Review

Sustainable Management of Central Appalachian Red Spruce

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Abstract: Red spruce (*Picea rubens*) was historically an important and dominant timber species in the central Appalachian mountain range. The tree species is now found in a small fraction of its original home range. Threatened and endangered organisms such as the Cheat Mountain Salamander (*Plethodon nettingi*) rely on red spruce associated forests for survival. This review provides a background on the history of forest management of red spruce in the central Appalachian region. A meta-analysis was conducted on recent literature (published 2000 or later) of red spruce in the central Appalachian region to highlight key management and conservation concerns. In particular, forest health concerns related to air pollution and climatic stress also are addressed. Approaches to examine the impact of environmental factors on red spruce site productivity are covered. This review also provides sustainable management options for restoration of red spruce in the central Appalachian mountain range.

Keywords: climate change; disturbances; montane forests; red spruce; restoration

1. Introduction

Red spruce (*Picea rubens* Sarg.) was once very common in the central Appalachian Mountains but is now found in only a small portion (estimated to be as low as 7 percent) of its distributional range compared to the past [1] (Figure 1). Forest disturbance resulting primarily from anthropogenic causes such as fire and logging have been large contributors to the decline of red spruce [2]. The natural history of the central Appalachian region indicated that during the maximum extent of the last Wisconsin glaciation, red spruce was dominant in the central Appalachian region and occurred as open red spruce woodlands present at low elevations [3]. With the retreat of the ice sheet approximately 10,000 years ago, red spruce migrated north to more climatically suitable habitat. Relict populations of red spruce were left to persist at high elevations in the Appalachian region.

Restoration of limited forest resources is critical for the future of many forest species. Forest restoration planning and activities rely on established silvicultural methods when deciding how to manage land to promote desired species. Silvics vary for every tree species, as every tree species has different growing and light requirements and reacts to treatments differently. A changing climate will create difficult scenarios in the future for the restoration and promotion of certain species. Considering the climatic shifts that are occurring, restoration approaches that target adaptation, promotion of resiliency, and mitigation of effects, all share a common goal of maintaining target species but use different management techniques to meet the goal [4,5].

Silviculture treatments such as thinnings and release harvests have proven to be effective in promoting the growth of many species throughout North America. Treatments that reduce residual tree densities can improve tree growth and promote resilience to climate change through increased tree vigor [6,7]. Carbon sequestration is an important regulating ecosystem service that forests provide and will continue to be more important

in the future to mitigate atmospheric carbon accumulation. Increases in the growth and health of managed forests can facilitate greater carbon gains through sequestration [8]. Using silvicultural manipulations, managers can sustainably harvest forests that provide long term benefits for the ecosystem and the forest products industry [9].

