

Northern White-Cedar Ecology and Silviculture in the Northeastern United States and Southeastern Canada: A Synthesis of Knowledge

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ABSTRACT

Sustainability of the northern white-cedar (*Thuja occidentalis* L.) resource is a concern in many regions throughout its range because of regeneration failures, difficulty recruiting seedlings into sapling and pole classes, and harvesting levels that exceed growth. Management confusion has resulted from the scarcity of research on northern white-cedar ecology and silviculture, particularly because northern white-cedar is an anomalous tree species. This article synthesizes recent and historical northern white-cedar literature, with a focus on ecology, regeneration, cedar-wildlife interactions, and silviculture. Although a number of past studies have produced contradictory findings, some generalizations of use to the practitioner can be made: northern white-cedar is of small stature, slow growing, decay prone except on cliff sites, and found in both early- and late-successional stands. Northern white-cedar appears to be a highly variable species that can adapt to a wide range of environmental stresses. Because management of this resource has proven difficult, northern white-cedar silvicultural guidelines are needed throughout its range.

Keywords: arborvitae, conifer, eastern white-cedar, swamp

Northern white-cedar (NWC; *Thuja occidentalis* L.), is common throughout southeastern Canada and the northeastern United States; its primary range extends from southeastern Manitoba to Nova Scotia, and from James Bay to southern New York, Ohio, and Michigan (Figure 1). Local populations can also be found south along the Appalachian Mountains from Pennsylvania to Tennessee, Anticosti Island in the Gulf of St. Lawrence, and west-central Manitoba (Johnston 1990). Despite its abundance, NWC is arguably the least studied commercially valuable tree species in its region (Scott and Murphy 1986). Studies of NWC ecology and silviculture are often limited in scope and geographical range (Hofmeyer et al. 2007); very little is known about NWC growth and management in the northeastern United States. Many useful papers about NWC were published in conference and workshop proceedings, or as university or government reports, as early as the 1910s. Such literature is often not readily accessible to the practitioner.

NWC stands in many regions are affected by browsing, harvesting, competition from associated tree and shrub species, and recruitment failures. Recent US Forest Service Forest Inventory and Analysis data from Maine, for example, suggest that there has been an annual negative net change of approximately 245,000 m³ of NWC growing stock since 1995 (McWilliams et al. 2005). This was primarily attributed to a lack of ingrowth, recruitment of poletimber to sawtimber without replacement, increases in cull volume, and har-

vest levels that exceeded net growth. In the Lake States, NWC is a common deeryard species because it provides critical winter habitat for white-tailed deer (*Odocoileus virginianus*). Regeneration and maintenance of stand structure have become problematic in many deeryards, leading to concerns about the sustainability of these stands (e.g., Miller et al. 1990, Van Deelen et al. 1996, Van Deelen 1999). With suggestions that recent NWC harvesting may not be sustainable throughout portions of its range, shortcomings in the NWC literature are strongly felt by forest managers.

Our objective was to synthesize past NWC research to outline current knowledge relevant to NWC management. Much of the information regarding NWC ecology and silviculture appears in the gray literature, which is often difficult to obtain. This document has been organized into five broad categories for ease of reference: general ecology, cliff ecology, regeneration, silviculture, and NWC-wildlife interactions. Information for this review was collected in a year-long literature search; a comprehensive list of NWC literature (English-language only, published before April 2007) relevant to forestry can be found in *Northern White-Cedar: An Annotated Bibliography* (Hofmeyer et al. 2007).

General Ecology

NWC is a medium-sized tree (12–15 m tall, 30–60 cm dbh) that commonly grows in subordinate canopy positions in mixed-species stands on poor sites throughout its range (Johnston 1990). NWC is

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This article uses metric units; the applicable conversion factors are: centimeters (cm): 1 cm = 0.39 in.; meters (m): 1 m = 3.3 ft; square meters (m²): 1 m² = 10.8 ft²; cubic meters (m³): 1 m³ = 35.3 ft³; hectares (ha): 1 ha = 2.47 ac.

