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Old-growth Characteristics of Northern White-cedar Stands

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OLD-GROWTH CHARACTERISTICS OF

NORTHERN WHITE-CEDAR STANDS

By

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By Nathan Wesely

Thesis Co-advisors: Dr. Shawn Fraver and Dr. Laura S. Kenefic

An Abstract of the Thesis Presented
in Partial Fulfillment of the Requirements for the
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Northern white-cedar (*Thuja occidentalis*; hereafter white-cedar) communities have received relatively little research attention, and managers lack the tools used in the management of other commercial tree species. This includes the recognition of old-growth characteristics and the differentiation between old-growth and partially harvested stands, particularly in the context of Forest Stewardship Council (FSC-US) certification. Specifically, there is very little information about characteristics that define old-growth white-cedar stands despite the species' abundance and wide distribution. Regional indices for late-successional or old-growth stands (Whitman and Hagan, 2007) do not include white-cedar. Forests dominated by white-cedar represent a type that currently lacks quantitative benchmarks for old-growth characteristics.

To identify the structural characteristics unique to old-growth white-cedar stands, we inventoried 16 old-growth and 17 partially harvested stands in Maine and New

Brunswick. In Chapter 1, we report the outcomes from a range of structural metrics commonly used in forest management such as basal area (BA, m^2 ha^{-1}), quadratic mean diameter (QMD, cm), large tree (≥ 40 cm dbh) density, and volumes of coarse woody material (CWM, m^3 ha^{-1}), along with a set of structural complexity indices (e.g., diameter distribution index, mingling index). Two significant predictors were identified that, in combination, differentiate old-growth from partially harvested white-cedar stands: advanced-decay coarse woody material volume (logs in decay stages 4 and 5 using a 5-stage system) and live tree QMD. No structural complexity indices were useful in predicting old-growth status. Our research improves the understanding of old-growth characteristics in white-cedar stands and provides an important tool for the successful management of white-cedar.

In Chapter 2, we present a practitioner-oriented guide to aid in the application of our findings by forest managers. Specifically, we provide an equation for determining the probability that a white-cedar stand has old-growth characteristics, as well as supporting information about how to collect and prepare the data needed to use this prediction tool. Illustrations and photographs are used to demonstrate the forest attributes of interest, and to aid the practitioner in measuring and determining the decay classes of coarse woody material. In addition, we discuss the relevance of our findings to ecological forestry prescriptions. This guide will prove useful for forest managers working under FSC guidelines, wherein the recognition of old-growth characteristics is institutionalized in requirements for reserving old-growth stands and maintaining old-growth characteristics where they are found in managed stands.

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Old-growth forests are declining globally (FAO, 2010). There is concern that this decline will correspond to a loss in ecosystem services. These services include biodiversity, as old forests can support specialist organisms often unrepresented in younger forest (Berg et al., 1994; Selva, 2003). Old-growth forests are also long-term carbon sinks and play a unique role in the global carbon cycle (Luyssaert et al., 2008). Promoting old forests and their associated features is recognized as an important way to mitigate climate change as well as global biodiversity loss (Gunn et al., 2014). Old forests also serve to influence human culture both directly through resource provision and indirectly by helping form social identity and individual well-being (Perlman, 1996). As old-growth forests become increasingly rare, the variety of ecosystem services they provide have growing importance.

Sustaining or maintaining these services requires protecting existing old-growth as well as restoring associated features to managed landscapes (Davis, 1996; Mossler et al., 2003; Ducey et al., 2013). These forest management goals can be achieved on working forest lands through ecologically modeled silviculture (i.e. ecological forestry) and forest certification programs. Ecological forestry models harvesting activities within the variability of natural stand development patterns (Seymour, 1999). Specific silvicultural methods can be used to develop and maintain old-forest characteristics (Bauhaus et al., 2009). Along with ecologically based practices, forest certification programs serve to hold forest owners to high standards of forest management based on the most current science (FSC, 2010). A common theme in many certification programs is the identity and maintenance of old-growth characteristics.

A major challenge to old-growth identification is the wide range of variability that these stages can possess. Old-growth forest communities have vastly different characteristics based on the species that compose them as well as site conditions (Spies, 2004). In order to achieve desired management objectives regarding old-growth, those characteristics unique to old-growth must be identified, and these characteristics must be identified for the specific forest type and region that they will be applied (Kimmins, 2003). For many forest types, quantitative benchmarks of old-growth characteristics do not exist, which poses a major challenge in identifying and maintaining old-growth characteristics. Specifically, northern white-cedar-dominated forests of northeastern North America lack quantitative targets for use in the identification and maintenance of old-growth white-cedar stands.

The goal of this study was to evaluate the structural and compositional characteristics potentially unique to old-growth white-cedar stands and develop guidelines for their identification by forest managers. Chapter one investigates the structural and compositional characteristics that distinguish old-growth from partially harvested white-cedar stands. Chapter two is a manager-oriented guide for identifying characteristics of old-growth northern white-cedar stands in the Acadian Forest region.

CHAPTER ONE

STRUCTURAL CHARACTERISTICS OF OLD-GROWTH AND PARTIALLY HARVESTED NORTHERN WHITE-CEDAR STANDS

1.1. Abstract

Forestry practitioners are confronted with challenges when managing northern white-cedar (*Thuja occidentalis*; hereafter white-cedar), including the recognition of old-growth characteristics and differentiation between old-growth and partially harvested stands, particularly in the context of Forest Stewardship Council (FSC-US) certification. To identify the structural characteristics unique to old-growth white-cedar stands, we compared inventories from 16 old-growth stands and 17 partially harvested stands in Maine and New Brunswick. Potential old-growth predictors used in the analysis included common structural metrics such as basal area (BA, $m^2\ ha^{-1}$), quadratic mean diameter (QMD, cm), large tree (≥ 40 cm dbh) density, and volumes of coarse woody material (CWM, $m^3\ ha^{-1}$), along with a set of structural complexity indices (e.g., diameter distribution index, mingling index). Using a generalized linear mixed-model approach, two significant predictors, in combination, were identified that differentiate old-growth from partially harvested stands: advanced-decay coarse woody material (logs in decay classes 4 and 5 using a 5-decay-class system) and live tree QMD. Advanced-decay CWM volumes averaged 60.6 and 20.8 $m^3\ ha^{-1}$, and QMD averaged 29.4 and 26.3 cm for old-growth and partially harvested stands respectively. None of the structural complexity indices were useful in predicting old-growth status. Our research shows that these two measures, commonly applied in forest management, can be used to identify old-growth

white-cedar stands, and it improves our understanding of old-growth characteristics in white-cedar stands, aiding in their successful management.

1.2. Introduction

Successful forest management planning includes identifying areas suitable for silvicultural treatments, as well as areas to be set aside from harvest because of their of high conservation value. High conservation value stands are those that provide exceptional non-commodity resources such as habitat for rare organisms, flood mitigation or erosion control, or representation of locally rare ecosystems (Forest Stewardship Council, 2010). Traditional resource extraction (i.e., logging) can homogenize stand structure (Seymour, 1992) and potentially reduce a stand's unique conservation values, particularly where old-growth forests and their associated features are involved (Simberloff, 1987; Essen et al., 1996; Franklin et al., 2007). Alternatively, ecologically based silvicultural methods allow resource extraction while maintaining or promoting unique features or conditions that have conservation value (Franklin et al., 2007; Bauhus et al., 2009). Given the importance of high conservation value stands, their identification and treatment has been institutionalized through forest certification guidelines.

One of the most challenging yet critical aspects of this process is determining which stands or communities have high conservation value. Such communities are often assumed to have characteristics typical of old-growth, such as large live and dead trees (Whitman and Hagan, 2007), structural heterogeneity (Franklin and Van Pelt, 2004; McElhinny et al., 2005), and large volumes of coarse woody material (Franklin and Spies, 1991; Ziegler, 2000). Though definitions of old-growth vary, the Forest Stewardship Council (FSC) guidelines for the Northeastern United States (Forest

Stewardship Council, 2010) specify old-growth as, “the oldest seral stage in which a plant community is capable of existing on a site, given the frequency of natural disturbances.” The guidelines further divide old-growth forests into two types: Type 1 old-growth is a stand ≥ 1.2 hectares that has never been harvested and that displays old-growth characteristics, and Type 2 old-growth is a stand ≥ 8 hectares that has been logged to some extent but retains significant old-growth characteristics (Forest Stewardship Council, 2010). These definitions have important management implications, as FSC guidelines specify that Type 1 old-growth requires reserve status (i.e., no harvesting), and Type 2 requires the maintenance of old-growth characteristics during management operations (i.e., ecologically based silviculture).

Although certification programs contain the impetus for the conservation of old-growth and old-growth characteristics, quantitative targets for old-growth characteristics are left to be defined by managers (Ducey et al., 2013). Guidance has been provided for some forest types (Franklin and Spies, 1991), but is incomplete or lacking for many forest types (Mosseler et al., 2003). Forest-type specific definitions and guidelines are clearly needed, given the large variability between types (Kimmins, 2003). Such definitions are important when practitioners are called upon to make determinations about the old-growth status of forest stands from a certification perspective.

Forests dominated by northern white-cedar (*Thuja occidentalis*) represent a type that currently lacks quantitative targets for old-growth characteristics. White-cedar is a common tree species in northeastern and north-central North America. It is a very long lived, medium-sized tree that often occurs as a secondary component in mixed-species stands. However, it is generally found as a dominant on a range of low quality sites, from

very poorly drained soils in lowlands to excessively well drained uplands (Johnston, 1990). It is most commonly associated with wet areas and is an important species in forested wetlands throughout the region (Curtis, 1946). Two white-cedar-dominated forest types are commonly recognized: cedar seepage and cedar swamp communities (Gawler and Cutko, 2010). Both are dominated by white-cedar, with balsam fir (*Abies balsamea*), spruce (*Picea* spp.), and other species present. Seepage forests occur on gentle slopes with soils composed of a shallow organic horizon over mineral deposits with moving groundwater, while white-cedar swamps occupy basins with limited drainage and groundwater present (Gawler and Cutko, 2010). White-cedar dominated communities develop under low disturbance severity over long periods of time (Fraver et al., 2009; Larouche et al., 2010). The conditions necessary for the development of white-cedar stands create a wide variety of microhabitats and potential biological niches for specialist organisms (Selva, 2003).

There is very little information about characteristics that define old-growth white-cedar stands (but see Fraver et al., 2009), despite the species' abundance and wide distribution. Regional indices for late-successional or old-growth stands (Whitman and Hagan, 2007) do not include white-cedar. Any indices or criteria based on tree age alone are especially problematic for this species: its susceptibility to internal stem decay makes age largely indeterminable by tree-ring methods (Fraver et al., 2009). Further, its shade tolerance variability, longevity, and slow growth make stem diameters particularly unrepresentative of age (Hofmeyer et al., 2010). Thus, the identification of the structural characteristics of old-growth white-cedar stands is warranted to assess conservation value and ultimately improve management of this forest type.

In order to facilitate forest management planning, and in particular compliance with certification requirements for identifying old-growth stands and those with old-growth characteristics, we undertook a study of the structural and compositional attributes of various white-cedar-dominated stands. We focused on identifying the structural attributes most strongly associated with old-growth (defined for this study as stands with no known or visible history of harvesting) and previously partially harvested white-cedar stands. Specifically, our objectives were to: 1) characterize the structural and compositional attributes of old- and partially harvested white-cedar stands, 2) identify the structural features unique to old-growth white-cedar stands, and 3) create a metric for decision making in the context of old-growth white-cedar determination under forest certification. We addressed these objectives by analyzing detailed structural information on 16 known old-growth stands as well as 17 stands with evidence of past harvesting throughout the Northeastern region.

