Influence of Soil Site Class on Growth and Decay of Northern White-Cedar and Two Associates in Maine

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ABSTRACT

Basal area growth of outwardly sound northern white-cedar (*Thuja occidentalis* L.) was compared with that of balsam fir (*Abies balsamea* [L.] Mill.) and red spruce (*Picea rubens* Sarg.) across site and light exposure class gradients on 60 sites throughout northern Maine. Once adjusted for sapwood area, northern white-cedar basal area growth was not strongly affected by site or light exposure class; growth was similar to that of red spruce but generally lower than that of balsam fir. Site index did not differ appreciably among soil drainage classes for red spruce and northern white-cedar, although small sample size limited analysis on upland site classes. Incidence of central decay was higher in northern white-cedar than balsam fir, which was higher than red spruce. Incidence of decay in outwardly sound northern white-cedar and balsam fir was highest on well-drained mineral soils, and mean proportion of basal area decayed at breast height increased in outwardly sound northern white-cedar as drainage improved from poorly drained to well-drained soils. These data suggest that northern white-cedar on lowland organic and poorly drained mineral soils in Maine have less decay, similar basal area growth, and similar site index relative to upland northern white-cedar communities.

Keywords: Acadian, Arborvitae, conifer, eastern white-cedar

Northern white-cedar (*Thuja occidentalis* L.) is a common tree species in mixed transitional forests of southeastern Canada and northeastern United States (Johnston 1990). In Maine, it is commonly found in association with balsam fir (*Abies balsamea* [L.] Mill.), red spruce (*Picea rubens* Sarg.), black spruce (*Picea mariana* [Mill.] B.S.P.), and eastern larch (*Larix laricina* [Du Roi] K. Koch). Northern white-cedar is the third most abundant conifer in Maine, after balsam fir and red spruce; these species account for 6.3, 21.7, and 12.7 million cubic meters of timberland, respectively (McWilliams et al. 2005). Although northern white-cedar is prevalent in the landscape, it has historically been underrepresented in ecology and silviculture research throughout its native range, particularly in the northeastern United States (Hofmeyer et al. 2007).

Red spruce and balsam fir are commonly associated species in the spruce-fir forests of Maine. These species occupy similar sites, are both shallow-rooted (although fir is rooted slightly more deeply than spruce), are very shade tolerant, and can be considered climax species in that they reproduce under their own shade (Zon 1914, Murphy 1917). The most common and widespread occurrence of the spruce-fir type occurs on "spruce flats": relatively shallow soils extending from swamp sites to lower slopes (Westveld 1931). These soils are generally moist, with perched water tables during the active growing season. Aboveground growth of spruce and fir is related to site class; growth increases as soil drainage improves from poorly drained to well drained (Williams et al. 1991, Briggs 1994). Little research has been conducted regarding growth on organic soils because red spruce-balsam fir forests have less merchantable importance on these soil types.

Northern white-cedar can occur in nearly pure stands on both upland (e.g., abandoned pastures) and lowland (e.g., poorly drained mineral and organic soils) sites in Maine (Curtis 1944, 1946). Northern white-cedar also occurs in mixtures with red spruce and balsam fir in transitional stands with improved drainage, becoming more widely scattered as drainage improves to moderately well drained in mixedwood stands with an important component of mesic northern hardwoods.

