum of our study area (Table 4). In addition, despite being set with stakes and replaced annually, the protective sleeves were displaced by frost heaving and snow, exposing the seedlings. Threats like these suggest that better means of protecting planted and naturally occurring seedlings are needed at localities with high populations of small browsing animals.

Although we detected few significant differences in immediate outcomes between moderate and intensive rehabilitation, remeasurements taken 3 years after treatment showed that overstory TPA was lower in the intensive treatment than in the control. There were no other differences in overstory stocking among treatments. We did not number trees on the overstory plots and cannot measure mortality or recruitment explicitly, but this result suggests reduced ingrowth from the sapling class in the intensive treatment. This would be more likely because the TPA of saplings was reduced by rehabilitation (Table 3).

Because we only have 3–4 years of data since the treatments were applied, our ability to evaluate growth response is limited. We did not find a treatment difference in periodic overstory BA increment; in the intensive treatment, better growth of residuals may be compensating for reduced ingrowth, as suggested by treatment differences in overstory TPA but not BA or BA increment. Crop tree growth, however, was greater in the moderate and intensive rehabilitation treatments than in the control. This is not surprising, because most crop trees were in previously overtopped classes and were released through treatment.

Precommercial rehabilitation as applied in this study took 19 hours $acre^{-1}$ for moderate treatment and 50 hours $acre^{-1}$ for intensive treatment, at a cost of \$380 and \$795 $acre^{-1}$, respectively (including herbicide and fuel). We used student laborers for mechanical release and planting. Production rates may have been lower than those of professional contractors, but this was compensated for to some extent by reduced hourly rates. Costs appear comparable to those for similar operational treatments in the region; Greene (2014) reported a cost of \$312 $acre^{-1}$ (not including fuel) for brushsaw release of 94 crop trees $acre^{-1}$ to a 7-ft radius in rehabilitation on land owned by the Great Pond Mountain Conservation Trust in Orland, Maine. Labor-only cost of CTR in our study (77–112 crop trees $acre^{-1}$ in moderate rehabilitation, including brushsaw removal of competing trees in an 8- to 12-ft radius, chainsaw removal of overtopping residuals, and herbicide treatment of red maple sprout clumps) was \$231 $acre^{-1}$.

The projected value of the treated stands did not differ from that of the control over the long-term. Although not rehabilitating is an option, early stand intervention is necessary in many degraded stands to restore production potential and shift management toward sustainable forestry practice. This may require that the landowner invest in the stands to allow for greater future options. To be cost neutral or generate a profit, the projected values of the treated stands must meet or exceed the compounded costs of treatment. Our simulations suggested that this will occur 10–20 years after moderate rehabilitation; the projected value did not exceed compounded costs (at a 4% interest rate) after intensive rehabilitation.

Recent work has demonstrated that FVS-NE is biased for managed stands within the Acadian forest type (Saunders et al. 2008, Bataineh et al. 2013, Russell et al. 2013); specifically, merchantable volume of managed stands may be underestimated (Saunders et al. 2008). Although constraints based on observed growth and mortality have been imposed on model outputs in other studies in this region (e.g., Saunders and Arsenault 2013), the unique nature of our treatments and lack of relevant long-term data sets precluded calibration. As a consequence, the potential benefits of rehabilitation relative to those of the control may be underestimated. In addition, although improvements in species composition, regeneration stocking, and cull are accounted for in the simulations and value calculations, accelerated growth of crop trees (observed over too short a time to be used in model calibration) and the increased proportion of AGS (i.e., quality improvements) are not. The latter may result in additional increases in value from rehabilitation. Nevertheless, because the compounded cost of intensive rehabilitation is almost twice the projected value, it is not likely that better growth of crop trees, reduction of UGS, and/or improved growth-model performance would make up the difference. Continued monitoring of the plots will clarify the matter.

Rehabilitation also affects the potential for application of and profit from other silvicultural treatments in the future. Improved species composition and enhanced growth will improve chances for later commercial thinning, whereas conditions in the untreated stands might not support those operations for a long time. Other long-term considerations such as species available for seed trees, seed-tree vigor, and abundance and distribution of advance regeneration at the time of the next regeneration cutting also deserve consideration, as do the potential ecological benefits of silvicultural treatments controlling species composition, stand structural conditions, and pattern of stand development (Carey 2006). Although benefits such as these are difficult to quantify, they represent potential improvements in the forest condition relative to that of a degraded stand. Whether these factors help compensate for the compounded costs of rehabilitation and especially those of intensive treatment remains unclear. Perhaps they help justify some level of rehabilitation, regardless of projected financial outcomes. Remeasurements of the PEF experiment may help to answer these questions in time.

Conclusion

The objective of this study was to evaluate alternative approaches to silvicultural rehabilitation in northern conifers degraded by exploitative cutting. The study area was representative of many stands in the region: dominated by fir, red maple, and low-value and noncommercial species, with a patchy distribution of growing stock, UGS, and insufficient regeneration and seed sources of desirable species. Short-term assessment of no, moderate, and intensive rehabilitation showed that rehabilitation decreased BA and TPA of sapling hardwoods, increased growth of crop trees, and decreased cull.

There were few differences between intensities of rehabilitation, although intensive treatment resulted in greater spruce seedling stocking and a projected longer-lasting increase in softwood composition. The values of the projected future condition after rehabilitation treatments were not differentiated from those after no treatment. However, the value of the projected future condition after intensive rehabilitation was less than the compounded cost of treatment, whereas that after moderate rehabilitation was greater than the cost. Limitations of the simulation model in accounting for increases in stem quality and more rapid growth of crop trees, as well as underlying problems with prediction of managed stands in this forest type, suggest that answers regarding financial aspects of the study await future remeasurement.

Regardless, the benefits of rehabilitation of softwoods and low-value hardwoods are unlikely to increase stand values sufficiently to compensate for the high cost of intensive rehabilitation, serving as a cautionary tale for those considering exploitative cutting of northern conifers. Those faced with stands already degraded have few management options. Some combination of the rehabilitation treatments presented here and steps to reduce costs (e.g., subsidies for small landowners and/or delaying treatment until stems are merchantable) may allow forest managers to restore composition and quality to degraded stands. Such efforts may provide values not well incorporated into financial analysis (e.g., aesthetics, recreation, wildlife habitat, or carbon sequestration) and facilitate later silvicultural treatments that might otherwise not be possible due to insufficient quantity or quality of AGS or desirable species. By creating conditions that give landowners more management options, rehabilitation serves as a mechanism to move a stand with a history of exploitative cutting toward sustainable forest management.

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