Restoration of Old Forest Characteristics in a 1957 Spacing Trial in the Malcolm Knapp Research Forest, British Columbia

by

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Abstract

Forest managers are interested in determining how stands that have been logged might be managed to restore features characteristic of forests in later-stages of development. Incorporating forest restoration into forest management enables the use of forest-management skills, such as silviculture and regeneration techniques, to manage individual stands for multiple objectives. Therefore, I performed a comparative analysis of large trees, very-large trees, large snags, very-large snags, and large CWD among three stand types (i.e., 60-yr-managed, 140-yr-natural, and 500-yr-natural stands). The 140-yr-natural and 500-yr-natural stands were used as reference conditions to guide the restoration of a 59-yr-managed spacing trial. All attributes differed among stand-types; however, large snags were the most similar attribute between 140-yr-natural and 500-yr-natural stands. Large trees were the fastest attribute to recover in 60-yr-managed stands, however mean values among stand-types still differed. This study highlights the potential of restoring old-natural attributes in younger-managed stands to increase ecological resiliency.

Keywords: forest; natural; managed; prescription; restoration; old-natural attributes

Dedication

This project is dedicated to the old and wise forests for they always leave me curious. In addition, this project is dedicated to my grand-parents and parents for their unconditional love and support, to my siblings for their tough-love, to Ben for his comfort and contagious laughter, and to all my friends for their warm and open hearts.

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List of Acronyms

B.C.	British Columbia
Cw	Western redcedar
CWD	Coarse woody debris
DBH	Diameter at breast height (0.3 m)
Fd	Douglas-fir
Hw	Western hemlock
MKRF	Malcolm Knapp Research Forest

Glossary

Biological legacies	Organisms, organic materials, and organically-generated environmental patterns that persist through a disturbance and incorporated into the recovering ecosystem (Franklin et al. 2000).
Disturbances	Temporally discrete events that modify the biotic and/or abiotic components of the ecosystem (White and Pickett 1985). Disturbances are often described in terms of a disturbance regime (i.e., aggregate behavior of various disturbances) and by disturbance physical attributes, such as type, magnitude, intensity, timing, and spatial distribution (Heinselman 1981, Pickett and White 1985).
Ecological resilience	Capacity of natural systems to absorb disturbances without undergoing change to a fundamentally different state (Holling 1973, Holling 1986, Peterson et al. 1998).
Ecosystem function	Biophysical processes, properties, or activities that take place within an ecosystem (e.g., decomposition of organic matter, soil nutrient cycling, and water retention) (Nasi et al. 2002, Aerts and Honnay 2011).
Ecosystem services	Benefits that people obtain from ecosystems. Services are classified into four categories: provisioning (e.g., food and timber), regulating (e.g., carbon sequestration), cultural (e.g., recreation and spiritual), and supporting (e.g., photosynthesis and species niche requirements) (Nasi et al. 2002).
Forestry	An advanced field, equipped with many valuable techniques of mensuration, silviculture, and analytical skills (Sarr et al. 2004).
Growth efficiency	Relationship between foliage and biomass growth related to productivity (Gersonde and O'Hara 2005).
Silviculture	The the art and science of controlling the establishment, growth, composition, health, and quality of forests for landowner's objectives (SAF 1971, Tappeiner et al. 2007).
Site series	As part of the British Columbia (B.C.) biogeoclimatic ecosystem classification guidelines, site series are the smallest unit of classification for management and research of B.C. forests. Site series are characterized by the vegetation that reflects the combinations of climate, topography, soil moisture and nutrients (BC MOF 2009).
Site productivity	Quantitative estimate of the potential site to produce woody biomass (Skovsgaard and Vanclay 2008).
Structural attributes	Define the structural, functional, and compositional attributes of a stand (Franklin et al. 2002). Structural attributes correspond to individual structure's size, condition (e.g., level of decomposition), and spatial arrangement (Franklin et al. 2002).
Tree vigour	Relative capacity for tree growth, expressed as above-ground biomass increment per unit of photosynthetic tissue (Rosso and Hansen 1998).

Stand Images

I believe that photos describe the stands better than words. Please refer to these images when comparing structural complexity among 60-yr-managed (A), 140-yr-natural (B), and 500-yr-natural (C) stands.

Chapter 1.

Introduction to research

Introduction

Ecological Restoration in Forestry Context

I am interested in determining how forest stands that have been logged might be managed to restore features that are characteristic of old forests that have never been logged. Old forests provide a variety of structural, biological, and ecological characteristics that are missing from forests that are managed primarily for the production of wood (Franklin 1989, Spies and Franklin 1991, Franklin 1993, Lindenmayer and McCarthy 2002, Seymour et al. 2006, Banner and LePage 2008). These differences are attributed to the homogenized stand structure, high tree densities, low variation in tree size, reduced number of snags, and reduced number of woody debris in even-aged-managed stands compared to old-growth stands (Spies and Franklin 1991, Berg et al. 1994, Angelstam 1996, Poage and Tappeiner 2002). In addition, the structural attributes of old forests are linked with other ecosystem services besides the maintenance of biodiversity (Sutherland et al. 2016). While all forests provide ecosystem services, such as the harbouring and contribution of biological diversity (Franklin et al. 1981), carbon storage and sequestration (Carey et al. 2001), and hydrological regulation (Vertessy et al. 1996), data from Vancouver Island indicate that old forests provide three times higher carbon storage, nine times higher wood volume, and eighteen times higher canopy habitat services than second-growth forests (Sutherland et al. 2016).

I also am interested in how old-forest attributes can be restored in logged stands because society cannot rely solely on forest reserves to maintain the attributes and ecosystem services provided by old forests. Forest reserves have been a key approach for conserving old forests in national parks, wilderness areas, and ecological areas (Norton 1999). However, forest reserves have challenges meeting the needs of species movement and connectivity, are susceptible to natural disturbance, and de-emphasis structural attributes necessary for many species' persistence (Norton 1999, Franklin and Lindenmayer 2009, Spies et al. 2009). Given that forest reserves alone are insufficient to maintain the features of ecologically resilient forests, researchers have sought alternative approaches such as accelerating the development of old-forest attributes in young managed stands.

Ecological restoration can assist the creation of old-forest attributes using stand-level silviculture prescriptions (Duncker et al. 2012). Restoration re-establishes the composition, structure, pattern, and ecological processes necessary for ecosystem resiliency (USDA 2012). Forest managers use silviculture prescriptions to meet a range of objectives (e.g., wood production, wildlife, recreation, and aesthetics); however, the objectives are often in conflict with each other, resulting in stand management for a single objective (Oliver et al. 1999). For example, silviculture for wood production decreases the structural complexity of forests. Prescriptions for wood production include short rotation cycles (i.e., covering 10-40% of potential stand development; Scherzinger 1996, Oliver et al. 1999), skipping successional stages, decreasing time during certain development stages, and uniform thinning performed from below (Oliver et al. 1999, Franklin and Johnson 2012). Ecological restoration can provide insight and compliment the conceptual development of a new era of “ecological forestry” (Sarr et al. 2004).

Ecological Forestry

Ecological forestry follows the premise that natural disturbance and forest regeneration should guide the rate and spatial scale of logging to reflect the dynamics and structure of natural-landscape mosaics (Seymour and Hunter 1999, Franklin et al. 2007, North and Keeton 2008, Long 2009). Ecological forestry emerged during the 1990s when research suggested that the rate, scale, and configuration of logging were inappropriate to sustain the economic, social, and ecological goals of forestry. A key driver in the emergence of ecological forestry was that the rate of logging of old-growth forests was jeopardizing the ecological resiliency of forested landscapes and accelerating the loss of biodiversity (Swanson and Franklin 1992, Aber et al. 2000, Spence 2001, Pommerening and Murphy 2004, Puettmann et al. 2009).

Old-Growth Forests and Old-Natural Forests

Increased knowledge about old-growth forests resulted in efforts to characterize and define “old-growth forests”. A universal definition of old-growth is challenging because of the diversity of forest types, biogeoclimatic zones, and the range of social values that are tied to old forests. While social and economic definitions of old-growth exist (Timoney 2001, Suffling et al. 2003), forest practitioners and ecologists typically focus on ecological definitions. Hilbert and Wiensczyk (2007) classified ecological old-growth definitions into three categories

1. conceptual structural, which characterizes the physical parts and arrangement of the forest (e.g., CWD in various stages of decay),
2. compositional functional, which characterizes forest development (e.g., later stages of stand development), and
3. quantitative working definitions, which characterizes structural characteristics and minimum age thresholds (e.g., British Columbia's coastal forests are defined as old-growth if the trees are > 250 yrs).

Ambiguity around definitions of old-growth also arises from the question of whether a forest that has been disturbed by humans can be defined as old growth (Hendrickson 2003). Considering that First Nations have a long history of forest management in coastal B.C., the long-lived tree species (i.e., ~1,000 yrs) that are present today likely have been "influenced" by humans.

To clarify the intent of my work, I use the term "old-natural" forests to define forests that have never been commercially logged and that exhibit the ecological characteristics of "old-growth" forests. In this use, "old-natural" forests are not synonymous with pristine forests. In fact, First Nations have traditionally logged single trees to build homes, canoes, and poles; however, the spatial scale and ecological effect of aboriginal forestry has had far less influence on the ecological trajectory of the forest than modern harvesting methods. The structural attributes of old-growth temperate forests have been quantified in the literature (e.g., Spies and Franklin 1991, Acker et al. 1998, Wells et al. 1998, Bauhus 2009). However, the definition of old-growth used in the literature provides no historical context and is often determined based on an arbitrary age. In addition, it is un-clear whether the researcher's definition of old-growth assumes a pristine state. As pristine old-growth forests become increasingly rare, there is forest-management interest to consider the extent that old-growth values can be cultivated in younger stands. In this work, I intend to examine very old stands in contrast to stands that are not 'old-growth' but are far older than those found on industrial-forestry landscapes (I refer to as 'old-natural'), and examine whether the structural attributes and associated ecological and cultural values are similar.

Silviculture for Old-Natural Attributes

Expanding the focus from forest "management" to forest "restoration" enables the use of forest-management skills, such as silviculture and regeneration techniques to manage individual stands for multiple objectives. Silviculture for restoring old-natural attributes focuses on development of large-diameter trees that eventually lead to recruitment of large snags and CWD, complex branch systems for canopy habitat, shade-tolerant species, and spatial heterogeneity (Franklin and Johnson 2012). Thinning for restoration objectives can create variability in spatial intensity (i.e., thinned and un-thinned patches), stimulate tree growth, develop complex branch systems for canopy habitats, stratify canopy layers, and increase light to the understory to promote understory regeneration (Carey 2003, Beggs 2004, Ishii et al. 2004). Additional silviculture prescriptions for forest restoration can include killing live trees to generate snags or CWD, reducing stand density, wounding or infecting trees to stimulate decay, and tree planting (Carey 2003, Mitchell et al. 2003, Lindh and Muir 2004, Franklin and Johnson 2012,).

Knowledge Gaps for Restoring Old-Natural Attributes

Forest restoration requires site-specific knowledge about structural development; however, there are few studies that summarize the recovery of old structural attributes and provide reference ranges of structural attributes for managed stands compared to old and very old stands in coastal-temperate forests of B.C. (Tappeiner et al. 1997, Negrave et al. 2008). No research has examined if old-natural forests exhibit structural attributes and associated ecological and cultural values as old-growth forests. Most silviculture treatments intended to accelerate old-natural attributes has been implemented in Douglas-fir (*Pseudotsuga menziesii*) forests in the United States (Carey et al. 2003, Mitchell et al. 2003, Ishii et al. 2004, Lindh and Muir 2004).

Moreover, researchers have focused on the development of young forests for maximum wood production or old-growth forests for the conservation of biodiversity (Wells 1996, Peet and Christensen 1998). Focusing on young and old-growth forests de-emphasizes the significance of biotic and abiotic components of stands in all development stages. A challenge for forest managers and restoration practitioners is developing guidelines with mean values and variation levels for stand structural attributes (Gerzon et al. 2011). While many structural attributes related to stem density and biomass have been well described for many coastal-temperate forests (e.g., Franklin and Spies 1991, Gerzon et al. 2011), other structural attributes and their developmental patterns still lack adequate descriptions (e.g., decay classes and CWD: Wells 1996, Peet and Christensen 1998). Structural-attribute development varies depending on biogeoclimatic zone and site factors (e.g., nutrient and moisture levels); however, current research has not examined attribute development at such fine levels. Instead, because of the long time frame of CWH forests (e.g., 1000 yrs) one needs to hypothesize if managed stands will develop old-natural attributes, at what rate these attributes will develop, and what silviculture treatments can be applied to ensure old-natural attributes develop (Tappeiner et al. 1997).

Table 1. Common old-growth structural attributes, minimum values, and means ($\pm$ SD or 95% CI) of temperate forests in the Pacific North West (adapted from Bauhus et al. 2009).

Old-Growth Structural Attributes	**Minimum Value**
Large basal area of big trees	$\geq$ 50 cm[a], 113 $\pm$ 22 stems/ha[b*] $\geq$ 100 cm, 19 $\pm$ 9.6 stems/ha[b*]
Tree diversity (size, species, live/dead)	2+ species
Snag diversity (size, species, decay class)	$\geq$ 50 cm[a], ~23 stems/ha[b*] $\geq$ 100 cm, 8 $\pm$ 5.6 stems/ha[b*]
Coarse woody debris diversity (size, species, decay class)	$\geq$ 25 cm[a] 2+ species, decay classes 1-5
High stand volume or biomass	$\geq$ 50 cm, 1071 $\pm$ 260 m^3/ha * $\geq$ 100 cm, 470 $\pm$ 260 m^3/ha*
Large basal area of dead or dying standing trees (snags)	
Large mass and volume of coarse woody debris (CWD)	430 $\pm$ 170 m^3/ha[b]*
Vertical heterogeneity (i.e., multiple canopy layers)	
Horizontal heterogeneity (i.e., canopy gaps and tree spacing)	Many small gaps, 30 $\pm$ 17.5[c**]
Intermediate species richness and percentage coverage of late successional or shade tolerant species compared to young forests	Species Richness, 37 $\pm$ 7.7%[d**] Coverage, 83 $\pm$ 27%[b*]
Presence of multiple cohorts	
Thick forest floor	
Pit and mound topography	
Presence of special trees (e.g., cavity trees)	

[a] Bunnell et al. 2002 [b] Gerzon et al. 2011 [c] Lertzman et al. 1996 [d] Banner and Lepage 2008
**Standard Deviation, **95%CI*

Study Site

The Malcolm Knapp Research Forest (MKRF) is in the foothills of the Coast Mountains (Fig. 1). The forests of this region are characterized as the Coastal Western Hemlock (CWH) zone (Meidinger and Pojar 1991, BC MOF 2009). The CWH climate is cool mesothermal, has a mean annual temperature of 8°C, mild winters, and receives 1000-4000 mm of precipitation annually (Meidinger an Pojar 1991). The MKRF is located in the low and middle elevations of the Coast Mountains, corresponding to the CWH dry maritime (dm) and CWH very wet maritime (vm) subzones.

The MKRF is a research forest that was established by a Crown Grant to the University of British Columbia in 1949. Experimental harvesting and reforestation began in the 1950s (C. Power, MKRF, pers. comm.). Initially, most reforestation was focused on planting Douglas-fir because of its availability and silvicultural techniques for other species were in experimental phases (C. Power, MKRF, pers. comm.). Over the years other species (e.g., western red cedar (*Thuja plicata*), grand-fir (*Abies grandis*), amabilis fir (*Abies amabalis*), yellow cypress (*Cupressus nootkatensis*), western white pine (*Pinus monticola*), and red alder (*Alnus rubra*) were planted (C. Power, MKRF, pers. comm.) while natural regeneration (i.e., western hemlock (*Tsuga heteropylla* and deciduous species) was a key component of reforestation (C. Power, MKRF, pers. comm.). Currently, the MKRF is estimated to be about 40% logged and reforested, with clear-cut, clear-cut with reserves, and, to a lesser extent, variable retention as the most common silviculture systems. Shelterwood and seed-trees rarely are used. Stand rotations vary but range between 40 and 150 yrs (C. Power, MKRF, pers. comm.). An estimated 23% (i.e., excluding no forested areas and water) of the MKRF is comprised of reserves. Two reserve systems are used: traditional reserves (9.2%) and restricted-harvest reserves (13.6%). Restricted harvest refers to scenic areas and stands where timber management is a secondary objective (C. Power, MKRF, pers. comm.).

