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Decision Support Tools to Inform the Rehabilitation and Management of High Graded Forests

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Abstract

Numerous forests in the eastern United States have been degraded due to past exploitative timber harvesting known as high grading. High graded forest stands may not improve without active rehabilitation and may require targeted silvicultural treatments. This study focuses on high graded mixed-oak (mixed-*Quercus* spp.) stands and aims to develop a model that can identify past high grading and to determine modifications that may improve forest management recommendations provided by the prominent decision support tool, SILVAH. We present a model that uses standard forest inventory measurements and does not require knowledge of preharvest stand conditions to predict with moderate to high accuracy whether a stand was high graded, which could be particularly useful for nonindustrial private forests. Results indicate that modifications to SILVAH may be necessary to improve its utility for prescribing silvicultural treatments in high graded stands.

Study Implications: High graded forest stands are often not readily apparent and likely require specific forest management practices. We present a tool that uses standard forest inventory measurements to predict past high grading, which can be used to inform and prioritize forest management decisions. We also present suggested modifications to the prominent decision support tool, SILVAH, that may improve its ability to prescribe optimal silvicultural treatments for high graded stands. Results from this study provide forestry professionals/landowners working in the mixed-oak forests of the northeastern United States with tools to inform forest management decisions that aim to return degraded stands to healthier and more productive states.

Keywords: high grading, mixed-oak, mixed-hardwood, forest degradation, SILVAH

The extensive forests of the eastern United States have a long history of timber harvesting since European settlement. Although timber harvesting practices after European settlement varied through time and by region, exploitative timber harvesting practices were commonly used (Kelty and D'Amato 2006). High grading is a form of partial harvesting that involves the selective removal of the largest and most economically valuable trees (Deal 2018) and does not consider the future forest. This harvesting practice persists as one of the most common exploitative methods of harvesting timber in eastern forests (e.g., Fajvan et al. 1998, Nyland 2000, Belair and Ducey 2018) and on nonindustrial private forests (NIPF) of the eastern US (e.g., McGill et al. 2006, Metcalf et al. 2012). High grading includes practices such as diameter-limit cutting and select/selective cutting, as these harvests commonly result in residual forest conditions similar to those created by high grading (Ward et al. 2005, Kenefic and Nyland 2006, Coufal et al. 2010). Although the impact of high grading on residual forest conditions depends on initial forest conditions such as tree species composition, amount of basal area removed (e.g., diameter limit used), and number of successive high grade timber harvests, results tend to be an increased relative abundance of unhealthy and poorly formed trees (e.g., Fajvan et al. 2002, Ward et al. 2005, Brown et al. 2018, Curtze 2021), old and small-diameter trees (Curtze 2021), and less desirable overstory tree species (e.g., Heiligmann and Ward 1993, Fajvan et al. 1998, Ward et al. 2005, Curtze 2021). High graded stands can also exhibit more irregular spatial distributions and variable basal area per acre of overstory trees than stands that have received certain silvicultural treatments (Grushecky and Fajvan 1999, Bohn 2005), which may consequently affect the spatial distribution of tree regeneration (Nyland 2006, Deluca et al. 2009). These residual characteristics of high graded stands have the potential to limit forest management options (Nyland 2006, Lussier and Meek 2014) and may hamper the ability of forests to continually supply valuable wood products (Castle et al. 2017, 2018) and provide ecosystem services such as carbon sequestration (Curtze 2021) and habitat for specific wildlife species.

High graded stands may benefit from active silvicultural rehabilitation treatments. Without active management, high graded stands are less likely to improve through time because growth is primarily focused on unhealthy and poorly formed trees, old and small-diameter trees, trees of less desirable species, and trees of poorer genetics (Hawley et al. 2005, Clatterbuck 2006, Nyland 2006). Evidence from rehabilitation treatments in diameter-limit cuts and commercial clearcuts (i.e., stands wherein all merchantable stems were harvested; see Puhlick et al. 2019), indicate that active rehabilitation can increase the relative abundance of desirable tree species and of trees with good form and health as well as increase diameter growth of crop trees (e.g., Bédard et al. 2014, Kenefic et al. 2014, Puhlick et al. 2019). Thus, rehabilitation shows promise for helping to ensure that eastern forests continue to supply people with ecosystem services, abundant wildlife, and valuable wood products.

The ability to quantitatively identify past high grading is a critical first step to inform the selection of rehabilitation treatments, prioritize silvicultural investments at landscape and regional levels (e.g., state-level organizations), quantify the pervasiveness of high grading at regional levels, and potentially inform policy. Published classification charts that use pre- and post-harvest inventory data to classify the type of timber harvest have been used to bring attention to the ubiquity of nonsilvicultural partial cuts in eastern forests (Fajvan et al. 1998, Belair and Ducey 2018). However, the use of these classification charts is limited to stands that have records on preharvest stand conditions or recently harvested stands wherein preharvest stand conditions can be recreated using stumps. Thus, models that can aid in the identification of past high grading and that do not require detailed knowledge of preharvest stand conditions are particularly important for the management of high graded stands and for enhancing awareness of how prevalent high grading is. This could be particularly useful in NIPFs and family forests because the management history of these forests is likely obscured due to (1) timber harvesting shortly before ownership transfers (Metcalf et al. 2012), (2) short forestland ownership periods (17–23 years on average, Butler and Ma 2011, Caron et al. 2012), (3) frequent lack of forest management plans (Caron et al. 2012, Metcalf et al. 2012), and (4) parcelization (Butler and Ma 2011). Consequently, forest management activities on NIPFs and family forests may not be documented in detail or successfully transferred to the current landowner. Therefore, there is a need to be able to objectively identify past high grading without detailed knowledge of preharvest stand conditions.

After a stand has been recognized as high graded, decision support tools to guide management are critical because they provide objective and systematic evidence-based management recommendations by using quantitative thresholds that are based on ecological and societal criteria (Martin et al. 2009, Addison et al. 2016, Cook et al. 2016). They have been shown to be effective in the conservation field (Martin et al. 2009, Addison et al. 2016, Cook et al. 2016) and their application may increase the likelihood of successful forest rehabilitation. As an example, one prominent decision support tool in eastern North America, the Silviculture of Allegheny Hardwoods (SILVAH; Marquis et al. 1992, Brose et al. 2008), provides objective and consistent silvicultural prescriptions that are based on decades of forestry research (Stout and Brose 2014). The foundation of the SILVAH decision-making process is a series of decision charts comprising multiple dichotomous decision nodes. At each decision node, stand summary values (e.g., regeneration abundance, density of overstory trees) are compared to ecologically-based thresholds to arrive at a silvicultural prescription. Since its inception in Pennsylvania roughly 40 years ago, SILVAH has gained in popularity in eastern North America and is used by various organizations such as the Pennsylvania Department of Conservation and Natural Resources Bureau of Forestry (BoF), Pennsylvania Game Commission (PGC), and the US Department of Agriculture Natural Resources Conservation Service's (NRCS) Working Lands for Wildlife (WLFW) and Regional Conservation Partnership Program (RCPP) to guide forest management activities.

