REHABILITATION OF POORLY STOCKED STANDS USING A MICROSTAND APPROACH

Jeffrey S. Ward

Abstract—Nearly one-quarter of upland oak forests in the Eastern United States are poorly stocked, often as the result of high-grading or repeated diameter-limit harvests. Returning poorly stocked stands to their economic and ecosystem services potential will require innovative rehabilitation practices that are cost-neutral at a minimum. One approach developed for northern hardwoods in Quebec was to recognize that poorly stocked stands are a conglomerate of stand types at the microstand scale (~0.1 acre) and to assign unique treatments to each microstand type. In 2012, we initiated research at five study areas in Connecticut to examine rehabilitation of poorly stocked stands. Rather than a single prescription for the entire stand, we used the decision tree approach to assign treatments at the microstand scale to account for the irregular, spatially patchy structure typical of high-graded stands. The treatment prescriptions incorporated earlier research showing that crop tree release can greatly increase diameter growth and survival, together with timber stand improvement, for the several microstand types commonly found in poorly stocked stands: poletimber, two-aged, sapling, or regeneration. On untreated control plots, 4-year basal area growth of unacceptable growing stock (UGS) was 60 percent greater than for acceptable growing stock (AGS). In contrast, AGS basal area growth was more than double that of UGS on treated plots. Crop tree release on treated plots increased 4-year diameter growth of sapling and pole crop trees, doubling growth of upland oaks. A microstand approach has potential where a commercial biomass market exists or for landowners cutting their own firewood.

INTRODUCTION

Across much of the 133 million acres of oak-hickory forest in the Eastern United States, poorly stocked stands are a common problem—occupying >32 million acres in the region (Miles 2018). In addition, there are another 57 million acres with medium stocking that are potentially one high-grade harvest away from becoming poorly stocked. Oak forests that are not fully stocked are especially at risk of "exploitive and unsustainable timber harvesting [high-grading]" that can create poorly stocked forests (Schuler and McGill 2007). Please note that descriptive terms for stocking levels in this paper follow Forest Inventory and Analysis standards (Arner and others 2003): poorly stocked (<35 percent stocking), medium stocked (35–59 percent), and fully stocked (60–99 percent). Poorly stocked stands are nearly synonymous with "degraded" stands as described by Clatterbuck (2006), and the terms will be used interchangeably throughout.

Poorly stocked stands rarely develop on publicly managed lands and other professionally managed forests except following severe weather, repeated defoliations, or wildfire. While the majority of privately owned, family forest land is held for non-financial amenities such as scenic beauty or protecting nature, there is a much higher risk of poorly stocked stands developing on family forests as the majority have not received professional consultation (Butler 2008). Recent studies have reported that 60 percent of harvests in Kentucky were high-grades (Stringer 2008), and high-grading was the most common practice in West Virginia (Fajvan and others 1998, Luppold and Alderman 2007). High-grading is also a problem in Massachusetts (Catanzaro and D'Amato 2006), Mississippi (Ezell 2011), Pennsylvania (Egan and others 2001), and New York (Munsell and others 2009, Tabolt and Smallidge 1999). Diameter-limit harvesting mandated by law in Ontario has led, in some cases, to high-graded stands (Schwan and Elliot 2010).

Hardwood silviculture demonstration plots established in the early 1950s suggested that diameter-limit cutting reduces the quality of trees in the residual stand, creates irregular stands that are logistically more difficult to manage, and increases the time between commercially feasible harvests (Blum and Filip 1963). These predictions have proven to be prescient. In West Virginia, 37 percent of poletimber trees were damaged following a 30-cm (12-inch) diameter-limit harvest (Fajvan and others

Author information: Jeffrey S. Ward, Chief Scientist, Department of Forestry and Horticulture, The Connecticut Agricultural Experiment Station, New Haven, CT 06504.

Citation for proceedings: Clark, Stacy L.; Schweitzer, Callie J., eds. 2019. Oak symposium: sustaining oak forests in the 21st century through science-based management. e-Gen. Tech. Rep. SRS-237. Asheville, NC: U.S. Department of Agriculture Forest Service, Southern Research Station. 192 p.

2002). Diameter-limit cutting increased 30-year volume growth for white oak poletimber, but development of persistent epicormic branches degraded log quality (Miller and others 2011). Repeated diameter-limit cutting lead to a decrease in the proportion of grade 1 buttlogs in West Virginia (Brown and others 2018).