The objective of this review paper is to provide an overview of different themes related to sustainable management of red spruce in the central Appalachian region. This review provides a background on the history of forest management of red spruce in the central Appalachian region. Forest health concerns related to air pollution and climatic stress are addressed. Approaches to examine the impact of climate on red spruce site productivity are covered. This review also advances sustainable management options for restoration of red spruce in the central Appalachian mountain range.
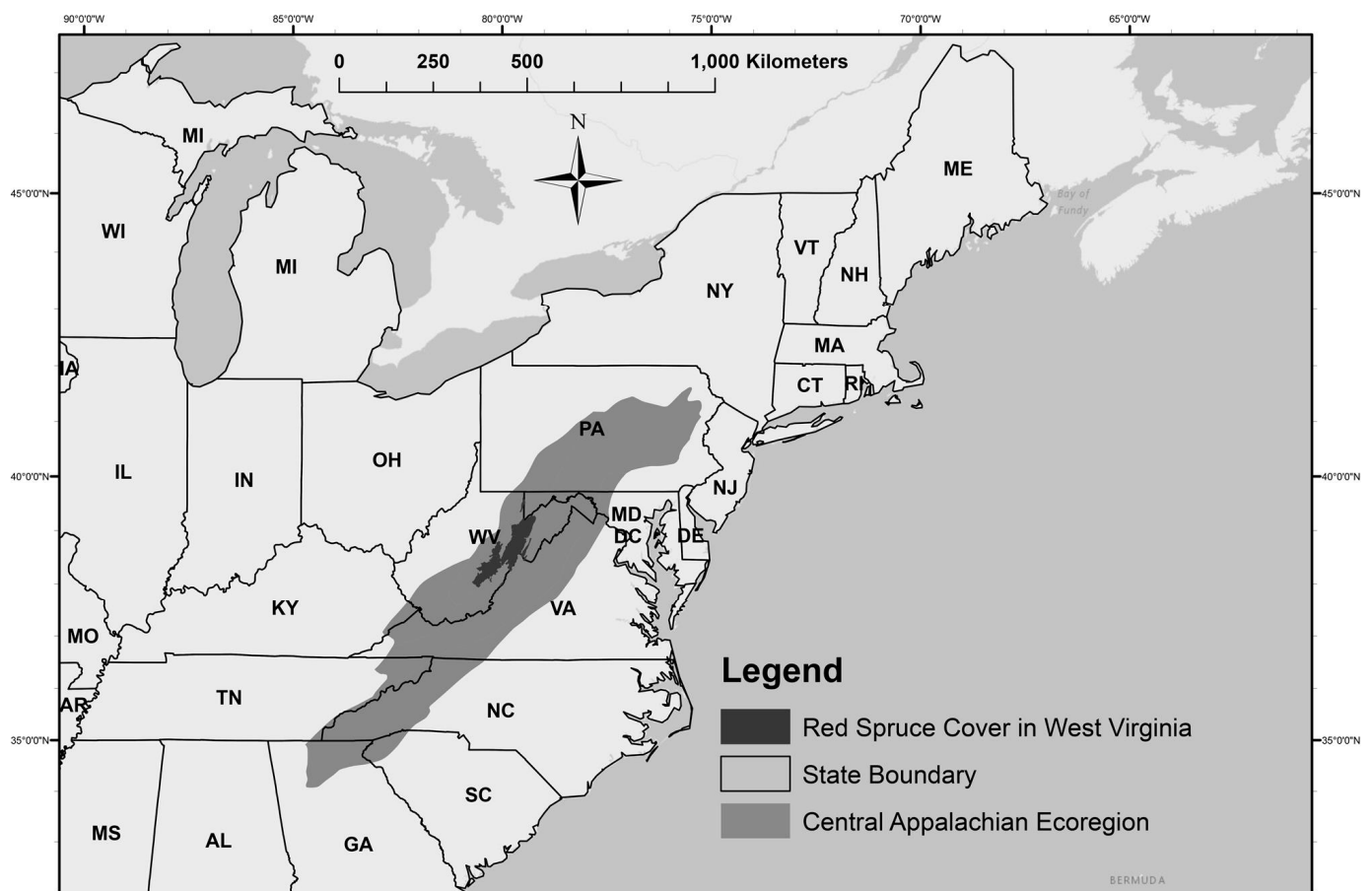

Figure 1. Range distribution map of red spruce in West Virginia [10] within the central Appalachian ecoregion [11].

