MANAGING OLD-GROWTH FORESTS FOR MULTIPLE ECOSYSTEM SERVICES

by

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TABLE OF CONTENTS

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Abstract

Old-growth forest reserves offer the potential to facilitate the maintenance of multiple ecosystem services (ES), such as carbon storage, water and recreation, in managed landscapes. However, substantial challenges exist with regard to defining and identifying old-growth forests, and suitably locating priority areas for old-growth conservation. To address these issues, I developed a structure-based old-growth index using field and LiDAR metrics that allowed old-growth values to be estimated at a fine grain across a landscape. I then used a spatial prioritization tool to simulate old-growth reserves for multiple ESs. Using this framework I evaluated trade-offs between forest ESs including timber. This thesis contributes to the management of old-growth forests by providing a quantitative and repeatable framework to identify, assess and monitor old-growth values while indicating the scope for the establishment of old-growth reserves for multiple ESs.

List of Figures:

List of Tables:

List of Acronyms:

ABA - Area-Base Approach
ALS - Airborne Laser Scanning
BEC - Biogeoclimatic
CCF - Chinook Community Forest
CMI - Change Monitoring Inventory
CWD - Coarse Woody Debris
dGPS - differential Global Positioning System
DSM - Digital Surface Model

DTM - Digital Terrain Model
ES - Ecosystem Service
GIS - Geographic Information System
InVEST - Integrated Valuation of Ecosystem Services and Tradeoffs
LiDAR - Light Detection and Ranging
LULC - Land Use/ Land Cover
MFLNRORD - Ministry of Forests, Lands, Natural Resource Operations & Rural Development
OGMA - Old-Growth Management Area
TIN - Triangulated Irregular Networks

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Dedication:

Dedicated to my mom, Lucia Helena de Paiva Barros (1960-2017), a strong and gentle soul who with love and patience taught me to believe in hard work and to appreciate the small things in life as not much is needed for one to be happy.

1. GENERAL REVIEW ON OLD-GROWTH FORESTS AND THEIR PROVISION OF ECOSYSTEM SERVICES

1.1. Introduction:

"Old-growth" is a term associated with forests in the advanced development stage, with specific structures, natural processes, and no significant anthropogenic interference (Mosseler et al. 2003c, Spies 2004, Hilbert and Wiensczyk 2007). When a forest is allowed to reach the latest stages of development, it attains attributes critical for the maintenance of biodiversity in the landscape (DellaSala et al. 1996, Spies 2004). Forests with these characteristics are valuable and rare resources declining rapidly worldwide (Watson et al. 2016, 2018). Furthermore, the location and abundance of old-growth attributes enable the provision of a range of ecosystem services (ES) that includes carbon storage and sequestration (Luyssaert et al. 2008, Maxwell et al. 2019), water provision (Bithell and Brasington 2009), indigenous cultural values, and the maintenance of human health (Wirth 2009, Watson et al. 2018). Therefore, the value of retaining old-growth forests in the landscape goes beyond old-growth conservation per se. It may offer the opportunity to simultaneously maintain landscape biodiversity and ESs essential for people's wellbeing.

Old-growth forests have been historically valued as wildlife habitat (Mosseler et al. 2003c). Strategies to promote the retention of old-growth forests in the landscape do exist, such as the Old-growth Management areas (OGMAs) in British Columbia, Canada (Arsenault 2003, Gillis et al. 2003, Environmental Law Centre 2013). Notwithstanding, the selection of such areas is a difficult task due to the lack of a standard definition for what constitutes an old-growth forest (Hilbert and Wiensczyk 2007). Old-growth forest types vary in terms of stand age, disturbance frequency, anthropogenic interference, and abundance of specific forest structures such as the abundance of large and old tree and coarse woody debris (Mosseler et al. 2003c, Spies 2004, Bauhus et al. 2009). Moreover, the management of landscapes often involves conflicting objectives such as timber to one group of people and recreation to another (Ninan and Inoue 2014). Also, the relationships between ESs are complex, and our knowledge of their response to management strategies is limited (Kremen and Ostfeld 2005). As human populations continue to grow, demand for ecosystem services is also increasing (MA 2005, United Nations 2018), and so are the conflicts between multiple objectives.

The identification of strategies for the retention of old-growth values and multiple ecosystem services, while leaving opportunities for timber harvesting, is a complex spatial optimization problem (Schröter and Remme 2016, Snäll et al. 2016). Two steps are required to address this problem. First, it is necessary to define and locate old-growth forests and ESs in the landscape. Second, we need to apply a thoughtful strategy to allow old-growth conservation while leaving opportunities for timber harvesting in the landscape. A systematic conservation-planning tool can be used to identify management strategies that can cope with multiple objectives landscapes. In the following sections, I outline the background and motivation for this thesis.

A general review divided into six sections provides information to understand the problem and identify a framework for its solution. The first section, “Old-growth” highlights the diversity of old-growth forest types and the multiple definitions available. A general review of the ESs literature is provided in section two, “Ecosystem Services.” Section three, “Forest state and ecosystem services,” touches on the relationship between forest succession and the provision of multiple ESs. Section four, “Airborne Laser Scanning (ALS),” summarizes some of the literature on the use of Light Detection and Ranging (LiDAR) to evaluate forest attributes and succession, as well as its potential for ESs estimation. The fifth section, “ Systematic Conservation Planning,” introduces the systematic conservation planning theory and spatial prioritization tools developed to solve conservation problems. Finally, the sixth section, “Thesis Objective,” outlines the research gaps identified in the previous section and the objectives and structure of this thesis.

1.2. Old-growth

In previous years, the public concerns about the decline of older forests have pushed policymakers to place great importance in the old-growth forest conservation (Mosseler et al. 2003c). However, the public concept of old-growth is usually of tall and large trees, whereas old-growth forests are much more complex (Wirth et al. 2009b). Spies (2004) defines an old-growth forest as mature or senescent forest, associated with specific structures (ex. snags, coarse woody debris) and processes (ex. gap dynamic, natural regeneration). These forests differ in character and degree depending on the forest region, and are not necessarily primary forests (Spies 2004). Old-growth types vary in terms of longevity of dominant species, return period of natural disturbances, human intervention, shade tolerance, and presence of specific structures such as coarse woody debris. Therefore, multiple regional specific definitions of old-growth are more desirable than one standard definition of old-growth, given the diversity of forests (Spies 2004).

Forest composition, stand age, diameter, snags and vertical diversity are attributes commonly evaluated by managers to define old-growth (McElhinny et al. 2006a, Bauhus et al. 2009), but which levels of those attributes are considered old-growth? Age is commonly used to define old-growth, a useful proxy in an even-aged forest, but less valuable in multiage forests (Spies 2004). For example, according to (MFLNRORD 2003), BC's coastal forests are considered old growth if trees are more than 250 years old. In the province's interior, where the longevity of trees are shorter and disturbances more frequent than in the coastal forests, old growth is defined as more than 120 years of age for forests dominated by lodgepole pine or broadleaf species. As well, other forests such as Englemann spruce, white spruce and Interior Douglas-fir reach old-growth status with 140 years.

Structural complexity is also another characteristic utilized to define the old-growth forest. Compared with old forests, young natural forests or intensively managed forest plantations have less complex structures. Old-growth attributes are dynamic, which means that one stand classified as old-growth may not display old-growth attributes after disturbances (Spies 2004). On the other hand, young stands can develop old-growth attributes over time (Mosseler et al. 2003c). The authors recognize that for regions where fire-rotation and other disturbances occur over exceptionally long periods, it is easier to designate an old-growth stand, whereas areas more affected by disturbances are less clearly defined. Based on the results of past efforts, it is clear that there are challenges to providing a universal definition of old-growth forests.

Policymakers and managers need specific definitions of old-growth to better track and map old-growth forests within their management areas, and to avoid conflicts with other types of management. Multiple local definitions have been developed (Table 1.1), where the most common are definitions based on the abundance of some forest structures (Wirth et al. 2009b, Bauhus et al. 2009). Spies (2004) points out the importance of defining and mapping old-growth forest for each forest type using measurable structural features and biophysical site conditions, considering the continuous nature of forest structure development. The combination of the structural attributes, species composition, and ESs to provide an index for a particular forest type of ecological region could clarify the old-growth identification, and consequently, conservation (Mosseler et al. 2003c). To determine which variables are most relevant for an old-growth index requires a strong understanding of the ecology of each forest type. For example, the index could also consider animal associations since many of the old-growth structures have a close association with biodiversity and species habitat (Mosseler et al. 2003b, 2003c, Spies 2004, Bauhus et al. 2009).

Different researchers have endorsed the development and use of an index that could track old-growth values in the landscape, rather than only using stand age classes (Mosseler et al. 2003c, Spies 2004, Hilbert and Wiensczyk 2007). Compared with old forests, young natural forests or intensively managed forest plantations have a simpler structure (Spies 2004, McElhinny et al. 2006a). Thus, the abundance of old-growth attributes (e.g. large trees, snags, and accumulated woody debris), which contribute to the structural complexity in old-growth forest, may be used as a proxy for old-growth forest mapping. Much work has been conducted using traditional field-based measurement of forest attributes to classify forest succession and assess the quality of old-growth forests (McElhinny et al. 2005, 2006, Bauhus et al. 2009) (See more in Table 1.1). Even though field-based methods are essential for most forest studies, they are less applicable for landscape-scale evaluation.

Broad scale definitions of forest succession using remote sensed imagery have also been developed (Table 1.1). For example, Hansen et al. (2019) utilized forest structural complexity as a proxy for forest quality and capacity to support biodiversity and provide ESs. The study was undertaken for tropical forests in a broader scale utilizing optical sensors, and validated with airborne LiDAR. Other similar studies are listed in Table 1.1. However, none of these studies have focused on identifying old-growth per se. Moreover, while it is interesting to have a broad scale definition and mapping of old-growth, it might not be desirable in a ecological perspective. As discussed by many authors (Mosseler et al. 2003c, Hilbert and Wiensczyk 2007, Wirth et al. 2009b, Bauhus et al. 2009), old-growth conditions are particular to local environment conditions. The conditions for a forest to became old-growth include, in addition to time, the presence of multiple forest attributes that may not be capture by optical sensors (Lefsky et al. 2002). In addition, such broad definitions can underestimate the value of old-growth forests types in landscapes more prone to natural disturbances where old-growth attributes are less prominent than in coastal temperate and tropical forests (Spies et al. 2006). Thus, multiple definitions of old-growth based on local conditions might be more desirable, and LiDAR offers the potential to accurately measure these conditions and aid in the mapping of old-growth values in the landscape.

Table 1.1 Method utilized to identify and map old-growth forests.

Method	Description	Reference
Field metrics	Classification of forest succession in a stand level based on age thresholds defined for each Biogeoclimatic (BEC) zone and fire return interval, utilizing outdated forest cover maps.	(MFLNRORD 1995)
	Use a series of forest attributes associated with old-growth forest to create an old-growth index succession and evaluate old-growth forest reserves in different BEC zones.	(Braumandl and Holt 2000, Holt 2000, Holt et al. 2001, 2002, DeLong et al. 2004)
	Reviewed and listed a series of forest attributes strongly associated with old-growth forest to identify silvicultural approaches that could promote old-growth forests.	(Bauhus et al. 2009)
	Evaluated different plot sizes to determine the minimum plot that still captures old-growth indicators (e.g. number of living trees, trees with DBH >50cm, dead wood volume, etc).	(Lombardi et al. 2015)
	Review of old-growth static and dynamic attributes and use of cohort basal area ratio (understory cohort/post-disturbance cohort) as a proxy for old-growth forests in boreal forest, simultaneously addressing the dynamic nature of forest.	(Kneeshaw and Burton 1998, Kneeshaw and Gauthier 2003)
	Mapping of individual stems and their respective features (e.g. height, crown area) in temperate old-growth forests to study forest structure and dynamics.	(Chen and Bradshaw 1999, Hao et al. 2007)
	Developed a stand-scale index of structural complexity combining a core set of forest structural attributes.	(McElhinny et al. 2006a)
Optical Sensors	Forest succession model (ZELIG) and a canopy reflectance model (GORT) were applied to compare with forest succession from Landsat TM and test the potential of remote sensing on mapping successional stages.	(Song et al. 2007)

	Landsat ETM+ combined with ecological land unit classifications.	(Bergen and Dronova 2007)
	Landsat TM image resampled to 25m cell size and 106 ground reference stands of tree density, basal area.	(Cohen et al. 1995)
	Mapping of structural stage classes with Landsat TM data through ISODATA analysist technique.	(Miller et al. 2003)
	Spatial manifestation of forest succession in optical imagery (Landsat TM) through three types of model.	(Song and Woodcock 2002)
LiDAR	Use of Lidar delivered metrics (e.g. height percentiles and statistics, % of vegetation returns, % of first returns, and etc.) with Random Forests statistical analysis to identify seven stages of forest succession.	(Falkowski et al. 2009)
	Documented increasing vertical structure complexity along five development stages in western coastal forests with five field, six LiDAR metrics, and their combination.	(Kane et al. 2010b)
	Use of LiDAR-delivered tree height variance to distinguish between single-story (young forests) and multistory vertical structural classes (old forests).	(Zimble et al. 2003)
	Use of two principal components (PCA) of the Integration of airborne LiDAR (canopy height model) and spectral data (12 wavebands of HyMap) to perform an unsupervised classification of forest classes.	(Hill and Thomson 2005)
	Estimated stand age across 158 plots in managed Boreal forest with forest structures and site attributes delivered from LiDAR.	(Racine et al. 2014)

1.3. Ecosystem Services

Costanza et al. (1997) describe ESs as the goods and services derived from ecosystem functions that benefit human well-being directly or indirectly. MA (2005) divided ESs into four main categories: provisioning services (e.g food, water, and raw materials), regulating services (e.g. erosion control, carbon sequestration, water and climate regulation), cultural (e.g. aesthetics values, the spiritual experiences, scientific endeavors, recreation opportunities), habitat services (life cycle of all materials and the genetic reservoirs). Forested ecosystems are responsible for the provision of a large amount of these services (Pearce 2001, Watson et al. 2018). Much discussion has been given to the theory behind ESs (Costanza et al. 1997, Kremen and Ostfeld 2005, Kremen et al. 2007, Isbell et al. 2011, Crossman et al. 2013), and methods to measure and evaluate them (MA 2005, Balvanera et al. 2006, Nelson et al. 2009, Polasky et al. 2011, Kareiva 2011, Schirpke et al. 2016). As human populations continue to grow, demand for ecosystem services is also increasing (MA 2005, United Nations 2018). The increasing demand for ecosystem services may increase biodiversity loss in various ecosystems and the services derived from them if the landscape is managed by one or few services (Coomes et al. 2008, Lindenmayer et al. 2012, Gaston et al. 2013). Despite the gravity of the issue, the management of ecosystem services is rarely incorporated into decision-making.

As discussed in the Millennium Ecosystem Assessment (MA 2005), the focus on timber, agriculture and other provisioning services has driven changes in landscapes, often simplifying their structure and reducing their species diversity (Coomes et al. 2008, Polasky et al. 2011). In general, these working landscapes are typified by high production yields and low per unit production costs, yet provide reduced stocks and flows of other non-target ESs

(MA 2005). Managing for multiple services is an alternative to reduce these tradeoffs and increase synergies between ESs. Also prioritizing regulating services (Bennett et al. 2009) and biodiversity (Polasky et al. 2008) has shown increasing provision of multiple ESs. For example, the Catskill Mountains watershed experienced improvements in the provision of ESs such as flood control, wildlife habitat, and recreation value after being managed to improve water quality (Lubchenco 1998). Wendland et al. (2010) identified areas in Madagascar, which protect biodiversity and offer multiple ES, for projects involving payment for ESs. Many researchers have also modeled conservation plans for multiple ESs (Naidoo and Ricketts 2006, Venter et al. 2009b, 2009a, Nelson et al. 2009, Schirpke et al. 2016). According to the works above, conserving for biodiversity, especially in forested ecosystems, seems well related to the provision of many other ESs in the landscape.

1.4. Forest state and ecosystem services

Forest loss is often associated to a subsequent decline in ESs provision, such as declining climate regulation, carbon storage, water quality and quantity, disease control, recreation opportunities (Pearce 2001). In places, forests are increasing due to forest regeneration in abandoned croplands and afforestation for commercial or environmental purposes, mostly in the northern hemisphere (FAO 2016). However, a degraded forest ecosystem may only partially recover its potential for biodiversity and ESs provision after restoration (Chazdon 2008). Also, primary forests and old-growth forests provide many of these ESs (MA 2005, FAO 2016, Watson et al. 2018), yet are under high pressure from logging, agriculture and urban expansion (Pearce 2001, Mosseler et al. 2003c). Thus, it is crucial to understand the behaviour of ESs in different forest states.

The different levels of forest structures development provide different levels of ESs. Early-successional forest ecosystems, developed post-disturbances, are biodiverse and abundant in biological legacies such as individuals resistant to the disturbance and organic matter resultant from the fallen trees. It can also provide an opportunity for recharging the nutrient pool of soil through the mineralization of organic material (Swanson et al. 2011). Forest regeneration and forest plantations established for commercial and restoration purposes can improve ecosystem services and enhance biodiversity conservation (Chazdon 2008), even not reaching original levels (Hobbs et al. 2006, Chazdon 2008).The restoration of watershed successfully restore water regulation service (Chichilnisky and Heal 1986) and consequently promoted a series of associated ESs (Lubchenco 1998). Despite the value of early forest successions and second growth forest, it is on the primary and old growth forest that the provision of multiple services seems to peak.

Various studies highlighted the importance of old-growth forest for the provision of ESs (e.g. Mosseler et al. 2003, Luyssaert et al. 2008, Wirth 2009, Keenan et al. 2015, Watson et al. 2018). Old-growth forests are not only massive carbon storages but also carbon sinks (Luyssaert et al. 2008), as these forests provide an environment for increasing the accumulation of carbon into the soil (Zhou et al. 2006). If disturbed, the carbon stored both in the biomass above ground and in the soil that risks being released back into the atmosphere is much higher than first expected (Maxwell et al. 2019). Other benefits of these mature and old-growth forests are the high biodiversity of trees and animals (Kremen et al. 2007, Isbell et al. 2011). Old-growth forest populations can serve as gene pool and seed sources for forests to adapt to future environmental conditions, as long as they are large enough to avoid inbreeding and genetic drift (Mosseler et al. 2003b). In addition to adaptive capacity, genetic resources of old-growth forests might also be the source of new medical discoveries

(Costanza et al. 1997, Keenan et al. 2015, FAO 2016). Isbell et al. (2011) demonstrated the importance of high plant diversity to ESs provision, where the extinction of species may mean the reduction of ESs. For example, many pollinators and pest controllers, crucial for agriculture and other services, inhabit these forests (Kremen et al. 2007). The works cited above indicated direct or indirect relations between forest state and ESs. However, ESs modelling requires improvements to increase confidence in the predictions of their amount and location in the landscape.

Improving the resolution, extent and quality of ESs estimates has the potential to improve evaluations of the link between forest state and ESs. Some authors have already pointed out this need for increased reliability on ESs estimations (Polasky et al. 2011, Naidoo et al. 2008). For example, Naidoo et al. (2008) observed that areas that maximize biodiversity did not provide more ESs than randomly selected places. However, when utilizing data with higher resolution, they identified areas with simultaneous high biodiversity and ESs. Thus, different resolutions can lead to complete different conclusions. The lack of high-resolution data is also an issue for old-growth forest definition and mapping (Holt 2000, Mosseler et al. 2003c, Hilbert and Wiensczyk 2007). Airborne LiDAR may offer the resolution needed for an accurate assessment of old-growth and ESs.

1.5. Airborne Laser Scanning (ALS):

The rapid emergence of remote sensing technologies has enabled researchers to, for instance, identify forest succession in broad scales (Hermosilla et al. 2015) (See also Table 1.1). Nevertheless, remotely sensed images are often two-dimensional (x and y), which cannot fully represent the nuances of the three-dimensional (3D) structures present in old-growth forests (Lefsky et al. 2002). On the other hand, ALS has been proven to be an effective technique to estimate 3D forest attributes.

ALS is active remote sensing, which emits high pulse frequencies in the near-infrared wavelength (e.g. 1064 nm), and further captures the intensity of returns reflected by different surfaces (Goodwin et al. 2006). The surface location is acquired from an onboard differential global positioning system (dGPS) (Hofton et al. 2000, Gaveau and Hill 2003). This technology performs accurate mapping of terrain and the 3-dimensional attributes of vegetation (Lefsky et al. 1999, Hyyppä et al. 2008, Bater et al. 2009). Starting with civil engineering applications (Meng et al. 2010), airborne LiDAR has been rapidly incorporated in forest management (Reutebuch et al. 2005, Wulder et al. 2008), wildlife habitat assessment (Hyde et al. 2006, Martinuzzi et al. 2009), evaluating of the effect of pests (Bright et al. 2013), and other applications (see Table 1.1). For forests, ALS has been widely used to measure tree height and forest biomass (Næsset 2002, Hyde et al. 2006), along with a variety of other old-growth forest attributes (Table 1.2). Furthermore, forest attributes can be assessed for an individual tree and area-base approach (ABP) (Reutebuch et al. 2005). These abilities make airborne LiDAR an effective way of mapping old-growth forests and a useful means for the estimation of ESs on a landscape scale.

Although the use of ALS for the assessment of multiple ESs is still in its infancy (Ayanu et al. 2012), there are examples of the successful use of this remote sensing technique to estimate a wide range of services. The most common ESs estimated with ALS are timber volume (Reutebuch et al. 2005, Wulder et al. 2008) and carbon storage (Mascaro et al. 2011). Researchers have also used ALS to estimate water-related services, such as the potential water storage capacity (Lang and McCarty 2009) and understory inundation (Lane and D'Amico 2010). Moreover, Müller and Vierling (2014) discussed the use of ALS for the assessment of biodiversity, while Simonson et al. (2014) reviewed the application of ALS on the estimation of animal diversity. Even cultural services have been recently estimated with ALS (Dade 2018, Van Berkel et al. 2018). These studies highlighted the potential of ALS to estimate individual ESs. However, the potential of ALS for the management of multiple ESs has been rarely tested.

ALS is a remote sensing technique that proved to be an efficient means for estimating forest values and a wide range of ESs in a landscape-scale. The use of ALS can, therefore, allow for more transparent management of forested landscapes for multiple ESs. However, ensuring that forest management actions retain multiple ecosystem services while providing opportunities for timber extraction is a complex spatial optimization problem. The next section offers an introduction to Systematic Conservation Planning and the use of spatial prioritization tools as a means to design conservation areas.

Table 1.2 Airborne LiDAR delivered metrics for old-growth forest attributes with area-based approach (ABA) and individual tree detection (ITD).

Old-Growth Attribute*	Lidar Estimators	Scale	Reference
Tree height	Treetops were detected with the highest return of point cloud from each tree and compared with high precision field measured of treetops.	ITD	(Andersen et al. 2006)
	Estimation of plot based height measurements (e.g. average, maximum, standard deviation) with LiDAR delivered metrics, indicating correlation close to 1:1.	ABA	(Hopkinson et al. 2006, Goodwin et al. 2006)
Basal area	Random Forest models were developed with LiDAR delivered metrics with and without intensity metrics to predict total, live and dead basal area.	ABA	(Bright et al. 2013)
Number of dead standing trees (snags)	Filtering algorithm based on density and intensity statistics to remove points associated with living trees, followed by an individual tree detection procedure.	ITD	(Wing et al. 2015)
	Correlation of height metrics with field observed frequency of snags to estimate snag frequency for the landscape.	ABA	(Bater et al. 2009)
	Median absolute deviation of height was associated with the abundance of snags in different DBH classes, as well as different other canopy and topography metrics, using Random forest algorithm	ABA	(Martinuzzi et al. 2009)

	Intensity, density and height statistics were used to estimate basal area (BA) of live, dead trees, and total BA through Random Forest models	ABA	(Bright et al. 2013)
Structural Complexity	Canopy volume profile estimates and leaf area index (LAI)	ABA	(Lefsky et al. 1999, Coops et al. 2007)
	Complexity of vertical forest structure was estimated with LiDAR derived height variance	ABA	(Zimble et al. 2003)
	Indicates that the 95th height percentile, rumple (ratio of canopy outer surface area to ground surface area), and canopy density had the strongest correlation with field measured stand complexity.	ABA	(Kane et al. 2010b, 2010a)
Biomass	LiDAR height percentile (h80) and crown width (CW) measurement were the best metrics for aboveground biomass (AGB) estimates using a multilinear model	ITD	(Wan-Mohd-Jaafar et al. 2017)
	Quantiles and full returns against field measurement, and other simple LiDAR metrics were tested against field estimates with correlation analysis and multilinear models	ABA	(Næsset 2011, Ahmed et al. 2013, Næsset et al. 2013)
Understory Density	First returns in a specific range of intensity in lower strata of the canopy was utilized to estimate live understory distribution	ABA	(Koukoulas and Blackburn 2004a, Vepakomma et al. 2008, Wing et al. 2012, White et al. 2018)
	Proportion of ground returns, vegetation return between 1 and 2.5 m in height and percent slope times cosine of aspect were fed to a random forest model to predict presence and absence of understory vegetation	ABA	(Martinuzzi et al. 2009)

	LiDAR delivered metrics were proven more accurate predictors of coarse woody debris (CWD) than field measurement of living trees, and indicated as important auxiliaries in the prediction of CWD in the landscape	ABA	(Seielstad and Queen 2003, Pesonen et al. 2008, 2009)
Canopy Gap	Canopy gap was measured based on a canopy height mode (CHM) with a height threshold measured during field (4-5m) and gap area of 5m^2. Slope from CHM was also an important feature to map canopy gaps.	ABA	(Koukoulas and Blackburn 2004b, Vepakomma et al. 2008)
	Applied fixed and variable height thresholds to a 1m resolution CHM to detect gaps, further filtered by area. Gap areas <5m^2 and >2ha were excluded.	ABA	(White et al. 2018)

1.6. Systematic Conservation Planning

Systematic conservation planning was developed to ensure the efficient use of limited resources for conservation, aiming to direct conservation investments to priority areas (Margules and Pressey 2000, Wilson et al. 2009). The most straightforward conservation problem formulation involves the binary decision of whether to select a planning unit for prioritization or not. Many conservation planning problems are incredibly complex, involving thousands of planning units and a myriad of features to be prioritized (e.g. species' habitats and ecosystem services). Chan et al. (2006) found that systematic planning provides a framework useful for identifying valuable synergies and potential trade-offs between conservation for biodiversity and ESs. This framework can, thus, be applied to identify priority areas for the conservation of old-growth forests, while simultaneously targeting multiple ESs. However, in some forested landscape, setting aside old-growth forest for old-growth conservation can conflict with other management actions. Ensuring that management actions retain multiple landscape values to target levels while meeting the objectives of different stakeholders is a complex spatial optimization problem (Schröter and Remme 2016, Snäll et al. 2016).