Confirming the predictions of Blum and Filip (1963), it was reported that diameter-limit cutting "provides no control of spacing, and so results in a clumpy stand with clearcut and partially-cut areas interspersed with overly-dense areas" (Trimble 1971). Diameter-limit harvests resulted in an irregular stand structure of gaps and residual canopy (Grushecky and Fajvan 1999). The last prediction of Blum and Filip (1963) was that diameter-limit cuts would increase intervals between harvests. Nearly half of harvests were so heavy (i.e., high-grading) that no sawtimber harvests would be possible for decades in both West Virginia (Fajvan and others 1998) and upstate New York (Munsell and others 2009). There was insufficient volume for an economically viable harvest 14–17 years after an 11-inch high-grade cut in Connecticut (Ward and others 2005).

While there are suggested guidelines for rehabilitating poorly stocked stands, research has been limited to studies in southern pine and hardwoods in Arkansas (Baker and Shelton 1998, Montgomery and others 2006) and a recently begun study in mixed hardwood-conifer stands of northern Maine. Suggested approaches have focused on stand-level treatments, i.e., having a single prescription for an area several acres or larger (Clatterbuck 2006, Ezell 2011). This one-prescription-fits-all approach, unless the stand is uncharacteristically homogeneous for a poorly stocked stand, will result in inappropriate treatment for some of the stand and will likely be unacceptable to many landowners with <100 acres. A different approach is the innovative decision tree model developed for northern hardwoods in Quebec (Lussier and Meek 2014). Their method recognizes that a variety of silvicultural prescriptions will be required to optimally manage poorly stocked stands. The Canadian model evaluates microstands (0.03 ha, ~0.1 acre) and assigns each microstand to one of four microtypes. Each microtype is then assigned a unique prescription which is implemented by the harvester.

After myriad discussions with other foresters, a thorough literature search, and a half-day meeting with Connecticut Department of Energy and Environmental Protection – Division of Forestry field staff; the consensus was that most poorly stocked stands in southern New England had highly irregular structures that could be placed in four types at the microstand scale: (1) areas with sufficient poletimber (diameters ≥5 inches) to develop into a fully stocked stands, (2) areas with sufficient sapling density (diameters between 1–5 inches) of desirable species, (3) areas with some poletimber that could be developed into a two-aged stand, and (4) all other areas where regeneration should be released or initiated. This last microstand type includes a variety of initial conditions such as beech thickets or clumps of cull trees and is not covered in this paper. These observations suggested that a decision tree model might be appropriate for poorly stocked stands in the region (fig. 1). A combination of crop tree release (CTR) and timber stand improvement (TSI) could be used for the first three microstand conditions in the previous paragraph.

Earlier research has shown that for most species, CTR increases survival and diameter growth across a wide range of diameters (Miller and others 2007, Schuler 2006, Voorhis 1990, Ward 2017). Relative to area-wide thinning, the rationale for CTR is easy to explain as assisting selected trees to thrive and is straightforward to implement for family forest owners. This low-intensity, minimal- or no-cost approach could be implemented on family forests by owners harvesting firewood and, in some cases, removing cull trees and releasing a limited number of saplings to promote desired stems. Alternatively, it could be implemented on larger parcels by recognizing the effective work radius of mechanized harvesters in approximately 0.1 acre as has been done in Quebec (Lussier and Meek 2014). This system would eschew converting stands to a homogeneous standard, but recognize the high-graded stands are a heterogeneous mix of initial conditions, and would apply a set of criteria to create a stand with several distinct structures. In concept, the treated stand would be similar to a stand after several cutting cycles using small group selection.

The objective of this study was to evaluate the potential of a microstand approach to rehabilitate poorly stocked stands. Specific objectives were: (1) determine if this approach could be used to shift allocation of stand growth from low-value to high-value trees, and (2) examine whether the diameter-growth response to treatments differed among species.

METHODS

Study Areas

Five study areas were established in 2012 in poorly stocked stands in western and central Connecticut with low-quality trees (table 1). Two of the areas (Ehlich, Bass Road) had been high-graded before being donated to local land trusts. One area (Rebekah) had been high-graded during a temporary change in management oversight. Two areas were poorly stocked because of a predominance of low-quality red maple/dying ash (Bantam) or American beech (Guilford). Stand histories prior to high-grading were not known. To minimize risk of selecting target trees that would form epicormic branches following treatment, study areas were where the last harvest had been in 2006 or earlier.