My research focused on the lower elevation CWH dry maritime (CWHdm) subzone, specifically the 05 (i.e., Cw-Sword fern) and 07 (Cw-Foamflower) site series (Green and Klinka 1994). The 05 and 07 site series have nutrient rich and moist soils (Green and Klinka 1994). Site productivity is greatest with high soil nutrients and moisture; therefore, the 05 and 07 site series are productive forest sites. The stands on these sites are structurally unique and rich in biodiversity. Forests of the CWH are predominated by large and longed-lived species, such as western hemlock, Douglas-fir, and western red-cedar. These species can live more than 1,000 yrs and reach a height of 80 m in 250-yr-old forests (Mackinnon 2003, Parish and Antos 2004). The long-lived species create structurally diverse forests; therefore, the CWH harbors some of the greatest biodiversity in the northern temperate area (Bunnell et al. 2009).

Large and long-lived species of CWH forests are the result of the natural landscape pattern that is influenced by low frequency natural disturbances (Foster et al. 1998, Harper et al. 2005). The MKRF's disturbance history is typical of a coastal temperate forest where stand-replacing disturbances (i.e., fires) are secondary to canopy gap dynamics (e.g., wind and disease; Dorner and Wong 2003, Wong et al. 2003, Daniels and Gray 2006). The fire return interval in the CWH is expected to be approximately 750-1,000 yrs (Arsenault 1995, Daniels et al. 1995, Pearson et al. 2000, Lertzman et al. 2002, Gavin et al. 2003, Hallet et al. 2003). Recent disturbances in the MKRF include human-caused fires (1868, 1925, 1926, and

1931), a large windstorm (1962), and various logging practices that started in 1912 (C. Power, MKRF, pers. comm.).

Considering area-wide stand-replacing disturbances are uncommon in the CWH (Arsenault 1995, Lertzman et al. 2002), it is justifiable to assume that today the MKRF is composed of more young stands and fewer mid-aged and old-natural stands than would be considered under natural historic disturbance regimes (Wulder et al. 2009). Even-though the MKRF has less old-growth than historically, the MKRF uses various silviculture methods and are interested in trying experimental harvesting methods that can achieve restoration outcomes of this project.

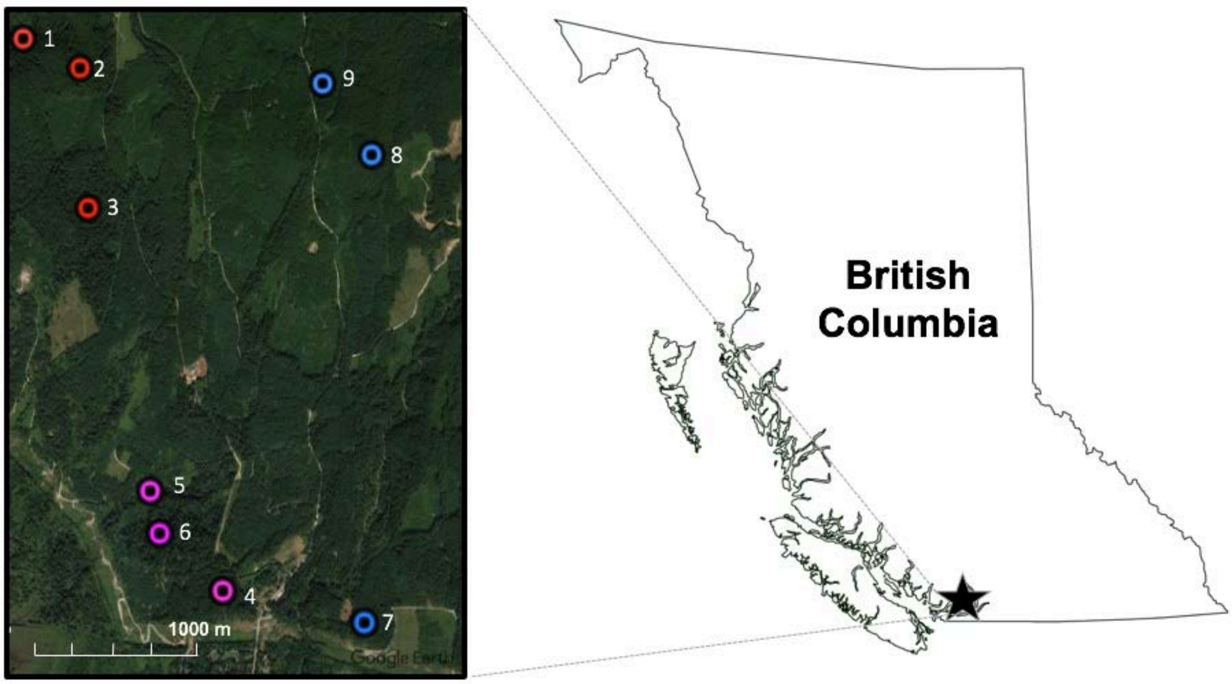

Fig. 1. Location of the MKRF within B.C. Inset depicts sampling sites which are represented as: 500-yr-natural (#1-3 red), 140-yr-natural (#4-6 purple), and 60-yr-natural (#7-9 blue), August 2016.

Research Objectives

I measured and compared structural attributes among three stand ages of the same site-series (CWHdm 05/07). Comparisons can inform restoration practitioners regarding the silviculture prescriptions and guidelines that can restore mid-aged and old-natural stand attributes to managed stands. I examined the prevalence of large live trees (i.e., diameter breast height (DBH) > 50 cm), very large trees (i.e., DBH > 100 cm), large snags (i.e., DBH > 50 cm), very large snags (i.e., DBH > 100 cm) and large and well-decayed coarse woody debris (CWD) (i.e., decay class 3-5 and DBH > 25 cm). Large trees, large snags, and well-decayed large CWD are associated with later stages of stand development (Spies and Franklin 1988, Bunnell et al. 2002, Bauhus et al. 2009, Gerzon et al. 2011). My research provides insight into the restoration of managed forests because I used empirical data from three stages of forest development to guide the recovery of ecological attributes in an intensively managed stand.

Objective one (Chapter 2): I used a chronosequence (i.e., using a space-for-time substitution) approach to collect empirical data on the development of large and very large live trees, large and very large snags, and large well-decayed CWD, and compared these attributes among three stand types (1) ~60-year-old-managed stands (herein referred to as 60-yr-managed), (2) ~140-year-old-natural stands (herein referred to as 140-yr-natural), and (3) ~500-yr-old-natural stands (herein referred to as 500-yr-natural). Managed stands experienced similar site preparation, including the removal of CWD, removal of snags, planted with a monoculture of Douglas-fir with specific spacing between 2.7 – 3.7 m. Natural stands were self-regenerated following fire. My age classification corresponded to the oldest tree in the stand. The comparative analysis quantified the range of natural variation and significant differences in structural attributes among 60-yr-managed, 140-yr-natural, and 500-yr-natural stands of the MKRF. I used the range in the structural attributes from the 140-yr-natural and 500-yr-natural forests to develop restoration guidelines for accelerating mid-aged and old-forest attributes in managed stands.

Objective two (Chapter 3): Based on my data analyses in chapter two, my objective in this chapter was to use comparative analysis with an additional set of field sites (i.e., an intensively-managed spacing-trial site) to inform restoration prescriptions for managed stands with a focus on species composition and density of structural attributes. I collected data on the number of large trees, very large trees, large snags, very large snags and large CWD for a managed stand of restoration interest and compared the mean values to the range of natural variation in 140-yr-natural and 500-yr-natural stands determined in chapter two. The restoration site is a 59-yr-old spacing trial site that contains various spacing densities of Douglas-fir, with some western hemlock stands.

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Chapter 2. Quantifying the structural attributes of CWHdm 05/07 sites in MKRF and comparing these attributes among 500-yr-natural, 140-yr-natural and 60-yr-managed stands.

Introduction

Large and long-lived species of CWH forests reflect the natural disturbances regime of these landscapes (Foster et al. 1998, Harper et al. 2005). Disturbance type and severity affect soil, vegetation, and biological legacies (e.g., organisms, fugal hyphae, and structural attributes) (Foster et al. 1998, Franklin et al. 2007). Biological legacies contribute to long-term sources of energy and nutrients (Franklin et al. 2000), provide critical habitat for vertebrates and invertebrates (Harmon et al. 1986, Maser et al. 1988), and aid in post-disturbance recovery (Franklin et al. 2000). Composition of biological legacies differ between post-logging conditions and natural post-disturbance. For example, CWD was abundant in post-windstorm stands and few in post-logging stands while snags were abundant in post-fire stands and variable in post-logging stands (Franklin et al. 2002).

The trajectory of stand structure depends on historic and on-going disturbances, biological legacies, abiotic conditions, biotic conditions and processes (Johnson 1996, Franklin et al. 2002, Chen et al. 2009, Ilisson and Chen 2009). A hierarchical framework describing vegetation succession was proposed by Pickett et al. (1987) (Table 2). This framework highlights the biotic processes that influence vegetation succession, such as colonization, competition, growth rate, and longevity/mortality (Spies and Turner 1999). However, stand succession is more than vegetation dynamics and includes changes in structural attributes (e.g., CWD, snags, canopy gaps, and understory patches). An eight-stage development model proposed by Franklin et al. (2002) incorporates the development of structural attributes and live trees (Table 3). Franklin et al. (2002) model acknowledges that stand development is continuous, spatial heterogeneity occurs throughout the stand's lifecycle, and certain stands can skip development stages.

Forest structural attributes vary during successional development and provide numerous ecological, chemical, and biological functions. Structural attributes are used to describe stand elements such as foliage (e.g., foliage height diversity; Sullivan et al. 2001), canopy cover (gap size classes; Tyrell and Crow 1994), tree diameter (e.g., DBH; Spies and Franklin 1991), tree height (e.g., height of overstory; Spies 1998), tree spacing (e.g., number of trees per ha; Acker et al. 1998), stand biomass (e.g., stand volume; Spies 1998), tree species (species diversity; Sullivan et al. 2001) , understory vegetation (e.g., shrub height; Berger and Puettmann 2000), and deadwood (e.g., volume CWD; Sullivan et al. 2001). Structural attributes are easy to quantify in the field; therefore, structural attributes are used as surrogates for forest functions such as habitat supply and provision of forest goods and services (Franklin et al. 2002, Sutherland et al. 2016).

Table 2. Hierarchy of successional causes. Highest level describes broadest cause of succession, intermediate level describes the mechanism of change for the highest level, and the lowest level are specific factors that determine the outcome of the intermediate-level processes (Picket et al. 1987).

Hierarchical Levels		
High: general causes of succession	**Intermediate:** contributing processes or conditions	**Low:** defining factors
Site availability	Coarse-scale disturbance	Size, severity, time, dispersion
Differential species availability	Dispersal	Landscape Configuration
	Propagule pool	Dispersal agents, time since disturbance, land use
Differential species performance	Resource availability	Soil conditions, topography, microclimate, site history
	Eco-physiology	Germination requirements, assimilation rates, growth rates, population differentiation
	Life history strategies	Allocation pattern, reproductive timing, reproductive mode
	Stochastic environmental stress	Climatic cycles, site history, prior occupants
	Competition	Presence of competitors, identity of competitors, within-community disturbance, predators and herbivores, resource bias
	Allelopathy	Soil characteristics, microbes, neighboring plants
	Herbivory, disease, and predation	Climatic cycles, consumer cycles, plant vigor, plant defense, community composition, patchiness

Examples of structural attributes used as surrogates include dead wood (CWD or snags) as an indicator for decomposition and nutrient cycling (Franklin et al. 1981), species composition and abundance as an indicator for canopy layering (Franklin et al. 2002), and bark shedding as an indicator of invertebrate abundance (Kavanagh, 1987, Dickman 1991).

Key to managing forests efficiently and sustainably is understanding the trajectories of multiple forest attributes through forest succession. In coastal temperate forests of North America, researchers have outlined how structural attributes vary during successional development. Spies and Franklin (1988) present two trajectories categorizing structural attributes for Douglas-fir stands after a stand-initiation event: “U-shaped” and “S-shaped”. “U-shaped” successional attributes are in high abundance post-disturbance and during older stages of development, and low abundance during intermediate stages (Spies and Franklin 1988). Typical “U-shaped” attributes include CWD, snags, heterogeneity of understory, plant species, and diversity of vertebrate species (Harris 1984, Spies and Franklin 1988). “S-shaped” successional attributes are in low abundance during early development and increase to a plateau in later successional stages (Spies and Franklin 1988). Attributes that follow an “S-shaped trajectory” include average tree diameter, diversity of tree sizes, incidence of broken tops, forest floor depth, surface area of boles and branches, and wood biomass (Spies and Franklin 1988). Even though these trajectories were based on Douglas-fir stands, similar trends have been seen in CWH stands (Arsenault and Bradfield 1995, Wells 1996).

Forest restoration requires site-specific knowledge about structural development; however, there are few studies that summarize the recovery of old structural attributes and provide reference ranges of structural attributes for managed stands compared to old and very old stands of coastal-temperate B.C. (Tappeiner et al. 1997, Negrave et al. 2008). While structural attributes related to stem density and biomass have been well described for many coastal-temperate forests, descriptions of attributes in later stages of development are still lacking (e.g., CWD decay class; Day 1972, Wells 1996; Peet and Christensen 1998). Structural-attribute development varies depending on biogeoclimatic zone and site factors (e.g., nutrient and moisture levels); however, existing studies have not examined attribute development at such fine levels. The long life cycle of CWH stands make it challenging to monitor stands through each successional stage resulting in the use of simplified models to predict stand development. In addition, models classify stands into few age categories assuming the gaps between age categories follow predicted development trends (Day 1972, Spies and Franklin 1991, Arsenault and Bradfield 1995, Wells 1996). Therefore, more information on stand development is required to enable forest practitioners to manage structural attributes to support a range of forest values (Chapter 3).

Table 3. Description of structural development stages for Pacific North West stands proposed by Franklin et al. (2002).

Development Classification	Approximate Stand Age	Description of Dominant Attributes and Processes
Disturbance and legacy creation	0	▪ Disturbance varies with type, intensity, size, and frequency (e.g., fire vs. wind). ▪ Biological legacies (i.e., persisting living trees and dead structures) are main.
Cohort establishment	0-20	▪ New generation of trees established (duration varies) ▪ Establishment limitations: seed source, environmental conditions, and competition. ▪ Disturbance type influences seedling density. ▪ Low density has gradual canopy closure, no density-dependent mortality. ▪ High density has intense self-thinning processes.
Canopy closure	30	▪ Individual tree canopies overlap. ▪ Marked change in composition and function. ▪ Understory changes such as decreased light, moderate temperature regimes, increased relative humidity, and near-exclusion of wind. ▪ Shrubs, herbs, and lichens decline or are eliminated. ▪ Saprophytes and invertebrate detrivores increase. ▪ Canopy closure depends on density and site productivity (e.g., denser sites).
Biomass accumulation/ competitive exclusion	30-80	▪ Extended period of young stand development. ▪ Stand development processes such as the development woody biomass (diameter and height), competitive exclusion many organisms, density-dependent tree mortality (smaller diameter trees) or self-thinning, natural pruning of lower tree biomass, and crown-class differentiation. ▪ Species diversity (e.g., vertebrates) typically declines because shading or eliminating light for understory plants and reduces herbivore's food source. ▪ Sapropyhtes and detrivores flourish. ▪ Thinning process increases in managed stands with high planting densities.
Maturation	80-200	▪ Pioneer cohort trees reach maximum height and crown spread. ▪ CWD levels are minimal. ▪ Re-establishment understory community and shade tolerant trees (Western redcedar and western hemlock). ▪ Density independent mortality (e.g., pathogens and wind). ▪ Slowing of growth in overstory trees from sub-lethal damage, creating diversity in individual trees, which increases niche diversity.
Vertical diversification	200-300	▪ Marked development of late successional seral or old-growth attributes. ▪ Canopy becomes continuous (ground to top) and slowing of tree growth. Both processes stimulated by increased light due to thinning or mortality of the overstory. ▪ Structural complexity created by sub-lethal damage and mortality. Slowing of growth is caused by top breakage, wood rots, scarring and mistletoe. ▪ Increased number snags and CWD. ▪ Density-independent mortality dominants and much of the mortality is aggregated to create gaps or expand gap size. ▪ Density-dependent tree mortality is occurring primarily among cohorts of shade tolerant saplings and poles (in canopy gaps). ▪ Significant cover and biomass of bryophytes and foliose lichens develop.
Horizontal diversification	300-800	▪ Stand evolves into multiple structural units (i.e., gap creation and expansion). ▪ Gap development is dominant (created by wind, disease, and insects). Spatially aggregated mortality and groups of heavily shaded areas. ▪ Light entering mid/lower canopies controlled by shade-tolerant species. ▪ Patterns of foliage are distinctive and predictable, highly variable mid canopies, and low variable in upper and lower canopies.
Pioneer cohort loss	800-1200	▪ Shade-intolerant species present in sere but gaps present in older stands too small for regeneration.