1.3. Methods

1.3.1. The Acadian Forest Region

The Acadian Forest Region represents a transitional zone between the eastern boreal forest and the temperate deciduous forest of North America, and it harbors components of each of these major biomes. It is delineated as the zone characterized by the overlapping ranges of balsam fir and red spruce (*P. rubens*) (Seymour and Hunter, 1992). The modern landscape features of the Region are largely shaped by the Laurentide Ice sheet from the last glaciation of North America. Deposition of glacial till and its composition dictates modern site quality, with best sites occurring in unsorted till on slopes and low elevation mountaintops and the poorest sites in outwash and alluvial materials (Seymour, 1994).

1.3.2. Study Site Selection

For the purpose of this study, old-growth was defined as a forest in late developmental stages that has no historical or visible evidence of timber harvesting (such as cut stumps). Potential old-growth sites were identified through consultation with regional scientists, state agencies, and conservation organizations. Four sites, out of 16 suggested for field reconnaissance, ultimately met our old-growth criteria and were selected for this study. All four sites are currently managed as protected areas in Maine and New Brunswick (Figure 1.1), including Deboullie Ecological Reserve, Big Reed Forest Reserve, Baker Branch Reserve on the St. John River, and MacFarlane Brook Protected Natural Area. Two of these sites (Deboullie and MacFarlane Brook) had been used to study rare lichen communities associated with unharvested forests (S. Selva, unpublished data); one site (Big Reed) had been used in previous research examining historical natural disturbances (Fraver et al. 2009).

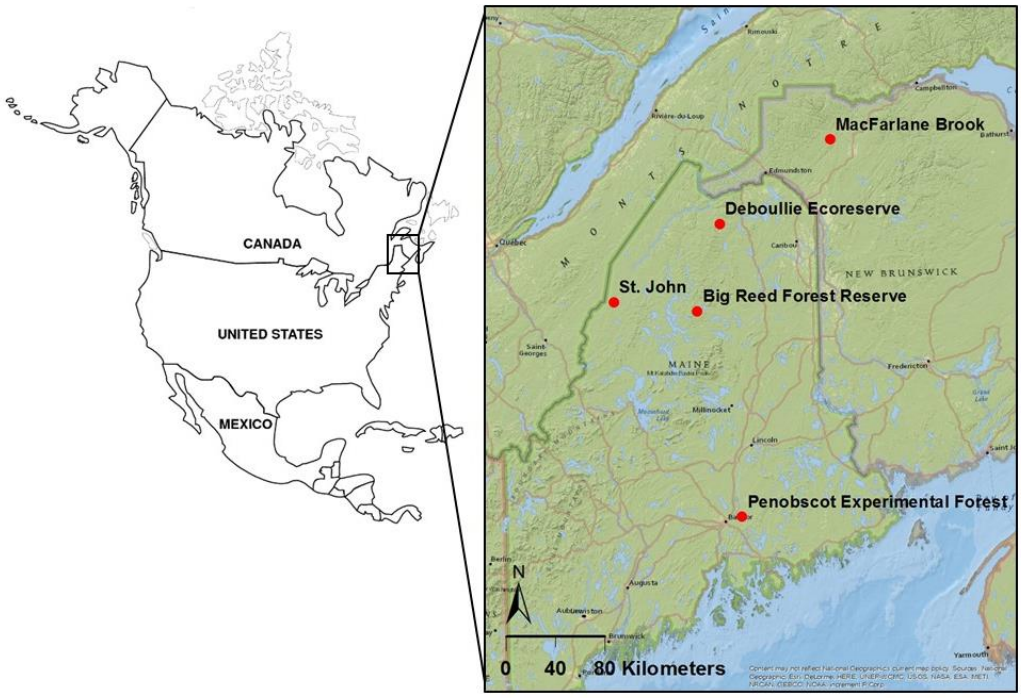

Figure 1.1. Location of the five northern white-cedar study sites used in this study.

Partially harvested stands were those that had experienced irregular cutting in the past 15 to 40 years, as evidenced by cut stumps in varying states of decay. Our intent was to select partially harvested stands near or adjacent to the old-growth stands, thus forming a paired sampling design. Although we were able to do this for three of the four old-growth sites, we were not able to do so for the Big Reed old-growth sites. Additional partially harvested stands were sampled at the Penobscot Experimental Forest, Maine, to provide a wider range of stand conditions in analyses.

1.3.3. Site Description

Mean annual temperature across sites ranged from 3.1 to 6.4°C, and annual precipitation ranged from 1075 to 1155 mm (PRISM, 2016; Table 1.1). Elevations ranged from 41 m a.s.l. at the Penobscot Experimental Forest to 383 m a.s.l. at the Big Reed Forest Reserve

(U.S. Geological Survey, 2016; Table 1.1). All sites (old-growth and partially harvested) had loamy soils derived from glacial till with varying levels of organic material ranging from deep, predominately organic soils to soils with a shallow organic horizon over mineral deposits. Drainage of all sites ranged from very poorly drained to somewhat poorly drained soils with an average depth to water table ranging from 0 cm to 30 cm (Web Soil Survey, 2016). Our sampling include both the swamp forest type (18 stands) and the seepage type (15 stands; Table 1.2).

Table 1.1. Characteristics of the five northern white-cedar sites used in this study. Elevation from digital elevation model, U.S. Geological Survey. Annual temperature and precipitation based on normalized means between 1981 and 2010 from PRISM Climate Group, Oregon State University.

Site	Lat., Long.	Elevation (m)	Annual Precip. (mm)	Mean Annual Temp. (°C)
Deboullie Ecoreserve	46°59' N, 68°49' W	301	1092	3.6
Baker Branch of the St. John River	46°24’ N, 69°57’ W	358	1155	3.1
Big Reed Forest Reserve	46°25' N, 69°50' W	383	1091	3.4
Penobscot Experimental Forest	44°50’ N, 68°36' W	41	1075	6.4
MacFarlane Brook	47°36' N, 67°37' W	294	1104	3.5

Table 1.2. Distribution of stands by forest type and old-growth status.

Forest Type	Status	No. Stands
White-cedar swamp	Old-growth	8
White-cedar swamp	Partially harvested	10
White-cedar seepage	Old-growth	8
White-cedar seepage	Partially harvested	7

1.3.4. Field Sampling and Calculations

At each stand, fixed-radius circular plots (0.1 ha) were randomly established to record species, diameter at breast height (DBH, 1.37 m), and location (distance and azimuth from plot center) for all living and dead trees ≥ 10 cm DBH. Most stands were rather small, allowing just one plot per stand. However, three of the old-growth stands were large enough to permit up to four plots per stand, maintaining a minimum distance of 80 m between plots. In these cases plot values were averaged to produce stand-level values for analysis. Coarse woody material volume was estimated by the line-intercept method (Brown, 1971), using three 40-m transects (120 m total) radiating outward from plot center at fixed azimuths (Figure 1.2). For each coarse woody material piece ≥ 10 cm diameter at the point of intersection with the sampling transect, we recorded diameter at intersection, species, and decay class (following the five-class system of Sollins et al., 1987). These values were converted to volume ha^{-1} following formula presented in van Wagner (1968) and Brown (1971). Calculated volumes of decay class 4 and 5 pieces were reduced to account for their collapse resulting from advanced decay, following Fraver et al. (2013). With these data we calculated stand structural and compositional measures commonly used in forest management, including live and dead tree basal area (BA; $m^2\ ha^{-1}$), number of trees per hectare (TPH), quadratic mean diameter of live and dead trees (QMD; cm), BA and TPH of live and dead large trees (≥ 40 cm DBH), and volumes of coarse woody material by decay class ($m^3\ ha^{-1}$).

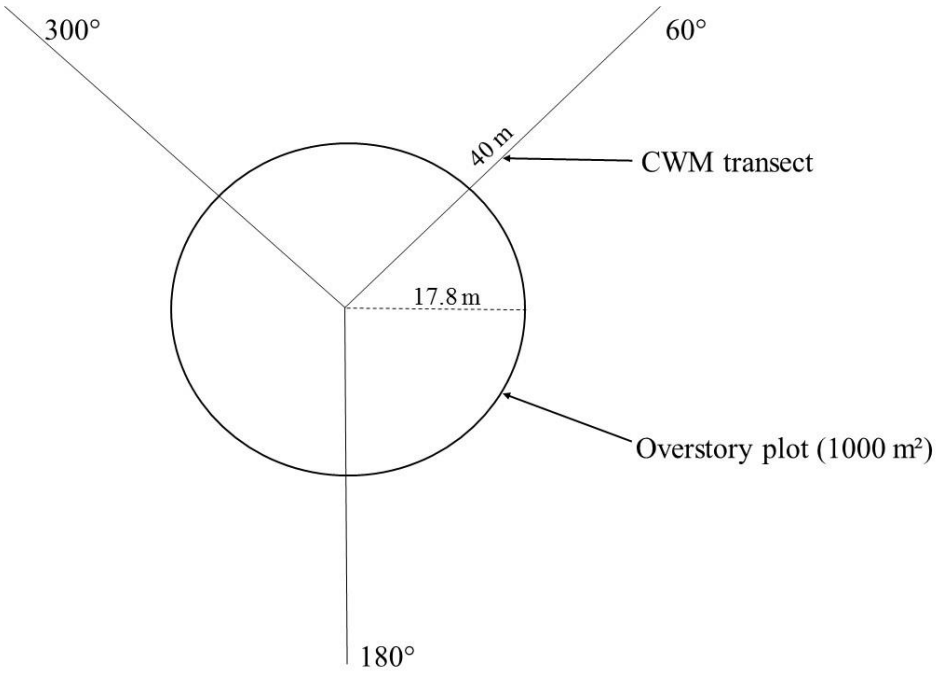

Figure 1.2. Layout of overstory plot and CWM transects established at each white-cedar stand.

These same data also allowed us to calculate seven structural complexity indices, including both spatially explicit and spatially non-explicit indices, that we hoped would capture the potentially subtle differences between old-growth and partially harvested stands.

Specifically we calculated:

- Gini coefficient, a measure of the range of variability represented in diameters with the theoretical value of 0 representing a stand of all similar sized trees and a value of 1 representing maximum heterogeneity (Peck et al., 2014);
- Shannon-Weaver index based on diameters and tree species, a relative measure of diversity or variability represented across groups (Shannon and Weaver, 1949);

- Diameter differentiation index, a measure of the spatial distribution of tree sizes with values ranging from 0 to 1 with increasing values representing greater difference between the diameter of a reference tree and its nearest neighbor (Pommerening, 2002);
- Mingling index, a measure of the species diversity in reference to a focal tree and its closest neighbors (Pérez and Kramer, 2006);
- Clark-Evans index of aggregation, a measure of the regularity of the distribution of trees across a horizontal axis, with a value of 1 pertaining to a random configuration, lower values representing aggregation, and higher values increased regularity (Pérez and Kramer, 2006); and
- Mean directional index, a measure of the arrangement of trees around a focal tree, with a value of 0 for a square lattice and higher values representing greater clustering (Corral-Revis, 2006).