Although SILVAH is a popular decision support tool in eastern North America, its use may be limited in high graded stands because they were not specifically considered during the development of the tool (see Stout and Brose 2014). As such, it is unclear whether SILVAH can recognize high graded stands and provide optimal management recommendations that account for their unique characteristics. Given the extensive usage of SILVAH to guide forest management activities and the prevalence of high graded stands, an assessment of its recommendations in these situations is warranted.

The objectives of this study were to (1) develop a model that can quantitatively identify, without knowledge of preharvest stand conditions, whether a mixed-oak (mixed-*Quercus* spp.) stand was high graded, (2) provide an example of how the classification model can be applied to aid forest management, and (3) evaluate management prescriptions for high graded mixed-oak stands provided by the decision support tool, SILVAH for oak stands, and identify potential areas of improvement. Focusing on the mixed-oak forests of Pennsylvania, we selected stands that received a high grade timber harvest and stands that received the establishment cut of a shelterwood regeneration sequence. The establishment cut of a shelterwood regeneration sequence was selected to serve as a comparison silvicultural treatment because this practice is commonly used as an initial entry to regenerate mature mixed-oak stands in the eastern US (e.g., Loftis 1990, Brose et al. 2008). The establishment cut of a shelterwood regeneration sequence can be confused with high graded stands by landowners that may have limited forestry backgrounds because these timber harvests leave similar amounts of residual basal area. Our ultimate goal is to increase the set of tools available to aid in the rehabilitation of high graded mixed-oak stands.

Methods

Description and Selection of Study Sites

To address the objectives of our study, we used three datasets. The first dataset includes eighteen stands for which we conducted forest inventories in 2019 ("base sample" hereafter). The second dataset includes the base sample plus an additional ten stands provided by the BoF and WLFW program for a total of twenty-eight stands ("augmented sample" hereafter). The third dataset includes one hundred NIPF stands that were inventoried following SILVAH protocols (Brose et al. 2008) for consideration as a WLFW project ("demonstration sample" hereafter). We used the augmented sample to develop the classification model (objective 1), the demonstration sample to show the applicability of the classification model (objective 2), and the base sample to evaluate SILVAH prescriptions (objective 3).

For the base sample, we selected nine stands that were reported by the current landowner or forest manager to have been high graded 8 to 15 years ago (hereafter "high graded stands"). For comparison, we selected nine stands that were reported by the BoF or PGC to have received the establishment cut ("first removal cut" in SILVAH's terminology for oak stands) of a uniform shelterwood regeneration sequence 4 to 10 years ago (hereafter "shelterwood stands"). All of the shelterwood stands were mixed-oak, whereas the high graded stands were either currently mixed-oak stands or stands surmised to have been mixed-oak prior to the most recent high grade timber harvest. To surmise the preharvest forest type of the high graded stands, we assessed the species of stumps, asked the landowner or forest manager about their recollection of preharvest species composition, and assessed the species composition of adjacent unharvested forests of similar topographic position and aspect. Due to sample size constraints, we restricted the selection of high graded stands to those with areas of at least 4.05 ha (10 ac) and those with a total basal area (BA) of roughly 12.6 to 27.5 m^2/ha (55 to 120 ft^2/ac) for all living stems ≥ 12.7 cm (5 in.) in diameter at breast height (dbh, measured at 1.37 m [4.5 ft] from the ground) at the time of this study's measurements to exclude very intense (e.g., approaching commercial clearcuts) and very light high grade timber harvests. Including more atypical cases would have required a much larger sample size due to increased variation. We selected shelterwood stands that fell within the same stand area and BA range as the high graded stands at the time of this study's measurement. We avoided stands that received a salvage timber harvest due to mortality from *Lymantria dispar.* The base sample provided a detailed assessment of stand conditions, especially for the understory vegetation, which was needed for evaluating the management prescriptions provided by SILVAH and for identifying potential areas of improvement.

To augment the base sample, we selected three high graded and seven shelterwood stands that satisfied the same criteria used to select base sample stands. Data for these stands were operational (i.e., collected by foresters to inform management) and allowed for calculation of stand level variables. This resulted in twelve high graded and sixteen shelterwood stands in the augmented sample. Overstory summary statistics and locations of the stands for the base and augmented samples are presented in Table 1 and Figure 1, respectively.

The demonstration sample was obtained from a total of 233 available NIPF stands using the following criteria: (1) forest type was mixed-oak or transition (i.e., stands that include a mixture of mixed-oak and northern hardwood species) based on Knopp and Stout (2014), (2) total BA fell within the BA range that was used to select the base and augmented samples, and (3) stand inventory used the number of plots recommended by SILVAH for a given area (see Brose et al. 2008). We specified the forest type and BA criteria to ensure that the classified stands conformed to the conditions under which the classification model was built. We specified the number of plots criterion to ensure that the estimated inventory statistics were based on an adequate sample size to provide reliable estimates. A summary of overstory characteristics for the demonstration sample is presented in Table 1.

Field Data Collection

Base Sample

Because the base sample was used to assess SILVAH prescriptions, we followed the SILVAH inventory protocols described in Brose et al. (2008) for field data collection. We collected data on the overstory trees, tree regeneration, and interfering vegetation using nested, circular fixed-area plots that were systematically located throughout the stands using ArcGIS 10.6 (ESRI 2017). The number of regeneration plots were allocated at a rate of twenty plots for the first 4.05 ha (10 ac) and then two additional plots for every additional 2.02 ha (5 ac) over 4.05 ha (10 ac). Overstory plots were allocated at half the rate of the regeneration plots. Supplementary Table S1.1 includes all species recorded in the overstory and regeneration plots and which species we considered desirable.

To inventory the overstory trees, we measured all living trees ≥ 12.7 cm (5 in.) dbh in 405 m^2 plots (0.1 ac) in each stand. In each plot, we recorded tree species, dbh, and tree quality. Tree quality was assessed by classifying each tree as acceptable growing stock (AGSspp) or unacceptable growing stock (UGS). A tree qualified as AGSspp if it is healthy enough to live for another 15 years, of good form (e.g., straight stem) such that it currently can (or will in the future) produce salable wood products (i.e., will produce at least one 2.44 m [8 ft] log meeting minimum requirements for sawtimber), and a desirable species (Brose et al. 2008). We measured all living trees between 2.5 to 12.6 cm (1 to 4.9 in.) dbh in 40.5 m^2 (0.01 ac)

Table 1. Descriptive summary of overstory characteristics (stems ≥ 12.7 cm dbh) for the base sample (n = 18 stands), augmented sample (n = 28 stands), and demonstration sample (n = 100 stands). Values represent means (standard deviation in parentheses).

