Red Spruce Stand Dynamics, Simulations, and Restoration Opportunities in the Central Appalachians

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Abstract

Red spruce (*Picea rubens*)–dominated forests occupied as much as 600,000 ha in West Virginia prior to exploitive logging era of the late nineteenth and early twentieth centuries. Subsequently, much of this forest type was converted to northern hardwoods. As an important habitat type for a number of rare or sensitive species, only about 12,000 ha of red spruce forests presently remain in the state. In order to assess the prospects for restoration, we examined six northern hardwood stands containing understory red spruce to (1) characterize stand dynamics and regeneration patterns and (2) simulate the effectiveness of restoration silviculture to enhance red spruce overstory recruitment. Stands originated in the late 1800s to early 1900s and are currently in the (late) stem exclusion or understory reinitiation stages. Five of the six stands had even-aged overstories that originated after clear-cutting. Tree-ring chronologies show high initial growth rates consistent with stand initiation. One stand, partially harvested in 1915, was uneven aged with older, legacy residuals in the canopy. Most stands had two cohorts of understory red spruce, with more than 40% of these individuals showing prior release. Our 100-year growth simulation suggested that a 50% basal area thinning from above could double red spruce basal area to support a mixed spruce–hardwood stand in approximately 20–40 years. These results indicate that restoration silviculture could be an effective tool for increasing the amount and quality of this reduced forest type in the central Appalachians.

Key words: natural disturbance regime, natural regeneration, northern hardwood forests, tree release.

Introduction

Ecological restoration is the process of assisting the recovery of natural systems that have been degraded, damaged, or destroyed (SER 2004). In the United States, restoring degraded forest ecosystems is a major new focus of applied research. For example, in the south, considerable public and private management resources have been committed to restoring bottomland hardwoods in the Mississippi Alluvial Valley (Stanturf et al. 2001), Shortleaf pine (*Pinus echinata*) woodlands in the Ozark and Ouachita highlands (USDA Forest Service 1996), and Longleaf pine (*P. palustris*)–Wiregrass (*Aristida*) communities in the Atlantic and Gulf Coastal Plains (Hermann 1993). In these instances, active restoration is often necessary because altered disturbance regimes (e.g., fire suppression), landscape fragmentation, and/or wholesale conversion make community recovery unlikely without intervention. Reference communities can provide a benchmark for determining target composition, structure, and function. Falk (1990) noted that "restoration uses the past not as a goal but as a reference point for the future. If we seek to recreate … communities of centuries past, it is not to turn back the evolutionary clock but to set it ticking again." Accordingly, adoption of a reference ecosystem as benchmark is consistent with returning an ecosystem to its historic trajectory (SER 2004) or dynamics (Christensen et al. 1996), after which natural self-renewing processes operate within the historic range of variability and a forest management context.

Appalachian Red spruce (*Picea rubens*) forest communities are considered one of the most endangered forest systems in the United States (Christensen et al. 1966; Noss et al. 1995). Among the several southern forest types that have lost more than 90% of their pre-settlement area (Trani 2002), this type is a high priority for restoration. In east-central West Virginia, red spruce forests have a fragmented distribution on high peaks and ridgelines in the Allegheny Mountains. A relict from the end of the last glacial period, this forest is the primary habitat for two endangered species: the Cheat Mountain Salamander (*Plethodon nettingi*; Petranka 1998) and Virginia Northern flying squirrel (*Glaucomys sabrinus fuscus*; Odom et al. 2001; Ford et al. 2004). Moreover, there are numerous other endemics with northern affinities that are largely restricted to these forests (McDonald 1993; White et al. 1993).

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Prior to European settlement, Hopkins (1899) estimated 600,000 ha of subalpine coniferous forests existing in West Virginia where red spruce comprised 50% of the overstory in association with northern hardwood species such as Yellow birch (*Betula alleghaniensis*), Sugar maple (*Acer saccharum*), American beech (*Fagus grandifolia*), Black cherry (*Prunus serotina*), and Eastern hemlock (*Tsuga canadensis*). The advent of the railroad expansion (1880–1920) combined with advances in sawmill technology resulted in the harvest of most of the red spruce–dominated forests (Clarkson 1964; Lewis 1998). Following harvest, large-scale wildfires burned much of the area repeatedly, sometimes consuming the entire humus layer to bedrock; severe wind and water erosion of the topsoil further added to the degradation (Allard & Leonard 1952; Lewis 1998).

The most severely disturbed red spruce stands were converted to shrub- or grass balds (Brooks 1911; Rentch & Fortney 1997). However, most regenerated to northern hardwood communities, with a negligible red spruce presence (Schuler et al. 2002). For example, the 14,000 ha Canaan Valley area was dominated by red spruce–eastern hemlock forests prior to logging; by 2000, less than 500 ha remained (Fortney & Rentch 2003). Similarly, USDA Forest Service Forest Inventory and Analysis data suggest that only 12,000 ha of red spruce forests remain in West Virginia (USDA Forest Service 2006*b*); however, ample opportunities exist on as much as 60,000 ha available for potential red spruce restoration (Moore 2005).

Regional assessments of red spruce growth, health and vigor, ownership patterns, and the maturation of the northern hardwood forests that occupy much of the historic red spruce habitat suggest that the present period might be an optimal time for spruce restoration. During the 1980s and 1990s, reductions in health and vigor of high-elevation red spruce were reported throughout its eastern range, including the central (Adams et al. 1985; Eager & Adams 1992) and southern (Cook 1988; Bruck et al. 1989) Appalachians. However, studies by Leblanc et al. (1992) and Reams et al. (1993) concluded that this decline was within the historical range of variability for southern red spruce populations. Moreover, there are recent reports of stabilization of annual growth rates (Reams et al. 1993; Hornbeck & Kochenderfer 1998) and improvements in red spruce crown condition and nutrient status (Audley et al. 1998) in the region. Nevertheless, concerns persist that airborne pollution, acid deposition, ozone, and climatic change are contributing to a regional decline in red spruce radial growth (Webster et al. 2004) and ecosystem function (Boggs et al. 2005; Petty & Thorne 2005). On private lands, surface mining and recreational, second home, and wind energy development also pose ongoing forest fragmentation and conversion threats to red spruce stands (Schuler et al. 2002).