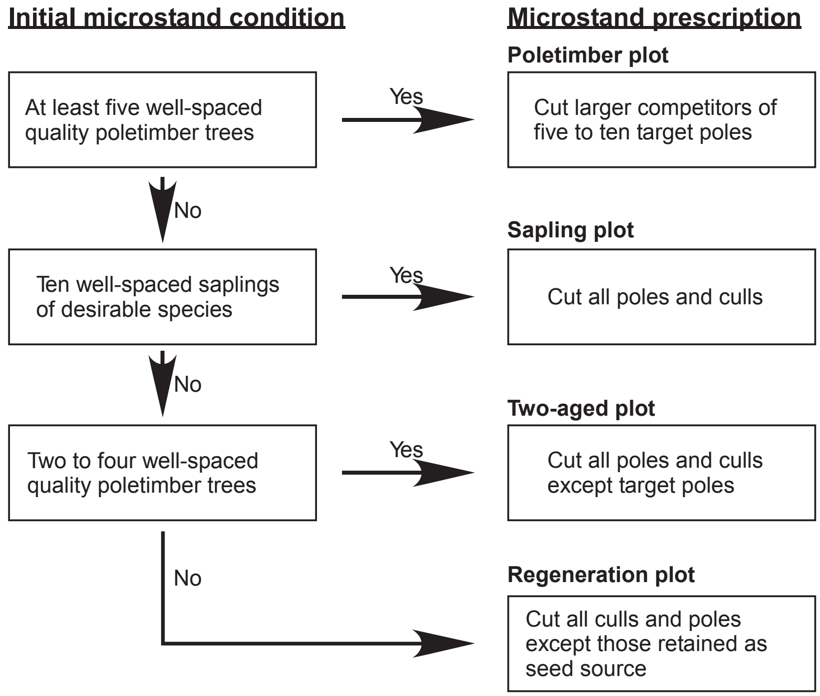

Figure1—Decision tree for microstand rehabilitation prescriptions of poorly stocked stands.

Table 1—Initial mean (standard error) tree characteristics by study area in a southern New England rehabilitation study

Study area	Diameter *inches*	Total height[a]	Pulpwood height[a]	Sawlog height[a]	Buttlog grade	Sample size AGS/UGS	Density (n/acre)
Poletimber (5.0–10.0-inch diameter)							
Ehlich	6.8 (0.2)	38.1 (1.1)	22.2 (1.2)	—	4.0 (0.1)	6/79	47.8
Guilford	7.5 (0.1)	53.8 (1.1)	33.0 (1.2)	—	3.4 (0.1)	33/95	71.9
Bass Road	7.4 (0.1)	52.4 (1.2)	29.9 (1.1)	—	3.7 (0.1)	31/105	76.4
Rebekah	7.5 (0.1)	52.5 (0.8)	31.6 (0.7)	—	3.7 (0.0)	90/272	130.8
Bantam	8.0 (0.2)	57.5 (1.6)	39.1 (1.5)	—	4.1 (0.1)	1/79	89.9
All poletimber	7.4 (0.1)	51.7 (0.5)	31.3 (0.5)	—	3.8 (0.0)	161/630	87.9
Sawtimber (≥10.6-inch diameter)							
Ehlich	15.8 (0.5)	73.7 (8.1)	53.4 (1.8)	29.8 (1.5)	3.7 (0.1)	12/53	36.5
Guilford	14.3 (0.3)	75.0 (1.2)	56.3 (1.1)	32.5 (1.0)	2.7 (0.1)	84/26	61.8
Bass Road	14.0 (0.4)	75.0 (1.3)	53.5 (1.1)	26.0 (1.1)	3.5 (0.1)	33/53	48.3
Rebekah	13.2 (0.2)	71.3 (1.0)	53.5 (0.9)	27.3 (0.8)	2.9 (0.1)	91/102	69.7
Bantam	13.8 (0.4)	72.8 (1.2)	54.1 (1.0)	22.9 (1.2)	3.9 (0.1)	2/64	74.2
All sawtimber	13.9 (0.1)	73.2 (1.1)	54.2 (0.5)	27.9 (0.5)	3.2 (0.1)	222/298	57.8
Combined	10.0 (0.1)	60.2 (0.6)	40.4 (0.5)	27.9 (0.3)	3.6 (0.0)	383/928	145.8

[a] Heights were measured to nearest foot.

Soils were stony to extremely stony, fine sandy loam Typic Dystrudepts and Oxyaquic Dystrudepts derived from gneiss, schist, and granite glacial melt-out and lodgment tills, respectively. Elevations ranged from 590 to 1050 feet above mean sea level. The area is in the northern temperate climate zone. Mean monthly temperature ranged from 27 °F in January to 73 °F in July with an average of 176 frost-free days per year. Average annual precipitation was 46 inches per year, evenly distributed over all months.