	Number of stands	Basal area (m^2/ha)		Trees per hectare		Area (ha)
		All species	Oaks	All species	Oaks	
Base sample						
High graded stands	9	19.2 (3.9)	7.3 (4.4)	378.4 (83.9)	109.5 (75.4)	10.8 (3.9)
Shelterwood stands	9	19.4 (6.4)	15.4 (5)	144.3 (65.1)	83.1 (36.5)	12.1 (4.7)
Augmented sample						
High graded stands	12	19.7 (3.5)	7.6 (3.9)	386.6 (79.7)	120.4 (78.2)	9.9 (4.1)
Shelterwood stands	16	19.6 (5.2)	15.7 (4.5)	171.9 (67.2)	109.4 (46.7)	13.5 (4.3)
Demonstration sample						
All stands	100	20.5 (3.7)	11.5 (5.1)	412.4 (105.1)	181 (107)	8.4 (5.3)

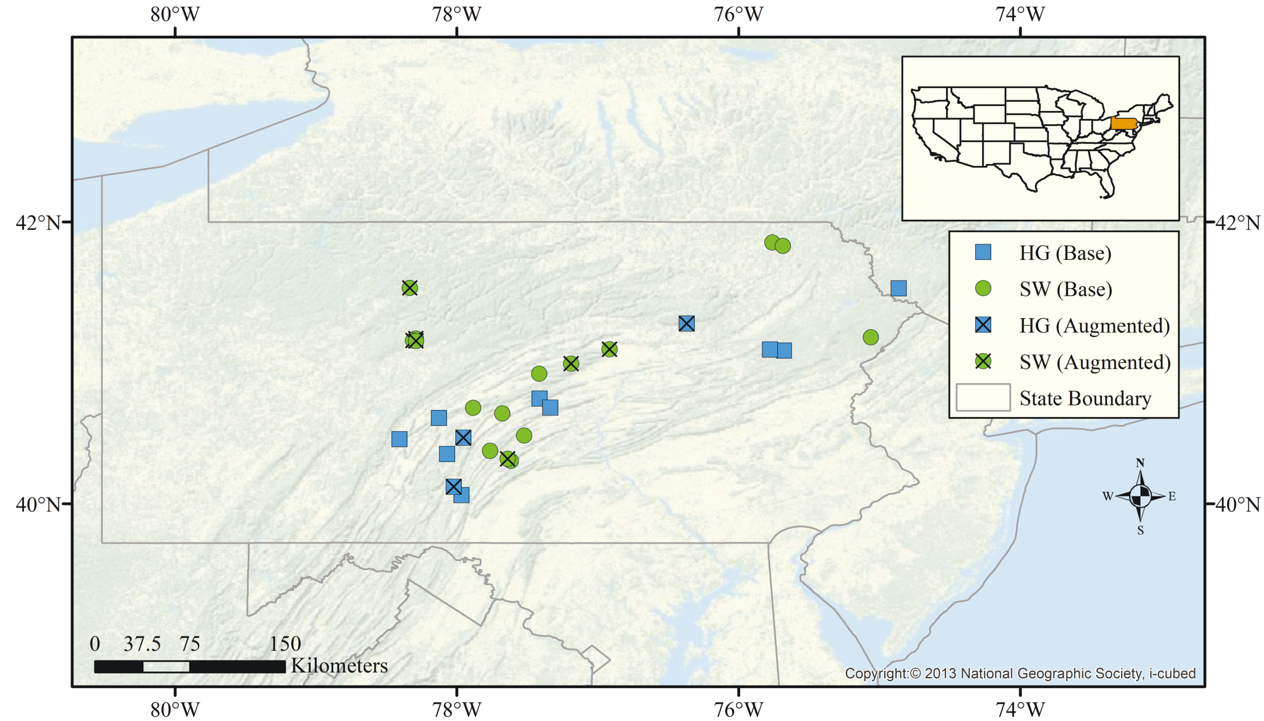


Figure 1. Geographic location of high graded (blue squares) and shelterwood (green circles) stands for the base sample and additional stands in the augmented sample (HG = high graded stand and SW = shelterwood stand). Locations have been slightly shifted in random directions to preserve landowner privacy.

plots in each stand. In each plot, we recorded tree species and dbh and classified all stems as AGSspp unless the tree was an undesirable species (Supplementary Table S1.1).

To inventory tree regeneration, we recorded all seedlings ≥ 5.1 cm (2 in.) tall and < 2.5 cm (1 in.) dbh by species using 10.5 m^2 (6-foot radius) circular fixed-area plots. Seedlings were then divided into height classes as required to run SILVAH. For oak seedling stump sprouts, we recorded up to three stems in the sprouting cluster. For any undesirable or poorly formed desirable tree or shrub over 1.83 m tall (6 ft), we recorded the species that interfered the most with desirable tree regeneration following SILVAH protocols ("tall woody interference" in Brose et al. 2008).

To measure interfering vegetation, we visually estimated the percent cover of competing low woody vegetation (i.e., shrubs and undesirable trees less than 1.83 m [6 ft] tall and any foliage from taller trees that was also present within this layer) and recorded the dominant species, fern, and grass and sedges using 197.3 m^2 (26-foot radius) circular fixed-area plots. We also recorded the number of grapevines present in the plot and whether there were signs of poor drainage, thin or rocky soil, or a thick organic layer in the plot (Brose et al. 2008).

Augmented Sample

Inventory data collected to support forest management activities ("operational inventory data" hereafter) for the additional stands in the augmented sample (n = 10), were provided by the BoF and WLFW. The data were collected using standard SILVAH protocols similar to those described for the base sample. An average of eighteen (range: ten to thirty-one) overstory and thirty-three (range: twenty-one to fifty) regeneration plots were used to inventory the seven shelterwood stands, while an average of eleven (range: ten to fourteen) overstory and twenty-two (range: nineteen to twenty-eight) regeneration plots were used to inventory the three high graded stands.

Demonstration Sample

Operational inventory data for the demonstration sample were provided by WLFW. The data were collected by partner foresters using standard SILVAH protocols similar to those described for the base sample. An average of thirteen (range: nine to twenty-five) overstory and twenty-five (range: nineteen to forty-nine) regeneration inventory plots were used to inventory the one hundred sample stands.

Data Analyses

Classification Model Development

We developed the classification model using the augmented sample and Random Forests (RF), a machine learning algorithm useful for classifying large amounts of data accurately (Breiman 2001). An RF model is composed of numerous decision trees, each of which predicts the group to which an observation belongs. The goal of this modeling was to create a RF model that can predict whether a stand was high graded based on forest attributes. To develop the RF model, we used variables that have been found to characterize high graded stands in previous studies (e.g., Curtze 2021, listed in Table 2) and selected which of these variables to include in the final classification model using standard variable selection procedures for RF models. A detailed description of the development of the RF model is presented in Supplementary Text S2.1.

Application of the Classification Model

One of the benefits of RF models is that they are comprised of numerous, unique decision trees (1,000 decision trees in our case). Each decision tree predicts a group (either high graded or shelterwood stand in our case). The predictions of all decision trees are combined, and the RF model prediction is that made by the majority of the decision trees (i.e., the group predicted by the majority of decision trees). This framework provides users with a measure of support for a particular classification. For example, an RF model prediction wherein 450 of 500 decision trees (90%) classify the stand as high graded provides much stronger support that the stand was high graded than an RF model prediction wherein 251 of the 500 decision trees (50.2%) classify the stand as high graded. Although in both instances, the majority of decision trees support the final classification of high graded stand, the former classification (i.e., 450 of 500 decision trees classifying the stand as high graded) indicates that the stand exhibits more attributes characteristic of high graded stands than the latter classification. For each of the WLFW stands in the demonstration sample, we used the RF model to predict the past management type (high graded or shelterwood stand) and used the percentage of decision trees classifying the stand as high graded to place the stands into four predicted past management groups (Table 3) according to the level of support (i.e., reflected by the percentage of decisions trees classifying the stand as high graded) for a classification of high graded stand. To inform thresholds between these four predicted past management groups, we used the range of the percentage of decision trees classifying the stand as high graded for the correctly and incorrectly classified high graded and shelterwood stands from the twenty-eight augmented sample stands used to develop the RF model.