In comparison to other montane coniferous species such as eastern hemlock and Balsam fir (*Abies balsamea*) in the central Appalachians, red spruce has relatively fewer natural or exotic pests and diseases (Blum 1990; but see Hicks & Mudrick 1994), at least until it matures (Hopkins 1899; Frank & Bjorkbom 1973). Hopkins (1899) documented extensive outbreaks of the Spruce bark beetle (*Polygraphus rufipennis*), although these were in older and larger diameter stands prior to extensive harvest. West Virginia is south of the natural range of the Eastern spruce budworm (*Choristoneura fumiferana*) (Kucera & Orr 2006; Karen Kish, West Virginia Department of Agriculture, personal communication, 2006), a serious pest of red spruce. White-tailed deer (*Odocoileus virginianus*) herbivory, a significant problem for many woody species in this portion of the central Appalachians (Campbell et al. 2006), has much less impact on red spruce. Typically, red spruce is a less preferred browse than balsam fir, eastern hemlock, or almost all the hardwood species occurring in region (Telfer 1972). Fortunately, in the 80–100 years since logging and catastrophic burning, a continuous hardwood canopy cover has also improved soil conditions, favoring germination and survival of red spruce seedlings (Pielke 1981), and there is evidence that red spruce is naturally reestablishing itself on sites where it formerly occurred (Adams et al. 1995; Mayfield 1997).

By integrating knowledge of site quality, tree life history traits, and competitive growth strategies, appropriate silvicultural practices can be designed for nearly any forest restoration objective, including wildlife habitat (particularly for rare species), biodiversity, and accelerating old-growth conditions. In the central Appalachians, patches of northern hardwood forests with a suppressed red spruce understory provide focal points for restoration aimed at increasing the extent of red spruce and improving habitat for rare species dependent on conifers. Restoration forestry that modifies species composition and stand structure can steer the future trajectory of extant forests toward a desired condition of increased red spruce composition (Schuler et al. 2002; Stanturf et al. 2004; Menzel et al. 2006).

In an effort to better understand the existing red spruce resource and to assess its restoration potential, we examined second-growth northern hardwood stands with a red spruce component. Herein, we had three following objectives: (1) to examine stand development histories, with a focus on understory red spruce dynamics (tree size, growth rates over time, age of establishment, indications of prior release); (2) to explore if silvicultural thinning can promote overstory red spruce using a 100-year growth simulation; and (3) to assess the prospects for red spruce restoration in context of the central Appalachian landscape (e.g., opportunities/restrictions due to diverse ownership patterns and management activities and prevailing natural disturbance regimes).

Methods

Study Area

Regionally, red spruce and spruce–northern hardwood mixtures occur along high ridges and plateaus (>1,000 m) in the Allegheny Mountain subsection of the Appalachian Plateau Physiographic Province (Fenneman 1939). Mountains are capped by Pennsylvanian sandstone and shale; soils are frigid silt or sandy loam soils that are stony, strongly acid, and relatively infertile (Losche & Beverage 1967; USDA Soil Conservation Service 1982; Flegal 1999). Red spruce site indexes (base age 50 years) ranged from 12.8 to 19.8 m depending on elevation and soil type (Flegal 1999). Climate is continental, with frequent fog, high annual precipitation, and the possibility of freezing temperatures any month of the year. Average daily minimum and maximum temperatures are, respectively, –9.1 and 1.3°C in January and 13.0 and 24.3°C in July (SRCC 2006). Average annual precipitation is 152 cm/yr, with more than 380 cm of average annual snowfall.

Our study area was characterized by large tracts of public forestland that contains more than 66% of the existing and potential red spruce forest habitat in West Virginia (Menzel et al. 2006). We selected two study stands in each of the following locations: Monongahela National Forest (MNF; MNF1 and MNF2) in Greenbrier and Pocahontas counties; Kumbrabow State Forest (KSF; KSF1 and KSF2) in Randolph County; and Canaan Valley National Wildlife Refuge (CVWR; CVWR1 and CWWR2) in Tucker County. Our study stand selection on the MNF was constrained by the need to avoid impacts to existing populations of Virginia northern flying squirrel and Cheat Mountain salamander, as well as planned silvicultural activities (MNF Land and Resource Management Plan 2005), whereas those on the KSF and CVWR stands were linked to ongoing Virginia northern flying squirrel investigations (B. Breshock, West Virginia Division of Forestry, personal communication and K. Sturm, USDI Fish and Wildlife Service, personal communication, 2006). Study stand size was variable due to density of understory spruce; however, each ranged from 10 to 15 ha.

Data Collection

In September–October 2005, we established sample plots (radius = 6.1 m) in each study stand centered on thrifty understory red spruce that were likely candidates for overhead release; these were overtopped trees ranging from 2.5 to 16.0 cm diameter at breast height (dbh) and live crown ratios greater than 60%. We measured dbh and total height of each target understory tree and projected a vertical cylinder above the crown of each target tree and tallied, measured, and marked (for simulated removal) all trees whose crown fell within that space. All remaining stems greater than 2.54 cm dbh were identified to species, measured at dbh, and assigned a crown class. To avoid confounding effects of adjacent sample plots, we maintained a distance of at least 20 m between plots centered on target trees. Target trees averaged 7.7 ± 0.2 cm in diameter and 5.5 ± 0.1 m in height ($\overline{X}$ ± SE); 18–30 plots/stand were sampled depending on stand size, configuration, and target tree availability. Two target trees were identified in some sample plots if both met our selection criteria and would be released by removal of the same overtopping hardwood trees.

To assess stand establishment and growth/disturbance history, we cored approximately 25 trees for age and radial growth analyses at each study stand. On average, this included 15 red spruce understory trees and 10 overstory trees, including codominant hardwood and coniferous trees (n = 165). We cored red spruce saplings approximately 0.3 m from ground surface and overstory codominants at breast height. We extracted cores parallel to topographic contours to avoid tension or compression wood and prepared sample cores and cross-sections using standard dendrochronological techniques (Stokes & Smiley 1968). We measured annual rings under a dissecting microscope to the nearest 0.01 mm in conjunction with J2X software (VoorTech Consulting 2000). We further validated tree-ring dating using COFECHA (Grissino-Mayer et al. 1997), using 50-year segments lagged successively by 25 years. Abrupt and prolonged increases in radial growth resulting from canopy mortality and release of growing space were identified using a percent growth change (%GC) technique that compared preceding to superceding 10-year radial means (Nowacki & Abrams 1997). A 25%GC threshold was used to identify releases for overstory trees (Nowacki & Abrams 1997), whereas a 100% threshold used for understory red spruce (Lorimer & Frelich 1989). Releases for overstory trees and understory red spruce were summed separately and reported by decade to depict stand development histories.