The minimum set problem in conservation prioritization is designed to secure a target level of each conservation feature with the smallest possible set of areas, often referred to as planning units (Wilson et al. 2009). There are two main approaches to solving the minimum set problem, the integer linear programming (ILP) and heuristics, most commonly simulated annealing (Beyer et al. 2016). Marxan is the most common conservation planning software that uses simulated annealing (Ball et al. 2009, Watts et al. 2009). To promote connectivity and management effectiveness, Marxan includes a mechanism to control the degree of aggregation among selected units. Instead of enforcing hard constraints, Marxan utilizes a "shortfall penalty" function, which assumes that even configurations of planning units that do not meet all of the targets may still have value. The "shortfall penalty" provides a way of finding reasonable solutions where all targets cannot be met (Beyer et al. 2016). The main concern with the simulated annealing approach is that there is no measure of how far from optimal the solutions is (Underhill 1994, Önal and Briers 2002). While simulated annealing approaches stochastically explore the decision variables providing a range of solutions, problems solved with ILP have only one optimum solution or a solution with a specific distance from optimum.

Although very similar to Marxan, "PrioritizR" utilizes integer linear programming (ILP) and is implemented in an "R package." PrioritizR provides a flexible interface for building and solving conservation planning problems (Hanson et al. 2019). PrioritizR also supports a broad range of functions and modifiers to attend to the particularities of a conservation planning exercise. Once built, PrioritizR problems are solved using a solver algorithm, such as Gurobi (V.7.0) and "SYMPHONY in R" (Harter et al. 2017). ILP is recommended over simulated annealing whenever this is possible because it offers higher quality solutions in less processing time over a wide range of problem sizes and for both linear and quadratic models (Beyer et al. 2016). It also facilitates the development of trade-off curves and comparison between multiple scenarios.

The systematic conservation planning solutions are flexible and defensible, allowing the critical review of multiple management decisions (Margules and Pressey 2000). "PrioritizR" can simulate the allocation of different management actions (e.g. harvesting and old-growth protection), allowing practitioners to identify solutions that meet multiple objectives.

Therefore, "PrioritzR" will be utilized as a conservation planning tool for the identification of priority areas for old-growth and multiple ESs in Chinook Community Forest.

1.7. Thesis Objectives

The location and abundance of "Old-growth" forest attributes enable the provision of a range of ecosystem services (ESs) (Hendrickson 2003, MA 2005, McElhinny et al. 2005, Isbell et al. 2011). These forests are also the habitat of different animal species (Mosseler et al. 2003a). Therefore, it might be possible that identifying and retaining old-growth forests can simultaneously retain essential ESs in the landscape. Nevertheless, there is a great diversity of old-growth forests, as well as the definitions and approaches to classify them, which makes the selection of such areas a difficult task (Hilbert and Wiensczyk 2007). The primary strategy utilized to define and locate old-growth forests in the landscape is the "age" classification (Environmental Law Centre 2013). Although "age" is an important metric, "age" by itself may fail to capture some old-growth features (Braumandl and Holt 2000). This thesis addresses two main objectives to approach these knowledge gaps.

1. Develop an old-growth index through the use of LiDAR to enable the definition and location of old-growth forests in a landscape scale.
2. Evaluate the opportunity for multiple ESs provision in a complex landscape managed manly for timber through the spatial prioritization of old-growth values.

This thesis addresses the two objectives in the Chinook Community Forest (CCF), located in Burns Lake, British Columbia, CA. A community forest is an area-based tenure for "any forestry operation managed by a local government, community group, or First Nation for the benefit of the entire community" (MFLNRORD 2017a). The community forest is located within the Skeena region and overlaps with six First Nations' and Bands' territories: Cheslatta Carrier Nation; Lake Babine Nation; Burns Lake Band; Wet 'suwet 'en First Nation; Skin Tyee Nation; and Nee Tahi Buhn Band. The diversity of stakeholders adds greater complexity to the management of community forest and makes it a strong case study. While the main objective of the community forest is to manage the landscape for timber extraction, it should not affect the provision of other ESs for the local communities. The Old-growth Management areas (OGMAs) might be a strategy to maintain essential ESs in the landscape while providing opportunities for timber extraction.

Two data chapters follow this general review. In the first data chapter (Chapter 2), I tackle the first objective utilizing a combination of traditional field-based definitions of old-growth reviewed in this chapter (Chapter 1) with airborne LiDAR. For the second data chapter (Chapter 3), I utilize old-growth and ESs layers as inputs for a spatial prioritization tool, "PrioritizR." Different prioritization scenarios were tested to identify trade-off and synergies between old-growth and ESs and the possibility to design OGMAs for multiple ESs.

2. DEFINING OLD-GROWTH FORESTS WITH AIRBORNE LiDAR

Abstract: In this work, we developed a structure-based old-growth forest index tailored to map old-growth value in managed landscapes. Forests in their later stages of development attain attributes that support biodiversity and provide a variety of benefits to human populations. Despite their irreplaceable value, old-growth forests are declining worldwide due to anthropogenic pressures. A definition of old-growth is needed to facilitate mapping and delineation of old-growth in the landscape and old-growth reserves. LiDAR-derived metrics were utilized with a random forest (RF) modeling framework to develop an old-growth index across the landscape. Using this old-growth index, we found that forests with "Very-high" old-growth values cover 14.7% of the study area and only 24.9% of the current designated old-growth management areas (OGMAs). However, the set-aside forest with "Very-high" old-growth value is mostly fragmented between the OGMAs, as only one OGMA has more than 50% of its area covered by forests with "Very-high" old-growth value. This research brings light to old-growth, and OGMAs' definition and their assessment through the use of fine-scale remotely sensed data, LiDAR. While the index developed is specific to the study site, the framework, however, is generic enough to be adapted to other forest types and ecosystems. More importantly, the identification of the amount and location of old-growth forests over the landscape can aid in the conservation of this rare resource and its services.

Keywords: Community Forests, Conservation, Old-growth forests, remote sensing

2.1. Introduction:

"Old-growth" is a term associated with forests in the advanced development stage (Mosseler et al. 2003c, Spies 2004, Hilbert and Wiensczyk 2007). Forests with these characteristics are rare, and in decline worldwide, despite the multiple benefits they provide for the maintenance of human wellbeing (Wirth 2009, Bithell and Brasington 2009, Watson et al. 2016, 2018, Maxwell et al. 2019). Strategies to promote the retention of old-growth forests are often incorporated into landscape level forest planning (Arsenault 2003, Gillis et al. 2003, Environmental Law Centre 2013). Yet the identification of old-growth is a difficult task due to the lack of a standard definition for what constitutes an old-growth forest (Hilbert and Wiensczyk 2007). Old-growth forest types vary in terms of longevity of dominant species, return period of natural disturbances, human intervention, shade tolerance, and abundance of specific structures such as the number of large trees, snags, accumulated woody debris (Mosseler et al. 2003b, 2003c, Spies 2004, Bauhus et al. 2009). For example, coastal Douglas-fir forests may grow for centuries without disturbances, whereas Ponderosa pine forest is frequently disturbed by fires (Spies 2004, Spies et al. 2006). These ecological differences across forest types pose a significant methodological challenge to the characterization of these forests only based on disturbance frequency.

There exists multiple definitions and approaches to define and locate old-growth forests (Wirth et al. 2009b). Age is a proxy that has commonly been used to define and locate old-growth forests. For example, according to MFLNRORD (2003), BC's coastal forests are considered old-growth if trees are more than 250 years old. For forests dominated by lodgepole pine or broadleaf species in the northern interior, old-growth are forests with more than 120 years of age. In these landscapes, the longevity of trees tends to be shorter, and disturbances more frequent. Although age is a useful proxy, its measurement with traditional field methods is costly (Racine et al. 2014). As well, important structural elements of old-growth can be omitted using only an age threshold (Arsenault 2003, Gillis et al. 2003, Holt et al. 2008). More importantly, forest cover maps currently used to locate old-growth forests often do not accurately reflect the age class distribution in the landscape (Holt et al. 2008). This inaccuracy can lead to management that underrepresents old-growth forest in the landscape, or incorrectly identifies forests as being old-growth even though they do not exhibit the desired characteristics. As a result, in many areas, it may be prudent to move away from a simple age threshold for old-growth definition towards a more ecologically based representation of forest structures.

Different authors have pointed out the need to develop an index that could be used to track old-growth forest in the landscape, rather than only using stand age (Mosseler et al. 2003c, Spies 2004, Hilbert and Wiensczyk 2007). Compared with old forests, young natural forests or intensively managed forest plantations have a simpler structure (Spies 2004, McElhinny et al. 2006a). Thus, the abundance of old-growth attributes (e.g. large trees, snags, and accumulated woody debris), which contributes to the structural complexity in the old-growth forest, can be used as a proxy for old-growth forest mapping (Mosseler et al. 2003a, 2003c, Bauhus et al. 2009). A myriad of work has been conducted using a traditional field-based measurement of forest attributes to classify forest succession and assess the quality of old-growth forests (McElhinny et al. 2006a) (See also Table 1.1). Even though field-based methods are essential for most forest studies, they are less applicable for landscape-scale evaluation.

The rapid emergence of new technologies has allowed the development of highly precise measures of forest condition across broad areas (Hansen et al. 2019), which exceed what has been possible based on traditional field-based and areal interpretation methods

(Cohen et al. 1995, Song and Woodcock 2002, Hyyppä et al. 2008, Kane et al. 2010b). Typical applications of passive or active optical sensors have proven to be useful for a variety of ecological studies, enabling researchers to, for instance, identify forest succession in broad scales (Song and Woodcock 2002). Nevertheless, remotely sensed images are often constrained to two-dimensional (x and y) interpretation, which cannot fully represent the nuances of the three-dimensional (3D) structures present in old-growth forests (Lefsky et al. 2002). On the other hand, airborne LiDAR has been proven to be an effective technique to estimate 3D forest attributes, particularly for height and biomass (Næsset and Økland 2002, Hyde et al. 2006). Starting with civil engineering applications (Meng et al. 2010), airborne LiDAR has been rapidly incorporated in to forest management (Reutebuch et al. 2005, Wulder et al. 2008), wildlife habitat assessment (Hyde et al. 2006, Martinuzzi et al. 2009), evaluation the effect of pests (Bright et al. 2013), and other applications. In addition to height and biomass, a variety of other old-growth forest attributes can be accurately estimated with airborne LiDAR (White et al. 2018) (See also Table 1.2). Thus, airborne LiDAR has the potential to be an effective way of generating an old-growth index to effectively map old-growth forests.

The definition and mapping of old-growth forests with measurable structural and biophysical features, considering the continuous nature of forest structure, is imperative for their conservation and maintenance in managed landscapes. Throughout the years, different authors have attempted to map forest succession in the landscape (Table 1.1). However, few have used old-growth attributes to create an index for old-growth value, and none has done it in landscape scale. In this work, we aim to: (1) develop an old-growth index based on forest structures measured with traditional field methods; (2) extrapolate the old-growth index to the landscape utilizing LiDAR-derived metrics; and (3) evaluate the amount and quality of old-growth forest for the study site, simultaneously evaluating the set-aside old-growth forests currently present in the landscape.

2.2. Material and Method:

2.2.1. Study Area:

A community forest is an area based tenure meant for “any forestry operation managed by a local government, community group, or First Nation for the benefit of the entire community”(MFLNRORD 2017a). The Chinook Community Forest (CCF), located within the Skeena region, overlaps with six First Nations’ and Bands’ territories: Cheslatta Carrier Nation; Lake Babine Nation; Burns Lake Band; Wet‘suwet‘en First Nation; Skin Tyee Nation; and Nee Tahi Buhn Band. The forests in the study site are categorized into two biogeoclimatic zones (BEC), the Englemann Spruce – Subalpine Fir (ESSF) and Sub-Boreal Spruce (SBS). The tenure area for CCF operations is approximately 123,695 ha, currently encompassing around 40 set-aside old-growth forests or old-growth management areas (OGMAs). The total set-aside old-growth forests area is ~ 8,618 ha, 6.96% of the tenure area. The CCF area has five different management blocks (Figure 2.1). Figures in the results and discussion depict only block 04 to facilitate visualization. However, the analysis and numeric results are reported for the whole land base.

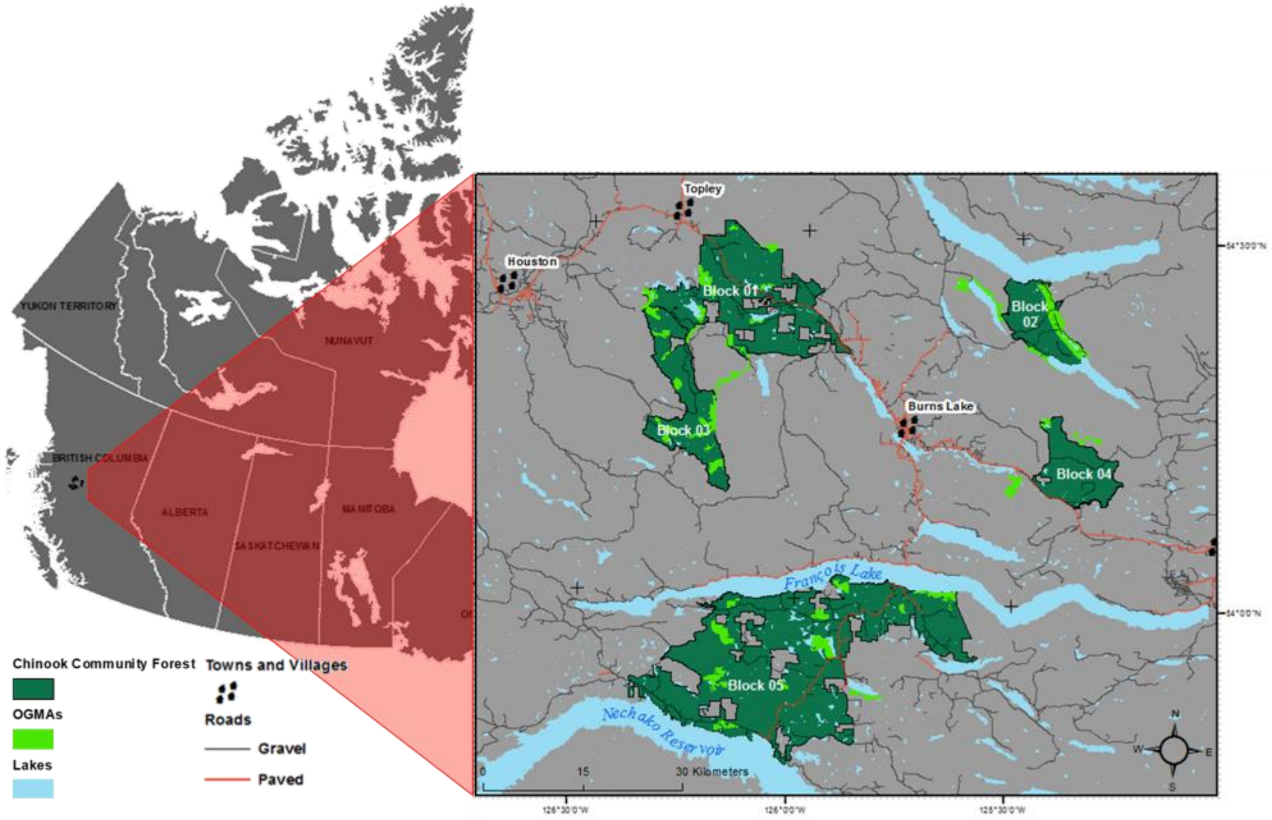


Figure 2.1 Location of Chinook community forest tenure areas and distribution of Old-growth management areas (OGMAs).

2.2.2. Data:

Empirical measurement of forest composition and structural attributes were collected from 99 plots of 10 m radius (Table 2.1; 5222 trees sampled). All trees greater than 4 cm DBH were measured such that forest structure in disturbed and young forests was recorded, increasing correlation with ALS metrics (Keränen et al. 2015). In addition, trees with a diameter smaller than 4cm were tallied to obtain the density of small trees and seedlings. The inventory followed the Change Monitoring Inventory (CMI) procedures used by B.C. Ministry (MFLNRORD 2017b). High precision GPS was used to obtain two measurements of ± 2m accuracy from the plot center. Geographic information system (GIS) exercises incorporate Airborne LiDAR and ground survey into old-growth maps and evaluate old-growth forests.

2.2.3. Old-growth attributes:

From the list of thirteen old-growth attributes indicated by Bauhus et al. (2009), I was able to estimate eleven of them for the Chinook Community Forest (Table 2.1). In addition to that, I also included maximum tree height as it has a strong correlation with age in old-growth assessment (Kneeshaw and Burton 1998, Hao et al. 2007). Tree diversity was also included, as old-growth is expected to have higher biodiversity (Mosseler et al. 2003b, McElhinny et al. 2006b). However, we only have information on the diversity of trees. Here I utilized these attributes as basis for forest classification and the development of an old-growth index. Aboveground biomass estimates were based only on the value of DBH in the form of an exponential curve developed by (Jenkins et al. 2003). DBH and height are the base for volume estimates calculated using volume equations developed by Penner et al. (1997) and Standish et al. (1985). A description of the equations and associated parameters utilized in this study are included in Appendix 6.2.

Table 2.1 Field measurement of Old-growth attributes.

	Old-growth Attribute	**Mean**	**Range**
1	Large trees density (number of trees - dbh>40cm/ha)	14.47	0 - 222.82
2	Presence of regeneration (number of trees <1.3m/ha);	4,564	0 – 37,179
3	Biomass of late succession species (Spruce, Balsam fir, tons/ha)	54.4	0 - 384.6
4	Coefficient of variation of DBH (Horizontal Complexity)	47.52	0 - 125.84
5	Coefficient of variation of height (Vertical Complexity)	37.08	0 - 110.79
6	Basal area of dead standing trees (m^2/ha)	180.38	0 – 1,655.21
7	Volume of dead fallen trees (m^3/ha)	13.08	0 - 115.16
8	Wide decay class distribution (Std of decay class)	1.32	0 – 3.56
9	Total Volume (m^3/ha)	170.44	0 – 614.62
10	Biomass (tons/ha)	3,297	0 – 14,322
11	Basal area (m^2/ha)	0.61	0 - 2.38
12	Abundance of special attributes (broken top, fork, scars, etc.)	3.19	0 – 14.49
13	Age (year)	63.81	0 - 262

2.2.4. Plot-level definitions of old-growth:

I developed eight indices of old-growth forests using the empirically measured forest attributes (Table 2.2). The first five of these indices were categorical and divided the forest into old-growth classes. The first index was based only on estimated stand age and divided the forest into four provincially defined forest age classes (MFLNRORD 1995): initiation (0 – 40 year), young (40 – 70 year), mature (70 – 140 year) and old-growth (>140 years). Four additional forest classification indices were developed including stand structural attributes (Table 2.1). For these other four classifications, stand structural attributes were delimitated into classes using unsupervised k-means classification (indices 2 and 3) or by using a stepwise procedure that used a random forest routine to reduce the dimensionality of the data prior to applying k-means classification (indices 4 and 5)(Shi and Horvath 2006, Afanador et al. 2016).

I also created three different old-growth indexes to capture the continuous nature of the forest structures. To allow the combination of multiple measures to form a single index, I scaled all old-growth attributes (Table 2.1) to a range from 0 to 1, such that each attribute had the same weight. Age was utilized as a continuous variable to create the first continuous old-growth index (index 6). The other two indexes were created utilizing all old-growth attributes, with and without age.

Table 2.2 Plot level definitions of old-growth forests.

Model Type	Old-Growth Definition	Method	Response Variable
Classification (Discrete Variable)	Age Classes	0 = Very-low; >0 and <= 40 = Initiation; >40 and <= 70 = Young; >70 and <= 140 = Mature; >140 Old-growth	AGE_CLASS
	Old-growth attributes + Age	Unsupervised K-means classification, 5 classes.	KOGA+AGE
	Old-growth attributes	Unsupervised K-means classification, 5 classes.	KOGA
	Old-growth attributes + Age	Reduction of dimensionality with random forest + Unsupervised K-means classification, 5 classes.	RFOGA+AGE
	Old-growth attributes	Reduction of dimensionality with random forest + Unsupervised K-means classification, 5 classes.	RFOGA
Regression (Continuous Variable)	Age	Age as a continuous variable ranging from 0 - 1	AGE
	Old-growth attributes + Age	Sum of all old-growth attributes, each as a continuous variable ranging from 0 - 1	OGA+AGE
	Old-growth attributes	Sum of all old-growth attributes, except age, each as a continuous variable ranging from 0 - 1	OGA

2.2.5. Lidar processing:

Airborne LiDAR was collected in a leaf-on condition with a minimum density of 2 pulses/m2, a half-scan angle of 12.5° from nadir, with a 50% overlap. The footprint is estimated to be from 30 to 70 cm. LAStools (version 161114) was the software utilized to process the LiDAR's point cloud. A pipeline for LiDAR processing was illustrated in the

Appendix 6.3. Tree height is one of the most fundamental measurements in the forest industry and has a critical role in the quantitative assessment of forest biomass, carbon stocks, growth, and site productivity (Andersen et al. 2006). Tree height is highly variable throughout forest succession, and it is considered an important old-growth attribute (Spies 2004, McElhinny et al. 2006a). Tree height was extracted from the difference between the Digital Surface Model (DSM) and DTM, where DSM is derived from the first returns and DTM from the last (Hopkinson et al. 2006, Andersen et al. 2006, Aryal et al. 2017). A list and description of the LiDAR metrics, mostly derived from height returns, are available in Table 2.3.

Table 2.3 LiDAR metrics utilized in the random forest models.

Metric name	Metric Description
AHR_Avg	Average of all height returns
AHR_Kur	Kurtoses of all height returns
AHR_Max	Max of all height returns
AHR_Qva	Average of squared height of all height returns
AHR_Ske	Skewness of all height returns
AHR_Std	Standard Deviation of all height returns
AHR_Dns	Number of all points above 1.3m / number of all returns.
H10PercT	Height 10th Percentile
H25PercT	Height 25th Percentile
H50PercT	Height 50th Percentile
H75PercT	Height 75th Percentile
H90PercT	Height 90th Percentile
H95PercT	Height 95th Percentile
STH1_Com	Coefficient of variation of returns of height >0.2m and <1.0m
STH1_Den	Density of points for returns >0.2m and <1.0m / Density of ground returns
STH1_Ske	Skewness of all height returns
STH1_Kur	Kurtoses of all height returns

STH1_Cov	Canopy cover (First returns at height > 3.0m/ all first returns*100)
STH2_Com	Coefficient of variation of returns of height >1.0m and <2.0m
STH2_Den	Density of points for returns >1.0m and <2.0m / Density of ground returns
STH2_Ske	Skewness of all height returns
STH2_Kur	Kurtoses of all height returns
STH2_Cov	Canopy cover (First returns at height > 3.0m/ all first returns*100)
STH3_Com	Coefficient of variation of returns of height >2.0m and <3.0m
STH3_Den	Density of points for returns >2.0m and <3.0m / Density of ground returns
STH3_Ske	Skewness of all height returns
STH3_Kur	Kurtoses of all height returns
STH3_Cov	Canopy cover (First returns at height > 3.0m/ all first returns*100)
STH4_Com	Coefficient of variation of returns of height >3.0m
STH4_Den	Density of points for returns >3.0m / Density of ground returns
STH4_Ske	Skewness of all height returns
STH4_Kur	Kurtoses of all height returns
STH4_Cov	Canopy cover (First returns at height > 3.0m/ all first returns*100)
UNDEN	Density of points for returns > 0.2m and < 3.0m / Density of ground returns
VERCOMP	Coefficient of variation of all height returns

2.2.6. Statistical analysis:

In this study, I used the machine learning technique called Random forest (RF) as it is a powerful classification technique and has been successfully utilized for forest succession classification (Belgiu and Drăguţ 2016, Cutler and Wiener 2018). RF is a machine learning method that adds randomness by randomly selecting subsets of the data with the same distribution without replacement, which increases the diversity of decision trees ("Regression Trees"). RF combines decision trees, considering the values of an independent random sample, for all the trees in the forest (Breiman 2001). Thus, each decision tree (regression tree) is built with not only a random subset of the response variable but also the predicting variables. This structure prevents overfitting and increases the robustness of the model. I applied the random forest (RF), statistical model, using the "randomforest" package (Cutler and Wiener 2018) in the R (R Development Core Team 2018) programming environment to connect field delivered metrics to LiDAR metrics.

Eight random forest models were generated, one for each of the old-growth indices described in Table 2.2. The models developed here utilized the plot-level classification and old-growth indexes delivered from fieldwork data as response variable. The predicting variables are the set of LiDAR metrics listed in Table 2.3. Figure 2.2 depicts the overall structure of the models. Each random forest model generated 10,000 decision trees to ensure the stabilization of the model. For each tree, "random forest" utilized a subset of 12 out of 36 predicting variables as suggested by (Breiman and Cutler 2003). In addition, I applied a k-fold (k=4) procedure with the r package "Caret" to divide the data into training and validation data set. Thus, each random forest model was generated with a subsample of 75% of the available data and validated with the remaining 25%. This procedure was repeated ten (10) times for each model. Mean accuracy, kappa and balanced class accuracy was reported as a means for comparison. Similarly, the random forest was applied in its regression mode for the old-growth indices (6-8 in Table 2.2). For the regression, we reported the means and standard deviation of the r-squared and the mean square error of the ten repetitions.

