MODELING THE LONG-TERM EFFECTS OF OAK SHELTERWOOD REGENERATION TREATMENTS ON SPECIES DIVERSITY AND OAK ABUNDANCE IN SOUTHERN APPALACHIAN FORESTS OF NORTH CAROLINA

Tara L. Keyser and Chad E. Keyser[1]

Abstract—In April 2008, the Upland Hardwoods Ecology and Management Research Work Unit of the U.S. Forest Service, Southern Research Station began a long-term cooperative study to describe forest ecosystem response to three oak (*Quercus* spp.) shelterwood regeneration treatments in the central hardwoods region of the United States. Pretreatment inventory data from 10 mature, mixed-oak forest stands on North Carolina Wildlife Resources Commission Game Lands were input into the Forest Vegetation Simulator (FVS) to analyze the long-term forest ecosystem response to the following oak shelterwood regeneration treatments: (1) shelterwood followed by prescribed fire and overstory removal, (2) shelterwood via herbicide followed by overstory removal, (3) repeated prescribed fire followed by overstory removal, and (4) control. In this study, FVS growth forecasts were used to analyze alternative oak shelterwood regeneration treatment effects on species diversity and oak abundance over the next 50 years.

INTRODUCTION

Historically, disturbance events such as low-intensity surface fires (both natural and human-caused), timber harvesting, grazing, loss of American chestnut (*Castanea dentata*), and land clearing for agriculture promoted overstory and understory conditions conducive to the establishment, development, and recruitment of midtolerant oak species (*Quercus* spp.) across the upland hardwood forest ecosystem (Abrams 1992, Lorimer 1993). As a result of repeated disturbance events, oak gained dominance in forest stands at the expense of competitors such as shade-tolerant red maple (*Acer rubrum*) and shade-intolerant yellow-poplar (*Liriodendron tulipifera*). Abundant evidence indicates that changing disturbance regimes are promoting the conversion of mixed-oak forests to forests dominated by shade-tolerant species such as red maple (e.g., Orwing and Abrams 1994), or by shade-intolerant species such as yellow-poplar (e.g., Beck and Hooper 1986, Rodewald 2003). For example, Aldrich and others (2005) observed an increase in the abundance of shade-tolerant sugar maple (*A. saccharum*) from ~1 percent of total stand density in 1926 to ~25 percent in 1992 in an old-growth forest in Indiana that had no active management since 1917. Similarly, in the same forest, Spetich and Parker (1998) reported a decrease in the biomass of small-diameter (10 to 25 cm) oak trees from 14 percent in 1926 to only 1 percent in 1992. The authors note that during the same time period, biomass of sugar maple in the same size class increased from 12 to 43 percent.

Ecologically, mixed-oak forests are among the most productive terrestrial ecosystems (Whittaker and Likens 1975), store substantial amounts of carbon (Greco and Baldocchi 1996), and are considerable sources of wildlife habitat, food resources, and overall biodiversity. The decline of oak as an overstory tree species, coupled with regeneration failures (Aldrich and others 2005), could have cascading ecological effects. Silvicultural practices are utilized to achieve numerous resource management objectives; including the creation and maintenance of wildlife habitat, habitat restoration, timber production, and maintenance of landscape-level biodiversity. Within the upland hardwood ecosystem, numerous silviculture prescriptions have been developed to specifically regenerate oak in mid- to high-quality stands (e.g., Brose and others 1999, Loftis 1990). In this paper, we examine efficacy of three recommended, but not widely tested, oak shelterwood regeneration treatments by modeling their impact on oak abundance and overall species composition over a 50-year period using available regeneration and growth-and-yield models.

METHODS

Study Site

The data from this study were collected from the North Carolina Wildlife Resources Commission, Cold Mountain Game Lands (CMGL) and serve as pretreatment data for the U.S. Forest Service's Research Work Unit 4157 (RWU-4157) Regional Oak Study. The CMGL, which lie within the Blue Ridge Physiographic Province of the Southern Appalachian Mountains, consists of mature, second-growth upland mixed-oak forests. Terrain is mountainous with steep slopes. Elevations range from 980 to 1200 m. Oak SI_{50} in the 10 units ranged from 19 to 31 m. Oaks [red (*Q. rubra*), white (*Q. alba*), chestnut (*Q. prinus*), and black (*Q. velutina*)], hickory (*Carya* spp.), black cherry (*Prunus serotina*), and yellow-poplar are the dominant overstory trees. Species composition in the midstory consists primarily of shade-tolerant species including sourwood (*Oxydendrum arboreum*), blackgum (*Nyssa sylvatica*), silverbell (*Halesia tetraptera*), flowering dogwood (*Cornus florida*), and red maple.