Evaluation of SILVAH Prescriptions

SILVAH can be used in two ways to arrive at a silvicultural prescription: (1) the computer program calculates stand summary values and returns a prescription, or (2) the user obtains stand summary values from the SILVAH program and manually navigates the decision charts to arrive at a prescription. To evaluate SILVAH prescriptions, we manually navigated the SILVAH version 7.0.4.5 decision charts for the eighteen stands in the base sample.

SILVAH takes different paths through the decision charts depending on (1) the goal or intention for the stand, and (2) the desired future forest type, set by the user. The goal or intention for the stand includes options to begin regenerating the stand using even-aged silviculture (i.e., “Create a New Stand”, charts D to K), improve an existing stand through thinning (i.e., “Improve Existing Stand”, chart C), or improve and regenerate the stand using uneven-aged silviculture (i.e., “Improve and Create”, chart B). When the user would like to begin regenerating the stand (i.e., “Create a New Stand”), SILVAH follows different paths depending on whether the desired future forest type is a mesic/mixed-oak type (“mixed-oak” hereafter, charts F to K) or an

Table 2. Description of variables used in the development of the classification model. All variables except for the CV desirable regen and CV sawtimber BA include all stems ≥ 12.7 cm dbh.

Variable name	Description
CV desirable regen	Coefficient of variation (CV) of plot-level estimates for desirable seedling density (seedlings ≥ 5.1 cm tall and < 2.5 cm dbh)
CV sawtimber BA	CV of plot-level BA estimates for sawtimber-sized trees (stems ≥ 29.2 cm dbh)
CV total BA	CV of plot-level BA estimates for all stems ≥ 12.7 cm dbh
DRatio	Stand-level median tree dbh divided by stand-level mean tree dbh
PropAGSspp	Proportion of total stand-level BA classified as acceptable growing stock (AGSspp)
PropOak	Proportion of total stand-level BA in oak species

Table 3. Name and description of predicted past management groups.

Predicted past management group	Description
Likely high graded	High likelihood that the stand was high graded.
Leaning high graded	Inconclusive. There is a possibility that the stand was high graded.
Leaning shelterwood	Inconclusive. There is a possibility that the stand received the establishment cut of a shelterwood regeneration sequence.
Likely shelterwood	High likelihood that the stand received the establishment cut of a shelterwood regeneration sequence.

Allegheny/mesic/mixed-hardwood type ("mixed-HW" hereafter, charts D and E) (Figure 2).

We specified "Create a New Stand" for the "Goal or Intention for Stand". For the shelterwood stands, we specified the "Desired Future Forest Type" as mixed-oak whereas, for the high graded stands, we ran SILVAH twice, specifying either mixed-oak or mixed-HW as the desired future forest type each time. We evaluated prescriptions for high graded stands under both settings, because prescriptions to regenerate a mixed-oak forest type when oak regeneration and seed source are scarce often require a substantial financial investment and thus, aiming for a mixed-HW forest type may be more feasible, especially for NIPF owners. Because the deer pressure level ("deer impact" hereafter) and site productivity specified in SILVAH can affect the prescription, we specified a deer impact of moderate (level three) and a site index of 19.8 m (65 ft) for black oak (*Quercus velutina*) at base age 50 years for all stands to minimize potential bias from differing deer impacts and site productivities between stands.

Results

Classification Model

Classification Model

The final classification model developed using the augmented sample included all variables described in Table 2 except for the coefficient of variation of plot-level estimates of total BA. The proportion of total BA in AGSspp (PropAGSspp, Table 2) and proportion of total BA in oak species (PropOak, Table 2) were the most important variables in the model (Figure 3A). Prediction error (i.e., out-of-bag prediction error reported by the RF model) was 25%, with seven of the twenty-eight stands being misclassified (four high graded and three shelterwood stands). When all other variables are held constant, a stand will most likely be classified as high graded when PropAGSspp is below ~65% or when PropOak is below ~50% (Figure 3B).

Application of the Classification Model

Development of thresholds. We determined the thresholds to separate predictions into four predicted past management groups (Table 3) by analyzing the range of the percentage of decision trees classifying a stand as high graded for the correctly and incorrectly classified high graded and shelterwood stands from the twenty-eight augmented sample stands used to develop the classification model. The resulting percentage ranges for the "likely high graded", "leaning high graded", "leaning shelterwood", and "likely shelterwood" groups are [75%, 100%], (50%, 75%), (20%, 50%], and [0%, 20%], respectively (Figure 4).

Classification of stands. Across both forest types, our model classified 22% of the stands in the demonstration sample as likely high graded, 30% as leaning high graded, 28% as leaning shelterwood, and 20% as likely shelterwood. Stands classified as likely high graded or leaning high graded were mostly transition forest type (forty-eight of fifty-two). In contrast, stands classified as likely shelterwood or leaning shelterwood were mostly mixed-oak forest type (thirty-seven of forty-eight). Stands whose forest type was mixed-oak contained, on average, a 9% higher percentage of PropAGSspp than the stands whose forest type was transition (beta regression, z = 2.71 and $P = 0.0067$; Figure 5A). Stands predicted to be likely high graded contained the lowest PropAGSspp and PropOak and stands predicted to be likely shelterwood contained the highest PropAGSspp and PropOak (Figure 5B), which reflects the importance of PropAGSspp and PropOak in the classification model (Figure 3A).

Evaluation of SILVAH Prescriptions

A summary of the SILVAH prescriptions for the high graded and shelterwood stands in the base sample is presented in Figure 6 and Supplementary Table S3.1.