Although there is a wealth of anecdotal evidence suggesting that growth rate of northern white-cedar is superior on upland soils and abandoned pasture lands (Curtis 1946, Caulkins 1967, Johnston 1990), this claim has not been rigorously tested. In a study of northern white-cedar on wet sites in Vermont, Hannah (2004) found differences in height and volume growth between the poorest and best lowland sites. Total yield of northern white-cedar stands in the Lake States increased as site index increased (Gevorkiantz and Duerr 1939), suggesting that volume increment increases as site conditions improve. However, fundamental research on soil-site relationships of northern white-cedar throughout its native range and growth comparisons with associated species across the soils continuum are lacking.
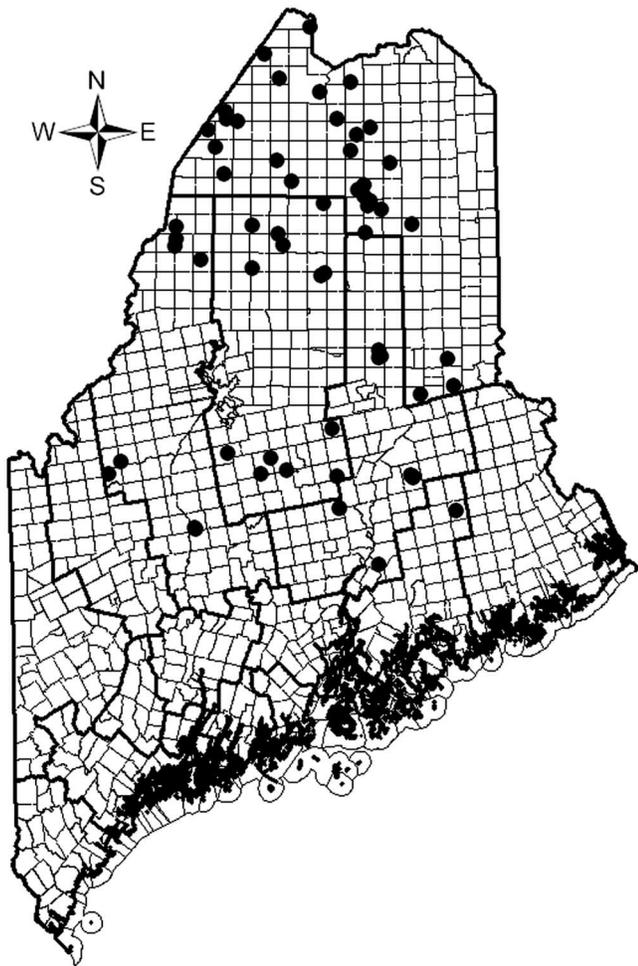
Figure 1. Study site locations in central and northern Maine.

Anecdotal evidence also suggests that northern white-cedar stem quality is better on upland sites (Curtis 1946, Johnston 1990). Central decay resulting from heartrot fungi is commonly cited as problematic for cedar throughout its native range (Harlow 1927, Johnston 1990), with the exception of stunted northern white-cedar trees growing on limestone cliffs in southern Ontario (Larson and Kelly 1991). Although decay affects a high proportion of northern white-cedar, no study has rigorously tested its occurrence by site class. The objectives of this study were to (1) compare basal area growth and decay of upper-canopy, outwardly sound northern white-cedar with those of balsam fir and red spruce as a function of site class and canopy position, and (2) compare site index of northern white-cedar with balsam fir and red spruce by site class.

Methods

Site Description

Sixty sites were selected throughout central and northern Maine for this study (Figure 1). Study sites were supplied by 10 landowners or land managers, each with different forest management objectives. Detailed forest history for each site is unknown. Observation of cut stumps in various stages of decay indicated that most sites had been partially harvested in the past; exceptions were sites within streamside management zones and white-tailed deer (*Odocoileus virginianus*) wintering areas.

Climate in northern Maine is cool and moist. National Oceanic and Atmospheric Administration long-term climate data indicate a mean annual temperature of 3.95°C (2.2–7.1°C) and mean annual precipitation of 97.5 cm (90.2–105.7 cm) for this region (NOAA 2008).

The dominant forest soils in Maine are Spodosols (approximately 65%) and Inceptisols (29%) (Fernandez 1992). Upland sites with improved drainage are typically Orthods (freely drained Spodosols), whereas areas of poor drainage are often Aquepts (wet Inceptisols with poorly developed B horizons). In general, these soils are acidic, high in organic matter, low in base saturation, and nutrient poor.

Although spruce–fir forests in Maine are generally associated with Spodosols and Inceptisols, northern white-cedar communities tend to be associated with Inceptisols and Histosols. Poorly drained Hemists occurring in low-lying areas and freely drained Folists resting on bedrock can support spruce–cedar communities, and occasionally cedar–fir. Northern white-cedar becomes more sporadic and is frequently replaced by northern hardwoods as soil drainage improves. Sampled sites in this study focus on red spruce–balsam fir–northern white-cedar associations on Spodosols, Inceptisols, and Histosols.

Field Data Collection

Sampling occurred from June 1 through August 30 in 2005 and 2006. Five upper canopy northern white-cedar, red spruce, and/or balsam fir trees were located at each site and their light exposure class was assigned following Bechtold's (2003) protocol to reduce errors associated with determining crown classes in stratified or multicohort stands (Nichols et al. 1991). Light exposure was rated on a 1 to 5 scale for each tree; class 5 is analogous to a dominant tree (light on the top and four sides) and class 1 is analogous to an intermediate tree (light on the top or one side only). Only trees in the continuous upper canopy with a light exposure ≥1 were sampled; no overtopped or outwardly defective trees were sampled. Each sample tree was double cored to the pith at breast height; cores were extracted perpendicular to one another. Each core was held to the sky to identify the boundary of translucent sapwood and opaque xylem prior to mounting in the field. Tree number, light exposure class, sapwood thickness, and point of decay (if present) were marked on the core board. Bark thickness was measured to the nearest millimeter with a bark gauge at each core location on the bole. Tree diameter was measured at breast height (1.3 m) with a steel diameter tape to the nearest millimeter. Total height, height of the live crown base, and height of the lowest live branch were measured with a Haglof Vertex III hypsometer. Live crown base was defined as the point on the bole with living branches covering at least 50% of the circumference of the bole.