1.3.5. Statistical Analysis

We first tested if the various groups (old-growth vs. partially harvested and swamp vs. seepage) differed with respect to tree species composition, using multivariate techniques applied to species' relative basal areas. Specifically, we used multi-response permutation procedures (MRPP), a nonparametric procedure that tests the hypothesis of no difference between two or more groups based on a matrix of Sørensen distances. MRPP produces a chance-corrected within-group agreement value (A), which is a measure of heterogeneity within groups compared to random expectation, ranging from -1 to 1, with a completely heterogeneous set having a value of -1, a random expectation of 0, and completely

homogenous set of 1. Tests were performed using PC-ORD Version 6.08 (McCune and Grace, 2002).

To determine if our structural metrics could distinguish old-growth and partially harvested white-cedar stands, we first needed to screen the large number of potential metrics to determine an appropriate subset for inclusion in a generalized linear model. To this end, we used a non-parametric approach, namely the variable selection using random forest (VSURF) package (Genuer et al., 2016) in R (R Core Team, 2014). The resulting top ranked predictors were then used to construct a generalized linear mixed-effects model using the lme4 (Bates et al., 2015) package in R. Here, old-growth status was used as the binary response variable while testing stand structural metrics as predictors. Location, forest type (cedar seep vs swamp), site productivity (parent material, lithology, and soil drainage, Web Soil Survey, 2016), and a measure of climate (climate site index, Weiskettel et al., 2010), were also included as predictors (as random effects) in these models. The model was refined by iteratively excluding insignificant predictor variables in a stepwise procedure until only significant predictors remained, and a model of best fit was identified based on the Akaike information criterion (AIC) score and area under the curve (AUC). A significance level of 0.05 was used for all main effects.

1.4. Results

1.4.1. Tree Species Composition and Forest Structure

Northern white-cedar dominated all stands, with an average relative basal area of 77% ±18% (stands pooled). Commonly associated species included red and black spruce (*P. mariana*), balsam fir, red maple (*Acer rubrum*), yellow birch (*Betula alleghaniensis*), and

black ash (*Fraxinus nigra*) in order of decreasing abundance by basal area. Swamps tended to have a greater dominance of white-cedar, while seepage stands had less white-cedar and a larger component of associated species, as is suggested by community descriptions for this region (Gawler and Cutko, 2010). Yet tree species composition did not differ significantly between cedar swamps and seeps (A=0.003, p=0.316) nor between old-growth and partially harvested stands (A=0.023, p=0.073).

Data pooled across all sites and developmental stages showed a mean living tree BA of 53.2 ±14.6 $m^2 \cdot ha^{-1}$ and TPH of 913 ±297, with a total CWM volume of 145.9 ±69.5 $m^3 \cdot ha^{-1}$. On average 27% of the CWM volume was in advanced stages of decay (classes 4 and 5) with an overall average volume of 40.1 ±37.4 $m^3 \cdot ha^{-1}$ (Table 1.3).

Table 1.3. Mean (standard deviation) and range of stand structural variables for old-growth and partially-harvested stands. Decay class system based on five classes, as per Sollins et al. (1987); (n=number of stands).

Stand Variable	Old-growth (n=16)	Partially harvested (n=17)	Total (n=33)
Living trees (DBH ≥10 cm)			
Basal area ($m^2 \cdot ha^{-1}$)	51.8 (17.9)	54.5 (11.1)	53.2 (14.6)
	26.6 - 94.2	37.3 - 76.3	26.6 - 94.2
Trees per hectare (no. ha^{-1})	765 (220)	1051 (98)	913 (297)
	300 - 1130	560 - 1680	300 - 1680
Quadratic Mean Diameter (cm)	29.4 (3.4)	26.3 (4.8)	27.8 (4.4)
	24.2 - 34.4	19.8 - 34.9	19.8 - 34.9
Large trees (≥40 cm DBH) per hectare	135 (67)	97 (68)	115 (69)
	70 - 280	0 - 210	0 - 280
Standing dead trees (DBH ≥10 cm)			
Basal area ($m^2 \cdot ha^{-1}$)	12.7 (10.0)	7.5 (2.5)	10.0 (7.5)
	3.2 - 31.9	2.5 - 12.0	2.5 - 31.9
Trees per hectare (no./ha)	164 (63)	182 (79)	173 (71)
	70 – 280	90 - 350	70 - 350
Quadratic Mean Diameter (cm)	26.7 (4.4)	23.3 (3.1)	25.0 (4.1)
	18.7 - 36.2	18.9 - 27.6	18.7 - 36.2
Large trees (≥40 cm DBH) per hectare	34 (42)	10 (7)	22 (32)
	0 - 110	0 - 20	0 - 110
Coarse woody material (≥10 cm diameter)			
Total volume ($m^3 \cdot ha^{-1}$)	168.1 (49.3)	125.1 (80.2)	145.9 (69.5)
	74.1 - 240.5	36.4 - 314.1	36.4 - 314.1
Advanced decay volume (Class 4 and 5; $m^3 \cdot ha^{-1}$)	60.6 (40.5)	20.8 (21.1)	40.1 (37.4)
	2.5 - 147.7	0 - 70.2	0 - 147.7

Table 1.4. Mean (standard deviation) and range of structural complexity indices for old-growth and partially harvested stands. Decay class system based on five classes, as per Sollins et al. (1987); (n=number of stands).

Stand Variable	Old-growth (n=16)	Managed (n=17)	Total (n=33)
Structural Complexity Indices			
TD	0.35 (0.04)	0.33 (0.03)	0.34 (0.04)
	0.28 - 0.44	0.27 - 0.39	0.27 - 0.44
M	0.50 (0.19)	0.43 (0.15)	0.46 (0.17)
	0.18 - 0.77	0.17 - 0.64	0.17 - 0.77
CE	0.30 (0.02)	0.29 (0.03)	0.29 (0.02)
	0.27 - 0.34	0.24 - 0.33	0.24 - 0.34
H	1.08 (0.44)	0.86 (0.30)	0.95 (0.38)
	0.38 - 1.64	0.40 - 1.35	0.38 - 1.64
R	1.86 (0.12)	1.94 (0.09)	1.90 (0.11)
	1.56 - 2.04	1.78 - 2.15	1.56 - 2.15
GINI	0.26 (0.03)	0.24 (0.04)	0.25 (0.03)
	0.22 - 0.29	0.18 - 0.29	0.18- 0.29
SIM	0.54 (0.20)	0.45 (0.16)	0.49 (0.18)
	0.19 - 0.77	0.19 - 0.70	0.19 - 0.77

Our initial screening of meaningful predictors using random forest analysis produced the following top predictors aimed at distinguishing old-growth from partially harvested stands: volume of advanced-decay coarse woody material, quadratic mean tree diameter, trees per hectare, total coarse woody material volume, and standing dead (snag) quadratic mean diameter.

The generalized linear mixed-effects model that followed identified two of these as significant predictors of old-growth status when used in combination: advanced-decay CWM (p=0.0134) and QMD (p=0.0391) (Table 1.5; Table 1.6). Advanced-decay CWM

volume averaged 60.6 ±40.5 and 20.8 ±21.1 $m^3 \cdot ha^{-1}$, while QMD averaged 29.4 ±3.4 and 26.3 ±4.8 cm for old-growth and partially harvested stands respectively (Figures 1.5 and 1.6, Table 1.3). None of the structural complexity measures were significant in predicting old-growth status, nor were location, forest type, and site productivity variables in this final model. The combined influence of advanced-decay CWM volume and QMD, as predictors of old-growth status, can be readily seen in Fig. 1.3, which demonstrates that as the values of both metrics simultaneously increase, so does the probability that a given stand can be classified as old-growth.

Table 1.5. AIC table of models tested with top variables identified in the preliminary analysis (VSURF) used to predict old-growth status. CWM_{ADV}=advanced-decay coarse woody material volume; QMD=quadratic mean diameter; CWM_{TOT}=total coarse woody material volume; TPH=trees per hectare; SN_QMD=standing dead (snag) quadratic mean diameter. * denotes significance ($p \leq 0.05$).

Model Predictors	k	AICc	ΔAICc	AICc Weight	AUC
CWM_{ADV}* + QMD*	4	37.8	0.0	0.62	0.84
CWM_{ADV}* + QMD* + CWM_{TOT}	5	39.3	1.6	0.28	0.75
CWM_{ADV}* + QMD + CWM_{TOT} + TPH	6	42.0	4.2	0.08	0.71
CWM_{ADV}* + QMD + CWM_{TOT} + TPH + SN_QMD	7	45.2	7.5	0.01	0.70

Table 1.6. Parameter estimates for fixed effects in final predictive model.

Variable	Parameter	Parameter Value (Standard error)	*P*-value
Intercept	a	-10.44 (4.60)	0.023
Advanced-decay CWM volume	b	0.06 (0.02)	0.013
Quadratic mean diameter	c	0.29 (0.14)	0.039

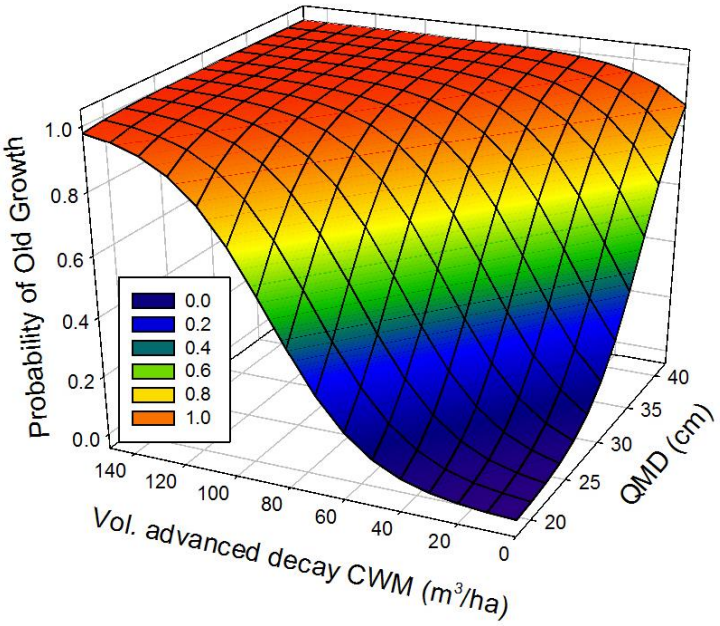

Figure 1.3. Three-dimensional representation showing probability of old-growth as a function of volume of advanced-decay coarse woody material (CWM) and quadratic mean tree diameter (QMD). As values of either one or both increase, so does the probability that a given stand can be classified as old-growth.