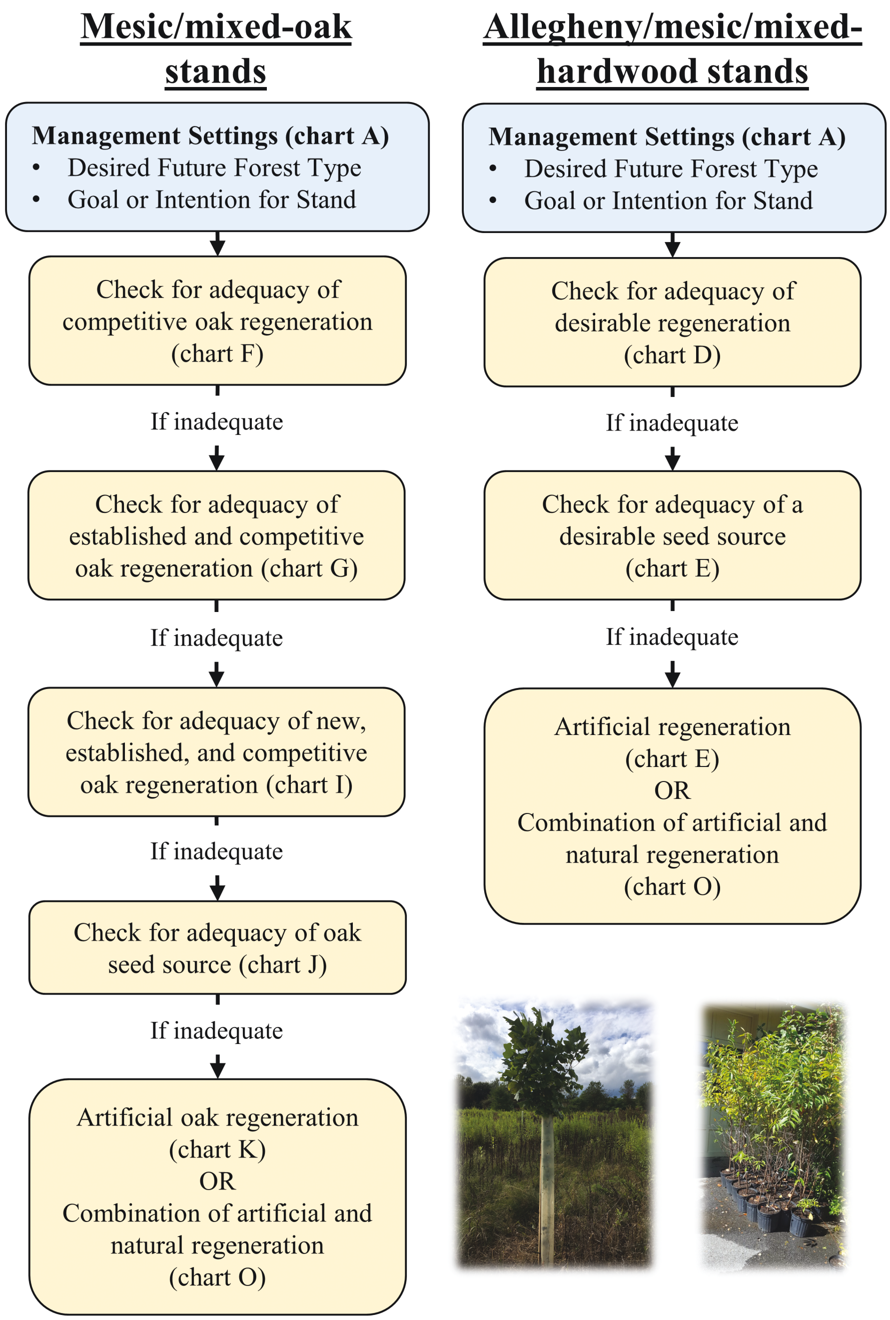


Figure 2. Schematic outlining the general logic of SILVAH for mesic/mixed-oak stands and Allegheny/mesic/mixed-hardwood stands when "Create a New Stand" is specified for the "Goal or Intention for Stand". Note that competitive oak, established oak, and new oak regeneration generally reflect oak seedlings ≥ 91.4 cm (3 ft) tall, oak seedlings 15.2 to 91.4 cm (0.5 to 3 ft) tall, and oak seedlings less than 15.2 cm (0.5 ft) tall, respectively (Brose et al. 2008).

When mixed-oak was specified as the desired future forest type, five of the nine high graded stands (56%) contained insufficient advance oak regeneration and seed source, according to SILVAH thresholds, and arrived at decision charts that provide rehabilitation-related prescriptions (charts K/O), such as a liberation cut, site preparation using prescribed fire or herbicide, or artificial regeneration (chart K), or a mixture of natural and artificial regeneration methods coupled with tending of overstory trees similar to concepts described in the rehabilitation literature (e.g., Clatterbuck 2006, Nyland 2006, Lussier and Meek 2014) (chart O). The other four high graded stands contained levels of advance oak regeneration that led to prescriptions of regeneration release treatment (i.e., overstory removal ["final removal cut" in SILVAH's terminology], chart H). Although these four release prescriptions were

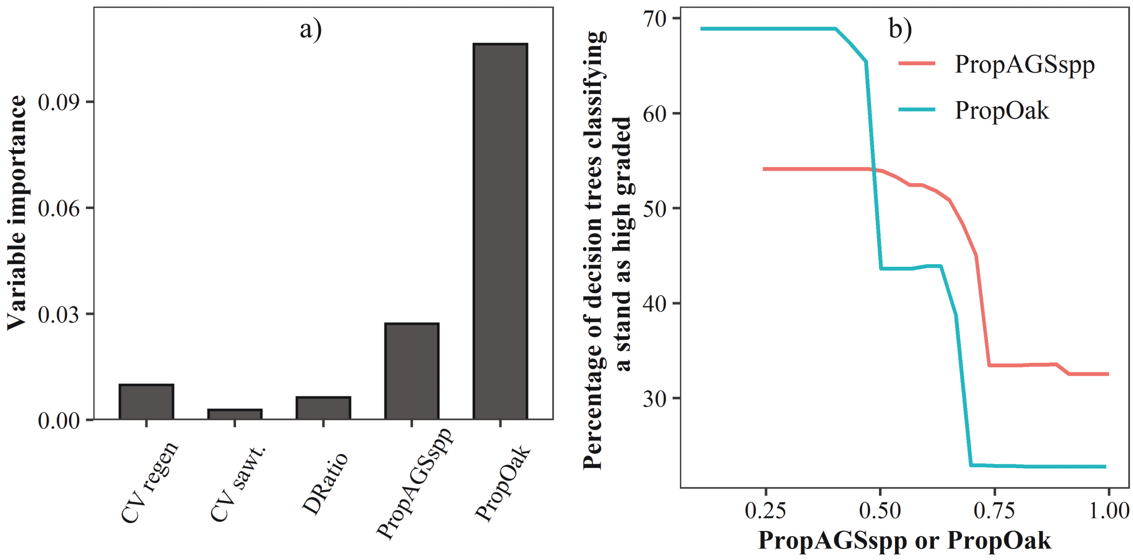


Figure 3. a) Conditional variable importance based on permutation (see Strobl et al. 2008) for variables included in classification model (CV regen = CV desirable regen, CV sawt. = CV sawtimber BA, all other labels follow those in Table 2). b) Partial dependency plot for PropAGSspp and PropOak (pdp R package, Greenwell 2017).