[1] Research Forester, U.S. Department of Agriculture Forest Service, Southern Research Station, Bent Creek Experimental Forest, Asheville, NC; and Forester, U.S. Department of Agriculture Forest Service, Forest Management Service Center, Asheville, NC, respectively.

Shelterwood Regeneration Treatments

Oak shelterwood regeneration treatments were designed to test the effectiveness of silvicultural methods currently suggested to regenerate oak in upland hardwood forests in the Eastern United States. Treatments were: (1) shelterwood/burn (SWB), (2) oak shelterwood via herbicide (OSW), (3) prescribed fire (RXF), and (4) control (CON). The prescription for the SWB treatment followed the guidelines outlined in Brose and others (1999). The initial step was to perform an establishment cut leaving approximately 7 m^2/ha of residual basal area (BA). Three years following the establishment cut, a prescribed fire was performed. Ten years after the establishment cut, the residual overstory trees were removed down to a target BA of ~2 to 3.5 m^2/ha. The prescription for the OSW treatment followed the guidelines presented in Loftis (1990). The initial step, e.g., establishment cut, was the removal of the competing midstory [trees ≥5.0 cm and <25.0 cm diameter at breast height (d.b.h.)] using herbicide. The goal of the herbicide treatment was to reduce total BA by 25 to 30 percent. Ten years following the herbicide treatment, the residual overstory trees were removed down to a target BA of ~2 to 3.5 m^2/ha. In the RXF treatment, prescribed fire was performed three times (return interval of 4 years). Ten years following the initial prescribed fire, the residual overstory trees were removed down to a target BA of ~2 to 3.5 m^2/ha. No silvicultural manipulation occurred in the CON treatment throughout the duration of this study.

Experimental Design and Data Collection

During the summer of 2008, we established twenty 5-ha treatment units on the CMGL. Treatments were randomly assigned to each treatment unit. Treatment units contained mature (>70 years old), fully-stocked, closed-canopied stands in which oak comprised at least 10 percent of the overstory tree (≥25.0 cm d.b.h.) BA, contained approximately 2 m^2/ha of BA beneath the main canopy, and contained at least ~1,000 oak seedlings/ha. Within each treatment unit six 0.05-ha (12.6 m radius) permanent vegetation plots were systematically located along a grid.

Within each 0.05-ha vegetation plot, all overstory trees (≥25.0 cm d.b.h.) were tagged and measured. Midstory trees (≥5.0 cm and <25.0 cm d.b.h.) were tagged and measured within a 0.01-ha (5.6 m radius) subplot nested within each of the larger vegetation plots. For each tagged tree, the data recorded included species and d.b.h. to the nearest 0.1 cm. Tree regeneration was sampled using two 0.004-ha (3.6 m radius) circular regeneration subplots originating 8 m from plot center at bearings of 45° and 225°. All arborescent regeneration sources were tallied by species in four height/diameter classes: (1) <0.6 m, (2) 0.6 to <1.2 m, (3) ≥1.2 but <3.8 cm, and (4) ≥3.8 cm.

Modeling

Ten of the twenty treatment units were selected for modeling the effects of the aforementioned treatments. To address the variability associated with the inventory sample of these units, a bootstrapping technique described by Hummel and Cunningham (2006) was implemented through the FVSBoot computer program (Gregg and Hummel 2002) to resample the plots within each unit. Each unit was resampled 500 times, which resulted in the creation of 5,000 boostrapped stands plus the original 10 stands, for a total of 5,010 stands.

Each stand was modeled under each treatment alternative (SWB, OSW, RXF, and CON) using the Southern Variant of the Forest Vegetation Simulator (FVS-SN) (Crookston and Dixon 2005, version 6.21, revision date 9-19-08). FVS-SN is the U.S. Forest Service nationally supported growth-and-yield modeling system that is used to forecast stand development with and without management or other disturbance events. Variants of FVS-SN have been calibrated to most forest types in the United States and can be downloaded through the U.S. Forest Service, Forest Management Service Center Web site (www.fs.fed.us/fmsc/). Each FVS-SN variant is a distance-independent, individual tree growth model that has the capability of including silvicultural, fire, and insect and disease impacts on forest stands. Users are able to track outputs of individual tree characteristics and stand characteristics such as density, volume, wildlife habitat, fire and health related indices, and carbon stocks.