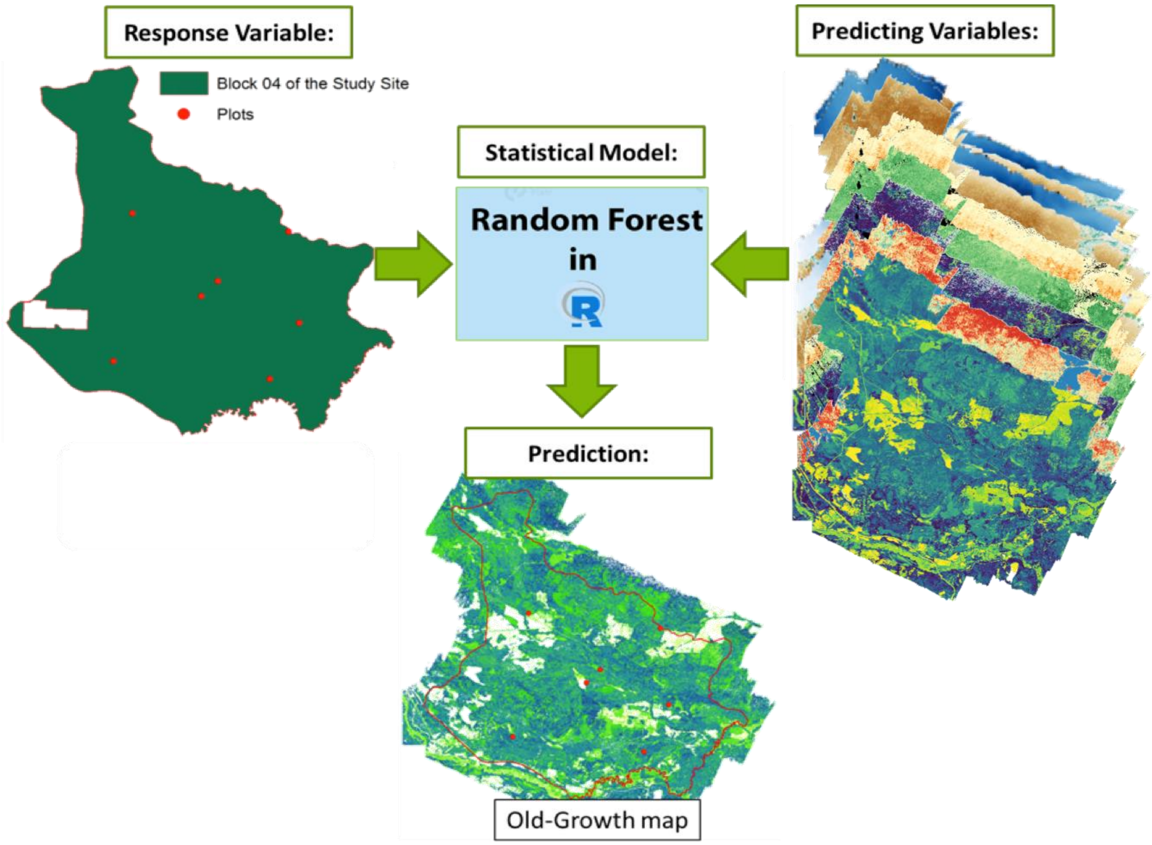


Figure 2.2 Method design for Random forest model generated to create old-growth maps from fieldwork classification of forest succession and old-growth indexes, where the response variable are the plot-level old-growth definitions (Table 2.2) and the predicting variable the LiDAR derived metrics (Table 2.3).

The R package “raster” was used to generate old-growth maps from the different old-growth models developed in this work. The five Random forest models ran with the plot-level forest succession classification were compared in terms of out of bag error and the old-growth misclassification error (Belgiu and Drăguţ 2016). The three Random forest models generated from the two old-growth indexes and age estimates were compared in terms of mean squared error. The most robust models, one from classification and one from regression (old-growth index), were used to generate old-growth maps for the whole study area. To make comparisons between the categorical and continuous models, I had first to break the continues model into classes. I utilized the natural breaks (Jenks) option from the ArcGIS classification method to create five classes analogous to the other categorical definitions of old-growth.

2.3. Results:

2.3.1. Fieldwork data:

I identify ten variables that were best correlated with age (Figure 2.3). None of the attributes displayed a normal distribution, which highlights the importance of choosing a no-parametric statistical framework, “random forest”, for the development of old-growth models. Nine out of the ten variable included in the development of the old-growth indices (Table 2.2) were identified and listed by Bauhus et al. (2009) as important old-growth attributes. From the old-growth attributes included in this study to Bauhus’ list (Table 2.1), only maximum height was among the highest correlated.

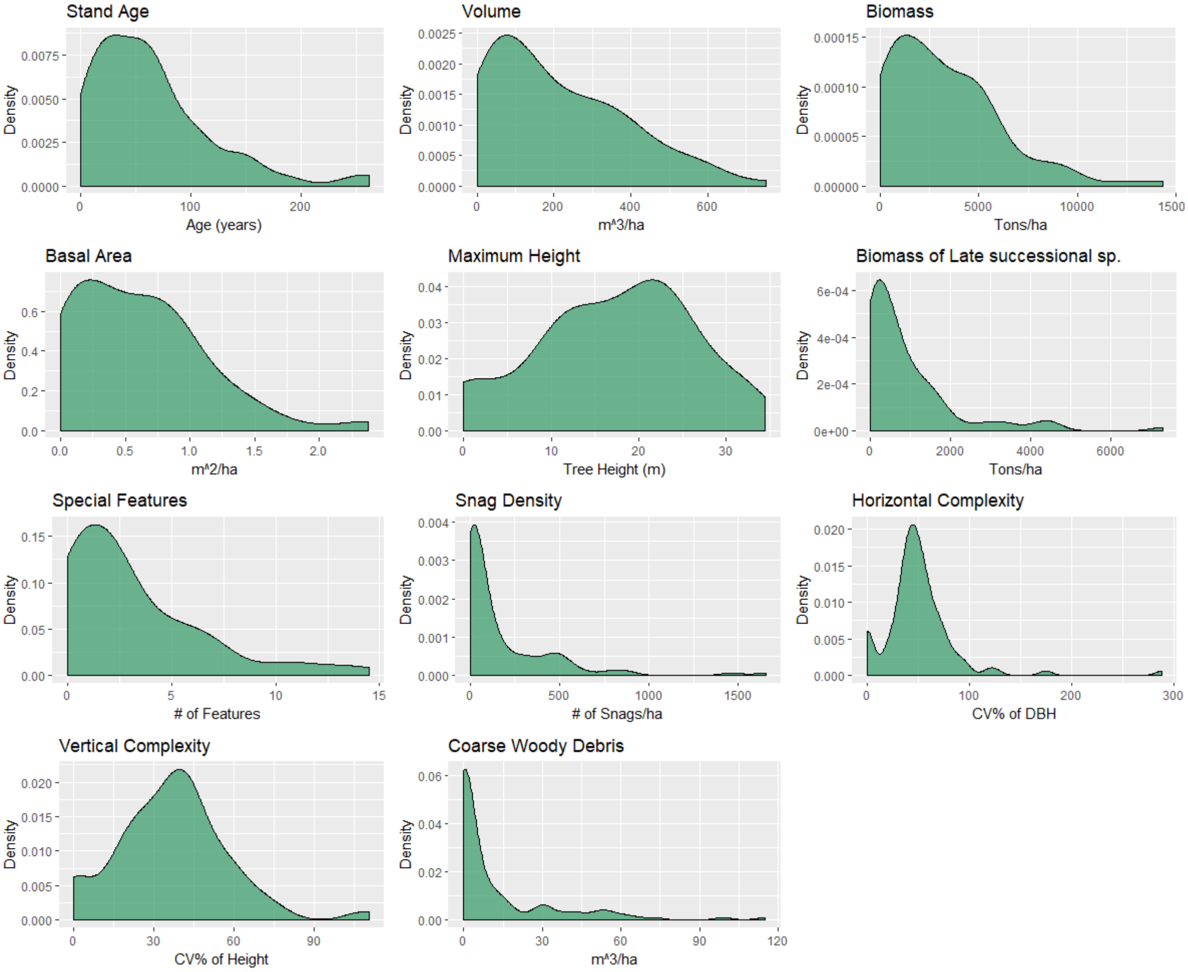


Figure 2.3 Histograms of old-growth attributes best correlated with age, displaying the distribution of the data. Distributions are not normal, which indicates the need for non-parametric models.

I found that for the classification models that utilized old-growth attributes without transformation (KOGA and KOGA+AGE), the number of plots classified as high and very-high old-growth value decreased when compared with the age classes (Table 2.4). Age was not an essential attribute for KOGA and KOGA+AGE as it did not change the classification. RFOGA and RFOGA+AGE had a closer distribution of plots in each old-growth value class as AGE_CLASS compared to the remaining models. However, RFOGA and RFOGA+AGE have a higher number of plots classified with very-high value for old-growth than any other classification.

Table 2.4 Plot level classification of old-growth values

	AGE_CLASS	KOGA+AGE	KOGA	RFOGA+AGE	RFOGA
Very-low	7	35	35	13	14
Low	29	26	26	15	17
Intermediate	29	23	23	19	18
High	22	6	6	22	25
Very-high	11	8	8	29	24

Age was not successfully differentiated into age classes in none of the classification methods developed here, except Age_Class (Figure 2.4). For the distribution of the other ten old-growth attributes according to the classes and old-growth indices developed in this study, refer to the Appendix 6.3. I found that, although the oldest stands were mostly classified into "High" and "Very-high" old-growth values in all classifications, there were still important misclassifications. The plot where the oldest tree was sampled was classified as either "Low" (Figure 2.4 b and c) or "High" (Figure 2.4 d and e) old-growth value depending on the classification method, where it is expected to be in the "Very-high" old-growth value. Similar to age, the other old-growth attributes were not well differentiated into classes in none of the classifications proposed here. However, for the age classification (AGE_CLASS), all old-growth attributes seem to follow a trend from very low abundance of old-growth attributes for the "Very-low" and "Low" classes to high abundance for the "High" and "Very-high" classes (Appendix 6.3 – Figure 6.3). This reinforces the importance of age as a proxy for forest succession and old-growth value. Similar trends were also present for the other classifications, although more clear only for the old-growth attributes "maximum tree height", "Biomass" and "Basal Areas". In addition, the old-growth class ("very-high") would be better differentiated by some old-growth attributes than to others. For example, “maximum tree-height” and “biomass” separated well the “very-high” class from the remaining classes in all models, except for AGE_CLASS. “Horizontal complexity” and “Volume” separated well the “Very-low” and “Low” old-growth value classes from the remaining classes. Yet, while one attribute separated one class well from the others, there were still overlaps between at least two classes in all classification for all attributes (Appendix 6.3). In addition, no single attribute provided a clear differentiation of all classes. This is mostly because there is not a clear threshold to indicate when a forest enters the old-growth stage since stand development is continuous (Wirth et al. 2009b). The continuous old-growth index might be a better way to demonstrate the continuous accumulation of old-growth attributes suggested in the classification methods.

AGE, OGA+AGE, and OGA represented the old-growth value in a continuous way instead of arbitrary age classes. In this case, instead of looking at only age or other arbitrary classifications, I focused on the overall abundance of old-growth attributes. Old-growth attributes that were well related to AGE were the “Maximum Tree height” and “Biomass,” both with r-squared >40% (Appendix 6.2 – Figure 6.8). No attributes had r-squared greater than 45% with AGE. Thus, the old-growth index purely based on age poorly represented most old-growth attributes, except “Maximum Tree Height,” “Biomass,” and “Age” itself. The Age-based old-growth index failed to represent other important features, such as the vertical and horizontal complexity, coarse woody material, dead standing trees, volume and etc. OGA+AGE and OGA, on the other hand, lost a bit on the age representation, r-squared 55.6% and 45.4% respectively (Figure 2.4 f and g), to gain a greater representation of all other old-growth attributes (Appendix 6.3 – Figure 6.9 and 6.10). For example, “Dead Standing Trees” r-squared increased from 8.0% in AGE definition to over 34.6% and 37.1% for OGA+AGE and OGA, respectively. Similarly, the r-squared for “Late succession species” increased from 9.7% to over 30% for OGA+AGE and OGA. Finally, even “Maximum Tree Height” and “Biomass,” the best-represented old-growth attributes in the age-based old-growth index (AGE), were significantly increased in OGA+AGE and OGA. “Maximum Tree Height” increased from 44.9% to 71.0% and 69.2% for OGA+AGE and OGA, respectively. For “Biomass” the r-squared was increased from 43.9% in the AGE model to 79.3% for OGA+AGE and 78.6% for OGA.

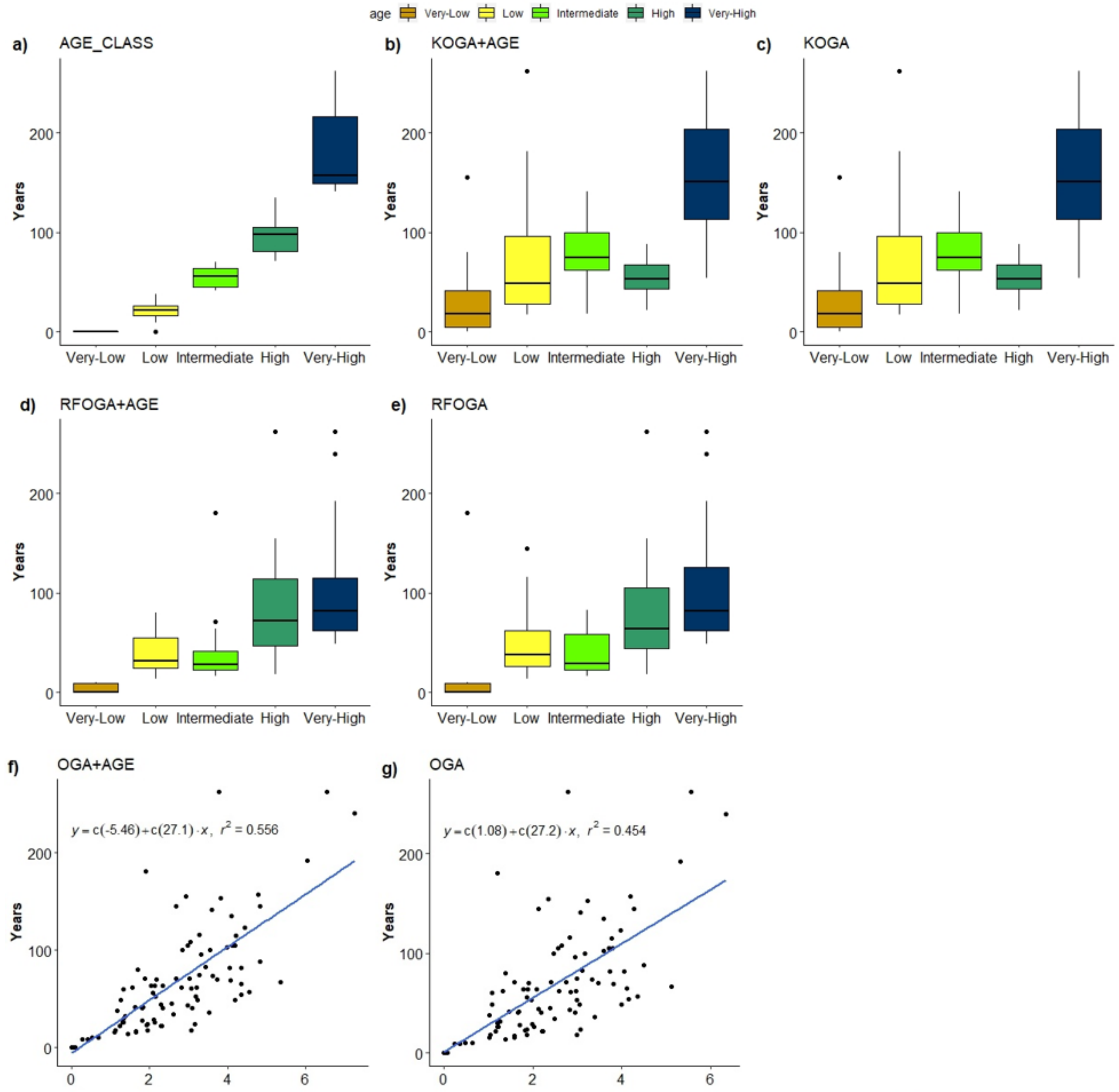


Figure 2.4 Age distribution according to each different old-growth definition developed in this study. The names on top of each graph represent one old-growth definition and are listed and described in Table 2.2.

2.3.2. Comparison between “random forest” models:

The AGE_CLASS model, which utilizes only age classes, performed well for the lowest levels of old-growth value (Table 2.5). The classes “very-low” and “Low” had the best class accuracy of all models, 95 and 86%, respectively. However, AGE_CLASS had a weak performance in the remaining classes and overall accuracy. KOGA and KOGA+AGE, which utilizes k-mean classes of old-growth attributes as response variables, did not perform better than AGE_CLASS. The stepwise classification applied for the RFOGA and RFOGA+AGE models, which involves the use of "random forest", substantially improve the model fit.

RFOGA and RFOGA+AGE had not only the best overall accuracy but also the best class accuracy for "Intermediate," "High," and "Very-high" classes. While RFOGA+AGE has greater predicting power for class "very-low" and "Intermediate," RFOGA performed better in class "Low," "High," and "Very-high." RFOGA based models were better at identifying forests with "High" and "Very-high" old-growth value than any categorical definition utilized here. However, the stepwise framework of the RFOGA based models involved the use of two classification methods ("random forest" and K-means) to reach the final classification. Using random forest to reduce dimensionality of the data added randomness to the plot classification, which was stabilized after multiple k-means classification on the data results of the unsupervised random forest. Thus, while the final RFOGA classifications have better performance than the others, the classification accuracy for pure age increased from 0.54 in pure age definition to 0.69.

Table 2.5 Summary of statistics for the five old-growth classification random forest models

Classification	Accuracy Mean (+/- SD)	Kappa Mean (+/- SD)	Very-Low	Low	Intermediate	High	Very-High
AGE_CLASS	0.54 (+/- 0.03)	0.39 (+/- 0.04)	0.95	0.86	0.61	0.53	0.63
KOGA+AGE	0.53 (+/- 0.03)	0.34 (+/- 0.05)	0.86	0.58	0.62	0.50	0.52
KOGA	0.55 (+/- 0.02)	0.37 (+/- 0.03)	0.86	0.61	0.64	0.51	0.53
RFOGA+AGE	0.69 (+/- 0.02)	0.60 (+/- 0.03)	0.92	0.71	0.83	0.73	0.84
RFOGA	0.68 (+/- 0.02)	0.59 (+/- 0.03)	0.89	0.75	0.74	0.75	0.86

The regression model generated with age only (AGE) did not perform as well as the old-growth index models (OGA+AGE and OGA) (Table 2.6). Besides, there was no difference between the performances of the old-growth index models when age was absent as an old-growth attribute. Additionally, the difference between the performance of the linear regressions between OGA and OGA+AGE with old-growth attributes were minimum (Appendix 6.3 – Figure 6.9 and 6.10). From all eight models developed, I selected three to predict old-growth values for the whole study site. First was AGE_CLASS, because it is the method currently used for defining and location old-growth forests (MFLNRORD 1995). Second, RFOGA because this was the model with the highest accuracy among the categorical models for the "high" and "very-high" old-growth values. The third and last model was OGA, because the model has a high performance when compared with the pure age model (AGE), and it did not include age, which is a costly attribute to be measured.

Table 2.6 Statistical summaries of old-growth index models

Regression	Adj. R-squared (+/- SD)	Residual standard error (+/- SD)
AGE	0.35 (+/- 0.04)	31.19 (+/- 1.84)
OGA+AGE	0.71 (+/- 0.01)	0.68 (+/- 0.02)
OGA	0.71 (+/- 0.01)	0.55 (+/- 0.01)

2.3.3. Comparison between old-growth maps:

The RFOGA map underestimated, by at least 1 class difference, 67.5% of the pixels in the AGE_CLASS map (Table 2.7). This percentage went up to 85.4% when comparing AGE_CLASS with the OGA map. The high percentage of underestimation suggests that

AGE_CLASS maps overestimated the old-growth value, especially for the “Very-high” class. The “Very-low” class was the one with the least difference between the models. In addition, the OGA map is the most conservative regarding old-growth mapping, as it mostly underestimated the “high” and “very-high” old-growth value classification comparing to both AGE_CLASS and RFOGA models. Besides, the AGE_CLASS map has a higher number of pixels classified as “Very-high” old-growth value than OGA. However, those pixels are more scattered and do not follow patterns observed in both RFOGA and OGA (Figure 2.5).

I noticed that AGE_CLASS mapping seems not to classify the classes with higher old-growth value correctly since the RFOGA and OGA models diverged from AGE_CLASS in a similar way. The OGA map captures patterns of aggregation between “High” and “Very-high” old-growth value, while AGE_CLASS has scattered pixels with very high values surrounded by pixels with intermediate and low values. I expected that clumps of the old-growth forest would intertwine with mature, and that old-growth would be the core of clumps of mature forests. The lack of pattern observed in the AGE_CLASS map suggests that age alone is a poor indicator of forest structures, which has also been observed with the empirical data (Appendix 6.3). Thus, when I tried to force random forest to predict age with LiDAR, the resultant model was weak and with a high error. Also, when we compare the RFOGA and OGA maps, RFOGA over-represented “intermediate,” “high,” and “very-high” old-growth value classes. However, the patterns of distribution of OGA correlate with the ones from RFOGA as overestimations were systematic throughout the old-growth value classes (Figure 2.5 and Table 2.7).

Overall, the results suggest that AGE_CLASS is not capturing the real pattern of distribution of old-growth values. Additionally, RFOGA is overly representing “high” and “very-high” old-growth classes. The use of such a map can wrongly indicate an abundance of high old-growth value forests. Setting definition thresholds by age or structure influences the perception of how much old-growth is in a landscape. If rarity is the impetus to conserving old-growth and if the old-growth definition is arbitrary, old-growth should be defined in a way that keeps it rare but not too rare. If old-growth is defined more broadly so that it is relatively common, it may be less valuable from a biodiversity perspective. Even though RFOGA is a robust model with high accuracy for “Very-high” old-growth value, its definition is too broad. Thus, we opted for a more conservative old-growth mapping, OGA. Finally, we also compared the difference between model OGA+AGE and OGA to make sure the exclusion of “age” as one of the old-growth attributes did not alter the patterns of distribution of old-growth values. We found that no pixel had a difference higher than +/- 0.66 (13%), which is less than one class difference.

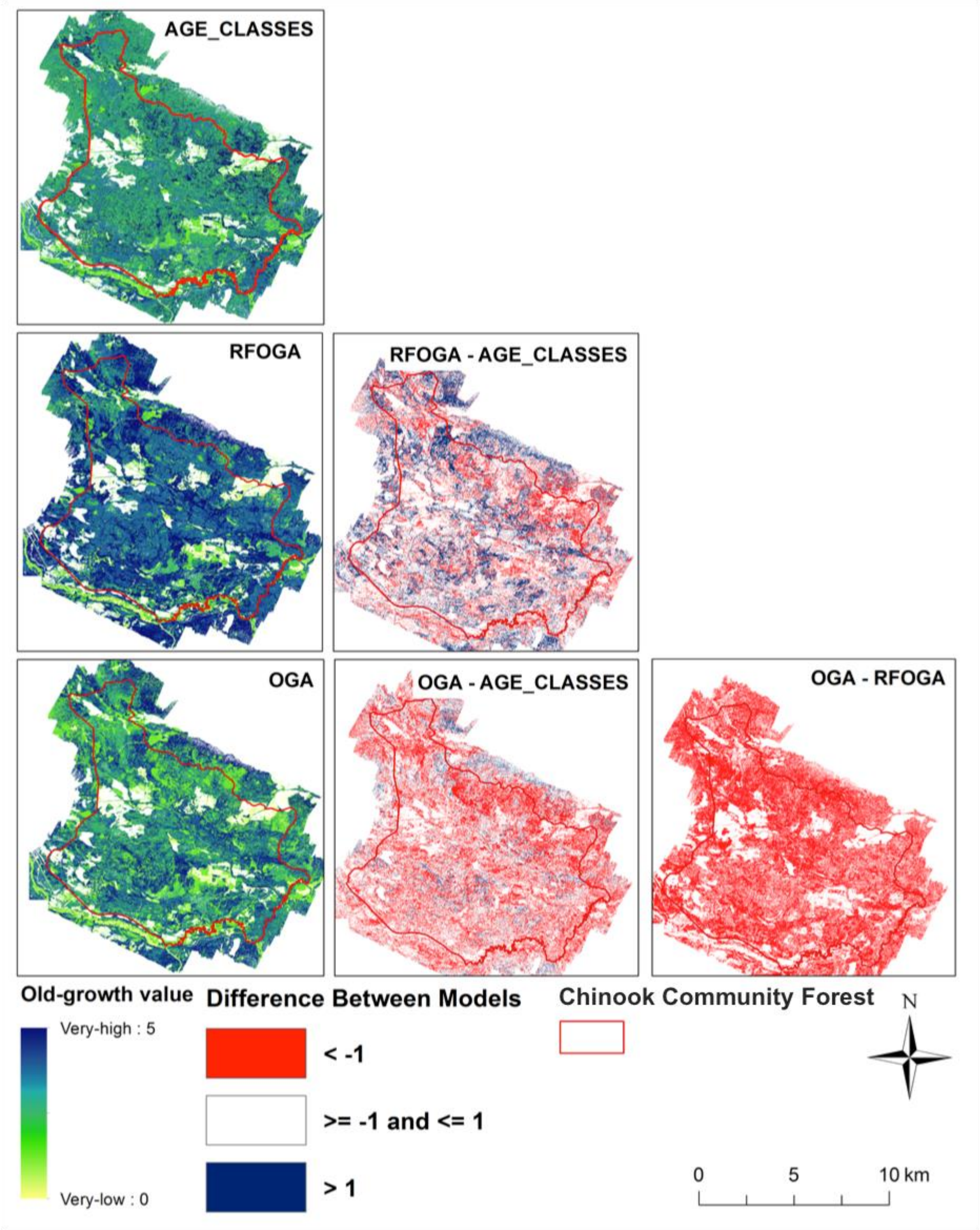


Figure 2.5 Spatial correlations and constraints between old-growth models with red representing underestimation and blue overestimations.

Table 2.7 Comparison between models to evaluate and locate differences between classes.