2. Importance of Red Spruce

Red spruce (*Picea rubens* L.) has been an important timber species throughout much of the northeastern part of North America. Red spruce occurs in pure (Figure 2a) and mixed-species stands (Figure 2b). This species has been valued for its harvestable resources and the ecosystem services it provides. The species' historic value was mainly for structural lumber, pulp fiber, and musical instrument components [2,12]. However, current non-timber values for red spruce are becoming more important and will continue to become more important as red spruce provides critical ecosystem services. Endangered and threatened organisms such as the Cheat Mountain Salamander (*Plethodon netting*) and the recently delisted Virginia northern flying squirrel (*Glaucomys abrinus fuscus*) rely on red spruce forests for survival [13]. Another important ecosystem service red spruce associated forests offer is the ability to sequester large amounts of carbon [14]. Expansion of red spruce would extend these non-timber benefits.
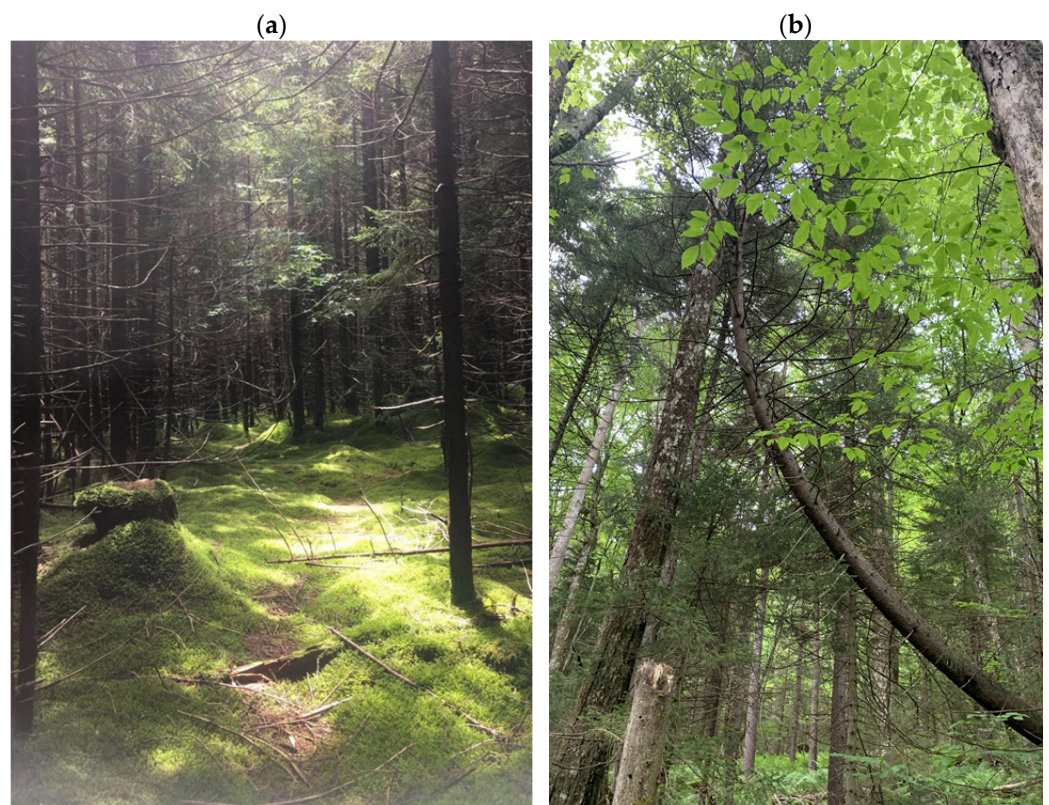
Figure 2. Example of forest stand dominated by red spruce (**a**) and a mixed-species stand containing red spruce and yellow birch (**b**) both located in Monongahela National Forest. Photographs taken by E. Yetter.

Both research and management focus are needed to restore this species back to more than just a fraction of its original extent. In the central Appalachians, red spruce historically covered about 600,000 hectares [15,16]. The species current extent is limited to approximately 10,000 hectares [15,16]. The benefits associated with this tree species point to the importance of maintaining and encouraging the expansion of red spruce forest cover. This literature review will outline important factors that will help aid the restoration of this once common timber species.

3. Red Spruce Silvical Characteristics

High shade tolerance is an important characteristic of red spruce that allows seedlings and saplings to persist in the understory for extended periods of time [17,18]. Red spruce is a long-lived tree species that can live up to 400 years [19]. Despite the longevity of this tree species, the larger stem diameters are usually around 61 cm and seldom reach 76 cm [2]. Total height of red spruce can reach 35 m in the central Appalachians [2]. Red spruce can grow on a variety of sites and soil conditions, including poor sites that are not productive for the growth of competing tree species [19].

Red spruce seldom reproduces from coppice methods [20], rather, it primarily reproduces from seed sources beginning to produce seed when around 30–40 years old [21]. Seed dispersal is facilitated by wind and gravity and can extend up to 100 m from the parent tree [21]. Regeneration and spread of spruce cover is limited by the distance of seed travel and seed source [22]. Seed germination is best in cool and moist sites with large decaying woody debris and softwood litter [23]. These germination requirements are characteristic of the undisturbed understory of spruce forests in the Central Appalachians.