Two control variables were adjusted in the FVS-SN model runs. First, default site index for each stand was estimated using methodology developed by McNab and Loftis (this proceedings) and entered into the FVS-SN forecasts. Secondly, Reineke's Stand Density Index maximums were reset by species based on FVS-SN estimates of forest-type maximums and an article by Schnur (1937).

A known constraint of the FVS-SN is the regeneration model. In FVS-SN terminology, the regeneration model is a partial establishment model, meaning only sprouts are estimated when a tree is cut or killed by fire. All other regeneration must be entered by the user. By default, you get two sprouts per tree cut or killed by fire; however, FVS-SN allows the user to turn off this automatic sprouting, modify the sprouting routine, or enter regeneration by species and size directly at any time during the growth forecast. Given the importance of regeneration estimates in forecasting stand development under the proposed treatments, we deemed the partial establishment model's sprouting routine insufficient[2] and decided to enter regeneration estimates based on literature and a local regeneration model. We provided regeneration estimates for two conditions: (1) following prescribed fire and (2) following substantial overstory removal. We entered regeneration estimates following prescribed fire based on Alexander and others (2008).

Regeneration estimates following substantial overstory removal were provided by the REGEN (version 1.0.2) model (Loftis 1988, Schweitzer and others 2004). REGEN is a model used to predict species composition of regeneration after

[2] Personal communication. David Loftis.

overstory removal in mixed-species stands. The model is driven by a pretreatment inventory of all existing regeneration sources enumerated by species and size class. Based on probabilities, the model adds sprouts as well as seedlings and root suckers to the regeneration plots. Seedlings and root suckers are only added for species that are capable of either producing root suckers or establishing new seedlings shortly after substantial disturbance. In the Southern Appalachians, these species include American beech (*Fagus grandifolia*), black locust (*Robinia pseudoacacia*), and sassafras (*Sassafras albidum*) for root suckers and sweet birch (*Betula lenta*), yellow birch (*B. alleghaniensis*), yellow-poplar, black cherry, and yellow pines (*Pinus virginiana*, *P. echinata*) for new seedlings. REGEN picks the dominant/codominant trees on each regeneration plot at crown closure based on a ranking of the postharvest performance of different regeneration sources which include new seedlings, various sizes of advance reproduction, and stump sprouts. Probabilities and rankings used in this study were provided by David Loftis (U.S. Forest Service, Southern Research Station, Bent Creek Experimental Forest). FVS-SN preharvest tree lists were entered into REGEN in the year of the simulated overstory removal. REGEN then predicted the type and amount of regeneration to input back into the FVS-SN growth forecasts. Details of the exact timing of treatments in FVS-SN and interactions between FVS-SN and REGEN are provided in table 1. Outputs tracked by FVS-SN over the growth period of 50 years included density by species group (table 2) within each stand. Metrics reported throughout the paper were calculated on the bootstrapped sample (n = 5010).

RESULTS

Pretreatment Data

The stands used in this study were dominated by oak and hickory species with 48 percent of the BA of dominant/codominant trees being in the oak-hickory (OH) species group, 35 percent in the intolerants (IN) species group, and 11 percent in the other (OT) species group (fig. 1A). Species within the midstory (MS) group contributed only 7 percent of the dominant/codominant BA. Within the OH species group, oak accounted for an average of 10.8 m^2/ha of BA or 71 percent of the dominant and codominant BA within the OH species group. Similarly, 51, 28, 9, and 12 percent of the dominant/codominant stems/ha were within the OH, IN, MS, and OT species groups, respectively (fig. 1B). Within the OH species group, oak accounted for an average of 86 stems/ha or 63 percent of the dominant/codominant BA within the OH species group. Prior to the implementation of treatments in FVS-SN or REGEN, the stand BA, density, and quadratic mean diameter averaged (±1 standard deviation) 37.1 (8.0) m^2/ha, 635 (139) trees/ha, and 27.5 (4.3) cm.