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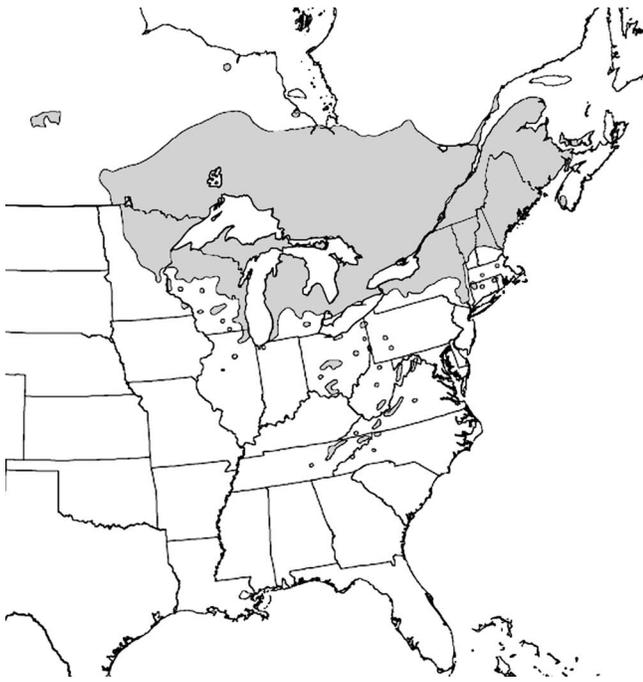


Figure 1. Distribution of northern white-cedar (*Thuja occidentalis* L.) (Little 1971).

often reported to be a highly plastic and adaptable tree species that has a bimodal site distribution, occupying both poorly drained lowland sites and xeric upland sites. Much of the ecological NWC literature has investigated differences among lowland, mesic, and xeric communities.

One of the oldest NWC studies on record (Fernald 1919) established an important link between forest vegetation and soils and underlying parent material in the Northeast. Fernald (1919) reported that although NWC can grow on acidic soils, the best growth and form were observed on calcareous sites (although this was not quantified). A comparison of bog NWC trees with limestone outcrop NWC in New York suggested that many wood properties (e.g., specific gravity, crushing strength) have greater variance within sites than among sites (Harlow 1927). Radial growth increment in that study was found to be higher in limestone communities than bog communities (3.10 mm/year versus 1.55 mm/year), although growth differences were partially attributed to “openness” of the limestone community. In Maine, NWC was noted to have a spiral grain pattern across all sites, although upland NWC reportedly had higher volume growth and better stem form (Curtis 1944, 1946). Curtis (1944) found NWC stands on abandoned pasturelands that were capable of growing 4.5 m³/ha/year in stands exceeding 73 m² of basal area per hectare.

NWC is considered a slow-growing tree species, attaining maximum heights of 24 m in 125 years on the best lowland sites in Vermont (Hannah 2004). Site index was commonly 8–16 m at 50 years in Vermont; the slowest height growth was associated with the most poorly drained sites. Volume increment data suggest that one could expect 0.08 m³ per tree on poor sites and up to 0.4 m³ per tree on better sites in 75 years. Hannah (2004) speculated that NWC would likely be replaced in the future by more competitive species on better sites. In a study of northern white-cedar basal area growth by drainage class in Maine, Hofmeyer (2008) found that once differences in sapwood area were accounted for, no breast height basal

area growth differences were detected among site classes or canopy positions.

Land use history of southern Quebec is similar to much of the northeastern United States in that land clearing and farm abandonment have had a great effect on present-day forest communities (de Blois and Bouchard 1995). They found that NWC typically exists in dense, pure communities that resist colonization by competing species. When land use practices modify soil and vegetation, NWC can invade more mesic sites. NWC colonization occurred on 95% of abandoned pasture lands in a study in southern Quebec; 68% of those were mesic sites (de Blois and Bouchard 1995). On some abandoned pasture lands in that region, 60–80% of NWC trees were of vegetative origin, with low genetic diversity even among individuals in mixed-species associations (Lamy et al. 1999). NWC trees in those stands had low levels of outcrossing, high levels of self-fertilization, and high rates of vegetative reproduction.