Growth Simulation

We simulated tree growth in each plot under release and no-release scenarios over a 100-year period using the north-east variant of the TWIGS growth model (NE-TWIGS), operating within the Forest Vegetation Simulator (FVS) and SUPPOSE version 1.18 (USDA Forest Service 2006*a*) platforms. Plot results were summarized as stand-level data. Simulations were run at 10-year intervals from 2005 to 2106, with a release event at 2010. We used the FVS keyword *Thin PRSC* to simulate a liberation cut that removed all trees that overtopped the crowns of target red spruce. On average, the release of target spruce required basal area and tree density reductions of 53 and 16%, respectively, per plot.

Because there was a wide disparity in initial red spruce basal area and trees per hectare, we grouped stands into "High" spruce (CVWR2 and MNF1) and "Low" spruce (MNF2, KSF1 and KSF2, and CVWR1). The two High spruce stands had a much larger component of existing overstory red spruce and contained three to four times more red spruce basal area and trees per hectare as well as larger target release trees on average (Table 1).

We used a multiplier of 1.1 to augment height growth of small red spruce trees (<12.7 cm dbh) and diameter growth of larger trees (≥12.7 cm dbh). In FVS, small tree diameter

Table 1. Initial data from six red spruce–northern hardwood red spruce stands in east-central West Virginia inventoried in 2005.

			Basal Area (m^2/ha)		Tph		Red Spruce	
Stand	Elevation (m)	Aspect	Red Spruce	Other	Red Spruce	Other	Average height (m)	QMD (cm)
CVWR1	1,219	SSW	1.6	29.3	345	1,264	5.1	7.7
CVWR2	1,195	SW	4.9	33.6	853	695	6.4	8.6
KSF1	1,097	NA*	1.0	34.3	305	1,219	4.6	6.5
KSF2	1,109	WNW	1.0	35.6	298	1,122	4.6	6.6
MNF1	1,280	N	7.0	26.7	937	1,092	6.3	9.7
MNF2	1,158	NE	1.6	24.4	251	1,177	6.5	9.1

Tph, trees per hectare; SSW, South, southwest; SW, southwest; NA, not applicable; WNW, west, northwest; N, north; NE, northeast.
Data represent sample plots containing target understory red spruce, projected to the stand level. Other includes all non-red spruce (*Picea rubens*) trees, primarily Red maple (*Acer saccharum*), Yellow birch (*Betula alleghaniensis*), Black cherry (*Prunus serotina*), and Eastern hemlock (*Tsuga canadensis*). Based on initial red spruce density, CVWR2 and MNF1 classified as High spruce and CVWR1, KSF2, and MNF2 classified as Low spruce.
* Stand was on a flat with no measurable aspect.

growth is estimated as a function of height, so the height growth multiplier also tends to increase diameter growth of these smaller stems. In contrast, height growth of large trees is calculated after diameter growth is simulated. The multipliers were added based on our assumption that the existing red spruce NE-TWIGS growth model, using red spruce growth and yield data from Adirondack and New England forests, underestimated growth of red spruce forests in southern and central Appalachian Mountains (Korstian 1937; Minckler 1940; Blum 1990).

Additionally, because our sampling method selected plot centers based on the presence of suitable target red spruce, reported metrics of basal area and tree density per hectare and tree height and diameter changes are biased, not based on either random or systematic sampling, and therefore should not be interpreted as true "stand" values. Rather, these values are representative of conditions in and immediately surrounding our sample plots. Because of the scattered or clumped nature of suitable understory spruce, true, unbiased, stand-level values for these metrics, as well as basal area removals during thinning, would all undoubtedly be lower.

We report all simulation results as values for "red spruce" and "other." The latter included stand-specific combinations of primarily yellow birch, Red maple (*Acer rubrum*), black cherry, and American beech. Additional species in this category were eastern hemlock; Black birch (*Betula lenta*); Serviceberry (*Amelanchier arborea*); sugar maple; Fraser magnolia (*Magnolia fraseri*); and a host of tall shrub species such as Mountain holly (*Ilex montana*), Striped maple (*Ac. pensylvanica*), and Witch hazel (*Hamamelis virginiana*).

Results

Stand History and Radial Growth Patterns

Age–diameter distributions and supporting inventory data suggest that two stands (CVWR2 and MNF2) are currently in the late stem exclusion stage of forest development (Oliver & Larson 1996), whereas four stands, possessing two distinct age cohorts, are in the understory reinitation stage (KSF1, KSF2, CVWR1, and MNF1). This distinction is important as thinning treatments would release a largely older component of red spruce saplings in stands still undergoing stem exclusion, whereas treatments in understory reinitiation stands would mostly release a younger generation of trees. In all stands, species are differentiated by growth rate and canopy position, with hardwoods consistently making up the larger size and crown classes (dominant, codominant, intermediate) and red spruce, though present in larger classes, mainly restricted to smaller size and crown classes (overtopped/suppressed). Overstories of five of the six stands comprised a single cohort originating after clear-cut harvests from 1890 to 1930 (Figs. 1–3, top graphs). MNF1 appears to have an uneven-aged, multicohort overstory, a probable artifact of partial harvests and natural disturbances that left larger residuals and released preexisting smaller trees. At this site, there was more or less continuous establishment of overstory red spruce, yellow birch, red maple, and American beech stems between 1845 and 1945. Based on the age and radial growth trends, we estimate that substantial logging took place around 1907. Understory red spruce in this stand tended to be larger, with stems up to 20 cm dbh subordinate to larger and older overstory trees.