Posttreatment Species Diversity and Oak Abundance

Treatments targeted towards oak regeneration had a substantial impact on overall species composition compared to pretreatment species composition. After 50 years, the distribution of the BA by species was most similar to pretreatment levels in the OSW treatment with 41, 40, 1, and 17 percent of the BA in dominant/codominant stems in the OH, IN, MS, and OT species groups, respectively (fig. 2A). The SWB treatment resulted in the greatest departure from pretreatment species composition. A substantial proportion of the BA in dominant/codominant stems, especially within the OH group, was the result of the ~2 to 3.5 m^2/ha of residual overstory (with preference given to oak species) left during the overstory removal that FVS-SN simulated in 2018. When examining the number of dominant and codominant stems/ha resulting from treatments, the departure from pretreatment conditions was more visible. However, the OSW treatment, again, best approximated the distribution of dominant and codominant stems/ha prior to treatment with 22, 48, 2, and 32 percent of the dominant/codominant stems/ha in the OH, IN, MS, and OT species groups followed by the RXF and SWB treatments (fig. 2B).

Despite substantial variability in model outcomes (fig. 3), little difference was observed in the 50-year model projections regarding the regeneration of oak species into dominant/codominant canopy positions. The BA of dominant/codominant oak stems in the OSW, RXF, and SWB treatments was between of 3.5 and 4.5 m^2/ha (fig. 3A). The similarity in oak BA among the treatments, again, is likely due to the ~2 to 3.5 m^2/ha of residual overstory left during the overstory removal that occurred in 2018. Despite substantial variability, after 50 years, the number of dominant/codominant oak stems/ha regenerated by the OSW and RXF treatments were most similar, averaging ~81 stems/ha whereas the SWB treatment resulted in an average of 24 dominant/codominant oak stems/ha. By the end of the modeling forecast, oaks accounted for 99 percent of the dominant/codominant stems within the OH species group in the OSW and RXF treatments and 92 percent in the SWB treatment.

DISCUSSION

Results from the model forecasts show that the efficacy of these treatments in regenerating oak and maintaining species diversity in upland forests of the Southern Appalachians varied by treatment. Oak shelterwood regeneration methods using the treatments modeled in this study have been suggested to regenerate oak: however, the success of these methods likely varies in response to the ecological differences, e.g., soils, climate, and species composition, that exist across the central hardwoods region (CHR) of the United States. For example, using a method similar to the OSW treatment, Loftis (1990) reported significantly higher oak regeneration on sites where BA was reduced by 30 percent the decade prior to overstory removal in highly productive sites in northern Georgia (oak SI_{50}). However, this method, which was highly successful in northern Georgia, has not been tested across the upland hardwood ecosystem. Similarly, repeated prescribed fire, which has been suggested as critical to successful oak regeneration (e.g., Abrams 1992), has shown promise as a method to develop large advance oak regeneration on dry to intermediate sites in southern Ohio (Iverson and others 2008) but has not been tested across the broad range of ecosystems that occur in the CHR. Before fire is used to regenerate oaks in the Southern Appalachians, more studies examining the effects of repeated burning in

Table 1—Description of modeling timeframe and linkages between FVS-SN and REGEN

Treatment and year/years	Description
OSW	
2008	- Read stand data into FVS-SN and create tree list file
2009	- Simulate establishment cut via herbicide treatment in FVS-SN
2018	- FVS-SN passes tree list to REGEN - REGEN estimates regeneration response to overwood removal - REGEN passes regeneration composition back to FVS-SN - FVS-SN simulates overwood removal and inputs regeneration
2018–58	- FVS-SN continues to grow stand
SWB	
2008	- Read stand data into FVS-SN and create tree list file
2009	- FVS-SN passes tree list to REGEN - REGEN estimates regeneration response to establishment cut - REGEN passes regeneration composition back to FVS-SN - FVS-SN simulates shelterwood harvest and inputs regeneration
2012	- FVS-SN simulates prescribed fire/mortality and sprouting from fire
2018	- FVS-SN simulates overwood removal
2018–58	- FVS-SN continues to grow stand
RXF	
2008	- Read stand data into FVS-SN and create tree list file
2009	- FVS-SN simulates prescribed fire/mortality and sprouting from fire
2012	- FVS-SN simulates prescribed fire/mortality and sprouting from fire
2016	- FVS-SN simulates prescribed fire/mortality and sprouting from fire
2018	- FVS-SN passes tree list to REGEN - REGEN estimates regeneration response to overwood removal - REGEN passes regeneration composition back to FVS-SN - FVS-SN simulates overwood removal and inputs regeneration
2018–58	- FVS-SN continues to grow stand
CON	
2008	- Read stand data into FVS-SN and create tree list file
2008–58	- FVS-SN continues to grow stand