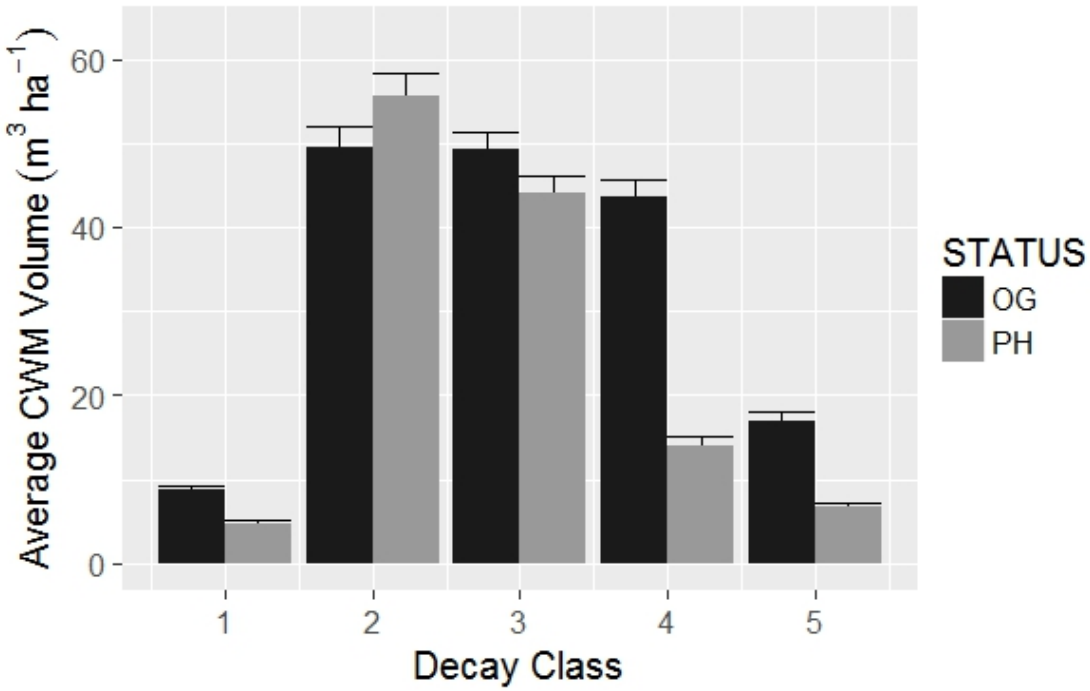

Figure 1.4. Decay class distributions of coarse woody material between old-growth (OG) and partially harvested (PH) stands. Error bars represent one standard error of the mean.

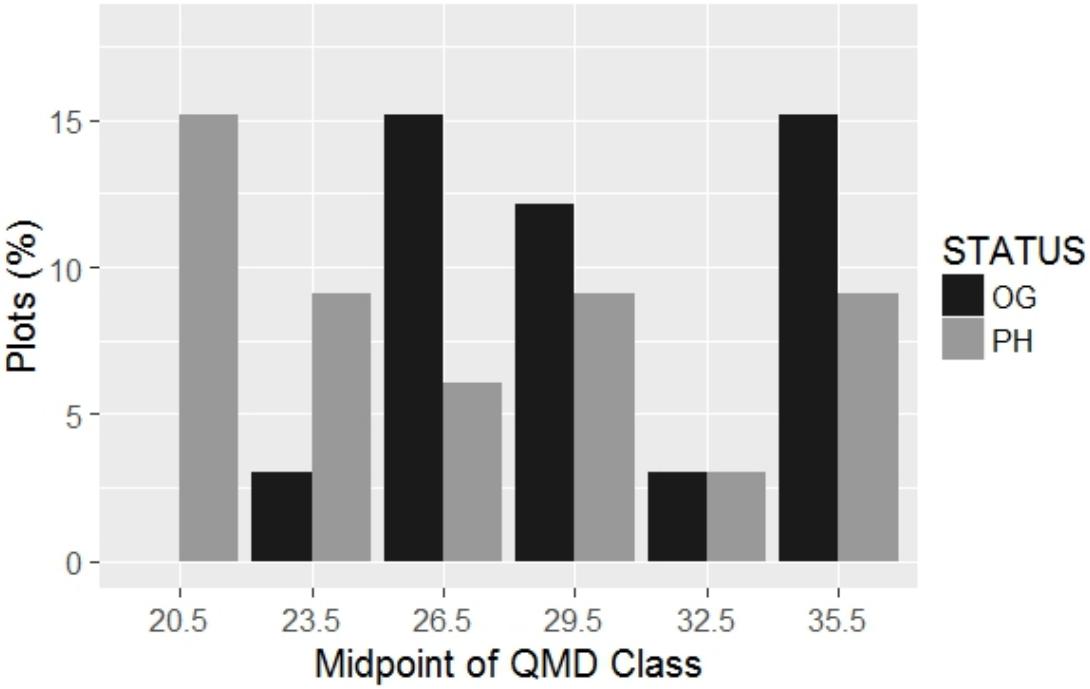

Figure 1.5. Distribution of QMDs by 3 cm classes between old-growth (OG) and partially harvested (PH) stands. Total plots (n) = 33.

Following from above, for a given stand of unknown status (old-growth vs. partially harvested), values of advanced-decay coarse woody material (CWM_{ADV}, $m^3 \cdot ha^{-1}$) and quadratic mean diameter (QMD, cm) can be entered into the following equation (Eq. 1.1) to yield the probability of that stand being classified as old-growth.

Equation 1.1. Probability of old-growth as a function of volume of advanced-decay coarse woody material (CWM_{ADV}) and quadratic mean diameter (QMD). Abbreviations and parameter values are represented in Table 1.5. Model construction is based on the transformation of the logit output from the model to probability (Weisberg, 2014).

$$Probability\ of\ old\text{-}growth = \frac{\exp[a + b(CWM_{ADV}) + c(QMD)]}{1 + \exp[a + b\ (CWM_{ADV}) + c(QMD)]}$$

1.5. Discussion

Although forest managers working within FSC certification guidelines have a clear need to identify old-growth characteristics, few quantitative criteria exist to aid in this process. Our results suggest that old-growth (never harvested) northern white-cedar stands can be distinguished from partially harvested stands by using two easy-to-obtain metrics. Specifically, old-growth stands had a greater volume of advanced-decay CWM and greater QMDs (Table 1.6, Figure 1.3). When used together, these metrics constitute practical old-growth criteria that can be obtained from standard forest inventories, a feature that greatly benefits forest managers (Wirth et al., 2009).

1.5.1. Tree Species Composition

It is recognized that late-successional, shade-tolerant species often characterize old-growth forests (Mosseler et al., 2003; Franklin et al., 2009), and some definitions of old-growth rely heavily on species composition (Oliver and Larson, 1996). Although previous studies report differences in species composition between old-growth and

harvested stands of various forest types (Ziegler, 2000; Burton et al., 2009; Keyes and Teraoka, 2014), our study found no significant differences in overstory species composition regarding management history. We note that our study differs from many previous comparative studies, in that we did not use for comparison true second-growth stands (those that developed following stand-replacing harvest); instead, we used stands that had experienced only partial harvesting (as evidenced by stump density), in order to evaluate the FSC Type 2 condition. This intensity of harvesting may have been insufficient to cause the shift in tree species composition evident in true second-growth stands (Burton et al., 2009; Keyes and Teraoka, 2014). White-cedar is a slow-growing, shade-tolerant species that often dominates stands that develop with repeated, small-scale disturbances, which further favor shade-tolerant species (Fraver et al., 2009; Ruel et al., 2014). The stands we sampled for comparison with old-growth had received moderate partial harvests, which would tend to favor more shade-tolerant species, as opposed to silvicultural treatments such as clearcutting that would favor shade-intolerant species. Thus our harvested stands would be more likely to maintain their pre-harvest species composition.

We also found that the white-cedar swamp forests did not differ, with respect to tree species composition, from the seepage forest types. Swamp and seepage forests occupy a continuum on the landscape, with swamps in poorly drained basins and seepage types occupying the wet, shallow rises around these complexes. The differences between swamp and seepage stands are subtle and often characterized by understory plant species composition and slight topographic and slope changes (several degrees; Gawler and Cutko, 2010). Further, white-cedar types can gradually intergrade with surrounding forest

types and can occupy small pockets (micro-stands; Boulfroy et al., 2012) in other forest types such as spruce-fir and northern hardwoods. Our stand selection criterion was based on dominance of white-cedar by basal area (≥50% BA, regardless of forest type), thereby focusing on one end of this white-cedar forest type continuum, which may have influenced our ability to detect differences in tree species composition that may have been evident in less pure white-cedar stands.

1.5.2. Forest Structure

Many previous studies have examined differences in forest structure between stands that have never been harvested (old-growth) and those that have experienced some level of harvesting. Results from studies in eastern North America conclude that old-growth forests have greater structural diversity (Keeton et al., 2007; D'Amato et al., 2008), more large trees (Goodburn and Lorimer, 1998; McGee et al., 1999; D'Amato et al., 2008), more diverse diameter distributions (McGee et al., 1999; D'Amato et al. 2008), greater snag size and abundance (McGee et al., 1999; D'Amato et al. 2008), greater woody debris volume (Goodburn and Lorimer, 1998; McGee et al., 1999; Ziegler, 2000, D'Amato et al., 2008), and greater total above-ground biomass (Keeton et al., 2007), when compared to second-growth forests. As above, unlike these previous studies, which used for comparison true second-growth forest, we used instead stands that had been only partially harvested in the past. However, our study also differs in objectives, as ours was to identify the structural attributes most useful in distinguishing between the old-growth and partially harvested stands. From these results, we have constructed a predictive equation that can be applied to other white-cedar stands to assess the probability of old-growth status.

Coarse woody material (CWM) is a prominent feature of old forests (Harmon et al., 1986) and has been used as an identifying characteristic for old-growth stands (Hale et al., 1999; Siitonen et al., 2000). CWM is critical to maintaining biological diversity in forested ecosystems because a large number of organisms depend on dead wood at some stage in their life cycle (Siitonen et al., 2000; Stokland et al., 2012). Furthermore, large volumes of CWM can be used as a surrogate for species richness of deadwood-dependent organisms, which comprise a major portion of forest biodiversity (Lassauce et al., 2011; Stokland et al., 2012). Large volume of advanced-decay CWM is among the structural attributes that take the longest time to develop in previously managed forests (Jönsson et al., 2009), yet it represents a particularly important substrate for rare organisms (Hofmeister et al., 2015). Because of consistent inputs in various size classes to the CWM pool as the result of small-scale natural disturbances (Fraver et al., 2002), along with slow decomposition rates (Morris et al., 2011), white-cedar stands have the potential to accrue high volumes of CWM across a range of decay classes. Given that harvesting activities remove trees that would have otherwise entered the CWM pool (Tyrrell and Crow, 1994; Fridman and Walheim, 2000), it follows that unharvested white-cedar stands would possess greater volumes of CWM, particularly in advanced stages of decay (Figure 1.4). In forest types and climates where wood decomposes more quickly, the presence of large volumes of advanced decay wood may not be as indicative of old-growth when compared to measures such as overall volume of CWM (Hale et al., 1999).

Similarly, large trees are a prominent feature of old forests (Franklin and Spies, 1991) and may be the most important forest structure used to identify late-successional stands in the northeastern U.S. (Whitman and Hagan, 2007; Ducey et al., 2013). Large

trees are increasingly uncommon forest structures, yet they serve an important role in forest processes and offer substrate for rare organisms (Selva, 2003; Franklin et al., 2007; Lindenmayer et al., 2012). Although the actual size of trees can be important in offering habitat structures for organisms (Goodburn and Lorimer, 1998; McGee and Kimmerer, 2002; Lindbladh et al., 2013), in some instances the developmental changes of the tree, such as deepening bark fissures, decorticated wood, and changes in acidity, are particularly important to rare epiphytes (Selva, 2003). Further, the actual size of a "large" tree is relative to a particular climate, region, ecosystem, and species; in the northeastern U.S. and New Brunswick, trees are generally smaller than those found in other areas where old-growth definitions have been developed (Spies, 2004).