The four understory reinitiation stands had two distinct understory red spruce cohorts: one that originated in the immediate aftermath of late-1800/early-1900 harvest (hence the same age as the current overstory) and a second cohort 20–60 years younger (Figs. 1–3, top graph). At KSF2 and CVWR1, only one cored understory red spruce appears to be a member of the harvest-initiated age class. For the two stem exclusion stands, the understory red spruce cohort initiated with the overstory following harvest with an extended period of spruce regeneration over time.

Annual radial growth curves for five stands with quasi-even-aged overstories show high initial growth rates of canopy trees consistent with stand initiation and free-to-grow conditions following harvest (Figs. 1–3, middle graph). There was a similar, although relatively smaller, spike in annual growth rates of residual trees around 1907

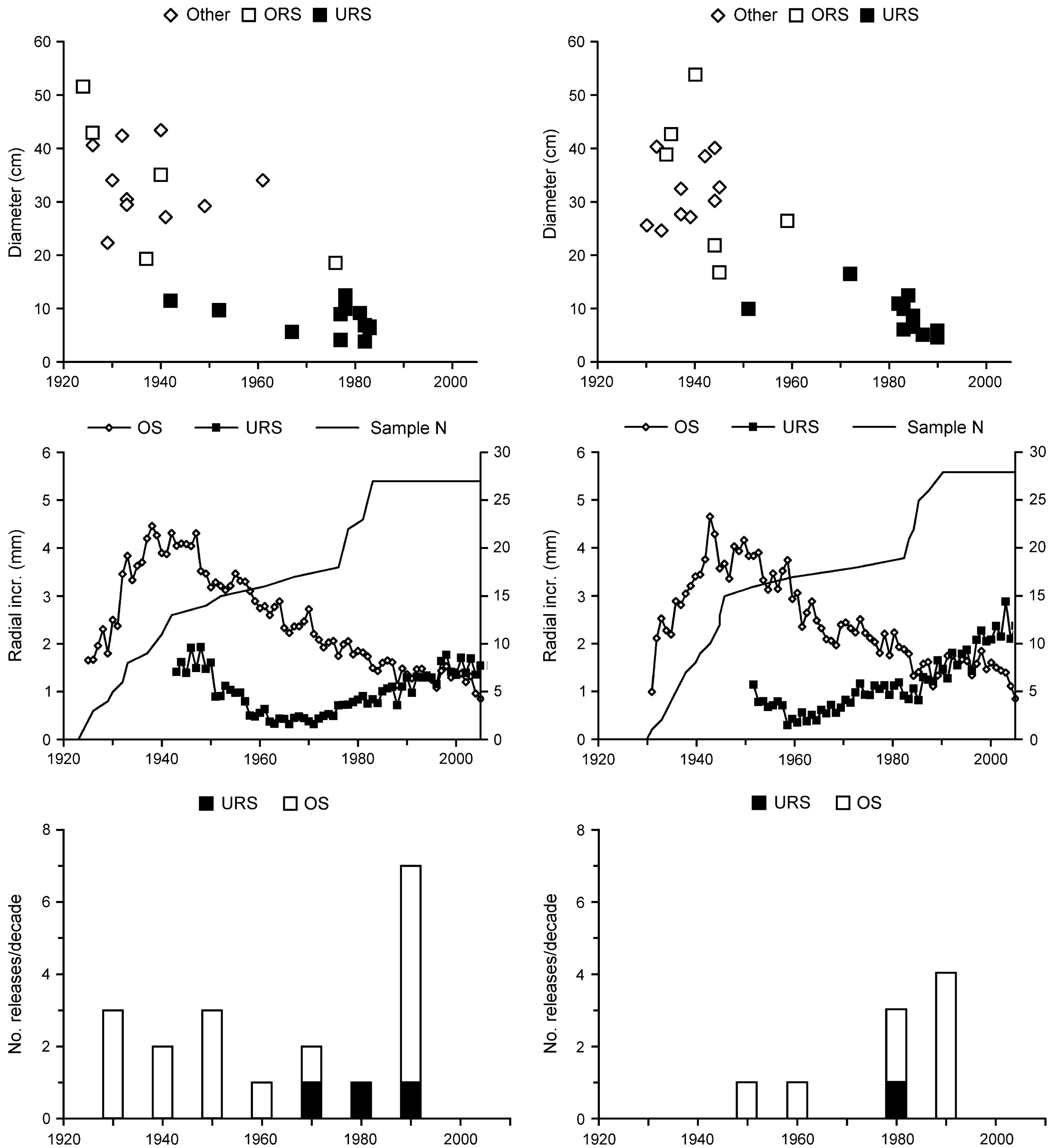

Figure 1. Age–diameter relations (top graph), radial growth chronologies and sample depth (middle graph), and sums of decadal tree releases (bottom graph) for KSF1 and KSF2 in West Virginia, 2005, for overstory Red spruce (*Picea rubens*) (ORS), other overstory trees (Other), all overstory trees (OS), and red spruce saplings (URS). Growth change percentages of 25–49%, 50–99%, and more than or equal to 100% used to depict minor, moderate, and major releases. For overstory trees, all releases shown; only major releases are shown for understory red spruce.

at MNF1. Between stand initiation and 1980, growth curves of suppressed understory red spruce were flat, averaging 0.60 ± 0.02 mm/yr. Since 1980, average understory growth rates increased for all stands to 1.08 ± 0.03 mm/yr and were approximately equal to those of overstory trees (both red spruce and hardwoods). This increase was most striking for the KSF sites where understory red spruce radial growth exceeded overstory growth rates after 1990.