I used a chronosequence approach (i.e., space-for-time substitution) to collect data on the development of large live trees (DBH > 50 cm), very-large live trees (DBH > 100 cm), large snags (DBH > 50 cm), very-large snags (DBH > 100 cm) and large well-decayed CWD (decay class 3-5 and DBH > 25 cm), and compared these attributes among three stand types: (1) 60-yr-managed, (2) 140-yr-natural, and (3) 500-yr-natural stands. The chronosequence is based on the assumption that time is the main explanatory variable and other effects are held constant (e.g., biota, topography, climate) through appropriate study design and site selection. The comparative analysis quantified the range of natural variation in structural attributes among 60-yr-managed, 140-yr-natural, and 500-yr-natural stands of the MKRF.

My objectives in comparing younger-managed stand attributes to mid- and older natural stand attributes was to:

1. compare the means and range of structural attributes among age classes,
2. examine if young-managed stands can develop mid- and old-forest attributes naturally, and, if not,
3. determine how silviculture techniques could be useful to accelerate the restoration of the structural attributes of old forests.

I examined three primary structural attributes based on their ecological, chemical, and biological relevance in old forests that can be managed with restoration prescriptions (Table 4).

Methods

Experimental Design

I established plots in replicates of three stand types to collect mensurative data (1) 60-yr-managed, (2) 140-yr-natural, and (3) 500-yr-natural (Fig. 1).

Natural Stands

Natural stands were comparable to managed stands' vegetation and structural attributes because all stands were in the same biogeoclimatic site series (CWHdm 05/07). I chose natural stands based on three requirements: age (i.e., 140 yrs or 500 yrs), old-growth attributes (Table 1), and no signs of previous management (e.g., thinning or logging).

Table 4. Structural attributes chosen for research based on ecological, chemical, and biological significance.

Element	Specified Attribute	Ecological, Chemical, and Biological Significance
Large Live Trees	DBH > 50 cm broken tops	▪ Stems > 50 cm DBH are old-growth indicators (Bunnell et al. 2002) ▪ Well-developed crowns provide unique niche structures for nesting and foraging (Huggard et al. 2009) ▪ Large trees facilitate development of open and diverse understory conditions. ▪ Large trees provide continual recruitment of large CWD and snags. ▪ Deformities provide micro-niches for various species (Kenefic and Nyland 2007).
Large Snags	DBH > 50 cm	▪ Snags with DBH > 50 cm and height > 5 m reported the highest diversity of birds and mammals in BC (Bunnell et al. 2002). ▪ Large snags are indicators of mid-aged and old-growth forest conditions (Kneeshaw and Burton 1998, Wells et al. 1998, Gerzon et al. 2011). ▪ Large snags provide niches for insects, invertebrates, birds, fungi, and epiphytes during different periods of their life cycle (Huggard et al. 2009). ▪ Large snag density is a better indicator of cavity nesters, in comparison to overall snag density (Bunnell and Allaye-Chan 1984). ▪ Snag density correlated with abundance of primary and secondary cavity nesters (Ohmann et al. 1994, Bunnell et al. 2013).
Large CWD	DBH> 25 cm well decayed (class 3-5)	▪ Managed stands have less CWD volume than unmanaged, specifically larger, well-decayed pieces (Maser and Trappe 1984, Kruys et al. 1999, Hautala et al. 2004). ▪ Large pieces have greater forest floor cover and provide greater substrate and nutrients, which increases abundance of truffles and truffle-like fungi (Amaranthus et al. 1994, Bull and Jackson 1995, Carey and Johnson 1995). ▪ Larger pieces used by vertebrates as dens, roost sites, corridors, protection, and shelter for reproduction (Harestad 1991, Corkran and Thoms 1996, Bunnell et al. 2002). ▪ Advanced decay classes are colonized by insects and provide foraging sites for vertebrates. ▪ Pileated woodpeckers prefer well-decayed logs because they are full of carpenter ants (Bull and Holthausen 1993). ▪ Small mammals easily burrow into decayed logs (Maser et al. 1979). ▪ Lichen flora is richer and more abundance in decay class 3 (McCullough 1948, Crites and Dale 1998, Bunnell et al. 2008). ▪ Western redback salamanders, clouded salamanders, and ensatina prefer decay class 3-4 (Aubrey et al. 1988, Corn and Burry 1991, Butts and McComb 2000). ▪ Plays a role in the biogeochemical cycling and carbon balance of forest ecosystems (Harmon et al. 1990, Gough et al. 2007). ▪ CWD buffers against disturbance and induced nutrient losses (Zimmerman et al. 1995). ▪ CWD collects and sequesters nutrients from forest floor and soil by wood-decaying fungi that translocate P through mycelial cords among pieces of CWD (Wells 1996).

Managed Stands

I chose managed stands based on two requirements: age (i.e., 57- to- 59 yrs) and similar site preparation. Site preparation included clear-cut patches with soil compaction, removal of snags and CWD, and planted with a monoculture of Douglas-fir with a 2.7-m or 3.7-m spacing.

Plot Establishment

I chose suitable natural and managed stands by stratifying geospatial maps and randomly assigning plot locations. First, maps of canopy structure derived from LiDAR (Light Detection and Ranging) were used to stratify stands within the MKRF. I used LiDAR maps to classify tree height (i.e., defined as the 95th height percentile height on LiDAR laser returns) and vertical complexity (i.e., defined as the standard deviation of LiDAR laser height returns) into five classes from lowest to highest.

By overlaying LiDAR maps with ortho-photos from years 1930, 1949, 1967, and 1973, I identified height classes and structural-complexity classes. I identified natural stands as stands that showed no signs of management from early ortho-photos, exhibited the highest trees, and showed greatest complexity. I identified managed plots with moderate height classes and complexity. All stands were selected based on previous BEC mapping of primary CWHdm 05 and CWHdm 07 stands (Klinka 1976). I selected three 500-yr-old natural stands, one 140-yr natural stand, and two 60-yr-managed stands to measure in 2016. The remaining 140-yr-natural and 60-yr-stands were sampled during the 2016 MKRF inventory. Using GIS (Geographic Information System), I placed polygons around selected stands and placed a 25-m buffer from polygon edge. The GIS randomly generated three plots that were 50 m apart in each stand polygon. I numbered plots 1-3 based on the first and last accessible by trail or road. Next, I visited plots for ground-truthing and to determine if the plots met the natural or managed criteria. I examined natural plots for previous management (e.g., selective logging based on the presence of stumps). If the first natural plot showed signs of management, I rejected that plot and moved to the second plot.

Concentric Ring Plot

I used a nested, concentric-ring plot similar to the National Forest Inventory layout for permanent sample plots (NFI 2005; Fig. 2).Their plots include

- five 1.73-m-radius regeneration plots (i.e., 0.001 ha),

- one 5.64-m-radius small-tree plot (0.01 ha) (i.e., DBH 2.0 cm to 7.5 cm DBH),
- one 11.28-m-radius large-tree plot (i.e., DBH 7.5-70 cm), and
- one 11.28-m-radius understory-vegetation plot (0.04 ha).

To ensure very-large trees (DBH > 70 cm) were represented adequately, I added a 25.23-m-radius plot (i.e., 0.2 ha).

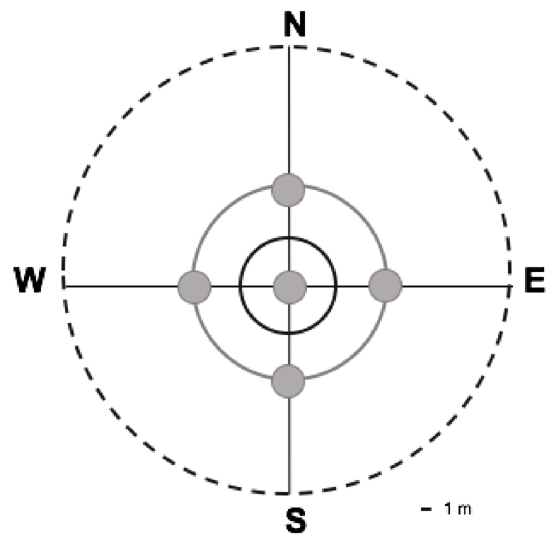

Fig. 2. Concentric-ring-sampling plot used for sampling all sites [adapted from MKRF vegetation VRI (2016)]: 1.78-m regeneration plots (grey circles), 5.64-m small-tree plot (black circle), 11.28-m large-tree plot (grey circle), and 25.23-m very-large-tree plot (dashed-black circle).

Plot Types

Plots were labeled based on the attribute sampled: regeneration plot, small-tree plot, large-tree plot, CWD plot, understory vegetation plot, and very-large tree plot.

I established regeneration plots at each cardinal direction at the 11.28-m-radius plot boundary and at the plot center. The five plots had a 1.78-m-radius, and I tallied all live trees less than 2 cm DBH. I measured species, and size class.

I used the 5.64-m-radius plot to record species and status (i.e., live or dead) of trees that were 2.0 ≤ DBH ≤ 7.5 cm.

I established the 11.28-m-radius plots to sample large live and dead, understory vegetation, two randomly assigned CWD transects, and a large-stump survey.

For the live and dead trees, plot radius was adjusted based on slope (increased if >10 %). I considered a tree to be “large” if the tree had a minimum DBH of 7.5 cm and a maximum DBH of 70 cm. A 7.5 cm DBH is used commonly in B.C. to distinguish tree sizes and for the silviculture model *Prognosis* (BC FLNRO 2015). I measured species, DBH, live or dead, loss indicator group, height (i.e., two trees of each species, any trees cored for age, broken trees, and dead self-supporting trees), logs, broken tops, and appearance code (i.e., decay class).

The 11.28-m-radius plot also included an understory-vegetation inventory. I noted species composition and estimated percent cover (below 2 m canopy height; or a select group of shrubs). Estimates were based on projection keys for visual calibration.

In addition, I established two 22.56-m coarse-woody-debris line-intercept transects that crossed the diameter of the 11.28-m-radius plots. Coarse woody debris is all dead organic material above the forest floor that is not self-supporting and is greater than 7.5 cm in diameter at the point where the transect crosses (RIC 1999). Using a 7.5-cm size threshold is commonly for CWD-line transects (NFI 2005, BC MFLNRO 2015) because this diameter is representative of the majority of woody-debris biomass across different forest stands (Wells and Trofymow 1997). Transect azimuths were randomly chosen by turning the compass at least five times. The transects were perpendicular to each other and originated from plot center (doing half the diameter (11.28-m-radius) at a time). I corrected the length of each transect for slope (>10%). I measured species, diameter, angle of horizontal, and decay class. Length was not required for biomass and volume estimations (Marshall et al. 2003).

Stump inventory took place in 11.28-m-radius large-tree plot. Stumps were defined as self-supporting remains of trees cut during forest management operations (MKRF VRI 2016). I measured species, diameter at 0.3-m high, height, and decay class.

I established 25.23-m-radius very-large-tree plot to measure trees with DBH greater than 70 cm DBH. A 70-cm DBH was used because trees with a minimum DBH of 70 cm are rare in post-harvest stands; therefore, I only expected to observe very-large trees in mid-aged or old-natural stands (Thompson et al. n.d.). A very-large-tree plot accounted for the decrease in stem-density for stands in later-stages of development, for the increased spacing needed for large stems, and in case my 0.04-ha plot fell within a canopy gap. I measured the same attributes as the large-tree plot.

Estimating CWD Density

To convert large CWD number of pieces/0.04 ha plot into CWD number of pieces/ha transect length (L), angle from the ground (λ), and piece length (l) is needed (Equation 1; Marshall et al. 2003). Piece length measurements were not collected during field sampling and piece length was estimated using mean height of snags with DBH greater than 25 m for each plot.

$$pph_i = \frac{10000 \times \pi}{2 \times L} \times \sum_{j=1}^{m_i} \frac{1}{l_{ij} \times \cos \lambda_{ij}}$$

Equation 1- Equation to estimate the number of CWD pieces per hectare using line intersect sampling (Marshall et al. 2003). Abbreviations are represented by pieces per hectare (pphi), length of the transect line at a sample point (L), number of CWD pieces at the i^{th} sample point (m_i), length of the j^{th} piece on the i^{th} transect (l_{ij}), and angle subtended by the j^{th} piece on the i^{th} transect and a horizontal plane (λ_{ij}).

Statistical Analysis

To visualize differences in structural attributes among the three forest types, I plotted total and species-specific means and standard errors of

- large and very-large live tree attributes (i.e., number of stems, DBH, and number of broken tops),
- large and very-large snags (i.e., number of stems, DBH, and height), and
- large CWD (i.e., number of pieces and diameter) for each stand type.

I used one-way ANOVA and post-hoc Tukey's honest significant difference (HSD) to compare snags, CWD, and the majority of live-tree attributes attributes among stand types. I used Brown-Forsythe test and post-hoc games-howell to examine if live tree DBH distribution, large and very-large Douglas-fir DBH, large western hemlock DBH, and very- large western redcedar DBH were significantly different among stand types, because the assumption of homogeneity of variance was violated. Significant differences were identified when $p < 0.05$ or $p < 0.01$. All analyses were computed in R (R Core Team 2016) with dplyr (Wickham and

Francois 2016), car (Fox and Weisberg 2011), onewaytests (Dag et al. 2016), and userfriendsceince (Gjalt-Jorn 2016) packages.

Results

Live Trees

Differences among stand-types were evident for distribution of live-tree DBH (Fig. 3), mean stems/ha of large-trees, mean stems/ha of very-large trees, and mean stems/ha of very-large broken trees (Fig. 4, Table 5). Large trees were 2x more abundant in 140-yr-natural stands compared to 60-yr-managed and 500-yr-natural stands (Fig. 4). Very-large trees were most abundant in 500-yr-natural stands and absent from 60-yr-managed stands (Fig. 4).

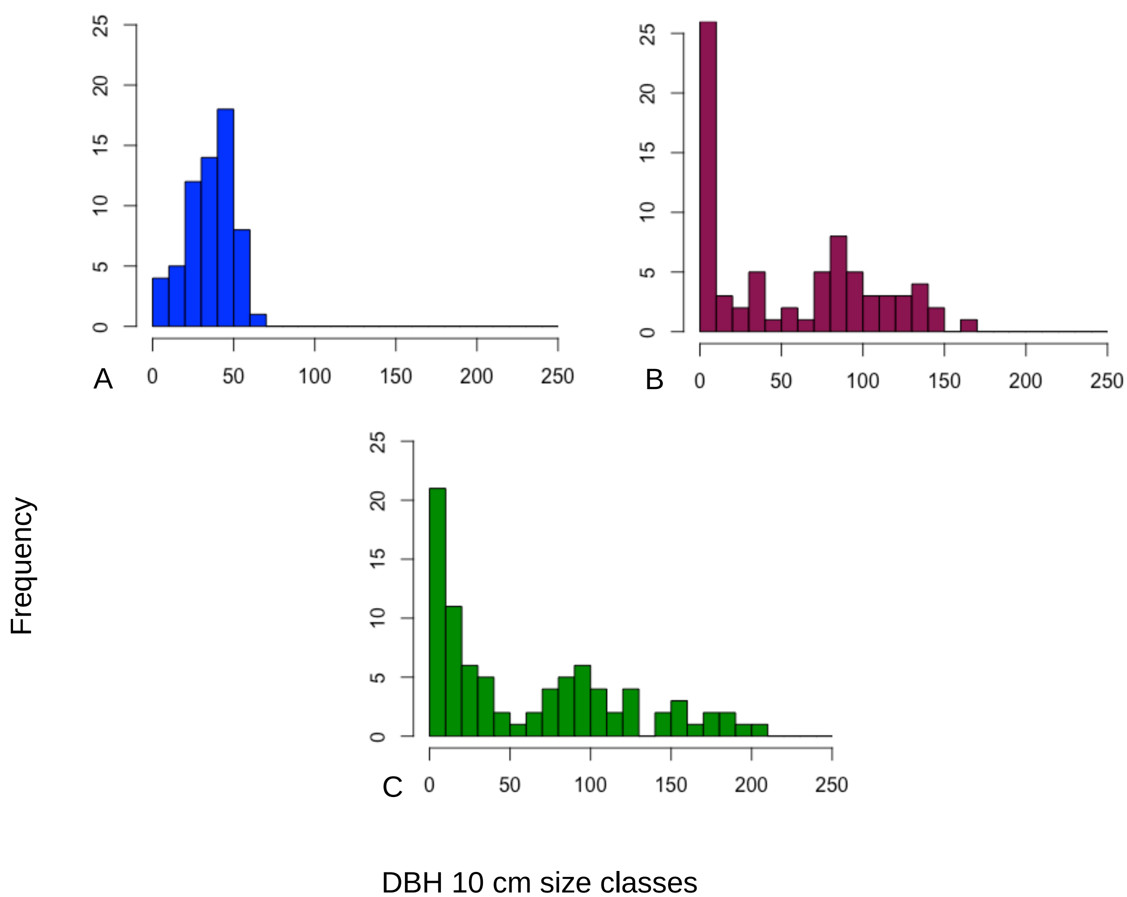

Fig. 3. Frequency distribution of live tree DBH distribution for three stand types: A) 60-yr-managed, B) 140-yr-natural, and B) 500-yr-natural, MKRF May - October 2016.