Living NWC trees are reportedly prone to decay from brown cubicle rot fungi, such as *Phaeolus schweintzii*, *Postia sericimollis*, and *Tyromyces balsameus*, throughout its range (Harlow 1927, Johnston 1990, Randolph et al. 2007). Although stem quality is often ambiguously defined in past NWC studies and may refer to bole straightness, branchiness, or grain, most researchers report superior stem quality on upland sites (e.g., Curtis 1946, Godman 1958, Johnston 1990). However, central decay from butt rot fungi may be higher as soil drainage improves. Hofmeyer (2008) reported that incidence of central decay in outwardly sound NWC trees was highest on well-drained sites in Maine. In addition, the proportion of basal area decayed increased as soil drainage improved from poorly drained organic and mineral soils to well-drained mineral soils.

Because NWC is widely recognized to have a bimodal site distribution (e.g., Potzger 1941, Musselman et al. 1975, Collier and Boyer 1989), several researchers have conducted comparative investigations to determine the likelihood that xeric and hydric communities are part of separate populations. Ecotypic variation is defined as genetic variation within populations dispersed across different environments. The hypothesis that NWC exhibits ecotypic variation was proposed by Potzger (1941) and has been tested in a number of regions. This is important to management, because guidelines developed for a given site or region may not apply to others if NWC trees are inherently (genetically) different.

Seedlings were collected from upland and lowland communities in Wisconsin and transplanted to the University of Wisconsin Arboretum to observe differences in seedling morphology (Habeck 1958). NWC seedlings from upland sites were found to have higher survival rates and more plastic root development than lowland NWC seedlings, leading Habeck (1958) to conclude that ecotypic variation does exist. A later study in Wisconsin supported this finding, suggesting that root structures changed from tap roots with few laterals to no tap root but many laterals as soil moisture levels increased (Musselman et al. 1975). Another study reports on seedlings (2-0 stock) from 32 widely distributed sites that were planted as windbreaks in Illinois (Jokela and Cyr 1977). After 12 years, no survival differences in growth rate or susceptibility to winter foliage damage were detected among provenances; moreover, no geographic pattern was observed. The authors speculated this could be a reflection of localized lowland and upland ecotypes in the seed stock.

The conclusion that NWC exhibits ecotypic variation has not gone unchallenged, however. Tree architecture was found to vary little among xeric and hydric sites, once age was corrected for

(Briand et al. 1991). Seed morphology followed a similar pattern: within-site variability exceeded differences among sites (Briand et al. 1992). Cell water potential, which has been shown to correspond with habitat moisture conditions in many species, provided another means to test NWC for ecotypic variation (Collier and Boyer 1989). Using hydrated foliage samples in a Pressure Bomb, water potential was found to be more negative in a xeric moisture regime, independent of parent stock. Investigating NWC drought response mechanisms, no significant differences were detected in transpiration rates and osmotic adjustment between well-watered and stress-conditioned individuals in subsequent moisture stress relief (Edwards and Dixon 1995). Cliff and swamp populations of NWC were tested for ecotypic differences in growth and tree physiology (Matthes-Sears and Larson 1991); no discernible patterns of productivity, nutrient levels, shading, or light saturation were observed among sites. Allozyme patterns among cliff and swamp sites have also been investigated (Matthes-Sears et al. 1991); only 1.9% of genetic variability distinguished stands within habitat types, and only 1.2% of genetic variability was detected between swamps and cliffs, suggesting that all trees studied were members of a homogeneous population.

In each of the cases in the preceding paragraph, the authors concluded that no inherent differences in NWC existed among sites. Many authors who rejected ecotypic variation suggested that NWC is a highly variable species and that variations are site-specific, not habitat-specific. Some authors suggest that this variability may allow NWC to establish and persist across a wide range of environmental conditions (Briand et al. 1992).