Predation from herbivores has little impact on red spruce regeneration because the species has low palatability to many browsers including white-tailed deer. Browse resistance may offer a competitive advantage for red spruce regeneration over compet-

ing species such as red maple (*Acer rubrum* L.) and yellow birch (*Betula alleghaniensis* Britton; [22]). In contrast, competition from other plant species limits spruce regeneration. For example, rhododendron (*Rhododendron maximum)* stems can grow into dense thickets and create regeneration problems for red spruce [24]. Beech (*Fagus grandifolia)* root sprouts that develop in canopy gaps created by beech bark disease grow fast and may end up filling canopy gaps with infected beech saplings instead of favorable red spruce regeneration [1,25].

Red spruce's growth productivity and efficiency is impacted by a variety of factors. One important growth factor for red spruce especially in central West Virginia is age. Being a highly shade tolerant species, red spruce can reach a considerably old age as evidenced by dendrochronological studies. As red spruce ages, biomass productivity, photosynthesis rates, and foliar efficiency decline [26]. Older red spruce trees can exhibit more symptoms of decline than younger understory red spruce affected by similar stressors [24,27]. Age of suppressed red spruce is important as older red spruce are less responsive to releases and will not be able to optimize growth [28]. In addition to age, tree structure can be important when considering red spruce productivity and efficiency. Studies have shown that red spruce experience decreased growth efficiency with a crown size that is too large [28,29].

Red spruce dominated forests are important for storage and sequestering of atmospheric carbon. A red spruce forest can store a large amount carbon and much of the carbon stored is in locations other than wood fiber. Over half of the carbon stored in spruce forests is located in organic and mineral soil horizons [30]. Extensive soil carbon was lost in the past due to harvests followed by wildfires. Soil carbon can be substantially drained from the ecosystem just from harvesting [14]. After a forest is harvested, microbes in the soil continue to break down carbon at rates faster than the rates at which organic matter can be replenished [31]. After a clear-cut harvest on red spruce stands, Diochon et al. [14] found that soil organic carbon decreases by more than 50 percent over for a 30-year period. It takes 100 years to replenish soil carbon to pre-harvest conditions [14]. Losses in soil organic matter can reduce moisture holding capacity and may hinder red spruce seeds ability to germinate [23]. In red spruce stands in the central Appalachian region, extracellular soil enzymes that are secreted by soil microorganism play an important role in the biogeochemical cycling of soil organic matter as well as increasing soil nutrient concentration [32]. In addition to soil carbon, overstory tree biomass and coarse woody debris [33,34] are other important carbon pools in red spruce forests. In contrast, understory vegetation only contributes a minor amount of soil carbon; for instance, Moore et al. [35] determined that herbaceous vegetation only contributed 1% of the total stand biomass.

4. History of Forest Management

Prior to the mid-1800s but diminishing up to the 1930s, the state of West Virginia, and particularly the area now designated as the Monongahela National Forest, was dominated by red spruce associated forest types [16]. This mountainous area is known for having steep terrain over a large portion of the region. Much of the forest area was difficult to extract timber resources from in the early logging period for this region [36]. As logging and railroad technology developed, harvesting crews were able to increase production throughout the eastern US forests [37]. Logging railroads allowed logging operations to extract large volumes of harvested timber out of the mountains and into West Virginia timber boom towns such as Cass, Richwood, and Spruce. Timber boom towns processed the raw forest materials into products such as lumber, furniture, and pulp [9]. Timberlands were generally large and usually owned by coal, railroad, or timber barrens. Timber was harvested from these lands with little regard for the environment or for future stand health. Common harvesting methods consisted of clear-cut type harvesting or high-grade selection harvesting [36]. Silviculture was not practiced when making large scale forest management decisions. The main objective that forests served was for unsustainable commercial production. Because of unsustainable harvesting, there were few mature forest stands available for harvesting by the 1930s. Most of the mature and un-harvested timber

in the central Appalachians was located in areas that were out of reach from logging railroads. Forest stands in excessively rocky, steep, or high elevations, were saved from early harvesting due to their low merchantability and difficult access [36].