Experimental Design and Measurements

Study areas had nine (Bantam), eighteen (Guilford, Ehlich, Bass Road), or twenty-eight (Rebekah) 65.6- by 65.6-foot (~0.1 acre) plots. Except at Rebekah, plots were arranged in a 3- by 3-plot contiguous block to form a square, i.e., each 197- by 197-foot block had nine plots. Because high-grading at Rebekah was proximate to the network of permanent logging roads, there was a 2- by 5-block, a 3- by 3-block, and three 3- by 1-blocks. Within each plot, a tree identification number and diameter measurement height of all stems [diameter at breast height (DBH) >4.9 inches] were permanently marked with paint. Species, stem diameter (at 4.5 feet aboveground), and crown class were recorded for each tree. Each tree was also classified as acceptable growing stock (AGS) or unacceptable growing stock (UGS). While metric units were used for all field measurements, values reported here are in English units for analysis and to facilitate communication with target audiences of practicing foresters and landowners.

After initial measurements were completed, each plot was evaluated and categorized as one of four microstand classes based on initial conditions: poletimber, two-aged, sapling, or regeneration (fig. 1).

Poletimber plots had at least five well-spaced AGS poletimber trees – equivalent to a minimum of 50 trees per acre. Two-aged plots had two to four well-spaced AGS poletimber trees. Sapling plots had at least 10 well-spaced saplings (diameters between 0.8–4.9 inches) of desirable species (e.g., oak, white pine) with good form. The last microstand class, regeneration, did not have sufficient sapling or poles to create a fully stocked future stand.

After each plot was assigned to one of the four initial microstand classes, plots were randomly designated as either control (no management) or treated (active management) with two treated plots for every control. The four treatments applied differed by microstand class. On the poletimber plots, five to ten AGS poletimber trees (diameter >4.9 inches) on each plot were given a four-sided crown release (complete crop tree). The AGS poletimber trees in the two-aged plots were given a four-sided release, and any AGS saplings not in direct competition were also given a CTR. On the sapling plots, all poles were cut and the 10 sapling crop trees were given a four-sided release. For the regeneration plots, all poles except those retained as seed trees were cut to either release seedlings of desirable species (seedling) or to prepare site for planting (initiate). Results for the regeneration microstand plots are not reported here.

To simulate operational implementation in low-value stands, target and cut stems were not designated prior to actual treatment. As this was a research study with random treatment allocation, harvesters entered each plot knowing the prescription goal, but made their own determination as to which stems were crop trees following defined criteria (table 2). To ensure quality control of target stem selection, harvesters were guided

Table 2—Criteria for crop tree selection[a]

Species (in order of preference)
Oak, sugar maple, black cherry, eastern white pine, yellow-poplar, birch, hickory, red maple, aspen. Species preference will depend on site quality and landowner objectives, and requires judgment of an experienced forester.
Buttlog characteristics
Minimum height of 16 feet (5 m) to first major fork, no branches with diameters >2 inches (5 cm), no live epicormic branches, lean <10 percent, sweep <6 inches (15 cm), no crook, no more than one seam, no exposed wood (catface) wider than 2 inches, no cankers or gum. No seams or exposed wood was acceptable for red maple or aspen because these species poorly compartmentalize decay.
Crown characteristics
Live crown equal to a minimum of 30 percent of total height, crown dieback <20 percent, free-to-grow before or after release, no broken branches with diameters >5 inches, no major forks below 33 feet (10 m) with included bark, no persistent insect or disease. Presence of a fork below 33 feet that did not have included bark was acceptable fo saplings.

[a] Criteria for defining a quality crop tree will vary depending on landowner objectives, but will usually include the characteristics we selected.

by a licensed Connecticut Certified Forester. After cutting was completed, the degree of canopy openness for all residual stems was assessed by the number of sides free of competition. As is typical in high-graded and poorly stocked stands, many stems not intentionally released, even in untreated control plots, nevertheless had one or more sides free of competition from prior harvests. Diameters of all live trees were measured during the dormant season for the following 4 years. Mortality was also recorded when appropriate.

Data Analysis

Six species groups were included in the analysis: upland oaks (*Quercus rubra*, *Q. alba*, *Q. velutina*, *Q. coccinea*, *Q. montana*), maple (*Acer rubrum*, *A. saccharum*), birch (*Betula lenta, B. alleghaniensis*), hickory (*Carya* spp.), conifer (*Tsuga canadensis*, *Pinus strobus*), and other major species (*Fraxinus americana*, *Fagus americana*, *Tilia americana*, *Betula papyrifera*, *Prunus serotina*, *Ulmus americana*, *Ostrya virginiana*). Species are listed in the order of importance within each species group and species fewer than five stems are not listed. Species-specific stocking provided by each tree was determined following procedures in Arner and others (2003).