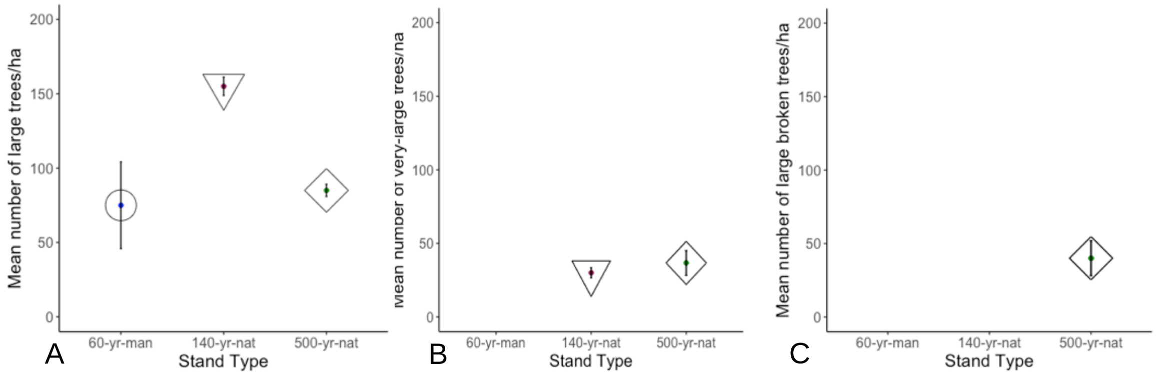

Fig. 4. A) Mean ± SE number of large trees/ha, B) mean ± SE number of very-large trees/ha, and C) mean ± SE number of very-large broken trees/ha for the three stand types. The symbol indicates stand-types that were 60-yr-managed (circle), 140-yr-natural (triangle), and 500-yr-natural (diamond), MKRF May - October 2016.

Table 5. Mean ± SE and one-way ANOVA for attribute count/ha of large trees, very-large trees, very-large broken trees, large snags, very-large snags, and large CWD for the three stand types, MKRF May - October 2016.

	60-yr-managed	**140-yr-natural**	**500-yr-natural**	**Statistical analysis**	
Attribute	**Mean ± SE**	**Mean ± SE**	**Mean±SE**	**F (2,6)**	**P value**
Stems/ha of large trees	75 ± 29	155 ± 6	85 ± 4	0.6	0.50
Stems/ha of very-large trees	0	30 ± 3	37 ± 8	9.0	0.02
Stems/ha of large broken trees	0	0	40 ± 12	9.1	0.020
Stems/ha large snags	2	28 ± 1	13 ± 2	2.0	0.20
Stems/ha of very-large snags	0	8 ± 1	8 ± 1	3.0	0.10
Pieces/ha of large CWD	1 ± 1	15 ± 9	9 ± 3	4.0	0.08

Snags

Differences among stand-types were seen for snag DBH distribution (Fig. 5), snag height distribution (Fig. 6), mean stems/ha of large-snags, and mean stems/ha of very-large trees (Fig. 7, Table 5), MKRF May - October 2016. The 140-yr-natural stands had 14x-higher large snag stems/ha compared to 60-yr-managed stands. Very-large snags were observed in equal densities for the 140-yr-natural stands and 500-yr-natural stands, while very-large snags were absent in 60-yr-managed stands (Fig. 7).

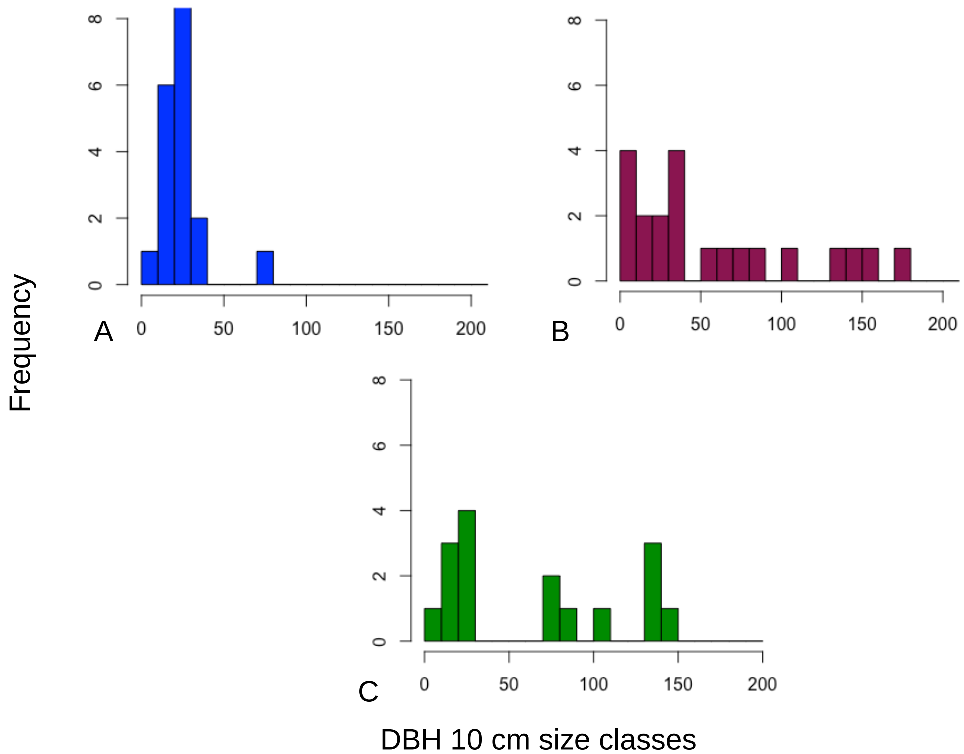

Fig. 5. Frequency distribution of snag DBH for three stand types: A) 60-yr-managed, B) 140-yr-natural, and C) 500-yr-natural, MKRF May - October 2016.

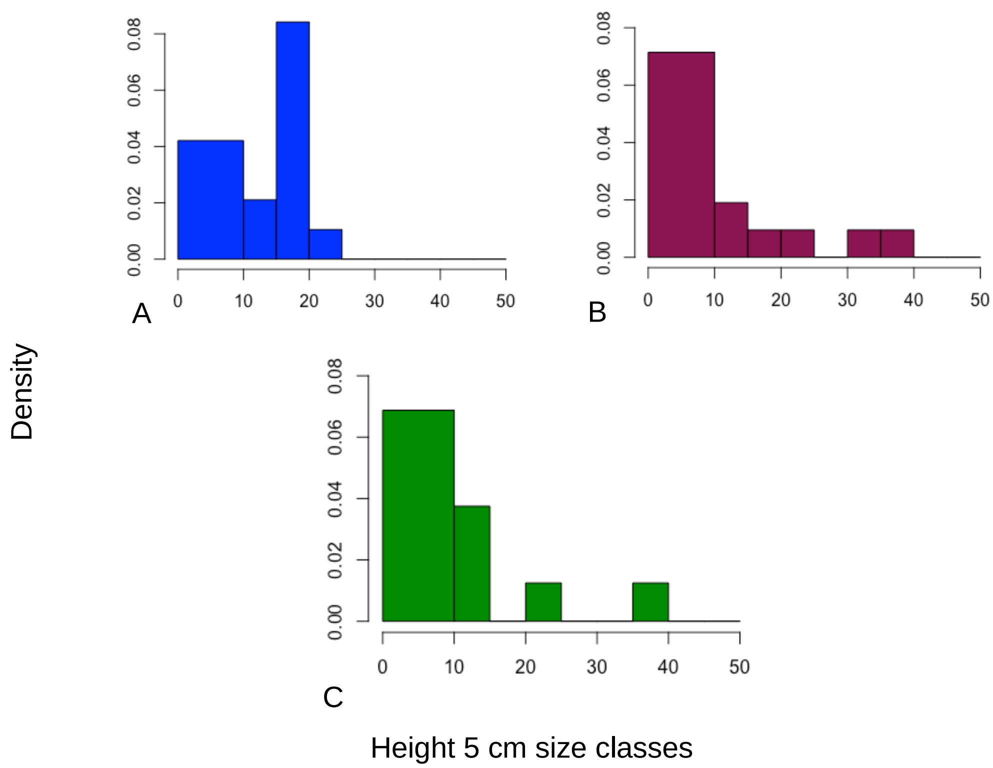

Fig. 6. Frequency distribution of snag height for three stand types: A) 60-yr-managed, B) 140-yr-natural, and C) 500-yr-natural, MKRF May - October 2016.

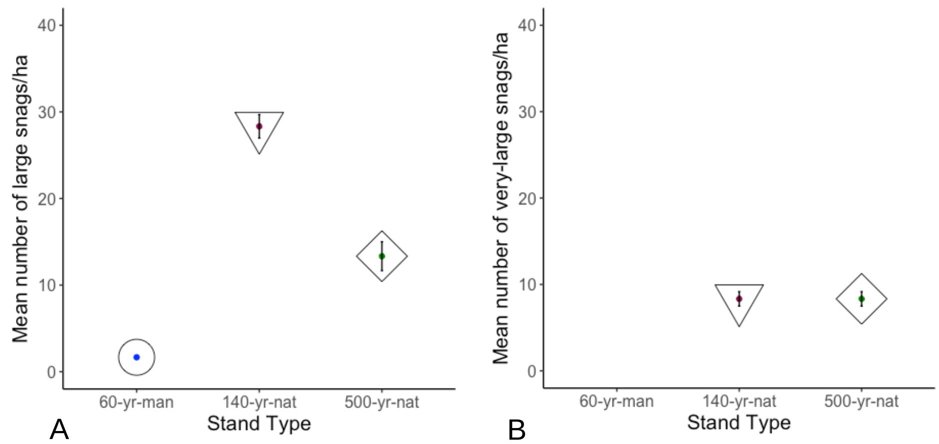

Fig. 7. A) Mean ± SE number of large snags/ha and B) mean ± SE number of very-large snags/ha. Symbols indicate stand-types that were 60-yr-managed (circle), 140-yr-natural (triangle), and 500-yr-natural (diamond), MKRF May - October 2016.

CWD

Differences among stand-types were seen for the distribution of DBH for CWD distribution (Fig. 8) and mean pieces/ha of large-CWD (Fig. 9, Table 5) , MKRF May - October 2016. Greatest quantities of large CWD were observed in 140-yr-natural stands with a 15x greater count compared to 60-yr-managed stands and an approximate 2x greater count compared to 500-yr-natural stands (Fig. 9).

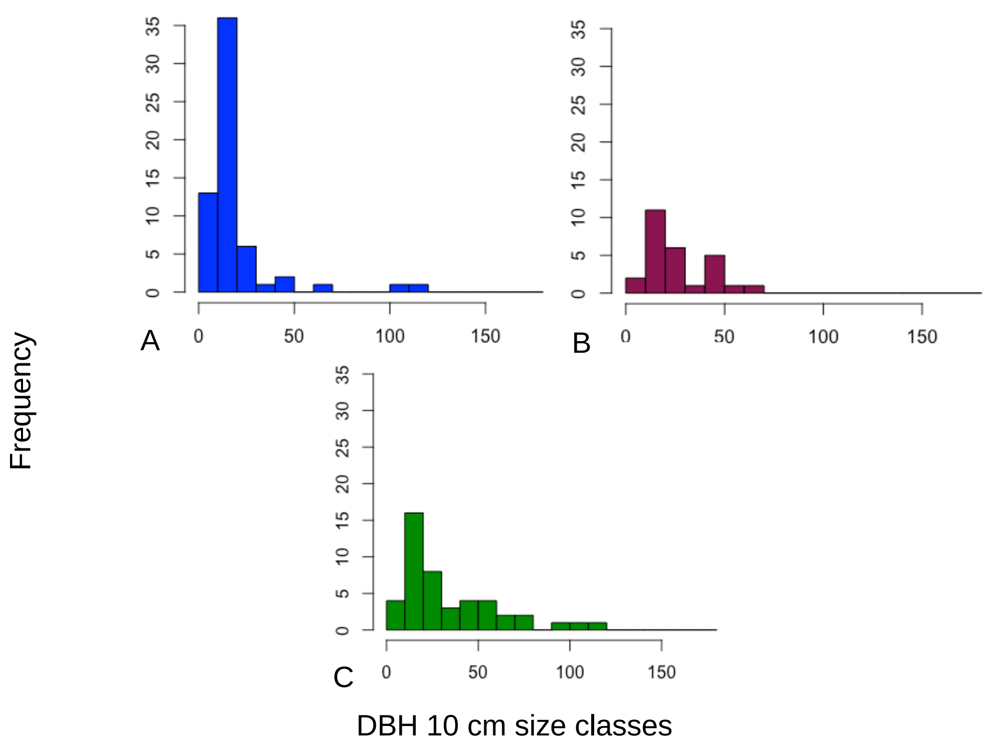

Fig. 8. Frequency distribution of CWD diameter for three stand types: A) 60-yr-managed, B) 140-yr-natural, and C) 500-yr-natural, MKRF May - October 2016.

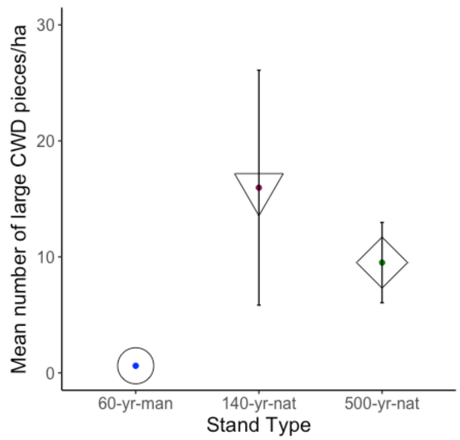

Fig. 9. Mean ± SE number of large CWD pieces/ha. Symbols indicate stand-types that were 60-yr-managed (circle), 140-yr-natural (diamond), and 500-yr-natural (diamond), MKRF May - October 2016.

Species Live Trees

Differences among stand-types were seen in species composition related to mean stems/ha of large-trees, mean stems/ha of very-large trees, and mean stems/ha of very-large broken trees (Fig. 10). In addition, tree-species differed in mean DBH among stand types (Fig. 11, Table 6, Table 7).

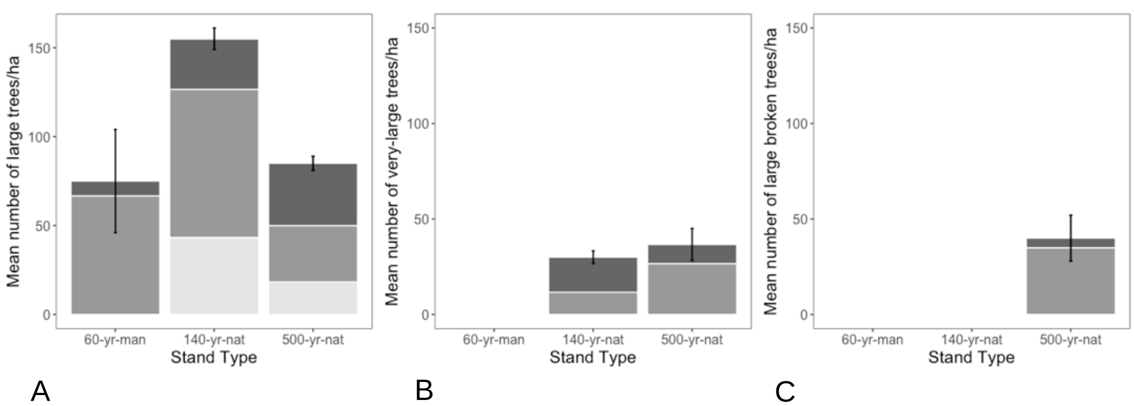

Fig. 10. A) Mean ± SE number of large trees/ha, B) mean ± SE number of very-large trees/ha, and C) mean ± SE number of very-large broken trees/ha for the three stand types. Shading indicates the proportion of the total number of large broken trees in the plot that were Douglas-fir (medium grey), western hemlock (light grey), and western redcedar (dark grey), MKRF May - October 2016.