The thick layer of organic matter on the forest floor and incorporated into soil horizons of red spruce dominated forests is typically moist under the closed canopy of an undisturbed forest [13,14]. However, if allowed to dry, the thick organic layer can be susceptible to wildfires. Logging operations during the 1800′s to the early 1900′s in this area left tremendous amounts of slash in the recently cleared forests, either scattered or in slash piles. Post logging conditions consisting of a dry organic layer and evergreen slash was a readily available fuel found throughout the harvested landscape. Logging railroads used to harvest the regions timber were a major spark source that started wildfires in this area [9,36]. Once ignited, few resources and little effort were expended to try to stop these wildfires. Logging and wildfires collectively disturbed an estimated 97% of central Appalachian red spruce's home range throughout the 1800′s and 1900′s, with an estimate of over 580,000 hectares of forest disturbed over the historical exploitation period [16]. Logging followed by wildfire resulted in disturbance conditions not optimal for the growth of red spruce saplings and seedlings but instead promoted the establishment of hardwood species, which offer considerable competition for red spruce [1,6]. Many competing hardwood species that have replaced red spruce's dominance such as red maple and beech readily reproduce through coppice regeneration in the form of stump sprouts. Stump sprouts have growth advantages from established roots and can outcompete seedling regeneration.

In addition to intensive forest exploitation, land clearing for agricultural purposes negatively affected red spruce and other woody species. Forest land was converted to grazing lands for cattle which favored the growth of cool season grasses, not woody plants [9,22]. Privately owned forest lands experienced minimal silvicultural treatments or management that promoted the growth of red spruce. Publicly owned timberlands however, such as the Monongahela National Forest (MNF), did experience timber stand treatments/improvements which promoted the growth of red spruce [16]. These treatments involved girdling or applying herbicide to individual trees competing with red spruce stems. Where selection harvests were conducted on privately owned forest lands, these manipulations acted as release events, promoting some residual red spruce growth and recruitment. Red spruce forestlands have also experienced disturbance from mining operations [38]. Surface mines destroyed red spruce habitat. Remnants of old surface mines can be observed frequently within areas of the central Appalachians that were once dominated by red spruce.

5. Issues Affecting Red Spruce Management and Restoration

In the first subsection (Section 5.1), a broad range of disciplinary subject areas are first presented through a meta-analysis of recent literature of red spruce in the Appalachian region. The next sub-sections (i.e., Sections 5.2 and 5.3) then go into further detail around concerns related to climate change and pollution.

5.1. Meta-Analysis of Disciplinary Topic Areas

A meta-analysis was conducted on recent literature (published 2000 or later) of red spruce in the Appalachian region to highlight key disciplinary topic areas. This analysis was carried out using Web of Science using the following search terms: "*Picea rubens* and Appalachian". The search was confined to the abstract region of the paper. The results were then filtered to only include primary research articles published in the year 2000 or later. Most studies of red spruce have been carried out primarily in the forestry disciplinary area (40% of all articles) followed by the ecology subject area (37.5% of all articles) (Table 1).

Table 1. Key topic areas for studies of red spruce in the Appalachian region of the United States based on a meta-analysis of recent primary literature (i.e., journal articles) published from 2000 and later.

Web of Science Category	Number of Articles	Percentage of Total Articles (%)
Forestry	16	40.0
Ecology	15	37.5
Biodiversity Conservation	9	22.5
Soil Science	5	12.5
Agronomy	2	5.0
Chemistry Analytical	2	5.0
Environmental Sciences	2	5.0
Plant Sciences	2	5.0
Evolutionary Biology	1	2.5
Genetics Heredity	1	2.5
Instruments Instrumentation	1	2.5
Meteorology Atmospheric Sciences	1	2.5
Mycology	1	2.5

5.2. Red Spruce and a Changing Climate

Climate change is a major factor that land managers must consider when focusing on red spruce restoration. With a warming climate and altered precipitation regime in the future, it is difficult to predict exactly how red spruce will be affected. Literature points to growth declines and or advances associated with climate change [30,39–41].