Density of trees above a particular diameter threshold such as those used in previous old-growth research in this region (e.g., 40 cm; Whitman and Hagan, 2007) did not improve our ability to distinguish old-growth from partially harvested white-cedar stands; instead, we found average live tree diameter (QMD) to be more useful. Our study focused on areas where white-cedar dominates the overstory, which tend to be poorly drained, less productive sites. In these communities, it may be more informative to use average living tree size (QMD) than density of trees above a given diameter threshold because of differences in growing conditions from the stand types in which the thresholds were developed (Siitonen et al., 2000; Whitman and Hagan, 2007). Although tree size is not indicative of age for white-cedar (Hofmeyer et al., 2010), relatively large trees tend to be found in old, unharvested stands, as white-cedar has the ability to attain relatively large sizes, at times achieving 120 cm DBH (Curtis, 1946). It is important to note that QMD by itself was not a significant predictor of OG status; it works as a relatively weak

predictor in combination with volume of advanced-decay CWM to strengthen the final predictive model (Table 1.5; Figure 1.3). As white-cedar grows on a range of sites, it is possible that with better site conditions large QMDs could develop more readily. On such sites, it is important that the volume of advanced-decay CWM be sufficient to classify the stand as having the old-growth characteristics of white-cedar stands.

Various structural complexity indices have recently provided insight into vertical and horizontal stand structure that may not be captured in basic inventory data (Motz et al., 2010; Peck et al., 2014). As old-growth forest can possess aspects of structural complexity that are unrepresented in younger forests (Franklin and Van Pelt, 2004), these measures can offer greater insight into that complexity. To our surprise, these measures did not enhance our ability to differentiate old-growth from partially harvested stands. Similarly, Kuehne et al. (2015) report only marginal differences in structure, using these same complexity indices, between various silvicultural treatments and unharvested control stands. Our finding could result from a large degree of structural and spatial heterogeneity in many white-cedar stands, even at earlier stages of recovery from harvest (Donato et al. 2012). In addition, field observation suggested that all study stands, regardless of harvesting history, exhibited clustering of white-cedar trees; this would confound any distinction of types based on the Clark-Evans or mean directional indices. Finally, the finding that harvesting history had no bearing on tree species composition in our study stands could explain the inability of the mingling index to differentiate stands based on previous harvesting. Plot size can have an influence on the performance of some of these indices and could have played a role in our ability to detect an influence as a result of our relatively small plot sizes (0.1 ha).

Because of the long history of logging in the northeastern U.S. (Seymour, 1992), old-growth forests are particularly rare. Although our sites represent the full set of known old-growth white-cedar in the region, we recognize the limitations of a relatively small sample size (16 old-growth stands). Small sample sizes can decrease the power of statistical tests and limit inference to the population of focus (Eberhard and Thomas, 1991). Nevertheless, our results are supported by previous work that has drawn attention to tree size and CWM abundance in old-growth forest of the region (Whitman and Hagan, 2007; D'Amato et al. 2008; Ducey et al. 2013). Furthermore, the methods employed here can be applied to other forest types for a similar purpose. Successful old-growth definitions build on well-recognized structural attributes, such as those found here, yet need to be "calibrated" for specific forest types and regions (Kimmins, 2003; Wirth et al., 2009). This can be particularly useful when metrics are based on common forest inventory data, as it creates old-growth definitions that are easily understandable by land managers and can more readily be implemented in management.

1.5.3. Management Implications

We have constructed a model that predicts the probability that a given stand has old-growth structural characteristics by combining two forest inventory measures: volume of advanced-decay coarse woody material and quadratic mean diameter (Eq. 1.1). With this tool, a manager can input their values of these measures and calculate the probability that a particular stand has old-growth structure, which may inform management decisions based on their desired level of confidence. As decisions about old-growth and associated features can be very complicated in forest management (Davis, 1996), it is important to have a tool that allows managers to decide what meets their objectives for given forests

and communities. A strength of the approach proposed here is that probability is expressed on a continuous scale. This is particularly important in the context of old-growth features, as they do not possess distinct thresholds and change over time (Hunter and White, 1997).

A particular challenge for land managers is the distinction between Type 1 and Type 2 old-growth under FSC-US guidelines. Our model gives managers the ability to make this distinction with a given level of confidence. If a stand possesses old-growth structural characteristics but has no history of harvest, it would be classified as Type 1 old-growth; if a stand has old-growth characteristics but evidence of past harvest, it would be classified as Type 2 old-growth. This is an important distinction, because under FSC-US guidelines Type 1 old-growth is assigned reserve status, while Type 2 old-growth can only be harvested if the characteristics of old-growth are maintained.

The structural features typical of old-growth vary in the time they take to accumulate post disturbance (i.e., the cessation of management) (Jönsson et al., 2009). Because these structures are dynamic, white-cedar stands that do not currently possess old-growth features (i.e., large average tree sizes and high volumes of advanced-decay CWM) can be managed in a way that promotes their development. In fact, a growing focus in forest management is the creation and maintenance of unique structural features associated with old-growth through ecological silvicultural techniques (Seymour and Hunter, 1999; Franklin et al., 2007; Bauhus et al., 2009). Our results may aid those interested in developing ecologically based silvicultural prescriptions for white-cedar stands by suggesting structural features (i.e., large diameter trees and dead wood) on

which to focus. Irregular shelterwood and other types of partial cutting suggested for white-cedar stands (Boulfroy et al., 2012) may be compatible with the development of old-growth structural features (i.e., Franklin et al., 2007; Seymour and Hunter, 1999) if individual trees or micro-stands are retained over multiple rotations. In addition, white-cedar trees respond well to release from competition (Ruel et al., 2014), suggesting that thinning can be used to focus growth on residual trees, both to accelerate growth to larger sizes and diversify diameter distributions over time (Keeton, 2006).

Recent studies have suggested methods to increase coarse woody material abundance in post-harvest stands by felling some low value or cull trees (D'Amato et al., 2015). Other operational considerations include avoiding areas of coarse woody material accumulation during harvest layout, and in-woods retention of some tree tops and branches ≥ 10 cm in diameter to increase the pool of coarse woody material in harvested stands. Such practices may also facilitate regeneration, and thus long-term sustainability of white-cedar stands, because of the importance of CWM as a substrate for white-cedar germination (Cornett et al., 2000) and the potential for intact tree tops and branches to provide low shade and limit herbivore access to seedlings (Verme and Johnston, 1986; Schaffer, 1996).

CHAPTER TWO

PRACTITIONER'S GUIDE TO IDENTIFYING OLD-GROWTH CHARACTERISTICS IN NORTHERN WHITE-CEDAR STANDS

2.1 Background

2.1.1. Northern White-cedar

Northern white-cedar (*Thuja occidentalis*, hereafter white-cedar) is a common tree species in the northern forest region of the northeastern and north-central United States and adjacent portions of Canada (Figure 2.1). It is a very long lived, medium-sized tree found both as a companion species in mixed-species stands and as a dominant species on low productivity sites such as very poorly drained lowlands and excessively well-drained uplands (Johnston, 1990). Notably, white-cedar is often associated with wet areas and is an important species in forested wetlands throughout its range (Curtis, 1946).

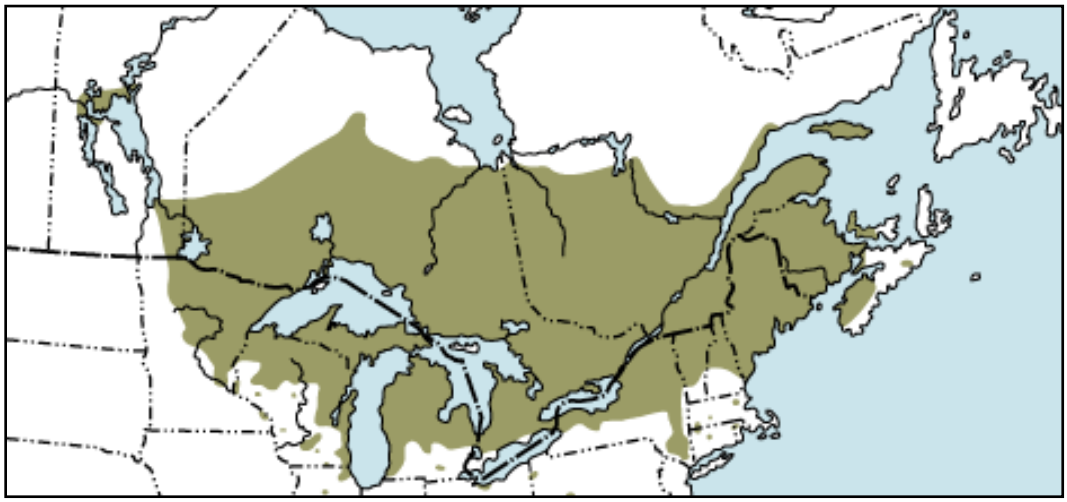

Figure 2.1. Range of northern white-cedar in the northeastern and north-central U.S. and Canada. Image: Natural Resources Canada.

White-cedar has received relatively little research attention relative to other commercial tree species, and practitioners lack information about effective management. This knowledge gap led to a collaborative research effort between university and government researchers in the U.S. and Canada, beginning in the early 2000s. Despite progress that has been made in understanding white-cedar trees and forests in the last 15 years, it remains one of the least studied commercially important species of the northern forest region.

2.1.2. Old-growth Forests

Though definitions of old-growth forests vary, we define them for this work as forests that have largely developed without direct human influence (e.g., harvesting) or natural stand-replacing disturbance. Old-growth forests and their associated features have become increasingly rare within the range of white-cedar due to a long history of timber harvesting (e.g., Mosseler et al., 2003). Yet old-growth forests provide habitat for rare organisms such as lichens, bryophytes, and some vertebrates (e.g., spotted owl in the Pacific Northwest), and thus serve a critical role in the conservation of biodiversity (Simberloff, 1987; Selva, 2003; Hofmeister et al., 2015). Remnant old-growth stands serve as references for researchers and practitioners interested in the late stages of forest development, and serve as a baseline for assessing long-term impacts of forest management. Lastly, old-growth forests play a special role in human spirituality, particularly in Native American and First Nations cultures (Perlman, 1996). Forests that developed through natural processes can be humbling places that offer a unique perspective and influence on the human psyche. Given the broad range of values old-

growth can provide to local- and landscape-level biodiversity and human well-being, it follows that much has been done to aid in the conservation of this resource.

Understanding the characteristics of old-growth forests is paramount to forest conservation and management. Yet old-growth communities have vastly different characteristics based on the species that compose the forest type as well as specific site conditions (Spies, 2004) and require forest-type and region-specific definitions (Kimmins, 2003). Once the characteristics of old-growth are identified they can be used by forest managers to identify additional stands with old-growth characteristics. Once identified, the specific context of the stand can inform managers in applying a prescription, whether that be silvicultural treatment or conservation. Given the importance of old-growth stands, their identification and treatment have been institutionalized through forest certification.

2.1.3. Forest Certification

Certification programs were created as the result of concern over potential environmental impacts of natural-resource-based industries. They work via third party assurance that a product or service meets specific requirements that include ecological, economic, and societal interests. Forest certification schemes were some of the first to develop and have served as a model for other sectors (Auld et al., 2008). The Forest Stewardship Council (FSC) certification was the first to be developed for forestry and represents diverse interests of stakeholders both within and outside of forest industry (Auld et al., 2008).

In North America, Sustainable Forestry Initiative (SFI) and FSC are the two most common forest certification systems and between the two have nearly 450 million acres (180 million ha) of certified land in the US and Canada (us.fsc.org; sfiprogram.org).