In addition to plasticity in a wide range of soil qualities, NWC is also difficult to place in terms of its shade tolerance and successional niche. NWC is reported to be a long-lived pioneer on dune sites in the Lake States that is expected to be replaced by shade-tolerant hardwoods (Scott and Murphy 1986), a pioneer of abandoned pasture lands in Quebec (de Blois and Bouchard 1995) and Maine (Curtis 1946), a stable component of lowland mixed sites in Ohio (Collins et al. 1979, Kangas 1989), a transitional bog species in Michigan (Kangas 1989) and Vermont (Hannah 2004), and a stable pure community on limestone cliffs (Larson and Kelly 1991). Its shade tolerance has been described to range from very shade tolerant to intermediate (Curtis 1941, Johnston 1990). Hofmeyer (2008) found that mature, upper-canopy NWC followed a stemwood volume increment per unit leaf area pattern that is atypical for shade-tolerant trees, where volume increment increases nearly linearly with respect to increasing leaf area. However, because NWC often exists in subordinate canopy positions for over 200 years, it is clearly tolerant of overhead shade (Hofmeyer 2008). It might be useful to classify NWC not by its shade tolerance but as a stress-tolerant species (after Grime 1977) or as an understory tolerant species (after Barnes et al. 1998).

Cliff Ecology

The majority of the NWC literature concerning cliff ecology comes from the Cliff Ecology Research Group (CERG) at the University of Guelph, investigating communities on limestone cliffs along the Niagara Escarpment in Ontario. These NWC-dominated forests are perhaps the most extensive old-growth forests in eastern North America (Larson and Kelly 1991). The Niagara Escarpment forests are considered to be free from large-scale disturbance, although rockfall is a common small-scale disturbance (Kelly and Larson 1997). Portions of root systems are often damaged by rockfall disturbances. Links between damaged portions of root and shoot

systems led researchers to discover that some NWC trees have a radially sectorized architecture that allows the tree to continue growing when portions of the roots, shoots, and cambium die (Larson et al. 1993, Larson et al. 1994). Investigations have demonstrated that some NWC trees possess stem stripping (alternating vertical bands of living and dead wood); researchers hypothesize that this results from cavitation events in old trees and allows for stress tolerance in harsh environments (Matthes-Sears et al. 2002). NWC trees on these sites have been compared to bristlecone pine (*Pinus longaeva* D.K. Bailey) because of their advanced ages (some exceeding 1,000 years), distorted architecture, slow radial growth rates (<0.1 mm/year), and cambial mortality in living specimens (Kelly et al. 1992).

Although the Niagara Escarpment is a harsh site, there is apparently adequate moisture, nutrients, and mycorrhizal colonization for NWC growth (Matthes-Sears et al. 1992, 1995). As such, there has been extensive work by the CERG to compare and contrast cliff NWC to noncliff NWC. Cliff-dwelling NWC trees have higher specific gravity, crushing strength, and modulus of elasticity and rupture than noncliff NWC (Larson 2001); many of these properties have been linked to slow growth rates and a high proportion of lignin-rich latewood. Larson (2001) also reported a typical lifespan of only 80 years (maximum of 400 years) for noncliff NWC, whereas NWC ages on cliffs have exceeded 1,030 years (Kelly et al. 1992). Aside from age, growth rate, and strength properties, cliff NWC trees are considerably different from other NWC populations in that they rarely are afflicted with central decay. Resistance to central decay, long lifespan, and stability of wood structure after tree death has led to extensive use of cliff NWC in dendroclimatology and dendroecology research (e.g., Kelly et al. 1992, 1994, Buckley et al. 2004).

Research in northwestern Quebec has identified similar populations of old trees on harsh sites. Specimens exceeding 800 years of age have been discovered on xeric sites and used for dendroclimatology (Archambault and Bergeron 1992). NWC trees from hydric sites have also been used in northwestern Quebec in dendroclimatology work (Tardif and Bergeron 1997). In both northwestern Quebec and southern Ontario, radial growth has been correlated with the previous summer temperature and moisture; reduced radial growth was observed in years that followed a hot, dry summer (Kelly et al. 1994, Tardif and Bergeron 1997).