Dendroclimatology involves analyzing tree core ring measurements and comparing annual ring measurements to climate data for that year and location. Using dendroclimatology, scientists can determine how climate affects the growth of woody plants. Studies have shown both positive and negative responses to increased temperatures [36,39,42]. The results of dendroclimatic studies allow us to determine the impacts historic climate had on tree growth. Dendroclimatic results also allow us to make estimates on how the species of interest could potentially respond to future predicted climate values. Yetter et al. [43] used dendroclimatology to characterize the seasonal climatic factors influencing radial growth of central Appalachian red spruce. Yetter et al. [43] reported that growth was negatively impacted by high summer temperature stress, but responded favorably to high fall temperatures; furthermore, growth was associated with the degree of winter harshness, and responded favorably to warm spring temperatures.

Red spruce responds differently to temperature depending on time of year and growing season [30,40]. Radial growth of southern red spruce trees shows negative growth relationships with excessive heat, this negative impact on spruce growth can be observed in the following growing season and is noted with a narrow growth ring [44]. The southern extent of red spruce in the Appalachians is restricted by maximum summer temperatures [36]. In the northern extent of red spruce's range, it appears that the species is not restricted by warm temperatures and red spruce growth has increased with increasing temperatures, particularly at higher elevations [30,39]. Warming summer temperatures may extirpate spruce from lower latitudes and elevations, especially in the southern portion of its range [36].

A warmer climate will result in an extended growing season by lengthening growing degree days. Longer growing seasons and an increase in average mean temperature may allow red spruce to increase carbon capture and also increase respiration [39]. This extra carbon production could lead to growth increases as long as growth declines from high summer temperatures are not severe [30]. Early spring growing conditions can increase tree growth [45]. Being an evergreen, red spruce can photosynthesize whenever conditions are suitable [46]. Due to this growth advantage, warmer winters and springs may make the species more productive. Winter thaws that lead to red spruce conducting photosynthesis can help the tree sequester extra carbon, but sudden freezing events can damage spruce trees through frost damage [47].

Precipitation extremes may be a more important growth variable than temperature. Spruce can be more sensitive to water availability in terms of water shortages, but excess moisture in the spring has a negative impact on southern red spruce growth [36,48]. The magnitude of effects caused by climate change and precipitation vary between elevations, and are usually more severe at lower elevations [22]. Loss of snowpack can contribute to red spruce declines through the loss of growing season moisture from snow melt and also through loss of insulation leading to root damage [49].

A warming climate has increased the competitiveness of many competing hardwood species frequently associated with red spruce. The future climate could offer competing tree species, in particular hardwoods, a competitive advantage and potentially lead to a decline in red spruce forest cover [44]. Silviculture and management activities such as thinning and single tree selection harvests offer options to land managers that may promote the growth of spruce through harvests that create release events for residual red spruce [8].

A significant concern regarding central Appalachian red spruce is the loss of suitable lands for restoration. This loss of land is not from deforestation, but from the warming of seasonal temperatures and an altered hydrologic cycle. Climate change models predict that as future conditions persist there will be fewer suitable locations available for red spruce restoration [50]. Forest lands that may be marginal for restoration of the species in the present may no longer be viable land for restoration in the future due to climate change [9,50]. By selecting locations with the greatest likelihood of red spruce restoration success, the limited available resources can be allocated to efforts in areas that will likely be able to support red spruce in future years [9]. Walter [50] predicts that even under optimistic climate projections, the health of red spruce forests will depend on well executed restoration efforts. Common restoration efforts for central Appalachian red spruce include seedling plantings, understory competition treatment, and harvests/gap establishment to promote or release red spruce regeneration [1,9,16]. Human disturbance in spruce forests could intensify red spruce's response to climate change. Large canopy altering events such as harvests can intensify the species' sensitivity to climate change [21,36].