While SFI requires support of and participation in old-growth conservation in the region of ownership (Sustainable Forestry Initiative, 2015), FSC outlines specific requirements for old-growth management. The FSC-US Forest Management Standard (v 1.0, 2010) defines old-growth as, "the oldest seral stage in which a plant community is capable of existing on a site given the frequency of natural disturbances." The guideline further divides old-growth forest into two types:

- Type 1 old-growth: a stand ≥ 3 acres (1.2 hectares) that has never been harvested and that displays old-growth characteristics, and
- Type 2 old-growth: a stand ≥ 20 acres (8 hectares) that has been logged but retains significant old-growth characteristics (Forest Stewardship Council, 2010).

These definitions have important management implications, because FSC guidelines specify that certified landowners reserve Type 1 old-growth (i.e., no harvesting is allowed). Type 2 old-growth may be managed, but management must maintain old-growth characteristics (e.g., through the application of ecological forestry).

Although certification programs provide an impetus for the conservation of old-growth forests and old-growth characteristics in managed stands, criteria for identifying old-growth stands are left to be defined by managers. Guidance has been provided for some forest types (Whitman and Hagan, 2007), but is incomplete or lacking for many forest types, including white-cedar. Such guidance is important when practitioners are called upon to make determinations about the old-growth status of forest stands from a certification perspective.

2.2. Research Approach

In order to facilitate forest management planning, and in particular, compliance with certification requirements related to identifying old-growth stands and those with old-growth characteristics, we evaluated structural attributes of white-cedar-dominated stands in the northeastern U.S. and adjacent Canada. We focused on stands in which white-cedar comprised at least 50% of the overstory basal area in seepage and swamp communities as defined by Gawler and Cutko (2010). Both communities are dominated by white-cedar, with balsam fir (*Abies balsamea*), spruce (*Picea* spp.), and other species present. Seepage forests occur on gentle slopes and have a shallow organic horizon over mineral deposits with moving groundwater, while white-cedar swamps occupy basins with limited drainage and still water present (Gawler and Cutko, 2010).

Our objective was to identify stand structural attributes most strongly associated with old-growth as defined in the FSC standard, and which could be used to distinguish such stands from those with a history of harvesting. Four sites designated as protected areas in Maine and New Brunswick were sampled: Deboullie Ecological Reserve, Big Reed Forest Reserve, Baker Branch Reserve on the St. John, and MacFarlane Brook Protected Natural Area (Figure 2.2., Table 2.1). Consistent with old growth as defined by FSC, study stands had no visible evidence or historical records of timber harvesting. Nearby partially harvested stands were selected for comparison. The latter were harvested in the past 15 to 40 years, as evidenced by cut stumps in varying states of decay. Additional partially harvested stands were sampled at the Penobscot Experimental Forest in central Maine. A range of structural variables were measured on fixed-radius plots (overstory trees) and transects (coarse woody material). In total, our sampling yielded

data from 16 known old-growth stands (8 seepage and 8 swamp) and 17 harvested stands (7 seepage and 10 swamp).

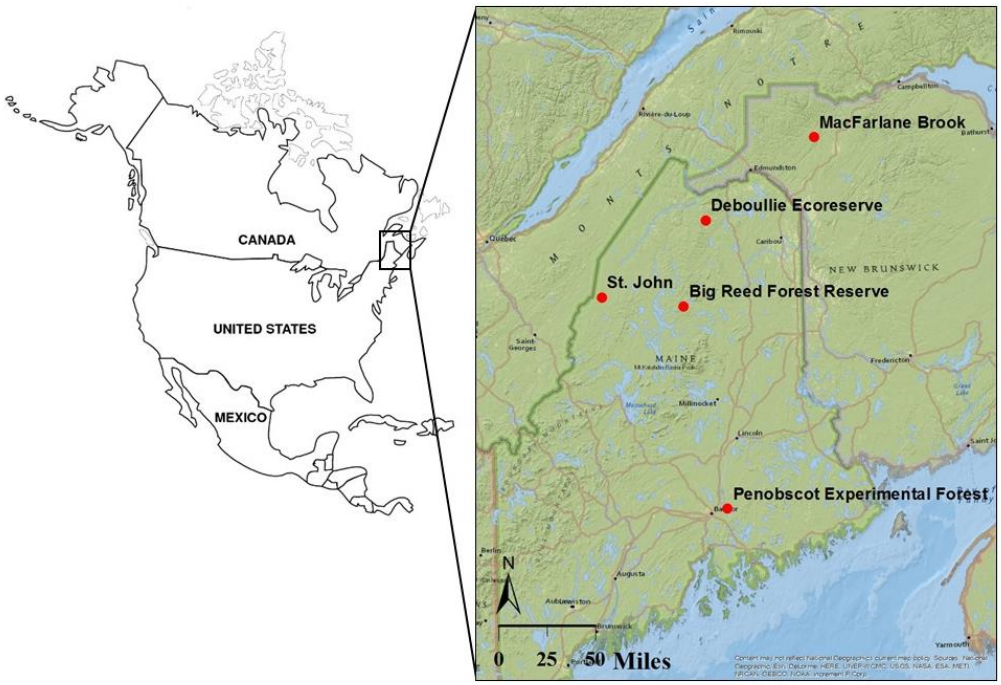

Figure 2.2. Location of the study sites.

Table 2.1. Characteristics of the white-cedar sites used in this study. Elevation from digital elevation model, U.S. Geological Survey. Annual temperature and precipitation based on normalized means between 1981 and 2010 from PRISM Climate Group, Oregon State University. Soil drainage information from USGS (Web Soil Survey, 2016).

Site	Lat., Long.	Elevation (ft)	Annual Precip. (in)	Mean Annual Temp. (°F)	Soil Drainage Class
Deboullie Ecoreserve	46°59' N, 68°49' W	987	43.0	38.5	Very poorly drained
Baker Branch of the St. John River	46°24’ N, 69°57’ W	1174	45.5	37.6	Somewhat poorly drained
Big Reed Forest Reserve	46°25' N, 69°50' W	1256	43.0	38.1	Poorly drained
Penobscot Experimental Forest	44°50’ N, 68°36' W	134	42.3	43.5	Very poorly drained
MacFarlane Brook	47°36' N, 67°37' W	964	43.5	38.3	Very poorly drained

2.3. Findings

Volume of coarse woody material in advanced stages of decay (CWM_{ADV}) and quadratic mean diameter (QMD: a measure of average tree size) were associated with old-growth status. Other measured stand attributes (e.g., overstory tree density and stocking, tree size class distribution, amount of standing dead wood, and structural complexity indices; Chapter 1) were not useful in distinguishing old growth from partially harvested stands. Measured attributes also did not differ between stands in seepage and swamp communities.

2.3.1. Interpretation

Coarse woody material in advanced stages of decay are dead logs that are very soft and easily penetrated by roots or a knife. The bark is nearly or all gone and often colonized by understory plants or tree seedlings (see Table 2). High volume of CWM_{ADV} is among the structural attributes that take the longest time to develop in previously managed forests (Jönsson et al., 2009). The reason that old-growth stands have large volumes of coarse woody material is that in managed stands, trees that would have otherwise died and joined the deadwood pool were removed during harvest. Because white-cedar has a natural high resistance to decay, white-cedar deadwood has greater longevity than other associated species (Russell and Weiskittel, 2012). This facilitates an accumulation of high volumes of CWM_{ADV} in white-cedar stands over time.

The number of trees (per acre) above a particular diameter threshold as used in previous old-growth research (e.g., 16 in. diameter at breast height (DBH, 4.5 ft), Whitman and Hagan, 2007) was not as useful as QMD for distinguishing old-growth and harvested stands in our study. We focused on areas where white-cedar dominates the overstory, which tended to be poorly drained, less productive sites. Although white-cedar tree size does not equate to age (Hofmeyer et al., 2010), large trees tend to be found in old, unharvested stands, as white-cedar has the ability to attain relatively large sizes, at times achieving 45 inches DBH (Curtis, 1946).

Our findings suggest that old-growth white-cedar stands (i.e., those with no history of harvesting or stand-replacing natural disturbance) can be distinguished from partially harvested stands by using two easy-to-obtain metrics in combination. Specifically, old-growth white-cedar stands have a greater volume of CWM_{ADV} and larger QMD (Figure 2.4). When used together, these metrics constitute a practical old-growth criterion that can be obtained from common forest inventories.

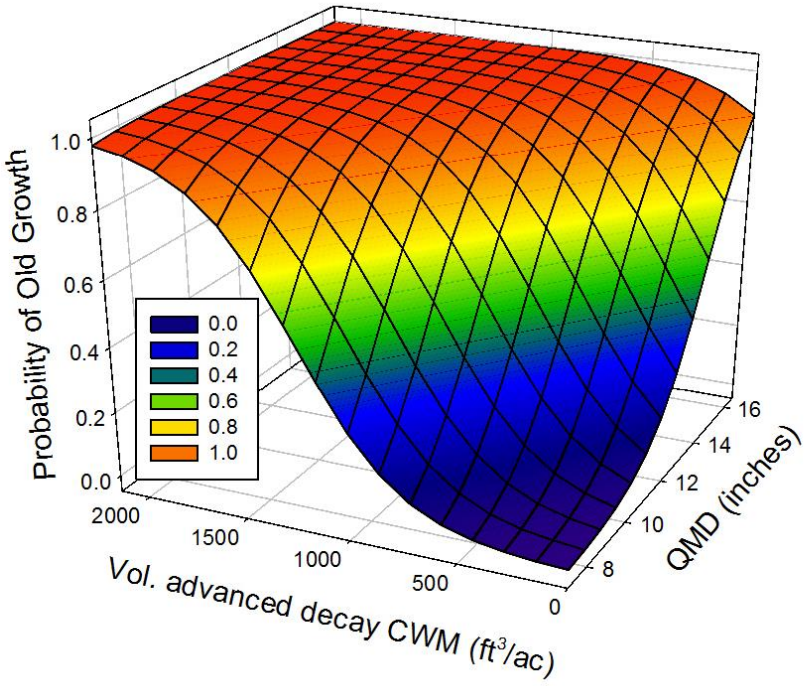

Figure 2.3. Three-dimensional representation showing probability of old-growth as a function of volume of advanced-decay coarse woody material (CWM_{ADV}) and quadratic mean tree diameter (QMD). As values of either one or both increase, so does the probability that a given stand can be classified as old-growth.

2.4. Application

2.4.1. Step 1. Collect and Prepare the Data

We measured overstory tree attributes using fixed-radius 0.25 acre circular plots, recording species and DBH for all trees ≥ 4 inches DBH (Figure 2.4). Plot values were averaged to produce stand-level values. Other methods of measuring the overstory, such as variable-radius (prism) plots are also acceptable. Sampling density should be sufficient to capture the range of conditions in the study stand.