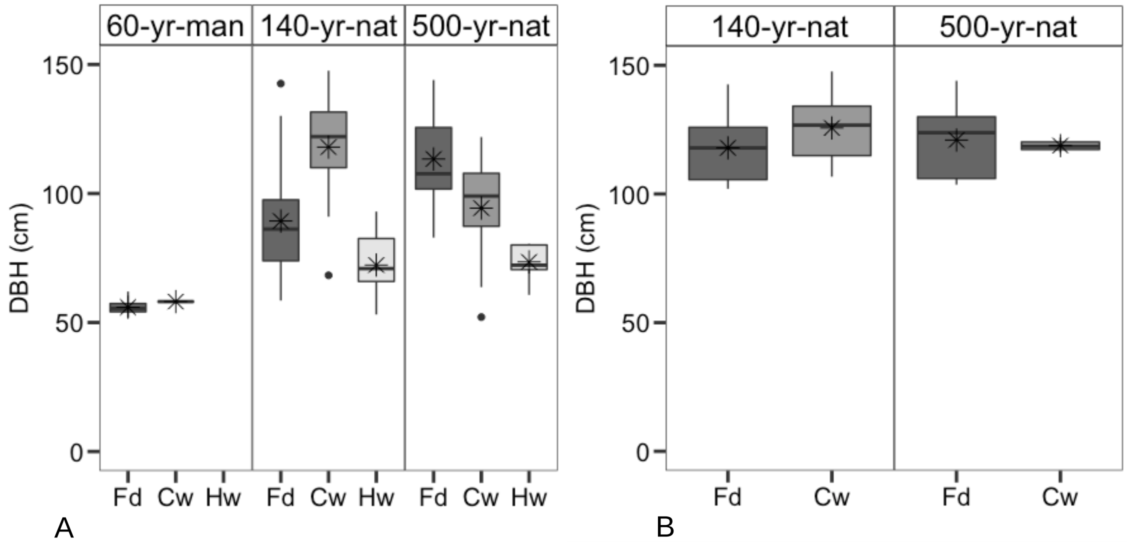

Fig. 11. DBH for A) large trees and B) very-large trees for 60-yr-managed, 140-yr-natural, and 500-yr-natural: Douglas-fir (Fd and dark grey), western redcedar (Cw and medium grey) and western hemlock (Hw and light grey). Boxplots show the mean (asterisk), median (horizontal line), 50% range of the data (box), >1.5 interquartile ranges above the median (whiskers), and outliers (dots) for tree species, MKRF May - October 2016.

Table 6. Mean ± SE and one-way ANOVA results for large tree DBH for three stand types. Species codes represent Douglas-fir (Fd), western hemlock (Hw), and western redcedar (Cw), MKRF May - October 2016.

	Mean DBH ± SE (cm) of large trees			**Statistical analysis**	
Species	60-yr-managed	140-yr-natural	500-yr-managed	F value (2, 6)	P value
Fd	55 ± 1	88 ± 4	119 ± 8	2.2	0.20
Hw	-	72 ± 4	74 ± 3	115.1	< 0.001
Cw	58	122 ± 7	109 ± 9	4.8	0.06

Table 7. Mean ± SE and one-way ANOVA results for very-large tree DBH for three stand types. Species codes represent Douglas-fir (Fd), western hemlock (Hw), and western redcedar (Cw), MKRF May - October 2016.

	Mean DBH ± SE (cm) of very-large trees			**Statistical analysis**	
Species	60-yr-managed	140-yr-natural	500-yr-managed	F value (2, 6)	P value
Fd	-	118 ± 6	129 ± 9	5.7	0.04
Hw	-	-	-	-	-
Cw	-	129 ± 5	138 ± 9	2.0	0.2

Species Snags

Differences among stand-types were revealed in species composition related to mean stems/ha of large snags and mean stems/ha of very-large snags (Fig. 12). In addition, tree-species differed in mean DBH and mean height among stand types. No results were statistically significant (Fig. 13, Table 8, Table 9).

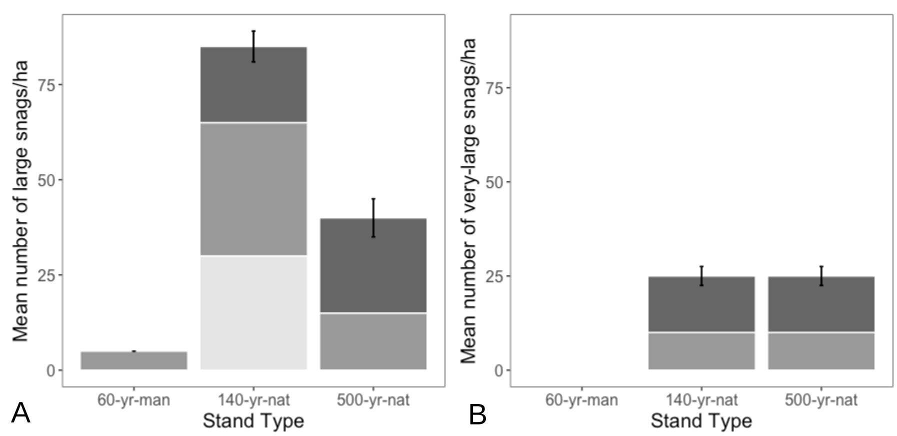

Fig. 12. A) Mean ± SE number of large snag/ha and B) mean ± SE number of very-large snags/ha. Shading indicates the proportion of the total number of large broken snags in the plot that were Douglas-fir (medium grey), western hemlock (light grey), and western redcedar (dark grey), MKRF May - October 2016.

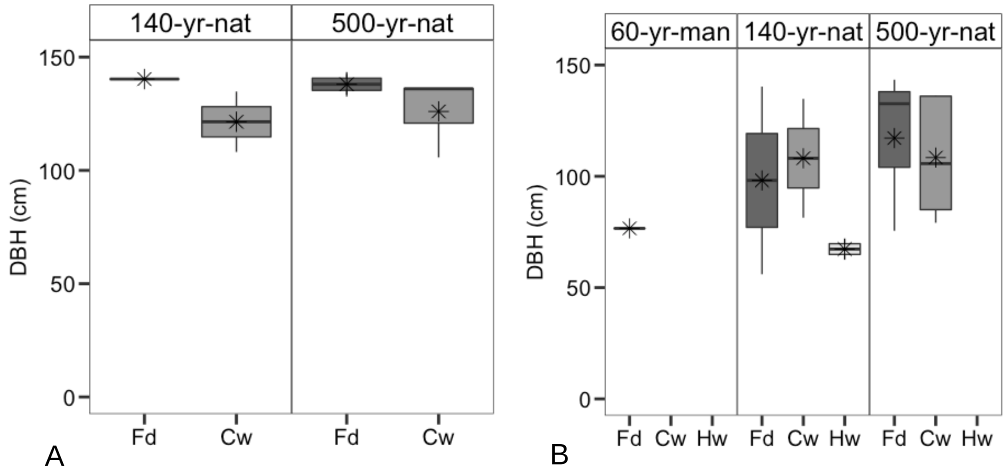

Fig. 13. DBH for A) large snags and B) very-large snags for 60-yr-managed, 140-yr-natural, and 500-yr-natural: Douglas-fir (Fd and dark grey), western redcedar (Cw and medium grey) and western hemlock (Hw and light grey). Boxplots show the mean (asterisk), median (horizontal line), 50% range of the data (box), >1.5 interquartile ranges above the median (whiskers), and outliers (dots) for tree species, MKRF May - October 2016.

Table 8. Mean ± SE height of large snags for three stand types. Species codes represent Douglas-fir (Fd), western hemlock (Hw), and western redcedar (Cw), MKRF May - October 2016.

	Mean ± SE height (m) of large snags			**Mean ± SE height (m) of very-large snags**		
Species	**500-natural**	**140-natural**	**60-managed**	**500-natural**	**140-natural**	**60-managed**
Fd	5 ± 1	4 ± 2	3.1	12 ± 9	10 ± 212	-
Cw	16 ± 15	8 ± 10	-	5 ± 1	2 ± 0	-
Hw	-	23 ±13	-	-	-	-

Table 9. Mean ± SE for large snag DBH for three stand types. Species codes represent Douglas-fir (Fd), western hemlock (Hw), and western redcedar (Cw), MKRF May - October 2016.

	Mean ± SE DBH (cm) of large snags			**Mean ± SE DBH (cm) of very- large snags**		
Species	**500-natural**	**140-natural**	**60-managed**	**500-natural**	**140-natural**	**60-managed**
Fd	117 ± 21	123 ± 35	76.6	138 ± 6	157 ± 17	-
Cw	108 ± 12	119 ± 15	-	126 ± 10	131 ± 12	-
Hw	-	67 ± 7	-	-	-	-

Species CWD

Differences among stand-types were seen in species composition related to mean pieces/ha (Fig. 14) and diameter for large CWD (Fig. 15). No results were statistically significant.

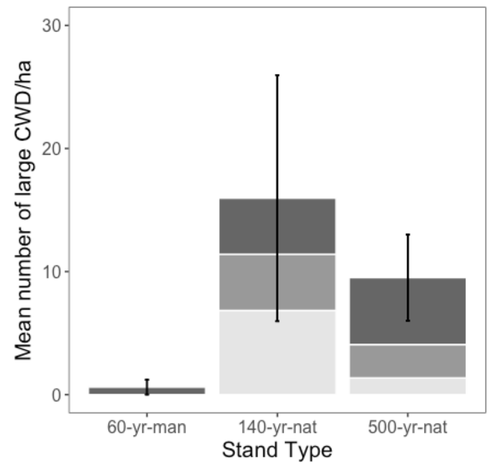

Fig. 14. Mean ± SE number of large CWD/ha. The shading indicates the proportion of the total number of large CWD in the plot that were Douglas-fir (medium grey), western hemlock (light grey), and western redcedar (dark grey), MKRF May - October 2016.

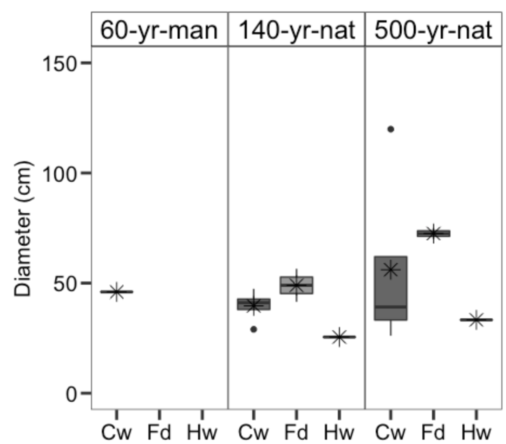

Fig. 15. Diameter for large CWD for 60-yr-managed, 140-yr-natural, and 500-yr-natural: Douglas-fir (Fd and dark grey), western redcedar (Cw and medium grey) and western hemlock (Hw and light grey). Boxplots show the mean (asterisk), median (horizontal line), 50% range of the data (box), >1.5 interquartile ranges above the median (whiskers), and outliers (dots) for tree species, MKRF May - October 2016.

Table 10. Mean ± SE and one-way ANOVA for large CWD diameter for three stand types. Species codes represent Douglas-fir (Fd), western hemlock (Hw), and western redcedar (Cw), MKRF May - October 2016.

	Mean ± SE CWD diameter (cm) for pieces > 25 cm			Statistical analysis	
Species	**Man 60**	**Nat 140**	**Nat 500**	**F value**	**P value**
Fd	N/A	49 ± 8	73 ± 3	(2, 6) 3.4	0.1
Hw	N/A	25.5	33	(2, 6) 0.517	0.6
Cw	46	40 ± 4	56 ± 22	(2, 6) 0.8	0.5

Discussion

Understanding and quantifying the range of mid-age and old-natural attributes within a specific landscape helps forest managers set restoration targets and prescribe appropriate silviculture treatments. For the MKRF, I quantified mean values and variation levels for large live trees, snags, and large CWD among three stand-types of CWHdm 05/07. The mean values of 500-yr-natural attributes differed from mean values observed in other literature on old-growth attributes (e.g., Wells 1996, Gerzon et al. 2011); however, the structural attributes associated with old-growth stands were consistent with old-natural stands. My observations were also consistent with other literature noting structural attributes in 140-yr-managed stands (i.e., intermediate age-classes) differed from 500-yr-old (old age classes, i.e., > 250 yrs) (Alaback 1984, Spies and Franklin 1991, Arsenault and Bradfield 1995). Primarily, I summarized differences among 60-yr-managed and old-natural stands (i.e., 140 yrs and 500 yrs) indicating that large live trees, large snags, and large CWD have not yet recovered; therefore, there is potential to accelerate the development of old-natural forest attributes in younger managed stands. The goal of restoring large trees, large snags, and large CWD is to restore the physical presence, and the associated ecological, biological, geochemical, and cultural services.

Large live-trees store more carbon than smaller trees (Sutherland et al. 2016), stems with well-developed crowns provides unique niches for foraging and nesting (Huggard et al. 2009), large trees facilitate the development of understory conditions, large trees provide continual recruitment of large CWD and large snags (i.e., additional wildlife features), and large cedar trees are of cultural significance to First Nations (Sutherland et al. 2016). With many species depending on large live-trees (e.g., wildlife, understory vegetation, and humans), large live trees are a key feature of forested landscapes and should be abundant. Large trees were most abundant in 140-yr-natural stands, with an approximate 2x greater stem count compared to 60-yr-managed and 500-yr-natural. Gerzon et al. (2011) observed large trees to be the first old-growth attribute to recover. My observations are consistent with Gerzon et al. (2011), because large-trees was the most abundant old-growth characteristic in 60-yr-managed stands compared to large broken trees, large snags, and large CWD. Large-tree and very-large tree development is based on various interacting processes that occur within a stand, such as disturbance, adequate growth-time, individual tree-vigour and growth-efficiency, available site resources (i.e., primarily light; Jia et al. 2016), competition, and species-specific requirements. If these ecological requirements are met, stands are able to support large-trees. Restoration practitioners and forest managers can support the presence of large trees by extending stand-rotation, increasing growing space for individual trees (i.e., removal of select trees), implementing various thinning techniques, increasing light availability, and adding nitrogen-rich fertilizer (Rosso and Hansen 1998, BC MOF 1999a, BC MOF 1999b). Very-large trees were absent from 60-yr-managed stands with the greatest number of very-large stems in the 500-yr-natural natural stands, with a 12x-greater stem count compared to 60-yr-managed. Wells (1996) noted very-large stems did not appear in plots young than 180 yrs and Gerzon et al. (2011) noted that stems with DBH greater than 75 cm had low correlation with many natural second-growth sites. Both findings are not consistent with mine, therefore mid-aged stands in the MKRF may have greater available site resources and higher quantities of trees with greater growth-efficiency and vigour compared to stands in similar studies (e.g., Wells 1996, Gerzon et al. 2011). The only attribute observed solely within 500-yr-natural stands was the presence of large trees with broken tops indicating that this attribute requires a very-long period to recover, however, could be manipulated with restoration. Without setting a DBH size threshold, the distribution of DBH resembled a "Reverse-J" for 140-yr-natural and 500-yr-natural stands and an approximate normal distribution for 60-yr-managed. In comparison to to the DBH distributions reported by Wells (1996) and Peet and Christensen (1987) where they observed "Reverse-J" distribution in young (i.e., 50 yrs) stands and old (i.e., 300 yrs) stands and intermediate (i.e., 75 yrs) having a normal distribution. However, when I set a threshold of DBH > 50 cm, the distribution resembles a normal distribution. The restoration prescriptions used to enhance the development of large trees will be the same prescriptions used in supporting very-large tree growth and characteristics associated with very-large trees (e.g., broken tops).