Class	RFOGA – AGE_CLASS Class Error (%)		OGA – AGE_CLASS Class Error (%)		OGA - RFOGA Class Error (%)	
	< -1	> 1	< -1	> 1	< -1	> 1
Very-low	0.0	0.1	0.0	0.0	0.0	0.2
Low	17.8	0.4	16.9	0.7	0.6	0.0
Intermediate	6.3	45.8	16.5	10.6	51.7	0.1
High	8.2	0.0	37.5	0.0	60.3	0.0
Very-high	67.5	0.0	85.4	0.0	76.6	0.0

2.3.4. Assessing Set-Aside Old-Growth Forests

The images collected during field visits supported the "classification" according to the OGA model (Figure 2.6). From the 14 sites visited, four plots were classified as "Very-high" old-growth value by OGA, against one by AGE_CLASS. As well, OGA classified only one plot as "Intermediate" old-growth value against seven by AGE_CLASS. AGE_CLASS classified most of the plots as "Intermediate" old-growth value, which supports the idea that age classification masks old-growth forest attributes. Additionally, the old-growth index (OGA) captured better the accumulation of old-growth attributes in comparison with AGE_CLASS. However, wetlands received low old-growth values in both models. While wetlands do not attain the characteristics we were tracking as important old-growth attributes, this environment usually represent significant pools of carbon and biodiversity (Adhikari et al. 2009, Kayranli et al. 2010). Despite its importance for biodiversity, carbon and water resources, these areas often do not have high value for timber and are difficult to access with machinery. Also, in the study site, wetlands already have legal protections, and have to be avoided during forest operations (MFLNRORD 1995). Although not accurately depicted in the map, wetlands are less likely to be affected by forest operations then old-growth forests.

In addition, all result suggested that OGA is the model to better capture old-growth values in the landscape. Thus, I utilized the OGA map to track old-growth values in the landscape and assess the current set-aside old-growth forests (OGMAs).

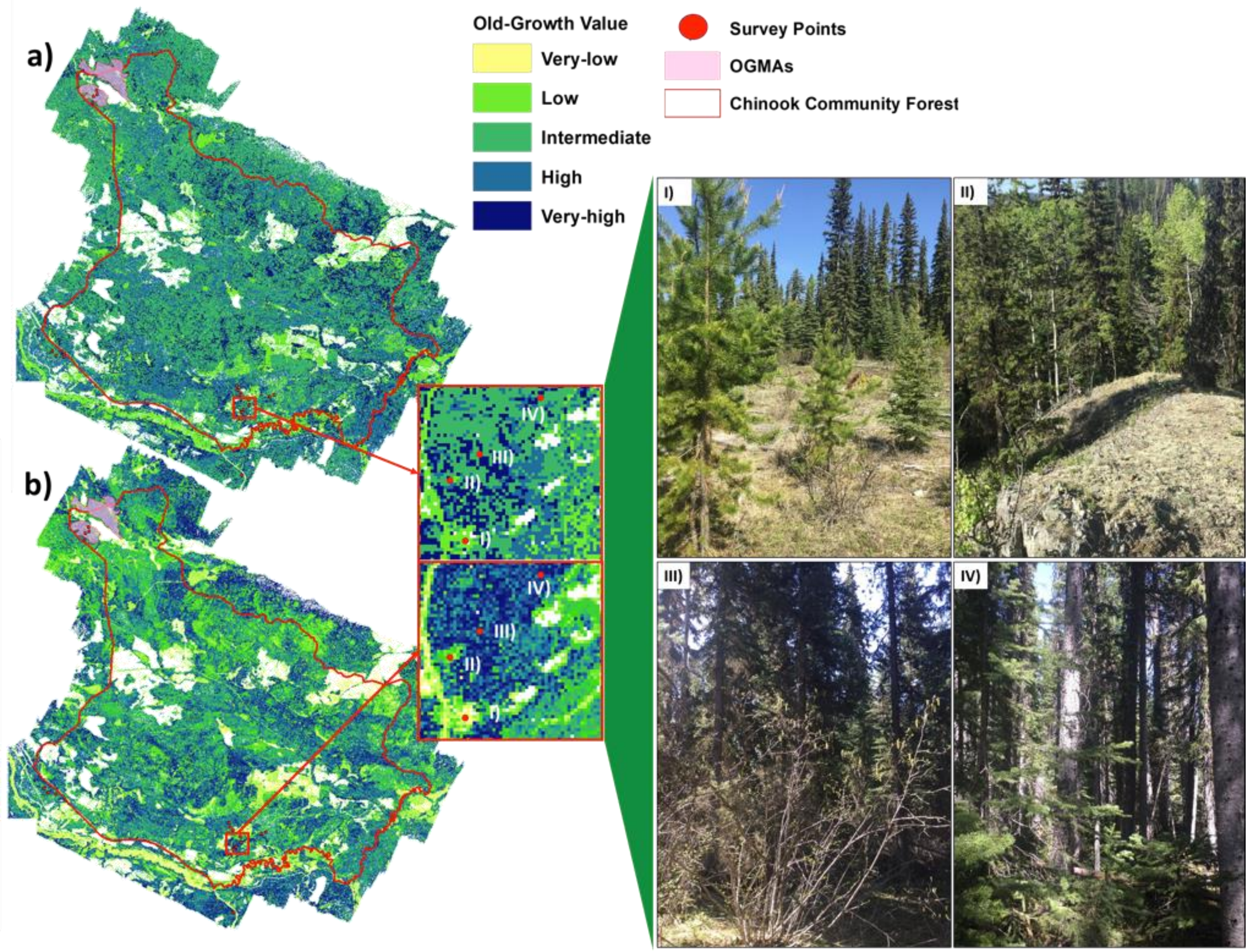


Figure 2.6 Forest was classified into a) four different forest successions (classification) and b) gradient of the abundance of old-growth attributes (regression). Fourteen locations were visited to evaluate the effectiveness of these two classifications. Four of those sites are depicted here: I) depicts low level of old-growth attributes (young forest), II) bare rock, III) intermediate level of old-growth attributes, and IV) high level of old-growth attributes. a) Model Accuracy: 54.4% and “Very-high” class error = 63,0%, b) R2: 71.5%, MSE= 0.55.

According to our old-growth index model, 14.7% of the tenure area has "Very-high" old-growth value (Figure 2.7). If we add the "High" old-growth value to it, it can go up to

41.6% of potential old-growth. However, from the 14.7% of the landscape that is covered by forest with "Very-high" old-growth value, only 13.5% is "protected" inside OGMAs. Additionally, only 2.55% of the OGMAs have "Very-high" old-growth value cover greater than 50%, and more half of OGMAs had less than 25%. These results suggest a high fragmentation of "Very-high" old-growth value forest within OGMAs. There is no specification regarding the percentage cover of old-growth forests one OGMA has to contain to be considered adequate. It is not the goal of this study to tell which OGMA is effective or not. However, it concerns that only 13.5% of all forests with "Very-high" old-growth value is inside OGMAs. Also, these forests are fragmented between the 40 existing OGMAs, since more than half of the OGMAs have less than 25% of the forest with "Very-high" old-growth value. Yet, areas with "High" old-growth value were generally surrounding areas with "Very-high" old-growth value, in a gradient. This pattern indicates that one OGMA while retaining a small percentage of "Very-high" old-growth value forests, may simultaneously contain "High" old-growth value forests.

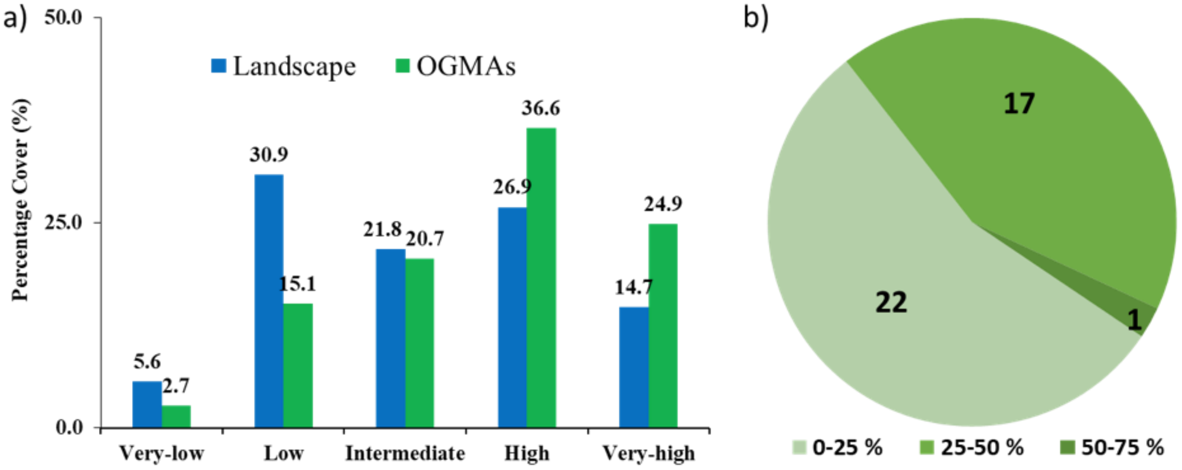


Figure 2.7 Summary of old-growth assessment in the study area, utilizing the old-growth index OGA, where a) displays the percentage cover of each old-growth value class for the whole landscape and only for the areas within OGMAs, and b) depicts the number of OGMAs per percentage forest cover of “Very-high” old-growth value.

2.4. Discussion:

2.4.1. The old-growth index:

The results suggest that the structure-based old-growth definition better captures the continuous nature of the forest than pure age. The exclusion of age from the models did not affect the overall models' performances. Moreover, age, although a useful indicator of old-growth, is not considered as valuable as some other indicators because the dominant species in old-growth forests are often multi-aged (Gillis et al. 2003). As well, forests of the northern interior of British Columbia, Canada, are under a regime of frequent large-scale disturbances, such as wildfire (DellaSala et al. 1996, Spies et al. 2006). In such a scenario, age estimates can become quite tricky due to the legacies (e.g. surviving trees, woody debris) left in the landscape after stand-replacing disturbances. The inclusions of these legacies during inventories could lead to the overestimation of stand age and drive wrong conclusion about the forest succession. Therefore, for forests that experience more frequent events of natural disturbances, the structure-based old-growth definition developed in this study is more indicated than age-based definitions.

The forest structure-based model OGA not only had better overall statistical performances than age-based models but also better captured old-growth attributes. Consequently, the old-growth index has a better chance to capture the functional old-growth forests in the landscape, as opposed to a forest with few old-trees. This is important because evidence suggests that the occurrence of many, but not all, species typically found in old-growth is linked to specific structural attributes and not to old-growth as such (e.g. McElhinny et al. 2006, Lonsdale et al. 2008). Due to environmental conditions created by old-growth forest structures, these forests are often the habit for many wildlife species

(Mosseler et al. 2003a, McElhinny et al. 2006b). Thus, the strict separation of forested landscapes in old-growth and non-old-growth may not represent an optimal species conservation strategy concerning the provision of habitats in the landscape (Bauhus et al. 2009). Stand development is continuous, and hence there is not a clear threshold to indicate when a forest enters the old-growth stage (Spies and Franklin 1991, Wirth et al. 2009b). Nevertheless, a classification of forest succession, either age- or structure-based, is still arbitrary (Hilbert and Wiensczyk 2007, Wirth et al. 2009b). Therefore, the use of the old-growth index (OGA) instead of binary classes is essential in dealing with the continuous nature of forest structural development and capturing functional old-growth forests.

2.4.2. Application:

Despite the advances in the old-growth definition, there are still important methodological challenges to be overcome. The old-growth index may be an alternative to the current landscape scale definitions and deal with some of these challenges. For example, due to the diversity of old-growth forests, a consensus on a single ecological definition of old-growth may never be reached, and may not be desirable given the diversity of forests (Spies 2004, Wirth et al. 2009b). Thus, it is impossible to use the same definitions and management practices everywhere. The framework utilized in this study can be the means for multiple local definitions based on measurable structural features and biophysical site conditions. Such multiple definitions have been long supported by different authors (Braumandl and Holt 2000, Mosseler et al. 2003c, McElhinny et al. 2006a, Hilbert and Wiensczyk 2007, Wirth et al. 2009b). Since the index is developed based on local abundance of old-growth attributes, the framework may facilitate the development of multiple local definitions. In addition, the degree to which old-growth forests and old-growth structures should be maintained or restored at the landscape level is a complex political question (MFLNRORD 1995, Environmental Law Centre 2013). The methods current used to select set-aside old-growth forests might be increasing the risk of old-growth loss as they are mostly based on stand-age (MFLNRORD 1995, Gillis et al. 2003, Environmental Law Centre 2013). The old-growth index allows for a holistic view of the landscape's old-growth values, which indicate the level of abundance or rarity of old-growth in a specific location. It may serve as the basis for setting local or regional targets for conservation and management activities.

The old-growth index could be used to design new old-growth reserves, assess current reserves, and monitor old-growth values as an alternative to the current age-based methods. However, set-aside forests may be prone to natural disturbances, especially in boreal and sub-boreal regions (Spies et al. 2006). Thus, as discussed by (Burton et al. 1999), protecting old-growth forests should be only part of the strategy to maintain old-growth value in the landscape. Also, while old-growth is the most vulnerable forest succession, there is not a forest succession considered as the most essential (Swanson et al. 2011). Areas outside reserves facilitate gene flow and migration of populations as well as provide complementary habitat (Lindenmayer and McCarthy 2002). Thus, the old-growth index can aid in the planning of long-term strategies to accommodate a dynamic population of old-growth stands in multiple stages of development within landscapes subjected to wildfire, pathogens, and climate change (Spies 2004). Since the index can track old-growth values throughout the whole landscape, set-aside forests can be complemented with managed forests that also retain key attributes of primary and old-growth forests. Such a strategy has been previously proposed by Beese et al. (2003), who suggested that set-aside old-growth should be combined with uneven-aged stand management to maintain late-successional forest attributes. This strategy is particularly important in areas where reserves are too small to ensure the occurrence of natural disturbances within their boundaries or to accommodate all developmental stages of forest succession (Kneeshaw and Gauthier 2003).

2.4.3. Pros and Cons of the old-growth index:

Despite the vast literature on the topic (Braumandl and Holt 2000, Holt et al. 2002, McElhinny et al. 2006a, 2006a, Hilbert and Wiensczyk 2007, Wirth et al. 2009b)(see also Table 1.1), this work is the first to create a landscape-scale definition of old-growth value based on field-measured old-growth attributes and ALS metrics. The advantages of this structure-based definition are that data from most forest inventories contain many of the attributes included in the index and the ease of measurement of those attributes (Mosseler et al. 2003c, McElhinny et al. 2006a). Additionally, the management objective can dictate the old-growth threshold. For example, in Chinook community forest forests are managed for timber and under the frequent regime of large-scale disturbances. In these conditions, it is expected that stands with high old-growth value to be rare (DellaSala et al. 1996, Spies et al. 2006). Thus, a threshold for the definition of old-growth based on the index can be set such that set-aside old-growth forests include forest with intermediate old-growth value. The definition of a threshold is as arbitrary as any other classification method. However, with the old-growth index the information of the distribution of old-growth values in the whole landscape is known, and the rarity of old-growth may be used to obtain desirable levels of old-growth.

The old-growth index allows the measurement of old-growth relative to the abundance of attributes present in the target landscape. A local old-growth index instead of broad definitions developed for entire regions can avoid misinterpretations of forest state

(Braumandl and Holt 2000, Holt 2000). However, while this framework gains in local representation, it loses in portability. Daniels (2003) pointed out that it is challenging to extrapolate structural definitions from one forest type to another. Indeed, while the methodology of this study may apply to other environments, the characteristic of the old-growth forest may change drastically. Also, old-growth includes many distinctive structural components that do not all change at the same rate and may not all be present in every stand (Spies 2004).

In addition to the lack of portability, the old-growth index and old-growth mapping have other caveats. The index includes the classification of wetlands as areas of low old-growth value. The wetlands are environments that play a significant role in the provision of ESs and biodiversity (Adhikari et al. 2009, Kayranli et al. 2010). Despite the importance of wetland ecosystems, these areas often do not have high value for timber and have difficult access to machinery. Also, in the study site, wetlands have already legal protections, and so have to be avoided during forest operations (MFLNRORD 1995). The inclusion of a wetness metric to the old-growth index could lead to overestimation of areas with low old-growth value that also are not valuable for wetland protection. Thus, while old trees might be present in wetlands, that should not be a reason enough to modify the old-growth index and classify them as old-growth forests. The other problem with the old-growth index is that it does not include any estimates of human or natural disturbance. In the interior forest, where natural distubances are more frequently, old-growth attributes can be less distinctive (DellaSala et al. 1996). Similar to natural disturbances, human disturbances often reduce the structural variability that is typical of many naturally developed older forests (Spies 2004). Nevertheless, Spies (2004) discuss that the source of the disturbance (e.g., human or fire) would be irrelevant if stands are defined primarily based on structural development.

2.5. Conclusion:

In this work, we developed an old-growth index based on forest structures measured with traditional field methods. While the index is specific to the study site, the methodology is adaptable to other forest types and ecosystems. We utilized the old-growth index to map old-growth value in the landscape and evaluate the amount and quality of the old-growth forest for the study site. This assessment showed that less than 15% of the forests in the study area have “very-high” old-growth value. Inside OGMAs, forests with “very-high” represent ~25% of the total set-aside forests. The main limitations of the index are in the identification of old-growth values in wetlands and other environments that limit tree growth (e.g. high elevation), and the portability of the index to other forest environments. The old-growth index map allows for a holistic assessment and monitoring of old-growth value in the landscape, which can aid managers to track the amount and quality of old-growth in the landscape and set targets for old-growth retention in a transparent manner. Most importantly, mapping old-growth value can aid in the conservation of this rare resource and its services in managed landscapes.

3. SYSTEMATIC CONSERVATION PLANNING OF OLD-GROWTH VALUES

Abstract: A systematic conservation-planning tool was applied to design and evaluate old-growth reserves that simultaneously provide multiple ecosystem services (ESs). Old-growth forests play an essential role in the provision of many ESs, such as stocks of carbon and habitat for many species. Current conservation policies, such as the old-growth management areas (OGMAs) may not be well situated to protect old-growth while ensuring the provision multiple services. Thus, identifying priority areas for old-growth forests conservation and multiple ESs can aid to the maintenance of these values in the landscape. First, ecosystem services were mapped using LiDAR and field measurements, then an spatial optimization tool, “PrioritizR,” was utilized to identify optimum reserves’ networks for alternate conservation scenarios. We discovered that ESs provisioning of current OGMAs are similar to designed optimum reserves, even though current and designed reserves have minimum shared territory. In addition, the synergies among the ESs and old-growth were increased when water was removed from scenarios. Finally, we observed that an increase in OGMAs areas are not likely to affect timber harvesting until 28% of the study site is set-aside, more than five times the current OGMAs’ area. The information obtained from "PrioritizR" can be used to indicate the scope for altering forest reserves locations and to guide the establishment of new reserves while ensuring the provision of multiple ESs.

3.1. Introduction:

Ecosystem Services (ESs) are the mental and physical benefits obtained by human populations from ecosystems. Despite recent advances in science, ESs have rarely been incorporated into management decisions (Chan et al. 2006). Old-growth forests have high provisioning of ESs, such as biodiversity (Spies 2004, Bauhus et al. 2009), ecotourism (FAO 2016), genetic resources (Mosseler et al. 2003b), and carbon storage and sequestration (Luyssaert et al. 2008, Maxwell et al. 2019). Therefore, using ESs provisioning as a way to manage older forests could provide a unique opportunity for their sustainability. However, land management decisions for multiple-user landscapes, such as old-growth forest management, can be complex if the users have different values. For example, the same parcel of land can be valued for timber extraction, recreation, biodiversity conservation, food production, or cultural values by different users (Coomes et al. 2008, Ninan and Inoue 2014). These conflicting values can lead to management problems. Therefore, thoughtful strategies are required to manage forest resources for the provision of multiple ESs.

The improvement of human well-being through strategies that promote ESs provisioning is one of the goals of many environmental policy initiatives (MA 2005, Raudsepp-Hearne et al. 2010, Guerry et al. 2015). In Canada, Quebec and British Columbia governments developed strategies to retain potential forest ecosystems for old-growth areas (MFLNRORD 1995, Arsenault 2003, Mosseler et al. 2003c). Canada has pledged, in the International Convention on Biological Diversity, to develop its forests sustainably, which requires close attention to old-growth (Mosseler et al. 2003c). Moreover, initiatives such as the United Nation's Sustainable Development Goals (SDGs) and the Reduced Emission from Deforestation and Environmental Degradation (REDD+) focus on managing multiple ESs (Alexander et al. 2011, Griggs et al. 2013). As well, the relationships between different ESs are complex, and our knowledge of the effect of the multiple drivers of change (e.g. timber harvesting) on ESs is limited (Nelson et al. 2009, Bennett et al. 2009, Kremen and Ostfeld 2005). Ensuring that forest management actions retain multiple ESs to target levels while providing opportunities for timber extraction is a complex spatial optimization problem (Schröter and Remme 2016, Snäll et al. 2016).

Unsustainable management strategies can cause unexpected declines in ESs provisioning and human wellbeing (Lindenmayer et al. 2012, Gaston et al. 2013). For example, logging can lead to increased areas for cattle grazing and meat production but also lead to decreased biomass carbon storage (Coomes et al. 2008). The loss of forests can also reduce habitat for bushmeat species, an important ES for some local communities (Damania et al. 2005). On the other hand, lower timber densities might be favourable for other bushmeat species (Swanson et al. 2011). Lastly, timber can be an essential part of local economies. If all logging operations were banned, local communities could be negatively affected. Consequently, a community dependent on timber extraction revenues might not value the other ESs provided by preserved forests compared to those of forest extraction. The participation of communities and smallholders in the management of forests is essential to increase society's access and recognition of ESs (FAO 2016). Thus, an alternative to protected areas, such as community management areas, might be an alternative conservation tool for managed forests (Rodrigues et al. 2004). A community forest is a notable example of the management of multiple ESs since timber is not the only target in these communities (MFLNRORD 2017a).

Several studies have previously focused on using systematic conservation planning (SCP) tools, such as Marxan and Zonation, to spatially optimize ESs provision (Chan et al. 2006, Nelson et al. 2009, Dade 2018)(see also Luck et al. 2012). Systematic conservation planning describes the process of identifying and preserving areas of conservation value (Margules and Pressey 2000, Wilson et al. 2009). It utilizes a spatial analysis of quantitative data to identify locations for conservation investment. For example, Chan et al. (2006) identified the priority areas for ecosystem service provisioning across a multi-functional region. Law et al.

(2017) identified the effect of different land-use strategies on achieving ecosystem service targets within a multi-use region of Borneo, Indonesia. More recently, (Dade 2018) utilized spatial prioritization in an urban setting to identify management strategies to enhance ESs provisioning in parks while promoting social equality. However, our knowledge on spatially optimization of the provisioning of multiple ecosystem services is still limited (Snäll et al. 2016). In addition, the concept of systematic conservation planning and spatial prioritization has not yet being applied to the conservation of old-growth values and multiple ESs in landscapes managed for timber.

In the conservation realm, old-growth forests have been traditionally valued as wildlife habitat (Mosseler et al. 2003c). However, conservation of old-growth forests should go beyond the protection of wildlife habitat as these forests offer vast ESs (Wirth et al. 2009a, FAO 2016). In contrast, the focus of landscape management has been the provisioning of timber, food and other raw materials, which can negatively affect other ESs (Monfreda et al. 2008, Ramankutty et al. 2008, Bennett et al. 2009). Therefore, finding a balance in management that retains key areas for the maintenance of the provision of ESs in old-growth forests is crucial if maintaining multiple values is a goal. This work aims to (1) analyze the spatial relationships between ESs and old-growth values, (2) identify strategies for the management of multiple ESs using a systematic conservation planning tool to, and (3) evaluate the trade-off between ESs' habitat protection versus timber harvesting. We perform this analysis in the Chinook Community Forest (CCF), located within the Skeena region, which management area overlaps with six First Nations' territories.

3.2. Material And Method:

3.2.1. Study Area:

(See section 2.2.1)

3.2.2. Estimating Ecosystem Services

A machine learning approach, Random forest (RF), was utilized to extrapolate plot-level estimates of ESs to the whole study area with LiDAR metrics (Wulder et al. 2008, Dade 2018) (See also Table 1.2). These services were timber volume (m^3), carbon storage (Mg), tree diversity (Shannon diversity index), and water values (wetness index) (Figure 3.1). The Shannon diversity was generated following the same procedures as DeJong (1975). The major difference is that we utilized aboveground biomass estimates of individual species to calculate the index. The allometric equations utilized to estimate timber volume, carbon and above-ground biomass at the plot level are described in Appendix 6.2.

RF is a powerful classification technique and has been successfully utilized for forest succession classification (Falkowski et al. 2009, Belgiu and Drăguţ 2016, Cutler and Wiener 2018). I applied the random forest (RF), statistical model, using the "randomforest" package (Therneau et al. 2011, Cutler and Wiener 2018) in the R (R Development Core Team 2018) programming environment to connect field delivered metrics to LiDAR metrics. RF is a machine learning method that adds randomness by randomly selecting subsets of the data without replacement, which increases the diversity of decision trees ("Regression Trees"). RF combines decision trees, considering the values of an independent random sample, with the same distribution, for all the trees in the forest (Breiman 2001). Thus, each decision tree (regression tree) is built with not only a random subset of the response variable but also the predicting variables. This structure prevents overfitting and increases the robustness of the model.

The prediction variables are the same set of LiDAR delivered metrics listed in Table 2.3. Since there are 36 predicting variables, 12 of them are randomly utilized in each division as indicated by Breiman and Cutler (2003). The response variables are the plot-level estimates of carbon, timber, tree diversity, and an index for old-growth value (see Chapter 2 – Section 2.2.5). The random forest model produced 10,000 decision trees to ensure the stabilization of the model. Then, a k-fold (k=4) procedure with the r package "Caret" divided the data into training and validation data set. Thus, a random forest model is generated with a subsample of 75% of the available data and validated with the remaining 25%. This procedure was repeated ten times for each model. The results are reported in terms of means and standard deviation of the r-squared and mean square error of the ten repetitions.