Silviculture

Given the importance of NWC throughout its range, it is surprising how few true silvicultural studies have been conducted. Many studies that report results of mature tree responses to treatment are unreplicated case studies with limited scope and applicability.

Volume and yield tables were constructed for the Lake States on the basis of a sample of 227 stems distributed throughout Michigan, Minnesota, and Wisconsin (Gevorkiantz and Duerr 1939). These tables suggest that NWC trees taper abruptly from the stump upward, commonly have a site index of 14 to 18 m at 50 years at stump height and can form dense stands with high yields. Hannah (2004) reported that NWC on moderately wet sites in Vermont had good growth potential, suggested that intermediate thinning treatments could be successful in these stands, and recommended small patch clearcuts, narrow strip clearcuts, or shelterwood regeneration methods in areas with controlled deer populations.

Early thinning trials on swamp sites suggested that reducing stand basal area increased quality and vigor of the residual trees (Roe 1947), although response to thinning was better on lowland sites with moving groundwater than on sites with stagnant groundwater. Many of the lowland stands were previously clearcut, diameter-limit cut, and/or otherwise selectively harvested, although Thornton (1957a) argued that no single treatment could be recommended or discouraged due to inconsistent stand responses. Protection of advance regeneration was emphasized to encourage NWC in future stands (Thornton 1957b). One study suggested that gross growth of NWC is unresponsive to stand density (Foltz and Johnston 1968); results indicate that NWC stands can be thinned repeatedly to a basal area 21 m²/ha without sacrificing gross growth. Partial cutting, group selection, and diameter-limit cutting have been discouraged in deeryards because they tend to reduce available browse and cover (Verme 1965). Indeed, the *Management Handbook for Northern White Cedar in the North Central States* stresses the need for managers to consider both timber and wildlife implications in any silvicultural treatment that is prescribed (Johnston 1977).

In the Lake States, NWC management is heavily affected by a lack of consistency in NWC regeneration and responses to silviculture, to some extent a result of local deer populations. Effective implementation of treatments for NWC regeneration and recruitment are limited by high browse pressure and slow seedling growth rates, as well as inconsistencies in the literature about NWC's successional niche and shade tolerance (e.g., Curtis 1946). Stand conversion is common because NWC is a poor understory competitor in comparison with species such as balsam fir (*Abies balsamea* [L.] Mill.). It is seemingly difficult to predict responses of mature NWC stands to silvicultural treatments: at times they respond well to release (e.g., Roe 1947), and at times they show no difference among treatment intensities (e.g., Foltz and Johnston 1968). These concerns make management of deeryards and other NWC stands problematic.

Regeneration and Recruitment

One of the most extensive NWC regeneration studies came from the Michigan Department of Conservation Game Division (Nelson 1951); this study outlined several principles that continue to guide management today. Nelson (1951) found that soil pH below 4.0 negatively affected germination, soil pH below 6.0 negatively affected seedling density, browsing and desiccation were the most common causes of seedling mortality, vegetative reproduction was common (primarily layering), and growth and development in the seedling stage is slower than that of competing species, such as balsam fir and tolerant hardwoods.

Research suggests that NWC seedlings can survive on nurse logs in later stages of decay that hold moisture through the dry portions of the summer (Caulkins 1967); nurse logs with an associated bryophyte mat are highly desirable for NWC seedlings (Holcombe 1976). Seedling densities have also been positively correlated with the proportion of the forest floor in hummocks on lowland pit and mound topography sites. In Michigan's Upper Peninsula, hardwood brush dominated the understory of NWC stands with less than 70% of the ground area in hummocks (Chimner and Hart 1996); NWC regeneration was observed to be successful if the ground area was greater than 70% hummocks. In nearly all cases, NWC seedling survival increases with adequate moisture.