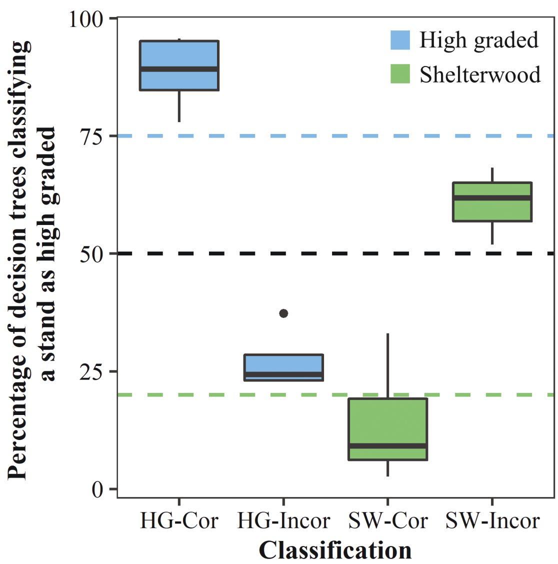


Figure 4. Range of the percentage of decision trees classifying a stand as high graded for the correctly and incorrectly classified twenty-eight augmented sample stands used to develop the classification model. Dotted blue, black, and green lines represent the selected threshold between likely and leaning high graded groups, the line at which the classification is equally split between high graded and shelterwood stand, and the selected threshold between likely and leaning shelterwood groups, respectively (HG-Cor = high graded stand correctly classified as a high graded stand [*n* = 8], HG-Incor = high graded stand incorrectly classified as a shelterwood stand [*n* = 4], SW-Cor = shelterwood stand correctly classified as a shelterwood stand [*n* = 13], SW-Incor = shelterwood stand incorrectly classified as a high graded stand [*n* = 3]).

partially a product of the specified site index value of 19.8 m for black oak, the levels of advance oak regeneration still exceeded SILVAH thresholds for site indices ≥ 20.4 m, resulting in oak regeneration enhancement treatments (i.e., release burn or herbicide, chart G) that are intended to set the stage for future release treatments. For the shelterwood stands, seven of the nine stands (78%) were prescribed to wait for an acorn crop and treat the interfering vegetation because these stands had insufficient advance oak regeneration but an adequate oak seed source (chart J). The other two shelterwood stands contained advance oak regeneration quantities beyond the threshold to recommend an overstory removal to release the advance oak regeneration. We found that the prescription for one of the two shelterwood stands was similarly affected by the specified site index of 19.8 m for black oak; however, the alternative prescription was an advance oak regeneration enhancement treatment (i.e., release burn or herbicide) (Supplementary Table S3.1; Figure 6A, C).

When mixed-HW was specified as the desired future forest type for the high graded stands, the advance desirable regeneration was considered sufficient by SILVAH in five of the nine high graded stands (56%), which resulted in a release treatment prescription (i.e., overstory removal; chart D). The other four high graded stands were judged to lack adequate desirable regeneration but contain an adequate desirable seed source to result in a regeneration establishment prescription such as shelterwood establishment cut (chart E; Supplementary Table S3.1, Figure 6B).

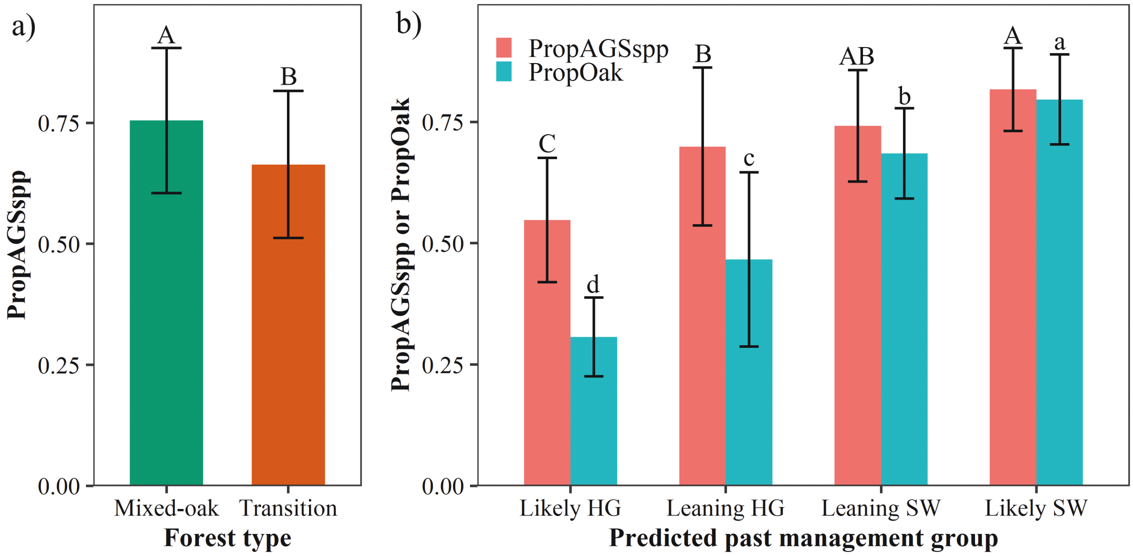


Figure 5. a) PropAGSspp by forest type, and b) PropAGSspp and PropOak by predicted past management group. Error bars represent one standard deviation, and different letters denote significant differences at alpha of 0.05 for PropAGSspp (upper case), for PropOak (lower case; Tukey's honestly significant differences) (HG = high graded stand and SW = shelterwood stand).

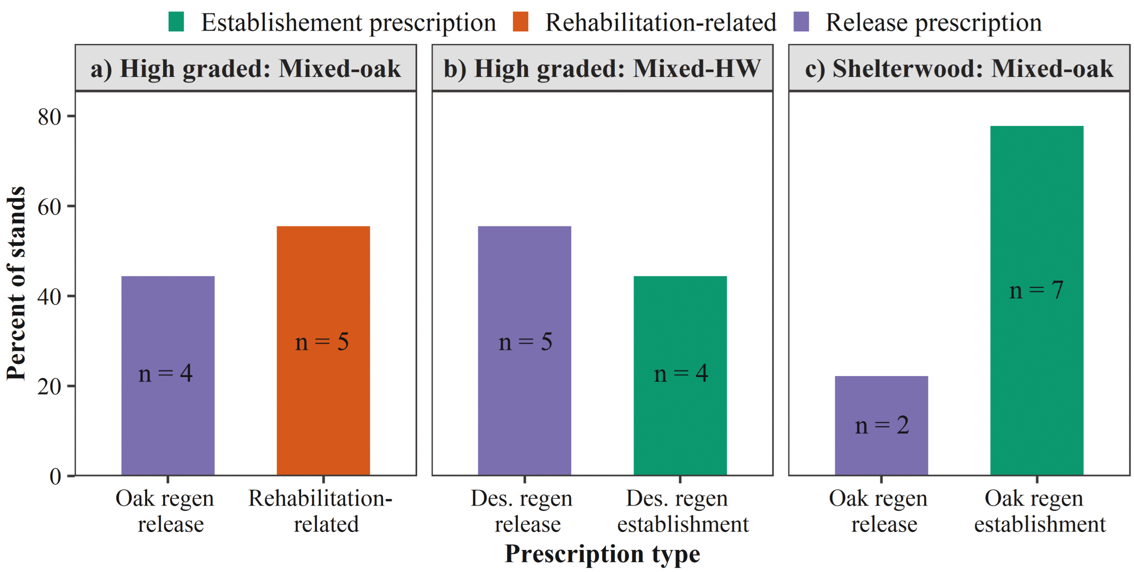


Figure 6. Summary of SILVAH prescription results for a) high graded stands with mixed-oak specified as the desired future forest type, b) high graded stands with mixed-HW specified as the desired future forest type, and c) shelterwood stands with mixed-oak specified as the desired future forest type (Oak regen release/Des. regen release = advanced oak regeneration/advanced desirable regeneration release treatments, Rehabilitation-related = rehabilitation-related treatments [charts K/O], Oak regen establishment/Des. regen establishment = oak regeneration/desirable regeneration establishment treatments).