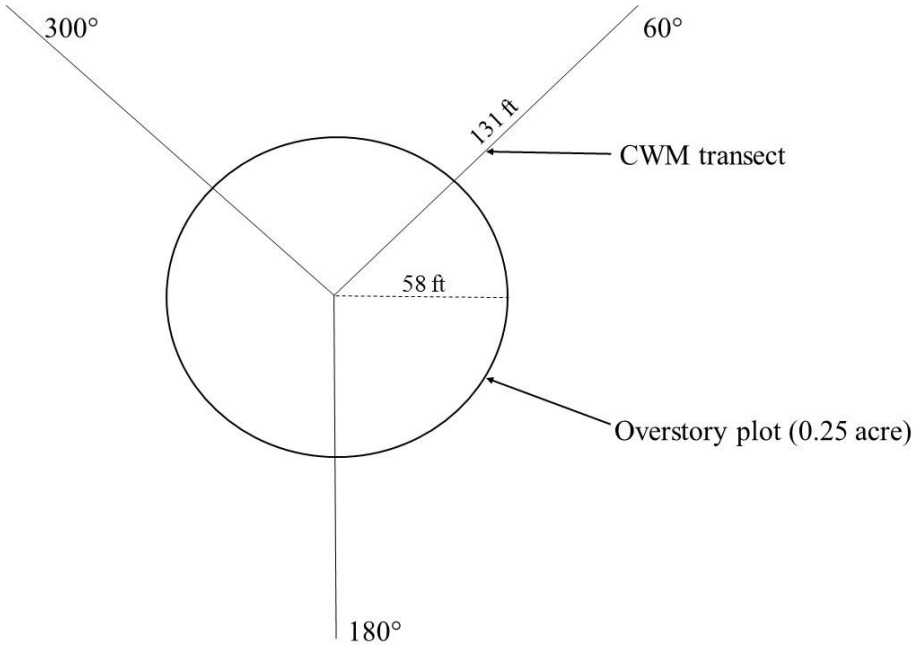

Figure 2.4. Layout of overstory plot and CWM transects established at each white-cedar stand.

2.4.1.1. Volume of Advanced-decay Coarse Woody Material

We recorded coarse woody material (pieces ≥ 4 in diameter) by the line-intercept method (Brown, 1971), using three 131-ft (40 m) transects (393 ft total) radiating outward from plot center at fixed azimuths (Figure 2.4). Research suggests that shorter total transect

lengths are not sufficient to accurately capture the characteristics of the deadwood pool (S. Fraver, unpublished data). For each piece of coarse woody material intersected by the sampling transect, we recorded diameter at intersection, species, and decay class following the five-class system of Sollins et al., 1987 (Table 2.2, Section 2.5.5). Diameters of pieces of wood in decay classes 4 and 5 were adjusted to account for their collapse resulting from prolonged decay, following Fraver et al. (2013) (Eq. 2.3). These values were then used to calculate volume per area following formula presented in van Wagner (1968) and Brown (1971) (Eq. 2.4). Other methods of coarse woody material measurement could also be used, including those that measure end diameters and lengths of all pieces within a fixed-area (e.g., Russell et al., 2015).

Table 2.2. Descriptions of decay classes in five decay-class system. Descriptions from Waskiewicz et al. (2015).

Decay Class	Description
1	Wood intact and hard. All bark intact. Twigs (<1 inch in diameter) present. Cross-sectional shape is round. Tree may be elevated by supporting branches. No invading roots.
2	Wood intact and hard. Bark has begun to detach. Twigs absent. Shape is round. Tree elevated or sagging slightly. No invading roots.
3	Wood is hard to partially soft. Some bark may remain attached. Shape is round. Tree sagging or near the ground. Roots invade sapwood.
4	Wood substantially decayed and pieces easily slough off. Inner heartwood, if present, may be soft but is intact. Shape elliptical. Tree usually on the ground. Roots invade the heartwood.
5	Wood decayed throughout. May be soft or punky and partially incorporated into forest floor. Shape elliptical to flattened. Tree is on the ground, partially sunken into the organic layer.

Equation 2.1. Diameter adjustments as the result of collapse due to advanced decay (classes 4 and 5). Constants from Fraver et al. (2013).

$$Adjusted\ diameter\ of\ decay\ class\ 4 = Diameter * 0.894$$

$$Adjusted\ diameter\ of\ decay\ class\ 5 = Diameter * 0.642$$

Equation 2.2. Volume calculation using line-intercept method. d_i=diameter of pieces (in feet) and L=length of transect (in feet). Equation from Van Wagner (1968). Units should be in feet and will give the output in $ft^3\ ac^{-1}$.

$$Volume\ per\ acre = 43560 * ({}^{\pi^2 \sum di^2}/_{8L})$$

2.4.1.2 Quadratic Mean Diameter

Quadratic mean diameter is the diameter of the tree of average basal area. The following equations can be used for calculating QMD (Eq. 2.3, Eq. 2.4, Eq. 2.5):

Equation 2.3. Equation to calculate QMD from the sum of the squared diameters of each tree (d_i) divided by the number of trees in a plot (n). Equation from Curtis and Marshal (2000).

$$QMD = \sqrt{{}^{\sum di^2}/_{n}}$$

QMD can also be calculated using stand basal area (BA in ft^2) and the number of trees in a plot with the following equation:

Equation 2.4. Equation to calculate QMD from stand BA and number of trees in a plot (n), where k=0.005454 for BA in ft2 and QMD in inches. Equation from Curtis and Marshal (2000).

$$QMD = \sqrt{{}^{BA}/_{k * n}}$$

Commercial forestry operations often use angular sampling techniques to increase the efficiency of forest inventories. In these occasions QMD can be calculated using the following equation:

Equation 2.5. Equation to calculate QMD using angular-sampling. n is the number of "in" trees in the sample, and *di* is the diameter of the trees.

$$QMD = \sqrt{[n/\sum(1/di^2)]}$$

2.4.2. Step 2. Determine If a Stand Has Old-growth Characteristics

For a given stand of unknown status (old-growth vs. partially harvested), values of CWM_{ADV} and QMD can be entered into the following equation (Eq. 2.6, using values from Table 2.3) to yield the probability of that stand having old-growth characteristics.

Note that this equation does not predict old-growth status, but the probability-threshold that a stand has old-growth characteristics. The user must choose the acceptable level of certainty in advance. As decisions about old-growth and their associated features can be very complicated in both a forest management and societal context (Davis, 1996), we believe it is important for managers to be able to determine the level of certainty appropriate for their forests and communities. A strength of this approach is viewing the outcome as a continuous scale, which is useful in this context because old-growth character is not dependent on distinct thresholds (Hunter and White, 1997). Furthermore, this approach does not limit itself to deciding whether a stand is old-growth or not but can be applied to examine old-growth features of managed stands and to help inform silvicultural prescriptions.

Table 2.3. Predictive equation parameter values for application in Equation 2.6.

Variable	Units	Parameter	Parameter Value
CWM_{ADV}	English ($ft^3\ ac^{-1}$)	a	0.004
QMD	English (inches)	b	0.75

Equation 2.6. Probability of old-growth (OG) as a function of volume of advanced-decay coarse woody material (CWM_{ADV}) and quadratic mean diameter (QMD). Corresponding parameter values for English units from table 2.3.

$$Probability\ of\ OG = \frac{\exp[-10.44\ +\ a\ (CWM_{ADV}) + b\ (QMD)]}{1 +\ \exp[-10.44\ + a\ (CWM_{ADV}) +\ b\ (QMD)]}$$

This equation can also be expressed as:

$$Probability\ of\ OG = \frac{2.72^{[-10.44+a(CWM_{ADV})+b(QMD)]}}{1 + 2.72^{[-10.44+a(CWM_{ADV})+b(QMD)]}}$$

2.4.2.1. Choosing a Threshold

When determining a threshold to apply in decision making it is important to select a level with respect to the tradeoffs associated at various thresholds. These tradeoffs are readily viewed in the model's ability to correctly identify the stands from our study (Table 2.4). In this setting a false positive is a stand that was predicted to have old-growth characteristics although it has been partially harvested. A false negative is an old-growth stand (defined a prior) that was not predicted to have old-growth characteristics. When choosing a threshold a balance between correctly and falsely identifying old-growth characteristics in stands must be made.

Table 2.4. Performance of model at various thresholds at identifying old-growth stands in our study (n=33 stands).

Model Threshold	Correct	False Positive	False Negative
90%	70%	0%	30%
80%	73%	0%	27%
70%	79%	0%	21%
60%	73%	6%	21%
50%	82%	9%	9%
40%	79%	15%	6%
30%	73%	21%	6%
20%	70%	27%	3%
10%	67%	30%	3%

As an example, at the 50% threshold, 82% of stands were correctly identified and there is the same amount of false negatives and false positives. If a manager does not have a reason to favor or disfavor old-growth characteristics this threshold could serve that purpose. If a manager has specific objectives to account for in decision making they can choose a corresponding threshold. If a higher threshold is chosen less stands will be identified as having old-growth characteristics. Alternatively, a lower threshold will identify more stands as having old-growth characteristics.

In the context of forest certification, a false positive is a partially harvested stand with old-growth characteristics (i.e., FSC-US Type 2 old-growth), while Type 1 old-growth is a stand that was identified as having old-growth characteristics and has no visible or historical signs of harvest. Therefore, the occurrence of Type 1 and Type 2 old-growth can be directly influenced by the choice of a threshold. This method allows managers to alter their threshold to fit their management objectives and their land base. It is very important that a threshold for decision making be well thought out and

deliberately chosen as it can have landscape implications. If the decision making threshold is very high, old-growth characteristics will be extremely rare and could be defined out of existence. Conversely, if the threshold is very low old-growth conditions will be overly common and not have clear conservation priority (Hunter and White, 1997).

2.4.3. Decide Whether Stumps are from Harvesting or Natural Mortality

Determining whether a stand has evidence of past management requires close examination of stumps. Though cut stumps often have a flat surface shortly after harvesting, the architecture of stumps changes over time due to decay. Additional information that will help to distinguish cut and natural stumps is the presence of the bole of the tree that created the stump (Figure 2.5). This requires inspection of the surrounding area for the log associated with the stump, recognizing that it may be in very late stages of decay. It is important to look for mounds or rises near stumps and to excavate them to determine if they are tree boles. Though felled trees are sometimes left in the woods after harvest, it is unlikely that this would happen repeatedly in a single stand. Also, stems that are left in the woods during operations are often those that were found to have substantial decay, which is often explored by sectioning the tree during operations, leaving the bole in segments. The observer's judgement is necessary to discern the origin of stumps and can be bolstered by additional information such as evidence of skid roads and historical records.

Figure 2.5. Natural stump with adjacent tree bole.

2.4.4. Applications and Limitations

The ability to identify old-growth characteristics is required to achieve a variety of management objectives including identifying old-growth stands, maintaining unique areas during management, and promoting biological diversity. Under SFI and FSC certification, landowners must to use the most up-to-date science in forestland management. Our research provides important information for managers to adhere to these standards in white-cedar stands.

Specific to FSC, the distinction between Type 1 and Type 2 old-growth can be a challenge for land managers. Our findings suggest that managers can identify the

structural characteristics of old-growth white-cedar stands (CWM_{ADV} and live-tree QMD), and thus aid in this distinction. If a stand possesses old-growth characteristics with no history of harvesting or stand-replacing disturbance, it could be classified as Type 1 old-growth. If a stand has old-growth characteristics but a history of past harvesting, it could be classified as Type 2 old-growth. This is an important distinction because under FSC guidelines Type 1 old-growth is placed in reserve and Type 2 old-growth can only be harvested if the characteristics of old-growth are maintained.