Large snags are considered wildlife-trees, supporting the highest diversity of wildlife in B.C. (Bunnell et al. 2002). Large-snags provide niches for insects, invertebrates, birds, fungi, and epiphytes during different periods of their life cycle (NHuggard et al. 2009). In addition, large snags store carbon and are future recruitments of CWD. In my study large snags and very-large snags differed among 60-yr-managed, 140-yr-natural, and 500-yr-natural stands. The 140-yr-natural stands had 14x-higher large snag stems/ha compared to 60-yr-managed, and 2x-greater large snag stems/ha compared to 500-yr-natural, and, exhibited an "Inverted-U" shaped trajectory with a DBH > 50 cm threshold. My observations are different from Spies and Franklin (1988) "U-shaped" snag density trajectory, in addition to Wells (1996) and Gerzon et al. (2011) studies; their studies reported that intermediate-aged stands (i.e., 129-229) had low numbers of large snags compared to old-growth stands (i.e., sites > 250 yrs). In addition, Wells (1996) observed no very-large snags in stands younger than 300 yrs, whereas I observed equal densities of very-large snags in 140-yr-old and 500-yr-old stands. Very-large snags were absent in 60-yr-managed, noting that very-large snags begin to recover post 60 yrs. Lastly, my 500-yr-natural observations of 13 large snags/ha and 8 very-large snags/ha is similar to B.C.'s old-growth mensuration data analysis reporting 11 large snags/ha in CWHvm1 variant (BCMOF 2001) and 5 very-large stems/ha (Huggard 2004). Both the 140-yr-natural and 500-yr-natural contained snags that exhibited a wider variation in DBH and height compared to 60-yr-managed. Mechanisms responsible for large tree growth contribute to snag development. Restoration can be used to accelerate snag development or snag creation by emulating the ecological processes responsible for large tree mortality. In B.C.'s coastal temperate forests various factors influence tree mortality (e.g., wind, pathogens, fire, drought, ice, frost, and lightening), however decay fungi and wind are the dominant processes responsible for large-tree mortality (Dorner and Wong 2003). Examples of restoration prescriptions for large-snag development include targeting large-trees for girdling, fungus inoculation, and burning. Restoring large-snags also contributes to the future recruitment of large CWD.

Large CWD pieces increase biogeochemical cycling, create diverse substrate for fungi and flora (Amaranthus et al. 1994, Bull and Jackson 1995, Carey and Johnson 1995), provide dens, roost sites, protect vertebrates (Cokran and Thomas 1996, Bunnell et al. 2002), and support the forest carbon balance (Harmon et al. 1990, Gough et al. 2007). Density of large CWD was similar between 140-yr-natural and 500-yr-natural stands but differed in 60-yr-managed stands. The mean diameter of large CWD was greatest in 500-yr-natural stands and lowest in 60-yr-managed stands. Differences in mean diameter were considered statistically significant (P-value < .08). A P-value of .08 was considered significant because the majority of CWD literature reported low significance due to the natural variability of the attribute, residual logs, and difficulty in sampling (Spies and Franklin 1991, Weisberg 2004, Gerzon et al. 2011). Statistical significance was attributed to the removal of old CWD in 60-yr-managed stands during site preparation in 1955. Mechanisms responsible for large tree growth contribute not only to snag development but CWD development. CWD relies on similar mechanisms as snags for development. Restoration can increase stand CWD quantities indirectly through creation of snags or directly by targeting large trees (i.e., selective logging).

A summary of large trees, large snags, and large CWD is a good starting point for understanding trends and creating restoration targets. While restoration can emulate ecological processes to meet mean values and variation levels of old-natural attributes, understanding and quantifying species-specific attributes has greater restoration implication and ecological significance. Restoration practitioners and forest managers should refer to the species composition of each attribute when creating or accelerating the development because each species has different characteristics (e.g., DBH, decay rate, branch systems, and hollow centres) which provide various micro-niches for different species. For example, vertebrates and non-vertebrates show affinities for specific tree species or groups of tree species (Bunnell 2002). Generally, vertebrates favour tree species depending on stem or log durability, resistance to decay (e.g., western hemlock decomposes faster than western redcedar), cones (e.g., Douglas squirrel (*Tamiasciurus douglasii*) and Douglas-fir), thickness of bark (e.g., bats and salamanders depend on thick bark of Douglas-fir; Bunnell and Dupuis 1995) or the presence of hollows to provide den sites (e.g., western redcedar; Bunnell 2002). Having a variety of tree species attributes will support greater biodiversity and in-turn create resilient forests (Drever et al. 2006). In general, large trees, large snags, and large CWD species composition had greater quantities of western hemlock and western redcedar composition compared to 60-yr-managed. The 60-yr-managed stands had less tree diversity due to monoculture plantings during site preparation and because of the fast-growing abilities of Douglas-fir in younger stages of forest development compared to western hemlock and western redcedar.

Lastly, attention should be noted when converting trees from plots to ha values, comparing research with similar studies, and relying solely on restoration as a tool to create ecologically resilient forests. Large trees and snags with DBH greater than 70 cm were absent in all 0.04 ha plots for each stand-type. Stems greater than 70 cm DBH were only seen in 0.2 ha plots. This finding illustrates that researchers should use caution when converting plot size into hectares/acres. Missing structural attributes during sampling procedures could miss details necessary in defining restoration targets. Differences in attributes density compared to the studies conducted by Wells (1996) and Gerzon et al. (2011) could be attributed to different BEC CWH variants and site series, as well as different sampling procedures. While restoration is a tool to promote heterogeneity in heavily-managed stands, it is a retroactive approach that can require a long time-frame of recovery (Sutherland et al. 2016). Therefore, this study quantified reference targets to aid the development of a proactive forest management policy, providing insight on the number of biological legacies which should be left within a stand.

Study Limitations

The main limitations of this study is the small sample size used to characterize stand-type and the use of a chronosequence approach. More conclusive results than this study could have been obtained with increased replicates for each stand-type. However, it was difficult to find plots within the MKRF of each stand-type that met the requirement of being in the similar BEC classification, that had similar management histories, and/or that have naturally regenerated. I acknowledge that no two sites will ever be identical but comparing stands with similar site series (i.e., CWHdm 05/07) and management history (e.g., removal biological legacies and similar spacing density) will improve statistical power to detect variation in attributes among treatments. Even with small sample sizes, this study was still sufficient in demonstrating the differences in large live trees, large snags, and large coarse woody debris among 60-yr-managed, 140-yr-natural, and 500-yr-natural stands of the MKRF. Although a great deal of theory on long-term stand-development has been gained from the chronosequence approach, I must acknowledge limitations that not all effects are time-dependent but instead can also be attributed to historical disturbance and site factors (Sutherland et al. 2016).

Conclusion

This study provides insight on how 60-yr-managed stands can be managed to restore features that are characteristics of forests in later stages of development. Forest trajectory is influenced by abiotic and biotic processes (Johnson 1996; Franklin et al. 2002, Chen et al. 2009, Ilisson and Chen 2009), therefore, without considering specific site-level factors (e.g., historical disturbances, plant-associations, and soil moisture and nutrient content), inferences about stand attributes and development can be over-simplified (Halofsky et al. 2011, Perry et al. 2011, DellaSala et al. 2013). For example, Wells (1996) and Gerzon et al. (2011) examined the temporal development of old-growth characteristics in second-growth stands within the CWHvm1 zone; the mean values quantified in their studies differed from the values reported in this study for the CWHdm zone. Therefore, each site variant and corresponding site series should have baseline reference conditions for natural stands in later-development stages to help guide forest management and restoration. In addition, by clearly defining baselines with comparable reference conditions of higher ecological resiliency, we avoid the creation of novel ecosystems (DellaSala et al. 2013). In summary, this study provided preliminary baselines to restoring mid- and old-natural attributes into younger managed stands of the MKRF and other forests classified as CWHdm 05/07.

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Chapter 3. Restoration prescriptions for a 1957 spacing-trial site (i.e., 60-yr-managed) in MKRF.

Introduction

In B.C.'s coastal-temperate forests, the majority of old-natural forests have been logged to managed forests, specifically lower-elevation forests because they are easily accessible and highly productive (Bunnell et al. 2009). Most landscapes are predominated by managed stands and lack old-natural structural attributes related to old-natural forests. The loss of old-natural attributes is concerning for people who place ecological and moral-spiritual values on these systems because old-natural attributes are linked to greater biodiversity (Franklin et al. 1981; Bunnell and Kremaster 1990), support the system's ecological resilience (Drever et al. 2006), are aesthetically pleasing, and large trees are spiritually and culturally significant (Blicharska and Mikusiński 2014).

While researchers gain knowledge about forests, society demands ecological (e.g., biodiversity), economic (e.g., logging), and social values (e.g., aesthetic) of these ecosystems. Forest management is difficult, because forestry is governed by many clients and decision makers with conflicting and competing values (King 1993). As a result, foresters have created techniques and planning approaches for meeting numerous values (Kohm and Franklin 1997, Seymour and Hunter 1999, Lindenmayer and Franklin 2003, Sarr and Puettmann 2008). Typically, foresters manage stands independently for a particular outcome (Oliver et al. 1999), which places forest stands into two opposing structural categories and can be visualized on opposing ends of a spectrum (Fig. 16).

1. Stands that are managed for economic values (i.e., primarily wood production) are typically comprised of a species-monoculture, single-aged, evenly-spaced, and have had biological legacies (e.g., CWD and snags) removed.
2. Stands that are managed for ecological or spiritual values are placed into reserves. Generally reserve stands are older, well-stratified, diverse in species mix and appearance classes, therefore, providing various niches to support biodiversity (Bunnell and Kremsater 1990).

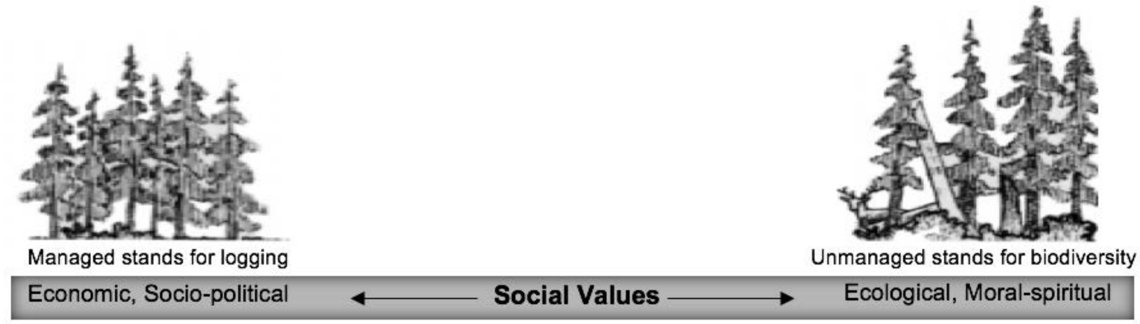

Fig. 16. Forestry value spectrum that illustrates forest types which represent different social values (images taken from Kies et al. 2003).

An opportunity is available to begin managing forests as a third category with overlapping values, coined by Seymour and Hunter (1992) as the “Triad Approach” (Puettmann et al. 2012). This approach enables different areas in a landscape to be managed one of three ways (1) protected and unmanaged, (2) intensively managed, or (3) extensively managed (Sarr and Puettmann 2004). Protected and unmanaged areas are intended to conserve biodiversity, serve as a reference condition and monitor natural disturbance regimes (Sarr and Puettmann 2004). Intensively managed stands will continue to serve economic profit (e.g., logging) (Sarr and Puettmann 2004) and stands managed extensively will blend economic, social and ecological values (Sarr and Puettmann 2004). Disciplines, such as ecological restoration offer complementary management techniques (Frelich and Puettmann 1999, Temperton et al., 2004) that could help integrate ecological, economic and social values into a stand. For example, forest restoration can be useful in accelerating the development of old and complex structural attributes. Candidate stands for restoration include

- regrowth and second-growth stands that have been managed for timber production, but will no longer be logged, resulting in the lack of structural complexity (Bauhus et al. 2009),
- second-growth stands subjected to poor logging practices that have compacted soil, lack biological legacies, and fail to reflect natural disturbance regimes, and
- landscapes dominated by managed or secondary stands and lack old-natural attributes.

Forest restoration can enhance structural complexity in managed stands, diversifying the range of ecological, economic, and social benefits of forested ecosystems, in which many interest groups value. As a result, I used stands in later stages of forest development (i.e., 140-yr-natural and 500-yr-natural) as reference ecosystems to guide restoration of a 1957 spacing-trial site (i.e., 59-yr-managed). The structural attributes used to compare reference stands to spacing-trial stands were outlined in Chapter 2 and chosen based on the structural attribute's biological, ecological, and chemical significance. My objective in comparing the variation and mean values of spacing-trial-stand attributes to 140-yr-natural and 500-yr-natural stand attributes was to determine

1. if particular spacing-trial stands were doing better than others and
2. if some spacing-trial stands were better candidates for restoration.

Quantifying mean values with variation of structural attributes enables forest managers and restoration practitioners to develop metrics-of-success to determine if restoration was successful because structural attributes can be used as surrogates for ecosystem function, ecological resiliency, and ecosystem services (Franklin et al. 2002, Sutherland et al. 2016).

Site of Restoration Interest

Historic Conditions

Prior to spacing trial establishment in 1957, the MKRF supported old-growth Douglas-fir, western hemlock, and western redcedar (Reukema and Smith 1987). During field sampling, stump data were collected, which provides insight on historic DBH and spacing densities of large western redcedar and Douglas-fir.

Spacing Trial Conditions (1955)

In 1955, the site was logged. Site preparation was done by bulldozer, CWD and snags were removed, but large stumps remained. Logging slash was piled and burned. Soil compaction occurred in some areas (Reukema and Smith 1987). The establishment of spacing trials assessed the effects of spacing on tree and stand development and determined the practicality and efficiency of different experimental designs (Smith 1959, 1978). Specifically, the area of restoration interest contained two experimental designs: 0.2-ha plots and 49-tree-plot trial.

The 49-tree-plot trial examined the effects of square spacing on development Douglas-fir, western redcedar, and western hemlock in pure stands (Reukema and Smith 1987). Spacing densities were 0.9 m x 0.9 m, 1.8 m x 1.8 m, 2.7 m x 2.7 m, 3.7 m x 3.7 m, and 4.6 m x 4.6 m. The 49-tree-plot trial ranged in size from 0.008 ha (0.9-m spacing) to 0.102 ha (4.6-m spacing) and each had two replicates (Fig. 6). Douglas-fir was planted in the fall of 1957, western redcedar was planted in the fall of 1958, and western hemlock was planted in the spring 1959. Dead seedlings were replaced in the first year and were weeded several time (Reukema and Smith 1987).

The 0.2-ha plot trial examined the effects of square spacings on the development of Douglas-fir and western hemlock (Reukema and Smith 1987). Douglas-fir spacing densities included 0.9 x 0.9 m, 1.8 x 1.8 m, 2.7 x 2.7 m, 3.7 x 3.7 m, and 4.6 x 4.6 m (Fig. 6). Density of 0.9 x 0.9 m was used for western hemlock (Fig. 6). Plots varied from 0.198 to 0.251 ha, plus buffers, and were not replicated. Douglas-fir was planted in the fall of 1957 and western hemlock was planted in the spring of 1959. Dead seedlings were replaced in the first year and were weeded several time (Reukema and Smith 1987).

Current Conditions

The intense management of the spacing trial site has resulted in homogenous stands (i.e., spacing, canopy, and species composition) that will develop along successional trajectories that differ from natural stands. In addition, the lack of structural diversity in the spacing trial resulted in the stands being more susceptible to disturbances. Even though disturbances are a natural part of the forest life-cycle (e.g., native forest pests and diseases), some disturbances can have an effect on forest productivity (e.g., *Armillaria* spp.). *Armillaria* spp. (i.e., root rot fungi) is present in the spacing trial and because of *Armillaria* spp. ability to hinder forest productivity, special attention should be given prior to forest management. It is not certain if *Armillaria* spp. was the cause of death, a factor in death, or a coincidental non-lethal issue in the western redcedar spacing-trial deaths, but by restoring structural heterogeneity, such as species composition, the possibility of losing an entire stand to one disturbance decreases. Stump disks from the dead western cedar were sent to Richard Hamelin's forest ecology lab at UBC. for further analysis and identification. These data will help guide restoration prescriptions.

Future conditions

Restoring forests aims to create ecologically resilient forests for the future. Ecological resiliency is defined as the capacity of a natural system to absorb disturbances without undergoing change to a fundamentally different state (Holling 1973, 1986, Peterson et al. 1998). Climate change projections should be taken into account when prescribing treatments for forest restoration. Climate change simulations for North America's west coast forecasts warming temperatures (i.e., mean annual temperatures warming to 3-5 degrees Celsius by 2100, with variable precipitation trends (e.g., decreased summer precipitation and increased winter precipitation) (Zhang et al. 2007, Salathe et al. 2008). Potential forest risks include increased moisture stress and drought, increased wildfire, change in growth rates and forest productivity, increased forest pests and diseases, increased storm damage, and loss of overstory and understory species (Hebda 1994, Hebda 1997, Spies et al. 2010, Braatz 2013). Potential response measures for risks associated with climate change and decreasing forest resiliency have been outlined by Braatz (2013). Examples include changing composition of species, increasing forest biodiversity, intensifying pest and disease management measures, adjusting tree spacing, planting windbreaks, and increasing forest connectivity (Braatz 2013).