Discussion

High graded stands are prevalent in the eastern US. This is particularly the case on NIPFs, and it appears that there is growing awareness and concern among private landowners about the negative impacts of high grading and the inadequacy of this practice to consistently sustain healthy and productive forests in the long-term (Allyson Muth and Jeffery Larkin, personal communication). It is thus expected that an increasing number of private landowners are likely to be interested in rehabilitating their high graded forested properties. The overarching goal of our study is to support the rehabilitation of previously high graded mixed-oak stands. Study results have the potential to support forest conservation through (1) individual forestry professionals and landowners, (2) peer volunteer networks such as Pennsylvania's Forest Stewards volunteer program and Women and Their Woods program, and (3) programs such as NRCS's WLFW and RCPP, which have implemented conservation practices on more than 12,000 ha of forest to create or enhance breeding habitat for the Golden-winged Warbler (*Vermivora chrysoptera*) and the Cerulean Warbler (*Setophaga cerulea*) since their inception (Bridgett Costanzo and Todd Fearer, personal communication, Email: June 10, 2020).

Classification Model and Its Application

The classification model is a tool that forestry professionals and landowners can use to inform and prioritize forest management decisions at different spatial scales when information about previous management is lacking. As with all empirical models, care should be taken to use the model within the range of conditions used in its development; that is, currently mixed-oak stands or stands surmised to have been mixed-oak prior to the most recent harvest (see Methods section for details) and with total BA between 12.6 to 27.5 m^2/ha (55 to 120 ft^2/ac) for all living stems ≥ 12.7 cm (5 in.) in dbh (see Table 1 for description of stands in all three samples). This tool uses standard forestry measurements that are already collected in many forest inventories (i.e., tree species, diameter, and quality via AGSspp/UGS) to identify past high grading history. Furthermore, unlike the existing published classification models that can predict past timber harvest types, such as a high grade timber harvest (i.e., Fajvan et al. 1998, Belair and Ducey 2018), our tool does not require the user to know preharvest stand conditions nor recreate preharvest conditions from stumps. Thus, our classification model can be used in more forested situations than the existing classification models. Because oaks are typically the dominant overstory species in mature eastern mixed-oak forests (e.g., Oliver 1978, Albright et al. 2017) and are commercially valuable, oaks are often removed first during a high grade timber harvest, and our model identifies a clear threshold of ~50% in PropOak, with values below that leading to strong predictions of high graded stand (supermajority of decision trees classifying the stand as high graded, Figure 3B). In the same manner, our model identifies a threshold of ~65% in PropAGSspp, below which the model predicts a high graded stand by a majority of decision trees classifying the stand as high graded (Figure 3B), suggesting that high graded stands exhibit unique and quantifiable characteristics. By further classifying predictions into broad groups of predicted past management, we address the limitations related to only predicting two past management types (i.e., high graded or shelterwood stand) and the uncertainty inherent with making predictions by assessing the support for a harvest type classification (Table 3). In cases where a stand has received a treatment that led to characteristics dissimilar to those created by the treatments considered in the model (but within the stand characteristics used to the develop the model, Table 1), we would expect the stand to be classified as either leaning high grade or leaning shelterwood and have close to 50% of decision trees classifying the stand as high graded. This framework thus provides the user with a level of certainty for a classification of high graded or shelterwood stand, which can be used to prioritize rehabilitation treatments. For instance, one may want to prioritize rehabilitation treatments in stands classified as likely high graded because these stands exhibit more attributes characteristic of high graded stands than leaning high graded classifications. Thus, rehabilitation treatments may be more beneficial or necessary in these stands. We underscore that this exercise was intended to demonstrate a potential application of the classification model and we do not assume the demonstration sample to be representative of all WLFW stands or stands on NIPFs. Nonetheless, the moderate proportion of WLFW stands being classified as previously high graded by our model is consistent with estimates reported in other studies for NIPFs (e.g., McGill et al. 2006, Metcalf et al. 2012).

Evaluation of SILVAH Prescriptions

Forest regeneration is a foundational aspect of silviculture. The SILVAH decision charts used to prescribe regeneration treatments follow a similar logic: check for the adequacy of desirable regeneration, and if insufficient, then check for the adequacy of a desirable seed source (Figure 2). For the mixed-oak (charts F to K) and mixed-HW (charts D and E) decision charts, the adequacy of advance desirable regeneration and a desirable seed source as judged by SILVAH determine whether a stand will receive a “traditional” (e.g., overstory removal) silvicultural prescription versus rehabilitation-related prescriptions (charts K/O). Modifications summarized in Figure 7 and discussed below (see Supplementary Table S3.2 for a detailed description of recommended modifications) may be needed to improve SILVAH’s utility.

Four of the nine high graded stands were judged to have sufficient advance oak regeneration by SILVAH (Figure 6A). When advance oak regeneration or advance desirable regeneration is abundant, a traditional regeneration release treatment, the overstory removal, could serve as the rehabilitation treatment. In these situations, the structure of the overstory is less important because it will be removed during the overstory removal and will no longer be needed to produce seed nor provide shelter for tree regeneration. Thus, differentiating high graded and not high graded stands is likely not critical in these situations. However, in some situations where the desired future forest type is mixed-oak, site productivity determines whether an overstory removal or an intermediate oak regeneration enhancement treatment meant to increase the size of the oak regeneration is prescribed. The importance of site productivity is based on the premise that oaks are more competitive on lower productivity sites (Brose et al. 2008). Therefore, obtaining a good estimate of site productivity could be particularly critical for managing high graded stands because it affects whether SILVAH prescribes an overstory removal that will immediately release the advance regeneration (chart H), or an intermediate treatment that retains a portion of the overstory canopy for a few additional years (chart G). In this latter case, because overstory health, and thus seed source, in high graded stands could be compromised and the spatial arrangement of overstory trees and desirable tree seedling densities tends to be irregular (e.g., Grushecky and Fajvan 1999, Bohn 2005, Curtze 2021), intermediate treatments specific to high graded stands may be necessary. This leads us to believe that modifications to the oak regeneration enhancement decision chart (chart G) that account for tree health and spatial variability in overstory BA and desirable tree seedling densities may be warranted to ensure optimal prescriptions for high graded stands.