To determine effects of level of release on tree diameter growth, all crop trees were assigned a release class after treatment. Trees with three or four sides free of competition were classified as fully released, regardless if the release was from treatment during this study or from the prior high-grading. Trees with one or two sides free were classified as partially released and those with no sides free of competition were classified as not released.

Repeated measures analysis of variance (ANOVA) was used to examine basal area growth of AGS and UGS stems. Years since cutting was the within-subjects factor, with study area, microstand classification, and treatment as between-subject factors. Reported *P*-values are those after applying the conservative Greenhouse-Geisser Epsilon correction for deviations from compound symmetry, i.e., non-sphericity (Hand and Crowder 1996). To examine how treatments influenced AGS vs. UGS basal area growth, a multifactor ANOVA with study area, microstand classification, treatment, and crossed effects was used. While full models and subsets were examined, only the most parsimonious model with the lowest Akaike Information Criterion (AIC) is presented (Hosmer and others 2013). Tukey's HSD test was used to test differences of sprout heights among treatments. Differences were considered significant at $P < 0.05$.

For each species group, repeated measures ANOVA was used to examine treatment effects on 4-year diameter growth. Years since cutting was the within-subjects factor, with study area, release category, and AGS/UGS as between-subject factors. Reported *P*-values are those after applying the conservative Greenhouse-Geisser Epsilon correction for deviations from compound symmetry, i.e., non-sphericity (Hand and Crowder 1996). When repeated measures ANOVA indicated a factor effect, a multiway ANOVA was used to determine if cumulative diameter growth differed between factor levels. While full models and subsets were examined, only the most parsimonious model with the lowest AIC is presented (Hosmer and others 2013). Tukey's HSD test was used to test differences of sprout heights among treatments. Differences were considered significant at $P < 0.05$. The same procedures were used to examine influence of release on sapling diameter growth.

RESULTS AND DISCUSSION

Stand Response

As is typical of many high-graded stands, total stocking and stocking of AGS varied greatly at the microstand (~0.1 acre) scale (fig. 2). Unacceptable growing stock stocking was higher than AGS stocking on over 70 percent of plots examined. Two of the stands (Ehlich and Bantam) had no plots with medium AGS stocking or better, and Bass Road only had 22 percent of plots with medium AGS stocking. While stocking of AGS on the Rebekah and Guilford stands ranged from fully to poorly stocked, only 11 and 33 percent of plots, respectively, had full AGS stocking. Both stands had more plots with poor stocking of AGS than full stocking. We found stocking levels were highly irregular within these poorly stocked stands as has been reported in West Virginia (Grushecky and Fajvan 1999, Trimble 1971), New York (Nyland 2006), and Quebec (Lussier and Meek 2014). The patchy distribution of trees in poorly stocked stands, especially those that had been high-graded has long been recognized as an impediment to developing a stand prescription (Blum and Filip 1963).

The treatments prescribed to shift growth onto higher quality residual stems had an immediate impact on the relative proportion of UGS to AGS stocking (fig. 3). Unacceptable growing stock stems initially accounted for 50 percent or more of plot stocking, but only 29 and 22 percent after management implementation on the poletimber and two-aged plots, respectively. Treatment also reduced UGS basal area on sapling plots when trees competing with quality saplings were removed. It should be noted that some UGS stems that did not compete with crop trees were left to provide structure for wildlife per all landowner's objectives.

Unacceptable growing stock basal area growth was greater than for AGS on both poletimber and two-aged plots during the 4 years after initial treatment (table 3). In contrast, basal area growth of AGS was greater than for UGS on treated plots. In general, AGS basal area growth was constant for a given microstand class regardless of