A centrally located sampling point was taken at each site with a BAF 10 prism to characterize stand density and species composition. Two soil pits were excavated at each site to determine site class. Soil pits were located at the edge of the widest portion of the site and along a topographic gradient where possible (e.g., one uphill and one downhill or one pit and one mound sampled). Depth to redoxymorphic features, depth to root restriction, and percentage of coarse fragments were recorded for each pit. Each site was then placed into the appropriate site class using Briggs' (1994) classification (Table 1). Sites with soil pits varying by more than one site class were rejected because of excessive soil variability. Because northern white-cedar is commonly found on organic sites with no redoxymorphic features present, organic sites were treated as a separate site class.

Table 1. Briggs' (1994) site class descriptions.

Site class	Drainage class	Depth to mottling[a]	Loam cap thickness
		. . . .(in.)	
1	Well drained	>24	
	Somewhat excessively drained		>12
2	Somewhat excessively drained		8–12
	Moderately well drained	16–24	
3	Somewhat poorly drained	8–16	
4	Poorly drained	4–8	
	Excessively drained[b]		
5	Very poorly drained	<4	

[a] Depth to seasonal high water table as indicated by low chroma (or gray) mottles.
[b] Shallow bedrock (<12 in.) or coarse sand and gravel.

Table 2. Mean height, diameter, and breast height age of sample trees.

Characteristic	Minimum	Mean	Maximum	SE
Total tree height (m)				
Balsam fir ($n = 171$)	10.0	17.4	23.8	0.228
Cedar ($n = 296$)	7.6	15.7	26.6	0.157
Red spruce ($n = 158$)	11.1	18.6	28.5	0.260
Diameter at breast height (cm)				
Balsam fir ($n = 171$)	10.7	22.8	37.6	0.419
Cedar ($n = 296$)	13.8	31.7	65.7	0.539
Red spruce ($n = 158$)	12.0	28.2	52.5	0.634
Breast height age (ring count)				
Balsam fir ($n = 134$)	23	68.2	151	2.84
Cedar ($n = 96$)	37	129.3	233	3.36
Red spruce ($n = 137$)	42	111.6	200	2.71

Table 3. Number of sample trees by site and light exposure classes.

Class	Balsam fir	Northern white-cedar	Red spruce	Total
Site class[a]				
2	28	32	10	70
3	30	40	15	85
4	20	50	30	100
5	63	105	58	226
Organic	30	69	45	144
Total	171	296	158	625
LE class[b]				
1	30	64	23	117
2	49	88	30	167
3	48	94	38	180
4	25	36	36	97
5	19	14	31	64
Total	171	296	158	625

[a] Site class descriptions follow Briggs' (1994) classification.
[b] LE class, light exposure class, after Bechtold (2003).

Mean diameter, height, and breast height age varied by species, although northern white-cedar had the shortest mean total height, the largest mean outside bark diameter, and the oldest mean breast height age (Table 2). Tree age was determined using only sound cores. In the event that sound cores did not intersect the pith, transparencies with concentric circles of equal radial width were used to estimate the number of years to the pith (after Applequist 1958). Sample trees of each species were present at each site and light exposure class level (Table 3).

Data Analysis

Tree cores were dried, sanded, and analyzed with Regent Instruments WinDendro software at 1,600 dpi resolution. Cores were analyzed from bark to pith, counting and dating annual radial in-

crement at the juncture of latewood and earlywood. Sapwood thickness was measured with digital calipers to the nearest 0.1 mm. Four balsam fir, four northern white-cedar, and two red spruce sample trees were removed from the analysis because of damaged cores.

Basal area increment was computed for the most recent complete 5 years of growth. Both sapwood area and basal area increment were determined at the core level and averaged for tree-level values. A no-intercept least-squares general linear model was used to describe the relationship of basal area growth as a function of sapwood area. Analysis of covariance was used to test differences in basal area growth among site classes and light exposures for each species at $\alpha = 0.05$. Sapwood area was used as a covariate in these analyses because of the allometric relationship between breast height sapwood area and foliage mass or area in coniferous tree species (e.g., Grier and Waring 1974, Gilmore et al. 1996, Maguire et al. 1998). Independent class variables (species, site, and light exposure) were tested for interactions. Mean separations were analyzed with Tukey's honestly significant differences test.