FVS-SN = Southern Variant of the Forest Vegetation Simulator; REGEN = a model used to predict species composition of regeneration after overstory removal in mixed-species stands; OSW = oak shelterwood via herbicide treatment; SWB = shelterwood/burn treatment; RXF = prescribed fire treatment; CON = control treatment.

various forest types throughout the Southern Appalachians are required. Surprisingly, the model projections did not show the SWB treatment to be as successful as the RXF and OSW treatments at regenerating oak despite a study by Brose and others (1999) where a technique similar to the SWB treatment simulated in this paper showed the treatment to be highly successful at regenerating oak on intermediate-quality (oak SI_{50} 23 m) sites in northern Virginia. The stands used in this study were, on average, higher quality sites than used by Brose and others (1999) with oak SI_{50} averaging 25 m creating a more competitive environment where oak may not outcompete faster growing species in the INT species group like black

Table 2—Designation of species groups

Species group	Species included
Oak-hickory	Oaks (*Quercus* spp.) and hickories (*Carya* spp.)
Intolerants	Yellow-poplar (*Liriodendron tulipifera*), black cherry (*Prunus serotina*), sweet birch (*Betula lenta*), black locust (*Robinia pseudoacadia*)
Midstory	Flowering dogwood (*Cornus florida*), red maple (*Acer rubrum*), blackgum (*Nyssa sylvatica*), sourwood (*Oxydendrum arboreum*), striped maple (*Acer pensylvanicum*), silverbell (*Halesia tetraptera*)
Other	Sugar maple (*Acer saccharum*), black walnut (*Juglans nigra*), magnolia (*Magnolia* spp.), others

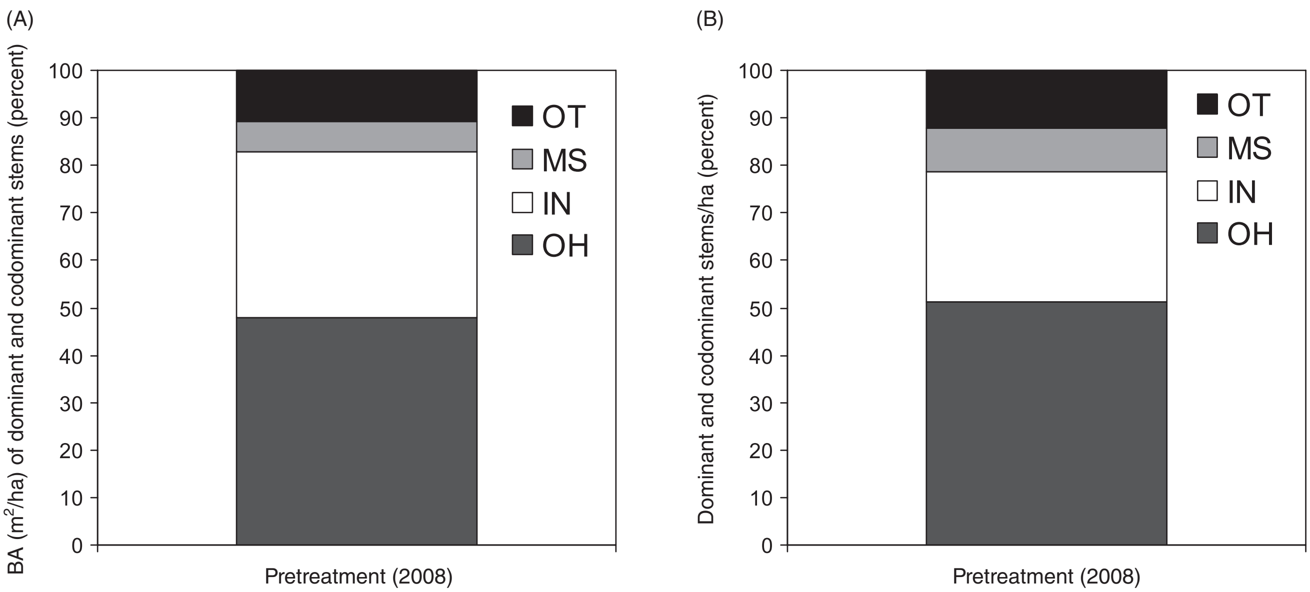

Figure 1—Pretreatment distribution of (A) basal area (BA) (m^2/ha) and (B) stems/ha within the oak-hickory, intolerant, midstory, and other species group within the 5,010 stands.

cherry and yellow-poplar, emphasizing, again, the need to test these treatments across a broad range of ecosystems before applying a one-size-fits-all oak regeneration treatment across the landscape.