Understory red spruce growth increases generally conform to spikes in the number of disturbance/release events during the period 1970–1990 (Figs. 1–3, bottom graph). The %GC analysis of these releases revealed that 40% of

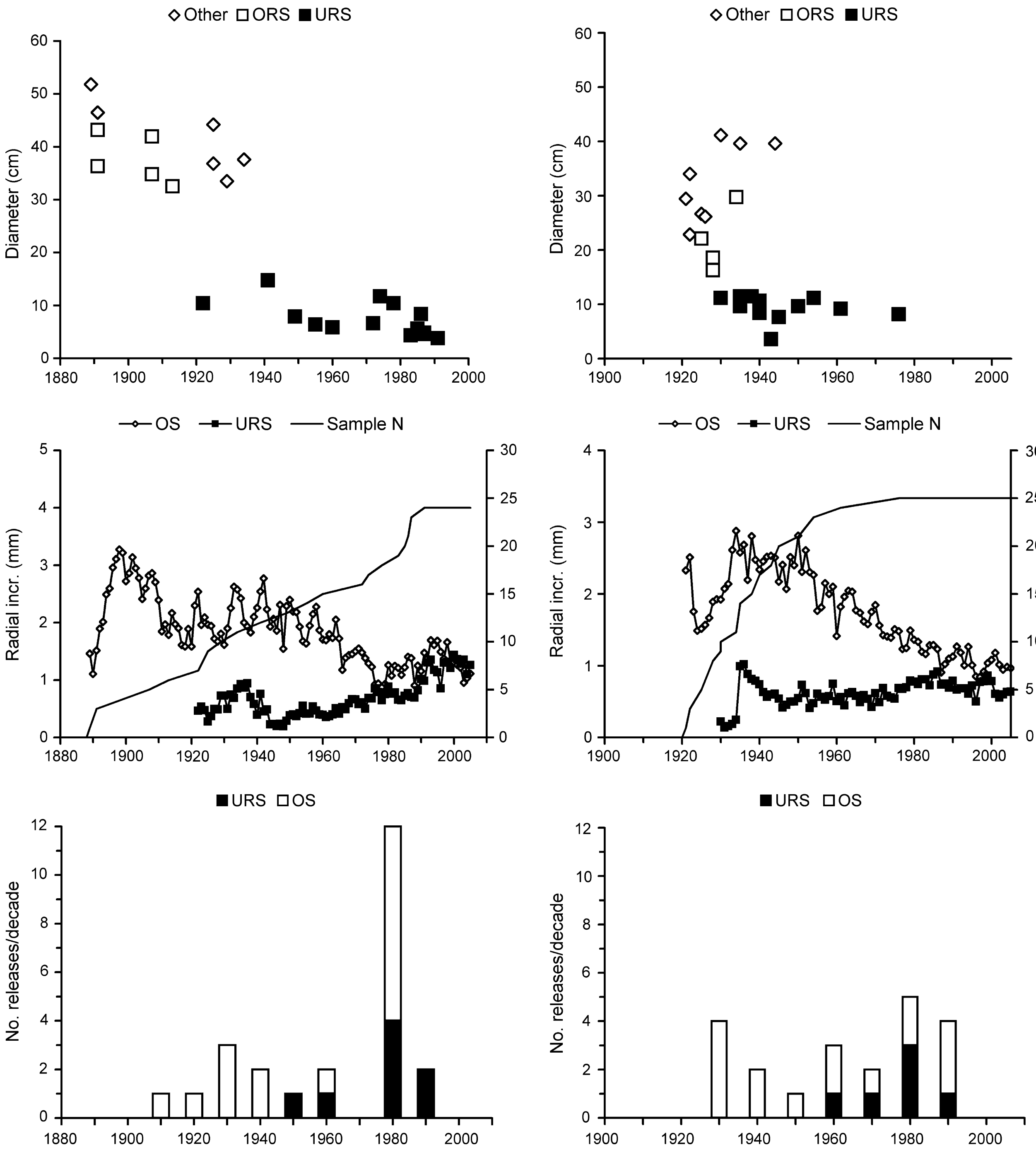

Figure 2. Age–diameter relations (top graph), radial growth chronologies and sample depth (middle graph), and sums of decadal tree releases (bottom graph) for CVWR1 and CVWR2 in West Virginia, 2005, for overstory Red spruce (*Picea rubens*) (ORS), other overstory trees (Other), all overstory trees (OS), and red spruce saplings (URS). Growth change percentages of 25–49%, 50–99%, and more than or equal to 100% used to depict minor, moderate, and major releases. For overstory trees, all releases shown; only major releases are shown for understory red spruce.

the understory red spruce saplings showed evidence of major releases (%GC $\geq$ 100%). Mean sapling age at release was 39 ± 4 years and mean diameter 2.1 ± 0.3 cm. Maximum ages and diameters at release were 79 years and 6.6 cm, respectively. About 6% of the understory red spruce experienced two or more releases.

Growth Simulation

High Spruce. In 2005, red spruce basal area (BA) and stem density averaged 5.9 m^2/ha and 891 trees/ha in sample plots containing target red spruce (radius = 6.1 m) (Fig. 4). On average, the removal of competing deciduous trees resulted in a 56% reduction in basal area and a 13%