Tree decay was investigated with two metrics: the proportion of sample trees with central decay and the proportion of sample-tree basal area that was centrally decayed. Trees were considered decayed if either of the two cores showed evidence of decay (i.e., decomposed cells) before the pith. Proportion of basal area decayed was quantified as follows:

Decayed area (m^2)

$$= \left[\left\{\left(\frac{dbh_{ib}}{2}\right) - CL\right\} \times 2\right]^2 \times 0.00007854, \quad (1)$$

where dbh_{ib} is the diameter inside bark (cm) and CL is the core length (cm). Decayed area was quantified for each core and averaged over both cores to determine the tree basal area decayed. The mean value from Equation 1 was divided by the inside bark basal area to determine the proportion of basal area that was decayed. Analysis of variance (ANOVA) was used to test for differences in the proportion of basal area decayed by site class and light exposure class for each species at $\alpha = 0.05$.

Tree cores with no evidence of decay were selected for site index analysis. Because site index trees should be dominant or codominant and free from suppression (Avery and Burkhart 2002), light exposure class 1 and 2 trees were eliminated from this analysis. Chronologies were made for each tree that was free from decay. Only individuals with no signs of early suppression, as evident by reduced radial increment in the chronology, were retained for this analysis. Nearly all of the red spruce and balsam fir trees in this study had spruce budworm (*Choristoneura fumiferana*) signals in their ring chronologies (see Hofmeyer 2008). To increase sample size, several trees with weak budworm signals were retained in the analysis. A five-parameter Weibull function was used to estimate site index with parameter coefficient estimates previously published by Carmean et al. (1989) for northern white-cedar and Steinman (1992) for red spruce and balsam fir. ANOVA was used to test site index differences among site classes for each species at $\alpha = 0.05$. SYSTAT, version 12, was used for all statistical analyses.

Results

Basal Area Growth

A general linear model of basal area growth as a function of sapwood area had significant slopes for all species and accounted for
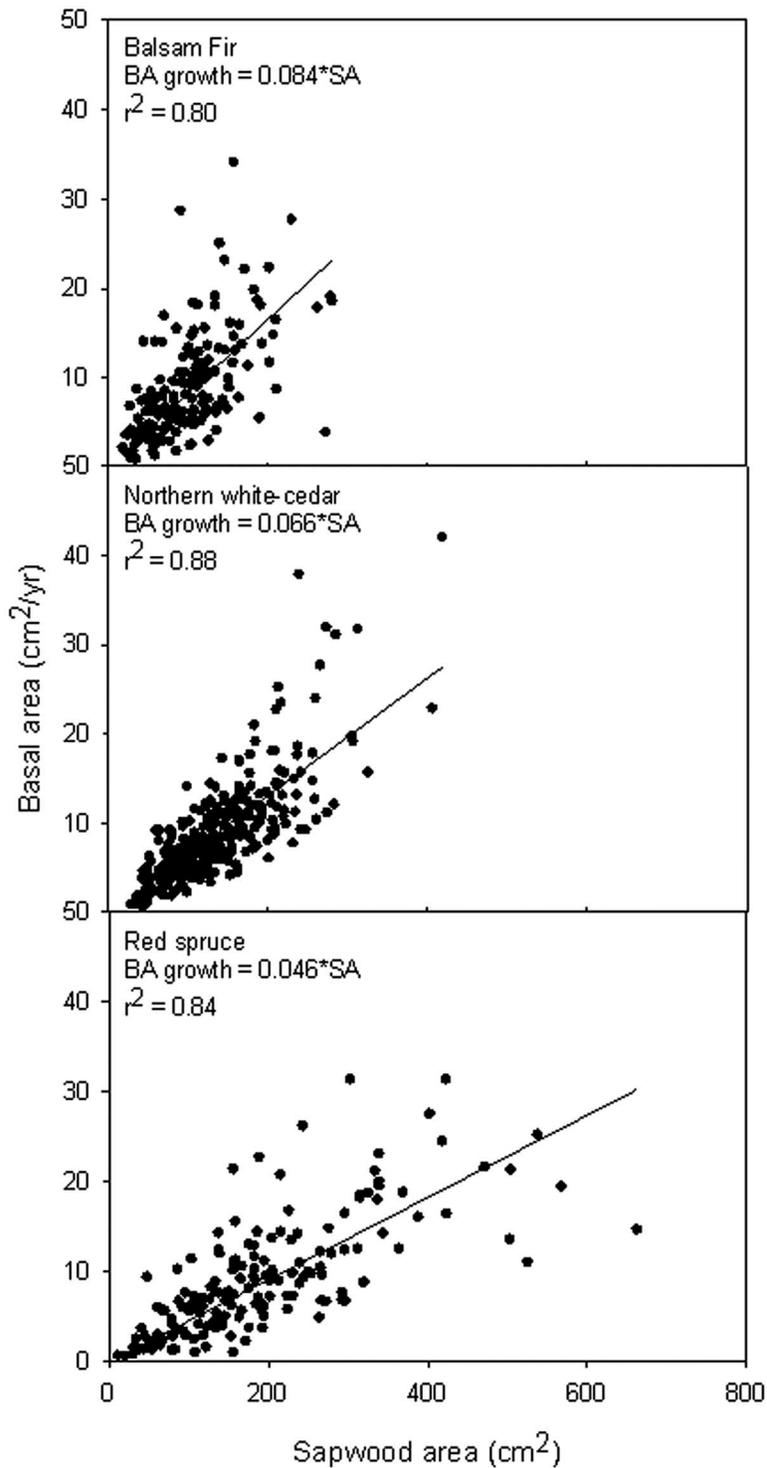
Figure 2. Basal area (BA) growth as a function of sapwood area (SA) by species.