5.3. Red Spruce, Pollution and Disturbances

In addition to climate change, pollution is a critical factor affecting many aspects of red spruce health and growth. Air pollution in the form of sulfur dioxide, nitrogen dioxide, and carbon dioxide resulting from combustion of fossil fuels such as coal has negatively affected red spruce growth historically [21,39,51]. Air pollution may be more important than climate change in the future when looking at the growth and health of red spruce. Red spruce at all elevations experience depressed growth from air pollution, however, higher elevation spruce has a higher sensitivity to air pollution [40]. Acid deposition, commonly in the form of acid rain, has been responsible for red spruce declines in the past [21,39,48,51]. Acid rain is a form of precipitation having a low pH value and is commonly associated with sulfur and nitrogen ions [52]. Acid rain consequently lowers soil pH which, if too low, can negatively affect plant growth. Acid rain causes other growth problems through soil leaching [52] with calcium being an important nutrient lost through this process [23,30]. When calcium shortages occur, red spruce can become more susceptible to winter injuries such as frost damage and crown dieback, resulting in growth and health declines [21,39,51]. Similarly, soil organisms can also be negatively impacted from air pollution and acid deposition. A decline in soil organisms can impede leaf litter decomposition and impact nutrient cycling [53]. However, air pollution levels have declined since the Clean Air Act of 1970 [54]. Red spruce growth has improved from lower levels of pollution and the increase in growth is expected if pollution levels continue to decline [39,40,45].

Past history of acid deposition has been linked to nitrogen cycling primarily in study sites located in the southern Appalachians including the Great Smoky Mountains National Park [33,35]. Excess nitrogen has been associated with reduced tree vigor [34]. It was identified that understory herbaceous vegetation took up substantial amounts of nitrogen and therefore represented a nitrogen rich component of red spruce ecosystems [35].

In mixed-species stand of red spruce where there is a fir component, balsam woolly adelgid (*Adelges piceae*), which is a non-native insect, is responsible for mortality of the fir component. In particular, Fraser fir (*Abies fraseri* (Pursch) Poir) is susceptible to balsam wooly adelgid, and infestations can cause variability in fir regeneration compared to relatively more consistent trends in red spruce regeneration [55]. Infestation with balsam wooly adelgid can lead to an increased amount of coarse wood debris which was quantified in a southern Appalachian spruce-fir forest [34].

6. Red Spruce and Site Productivity

Site index is a common metric used to explain forest stand productivity. Site index is commonly expressed as height of an overstory tree at a base age, usually of 50 years base age in eastern North America [56]. Site index values can be compared and used to determine areas that will be most productive for growth of specific trees [57]. There are a few common methods to develop site index curves. One of the more basic and commonly used methods for creating site index figure uses an anamorphic height equation with corresponding guide curves [58]. Polymorphic site index equations and curves are another commonly used method used to explain site index. This method uses a different curve equation for each site index value curve [58–60].

There has been research on site index development for northern and southern populations of red spruce [61–63]. All of the site index curves available for red spruce use historical data collected in the northern or southern portion of red spruces range. Traditional site index development methods require that sampled trees for site index creation have lived in free growing conditions in the overstory (codominant or dominant crown class) [38]. Due to red spruce's extreme shade tolerance and slow growth characteristics, red spruce frequently encounters periods of suppression [9]. Because of this growth characteristic, red spruce are not good candidates for traditional site index methods. Using diameter to predict height of red spruce is one way that previous studies have accounted for the growth suppression of red spruce when developing site index curves [62]. Using only free growth and replacing suppression periods with corresponding free growth periods has also been used to develop red spruce site index when the trees encounter suppression [63]. Carmean et al. [61] developed the most commonly used red spruce site index curves. This site index uses true age to predict height but uses outdated data collected in the 1920s [64].

Linear models have been developed that predict site index values of timber species using the site index values of associated species [65,66]. Having linear models that can predict site index where a species is currently absent from the overstory is an important way for land managers to determine potential productivity of forest lands for a species. Because much of the historic central Appalachian red spruce forest lands are now dominated by hardwoods, linear modeling that uses site index values of commonly associated timber species such as yellow birch and red maple to predict red spruce productivity could be useful in the central Appalachians. This approach to modeling the site index of Appalachian red spruce has only recently been implemented by Yetter et al. [67] in which they developed a linear model to predict site index of red spruce based on site index values of red maple and yellow birch.

There are limited site index curves available for central Appalachian red spruce. Yetter et al. [67] recent development of a site index curve that uses trees sampled from the central Appalachians outperforms the traditional age-height pair models previously used. These recently developed suppression-corrected age–height pair and DBH–height pair site index models are specific to central Appalachian red spruce. Traditional age-height site index models used for this central Appalachian resource were created with data taken from northern or southern populations of red spruce. Yetter et al. [67] reported red spruce sensitivity to a suite of climatic and geographic variables.