CONCLUSIONS

Forestry models provide land managers a means to assess potential effects of alternative treatments in forested stands and are especially useful when site-specific information regarding the potential effects of a treatment is lacking. In research, model outcomes can help stimulate new research ideas and formulate hypotheses. Using FVS-SN alone in this study was not acceptable given the inability of the southern variant of FVS to sufficiently predict regeneration success following overstory removals in the proposed treatments. Alternatively, using REGEN alone would not have allowed us to sufficiently predict the effects of the intermediate treatments, e.g., prescribed burn, on the regeneration pools or predict the long-term stand development patterns and tradeoffs in proposed treatments. By combining the two models, we were able to diminish weaknesses in both models, thus, allowing for multiscale comparisons of treatment alternatives.

Stage (1973) noted in his first publication on Prognosis, the predecessor of FVS-SN, that our ecological and silvicultural knowledge is incomplete and as such our forestry models are incomplete. With this in mind it is important that forestry models allow land managers the ability to adjust model relationships as needed. We found FVS-SN to be flexible with respect to modifying regeneration inputs. It is also essential that forestry models are consistently maintained to facilitate the incorporation of new ecological findings; such is the case with FVS-SN, which reflects over two decades of scientific development. To meet the modeling needs of mixed-oak forests in the Southern Appalachians, we recommend to the FVS-SN staff that the REGEN model be fully integrated within the FVS-SN.