at least 80% of the growth variability (Figure 2). Red spruce had the highest proportion of sapwood area per unit of basal area (SA:BA) (mean, 0.297; SE, 0.007), followed by balsam fir (mean, 0.252; SE, 0.006) and northern white-cedar (mean, 0.178; SE, 0.005). SA:BA differed by light exposure class only in northern white-cedar, with a significant trend of decreasing SA:BA with increased light exposure ($P = 0.006$).

Sapwood area was a significant covariate ($P < 0.001$) for tests of basal area growth differences among site and light exposure classes

by species. Site class was not a significant predictor of basal area growth in any species (Table 4). Balsam fir exhibited increased basal area growth with increasing light exposure ($P = 0.004$); however, neither northern white-cedar nor red spruce showed a growth response to increased light levels ($P = 0.881$ and $P = 0.425$, respectively). As expected, sapwood area and light exposure class were highly correlated in each species and may have masked differences in basal area growth among light exposure classes. Sapwood area did not differ among site classes within species.

Table 4. Mean basal area growth as a function of site and light exposure class with a significant sapwood area covariate. Mean growth is in cm²/year. LE class, light exposure class, after Bechtold (2003).

	Balsam fir		Northern white-cedar		Red spruce	
	Mean	SE	Mean	SE	Mean	SE
Site class						
2	8.76	0.90	9.32	0.64	9.96	1.44
3	9.72	0.86	8.24	0.57	9.91	1.18
4	9.91	1.06	8.23	0.51	10.58	0.83
5	9.10	0.60	9.18	0.35	8.68	0.60
Organic	7.36	0.86	9.05	0.43	9.06	0.68
LE class						
1	6.14[b]	0.91	8.83	0.50	8.35	1.03
2	8.37[a,b]	0.66	8.84	0.39	10.14	0.86
3	9.41[a,b]	0.66	8.67	0.38	9.51	0.74
4	11.34[a]	0.93	9.42	0.63	9.93	0.78
5	10.51[a]	1.15	9.21	1.01	8.43	0.86

[a,b] Means followed by different letters are different at $\alpha = 0.05$ (Tukey's honestly significant differences mean separation).

Table 5. Mean incidence of sample trees decayed by species and site class (standard errors in parentheses).

	Proportion of total sample trees decayed		
Site class	Balsam fir	Cedar	Red spruce
2	0.57 (0.09)[a]	0.97 (0.07)[a]	0.10 (0.10)
3	0.40 (0.08)[a,b]	0.88 (0.07)[a,b]	0.13 (0.08)
4	0.40 (0.10)[a,b]	0.64 (0.06)[b]	0.13 (0.06)
5	0.19 (0.06)[b]	0.73 (0.04)[b]	0.07 (0.04)
Organic	0.23 (0.08)[b]	0.74 (0.05)[b]	0.13 (0.05)
Mean	0.34 (0.03)[c]	0.80 (0.03)[d]	0.11 (0.02)[e]

[a,b,c,d,e] Means of the same species followed by different letters are different at $\alpha = 0.05$ (Tukey's honestly significant differences mean separation). Species' means were also significantly different.

Table 6. Proportion of breast height basal area decayed by species across site classes (standard errors in parentheses).