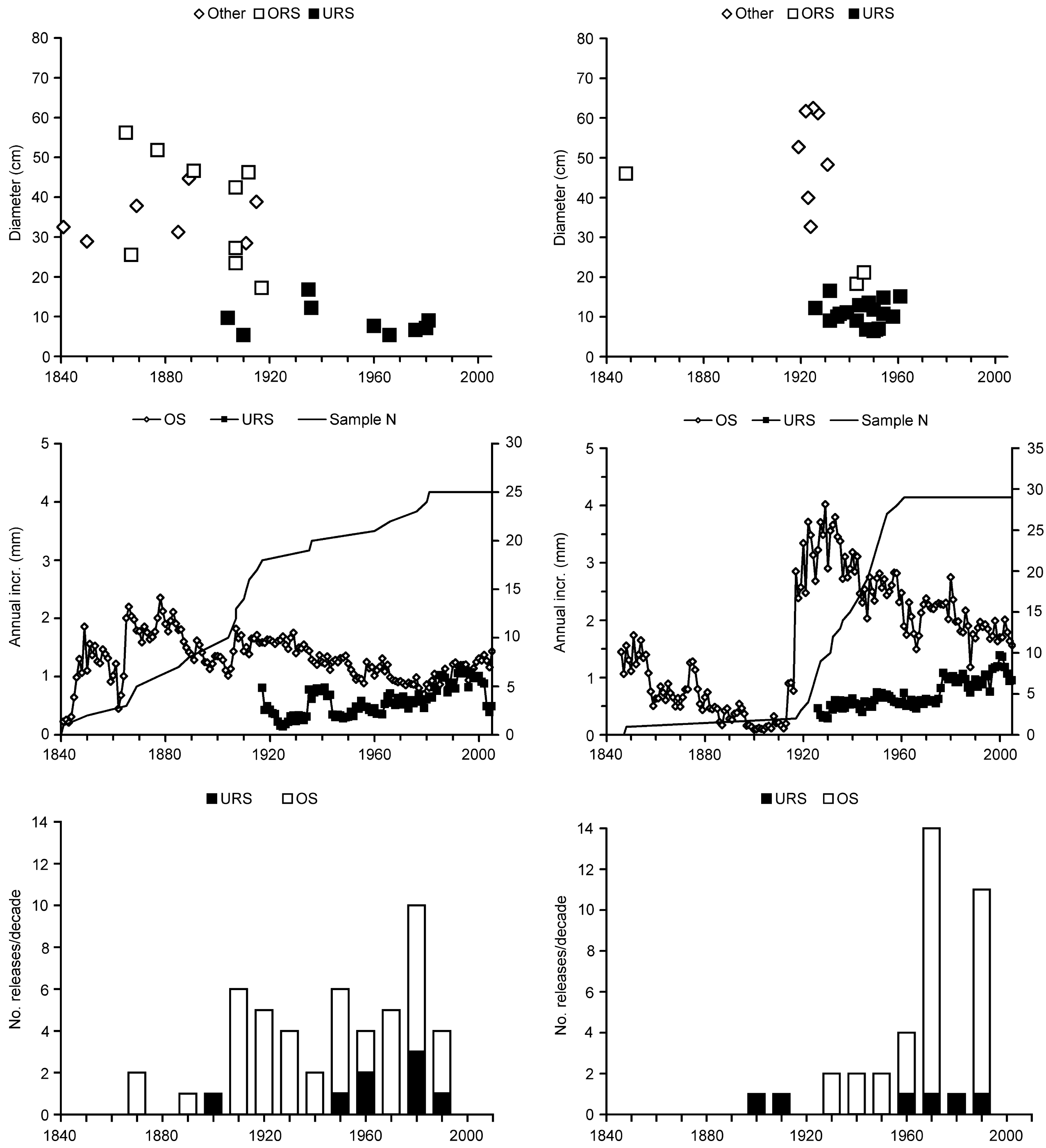

Figure 3. Age–diameter relations (top graph), radial growth chronologies and sample depth (middle graph), and sums of decadal tree releases (bottom graph) for MNF1 and MNF2 in West Virginia, 2005, for overstory Red spruce (*Picea rubens*) (ORS), other overstory trees (Other), all overstory trees (OS), and red spruce saplings (URS). Growth change percentages of 25–49%, 50–99%, and more than or equal to 100% used to depict minor, moderate, and major releases. For overstory trees, all releases shown; only major releases are shown for understory red spruce.

reduction in tree density. Because of the sampling methodology and scattered nature of target trees, true stand-level basal area reductions would be less. By 2015, the result was a mixed stand, with a 41:59% BA ratio of red spruce to competitors. By the end of the 100-year simulation, red spruce basal area showed a 4-fold increase to 24.4 m^2, whereas hardwood basal area decreased to 24.9 m^2. The rate of red spruce BA increase was greatest in the 20 years following thinning (>2.3 m^2/decade). For the no-release scenario, red spruce basal area in the vicinity of red spruce target trees only increased from 5.9 to 10.8 m^2/ha (22% of the total stand basal area by 2105).

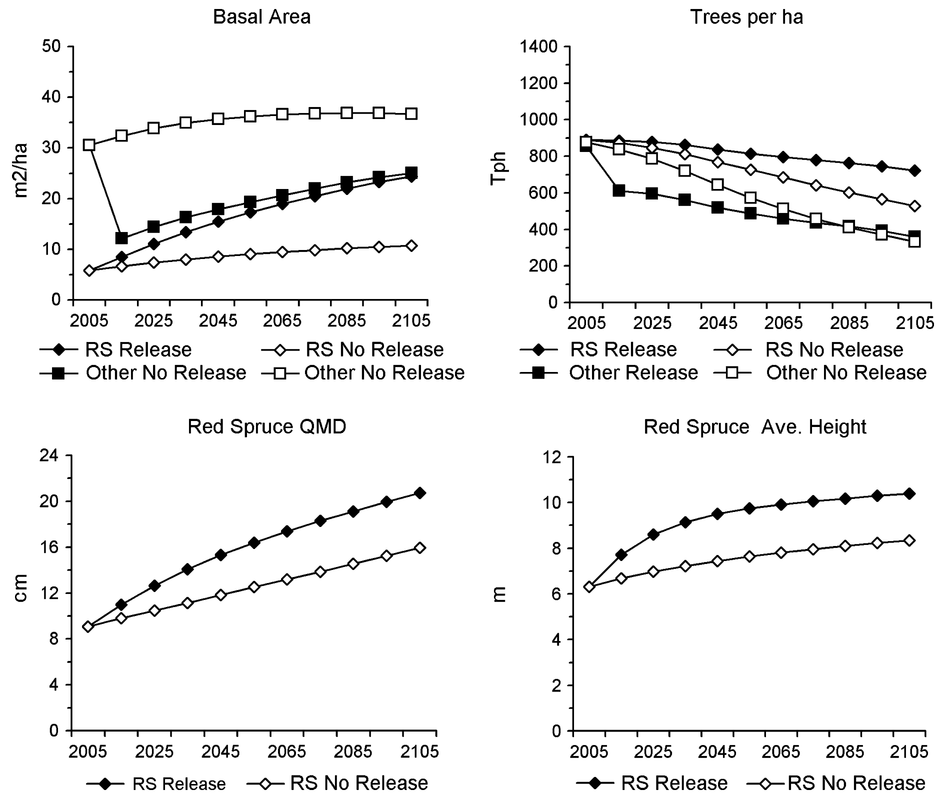

Figure 4. Changes in basal area per hectare (m^2/ha), trees per hectare, QMD (cm), and average height (m) over a 100-year simulation period after release of target Red spruce (*Picea rubens*) saplings at two High spruce stands in West Virginia. See legend of Table 1 for definition of Other. Values are weighted by the number of plots per stand.