Direct application of our findings is only recommended for white-cedar-dominated stands (stands in which white-cedar contributes ≥ 50% BA) in the region in which the work was conducted (northern New England and New Brunswick). Because of climate and site variables, old-growth stands dominated by white-cedar in other portions of its range (e.g., the Lake States) may have different stand structures. As temperature, precipitation, and soils are major drivers of tree growth, it follows that areas outside of our region would have varying growth potentials that would change the values of attributes observed in our study. These same climatic variables shape decomposition rates, leading wood to decompose more quickly in warmer climates and more slowly in cooler (Russell et al., 2014). With these important considerations in mind, the extrapolation of our results outside of the climate or ranges of structures seen in our study (Table 2.5) would be ill-advised. In addition, users should be aware that other variables not quantified in our study may be predictors of old-growth status, for example, Calicioid lichen composition (Selva, 2003). Such information, if available for the stand of interest, should be considered in addition to the characteristics presented here.

Table 2.5. Range of climate variables and stand structural metrics found in our study.

Site Variable	Minimum	Maximum
Mean Annual Temp. (°F)	37.6	43.5
Mean Annual Precip. (in)	42.3	45.5
Elevation (ft)	135	1256
Stand Metric		
QMD (in)	7.8	13.7
CWM_{ADV} ($ft^3\ ac^{-1}$)	0	2111

2.4.5. Silvicultural Applications

Characteristics of old-growth stands are dynamic and change over time. This has important implications for management, as stands that do not currently have old-growth characteristics can be managed in a way that promotes their development. A growing focus in forest management is the creation and maintenance of old-growth characteristics through silvicultural prescriptions informed by natural processes (Seymour and Hunter, 1999; Franklin et al., 2007; Bauhus et al., 2009).

Our study identifies the structural characteristics of old-growth white-cedar stands and thus informs ecological forestry prescriptions in this forest type. Practitioners interested in maintaining or creating old-growth structural characteristics in managed white-cedar stands could designate large-diameter trees and CWM for retention (Franklin et al., 2007; Seymour and Hunter, 1999). If a larger QMD is desired, an intermediate treatment such as thinning could be prescribed to focus growth on residual trees through release from competition. Silvicultural prescriptions for multi-aged stands, such as group selection or irregular shelterwood cutting, have been suggested for regeneration of white-cedar stands (Boulfroy et al., 2012) and could be used to create small canopy gaps while retaining overstory trees and micro-stands (sub-stand units as small as one to two tree

heights wide) where deadwood is present. It is important to note that we do not recommend increasing QMD simply by cutting small trees but by creating conditions that increases growth on large stems. Such prescriptions are consistent with the principles of ecological forestry, which aims to create and maintain conditions similar to those created through natural disturbance.

Harvesting often results in an influx of woody material in the form of harvesting residues. Coarse woody material (> 4 in or 10 cm), however, is often removed for commodity production. This is particularly true in whole-tree harvesting, which is commonly used in large-scale commercial forestry operations. Potential solutions to increasing the volume of CWM in a harvested stand include protecting snags for future downed log recruitment, or even felling and leaving low-value or cull trees (D'Amato et al., 2015). In order to maintain CWM_{ADV}, CWM already on site should be protected during harvest operations because these features take a very long time to develop. This can be achieved by scheduling harvests in the winter to allow some snow protection from mechanical crushing of downed logs by harvest equipment (Freedman et al., 1996). It is also important to lay out trails in a way that minimizes impact on CWM; re-using designated skid trails may prevent dispersed residual stand damage (Ostrofsky, 1984).

Whole-tree harvesting is increasingly common in commercial forestry operations (Leon and Benjamin, 2013). Many facilities that process white-cedar for shingles or posts are also equipped to chip residual wood to supply mulch markets. Where development of old-growth characteristics is an objective, in-woods retention of some tree tops and branches ≥ 4 inches (10 cm) in diameter would contribute to the pool of CWM in

harvested stands. Promoting CWM structures can also have a positive impact on regeneration, as CWM_{ADV} offers an important substrate for white-cedar germination (Cornett et al., 2000), and has been observed to protect seedlings from browsing in some areas (Verme and Johnston, 1986).

2.5. Examples

Following are examples of white-cedar-dominated stands in Maine and New Brunswick with descriptions and images to aid in application of the work presented here. The level of probability a manager chooses to use as a cutoff for classifying a stand as old-growth will vary as a function of land base (amount of late-successional forest on the landscape) as well as societal considerations (production vs. conservation-oriented objectives). We used a 90% level of probability as an acceptable level of confidence for the purposes of these examples.

2.5.1. Example Stand One (not Old-growth)

This is a white-cedar seepage forest with somewhat poorly drained soils (Briggs III; Briggs, 1994) on a gentle slope (~1-2°) (Fig 2.6). This stand has a single, high canopy and no canopy openings (i.e., equivalent to the stem exclusion phase of development; Oliver and Larson, 1996). There is little regeneration or coarse woody material. The stand basal area is 268 $ft^2\ ac^{-1}$ (92% white-cedar), tree density is 546 TPA, volume of CWM_{ADV} is 213 $ft^3\ ac^{-1}$, and QMD is 9.5 in. There is evidence of past harvesting in the form of cut stumps. Based on Equation 2.5, the probability that this stand has old-growth characteristics is 7%.

Conclusion: At our desired confidence level of 90%, we conclude that this stand does not have old-growth characteristics.

Figure 2.6. Example of forest with no old-growth structural characteristics with evidence of harvest.

2.5.2. Example Stand Two (Type 2 Old-growth)

This is a white-cedar seepage forest with poorly drained soils (Briggs IV) on a gentle slope (~0-1°) (Fig 2.7). This stand has a two canopy, patchy structure with canopy openings and visible coarse woody material and abundant regeneration. The stand basal area is 174 ft^2 ac^{-1} (62% white-cedar), tree density is 283 TPA, volume of CWM_{ADV} is

1177 ft^3 ac^{-1}, and QMD is 10.6 in. There is evidence of past harvesting in the form of cut stumps. Based on Equation 2.5, the probability that this stand has old-growth characteristics is 90%.

Conclusion: At our desired confidence level of 90%, we conclude that this stand has old-growth characteristics. As this stand has signs of management (cut stumps), we assign the stand Type 2 old-growth status.

Figure 2.7. Example of forest with old-growth structural characteristics and evidence of harvest (FSC Type 2 old-growth). QMD of 10.6 inches and volume of CWM_{ADV} of 1177 ft^3 ac^{-1}.

2.5.3. Example Stand Three (Type 1 Old-growth)

This is a white-cedar swamp forest with poorly drained soils (Briggs IV) situated in a basin (0°) (Fig 2.8). This stand has a multiple canopy structure with canopy openings and visible coarse woody material and abundant regeneration in gaps. The stand basal area is 222 $ft^2\ ac^{-1}$ (92% white-cedar), tree density is 240 TPA, volume of CWM_{ADV} is 1201 $ft^3\ ac^{-1}$, and QMD is 13 in. Based on Equation 2.5, the probability that this stand has old-growth characteristics is 98%.

Conclusion: At our desired confidence level of 90%, we conclude that this stand has old-growth characteristics. As the result of having no signs of management (visible or historic), we assign the stand type 1 old-growth status.

Figure 2.8. Example of forest with old-growth structural characteristics and no evidence of harvest (FSC Type I old-growth). QMD of 13 inches and volume of CWM_{ADV} of 1201 ft^3 ac^{-1}.

2.5.4. Illustrations of Coarse Woody Material Volumes

The following images are designed to show a range of overall volumes of CWM (i.e., all decay classes combined), as observed in white-cedar stands. These examples are not meant to be used as diagnostic tools, but rather to help practitioners understand what relatively high and low CWM volumes look like in white-cedar stands. This assessment is challenging because high volumes could be composed of a lot of small pieces of dead wood, or a few large pieces.

Figure 2.9. Image showing a partially harvested stand with low overall CWM volume: 663 ft^3 ac^{-1}.

Figure 2.10. Image showing a partially harvested stand with an average overall CWM volume in our study: 1811 ft^3 ac^{-1}.

Figure 2.11. Image showing an old-growth stand with high overall CWM volume: 3408 ft^3 ac^{-1}.

2.5.5. Examples of White-cedar Logs Using the 5 Decay Class System

These images illustrate the five decay-class system commonly used in research and management and implemented in this study (Sollins et al., 1987). CWM in white-cedar stands very commonly has moss growing on the pieces, which requires observers to look under moss for presence of bark and other identifying characteristics of decay class assignment.

Figure 2.12. White-cedar log of decay class 1. Recently recruited (felled) with intact wood and bark.

Figure 2.13. White-cedar log of decay class 2. Wood is intact, and bark is coming off in patches.

Figure 2.14. White-cedar log of decay class 3. Bark is mostly or all gone, and sapwood is beginning to soften.

Figure 2.15. White-cedar log of decay class 4. All bark is gone and has lost its circular shape and is in close contact with the ground.

Figure 2.16. White-cedar log of decay class 5. Sapwood is now partially incorporated into the forest floor with heartwood intact but soft and penetrable by roots.

Figure 2.17. Example of worker verifying log decay class. Often, in order to identify these logs (Decay class 4 here) it is required to dig through soil on the outer portion of the log to find heartwood.

EPILOGUE

This study has met the objective of providing managers with information for identifying and managing old-growth northern white-cedar stands in northern New England and adjacent parts of Canada. Two significant predictors were identified that, when used in combination, differentiate old-growth from partially harvested white-cedar stands: volume of advanced-decay coarse woody material (logs in decay stages 4 and 5 using a 5 decay-class system) and live-tree QMD. This finding is particularly useful for the application of our results by managers working within regional FSC guidelines.

Although our sites represent the known old-growth white-cedar in the region, we recognize the limitations of a relatively small sample size (16 old-growth stands). Old-growth northern white-cedar stands are quite rare as the result of a long history of timber harvesting in the region (Mosseler et al., 2003). We recognize that ours may not be the entire population of old-growth white-cedar stands in the region, especially considering those that may exist on private lands. The majority of our reconnaissance focused on public land and privately held reserves. Nevertheless, we believe we have identified and inventoried an adequate sample of known old-growth white-cedar in the region. Furthermore, our results corroborate those of previous work that found that tree size and coarse woody material abundance in old-growth forest of the region (Whitman and Hagan, 2007; D'Amato et al. 2008).

We recognize that biological organisms associated with old-growth forests, including lichen, fungi, and bryophytes, may be important indicators of old-growth (Selva, 2003; Hofmeister et al., 2015), but were not included in our study. The scope of

our work was limited to measures easily made by forestry practitioners, in order to facilitate widespread application. However, future research should focus on identifying and sampling as many old-growth white-cedar stands as possible throughout its range, broadening the types of site conditions and variables of interest. This could be particularly important to interpreting this work for other regions or climates (e.g., U.S. Lake States).

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Nathan Wesely was born in Mount Pleasant, Iowa on January 28, 1991 to Monica and Brad Wesely. He grew up in Mount Pleasant where he developed a love for the outdoors during his youth participating in the Boy Scouts of America where he achieved the rank of Eagle Scout. During high school he began working in forestry for a private consultant planting trees in abandoned agricultural fields. He quickly discovered his calling for the profession of forestry. After graduating from high school he achieved a Bachelor of Science degree in Forestry from Iowa State University. During his time there he worked in aspects of traditional forest management in Colorado and New Mexico. His undergraduate studies sparked his interest in modeling forestry operations after natural disturbance in order to restore and maintain ecological functionality of ecosystems during resource extraction. He enrolled in a graduate program at the University of Maine in the School of Forest Resources to examine the role of old-growth in forest management. He is a candidate for the Master of Science degree in Forest Resources from the University of Maine in December 2016.