The advance oak regeneration and advance desirable regeneration in the high graded stands was not adequate based on SILVAH thresholds in five and four cases, respectively (Figure 6A, B). In those cases, overstory structure and species composition becomes critical and SILVAH then evaluates the adequacy of the oak seed source (mixed-oak decision charts) or the desirable seed source (mixed-HW decision charts) based on the BA of desirable species (Figure 2). For the stands whose desired future forest type was specified as mixed-oak, the BA of the oak seed source (i.e., "Sawlog Oak BA", chart J) was the sole criterion that differentiated the paths through the decision charts for the high graded stands that lacked advance oak regeneration from the shelterwood stands that lacked advance oak regeneration. However, because of the low proportion of AGSspp in high graded stands, considering not only the BA but also the health and form of the oak seed source seems warranted. This is also the case for stands whose desired future forest type is specified as mixed-HW and that lack sufficient advance desirable regeneration. Sufficient BA in healthy seed trees that will survive to produce seed and provide shelter is essential for the success of oak seedling establishment (chart J) and desirable seedling establishment (chart E) prescriptions. It could then be necessary to include a

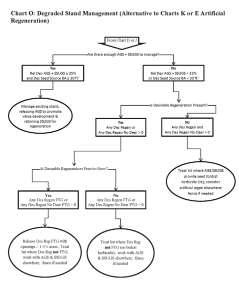
<table>
<tr><th>Desirable regeneration ✓</th><th>Desirable regeneration ✗
Desirable seed source ✓</th><th>Desirable regeneration ✗
Desirable seed source ✗</th><th>Other recommendations</th></tr>
<tr><td>Release prescription could serve as the rehabilitation treatment
</td><td>In high graded stands, seed source quality is as important as its quantity, so adding a tree health metric to the assessment of seed source is warranted
</td><td>Including chart O in the main decision chart flow and computer program would provide users with more rehabilitation practices
</td><td>• Users may want to run SILVAH twice by setting the "desired future forest type" equal to "retain current forest type" and to mixed-oak
• Record all tree seedlings by species and height class
• Collect AGSspp/UGS solely based on tree health and sawtimber potential</td></tr>
</table>

Figure 7. Visual summary of modifications that may be needed to improve SILVAH's utility in high graded stands (SILVAH decision chart image is from SILVAH version 7.0.4.5, USDA Forest Service 2021). Top row indicates characteristics of the stand, with a green check mark indicating that the SILVAH threshold is met, and a red x indicating that it is not. Second row describes the recommendation.

tree health metric (e.g., similar concept to AGSspp) in addition to the oak seed source BA as a decision point in SILVAH to better differentiate high graded stands from other stands (Figure 7; Supplementary Table S3.2, recommendation a.1). Mixed-oak and mixed-HW stands that fail the tree health metric could be sent to a chart that prescribes rehabilitation treatments (e.g., chart O or a chart of similar concept).

SILVAH currently includes two decision charts that prescribe rehabilitation-related treatments for stands that have inadequate advance desirable regeneration and desirable seed source: (1) one that prescribes extensive artificial regeneration prescriptions (chart K for mixed-oak stands), and (2) one that prescribes a combination of artificial and natural regeneration coupled with tending to overstory trees (chart O) that is conceptually similar to rehabilitation practices that are discussed in Clatterbuck (2006), Nyland (2006), and Lussier and Meek (2014). However, only the former is considered in the main SILVAH decision charts and SILVAH computer program. A better integration of the latter decision chart (chart O) in the flow of the main decision charts and in the computer program would likely render SILVAH more useful for high graded stands (Figure 7; Supplementary Table S3.2, recommendation a.2). An advantage of rehabilitation-related prescriptions that incorporate natural and artificial regeneration (chart O) over the other chart that prescribes extensive artificial regeneration prescriptions (chart K) is that the former capitalizes on any sources of natural regeneration to potentially reduce the costs associated with artificial regeneration, which is particularly important for NIPF owners who may have limited resources for implementing this management practice (Lutter et al. 2019).

In certain rehabilitation instances that lack advance oak regeneration and seed source, it may be beneficial to consider prescriptions aimed at regenerating a mixed-HW forest as an alternative to regenerating a mixed-oak forest. In those cases, specifying a future mixed-oak forest type will lead to rehabilitation-related prescriptions (charts K/O), which can be costly. In these instances, opting for regenerating the current forest type (e.g., mixed-HW) could be the best or only alternative. Although none of the four currently mixed-HW high graded stands in our base sample contained enough advance desirable regeneration to arrive at a desirable regeneration release prescription (chart D), the percentage of plots that satisfied the minimum regeneration density set by SILVAH (i.e., "stocked plot") increased, on average, from 17% to 18% (assuming moderate deer impact) and from 23% to 38% (assuming no deer impact; i.e., within a deer exclusion fence) for these four stands when all advance desirable regeneration was considered instead of only advance oak regeneration (Supplementary Table S3.1). For the mixed-HW prescriptions, regeneration release prescriptions (chart D) may be optimal when advance desirable regeneration is abundant; however, when advance desirable regeneration is lacking, seedling establishment prescriptions (e.g., shelterwood establishment cut; chart E) may be suboptimal (Figure 7; Supplementary Table S3.2, recommendation a.1) and caution should be exercised when considering these seedling establishment prescriptions (chart E). In essence, our results suggest that the forestry professional or landowner has three main management/rehabilitation options: (1) attempt to restore the stand to a mixed-oak type via extensive artificial regeneration, (2) attempt to restore the stand to a mixed-oak type via a combination of natural and artificial regeneration, or (3) implement treatments to regenerate a mixed-HW stand. Providing information to users attempting to convert a mixed-HW stand to a mixed-oak stand when there is insufficient advance oak regeneration and seed source seems warranted (Figure 7; Supplementary Table S3.2, recommendation a.3).

We recommend that users record all tree seedlings by species and height classes (e.g., "detailed regeneration counts" in SILVAH) and only consider tree health and sawtimber potential when classifying trees as AGSspp/UGS (Figure 7; Supplementary Table S3.2, recommendations b.1 and b.2). Collecting data in this way provides forestry professionals and landowners with greater detail and the flexibility to explore management options by changing which species are considered desirable. These benefits are not afforded by the traditional seedling regeneration counts that only record desirable species (i.e., "weighted regeneration counts" in SILVAH) and the traditional AGSspp/UGS classification that includes species desirability as one of the criteria.

Our overall goal was to provide tools for the management and rehabilitation of high graded mixed-oak stands of the northeastern US. The classification model we developed is a tool that can be used by forestry professionals and landowners to help inform and prioritize forest management decisions at different spatial scales when previous management information is lacking and to bring awareness to the pervasiveness of high grading. Our evaluation of SILVAH underscores the value of updating decision support tools to address new circumstances that were not originally considered when tools were first developed. Our study identifies points that have the potential to improve the ability of SILVAH to prescribe silvicultural treatments for high graded mixed-oak stands of the northeastern US. Overall, we conclude that (1) the rehabilitation-related prescriptions that include natural and artificial regeneration (chart O) could be useful for prescribing treatments for high graded stands, and (2) quantifying quality in addition to quantity of seed source when evaluating the desirable seed source for regeneration (charts E and J) has the potential to improve the identification of high graded stands and route those to rehabilitation-related prescriptions when appropriate.

Supplementary Material

Supplementary material is available at *Journal of Forestry* online.

Supplement 1: Table outlining all tree species recorded in overstory and regeneration plots and tree species considered desirable (base sample).

Supplement 2: Classification model development procedures.

Supplement 3: Summary of SILVAH prescriptions and recommended modifications to SILVAH.

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CRediT Author Statement

Alexander Curtze: conceptualization, methodology, formal analysis, writing—original draft; Allyson Muth: conceptualization, writing—review and editing, resources; Jeffery Larkin: conceptualization, writing—review and editing, resources, funding acquisition; Laura Leites: conceptualization, methodology, formal analysis, writing—original draft, funding acquisition.

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