	Proportion of area decayed		
Site class	Balsam fir	Cedar	Red spruce
2	0.086 (0.024)	0.151 (0.022)[a]	0.017 (0.028)
3	0.110 (0.023)	0.154 (0.020)[a]	0.039 (0.023)
4	0.033 (0.029)	0.125 (0.017)[a,b]	0.041 (0.016)
5	0.041 (0.016)	0.086 (0.012)[b,c]	0.051 (0.012)
Organic	0.050 (0.023)	0.060 (0.015)[c]	0.013 (0.013)
P value	0.092	<0.001	0.273

[a,b,c] Means of the same species followed by different letters are different at $\alpha = 0.05$ (Tukey's honestly significant differences mean separation).

Decay

Mean incidence of decay across all site classes was lowest in red spruce (11% of the sample), followed by balsam fir (34%) and northern white-cedar (80%). Balsam fir incidence of decay was higher on site class 2 than on class 5 and organic sites (Table 5). Similarly, northern white-cedar incidence of decay was higher on site class 2 than on class 4, class 5, and organic sites. Red spruce decay was not different among site classes. Site class did not affect the proportion of breast height area decayed in balsam fir ($P = 0.092$) or red spruce ($P = 0.273$) but was significant for northern white-cedar ($P < 0.001$) (Table 6). Northern white-cedar had a trend of increasing area decayed with improved soil drainage. Light exposure class did not influence decay in any tree species ($P > 0.20$).

Table 7. Site index (m) at breast height age 50 for balsam fir, northern white-cedar, and red spruce by site class determined from trees without radial growth suppression in light exposure classes 3–5 (standard errors in parentheses).

Site class	Balsam fir	Cedar	Red spruce	P value
2	14.8 (1.188)[a,b]	No data	12.1 (1.372)	0.196
n	4	No data	3	
3	14.6 (0.687)[a,b]	12.3	10.9 (1.023)	0.015
n	7	1	2	
4	17.2 (0.956)[a]	10.3 (0.956)	12.5 (1.022)	<0.001
n	8	8	7	
5	13.2 (0.334)[b]	10.5 (0.732)	10.6 (0.437)	<0.001
n	24	5	14	
Organic	13.6 (0.434)[b]	9.6 (0.614)	11.2 (0.367)	<0.001
n	10	5	14	
P value	<0.001	0.091	0.359	

[a,b] Column means followed by differing letters are different at $\alpha = 0.05$ (Tukey's honestly significant differences mean separation).

Site Index

Surprisingly, northern white-cedar and red spruce site index did not differ among Briggs' (1994) site classes ($P = 0.641$ and $P = 0.358$, respectively). Balsam fir site index was higher in site class 4 ($P < 0.001$); all other site classes were undifferentiated (Table 7). Balsam fir was taller at breast height age of 50 years than red spruce and northern white-cedar on most site classes. Although site indexes of red spruce and northern white-cedar were not significantly different from one another across site classes, red spruce generally had a higher mean site index. Small sample size reduced confidence in site index values on upland site classes.

Discussion
Basal Area Growth

Basal area growth is often difficult to interpret because it is heavily influenced by tree size, crown variables, and stand density. Sapwood area was used in this study as a surrogate for leaf area, which in turn reflects stand density and associated crown variables (Grier and Waring 1974, O'Hara 1988). Mean SA:BA results indicated that northern white-cedar had less sapwood area than red spruce and balsam fir for a given tree diameter, which is consistent with past reports that cedar has a narrow sapwood radius per given diameter (Curtis 1946, Behr 1974). Linear regression analysis indicated that northern white-cedar basal area growth per unit sapwood area is less than that of balsam fir, but more than that of red spruce (see Figure 2). Because of the high proportion of sapwood area and the strong influence of basal area growth per unit sapwood area, balsam fir appears to have the best basal area growth capabilities of the three species at a given diameter and canopy position. High correlation of sapwood area to light exposure class suggests favoring trees in superior canopy positions for all species because basal area increment increases with sapwood area.

We did not find relationships between basal area growth and site class for any species, or between basal area growth and light exposure class for northern white-cedar or red spruce. However, because of the correlation between sapwood area and light exposure class, much of the growth response was captured in the covariate. When sapwood area was removed from the analysis, all three species showed a strong significant increase in basal area increment at higher light exposures ($P < 0.01$). This is consistent with expectations of higher growth increment of trees in superior canopy positions (Assman 1970).