Even though High spruce stands contained some overstory red spruce, the initial diameter distribution was still heavily skewed toward the smallest dbh classes; for instance, 831 of 891 trees/ha were in the 5–10 cm dbh classes (data not shown). When the 2105 diameter distributions of the two treatments were compared, the release treatment produced 168 spruce trees/ha in the 25 cm and larger dbh classes versus only 28 for the no-release treatment. Over the entire simulation, spruce quadratic mean diameter (QMD) increased to 21 cm for the release scenario compared to 16 cm for no-release scenario (Fig. 4). The average height increase of the release treatment was nearly twice that of the no-release treatment; however, differences in relative height growth rates stabilized between the two treatments with canopy closure. Modeled red spruce mortality for the no-release treatment was 40.6% over the 100-year modeling period versus 18.9% for the thin treatment.

Low Spruce. Overstory red spruce was a rare feature in these four stands. In 2005, red spruce BA per hectare and trees per hectare averaged 1.4 m^2 and 303 trees in the vicinity of sample plots, respectively, representing only 3.6 and 21% of stand totals. By the end of the 100-year simulation, red spruce basal area showed a 4-fold increase to 7.2 m^2/ha, 17% of total stand basal area, and the rate of increase was relatively consistent over the first 40 years following thinning (Fig. 5). "Other" species rapidly recovered from early basal area removal, increasing from 17.3 m^2 in 2015 to 36.3 m^2 by the end of the simulation. For the no-release scenario, red spruce basal area also doubled; yet, by 2105, this species constituted only 7% of the total stand basal area.

As with the High spruce stands, the initial diameter distribution of red spruce was heavily skewed toward the smallest dbh classes (data not shown). When ending diameter distributions of the two treatments were compared, the release treatment produced 48 spruce trees/ha in the 25 cm and larger dbh classes versus only 8 for the no-release treatment, as well as an average height of 3.9 vs. 1.9 m. Changes in red spruce QMD and average height were somewhat lower but still comparable to those of the High spruce stands. Over the entire simulation, red spruce QMD increased from 7.6 to 18.5 cm for the release scenario compared to 14.2 cm for no-release scenario. Red spruce mortality in the no-release simulation was twice that in the thin simulation (31.3 and 13.9%, respectively).

Discussion

The northern hardwood stands sampled in this study were 80–120 years old and in or nearing the understory reinitation stage of forest development. It is during this stage

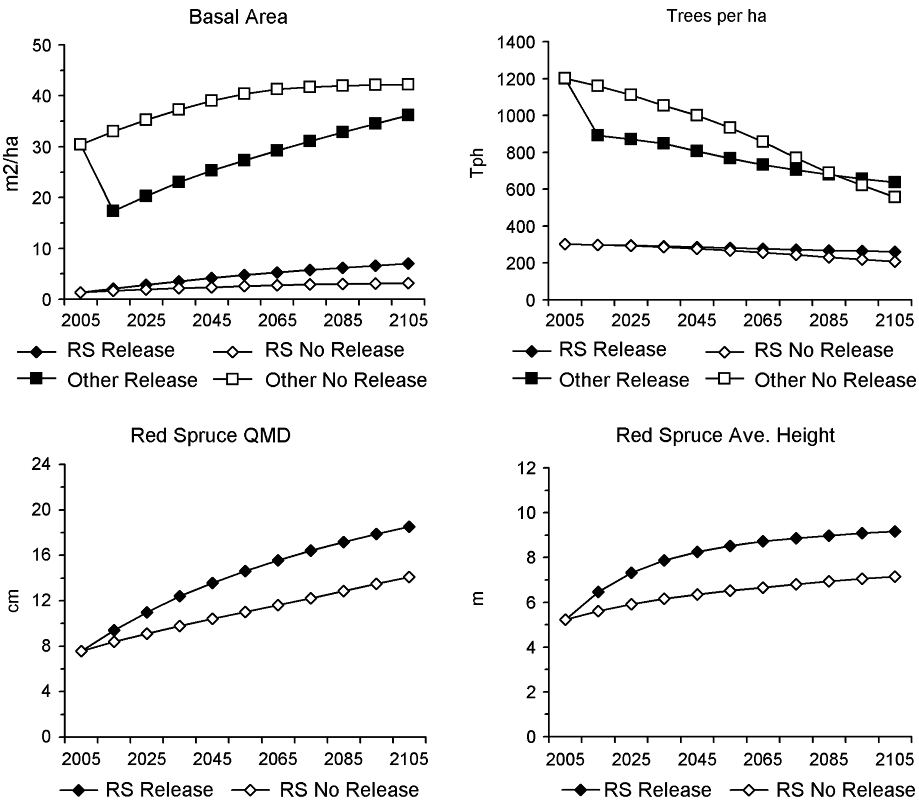

Figure 5. Changes in basal area per hectare (m^2/ha), trees per hectare, QMD (cm), and average height (m) over a 100-year simulation period after release of target Red spruce (*Picea rubens*) saplings at four Low spruce stands in West Virginia. See legend of Table 1 for definition of Other. Values are weighted by the number of plots per stand.

that the next generation of trees becomes established as existing canopy individuals die and release growing space (Oliver & Larson 1996). As stands mature, crown size increases, and canopy gaps become inherently larger, as does the likelihood that gaps will be filled by ingrowth rather than by lateral expansion of the existing overstory. New cohorts of regeneration coupled with currently higher radial growth rates of understory red spruce (since 1980) compared to the past suggest that canopy breakup and understory reinitiation are underway. Although there are relatively large numbers of tall shrubs in the understory, red spruce is the most abundant potential overstory tree species. Competition from remaining hardwoods can be reduced by active management, for example, by girdling or stem injection (Westveld 1937; Hornbeck & Kochenderfer 1998).

Based on our simulations, a release of target red spruce understory trees from competing overstory hardwoods should double red spruce basal area and yield a mixed spruce–hardwood stand after a relatively short time period. Where red spruce was initially more abundant, its basal area should approach as much as 40–45% of the total basal area in as little as 10–20 years. In linking stand characteristics to Virginia northern flying squirrel habitat needs, Ford et al. (2004) observed that more than 50% chance of occupancy by that endangered sciurid required an overstory importance value of 35% for red spruce, regardless of other habitat factors such as elevation or aspect. Where red spruce was less abundant, the relative proportion of red spruce should approach 15–20% after 50 years. This treatment could still provide suitable or occupied habitat at a predicted probability of 50–75% at elevations above 1,036 m (Ford et al. 2004; Menzel et al. 2006). Compared to the no-release treatment, the simulations project that thinning would double expected diameter and height growth. However, if specific red spruce are targeted for release in a liberation approach, resultant basal area, height, and diameter growth rates of released trees would probably be higher than those predicted by our simulation.