It was also the objective of this study to represent water value as an ES since old-growth play an essential role in the landscape hydrology (Wirth et al. 2009a). For that, the soil moisture index, or wetness index, might be a relevant proxy for water value (Lang and McCarty 2009). The wetness index from ArcMap 10.1, was derived from a LiDAR high-resolution digital elevation model (DEM), was utilized as a proxy for water values (Appendix 6.5). Biodiversity, although a critical ES, was only partially measured in this study. Since the actual representation of the variation of biodiversity within or between regions is not likely to be captured through neither fieldwork nor remote sensing, surrogates are still necessary to represent this ES. Old-growth values and tree diversity are the proxies for biodiversity value. As indicated by Wilson et al. (2018), there is divergence regarding the performance of surrogates. Regardless, the objective of this study is to test the use of the conservation prioritization tool “prioritizR” as an OGMAs’ designing tool. Thus, while the accuracy of the individual inputs is important, they do not limit the study.

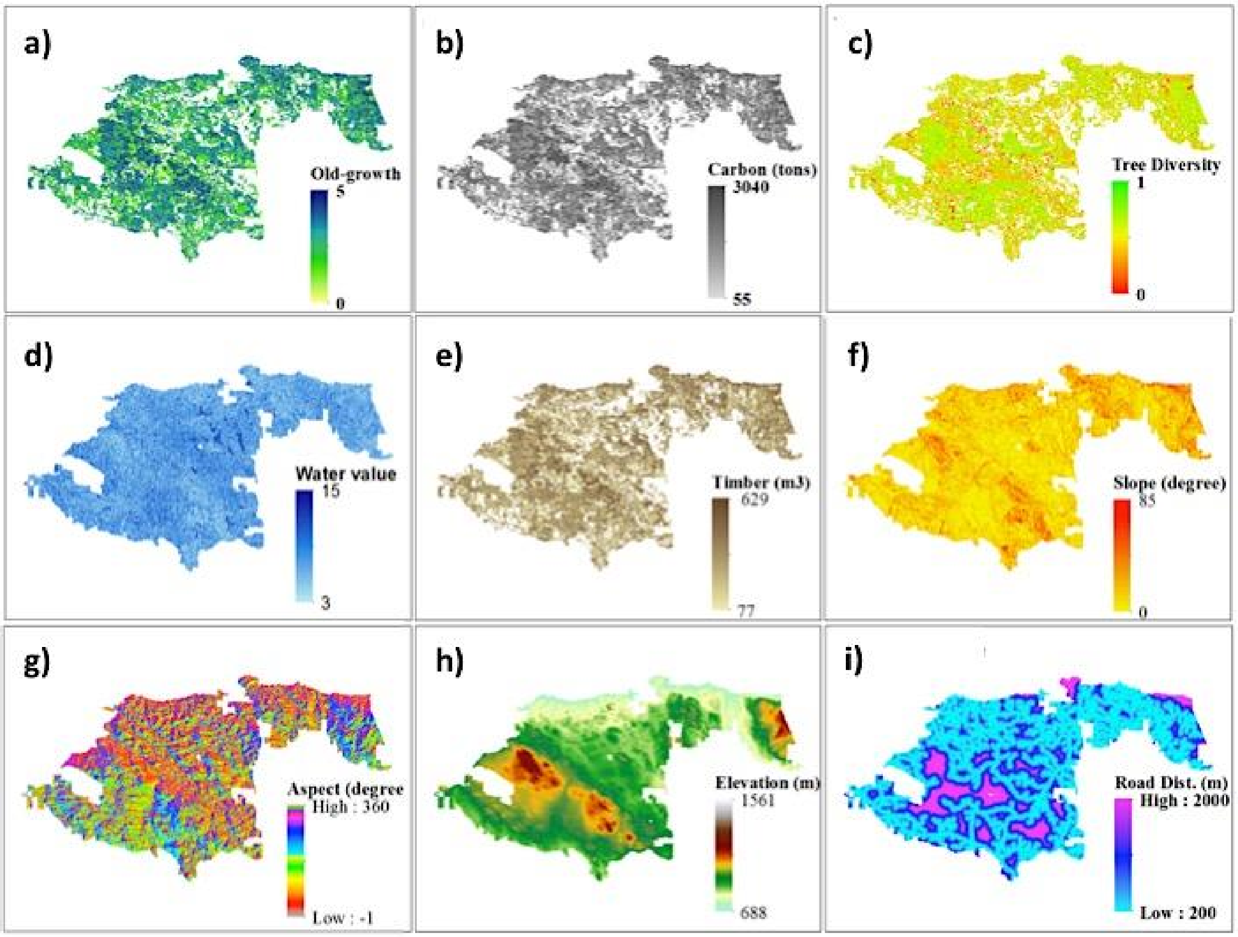


Figure 3.1 Ecosystem Services and landscape features utilized in the development of “prioritizR” scenarios. Section 2.2.5 describes the framework applied to generate the a) old-growth index (Figure 2.2). The ame framework was applied to estimate b) carbon, c) tree diversity, e) timber, and in Chinook Community Forest. The d) water value and landscape features f) to i) were developed with surface analysis in ArcMap.

3.2.3. Systematic Conservation for Old-Growth Values

As a conservation planning tool, I utilized “PrioritizR” to simulate optimum reserves’ networks for the provision of old-growth and multiple ecosystem services (Table 3.1). PrioritizR is an “R package,” which utilizes integer linear programming (ILP) techniques to provide a flexible interface for building and solving conservation planning problems (Hanson et al. 2019). Once built, conservation-planning problems were solved using the exact algorithm solver Gurobi (V.7.0). Our conservation-planning problems were the simulation of reserves that prioritize each ecosystem service individually (old-growth, carbon, water value, and tree diversity) and all of them together with the same area current set-aside for OGMAs in the study site. For that, we utilized the "maximum utility objective" function, which allocates the maximum of the target features into a limited number of planning units (limited area). High clumpness penalty was also applied to the problems to obtain contiguous reserves' design. More information on the selection of clumpness is available in the Appendix 6.7. We generated five OGMAs' networks as an alternative to the current one, where the location might be partially or entirely shifted while preserving the current OGMAs' extension. We also simulated increases in OGMAs areas having current OGMAs and the five optimum OGMAs' networks as a starting point (Table 3.1).

Timber harvesting has the potential to modify forest patterns in the landscape and negatively affect other ESs provisioning. However, the study site is primarily managed for timber values. In this conjecture, in order to prioritize areas for the conservation of multiple ES, harvesting scenarios have to be taking into account if we want to understand the trade-offs between protecting and harvesting. For that, we set "prioritizR" to simulate areas that are "priority" for harvesting, which are the areas with high value for timber, low elevation, flat slopes, and great proximity to existing roads (Table 3.1). The results of harvesting scenarios were plotted against OGMAs simulations to evaluate the trade-off between increasing protection and timber harvesting. It is worth noting that we did not discriminate forest stand that has not reached the harvesting stage, or timber that is no longer viable. Thus, the total estimated timber volume was corrected by harvesting yields (100, 75, and 50%) to account for losses in timber volume due to harvesting practices, bole rot, tree size, decay class, age, and other factors. The deductions were applied uniformly throughout the landscape.

Table 3.1 Conservation planning scenarios for OGMA design with "prioritizR"

Prioritizing Feature	PrioritizR Models	Same area Scenarios		Increase Area Scenarios	
		Percentage	Measure	Percentage	Measure
	Current OGMAs	5.39%	3541 ha	1 - 50%	1% = 669 ha
Old-growth	Old-growth OGMAs	5.39%	3541 ha	1 - 50%	1% = 669 ha
Carbon	Carbon OGMAs	5.39%	3541 ha	1 - 50%	1% = 669 ha
Tree diversity	Tree Div. OGMAs	5.39%	3541 ha	1 - 50%	1% = 669 ha
Water value	Water OGMAs	5.39%	3541 ha	1 - 50%	1% = 669 ha
All Features	All Features OGMAs	5.39%	3541 ha	1 - 50%	1% = 669 ha
Timber 100%	Landscape Features*	-	-	1 - 50%	1% = 148,047 m^3
Timber 75%	Landscape Features*	-	-	1 - 50%	1% = 148,047 m^3
Timber 50%	Landscape Features*	-	-	1 - 50%	1% = 148,047 m^3

*High value for timber, proximity with existing roads, low elevation, and flat slopes

3.3. Results:

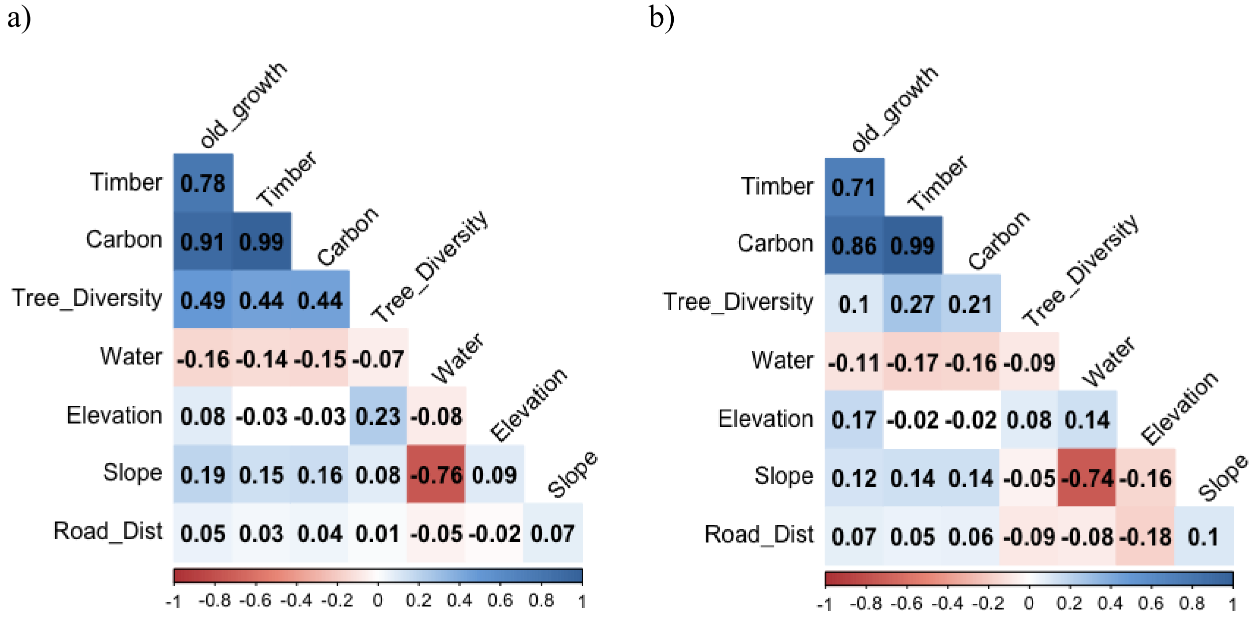
3.3.1. Ecosystem Services

Random forest models for the estimation of old-growth index and timber had higher r-squares the other estimated services (Table 3.2). The high standard deviation is expected due to the diversity of plots measured in the field. We encountered plots placed in lakes, barerock till plots in very high value old-growth forests. The estimated tree diversity was the least robust of the models. The inclusion of hyperspectral imagery metrics such NDVI could improve the estimates by aiding to the differentiation of species. For timber and carbon, the pixel value corresponds to per hectare measurement of timber volume (m3) and megagram of carbon (Mg). Old-growth and tree diversity are indices, where the former ranges from 0-5 and the latter 0-1. There was no measure of accuracy for the water value, as it was directly derived from a DEM.

Table 3.2 Summary of results from cross-validated random forest models (four fold stratifications with 10 replicates)

RF Model	Mean (+/- SD)	Adj. R-squared (+/- SD)	Residual standard error (+/- SD)
Old-growth	2.18 (+/-1.36)	0.71 (+/- 0.01)	0.55 (+/- 0.01)
Timber (m^3/ha)	169.17 (+/-153.30)	0.70 (+/- 0.03)	2.06 (+/- 0.07)
Carbon (Mg/ha)	0.04 (+/-0.03)	0.58 (+/- 0.01)	0.01 (+/- 0.00)
Tree Diversity	0.43 (+/-0.39)	0.35 (+/- 0.03)	0.19 (+/- 0.01)

As expected, carbon and timber had the greatest correlation, as carbon is a function of timber. Nonetheless, there was a strong correlation between old-growth and carbon compared to old-growth and timber, 0.91 and 0.78 respectively. The smaller correlation suggests that there is room for management of the landscape for old-growth and carbon values while maintaining areas for timber harvesting. The correlations between timber and water values with old-growth did not change substantially comparing OGMAs (Figure 3.2 b) with landscape (Figure 3.2 a). On the other hand, tree diversity has a much lower correlation with old-growth inside OGMAs compared to the landscape, 0.10 and 0.49 respectively. It both indicates that the current OGMA network does not effectively capture tree diversity and a need to develop strategies to promote such value both inside and outside OGMAs. The correlation between old-growth and elevation increased from 0.08 in the landscape to 0.18 for OGMAs. It suggests some bias in protecting higher altitude old-growth. However, other landscape factors such as slope, aspect and road distance did not differ from landscape correlation to OGMAs' correlations. Water values had a weak negative correlation with all other ecosystem services and old-growth, which was not expected as wetter environment are usually positively correlated carbon. However, it is worth noting that correlation does not mean causation. The correlation can give us an indication of which services are likely to have synergies or originate higher trade-off with one another. Yet, we still need to evaluate management scenarios to evaluate these relationships.



a)

	old_growth	Timber	Carbon	Tree_Diversity	Water	Elevation	Slope
Timber	0.78						
Carbon	0.91	0.99					
Tree_Diversity	0.49	0.44	0.44				
Water	-0.16	-0.14	-0.15	-0.07			
Elevation	0.08	-0.03	-0.03	0.23	-0.08		
Slope	0.19	0.15	0.16	0.08	-0.76	0.09	
Road_Dist	0.05	0.03	0.04	0.01	-0.05	-0.02	0.07

b)

	old_growth	Timber	Carbon	Tree_Diversity	Water	Elevation	Slope
Timber	0.71						
Carbon	0.86	0.99					
Tree_Diversity	0.1	0.27	0.21				
Water	-0.11	-0.17	-0.16	-0.09			
Elevation	0.17	-0.02	-0.02	0.08	0.14		
Slope	0.12	0.14	0.14	-0.05	-0.74	-0.16	
Road_Dist	0.07	0.05	0.06	-0.09	-0.08	-0.18	0.1

Figure 3.2 Correlation analyses of ecosystem services and landscape variables a) in the whole landscape, and b) within OGMAs. Values in the grid correspond to the correlation direction and strength between the variables, and the color scale, in the x axis, represents the significance level (p-value<0.01)

3.3.2. Systematic conservation planning applied to OGMAs

Only a fraction of the priority areas for the conservation of old-growth and other ecosystem services are currently inside OGMAs (Figure 3.4 a and d) (See also Appendix 6.8). The greatest overlapping between OGMAs and priority areas was for old-growth prioritization (7.68%), and the smallest for tree diversity (0.44%). Besides, only 1.05% of the area is shared among all alternative scenarios developed here. However, the difference between the percentages of each ES reserved in each alternative OGMAs' network was quite small (Figure 3.3). For instance, the highest percentage of old-growth representation was achieved by the old-growth prioritization (7.16%) and the smallest by water value prioritization (4.96%). The difference between the two scenarios is less than 30%. In addition, the current OGMAs' network has 6.44% of total old-growth represented within its area. The difference between current OGMAs to alternative reserves is also quite small. This is likely due to the areas constraint utilized. Even prioritizing areas for individual ESs provision, there is only a small room for improvement of current level of ESs provision in OGMAs. These results suggest that while multiple ecosystem services can be simultaneously reserved, the optimum areas for the provision of each ecosystem service are not aligned. Then, altering the location of OGMAS would no make significant difference in the amount of old-growth reserved and ESs provision. However, the quality of the forests selected in the prioritizing scenarios might be greater then in the forests currently set-aside (OGMAs).

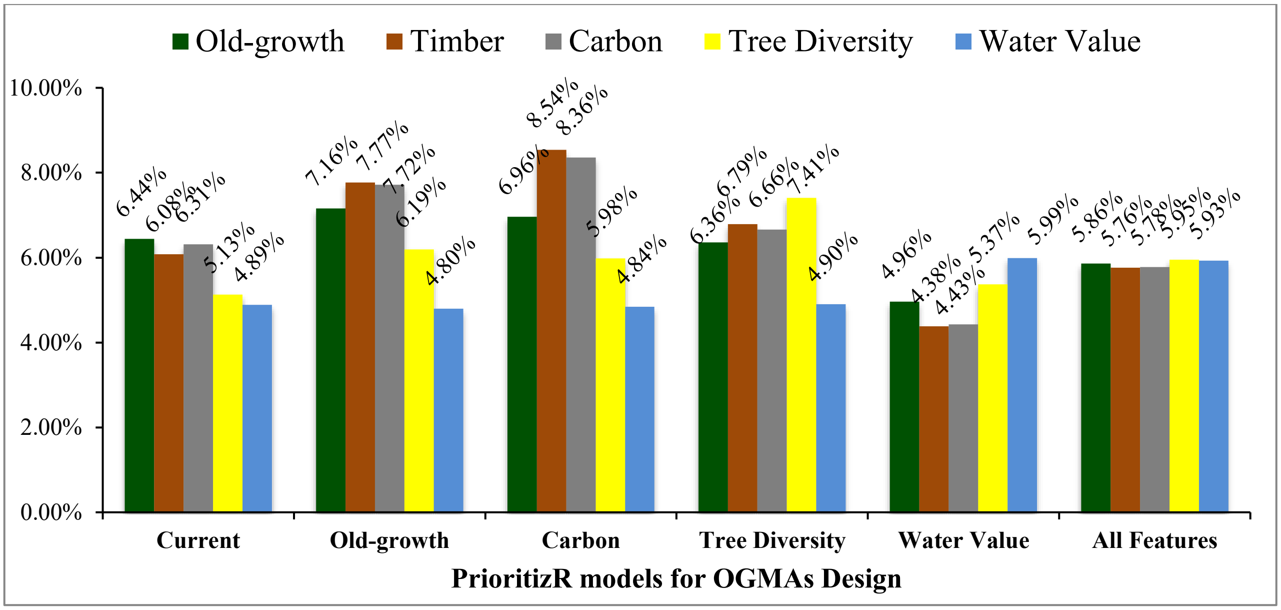


Figure 3.3 Ecosystem service provisioning represented (%) in current OGMAs network and each "prioritizR" model. Percentages are the amount of the ecosystem services within the reserve network in relation to the total amount of the ecosystem in the whole landscape.

The results in Figure 3.4 also suggest that current OGMAs do not need to be relocated. If the same prioritization strategy is utilized to set-aside new areas for conservation, it does not matter whether the current OGMAs are relocated to priority areas or not. The overlap between alternative reserves for old-growth starting from current OGMAs (Fixed) and priority old-growth areas (Not-fixed) increased from 7.68% to 33.25% with only 1% increase in total reserve areas (Figure 3.4 b). Tree diversity prioritization that had the smallest overlapping between current OGMAs and priority areas increased from 0.44% to 13.06% in the first 1% area increase (Appendix 6.8 – Figure 6.15). For a 10% area increase, the overlapping between "Fixed" and "Not-Fixed" scenarios was greater than 60% for old-growth prioritization, more than 70% for the prioritization of all ESs simultaneously (Figure 3.4 f). Not only that, the difference between ESs representation from "Fixed" and "Not-Fixed" scenarios are minimum, and rapidly decreased. For example, in a scenario of a 10%

area increase in OGMAs areas, the difference between the ESs provisioning inside “Fixed” and “Not-Fixed” reserves is less than 10% for all services analyzed. For old-growth prioritization scenarios, the fixed scenario had a slightly better ES representation. This suggests that there is a lack of scope for altering OGMAs location to priority areas if there is intension for OGMAs area increment.

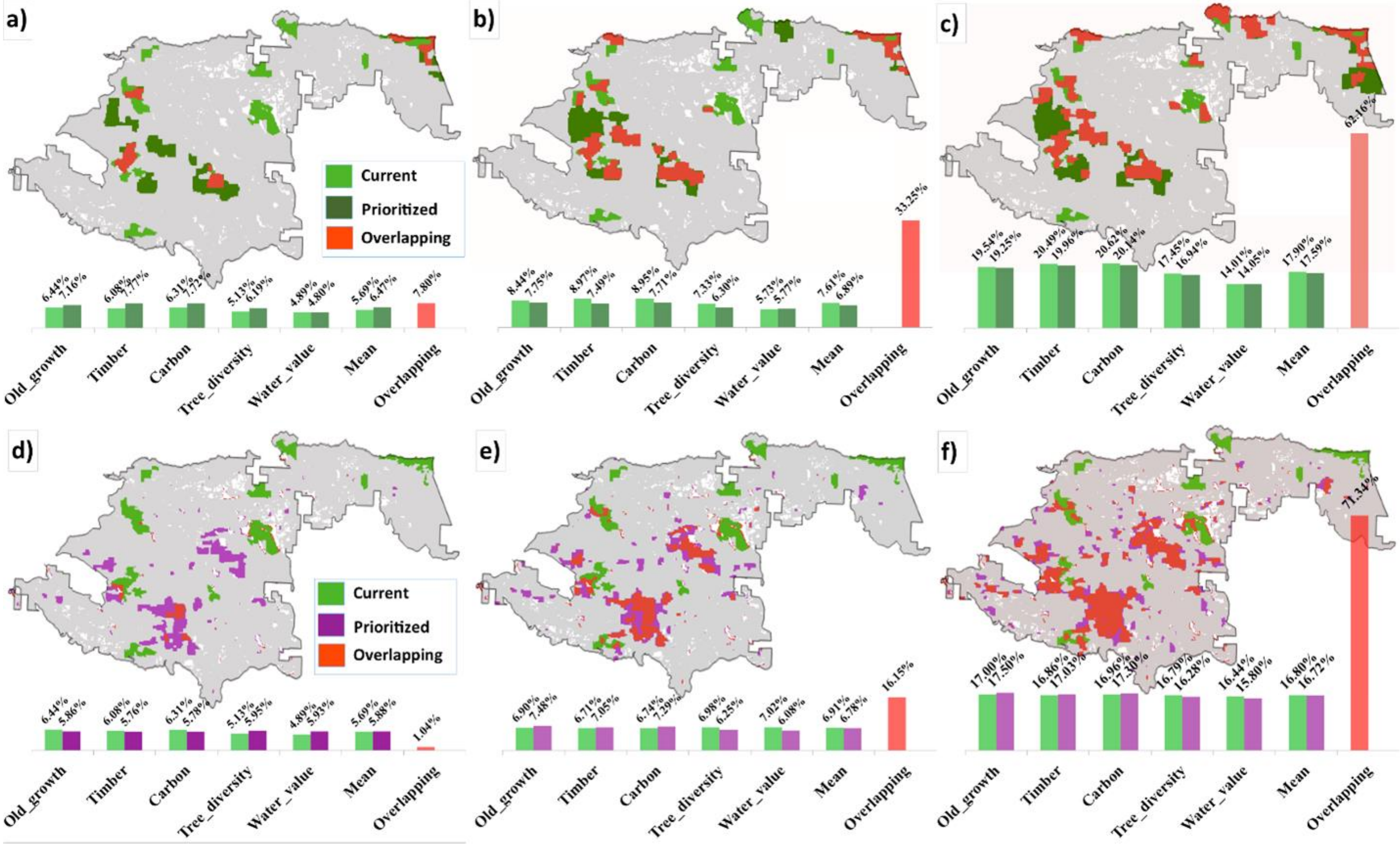


Figure 3.4 Comparison between increase in OGMAs' areas starting from current OGMAs (Fixed) and OGMAs designed to prioritize each individual ecosystem services and all features together (Not-fixed). Old-growth prioritization is represented in figures from a) to c), where a) represents scenarios with current OGMAs size (0% increment) b) and c) are the reserves with area increment of 1% and 10%, respectively. The reserves with the prioritization of all ESs are represented in the images from d) to f), where d) are the reserves with 0% increment in area, e)1%, and f) 10% increment. Each 1% increment equals to an addition of 669ha to the current OGMAs area.

The effect of timber harvesting on the provision of ESs is greater than 1:1, where for each units of timber, one unit of ESs provision would be affected. When we considered different yields, this relationship became even more detrimental to the ecosystem provision. The most linear effect of timber removal is on carbon storage loss, since in this study carbon is a function of timber. The relationship between harvesting and carbon storage loss was mostly linear, reaching up to a 1:2 relationship, considering the lowest harvesting yield (50%) (Figure 3.5 b). Besides, despite the low correlation between timber and water (-13%) and timber and tree diversity (42%) (Figure 3.2), these two values were strongly affected by timber harvesting (Figure 3.5 c and d). For water values, every 1% of the timber extracted from the landscape could affect up to 8% of the total water value provision (Figure 3.5 d). Similarly, the effect of timber removal on tree diversity was up to 1:4.6%. For old-growth value, that had a strong correlation with timber value (78%), the relationship between timber harvesting and old-growth value loss was up to 1:3.7%. For example, to harvest 148,047 m3 (1% of the total) affects 2% of the old-growth value assuming 100% yield, 3% for 75%, and 4% for a 50% yield (Figure 3.5 a). The effect of harvesting yields on the extent of the landscape affected by forest operations, and thus the ESs provided in it, are significantly increased considering lower harvesting yields. As well, the results suggested that correlations analysis alone can mislead to the actual ESs relationships, as we noticed a much greater trade-off between timber and water value than we would expect considering such a small correlation.