NWC regeneration is complex, in part because of the difficulties in determining its successional niche and shade tolerance. On sand

dune sites and abandoned pastures, NWC can act as a colonizing pioneer species that is replaced by competing species (Curtis 1946, Scott and Murphy 1986). Johnston (1990) suggested that differences in seedling shade tolerance may be associated with vegetative (very tolerant) versus seed origins (midtolerant). Kangas (1989) described NWC as a species that is shade tolerant but likely requires significant disturbance to regenerate. In attempts to mimic this regeneration requirement, strip clearcutting and strip shelterwood regeneration methods have been recommended silvicultural treatments (Johnston 1977). These prescriptions tended to have mixed success in NWC regeneration because of the detrimental effects of browse, logging slash, and desiccation (Thornton 1957a, Heitzman et al. 1999). Verme and Johnston (1986) found that broadcast burning of slash in strip and small block clearcuts, in the absence of deer browse, prepares a seedbed conducive to NWC regeneration. They cautioned that in drought years or with high deer populations, seedling mortality will remain high.

Curtis (1946) expressed a concern for future NWC stands in his observations of abundant seedlings but few saplings in Maine; a similar phenomenon was noted in western Nova Scotia (Ringius 1979). In a stand reconstruction study of the Big Reed Forest Preserve in Maine, Fraver (2004) noted that no NWC seedlings were recruited into the sapling class since the early 1900s, although seedlings were abundant in some stands in that forest. Multiple studies have documented slow NWC seedling and sapling height growth rates (e.g., Johnston 1990, Heitzman et al. 1997, Davis et al. 1998, Hofmeyer 2008). Stand reconstruction studies in the Lake States conducted by Heitzman et al. (1997) found that mean cedar sapling height growth was approximately 0.05 m/year, whereas Hannah (2004) found NWC early height growth to range from 0.15 to 0.3 m/year, depending on site quality, in Vermont. Hofmeyer (2008) found early height development to be slow in Maine as well; 0.08 m/year through the first 4 m of height development, requiring a mean of 42 years for a 0.3 m seedling to reach the sapling class (2.5 cm dbh) and 96 years to reach the poletimber class (12.7 cm dbh).

Although NWC early development is slow, overtopped NWC trees do have the ability to respond well to release. Fraver (2004) noted that NWC was the most complacent species in his study of the Big Reed Forest in Maine; however, this is not to say that they show no growth response to canopy disturbance. Research on regeneration requirements in Quebec suggested that seedlings are susceptible to desiccation in highly disturbed stands, but that established large seedlings and small saplings increase in height growth proportional to increased light levels (LaRouche et al. 2006). Heitzman et al. (1997) reported a tripling of height growth of previously established NWC in response to a reduction in overstory density from early logging practices. Hofmeyer (2008) found that nearly 80% of sound, mature, stem-analyzed NWC trees throughout northern Maine had suppressed early origins with a significant release coinciding with spruce budworm (*Choristoneura fumiferana*) epidemics. Growth releases were observed in trees with >130 years of suppression in the Heitzman et al. (1997) study and in trees with >250 years of prior suppression in the Hofmeyer (2008) study.

Many sites with NWC in the overstory are regenerating to competing species because of the difficulties in recruiting NWC seedlings to the sapling stage. Balsam fir has been shown to quickly overtop NWC seedlings on sites without a large component of downed woody material (Cornett et al. 1997); this may be because fir's larger seed size and quickly developing root system enables it to better withstand drought periods. In addition, Davis et al. (1998)

found that although high numbers of NWC seedlings can be recruited after low intensity ground fires, plots without deer exclosures had no NWC seedlings after 10 years. Balsam fir was common on those plots, likely because of preferential browsing of NWC and avoidance of balsam fir by white-tailed deer and snowshoe hare (*Lepus americanus*). In some stands where NWC is a component of a mixed-species association, shade-tolerant hardwoods are expected to dominate in the future because of slow NWC seedling growth (e.g., Thornton 1957b, Scott and Murphy 1986, Cornett et al. 2000).