Despite the age of the understory spruce, we do not believe that age of the understory spruce is a complicating factor for release and restoration attempts. Red spruce is very shade tolerant and can persist in the understory for long periods of time in heavily shaded conditions (Hart 1959; Blum 1990; Seymour 1992). Our data further validate the potential for red spruce to respond after extended suppression periods. This characteristic can give red spruce a height advantage over other understory species when released in small gaps (Seymour 1992), although larger disturbances may favor faster growing species such as black cherry and yellow birch. Red spruce can respond to release after as much as 100 years of suppression (Blum 1990; Seymour 1995). The vigor of its response is independent of the suppression severity, although full canopy release may require several release episodes (White et al. 1985; Wu et al. 1999). Moreover, the suppression duration has relatively less influence on the amount of growth after release than do release conditions such as gap size and orientation (Wu et al. 1999). However, the time necessary for growth recovery and canopy accession once release occurs is uncertain. Our simulation places some bounds on that time period; however, detection of true range expansion would require actual monitoring for changes in composition over a long time period.

Releasing suitable understory red spruce by creating small canopy gaps could be an effective way to restore the red spruce component by emulating the natural disturbance regime of the past. In spruce/spruce–fir forest types of the southern Appalachians, Gorman (2005) estimated a 650-year return interval for stand replacement fires that were associated with a combination of extended drought and large inputs of coarse woody debris from insect infestations or blowdowns (Hopkins 1891; Hopkins 1899). Nonreplacement surface fires were even less frequent because fuel moisture and humidity were generally high and lightning was accompanied by rainfall (Harmon 1981). Accordingly, the predominant disturbance regime is a single-tree or a small group gap-phase replacement characterized by frequent partial disturbances that produce a finely patterned, diverse mosaic dominated by late-successional species and structure (Seymour et al. 2002). For example, in an old-growth red spruce stand in Maine, Fraver and White (2005) found that 40% of the canopy gaps consisted of single-tree events and no evidence of stand-replacing disturbances. In North Carolina, 78% of the canopy gaps were created by the fall of a single tree (White et al. 1985), and mortality of overstory trees was concentrated in larger individuals (>60 cm dbh; Busing & Wu 1989).

Unlike other forest restoration projects that are burdened by fragmentation of potential habitat and land ownership, about two-thirds of the area of red spruce in West Virginia are located on the MNF and other public lands (Menzel et al. 2006) where management efforts to protect or enhance habitat for threatened and endangered species are mandated and protection from fire and exploitative logging exists. The current draft Forest Plan Revision identified approximately 60,000 ha available for red spruce restoration on the MNF (Moore 2005). Statewide, the Virginia northern flying squirrel habitat model by Menzel et al. (2006) identified approximately 224,000 ha throughout east-central West Virginia as occupied or potentially occupiable habitat. Conceivably, the spatial nature of this model could be combined with more resolute stand data and observations from our study to optimize identification of forest patches for red spruce restoration to benefit the habitat type as well as to increase patch size and habitat connectivity for the Virginia northern flying squirrel and other high-elevation faunal elements.

Whereas the proposed silvicultural treatment may prove to be a sound initial approach to red spruce restoration, additional ecological factors may have to be addressed. For example, vegetation models (Iverson & Prasad 1998) suggest that projected climate change may alter red spruce distribution (Webb et al. 1993) and complicate restoration, particularly on marginal habitat and in areas near the southern limit of its range. We suggest that restoration efforts should initially be concentrated in higher elevations where red spruce is most viable, even with potential climate change, and that these patches should be linked to subsequent efforts at lower elevations. Nevertheless, we admit that the impacts of climate change are not fully known and that restoration activates should be monitored with this in mind so that managers can prioritize restoration areas and select those with the greatest likelihood of success.

Conclusions

Our study complements earlier growth simulations employing silvicultural manipulations by Schuler et al. (2002) in mixed, even-aged natural stands and by Hornbeck and Kochenderfer (1998) in natural stands and 50-year-old plantations. The release simulation in this study involves the removal of approximately 50% of the basal area in sample plots centered on target understory spruce. Although this value is within the range recommended by Frank and Bjorkbom (1973) for secondary red spruce stands, the potential for windthrow persists and needs to be examined further. Comparable results may derive from repeated but lighter thinnings, or, if a liberation-release approach was used, by implementing less than a 100% release.

Forest restoration requires more than just altering forest structure and changing species composition; however, any effort must take into account the role of individual and, particularly, key species because these play a disproportionate role in ecosystem structure (Franklin et al. 2002) and function (Palmer et al. 1997). Implementation of our tree species–centered, silvicultural approach and the stand prescriptions modeled in our study can also be part of a diverse restoration strategy that includes underplanting red spruce on historic habitat where it is now absent, carefully managing second-growth stands for older age characteristics and structure, and protecting older stands with legacy elements as remnants of the original forest. Because one of the primary justifications for restoration of red spruce forests is increasing suitable habitat for the endangered Virginia northern flying squirrel and other biotic components of these high-elevation communities, future restoration plans should also incorporate a spatial component that targets the locations of existing red spruce–northern hardwood patches that with restoration would maximize overall patch size and habitat connectivity (Franklin et al. 2002; Menzel et al. 2006).

Implications for Practice

- Use of liberation cutting or herbicide injection to release understory red spruce can potentially double spruce growth rates.
- Red spruce restoration should be targeted for areas with northern hardwoods in the overstory and red spruce in the understory where red spruce formerly dominated the canopy prior to exploitive harvesting.
- Management efforts to enhance red spruce forests should emulate the natural disturbance regime of gap-phase replacement. Costs of restoration activities may be offset by light harvesting of valuable northern hardwood species, in some cases.
- Red spruce restoration in the central Appalachians also enhances Virginia northern flying squirrel habitat.
- Management interest in red spruce restoration is relatively new. Our guidelines have been developed by computer modeling; however, practitioners should use adaptive management to design, monitor, and modify restoration activities to meet specific management objectives.

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