Methods

Sampling plot establishment

The spacing trial site contains two experimental trials: 0.2-ha plots and 49-tree-plot trial (Fig. 17). I systematically established permanent sampling in the spacing trial site to represent all species compositions and spacing densities.

I placed the sampling plots in trial:

- 0.2-ha plot (i.e., Douglas-fir 0.9 m spacing),
- 0.2-ha plot (Douglas-fir 0.2 m spacing),
- 0.2-ha plot (Douglas-fir 4.6 m spacing),
- 49-tree-plot (Douglas-fir 3.7 m spacing),
- 49-tree-plot (Douglas-fir among 0.2, 0.9, and 2.7 m spacing),
- 49-tree plot (western hemlock 2.7 m spacing),
- 49-tree-plot (western hemlock 4.6 m spacing), and
- 49-tree plot (western hemlock among 0.2, 0.9, and 2.7 m spacing).

I placed sampling plots in the center of the spacing trial plots to reduce edge effect, with the exception of two plots that I placed within 0.2 m, 0.9 m, and 2.7 m spacing trials. Sampling plots were placed within the 0.2 m, 0.9 m, and 2.7 m spacing trials because large-tree sampling plots did not fit entirely in a 49-tree-plot. The 0.2-ha plot (Douglas-fir 2.7 m spacing) was not sampled because of a change in site series (i.e., CWHdm 12). The 0.2-ha plot (Douglas-fir 3.7 m and western hemlock 0.9 m) and all 49-tree-plots of western redcedar were logged in May 2016 because of recent tree mortality, therefore, no western-red cedar stands are observed in this study. All sampling plots in the spacing-trial stand lacked a very-large tree

25.23-m-radius plot, due to overlap in sampling plots and absence of very-large trees (i.e., DBH > 70 cm), which was checked in the field.

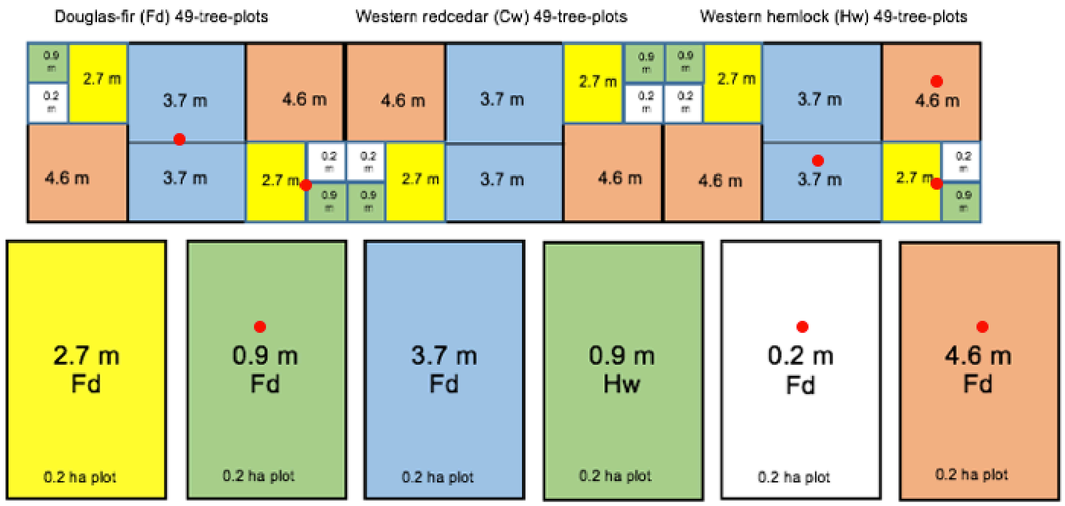

Fig. 17. Site layout of 1957 spacing trial. Colour represents spacing density: red (4.6 x 4.6 m), blue (3.7 x 3.7 m), yellow (2.7 x 2.7 m), white (0.9 x 0.9 m), and green (0.2 x 0.2 m). Each trial was planted with one conifer species: Douglas-fir, western hemlock, or western redcedar. Sampling plots are depicted by red dots.

Results

Mean values of structural attributes differed among spacing-trial plots and 140-yr-natural and 500-yr-natural stands (i.e., reference conditions).

Old-Natural Stumps

The mean (± SE) stump diameter (measured at 0.3 m) of old-natural stumps in the spacing trial site was approximately 140 ± 65 cm with three western redcedar stumps having diameters of 230 cm, 290 cm, and 272 cm.

Live Trees

Differences in the number of large tree stems/ha and mean DBH of large trees were seen between spacing trial plots and reference conditions. Spacing trial plots lacked very-large stems and large broken stems. Spacing trial 2 and 4 were the only plots to meet reference condition values (Fig. 18, Fig. 19, Table 11).

Table 11. Means ± SE of large trees, snags, and CWD for 140-yr-natural and 500-yr-natural stands (i.e., reference conditions) , MKRF May - October 2016.

Attribute Trees	**Large stems/ha**	**DBH large stems**	**Very-large stems/ha**	**DBH very-large stems**	**Large broken stems/ha**	**Large broken stems/ha**
140-yr-nat	155 ± 6	78 ± 2	30 ± 3	125 ± 4	0	0
500-yr-nat	85 ± 4	81 ± 3	37 ± 8	145 ± 7	40 ± 12	161 ± 13
Attribute Snags	**Large stems/ha**	**DBH large stems**	**Height large stems**	**Very-large stems/ha**	**DBH very-large stems**	**Height very-large stems**
140-yr-nat	28 ± 1	68 ± 6	14 ± 7	8 ± 1	141 ± 11	7 ± 4
500-yr-nat	13 ± 2	60 ± 20	12 ± 9	8 ± 1	131 ± 7	9 ± 3
Attribute CWD	**Large CWD pieces /ha**	**Diameter large CWD**				
140-yr-nat	15 ± 9	40 ± 4				
500-yr-nat	9 ± 3	58 ± 13				

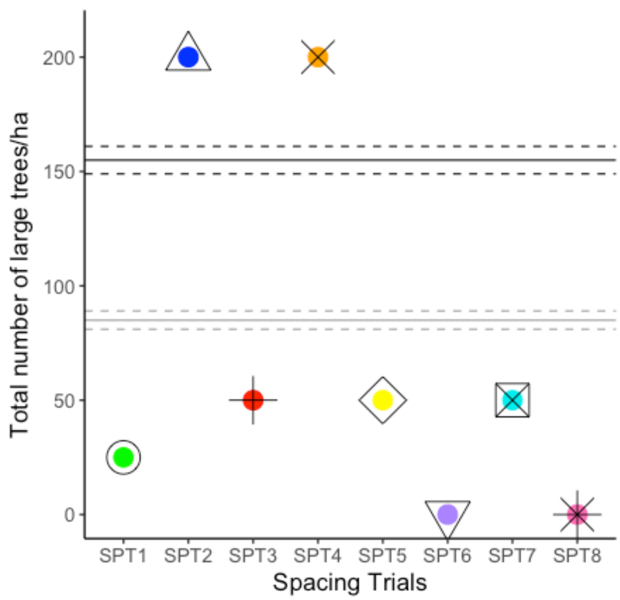

Fig. 18. Total number of large stems/ha for each spacing trial plot. Spacing trial plots are represented as spacing trial 1 (SPT1, green circle), 2 (SPT2, blue triangle), 3 (SPT3, red T), 4 (SPT4, orange X), 5 (SPT5, yellow diamond), 6 (SPT6, purple inverted-triangle), 7 (SPT7, blue box), and 8 (SPT8, pink star). Mean number of large trees in reference conditions are depicted by a solid line and standard error by a dashed line. Black lines represent 140-yr-natural stand conditions and light grey represent 500-yr-natural stand conditions, MKRF May – October 2016.

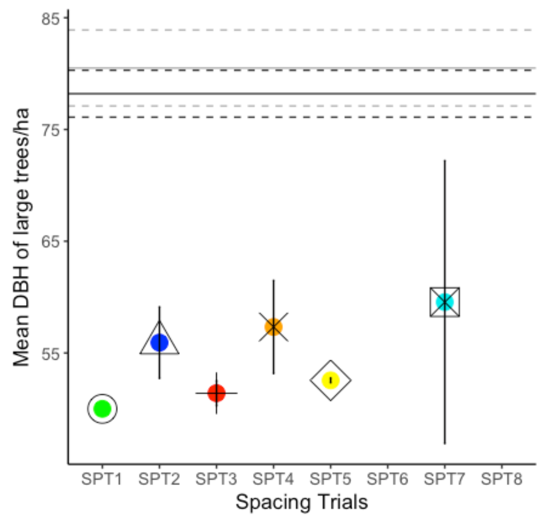

Fig. 19- Mean ± SD DBH of large stems/ha for each spacing trial plot. Spacing trial plots are represented as spacing trial 1 (SPT1, green circle), 2 (SPT2, blue triangle), 3 (SPT3, red T), 4 (SPT4, orange X), 5 (SPT5, yellow diamond), 6 (SPT6, purple inverted-triangle), 7 (SPT7, blue box), and 8 (SPT8, pink star). Mean DBH of large trees in reference conditions are depicted by a solid line and standard error by a dashed line. Black lines represent 140-yr-natural stand conditions and light grey represent 500-yr-natural stand conditions, MKRF May – October 2016.

Snags

Spacing trial plots had no snags large or very-large snags.

CWD

Differences in the number of large CWD pieces/ha and mean diameter of large CWD were seen between spacing trial plots and reference conditions. Spacing trial 5 and 6 were the only plots with large pieces of CWD, however the number of pieces and mean DBH was still below reference condition values (Fig. 20, Fig. 21, Table 11).

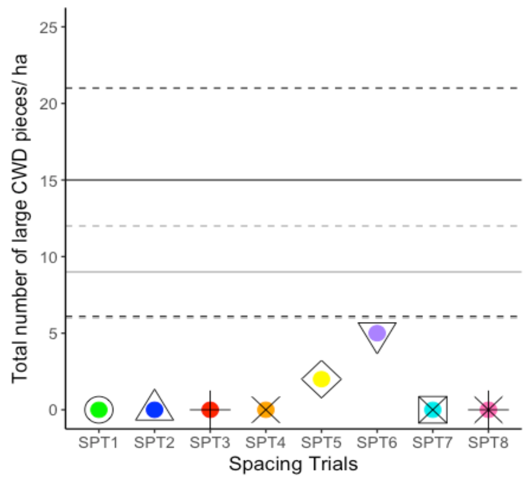

Fig. 20. Total number of large CWD pieces/ha for each spacing trial plot. Spacing trial plots are represented as spacing trial 1 (SPT1, green circle), 2 (SPT2, blue triangle), 3 (SPT3, red T), 4 (SPT4, orange X), 5 (SPT5, yellow diamond), 6 (SPT6, purple inverted-triangle), 7 (SPT7, blue box), and 8 (SPT8, pink star). Mean number of large CWD in reference conditions are depicted by a solid line and standard error by a dashed line. Black lines represent 140-yr-natural stand conditions and light grey represent 500-yr-natural stand conditions, MKRF May – October 2016.

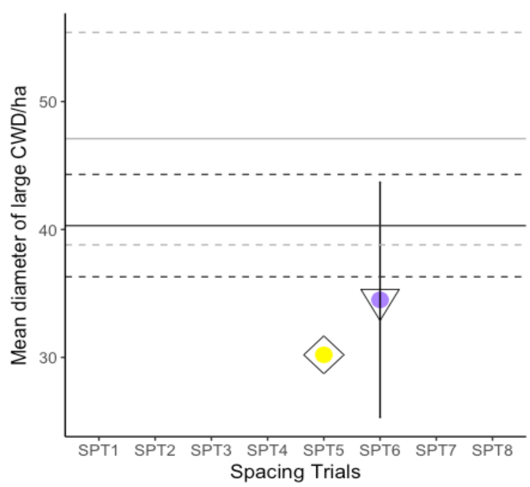

Fig. 21. Mean ± SD diameter of large CWD pieces/ha for each spacing trial plot. Spacing trial plots are represented as spacing trial 1 (SPT1, green circle), 2 (SPT2, blue triangle), 3 (SPT3, red t), 4 (SPT4, orange x), 5 (SPT5, yellow diamond), 6 (SPT6, purple inverted-triangle), 7 (SPT7, blue box), and 8 (SPT8, pink star). Mean diameter of large CWD in reference conditions are depicted by a solid line and standard error by a dashed line. Black lines represent 140-yr-natural stand conditions and light grey represent 500-yr-natural stand conditions, MKRF May – October 2016.

Live Trees Species

Each spacing trial was planted as a monoculture of Douglas-fir or western hemlock; however, natural regeneration of tree-species has occurred (Table 12, Table 13). Mean DBH are reported for species as a baseline to inform restoration prescriptions (Table 13).

Table 12. Total number and percentage of trees with DBH greater than 7.5 cm in each spacing trial plot (0.04 ha) and species codes indicate species composition. Mean reference conditions for 140-yr-natural and 500-yr-natural plots (0.04 ha) are included at the bottom for stems with DBH > 7.5 cm and DBH > 50 cm (140* and 500*). Species codes are Douglas-fir (Fd), western hemlock (Hw), western redcedar (Cw), and deciduous species (Xd), MKRF May – October 2016.

Spacing Trial	Total	Fd (%)	Hw (%)	Cw (%)	Xd (%)
1	29	97	0	0	3
2	19	100	0	0	0
3	22	100	0	0	0
4	15	93	7	0	0
5	24	100	0	0	0
6	11	0	82	9	9
7	21	0	58	17	25
8	25	0	12	0	88
140	14	27	38	15	20
140*	6	54	28	18	0
500	8	19	57	24	0
500*	3	38	21	41	0

Snag Species

In general, snag species were related to monoculture plant species (Table 14, Table 15). Mean DBH and height are reported for species as a baseline to inform restoration prescriptions (Table 15).

CWD Species

In general, CWD species were related to monoculture planting species (Table 15). Mean diameter of CWD are reported for species as a baseline to inform restoration prescriptions (Table 13).

Table 13. Mean ± SD DBH of trees with DBH greater than 7.5 cm in each spacing trial plot (0.04 ha) for each overstory species. Mean reference conditions (SE) for 140-yr-natural and 500-yr-natural plots (0.04 ha) are included at the bottom for stems with DBH > 7.5 cm and DBH > 50 cm. Species codes are Douglas-fir (Fd), western hemlock (Hw), western redcedar (Cw), and deciduous species (Xd), MKRF May – October 2016.

	Mean ± SD or (SE) DBH (cm)			
Spacing Trial	**Fd**	**Hw**	**Cw**	**Xd**
1	38 ± 8	0	0	42.4
2	48 ± 9	0	0	0
3	37 ± 9	0	0	0
4	52 ± 8	9	0	0
5	36 ± 8	0	0	0
6	34 ± 7	0	28	15
7	0	39 ± 19	21 ± 1	30 ± 5
8	0	26 ± 3	0	27 ± 7
140	83 (4)	46 (7)	103 (12)	9 (0.3)
140*	89 (4)	72 (4)	122 (7)	0
500	134 (10)	31 (4)	94 (10)	0
500*	139 (9)	74 (3)	108 (9)	0

Table 14. Total number and percentage of snags with DBH greater than 7.5 cm in each spacing trial plot and species codes indicate species composition. Mean reference conditions for 140-yr-natural and 500-yr-natural plots (0.04 ha) are included at the bottom for stems with DBH > 7.5 cm and DBH > 50 cm (140* and 500*). Species codes are Douglas-fir (Fd), western hemlock (Hw), western redcedar (Cw), and deciduous species (Xd), MKRF May - October 2016.

Spacing Trial	**Total**	**Fd (%)**	**Hw (%)**	**Cw (%)**	**Xd (%)**
1	9	100	0	0	0
2	1	100	0	0	0
3	18	100	0	0	0
4	1	100	0	0	0
5	21	95	5	0	0
6	6	0	100	0	0
7	10	0	90	10	0
8	1	0	100	0	0
140	3	29	33	38	0
140*	1	41	35	24	
500	4	5	36	59	0
500*	1	38	0	62	0

Table 15. Mean ± SD DBH (cm) and height of snags (m) for each overstory species with stems with DBH greater than 7.5 cm in each spacing trial plot (0.04 ha). Mean reference conditions (SE) for 140-yr-natural and 500-yr-natural plots (0.04 ha) are included at the bottom for stems with DBH > 7.5 cm and DBH > 50 cm (140* and 500*). Species codes are Douglas-fir (Fd), western hemlock (Hw), and western redcedar (Cw), MKRF May - October 2016.