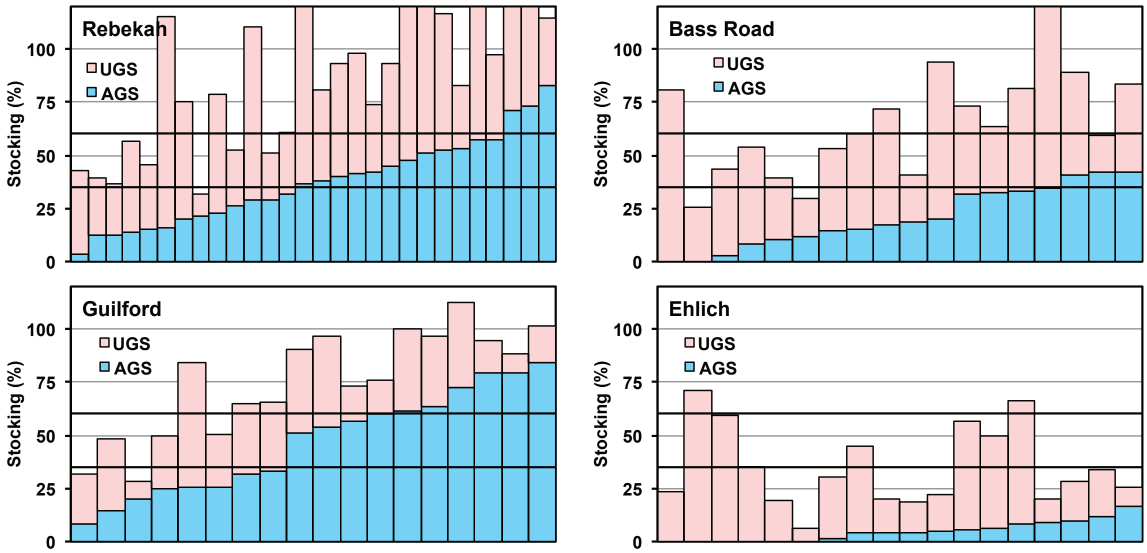

Figure 2—Stocking (percent) of acceptable growing stock (AGS) and unacceptable growing stock (UGS) among microstands (~0.1-acre plots) on study areas. Horizontal lines indicate minimal levels for medium-stocked (35 percent) and fully stocked (60 percent) stands. Values for Bantam are not shown as UGS stocking averaged 64 percent, seven plots had no AGS, one plot had 3 percent AGS stocking, and one plot had 11 percent AGS stocking.

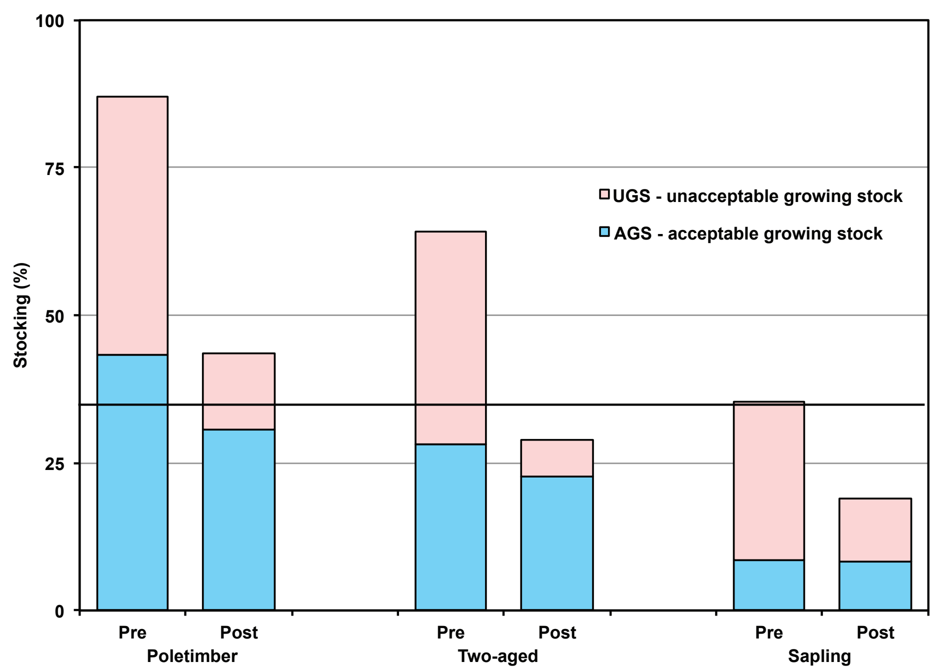

Figure 3—Mean initial (Pre) and post treatment (Post) stocking (percent) of acceptable growing stock (AGS) and unacceptable growing stock (UGS) by microstand classification.

Table 3—Mean (standard error) 4-year basal area growth (square feet per acre) of acceptable and unacceptable growing stock by microstand classification and subsequent treatment

Microstand type	Acceptable growing stock Mean (SE)[a]		N	Unacceptable growing stock Mean (SE)[a]		N	AGS/UGS *P*-value[b]
Two-aged (treated)	3.4 (1.3)	a	12	1.0 (1.0)	c	7	0.385
Two-aged (uncut control)	4.7 (1.4)	a	6	7.0 (1.0)	a	6	0.148
Poletimber (treated)	4.3 (1.2)	a	19	3.7 (0.8)	bc	18	0.594
Poletimber (uncut control)	3.8 (1.2)	a	11	4.3 (0.8)	ab	12	0.303
All plots (treated)	4.0 (0.5)	a	44	1.8 (0.6)	a	44	0.007
All plots (uncut control)	3.8 (0.7)	a	22	6.1 (0.6)	b	26	0.007

[a] Column values with same letter were not significantly different.
[b] AGS/UGS is P-value comparison within a row.

treatment, while UGS basal area growth was reduced following treatments that removed a large proportion of UGS stems.