On organic soils, balsam fir growth was significantly lower than that of red spruce and northern white-cedar. This is consistent with Briggs and Lemin (1994), who found that growth response of balsam fir to precommercial thinning was lowest on poorly and excessively drained soils. Meng and Seymour (1992) found that balsam fir saplings expressed significantly higher height and basal area growth in response to herbicide release treatment on well-drained site classes relative to poorly drained sites. Their data indicated that red spruce is relatively unresponsive to this cultural treatment by site class; height increment and basal area growth were lower in red spruce than balsam fir on well-drained sites.

We expected basal area growth of northern white-cedar to have a strong positive correlation with site class, but that relationship was not supported. Godman (1958) and Caulkins (1967) suggested that cedar growth was higher on upland soils and abandoned pasture lands than swamp sites in the Lake States. Harlow (1927) reported higher mean annual radial increment from a cedar community on a limestone outcrop (3.10 mm/year) than from a bog community (1.55 mm/year) in New York, but this difference was partially attributed to the "openness" of the limestone community. Curtis (1946) reported that volume growth was better on upland sites than lowland sites in Maine. In the present study, no differences were detected among upland and lowland communities once crown variables were accounted for with the sapwood area covariate.

It is important to note that our findings pertain only to basal area growth at breast height, and they may not apply to volume growth. Nevertheless, breast-height area increment is a commonly used metric of tree growth; results of the present study thus contribute meaningfully to our understanding of northern white-cedar stemwood growth dynamics.

Stem Decay

Species differences in mean breast height area decayed that were observed in this study are consistent with reports of high incidence of decay in northern white-cedar (Harlow 1927), moderate incidence of decay in balsam fir, and little decay in spruce (Whitney 1989). However, the trend in northern white-cedar for higher proportions of sample tree breast height area to be decayed on upland sites was somewhat unexpected. Several studies throughout the Northeast and Lake States suggest that stem quality is superior on upland sites (e.g., Curtis 1944, Godman 1958, Johnston 1990). Although "stem quality" is often ambiguously defined in cedar literature and might not be specific to internal decay, in terms of soundness, stem quality on well-drained sites in central and northern Maine is inferior to stem quality on very poorly drained and organic sites.

Results indicating no decay differences among light exposure classes suggest that cedar trees occupying all upper canopy positions are equally susceptible to decay fungi. Because no overtopped trees were sampled in this study, the degree to which canopy suppression is correlated with northern white-cedar's decay fungi vulnerability remains unknown. Reduced photosynthate and nutrient allocation to defensive compounds has been suggested to cause an increase in vulnerability to decay fungi (Waring 1987).

There was a significant site effect on decay incidence and proportion of sample tree basal area decayed. Several species of decay fungi have been observed to affect northern white-cedar, including *Armillaria mellea*, *Phaelus schweinitzii*, *Postia sericimollis*, and *Heterobasidion annosum* (Hepting 1971, Johnston 1990, Randolph et al. 2007). *P. schweintzii* and *A. mellea* have been reported as common

decay fungi infecting balsam fir in the Northeast. Basham et al. (1953) reported that butt rot was more common in balsam fir on upland "mixedwood slopes" than on "softwood flats." This relationship was attributed to fungus site preferences and the absence of many fungal species on the lower site classes. A similar site-decay relationship was reported earlier by Zon (1914); greater balsam fir decay on upland sites was attributed to frequent anaerobic conditions on lowland sites that limited fungal infection. Similar site influences on decay in balsam fir and northern white-cedar in this study support the notion that decay fungi are more prevalent and vigorous on upland sites.

Wood strength might play an important role in decay fungi entry and proliferation within the bole. Although cellulose is essentially the same in all trees, differences in hemicellulose and lignins do occur and affect tree responses to decay fungi (Manion 1991). Northern white-cedar is the lightest and weakest commercial wood in the United States; it has a density of 0.315 g/cm^3 and a modulus of rupture of 4.56 kg/mm^2, lower than those of balsam fir (0.414 g/cm^3, 5.42 kg/mm^2) and red spruce (0.414 g/cm^3, 7.15 kg/mm^2) (Seely 2007). Some evidence suggests that increased wood density provides some protection against pathogens (Loehle 1996). One might hypothesize from these metrics that decay would be more prevalent in northern white-cedar than red spruce and balsam fir. Whitney (1989) found that decay fungi were more common in balsam fir than black spruce (density of 0.428 g/cm^3; modulus of rupture of 7.24 kg/mm^2). Whitney (1989) observed high incidences of root decay in young balsam fir stands, perhaps as a result of the inability of balsam fir's weak wood to withstand environmental stressors (e.g., wind and snow). Decay results from this study suggest that decay and wood strength may be correlated in some species.