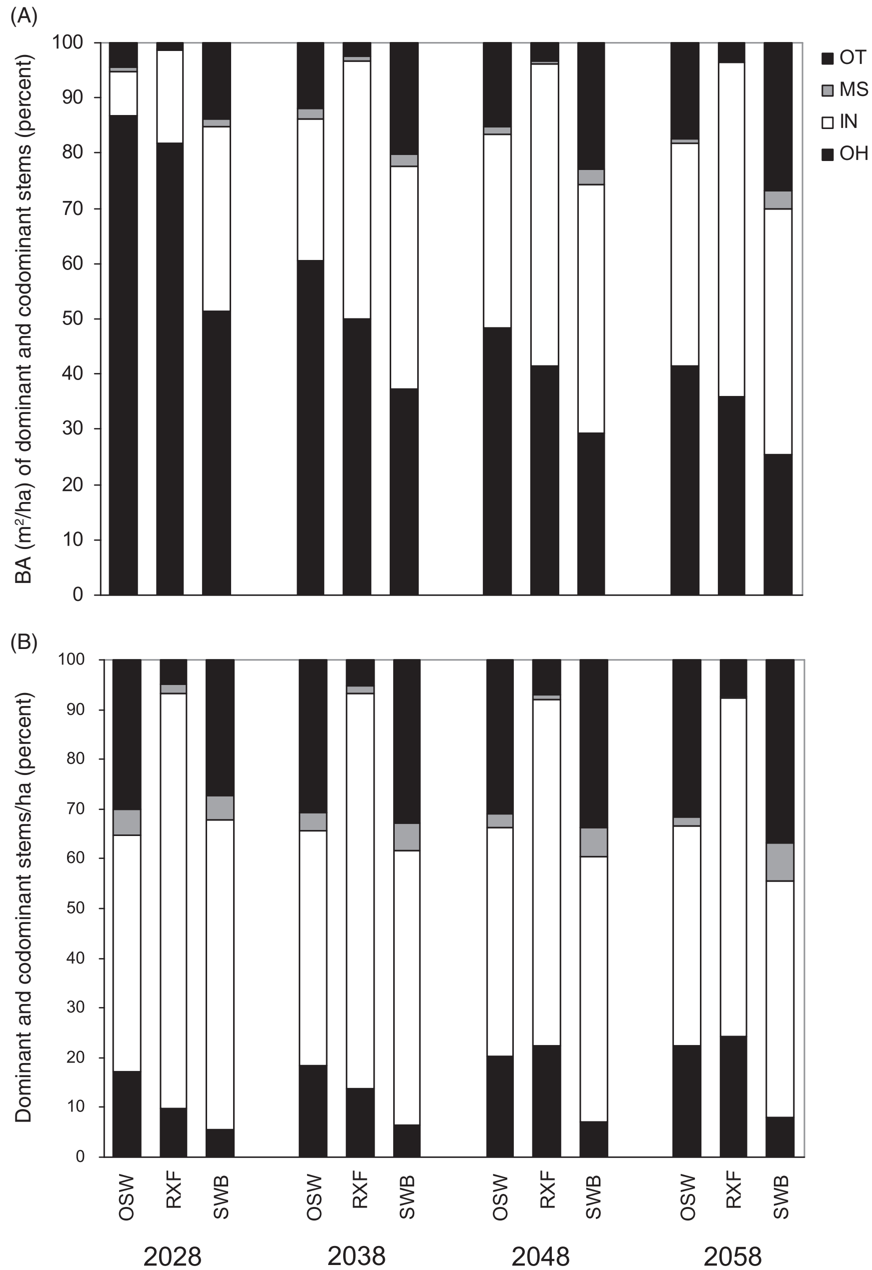

Figure 2—Predicted posttreatment distribution of (A) basal area (BA) (m^2/ha) and (B) stems/ha within the oak-hickory, intolerant, midstory, and other species group within the 5,010 stands. (OSW = oak shelterwood via herbicide, RXF = prescribed fire, SWB = shelterwood/burn).

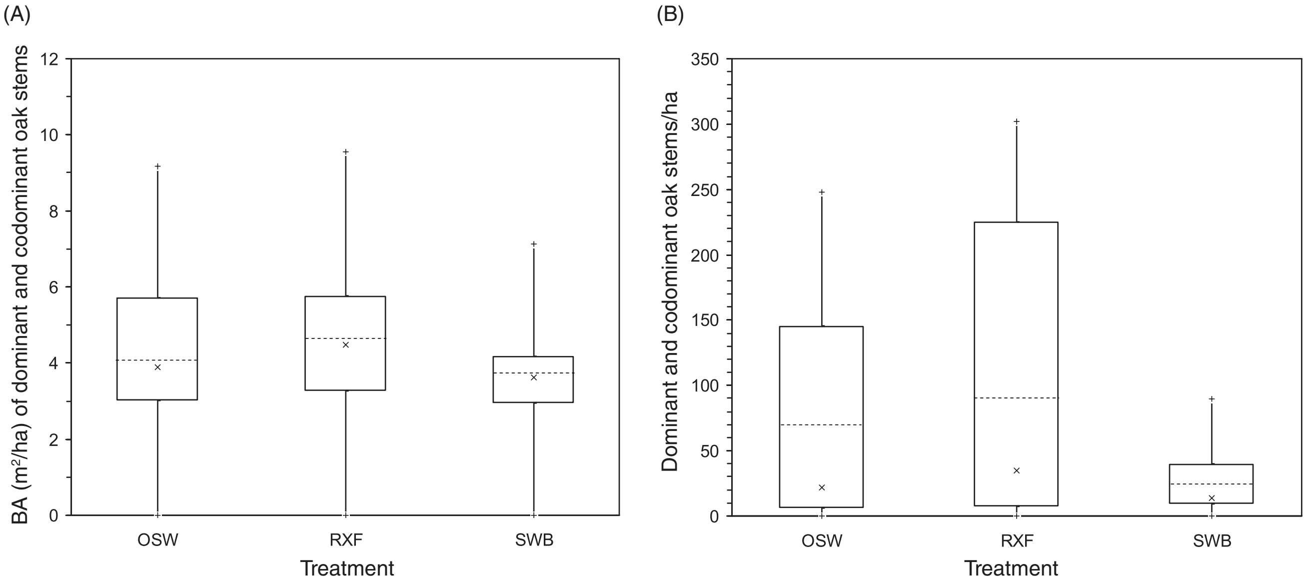

Figure 3—Predicted posttreatment (A) basal area (BA) (m^2/ha) and (B) stems/ha of oak species at the end of the 50-year forecast (year 2058) for the 5,010 stands. For each treatment, the + represents the minimum and maximum predicted values; x represents the median predicted value; the dashed line represents the mean predicted value; and the top and bottom lines of the boxes represent the upper and lower quartiles of the predicted variables, respectively. (OSW = oak shelterwood via herbicide, RXF = prescribed fire, SWB = shelterwood/burn).

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