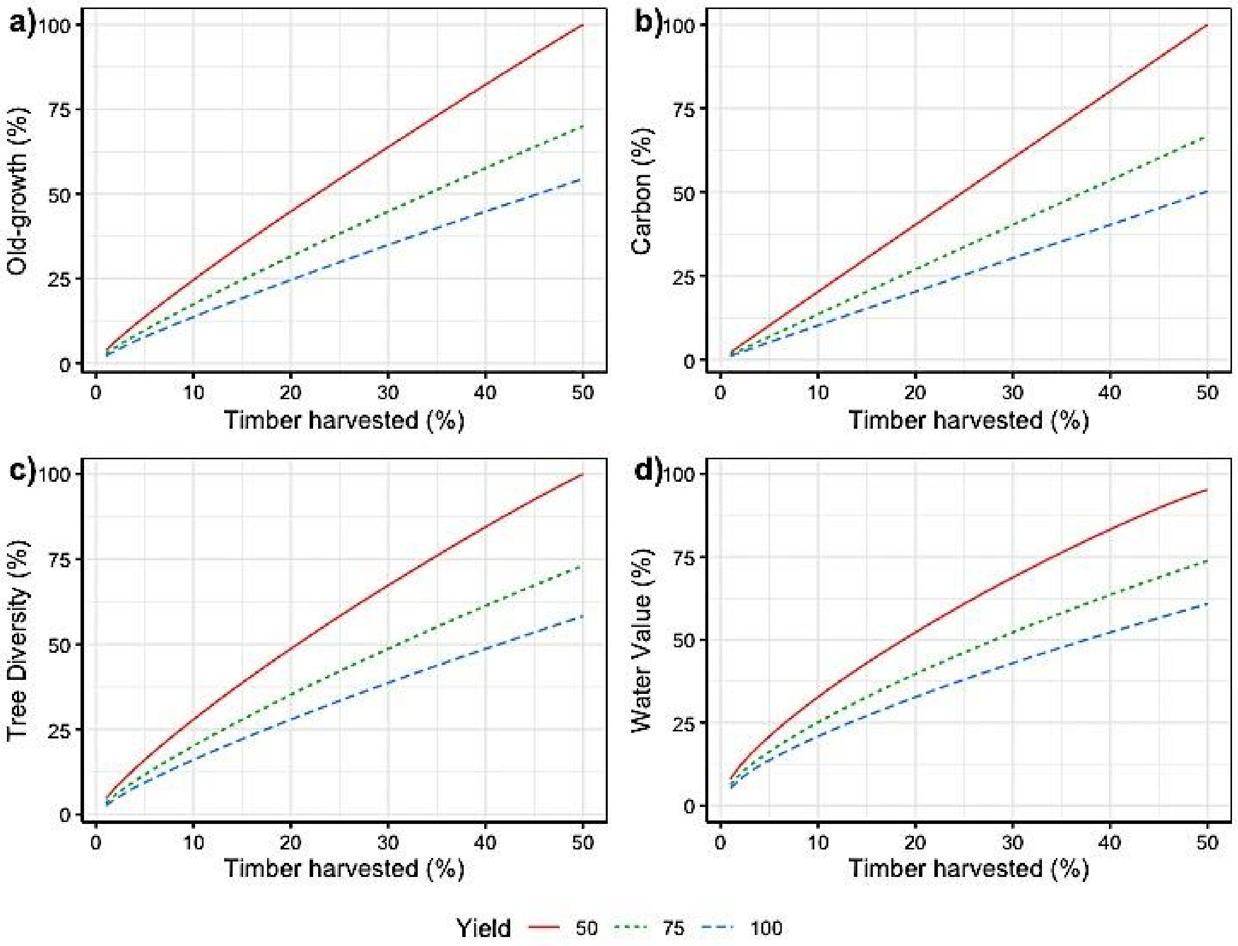


Figure 3.5 Trade-off between provision of ecosystem services and timber for harvesting. Images depict the effect of timber availability on the amount of representation of each ecosystem service that is removed together with timber. A) old-growth value removed from the landscape for harvesting scenarios for harvesting yields of 100% , 75%, and 50%, B) Carbon storage, C) Tree Diversity, and D) Water values.

The combination of curves of prioritizing scenarios enables the evaluation of trade-offs between protection and timber harvesting and identifying a threshold where protection would affect timber supply (Figure 3.6). For example, we observed that the increase in OGMAs areas is not likely to affect timber harvesting before 45% of the study site is set-aside for old-growth reserves, assuming that 100% of the non-protected timber is available for extraction with zero loss during the process (6,660,633 m^3). When we assume a loss of

25% of the non-protected timber (75% yield), up to 38% of the landscape could be set-aside for protection without affecting the availability of timber for forestry operations. Even for the most conservative scenario, where we assume that only 50% of the non-protected timber is viable for extraction, 28% of the landscape could be set-aside for protection without affecting harvesting operations (4,143,835 m^3 available) (Figure 3.6 a). Also assuming the most conservative scenarios (50% yield), reserves designed for the provisioning of all ESs could cover up to 30% of the study site before timber supply was affected (Figure 3.6 e). It is worth noting that the size of the OGMAs evaluated in this study cover less than 6% of the study site. Thus, a five-fold increment in OGMAs could occur without affecting forestry operations considering the most conservative scenario. Notwithstanding, even setting aside the maximum possible for protection, as indicated by the thresholds between protections and harvesting scenarios, does not mean that all "non-protect" timber is available for harvesting. In addition, a five-fold increment in OGMAs areas is not likely to happen. An alternative to clear-cut, such as partial-cut and selecting logging, could be implemented in the non-protected landscape to reduce the effect of harvesting on the ESs reserves.

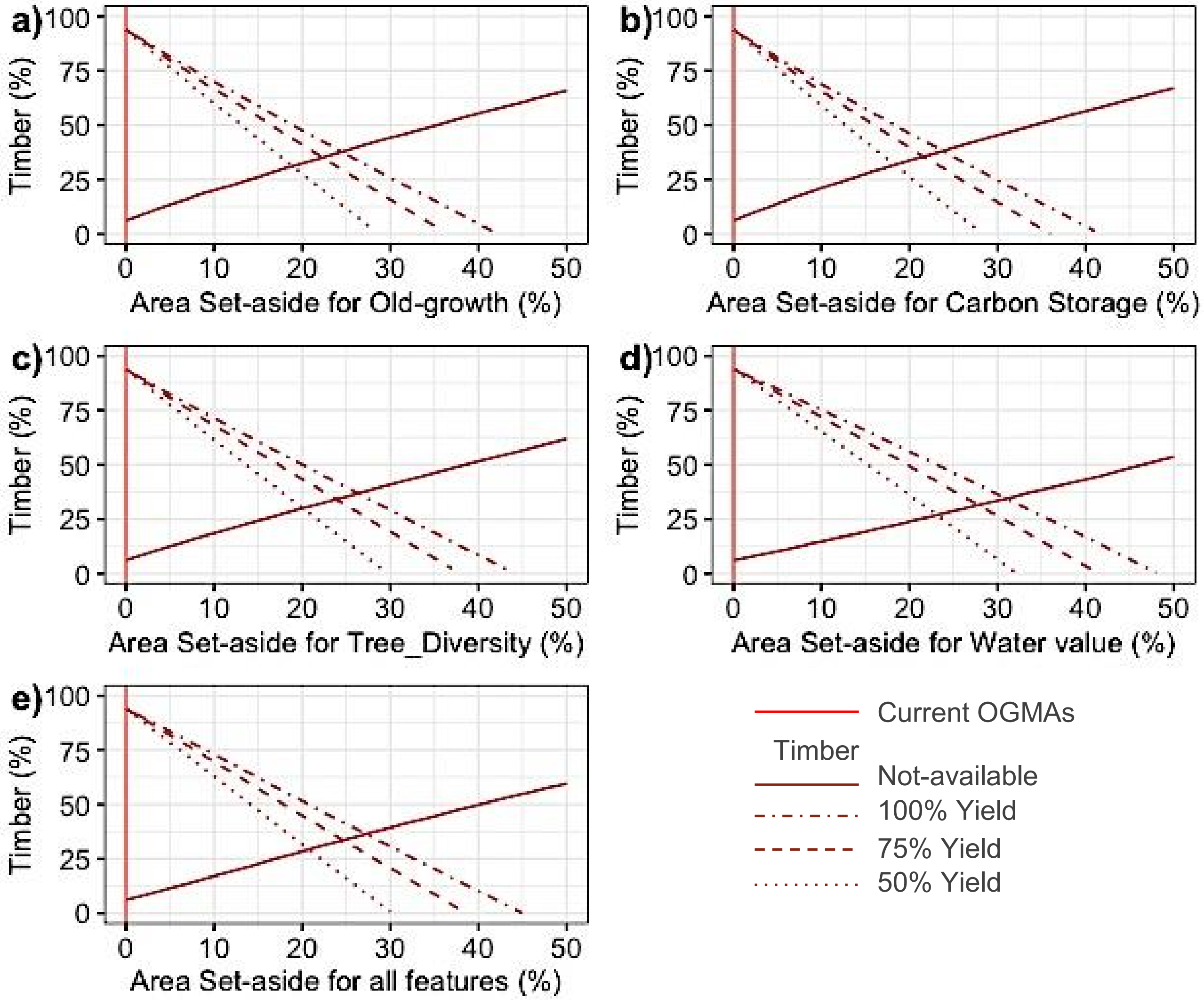


Figure 3.6 Trade-off curve between timber harvesting and setting aside areas for the provision of a) old-growth, b) carbon, c) tree diversity, d) water value, and e) all features together. Scenarios were designed to have a starting point at the current OGMAs network. Thus, 1% increase means that an additional of 1% of the landscape was set-aside and included in the current OGMAs' area network.

3.4. Discussion:

This study provides a new insight into the conservation of old-growth forest values in landscapes managed for timber. It also provides scope for the decision of whether or not to reallocate current set-aside old-growth forest (OGMAs), and if and how OGMAs can be designed for the provision of multiple ecosystem services in the landscape. Our results demonstrated that OGMAs could be a strategy to cope with the loss of old-growth (Watson et al. 2018), while maintaining the provision of multiple of other ESs, including opportunity for timber harvesting. With the use of a spatial optimization, it was possible to identify potential thresholds for the conservation of multiple ESs while leaving opportunities for timber harvesting in the landscape. This information is particular important for community forests and other land-base tenures that manage the landscape for timber. Since timber is the main ES that is directly harnessed from these forests (MFLNRORD 2017a), the idea of setting aside large areas from the land-base to maintain multiple ESs provisioning can be a conflicting subject. However, even in our most conservative scenario, assuming that only 50% of the non-protected timber would be available for harvesting, OGMAs areas could cover up to 28% (five-fold current areas) of the land base without compromising timber supply. The non-protected landscape play an important role in the connectivity of reserves, gene flow, animal habit etc. Thus the management of the non-protected timber has also to be strategically planned to retain multiple values, especially considering that unsustainable management strategies (e.g. clear-cut) can cause unexpected declines in ESs provisioning and human wellbeing (Lindenmayer et al. 2012, Gaston et al. 2013).

We noticed a much greater trade-off between timber and water value, as we would expect considering the small correlation between those values. This was similar to a study by Dade (2018), who also suggested that correlations analysis alone can be misleading regarding the relationships between ESs. The same was also observed to tree diversity. In addition, when timber extraction scenarios were evaluated, we found that even for the most correlated ES, carbon, the removal of timber had a much greater impact on the service provisioning them a 1:1 relationship. Considering that there is other multiple ESs simultaneously provided in forested landscapes, the indirect effect of unsustainable timber removal may have greater effect on other services. Some studies have pointed out that old-growth forests also support local economies by providing renewable resources and by attracting tourism and are important for cultural and religious values (Cronon 1995, MA 2005, Watson et al. 2018). Cultural values are considered the ES most difficult to be replaced (MA 2005). In addition, healthier forests are better habitats for some game species, which offers the human population both recreation opportunities and game meat (Damania et al. 2005). However, the harvesting scenarios considered here were all clear-cut, assuming the complete removal of forest structures. A diversity of forest management strategies may, however, reduce the impact of timber removal on the landscape provision of ESs (Duncker et al. 2012, Schwenk et al. 2012). In addition, diversifying silvicultural approaches in the non-protected landscape may also improve the overall representation of tree diversity in the landscape. Our results showed that not only tree-diversity had a low correlation with old-growth and other ecosystem values, but also it was poorly represented in all prioritization scenario, except where tree diversity was the service prioritized. This poor correlation was expected as tree diversity had a positive response in both early succession and late succession forest types (Schwenk et al. 2012). The diversification of strategies for timber management can create landscape pockets with different environmental conditions, which promote the diversity of tree species and biodiversity in general (McElhinny et al. 2006b, Isbell et al. 2011, Schwenk et al. 2012).

3.4.1. Ecosystem services reserves

Some reserves protect recreational and scenic values. Others protect ESs such as the delivery of clean water or the supply of timber or mitigate the expected adverse effects of over-clearing (Grove 1992). OGMAs were originally idealized to set-aside areas with high old-growth value in the landscape. However, over time, other features started to be incorporated, and OGMAs were selected for other values such as biodiversity and wildlife habitat (MFLNRORD 1995, Mosseler et al. 2003a, Environmental Law Centre 2013). Thus, it is possible to use the OGMA strategy to promote the provision of multiple ecosystem services. However, OGMAs are not protected areas per se (MFLNRORD 1995, Environmental Law Centre 2013). Their location can be changed for innumerous management reasons, including road building and savage of beetle infected trees. However, their sizes have to be respected, even if they are completely shifted to other regions of the landscape. This study demonstrated that spatial prioritization could be utilized to demonstrate whether or not OGMAs should be relocated to better capture the values they were design for. For the study site, for example, we observed that there would be only a small gain in the provision of ESs if OGMAs were shifted to areas found as priority for old-growth conservation. Even when ESs were prioritized individually, their provision were not substantially higher than in current OGMAs network to advocate for a complete or partial shift of OGMAs areas. However, the ecosystem features that sustain the provision of those services may change over time.

Natural disturbances such as wildfire and insect outbreaks, frequent in the landscape focus of this study (DellaSala et al. 1996, Spies et al. 2006), have the potential to change planning unit values on a large scale, which could drastically change solutions that were once considered optimum. Thus, the possibility of partially shifting OGMAs can also be used to maintain original reserves' levels of the provision of services. The framework utilized in this study offers a holistic view of old-growth and ESs values in the landscape, which provides the opportunity to set targets for their conservation relative to the landscape provision. All ecosystem services layers generated for this work were derived from field measurements and

LiDAR surveys, which can offer a great insight into forests and ecosystem services (Andrew et al. 2014, Campbell et al. 2017, Aryal et al. 2017). Even though the ESs estimates are surrogates or partial measures of the actual ecosystem services and old-growth values, it does not prevent their utilization in this work (Margules and Pressey 2000). Moreover, the conservation prioritization follows the principle of complementarity, which means that each reserve contributes to achieving the set of objectives of a prioritization problem for a reserve network (Margules and Pressey 2000, Wilson et al. 2009). Thus, the representation of old-growth values and ecosystem services may change rapidly for individual OGMAs, but less so for the OGMAs' network. New OGMAs could, then, account for the multiple ESs old-growth forests can provide, reducing management conflicts. However, OGMAs should not be the only strategy to promote ESs provisioning in the landscape.

Regulating services, such as water and carbon sequestration, usually have synergies with a few other ESs, such as recreation and habitat quality (Bennett et al. 2009). In this study, however, the prioritization of water values had the most significant trade-off with the other ESs evaluated, and was the most affected by timber harvesting, despite the low correlation between water value and timber. Water value was the liming factor for the simultaneous multiple ES representation, which means that the old-growth conservation by itself would not simultaneously protect water-values. These wetter environments tend to restrict tree growth (Adhikari et al. 2009, Kayranli et al. 2010). Thus, all values related to trees (e.g. old-growth, tree diversity, and above-ground carbon storage) were not well represented when water values were the focus of the optimization scenarios. As well, it might also be an effect of the water value surrogate utilized, the wetness index. The wetness index has the greatest values assigned to areas with poor drainage, and thus areas with limiting conditions to tree growth and old-growth characteristics (Lang and McCarty 2009, Lane and D'Amico 2010).

Even though wetlands had low correlation with other ESs evaluated in this study, these are important ecosystem that also provide a variety of ESs (Adhikari et al. 2009, Lang and McCarty 2009, Kayranli et al. 2010, Lane and D'Amico 2010, Stutter et al. 2012). Moreover, similarly to agricultural landscapes (Stutter et al. 2012), riparian zones and wetlands are also often unsuitable for forestry. In addition, there are legal restrictions to forest operations in riparian areas for the study site (MFLNRORD 1995). Thus, there is little competition between forestry and riparian ESs. In a scenario where water values were independently reserved, the overall ESs representation increased from 5.88% to 7.11% for the same reserve size. Implementing riparian protection in conjunction with OGMAs could increase water value representation in the landscape while playing an essential role in the total carbon pool and other ES. Reserves designed for multiple ESs could focus more on the services that have higher potential for synergies (e.g. carbon and old-growth).

Some assumptions were made in the reserve selection with systematic conservation planning problems. For this study, the most critical assumption is that the benefits associated with the selection of a planning unit are guaranteed, are not dynamic, and are independent of what happens in other planning units (Margules and Pressey 2000). In addition, the problems addressed in this study are simplified versions of real-world problems. The degree to which the optimal solution to the simplified problem also represents a good solution to the complex, real-world problem is generally not known and not evaluated (Langford et al. 2011). Then, future research on the topic should include to the ESs evaluated here some social aspects of the landscape values, such as cultural services. Due to the partnership that created the community forest focus of this study, Indigenous cultural values may play an important role in the management decisions. Thus, involving the Indigenous groups in an interdisciplinary study of the landscape values can offer a better insight on the relationships between ESs and the use of OGMAs for the maintenance of multiple ESs in the landscape. Building the relationship with local community and involving them with the research process might also be crucial to bridging the research-implementation gap so often mentioned (Knight et al. 2008, Beyer et al. 2016), and aid to validating the effectiveness of conservation plans through monitoring during and following implementation.

3.5. Conclusion:

Spatial prioritization was successfully utilized to simulate optimum networks of old-growth and ESs reserves. While current OGMAs are not placed in optimum areas, the ESs provisioning in optimum reserves are not substantially different from current OGMAs. Also, the differences between current OGMAs and optimum reserves decreased rapidly as new set-aside areas were added to the current and alternative reserves' network. These suggest a lack of scope for altering the location of current OGMAs. We also found that water value was the services that displayed the greatest trade-off among all scenarios. Since there is little competition between timber harvesting and water values, specific water conservation strategies should be implemented simultaneously to multiple ESs OGMAs. Lastly, the results suggested that an increase in OGMAs areas is not likely to affect timber harvesting before 28% of the study site is set-aside for protection. The information obtained from the spatial prioritization of old-growth and multiple ESs can be used to indicate the scope for altering OGMAs' locations or guiding the establishment of new OGMAs in the landscape. The spatial prioritization can be the means for identifying priority areas for ESs provisioning, designing OGMAs for multiple ESs, and the evaluation of trade-off between ESs due to management objectives.

4. CONCLUSIONS:

An underlying premise of my thesis is that identifying and retaining old-growth forests can aid to their conservation and the maintenance of other essential ESs in the landscape. Old-growth forests are ecosystems often associated with the provision of a range of ecosystem services (ESs) such as biodiversity, water provision, carbon storage and sequestration, cultural values and the maintenance of human well-being. Although old-growth forests are a valuable ecological resource, they are also rare and in a rapid decline worldwide. The Old-Growth Management Areas (OGMAs) in British Columbia, Canada is one example of strategy to protect and retain old-growth forests and their ESs in managed landscapes. However, the selection of such areas is a difficult task due to two critical problems. First, there are many definitions and approaches to define and locate old-growth forests due to their diversity across ecological types. Second, the relationships between ecosystem services and old-growth values are complex, and our knowledge of how ESs responds to forest management is limited.

To address these gaps, I studied the role of old-growth reserves on the provision of multiple ecosystem services (ESs), using the Chinook community forest, located in Burns Lake, British Columbia, Canada, as a case study. To bridge the knowledge gaps, I used review of literature on old-growth and ESs, a machine learning technique, field and ALS data on forest structures, and a conservation planning method. Specifically, I addressed three major objectives: (1) identify definitions of forest succession, structural attributes and ESs commonly associated with old-growth forests (Chapter 1); (2) develop a landscape scale definition of old-growth forest that is both quantitative and repeatable (Chapter 2); (3) understand and apply the synergies and trade-off between ESs and old-growth values to promote the use of OGMAs as strategies for the maintenance and provision of multiple ESs in the landscape.

In this concluding chapter, I synthesize the main findings from each of the chapters of my thesis while discussing their implications for the management of multiple ecosystem services in forests managed for timber, and recommend future research directions.

4.1. Main Findings and contributions:

4.1.1. General review on old-growth forests and their provision of ecosystem services:

Chapter 1 of this thesis presents a general review of the literature for the multiple definitions of old-growth forest and the structural attributes commonly associated with old-growth forests. Attribute-based definitions were found to be the most common and transparent approaches used in the literature. In addition, most of the old-growth attributes are already part of traditional field inventories, which aids their utility for identifying old-growth. However, methods to accurately assess these attributes across a landscape at an appropriately grain size have not been available. This has meant that spatially explicit estimates of old-growth forests have often been low accuracy, thereby limiting land managers ability to accurately identify and manage old-growth areas. Advances in remote sensing technology, such as Airborne LiDAR, potentially provide the ability to evaluate the 3D structural attributes of forest ecosystems, develop modeled estimates of old-growth characteristics, and incorporate this information into landscape planning that aims to maintain old-growth forests while also promoting multi-functional forestry that includes timber productions. The selection of old-growth is a difficult task due to the lack of a standard definition for what constitutes an old-growth forest (Hilbert and Wiensczyk 2007, Wirth et al. 2009b). In temperate forests, obtaining a definition of old-growth forest is somewhat easier as the fire-rotation periods are exceptionally long in such forests. However, in the other regions, a clear decision on when to designate a given stand "old-growth" is more difficult due to disturbances and successional changes that maintain the system in a dynamic, non-climax state (Mosseler et al. 2003a, Wirth et al. 2009b). As a result, developing a continuous index of old-growth attributes, instead of a categorical and somewhat arbitrary designation, have the potential to improve our ability to identify old-growth forests for conservation and incorporate them into landscape planning.

4.1.2. Defining Old-Growth Forests With Airborne LiDAR

In this work, we developed an old-growth index based on forest structures measured with traditional field methods. Old-growth attributes were utilized to develop a structure-based old-growth index tailored to map old-growth value in the Chinook Community Forest landscape. LiDAR-derived metrics were modeled using a "random forest" (RF) framework to estimate the old-growth index across the landscape. To obtain the landscape-scale old-growth index I first needed to evaluate means for assessing old-growth, and OGMAs, and develop quantitative definitions that could be used in conjunctions with fine-scale remotely sensed data such as ALS. While the index developed is specific to the study site, the framework, is generic enough to be adapted to other forest types and ecosystems. More importantly, the identification of the amount and location of old-growth forests in the landscape can aid in the conservation of this rare resource and its services.

I used the old-growth index OGA developed to map old-growth value in the landscape and evaluate the amount and quality of the old-growth forest for the study site. The old-growth index map developed in this study allows for a quantitative assessment and monitoring of old-growth value in the landscape. It can help managers to not only track the amount and quality of old-growth in the landscape but also set targets for old-growth retention in a transparent manner. Most importantly, the old-growth mapping value can aid in the conservation of this resource and its services in managed landscapes. The old-growth policy in Canada came from a public concern about the decline in the amount and distribution of older forests, especially those with large, old trees (Environmental Law Centre 2013). Moreover, Canada has pledged, in the International Convention on Biological Diversity, to develop its forests sustainably, which requires close attention to old-growth as a distinct component of those forests (Mosseler et al. 2003c). The old-growth index can serve as an alternative to the current old-growth definitions utilized (Gillis et al. 2003) (MFLNRORD 1995, Arsenault 2003). The old-growth index developed here, while specific for the study site, it can be adapted for other forest types.

This methodology offers a way to evaluate old-growth values in set-aside old-growth forests, OGMAs. Since the index can track old-growth values throughout the whole landscape, set-aside forests can be complemented with managed forests that also retain key attributes of primary and old-growth forests. Such a strategy has been previously proposed by Beese et al. (2003), who suggested that set-aside old-growth should be combined with uneven-aged stand management to maintain late-successional forest attributes. Other researchers also indicate the use of multiple silvicultural approaches simultaneously in the non-protected landscape, as a mean for retaining forest structures and ESs while extracting timber values (Duncker et al. 2012, Schwenk et al. 2012). This strategy is particularly important in areas where reserves are too small to ensure the occurrence of natural disturbances within their boundaries or to accommodate all developmental stages of forest succession (Kneeshaw and Gauthier 2003).

4.1.3. Systematic Conservation Planning Of Old-Growth Value

The management of landscapes often involves conflicting objectives such as timber to one group of people and recreation to another (Ninan and Inoue 2014). As human populations continue to grow, demand for ecosystem services is also increasing (MA 2005, United Nations 2018), and so are the conflicts between multiple objectives. Using the spatial optimization package "PrioritizR," I was able to evaluate how prioritizing different objectives can alter the spatial location of set-aside areas, and alter old-growth maintenance and ES provisioning. Current OGMAs locations are not optimum for any of the ESs evaluated. Although current OGMAs and priority ESs reserves barely overlapped, the provision of ecosystem services had a very small difference between scenarions. This is likely due to the size restriction. Since I was comparing current OGMAs, the size of current OGMAs was utilized in all scenarios. Thus, even using a spatial prioritaztion tool, the priority areas selected were still too small to provide a more substantial difference. I also simulated increases in OGMAs areas having current OGMAs and optimum ESs' reserves as a starting point. The differences between current OGMAs and optimum reserves decreased rapidly as new set-aside areas were placed and overlapping between scenarios increased. However, for a better comparison, I would have to select areas to include in current OGMAs in the same way they are currently selected. While the way the analyses were conducted in this thesis points to an interesting result, it does not offer the scope to say which method is more robust for OGMA designing.

As well, the smallest overall ESs representation was achieved in scenarios where water value is prioritized, indicating that water values is a limiting factor for the prioritization of multiple ESs. However, when water value is reserved separated from other ESs, the synergies between the remaining services are increased. Since there is little competition between timber harvesting and riparian areas where water values are often higher, removing water values from the prioritization scenarios can substantially increase other ESs, representation. A conservation plan that includes strategies to protect riparian and wetlands in conjunction with multiple ESs OGMAs can substantially increase synergies and overall representation of ESs.

Regarding increments in set-aside areas, OGMAs would not affect timber harvesting before receiving a five-fold increment in their current areas. This information can be used to indicate the scope for altering OGMAs' locations and guide the establishment of new OGMAs in the landscape. These findings suggest that the use of spatial prioritizing tools can be a new means for identifying priority areas for ESs provisioning, designing OGMAs for multiple ESs, and the evaluation of trade-off between ESs due to management objectives.