Plots that had some residual basal area showed a dramatic shift in allocation of basal area growth from predominately on UGS stems on untreated plots to predominately on AGS stems on treated plots. A full-model repeated measures ANOVA indicated that AGS basal area growth over the 4-year period was independent of year × initial microstand classification (F = 0.26, d.f. = 4,168, P_{GG} = 0.667, where P_{GG} is after Greenhouse-Geisser Epsilon correction), year × treatment (F = 0.25, d.f. = 4,168, P_{GG} = 0.680), and year × microstand classification × treatment interactions (F = 0.91, d.f. = 4,168, P_{GG} = 0.367); i.e., AGS basal area growth did not differ among microstand classification, treatment, or their interactions. In contrast, UGS basal area growth was not independent of year × treatment (F = 8.99, d.f. = 4,148, P_{GG} <0.001) and year × microstand × treatment interactions (F = 4.85, d.f. = 4,148, P_{GG} = 0.016), but was independent of year × microstand classification (F = 0.60, d.f. = 4,148, P_{GG} = 0.518). Standard ANOVA found that UGS basal area growth did not differ between poletimber and two-aged microstands (F = 0.39, d.f. = 1,37, P = 0.534), but did differ by treatment (uncut vs. treated) (F = 10.3, d.f. = 1,37, P = 0.003) and microstand × treatment interaction (F = 7.26, d.f. = 2,37, P = 0.011). A parsimonious model without initial condition had a lower AIC_c, and least square means from that analysis are presented in table 3.

Surprisingly, there may be regional differences in the long-term response of stands to high-grading and diameter-limit cuts. Relative to uncut and shelterwood stands in Connecticut, 15-year volume growth after high-grade harvests was depressed by >80 percent, and most volume was on grade 3 or cull trees (Ward and others 2005). Because practically all residual AGS trees in a high-graded stand are small, as are most following a diameter-limit cut, it will probably be a couple of decades or longer before a commercial harvest is feasible in northern New England (Leak 1996).

In contrast, volume growth was higher with repeated diameter-limit harvest than uncut control over 50 years in West Virginia (Schuler 2004). However, it should be noted that many of the stands in that study were on relatively high site indices with cutting return intervals of 15 or 20 years (Schuler 2004). Good long-term growth was also reported after high-grading in another West Virginia study, but it was recommended that diameter-limit harvests be accompanied by improvement cutting and release of trees smaller than commercial thresholds (Smith and Lamson 1977); i.e., proactive rehabilitation conducted simultaneously with the harvest. Basal area growth following high-grading that included removal of cull trees averaged 2.3 square feet per acre per year in West Virginia, similar to growth rates following a 16-inch diameter cut (Hutnik 1958). A rehabilitation cut that removed UGS and cull trees doubled stand volume over an 8-year period in Illinois (Plass and Greth 1959).

Tree and Sapling Response

Unacceptable growing stock class trees predominated in both poletimber and sawtimber size classes, 80 and 57 percent, respectively (table 1). Buttlog grades were poor as would be expected in these stands, with poletimber trees having an average potential buttlog grade of 3.8 and sawtimber trees an average buttlog grade of 3.6. Unfortunately, diameter growth for both low-quality (UGS) and better quality (AGS) trees did not differ. Repeated measures ANOVA found 4-year diameter growth was independent of year × AGS/UGS classification for all species groups (P_{GG} = 0.054–0.859). Diameter growth was not independent of year × release class (none, partial, full) for any species group, ranging from $F = 4.2$, d.f. = 8,412, $P_{GG} = 0.023$ for conifers to $F = 18.0$, d.f. = 8,564, $P_{GG} < 0.0001$ for birches. Two-factor ANOVA (study area, release class) indicated that fully released trees grew faster than those not released, except for the other species group (table 4). Full release more than doubled diameter growth of oaks, maples, and conifers. Partial release increased mean diameters of all species groups except hickory.

Sapling diameter growth was improved by full canopy release for the three species groups examined (table 5). Repeated measures ANOVA found 4-year diameter growth of oak saplings was independent of year × initial crown class ($F = 1.6$, d.f. = 3,96, $P_{GG} = 0.216$), but not year × release ($F = 6.9$, d.f. = 3,96, $P_{GG} = 0.002$). Four-year diameter growth of white pine ($F = 40.9$, d.f. = 3,111, $P_{GG} < 0.001$) and birch saplings ($F = 17.2$, d.f. = 3,261, $P_{GG} < 0.001$) was not independent of year × release. Two-factor ANOVA (initial crown class, release class) indicated that fully released trees grew faster than those not released for all species. Diameter growth of white pine and birch, but not oak, was greater for saplings that were initially in the upper canopy than for intermediate saplings.