	Mean ± SD or (SE) DBH (cm)			**Mean ± SD or (SE) height (m)**		
Spacing Trial	**Fd**	**Hw**	**Cw**	**Fd**	**Hw**	**Cw**
1	21 ± 9	0	0	7 ± 7	0	0
2	34	0	0	15	0	0
3	23 ± 7	0	0	12 ± 12	0	0
4	23	0	0	6	0	0
5	20 ± 10	15	0	7 ± 7	6.1	0
6	0	32 ± 10	0	0	14 ± 10	0
7	0	24 ± 4	13	0	15 ± 12	3
8	0	20	0	0	4	0
140	69 (21)	37 (10)	101 (21)	7 (5)	12 (5)	7 (4)
140*	123 (35)	67 (7)	119 (15)	4 (2)	8 (10)	23 (13)
500	117 (21)	20 (3)	69 (17)	4 (1)	7 (2)	5 (13)
500*	117 (21)	0	108 (12)	5 (1)	0	16 (15)

Restoration Prescriptions

The current conditions of the spacing trials are a result of historic site preparation, stand density, species composition, abiotic conditions, and biotic conditions (Johnson 1996, Franklin et al. 2002, Chen et al. 2009; Ilisson and Chen 2009). Because the spacing trial was established within a small area (~2 ha), the entire site is influenced by similar soil conditions (i.e., moisture and nutrients) and historical and on-going disturbances. However, each stand differs in spacing density; therefore, each spacing trial will develop along a unique trajectory dependent on that stand’s tree density. Spacing density largely influences the development of structural diversity and old-natural attributes primarily the development of large trees, large crowns, CWD, snags, and vertical complexity (Martin and Powelson 2001). Stands that have uniform and dense spacing have increased inter-tree competition and impede the development of large diameter trees, large crowns with large diameter branches, the production of large CWD, the production of large snags, and decrease sunlight to the forest floor, therefore, halting natural regeneration and the creation of a multilayered canopy stand (Martin and Powelson 2001).

Table 16. Total number and percentage of CWD with diameter greater than 7.5 cm in each spacing trial plot and species codes indicate species composition. Mean reference conditions for 140-yr-natural and 500-yr-natural plots (0.04 ha) are included at the bottom for stems with DBH > 7.5 cm and DBH > 50 cm (140* and 500*). Species codes are Douglas-fir (Fd), western hemlock (Hw), western redcedar (Cw), unknown conifer (Xc), and deciduous species (Xd), MKRF May - October 2016.

Spacing Trial	**Total**	**Fd (%)**	**Hw (%)**	**Cw (%)**	**Xc (%)**	**Xd (%)**
1	23	70	0	0	13	17
2	9	100	0	0	0	0
3	25	100	0	0	0	0
4	8	100	0	0	0	0
5	26	97	3	0	0	0
6	15	0	93	7	0	0
7	16	100	0	0	0	0
8	7	0	86	0	0	14
140	27	63	26	11	0	0
140*	1	30	30	40	0	0
500	46	43	43	14	0	0
500*	1	30	20	50	0	0

I observed that spacing trial stands with wider spacing density (i.e., trials 2 and 4) were the only stands that contained attributes characteristic of old-natural stands (i.e., large tree stems and mean DBH of large trees) and were less susceptible to disturbance (Table 18). In addition, the spacing trial stands with large trees have the potential to develop other old-natural characteristics, such as very-large trees, large snags and large CWD. In contrast, the denser-spaced stands (i.e., trials 1, 3, 5, 6, 7, and 8 (Table 18) showed more susceptibility to disturbance (i.e., wind or presence of deciduous trees) and did not meet 140-yr-natural or 500-yr-natural reference conditions. Therefore, restoration of old-natural attributes should be focused in the dense spacing trials, such as 1, 3, 5, and 8 and will be implemented using various silviculture prescriptions (Table 19).

Table 17. Mean ± SD DBH of CWD with DBH greater than 7.5 cm in each spacing trial plot. Mean reference conditions (SE) for 140-yr-natural and 500-yr-natural plots (0.04 ha) are included at the bottom for stems with DBH > 7.5 cm and DBH > 50 cm (140* and 500*). Species codes are Douglas-fir (Fd), western hemlock (Hw), western redcedar (Cw), unknown conifer (Xc), and deciduous species (Xd), MKRF May - October 2016.

	Mean ± SD or (SE) DBH (cm)				
Spacing Trial	**Fd**	**Hw**	**Cw**	**Xc**	**Xd**
1	14 ± 9	0	0	9 ± 1	12 ± 2
2	16 ± 7	0	0	0	0
3	12 ± 3	0	0	0	0
4	11 ± 4	0	0	0	0
5	18 ± 8	10.9	0	0	0
6	0	19 ± 9	9	0	0
7	0	14 ± 7	0	0	0
8	0	12 ± 3	0	0	8
140	26 (4)	29 (6)	19 (6)	0	0
140*	49 (8)	40 (4)	26	0	0
500	41 (8)	25 (4)	35 (9)	0	0
500*	73 (3)	33	56 (22)	0	0

Restoring old-natural attributes in dense managed stands involves the concept of restoring the range of natural variability (Drever and Wong 2002). The range of natural variability is the spectrum of natural conditions that reflects forest structure, composition, and function at both temporal and spatial scales (Swanson et al. 1994). Restoring the range of structural attributes increases the stand's ecological resilience through the enhancement of ecosystem integrity and biodiversity (Holling 1973, Folke et al. 1996). Therefore, the range of stand structural attributes reported in this study can guide forest management. Additionally, the spatial arrangement of stand's structural attributes should be restored with spatial variation, having areas within a stand that have structural attributes aggregated and widely distributed. Recent LiDAR of the MKRF could help inform the spatial arrangement of the old-natural structural attributes.

Table 18. Spacing trial summary of each stand, indicating the percent cover of dominant overstory and understory species, overstory spacing density, disturbance, and structural attributes within 140-yr-natural and/or 500-yr-natral reference ranges. Dominant understory species report percent coverage and include the following species: salmonberry (*Rubus spectabilis*), western swordfern (*Polystichum munitum*), and red huckleberry (*Vaccinium parvifolium*), MKRF May - October 2016.

Spacing Trial	Dominant overstory species	Spacing (m)	Recent Disturbance	Dominate understory species (% coverage)	Within 140-yr-natural reference range	Within 500-yr-natural reference range
1	Fd	0.9 x 0.9	Individual tree blow-down	salmonberry (70)	None	None
2	Fd	3.7 x 3.7	None	Salmonberry (35) & western swordfern (36)	Large tree stems/ha and DBH	Large tree stems/ha and DBH
3	Fd	0.2 x 0.2	Individual tree blow-down	swordfern (45) & salmonberry (25)	None	None
4	Fd	4.6 x 4.6	None	western swordfern (35)	Large tree stems/ha and DBH	Large tree stems/ha and DBH
5	Fd	0.2 x 0.9 x 2.7	None	western swordfern (65) & salmonberry (20)	None	None
6	Hw	3.7 x 3.7	None	western swordfern (30) & salmonberry (17)	None	None
7	Hw	4.6 x 4.6	Deciduous trees in overstory	western swordfern (35) & red huckleberry (10)	None	None
8	Hw	0.2 x 0.9 x 2.7	Deciduous trees in overstory	western swordfern (30) & salmonberry (25)	None	None

Restoring large trees, snags, and CWD in the spacing trial should be carried out in two phases (Table 20), using the reference values as targets (TABLE 21**). The initial phase is necessary in creating the environmental conditions for large tree growth (i.e., spacing) and ensuring diversity in species composition. The second phase should be carried out in the future when tree growth (i.e., DBH) and species composition is approximately equivalent to 140-yr-natural or 500-yr-natural conditions. Once some trees are large enough, a portion of the large trees could be manipulated for the addition of broken tops, snags, and CWD.

Table 19. Restoration prescriptions to accelerate the development of old-natural structural attributes (expanded from Keeton 2006, Bauhus et al. 2009).

Desired Attribute in Managed Stands	Restoration Prescriptions	Potential Outcomes
Live large trees DBH > 50 cm	• Long Rotations • Crown thinning to increase growth • Selective logging to decrease density and decrease competition • Fertilization to increase tree volume	• Future source of large snags • Future source of large CWD • Vertical canopy stratification from thinning • Horizontal stratification form selective logging • Regeneration from canopy openings
Large snags DBH > 50 cm	• Allow self-thinning • Tree girdling or poisoning • Fungus inoculation • Burning • Permanent retention of large trees (future snag source)	• Vertical stratification • Future source of large CWD
Large and well-decayed CWD diameter > 25 cm	• Tree felling • Permanent retention of large trees • Combining smaller pieces of CWD • Fungus inoculation	• Horizontal and vertical stratification from tree felling • Increased understory diversity because certain species rely on CWD) (e.g., Bryophytes)
Overstory diversity	• Plant under- represented species (e.g., western redcedar) • Selective logging • Natural regeneration	• Horizontal and vertical stratification (e.g., un-even tree ages and species composition)

Discussion

This study uses comparative analysis to inform restoration of old-natural attributes in managed stands and to help determine stands of restoration priority. Specifically, this study provides two reference conditions, summarizing mean values and quantifying levels of variation to inform restoration of characteristics that are reflective of forests in later stages of development. Reference conditions that reflect the natural variation of structural attributes can also be used as one metric-of-success for determining if restoration was successful.

Table 20. Two phase restoration example for restoring old-natural attributes in managed stands. Refer to Table 21 for target conditions.

Phase 1- Prepare stand conditions
1. Widen tree spacing with selective logging. Some logs can be harvested and others can be left as CWD. 2. Plant desired species mix, specifically western redcedar.
Phase 2- Tree size (DBH) of old-natural requirements are met
1. Large trees should be targeted one of four ways: A. leave large trees untouched to develop into very-large trees, B. create broken tops on large-live trees, C. creates snags, and D. fall trees to create CWD.

Restoration of old-natural attributes in managed stands should not be aimed at mimicking single stand conditions based on a given reference value because each stand has developed along a unique successional pathway and varies in structure. This study provides the range of structural variation for two stand-types (i.e., mid-aged and old) in the MKRF, which creates a trajectory of reference targets that helps guide restoration practitioners and forest managers in creating stands that are structurally diverse. While this study has exclusively quantified the structural attributes within the MKRF, the variation in mid-aged and old-natural reference conditions can be extrapolated in guiding restoration of managed CWHdm 05/07 stands in this region. Additionally, the contrast between structural attributes among forest ages provides insight on whether some attributes have already recovered or are near recovery to 500-yr-natural stands. Acknowledging which attributes take the longest to recover informs restoration practitioners and forest managers on which attributes should be prioritized during restoration and retained during logging. In this study, I observed the greatest similarity among snag attributes and greatest differences among live tree attributes. Specifically, snags were similar in number, DBH, and height, whereas live trees greatly differed in number, DBH, and broken tops. Therefore, the similarity of the number and size of snags between 140-yr-natural and 500-yr-natural provides rationale for longer-stand rotations of approximately 140-to-150 yrs if one intends to increase some stand structural heterogeneity (Bauhus et al. 2009, Gerzon et al. 2011). Extending stand rotation is not necessary for all stands because trade-offs exist with longer rotations (e.g., increased susceptibility to pests; Knoke 2003); however, extending the rotation time of select stands will increase the structural diversity in the landscape. In addition, longer-rotation periods would be considered passive restoration, which is less costly and time-consuming compared to active restoration.

Table 21. Restoration targets using 140-yr-natural and 500-yr-natural stands as reference conditions.

Stand type	**Large tree density (stems/ha)**			**Very-large tree density (stems/ha)**			**Large-broken tree density (stems/ha)**		
	Fd	Hw	Cw	Fd	Hw	Cw	Fd	Hw	Cw
140-yr-nat	125	65 ± 35	43 ± 8	12 ± 2	0	18 ± 10	0	0	0
500-yr-nat	95	28 ± 3	53 ± 3	27 ± 3	0	12 ± 9	12 ± 4	-	5 ± 2
	Mean ± SE DBH of large trees (cm)			**Mean ± SE DBH of very-large trees (cm)**			**Mean ± SE DBH of large-broken trees (cm)**		
	Fd	Hw	Cw	Fd	Hw	Cw	Fd	Hw	Cw
140-yr-nat	88 ± 4	72 ± 4	122 ± 7	118 ± 6	-	129 ± 5	-	-	-
500-yr-nat	119 ± 8	74 ± 3	109 ± 9	129 ± 9	-	138 ± 9	171 ± 11	-	92.7
	Large snag density (stems/ha)			**Very-large snag density (stems/ha)**			**Mean ± SE DBH of large snags (cm)**		
	Fd	Hw	Cw	Fd	Hw	Cw	Fd	Hw	Cw
140-yr-nat	12 ± 9	0	8 ± 6	3 ± 2	0	5 ± 3	123 ± 35	67 ± 7	119 ± 15
500-yr-nat	5 ± 3	0	8 ± 6	3 ± 2	-	5 ± 3	117 ± 21	-	108 ± 12
	Mean ± SE height of large snags (cm)			**Mean ± SE DBH of very-large snags (cm)**			**Mean ± SE height of very-large snags (cm)**		
	Fd	Hw	Cw	Fd	Hw	Cw	Fd	Hw	Cw
140-yr-nat	4 ± 2	23 ±13	8 ± 10	157 ± 17	-	131 ± 12	10 ± 212	-	2 ± 0
500-yr-nat	5 ± 1	-	16 ± 15	138 ± 6	-	126 ± 10	12 ± 9	-	5 ± 1
	Large CWD density (pieces/ha)			**Mean ± SE diameter of large CWD (cm)**					
	Fd	Hw	Cw	Fd	Hw	Cw			
140-yr-nat	5 ± 10	7 ± 10	5 ± 10	49 ± 8	26	40 ± 4			
500-yr-nat	3 ± 4	1 ± 4	5 ± 10	73 ± 3	33	56 ± 22			

Both active and passive forest restoration compliments the idea of managing stands using the Triad Approach (Seymour and Hunter 1992) to ensure that forested landscapes offer various values. While it is valuable to have stands that are left protected and unmanaged, unmanaged stands often are limited. Therefore, it is valuable that natural stand features are abundant throughout the entirety of the landscape to protect biodiversity, increase ecosystem connectivity, and support the ecologically resilience. The management of stands for the production of timber will typically be the focus of forestry, however, the incorporation of extensively managed stands that blend economic, social, and ecological values should be part of the focus. Extensively managed stands could include silviculture prescriptions such as extended-rotation periods (e.g., 140-yr-natural stands) and stand management that reflects old-natural attributes for ecological values while subjected to individual-tree logging for economic values. This study creates a specific guideline and metric-of-success to inform forest managers on what an extensively managed stand could look like (i.e., mean values with variation) and provide insight on what treatments could be prescribed to maintain or develop large trees, large snags, and large CWD which are ecologically, biologically, chemically, and culturally significant.

Metrics-of-success help determine if restoration treatments were successful or if adjustments to the restoration plan need to be made. Forest managers and restoration practitioners benefit from quantified values such as the ones provided in this study because during long-term monitoring programs it is easier to understand and assess if the prescribed treatment(s) accelerated the desired attribute. While this study provides insight if the restoration of structural attributes was successful, additional metrics-of-success should be considered when creating a restoration plan. Restoration metrics-of-success should encompass the diversity of values society places on forests, such as cultural values (e.g., presence of culturally significant cedar trees), wildlife values (e.g., increased niches for spotted owl), regulating values (e.g., carbon storage), and provisioning values (e.g., food and water). I suggest prior to implementing restoration prescriptions, additional research should quantify and create additional metrics-of-success to understand the trade-off in values that occur when restoring old-natural characteristics in managed stands. Research conducted by Sutherland et al. (2016) provide insight on how these metrics could be quantified using structural attributes as surrogates for various ecosystem services.

Lastly, ecological restoration will always benefit from experiments that include strong scientific and rigours designs with long-term monitoring programs (Rohr et al. 2016). This study provides an opportunity for forest-restoration experimentation using the three 60-yr-managed stands examined in Chapter 2. An experiment could be created because three 60-yr-managed stands exhibited similar site characteristics and management histories; therefore, researchers could examine the effects of different restoration techniques on these stands with controls, replicates, and long-term monitoring.

In summary, maintaining or enhancing ecological resilience within a landscape requires more than restoring stand level attributes. Ecological resilience requires landscape-level management that considers the arrangement of stand types within a landscape while acknowledging the trade-offs between different management practices (Martin and Powelson 2001).

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