4.2. Future research:

Future research for the old-growth definition would require testing the portability of the framework developed in this study to other forest types, evaluating other old-growth attributes, and which ones are better suited for which forest type. In addition, forest inventories have to be tailored for forest succession studies, including direct measurements of forest floor and coarse woody debris, likens and other attributes (Wirth et al. 2009b), if there is the intension of improving current definitions. The idea of the index developed here is that it can be repeated and applied in other regions, since most of the old-growth attribute utilized are present in tradition forest inventories for timber supply purposes (Gillis et al. 2003). However, improvement on the representation of old-growth could be achieved by a forest inventory with an ecological purpose, with data collection focused to capture old-growth attributes, biodiversity metrics, likens and fungi communities, ecosystem services and other relevant landscape values. Not only for the development of the old-growth index, this inventory can also support the production of better estimates of ESs estimates and include other services such as biodiversity, hunting opportunities, soil carbon, and cultural and recreational values.

Old-growth forests and other important ecosystems sustain critical ecological processes, e.g. water filtration, carbon sequestration, and nitrogen fixation) that constitute Earth's life support systems (e.g. provision of clean water and air, climatic stability) (MA 2005, Watson et al. 2018). They also support local economies by providing renewable resources and by attracting tourism and are important for cultural and religious values (Cronon 1995, FAO 2015). Culture and religion may play an essential role in the relationship of ESs in the landscape. Cultural services refer to the non-material benefits people obtain from ecosystems, such as aesthetic appreciation, different forms of recreation, and cultural identity (Daniel et al. 2012). I did not have any direct measure of culturally related ESs. However, it is possible to state that those values were partially prioritized by surrogates such as old-growth value. Such assumption is often made, but there is little research that accounted for the ecosystems and ecosystems functions that sustain the provision of those services (Milcu et al. 2013, Schirpke et al. 2016, Watson et al. 2018, Dade 2018). Cultural values are considered the ES most difficult to be replaced once lost (MA 2005). Thus, evaluating the role of old-growth for the local culture is an important relation that needs to be studies. The study site offers a unique opportunity for such research since it overlaps with six first nations territories (Chinook Community Forest 2017). Although the participation of local communities in the development of the study would offer an interesting and crucial perspective on the project, building such relations is out of the scope of this master's thesis.

Other services that are also simultaneously provided by old-growth values are game meat and recreation. Healthier forests are better habitats for some game species, which offers the human population both recreation opportunities and game meat (Damania et al. 2005). Old-growth forests are winter habitat for some of the these species (Mosseler et al. 2003c). As well, large mammals can also beneficiate from the conservation of such habitat (bears (Ursus spp.), wolves (Canis lupus), and wolverines (Gulo)) (Mosseler et al. 2003c). Not only that, old-growth forests are a unique environment with high eco-tourism value (MA 2005). The recreation aspect is already partially exploited by the community forest by means such as trails, sightseen spots, mountain biking, and camping sites (Chinnok Community Forest 2017b). However, those recreation opportunities still need to be inventoried, mapped and evaluated in terms of usage, surrounding environments, and other proxies for their quality. Therefore, the conservation of old-growth have potential to simultaneously provide multiple of other services not evaluated in this study. Further research on the provision of these other services has to be conducted before drawing conclusion about the importance of old-growth their provision.

Management plans often include the idea of uncertainty. Old-growth values, as well as all ESs, evaluated here were only estimated. Different harvesting yields were attempted to input an uncertainty measure for timber harvesting and its effect on ESs. The evaluation of all ESs and conservation plans should include a similar idea. Decision-makers have to know the risk of setting-aside areas and the uncertainty on the returns of their investment. Grêt-Regamey et al. (2013) discussed the idea of risk assessment for ESs provisioning and applied a Bayesian network for its assessment. Thus, future research may include a risk assessment to ESs provision on the prioritizing scenarios.

Finally, monitoring before and after the implementation of conservation plans for multiple ESs is a crucial step in future research (Margules and Pressey 2000, Wilson et al. 2009). This thesis offers a valuable framework to measure ESs and old-growth value in the landscape through ALS. Repetitive ALS expeditions are already expected to happen in the study site and might be the means for monitoring on a landscape scale the effects short and long-term management practices. Thus, old-growth value and ESs could be re-measured and used to the evaluation of the effect of timber harvesting implemented in the year following the first ALS expedition. As well, the degree to which the spatial prioritization solutions represents a good solution to the complex, real-world problem is generally not known and not evaluated (Langford et al. 2011). This is an important conservation planning shortcome (Margules and Pressey 2000, Wilson et al. 2009). Then, ALS expedition prior and after the implementation of spatial prioritization solution could aid to evaluate how systematic conservation problems correspond to the real-world problem, the effect of implementing them on the provision of ESs. To better capture the real world complexity, future research should include the ESs evaluated here with some social aspects of the landscape values, such as cultural services. Thus, building the relationship with the local community and involving them with the research process might also be crucial to bridging the research-implementation gap so often mentioned (Knight et al. 2008, Beyer et al. 2016), and help validate the effectiveness of conservation plans through monitoring during and following implementation.

4.3. Concluding Remarks

Due to the vital importance and rapid decline of old-growth forests, it is imperative advancement in polices for their conservation. Old-growth forests are often associated with the provisions of multiple ecosystem services. In the current scenario of increasing population and demand for ecosystem services, policies that promote the provision of multiple ecosystem services can be the means for the protection of old-growth forests. In that regard, my thesis advances our understanding on the multiple definitions of old-growth forests, provides a quantitative and repeatable framework for identifying old-growth values in the landscape, and recommends the use of spatial prioritization tool as the means to manage the landscape and design OGMAs for the provision of multiple ecosystem services.

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6. APPENDICES

6.1. Data collection information

Free Growing Forestry Company has conducted the field data collection in Burns Lake with teams of two members. Each team collects an average of 2 plots per day due to the walking distance to plot, site conditions, and the amount of data collected (Table 6.1).

Table 6.1 List of attributes measured for each plot

Data Collected	Description
Tree # :	
Species (2 Letter Code):	e.g. Pl =Lodgepole Pine, At= Trembling Aspen, Sx= Hybrid Spruce
Diameter:	DBH (cm)
Height:	Tree Length (m)
Loss Factor Information:	Tree Class; Conk; Blind Conk; Scar; Fork/ Crook; Frost Crack; Mistletoe; Rotten Branch; Dead/ Br. Top; Root Rot Code; Insect Code; Fire Code; and Blowdown Code
Live or Dead:	
Standing or Fallen:	
Crown Class (D, C, I, S):	D= dominant, C= Codominant, I= Intermediate, S= Suppressed
Site Tree Ages:	Age at DBH Counted - Field Age at DBH Counted - Office
# of small tree (DBH<4cm):	Species code; Length class: 10-30cm, 31cm-1.3m, >1.3m
Stumps >= 4cm DIB and length <1.3m:	Species code, frequency, DIB(cm), length(m), and %Sound

The steps for the data collection consisted in:

- Identify a referential tree and mark it with tape and ink (Figure 1 a));

- Find plot center with high precision GPS (Figure 1 b));
- Delimitate the work sector. Each plot is divided into 8 working sector;
- Each sector is sub-divided into 2.5 m and 5.64 m. From 2.5m circle, I measure trees with DBH smaller than 4 cm (saplings) and stumps. From the 5.64 circle, I collected the tree cores from the biggest specimen of the leading species;
- In each sector, I obtained species, DBH, height, tree features (scars, crooks, forks, broken top, etc), status (live or dead, standing or fallen), height to live crown, competition (dominant, co-dominant, intermediate and suppressed), etc.
- Trees on the ground are also measured if greater than 17.5 for spruce or 14.5 for pine, and if wood is still sound. When logs are rotten, they are not measured.

Figure 6.1 Illustration of the a) reference tree, b) plot center with the high precision gps, and c) tree core.

- After measuring all tree down to 4 cm in each of the 8 sectors in the plot, I selected the largest specimen of the leading and second leading species, extract on core from each (Figure 1 c), and count the growth rings in the plot (they are counted again in the office);
- Cored trees are located by their bearing and distance to the plot center;
- A second point is collected from the plot center with the high precision GPS before leaving the plot to improve the location accuracy (Figure 1 b));

- The plot location is signalized with tape, and path directions are transcribed into the document;

6.2. Allometric Equations for plot-level estimates of old-growth attributes:

6.2.1. Volume-Height, DBH

Volume equations (Standish et al. 1985, Penner et al. 1997) are based on the DBH and height.

$$v = p_1 \times 10^{-5} \times d \times e^{p_2} \times h \times e^{p_3} \tag{2}$$

Where

v = tree volume (m$^{3)}$

h = tree height (m)

d = diameter at breast height (cm)

p_1,p_2,p_3 = parameters of volume calculation, Parameters are below (table 6.2)

Table 6.2 Volume parameters (Penner et al. 1997, Standish et al. 1985)

Species Code	**Species**	**Latin Name**	**Volume parameters (m^3)**		
			p_1	**p_2**	**p_3**
Bl	SubalpineFir	Abies,las	5.106002228	1.87293	0.998274
Alder	GreenAlder	Alnus,crispa	NA	NA	NA
Ep	Birch	Betula,pap	3.60460765	1.90956	1.0525
NA	NA	genx,x	5.106002228	1.87293	0.998274
Sx	Spruce	Picea,gl*eng	5.079336672	1.85859	1.00779
Sb	BlackSpruce	Picea,mariana	5.079336672	1.85859	1.00779
Pl	lodgepole	Pinus,contorta	4.47194033	1.82276	1.10812

Acb	BalsamPopular	Pop,balsamifera	2.246823719	1.73518	1.35601
At	Aspen	Pop,trem	3.804275847	1.89476	1.05373
Fd	DouglasFir	Pseudotsuga,menziesii	4.139024528	1.74294	1.15641
Ww	Salix	Salix	NA	NA	NA
Hw	WesternHemlock	Tsuga,heterophyl	4.030574937	1.9429	0.990275
Dmaple	DouglasMaple	Acer,glabrum	NA	NA	NA

6.2.2. Biomass — Jenkins's equation

Aboveground biomass is calculated based only on the value of DBH (Jenkins et al. 2003) in the form of exponential curve. Component biomass, including foliage, root, stem bark and stem wood, is calculated by the ratio of the component and the total aboveground biomass.

$$ab = \exp(p_1 + p_2 lnd) \qquad (3)$$

Where

ab = aboveground biomass

exp = exponential function

d = DBH

ln = log base e (2.718282)

p1,p2 = parameters of aboveground biomass (table 6.4)

$$ratio = \exp(p_1 + p_2/d) \qquad (4)$$

Where

ratio = ratio of component biomass to total aboveground biomass

exp = exponential function

d = DBH

p1,p2 = parameters of component biomass (table.3)

Table 6.3 Parameters aboveground biomass and component biomass ratio (Jenkins)

Species	Aboveground biomass(kg)		Component Biomass							
			Foliage		Root		Stem bark		Stem wood	
	p1	p2	p1	p2	p1	p2	p1	p2	p1	p2
Subalpine Fir	-2.5384	2.4814	-2.9584	4.4766	-1.5619	0.6614	-2.098	-1.1432	-0.3737	-1.8055
Green Alder	-2.5384	2.4814	-4.0813	5.8816	-1.6911	0.816	-2.0129	-1.6805	-0.3065	-5.424
Birch	-1.9123	2.3651	-4.0813	5.8816	-1.6911	0.816	-2.0129	-1.6805	-0.3065	-5.424
NA	-2.5384	2.4814	-2.9584	4.4766	-1.5619	0.6614	-2.098	-1.1432	-0.3737	-1.8055
Spruce	-2.0773	2.3323	-2.9584	4.4766	-1.5619	0.6614	-2.098	-1.1432	-0.3737	-1.8055
Black Spruce	-2.0773	2.3323	-2.9584	4.4766	-1.5619	0.6614	-2.098	-1.1432	-0.3737	-1.8055
lodgepole	-2.5356	2.4349	-2.9584	4.4766	-1.5619	0.6614	-2.098	-1.1432	-0.3737	-1.8055
Balsam Popular	-2.22094	2.3867	-4.0813	5.8816	-1.6911	0.816	-2.0129	-1.6805	-0.3065	-5.424
Aspen	-2.22094	2.3867	-4.0813	5.8816	-1.6911	0.816	-2.0129	-1.6805	-0.3065	-5.424
Douglas Fir	-2.2304	2.4435	-2.9584	4.4766	-1.5619	0.6614	-2.098	-1.1432	-0.3737	-1.8055
Salix	-2.2094	2.3867	-4.0813	5.8816	-1.6911	0.816	-2.0129	-1.6805	-0.3065	-5.424
Western Hemlock	-2.5384	2.4814	-2.9584	4.4766	-1.5619	0.6614	-2.098	-1.1432	-0.3737	-1.8055
Douglas Maple	-1.9123	2.3651	-4.0813	5.8816	-1.6911	0.816	-2.0129	-1.6805	-0.3065	-5.424

6.2.3. Carbon

Carbon is calculated based on the volume (m^3), the woody specific gravity (g/cm3) (Jenkins et al. 2003) and the carbon content, which is generally around 50% (Lamlom and Savidge 2003).

$$c = g \times 10^3 \times v \times cc \times \% \qquad (7)$$

Where

c = carbon (kg)

g = woody specific gravity (g/cm3)

v = volume (m3)

cc = carbon content (%), parameters are below (table.3)

Table 6.4 Woody specific gravity and carbon content

Species Code	Species	Latin Name	Woody specific gravity (g/m3)	Carbon Content (%)
Bl	Subalpine Fir	Abies,las	0.4	50.08
Alder	Green Alder	Alnus,crispa	0.4	50.08
Ep	Birch	Betula,pap	0.43	48.37
NA	NA	genx,x	0.4	50.08
Sx	Spruce	Picea,gl*eng	0.36	50.39
Sb	Black Spruce	Picea,mariana	0.38	50.39
Pl	lodgepole	Pinus,contorta	0.38	50.32
Acb	Balsam Popular	Pop,balsamifera	0.32	47.09
At	Aspen	Pop,trem	0.34	47.09

Fd	Douglas Fir	Pseudotsuga,menziesii	0.4	50.5
Ww	Salix	Salix	0.46	49.05
Hw	Western Hemlock	Tsuga,heterophyl	0.43	50.6
Dmaple	Douglas Maple	Acer,glabrum	0.43	49.64

6.1. Additional Informal For The Methods In Chapter 2:

Gaps’ size, area and shape differ greatly depending on the forest stage (White et al. 2018) and thus could be used to differentiate forest succession. For this work, a LiDAR metric for canopy cover using only the vegetation point >3m high and further normalized with ground returns were meant to capture gap differences (STH4_Cov in Table 2.3). While this metric does not measure the canopy gap directly, canopy closure depicts the differences in canopy openness in different forest succession, especially when used together with other old-growth attributes developed for this work, such as vertical complexity. We utilized the coefficient of variation (CV) of ALS-derived tree heights. It has a high correlation with the number and complexity of canopy strata or vertical complexity (Zimble et al. 2003). Old-growth forests are expected to have higher complexity not only in the crown height but also in the understory. Thus, a metric for vertical complexity was calculated in multiple strata in the forest (0.2 – 1m, 1 – 2m, 2 – 3m, and >3m). The pipeline for these and other metrics is depicted in the Figure 6.2.

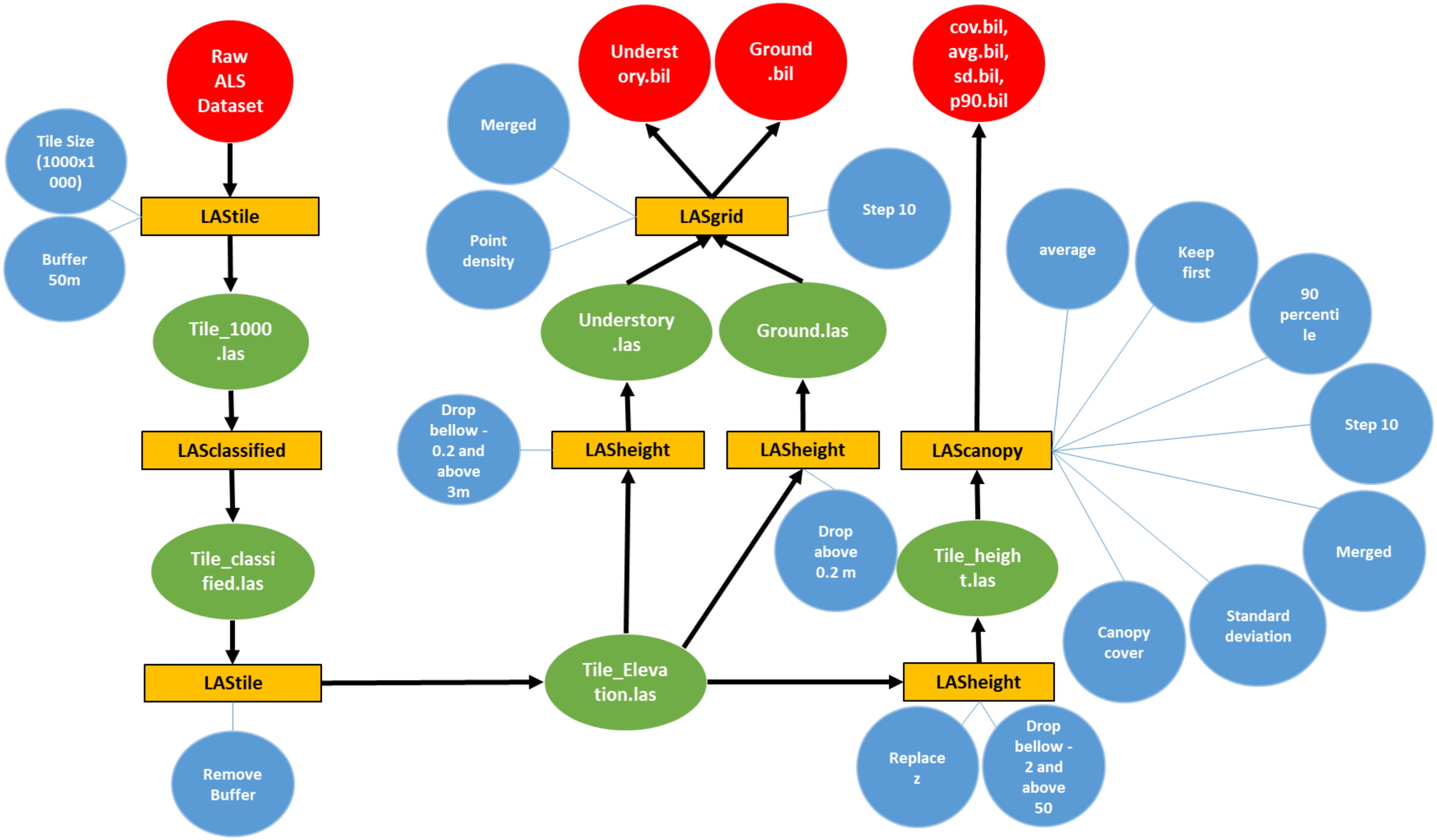

Figure 6.2 Pipeline of LiDAR processing using LASTools from the raw LiDAR files (.las) to the raster outputs (.bil) used to create ecological meaningful metrics for old-growth attributes.

Table 6.5 summarizes the correlation analyses done with a set of attributes indicated by different authors as important old-growth attributes (McElhinny et al. 2006b, 2006a, Spies et al. 2006, Bauhus et al. 2009). The idea of this correlation was to remove variables with a low correlation with age. We found that nine out of the ten variables best correlated with age were listed by Bauhus et al. (2009). Also, from the variables that we included in addition to Bauhus's list, only maximum height was among the ten best correlated. Early succession species had a negative correlation with age, which is ecologically logical. However, it was not among the ten best correlates. Figure 2.4 depicts the histograms of the ten variables best correlated with age. Maximum height, vertical and horizontal complexity was the only variable with distribution closer to normal. All other variables skewed towards small values. In order to use more common statistical models, such as multilinear regression, I would have to normalize the variable. We understand that such a procedure can induce a false conclusion. Therefore, we opted to use the original data format and chose a robust statistical approach that could deal with non-normal data distribution. Random forest is a powerful machine learning technique that learns with the data input. The random nature of this model avoids overfitting and generates robust classification and regression models. Forest succession classification and the old-growth indices (Table 2.2) utilized the ten old-growth attributes best correlated with age (Table 2.4).

Table 6.5 Correlation of old-growth attributes with stand age to select the best ten correlations of old-growth attributes with estimated stand age. CV% = Coefficient of variation, Std = Standard Deviation, dbh = diameter at the breast height.

Old-Growth Attributes		Correlation	p-value
Age	Maximum Height (m)	0.670	4.34E-14
	Above Ground Biomass (tons/ha)	0.662	1.12E-13
	Vertical Complexity (CV% of height)	0.588	1.95E-10

Basal Area (m^2/ha)	0.521	3.86E-08
Volume (m^3/ha)	0.509	8.49E-08
Horizontal complexity (CV% of dbh)	0.409	2.91E-05
Special Features (count #)	0.317	1.49E-03
Late succession species (tons/ha)	0.311	1.84E-03
Dead standing trees (m^2/ha)	0.284	4.58E-03
Coarse woody debris (m^3/ha)	0.262	9.04E-03
Tree class (std)	0.225	2.62E-02
Early succession species (tons/ha)	-0.223	2.74E-02
Basal areas of large trees (m^2/ha, dbh>40cm)	0.192	5.84E-02
Tree diversity (Shannon Index)	0.172	8.96E-02
Density of trees (#trees/ha)	0.172	8.98E-02
Density of small trees (# of trees dbh < 4cm/ha)	0.155	1.28E-01

6.2. Distribution of Old-growth attributes based on different old-growth definitions

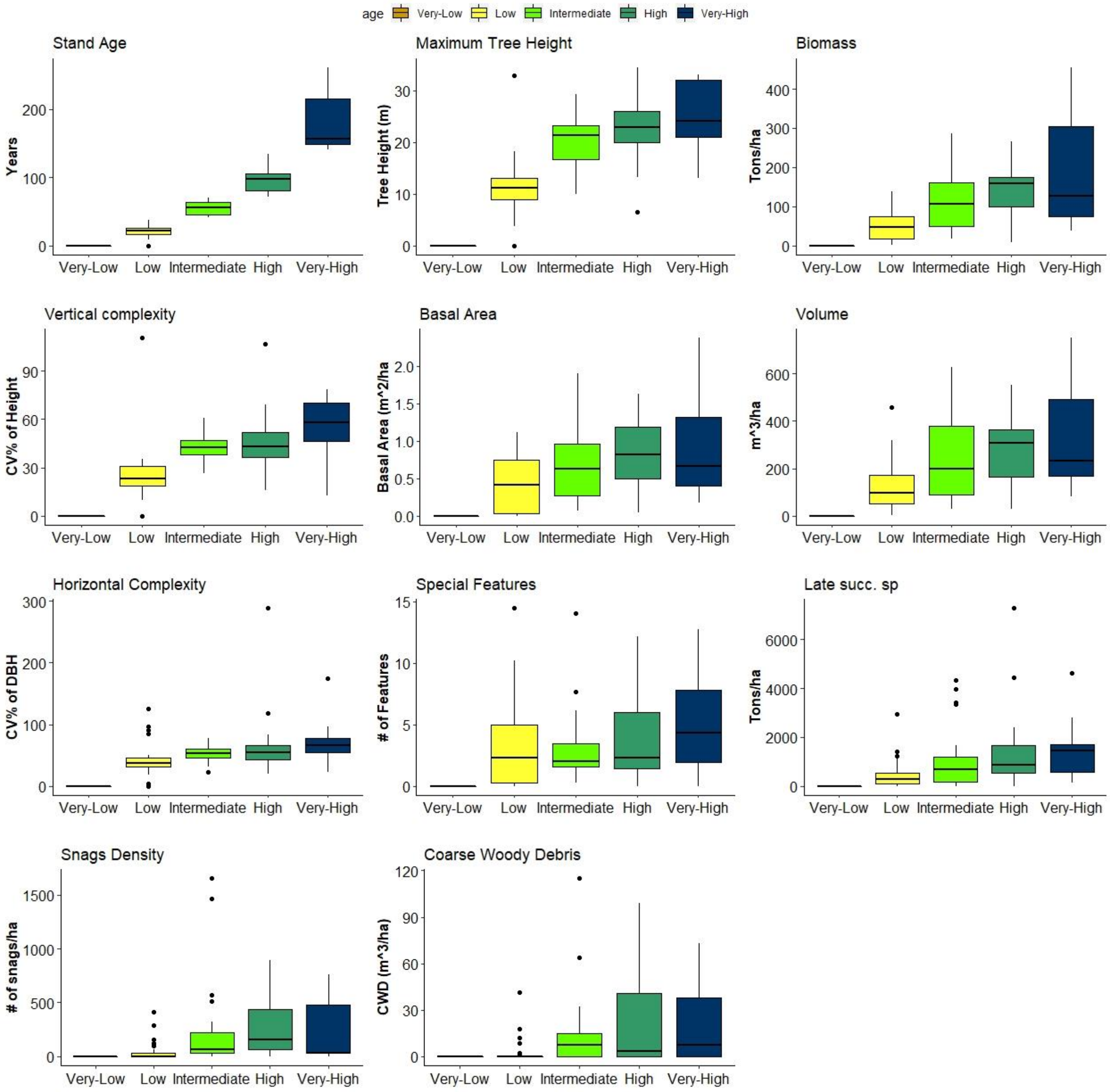

Figure 6.3 Distribution of old-growth attributes per forest succession defined by age classes (AGE_CLASS).