The positive response of both trees and saplings to CTR on poorly stocked stands suggests that forest managers and landowners can shift growth onto stems that have the potential to develop into quality trees. Prior crop tree research examined the response of trees in even-aged stands and focused on releasing higher quality stems. While unknown, it is probable that a large proportion of residual trees on the high-graded study areas were weak codominants or in the intermediate crown class prior to harvest. The increased diameter growth exhibited by all species following CTR suggests lower canopy trees have not necessarily stagnated, but can respond to release. Overtopped white oaks released from competition by a diameter-limit harvest and removal of adjacent trees grew 80 percent more over 30 years than similar trees in an adjacent uncut stand (Miller and others 2011).

At least 10 years will be required to determine if these treatments resulted in a permanent increase of stand growth allocated to AGS without causing a loss of buttlog grade due to increased epicormic branching on released trees (Miller and others 2011) or development of large branches of the buttlog of saplings. The UGS trees that we left for wildlife habitat or as a seed source on sapling and regeneration microstands will have to be carried through until at least the first commercial thinning to avoid damaging the smaller cohort during logging. The UGS trees we left, primarily white pine and birch, typically do not develop wide-spreading crowns.

Table 4—Mean (standard error) 4-year diameter growth (inches) of trees (>4.9 inches in diameter) by degree of tree crown release: non-competitive crowns on all four sides, partial-competitive crowns on two or three sides, full-crown free of competition on three or four sides

		------------------Release classification------------------						
Species group	*P*-value[a]	None		Partial		Full		N
Oak	<0.001	0.53 (0.02)	a	0.84 (0.02)	b	1.08 (0.02)	c	141
Hickory	0.004	0.46 (0.02)	a	0.53 (0.03)	a	0.75 (0.02)	b	64
Maple	<0.001	0.37 (0.02)	a	0.69 (0.02)	b	0.99 (0.03)	c	198
Birch	<0.001	0.65 (0.03)	a	0.86 (0.02)	b	1.20 (0.03)	c	147
Conifer	0.002	0.47 (0.04)	a	0.70 (0.03)	b	1.05 (0.05)	b	108
Other	<0.001	0.52 (0.02)	a	0.85 (0.03)	b	0.60 (0.03)	ab	106

[a] Row values with the same letter were not significantly different.

Table 5—Mean (standard error) 4-year diameter growth (inches) of saplings (diameters between 0.8 and 4.9 inches) by whether stems had full or no canopy release from other saplings

		--------------Canopy release---------------				Sample size	
Species	*P*-value[a]	None		Full		None	Full
Oak	0.001	0.31 (0.15)	a	0.95 (0.10)	b	11	24
White pine	<0.001	1.14 (0.12)	a	1.59 (0.12)	b	13	28
Birch	<0.001	0.92 (0.10)	a	1.39 (0.06)	b	24	66

[a] Row values with the same letter were not significantly different.

Therefore, it is unknown if the residual UGS trees will suppress sapling growth as was observed with oak reserve trees in West Virginia (Miller and others 2006).

The extensive expanse of poorly stocked or potentially poorly stocked forests in the Eastern United States has serious ramifications on the ability of forests to provide critical economic and ecological services. While there are sound silvicultural and practical administrative reasons for treating a poorly stocked stand as one unit, any recommendation to initiate a regeneration cut by removing all larger stems is unlikely to be implemented on a significant proportion of many family forests – the very forests that are most susceptible to high-grading disguised as a diameter-limit or 'selection' harvest. This study suggests that the microstand approach developed in Quebec by Lussier and Meek (2014) may be a practicable in poorly stocked stands in southern New England and probably throughout much of eastern hardwood forest when prescriptions are tailored to local species and stand conditions.

ACKNOWLEDGMENTS

We would like to thank technicians J.P. Barsky and M.R. Short and seasonals J. Cantoni, A. Massa, G. Cerne, A. Ellison, K. Nagy, and A. Simpson for their help with plot establishment and data collection. This research was made possible with in-kind help provided by Town of Guilford; Rebekah's Hill Flora and Fauna Preservation Society, LLC; Weantinoge Heritage Land Trust, Inc.; the White Memorial Foundation; and the Winchester Land Trust. This material is based upon work that was supported by the National Institute of Food and Agriculture, McIntire-Stennis Project CONH-578 (Accession No. 229098).

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