In summary, adoption of newly developed site index curve for central Appalachian red spruce may be beneficial in making decisions about restoration activities and eliminate the need to rely on site index curves that were created with data collected primarily from

northern or southern red spruce populations. Furthermore, linear models that estimate site index values of central Appalachian red spruce using associated species are expected to be useful in locations where red spruce is currently absent from the overstory. Monitoring the site productivity requirements is especially critical given that red spruce is a shade intolerant, slower growing tree species which in turn help bolster its competitive status in mixed-species stands.

7. Red Spruce Restoration

Obtaining acceptable regeneration is a critical and challenging step in forest restoration. A large part of silviculture deals with managing a forest to create regeneration for the next cohort of trees [68]. Suppressed red spruce can change their crown structure to sustain growth under heavy canopy cover [21]. Many of the overstory red spruce observed in the forest today started out as suppressed seedlings. Release events are needed to allow spruce regeneration to reach dominance in the canopy [1,69]. Release events through small canopy gaps are effective for red spruce recruitment; in contrast, full sunlight, created from large disturbances negatively affects regeneration [21]. Many spruce trees require more than one release to reach co-dominate or dominant status [15,70].

Red spruce has unique management and restoration requirements. A common management practice that promotes red spruce forest cover is timber stand improvements or harvesting in a way that creates canopy gaps [1,15]. In overstocked stand of red spruce, growth stagnates, and it is recommended that a thinning be conducted in the smaller size classes which would translate into better growth rates in the residual trees and help shorten the timeframe to reach old-growth structural characteristics [71]. Small canopy gaps are preferred over large gaps, as the species can be sensitive to full sunlight exposure [1]. Full sunlight from large gaps may cause temperature and water related stress. If merchantable, single tree selection harvesting and shelterwood harvesting are effective management tools to promote the growth of the next generation of red spruce [15,23,72]. Selection harvests should create small gaps and removed trees should be undesirable species and trees that are overtopping existing regeneration [15]. Red spruce are shallow rooted and prone to windthrow when residual stand densities are low after a harvest; thus windthrow avoidance is an important consideration when planning management activities [12]. Harvests may not be permitted or may be significantly limited in locations restricted by endangered species such as the Cheat Mountain Salamander (CMS). The ability of red spruce stands to store large amounts of carbon is an important factor when planning restoration activities. Disturbance events including harvesting leads to carbon loss from both stems and soil organic matter which is critical for maintaining soil moisture and establishing red spruce regeneration [25]. Loss of organic matter is a factor managers may want to consider when determining rotation lengths [14].

Restoration plantings can be used to expand red spruce habitat. Locating suitable locations to install red spruce plantings is important [50]. Existing hardwood and mixed spruce-hardwood stands where red spruce was historically more prevalent could benefit from plantings. Hardwood stands with spodic soils located within the central Appalachians can be used to identify lands that were once dominated by red spruce [73]. These soil characteristics may help isolate stands suitable for enrichment plantings after partial harvests. Restoration activities will likely be more successful at higher elevations [16]. Higher elevation areas will provide more favorable climatic conditions and also allow red spruce to be more competitive [44]. Planting spruce seedlings in recently partially harvested hardwood stands can be an effective method of introducing red spruce back into forests where it has been absent for decades [23]. It is important to plant seedlings in light gaps where they can benefit from full sunlight before over story canopy closure. Once canopy closure occurs, release activities may be necessary to promote growth of the established planted seedlings.

8. Conclusions

An increase in red spruce habitat will expand habitat for endangered wildlife species, sequester larger amounts of atmospheric carbon, promote the growth of a potentially important timber species, and increase aesthetic values for the landscape. Determining how climate and other factors have affected the growth of red spruce can potentially help land managers make critical management decisions when selecting future restoration locations and methods. Adoption of a newly developed site index curve for central Appalachian red spruce may be beneficial in making decisions about restoration activities and eliminate the need to rely on site index curves that were created with data collected using northern or southern red spruce populations. Linear models that estimate site index values of central Appalachian red spruce using associated species are expected to be useful in locations where red spruce is currently absent from the overstory.

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