Wildlife-NWC Interactions

Although NWC has been largely neglected in silvicultural research throughout its range, there are many studies on deeryard management, regeneration, and wildlife-cedar interactions. NWC has been found to be more palatable than several associated species, including aspen (*Populus* spp.), jack pine (*Pinus banksiana* Lamb.), and balsam fir (Ullrey et al. 1964, 1967, 1968). Although deer often lose body mass on a single-species diet, NWC can support them through harsh winters if there is at least 2 kg of cedar browse per animal per day (Aldous 1941). In addition to browse opportunities, deer frequently congregate in deeryards when there is more than 30 cm of snow to benefit from reduced snow cover and wind, communal trails, more stable, warmer temperatures, and predator avoidance (Sabine et al. 2001). Many of the challenges faced regarding managing NWC deeryards are related to the use patterns of deer herds.

White-tailed deer have been observed in wintering areas until April, preferentially browsing on NWC (Van Deelen 1999). Because of this browse preference and slow seedling growth rate, up to 40 years may be required for seedlings to grow out of deer browsing height (Van Deelen 1999). Herbivory pressure from white-tailed deer and snowshoe hare has led researchers to investigate the use of animal exclosures during the regeneration period (Miller 1990); more than 75% of NWC seedlings and saplings outside exclosures in some areas have been excessively browsed within 3 years (Cornett et al. 2000). NWC herbivory by white-tailed deer was shown to be detrimental only at higher population levels in Quebec (Larouche et al. 2007).

Historically, NWC swamps in northern Michigan were multi-story stands with plentiful browse opportunities for deer, but sparse winter cover (Verme 1965). Many NWC communities in the Lake States today originated after clearcutting in the early 1900s, a time period with relatively low deer populations (Heitzman et al. 1997, 1999). These even-aged stands offer more protection but less available browse, although deer populations in the Lake States are much higher than they have been in the past (Heitzman et al. 1997). An increase in deer populations, coupled with NWC's palatability, has led to difficulties regenerating NWC stands in that region. High deer populations have led to widespread regeneration and recruitment failures in the Lake States, often leading to stands dominated by NWC in the overstory and competing species, such as balsam fir or brushy hardwoods, in the understory (e.g., Johnston 1972, Van Deelen et al. 1996, Cornett et al. 2000).

Management Implications

Silviculture research is limited for NWC, and cutting trials have yielded inconsistent results regarding response to release. As such, it is recommended that managers retain large-crowned individuals

within each canopy stratum during partial harvests. Historical stem development studies indicate that NWC surviving in inferior canopy positions can respond well to release even after extended periods of suppression. Managers are encouraged to take advantage of suppressed sapling and pole trees during release treatments. In addition, basal area growth and volume increment per unit leaf area were found to be undifferentiated among site classes. Therefore, efforts should be focused where stem quality is best, whether that be in terms of internal stem decay, pistol butting, or main stem forking. Recent findings suggest that lowland sites with poorly drained soils often have a low proportion of the breast height basal area decayed. Much of the literature suggests that NWC is a highly variable species that can adapt to a wide range of environmental stresses and therefore has important potential for management across a wide range of site classes and stem densities.

Advance regeneration and subsequent release findings suggest that shelterwood and/or selection systems can be successful where deer density is low. Since NWC is a long-lived tree species, there are opportunities for extended shelterwood and reserve tree prescriptions when desired. Because of the nutritional and dense cover value of NWC, deer often congregate in monotypic NWC stands during deep snow winters. NWC seedlings grow slowly; managers regenerating NWC should be prepared for extended time periods before NWC saplings grow above deer browse height. Regeneration efforts should be timed with reductions in deer populations and/or fenced exclosures in areas where NWC stands are used as overwintering habitat for white-tailed deer. Efforts to reduce aggressive competitors such as balsam fir should be taken before, during, and after regeneration treatments to promote high seedling stocking and sapling recruitment.

Residual stand damage should be minimized in partial harvesting operations because NWC has the weakest wood strength of commercial tree species in North America (Behr 1976). Although not studied specifically in past NWC silviculture trials, personal observations from NWC harvests in Maine suggest that residual stand damage is often high because of the brittle nature of NWC branches. Reduction of residual stand damage is particularly important if NWC is desired in subsequent stands and there is an existing component of advance regeneration. NWC will continue to prove challenging to managers and researchers, but the limits of current knowledge provide opportunities for silvicultural innovation.

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