All sites selected for sampling were provided by members of forest industry with active harvesting operations. On many upland sites, forest operations preferentially removed balsam fir, red spruce, and valuable hardwoods. Northern white-cedar is often retained on these sites to meet minimum stocking levels post-harvesting. Residual stand damage is common after partial harvesting (Ostrofsky et al. 1986, Ostrofsky and Dirkman 1991). Northern white-cedar may be particularly susceptible to crown and root damage during harvesting because branches and roots are weak. If the branch collar remains intact during crown damage events, decay generally cannot spread throughout the bole (Shigo 1984). If a branch is stripped away because of wind, snow load, or harvesting and damages the branch collar, decay could enter the stem.

Worrall et al. (2005) noted that balsam fir has a high incidence of root damage due to chronic wind stress in high-elevation, old-growth red spruce–balsam–fir forests in New Hampshire. Many of the stems in that study were observed to be infected by *Armillaria* and other root rot fungi. Northern white-cedar stands commonly occur on shallow or poorly drained sites where individuals occupy soil mounds and decayed woody material that were once germination sites. These stems are frequently "pistol butted" because of a disturbance of the root system (e.g., harvesting operations, snow loads, and wind stress). Zon (1914) reported decay fungi entry through root damage from sharp rocks, strong winds, and logging operations in balsam fir. If decay fungi enter disturbed root systems in northern white-cedar as they do in fir, it seems that root breakage could be an entry mechanism.

Site Index

Several of the red spruce and northern white-cedar trees that were selected for site index analysis exceeded 100 years of age. Given the asymptotic nature of height growth with stem age, inclusion of these samples might have increased within-site variability, although residual analysis did not indicate any outliers. Trees were selected for site index analysis post hoc, after the field data collection period. Sample trees could not be assessed for minor crown damage or crown irregularities that may have affected total tree height. Although trees with significant radial increment suppression were removed, it is difficult to determine the degree of height suppression from minor radial suppression events.

High variability of height growth within site class has been noted for red spruce, often masking clear differences among site classes. Seymour and Fajvan (2001) reported mean site index (at stump height age 50) for previously suppressed red spruce trees to range from 12.4 to 11.3 m on good to poor soil classes, but they suggested that high variability may have been associated with the broad classes they used. Williams et al. (1991) reported mean site index (breast height age) for red spruce within a single catena as 17.4–15.1 m at 50 years on well-drained to poorly drained sites, whereas mean balsam fir site index ranged from 18.0 to 14.6 m. Restricting sampling in that study to a single catena may have reduced inherent soil variability and associated height growth variation. Red spruce mean site index values in this study ranged from 12.5 to 10.6 m; within-site variability was high. Many useable site index trees in this study were on Briggs' (1994) site class 4, 5, and organic soils, which makes comparisons with related studies problematic. Williams et al. (1991) did not sample trees on very poorly drained mineral or organic soils. Height variability among site classes in the present study could result from using drainage class to predict growth instead of chemical soil properties, although Steinman (1992) found that chemical properties accounted for little height variability after adjusting for physical soil properties in even-aged spruce–fir stands in Maine.

Although this study captured few differences in site index by site class within species, differences among species were detected. These data suggest that cedar will generally have lower site index than balsam fir along the site class continuum. Williams et al. (1991) also found that balsam fir has a higher site index than red spruce on better drained soils, although they reported an opposite relationship on imperfectly drained soils.

Conclusions

Conventional wisdom guiding northern white-cedar management throughout the Northeast had little quantitative support from this study. Field foresters often attribute higher growth rates and stem quality to upland cedar communities. Results suggest that northern white-cedar basal area and height growth were not affected by site class, although incidence of decay and proportion of basal area decayed were highest on the well-drained sites.

Although mechanisms for decay entry and physiology of decay responses in northern white-cedar are largely unknown, efforts to reduce residual stand damage during harvesting operations are encouraged. In addition to northern white-cedar's weak and brittle wood properties, our observations confirm a high incidence of decayed northern white-cedar on the working forest landscape. Careful logging could help to reduce crown and root disruptions in residual trees. Avoiding residual stand damage is important because northern white-cedar is commonly retained through several partial harvesting operations.

Northern white-cedar has historically been considered a slow-growing species relative to many of its competitors. Our study suggests that growth of mature upper canopy northern white-cedar is comparable to that of red spruce but less than that of balsam fir, regardless of site class or light exposure class. This may be particularly important because northern white-cedar commonly occupies a canopy position inferior to red spruce and balsam fir because of its small stature. Site index results from imperfectly drained soils indicate that on average balsam fir is taller than red spruce, which is taller than northern white-cedar.

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