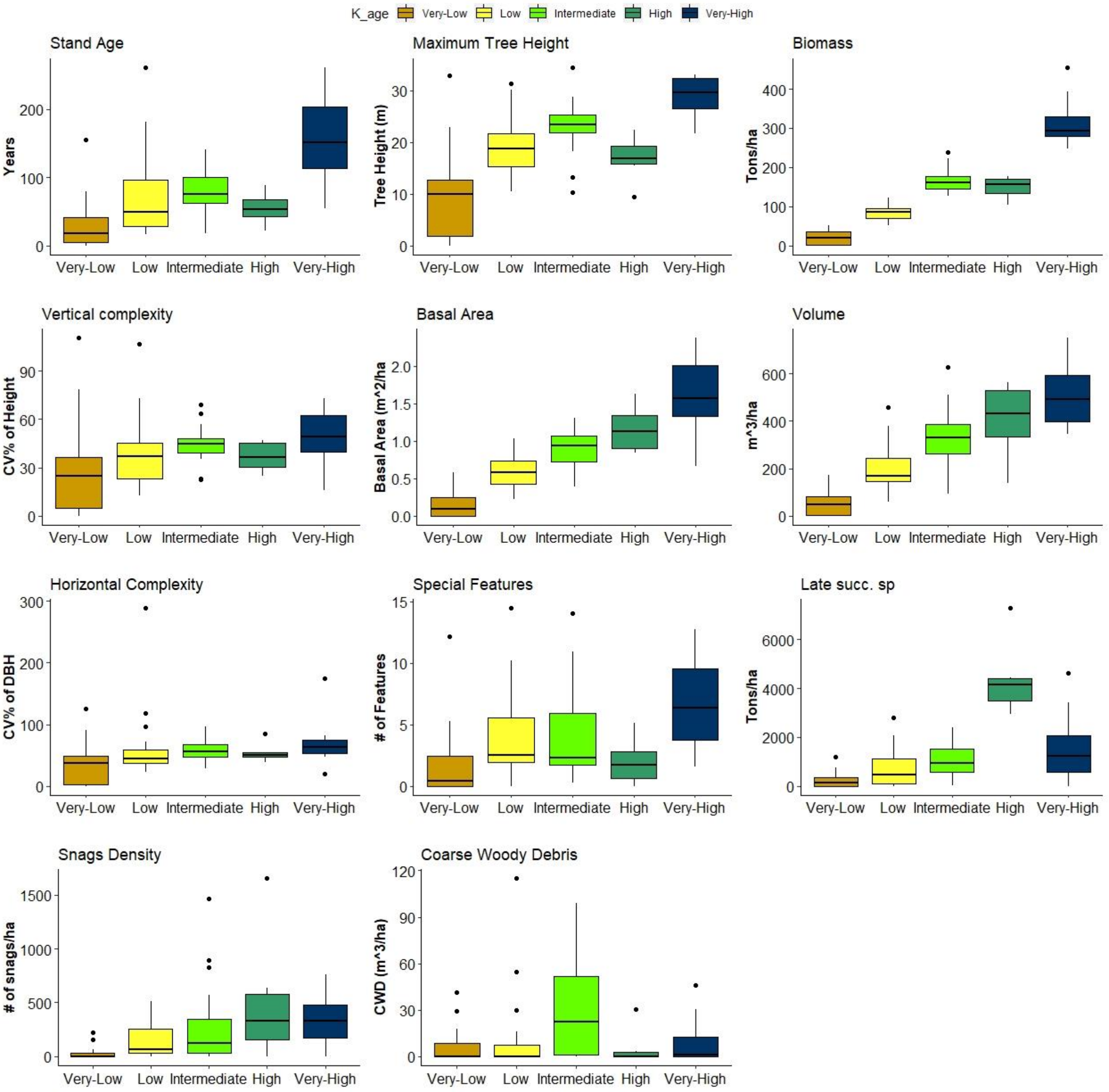

Figure 6.4 Distribution of old-growth attributes per forest succession defined by k.means classification of all old-growth attributes, including AGE (KOGA+AGE).

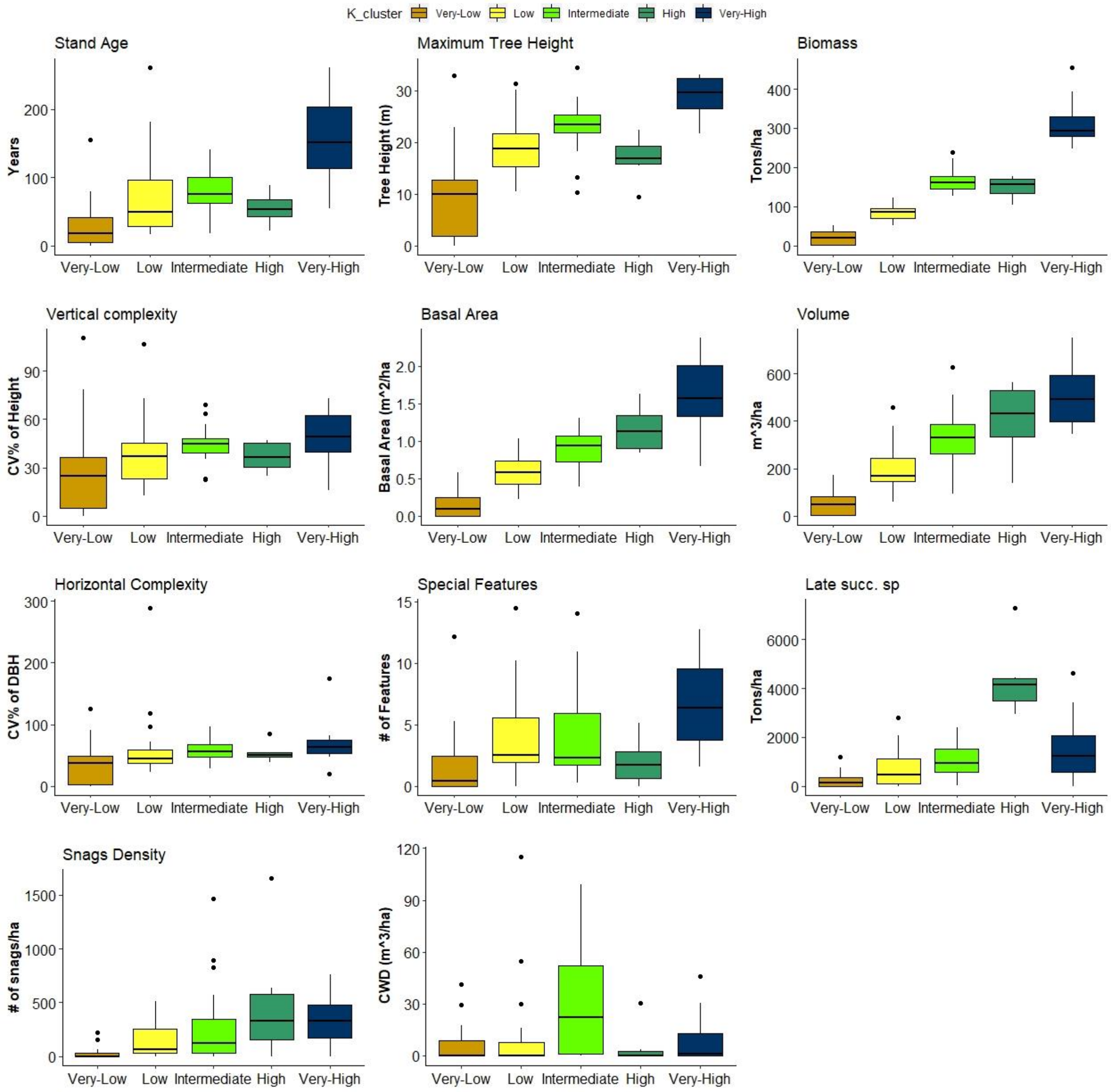

Figure 6.5 Distribution of old-growth attributes per forest succession defined by k.means classification of all old-growth attributes, except AGE (KOGA).

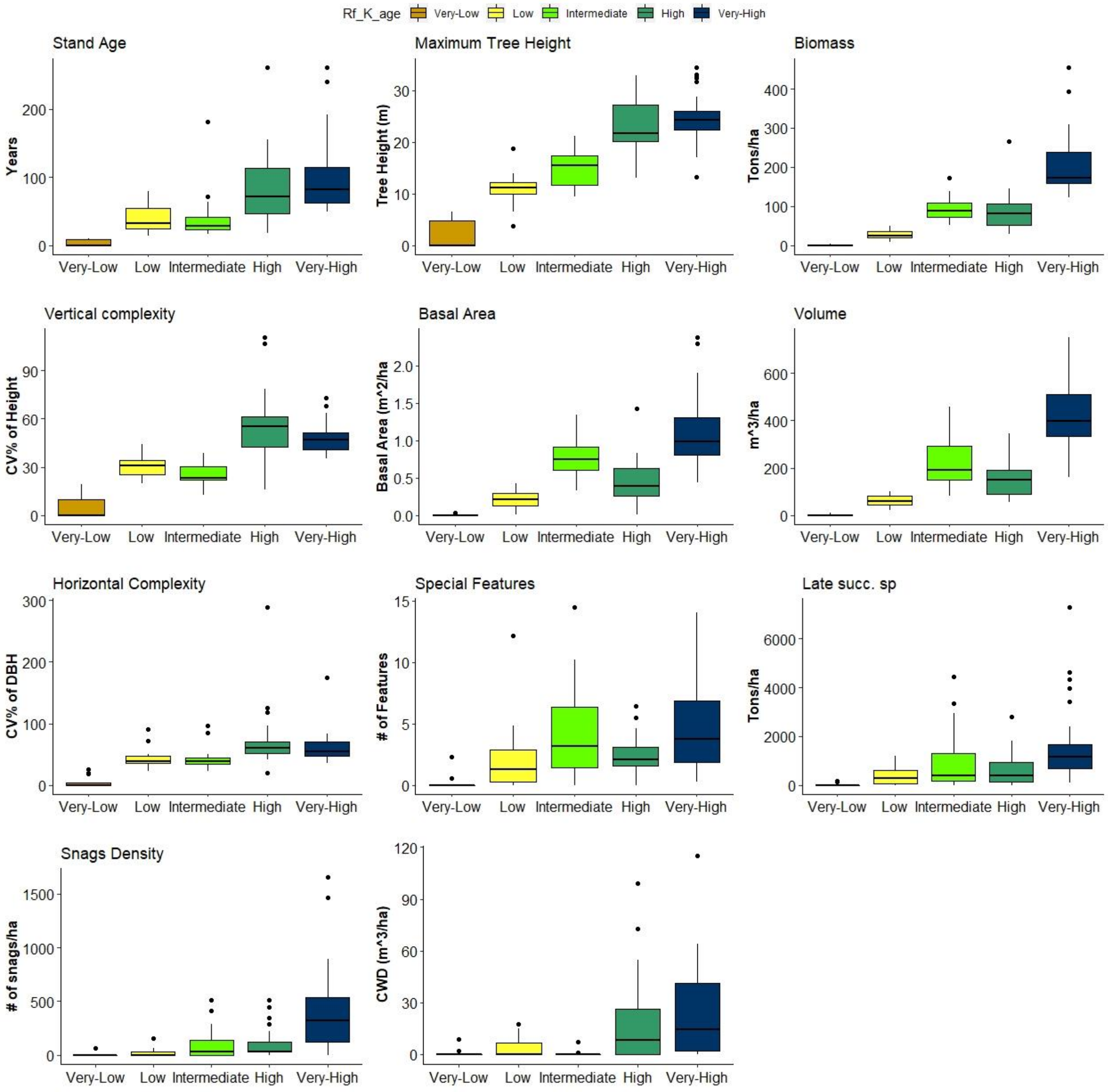

Figure 6.6 Distribution of old-growth attributes per forest succession defined by k.means all proximity values from unsupervised random forest of old-growth attributes, including age (RFOGA+AGE).

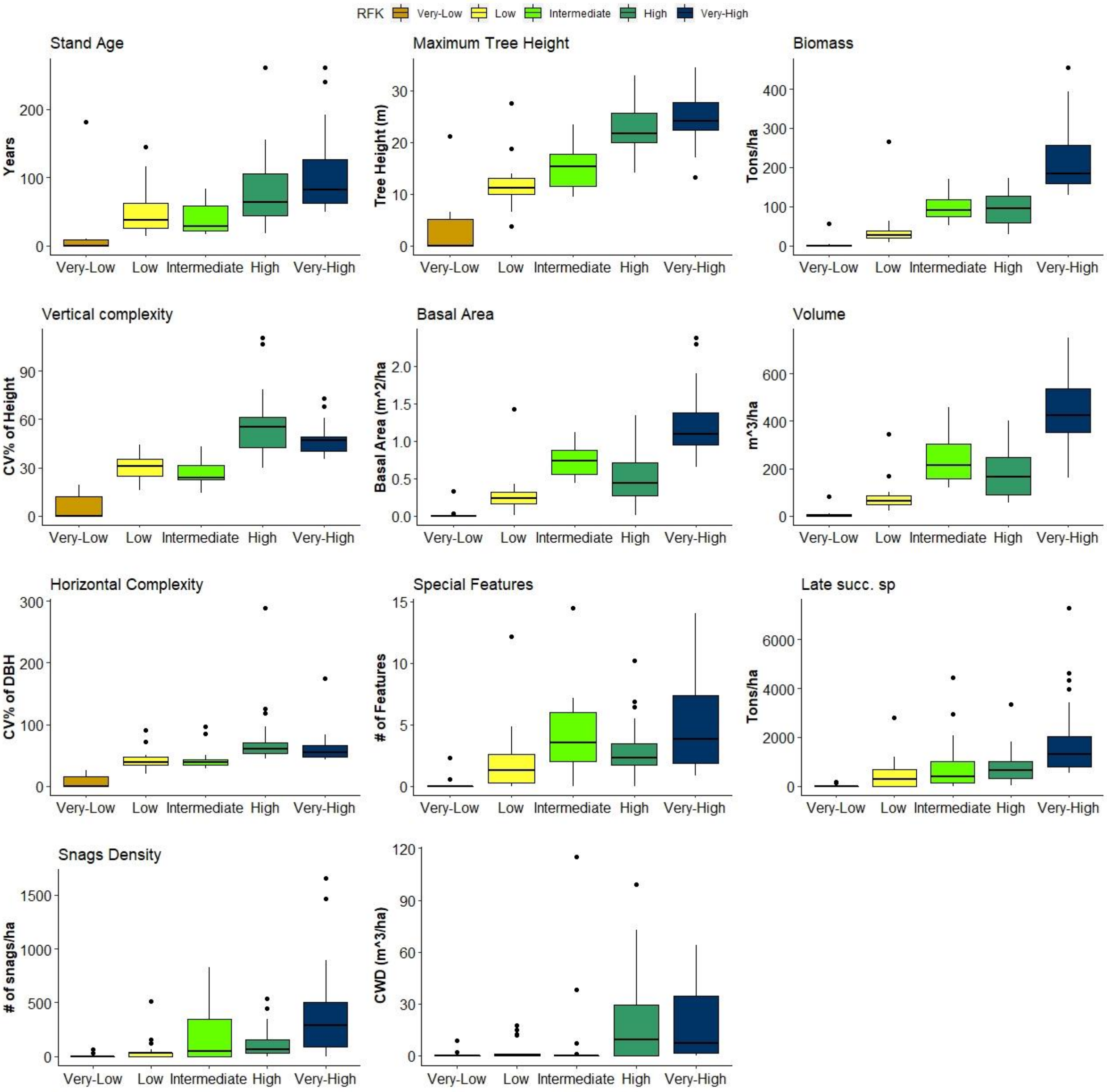

Figure 6.7 Distribution of old-growth attributes per forest succession defined by k.means all proximity values from unsupervised random forest of all old-growth attributes, except AGE (RFOGA).

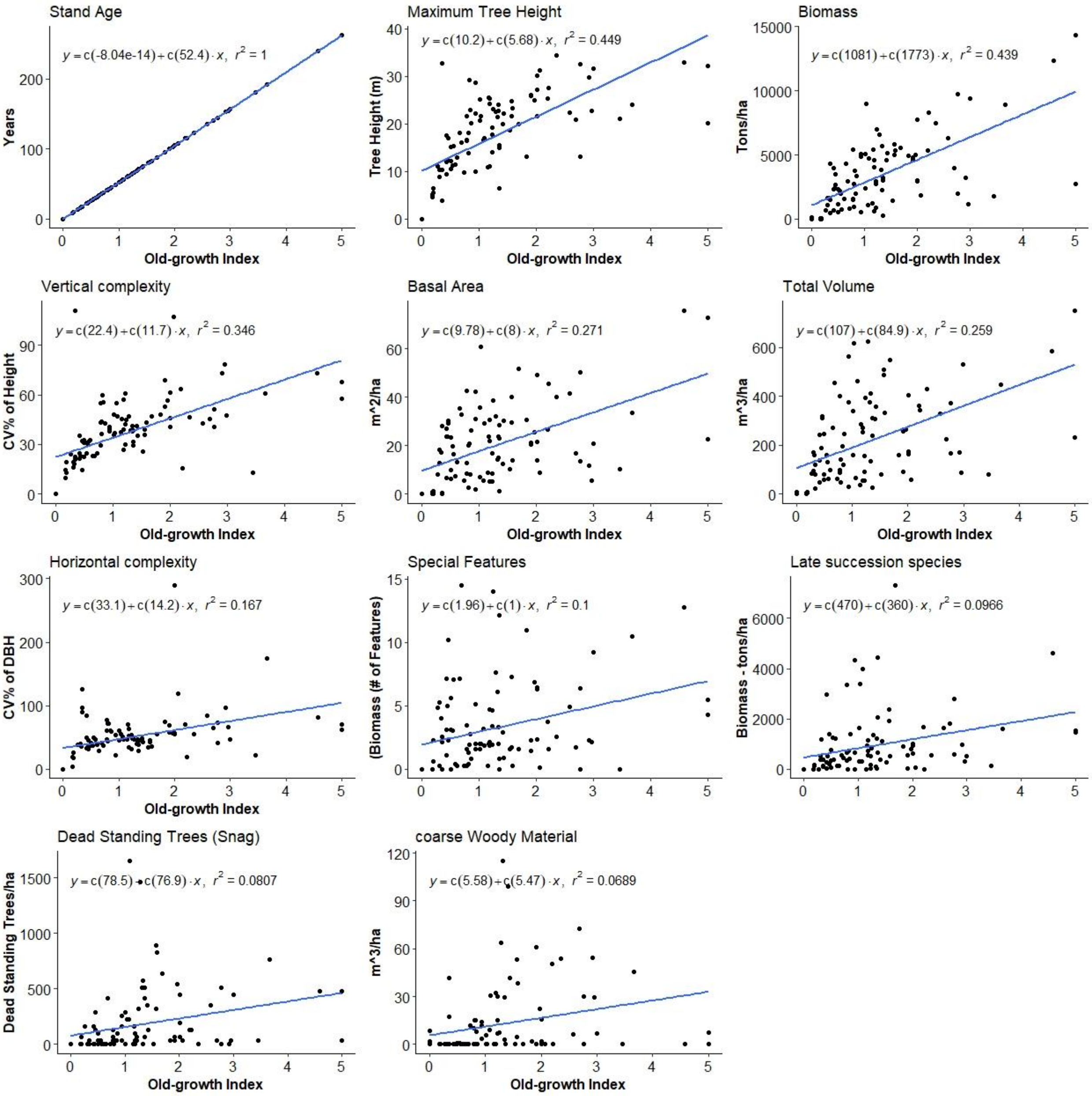

Figure 6.8 Distribution of old-growth attributes against age as a continuous variable (all plot ages were divided by the maximum age found during inventory and multiplied by five, since age classification was divided into five classes.

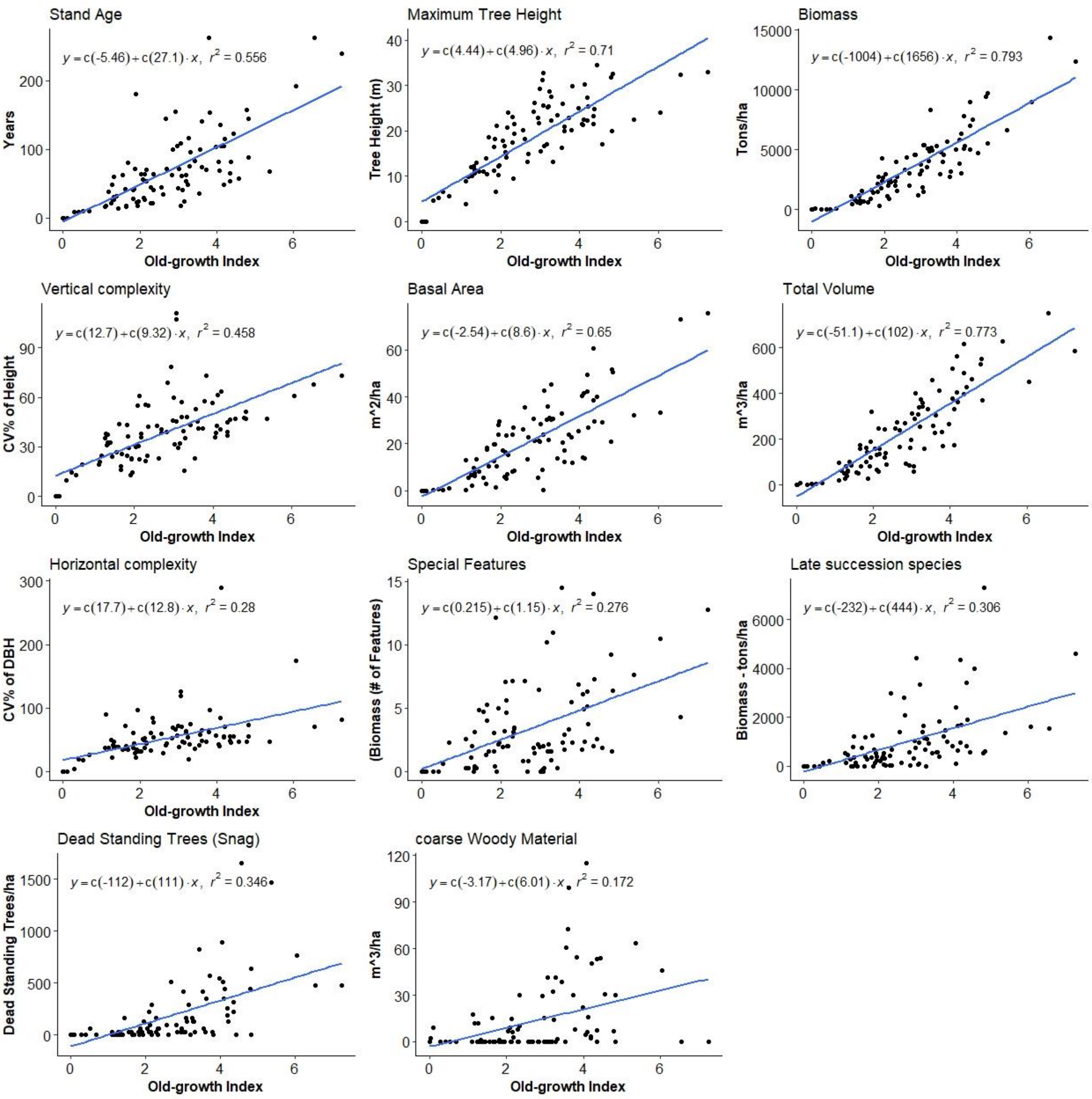

Figure 6.9 Distribution of old-growth attributes against old-growth index OGA+AGE (sum of all attributes).

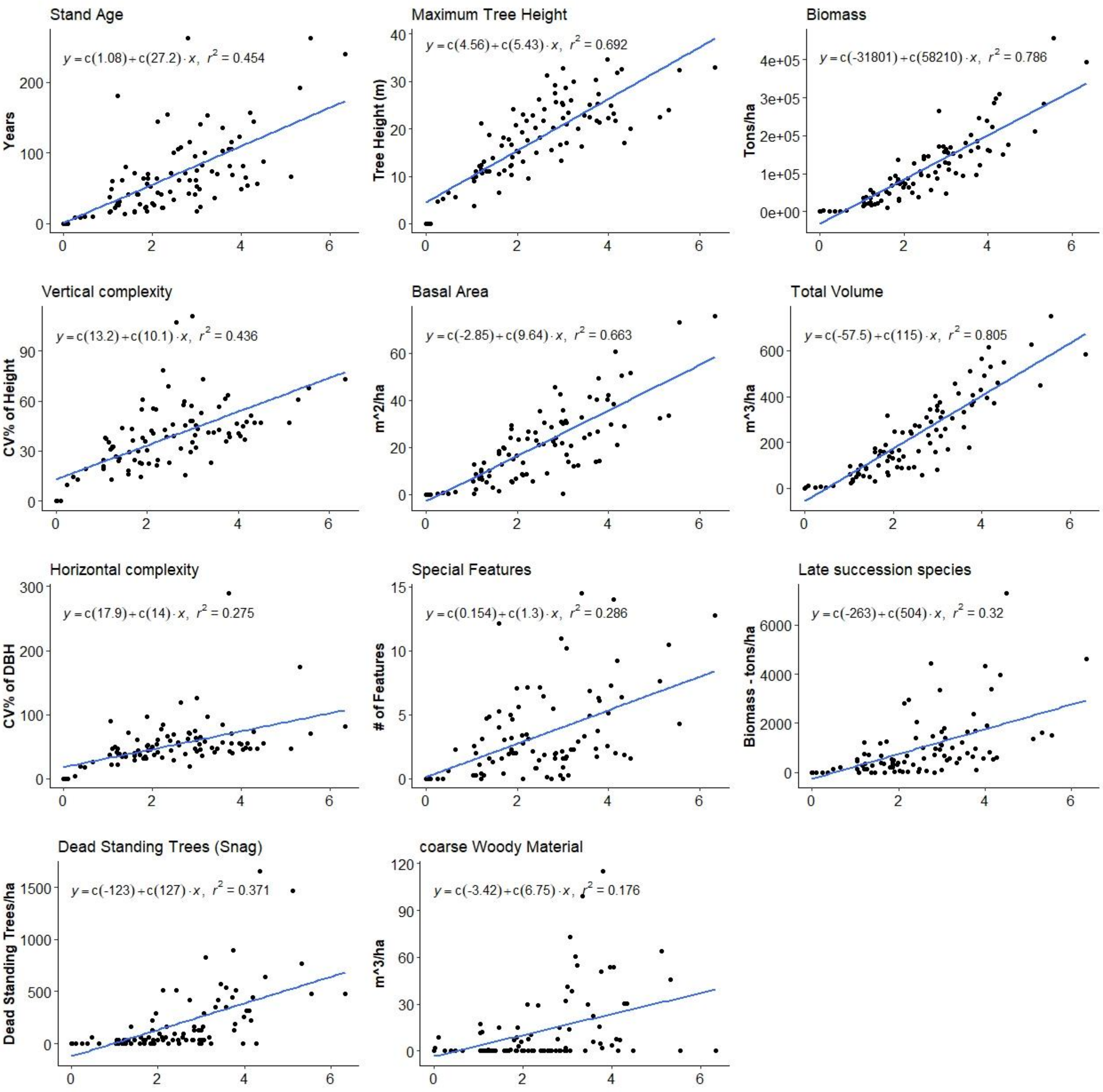

Figure 6.10 Distribution of old-growth attributes against the old-growth index OGA (sum of all attributes, except age).

6.3. Water value:

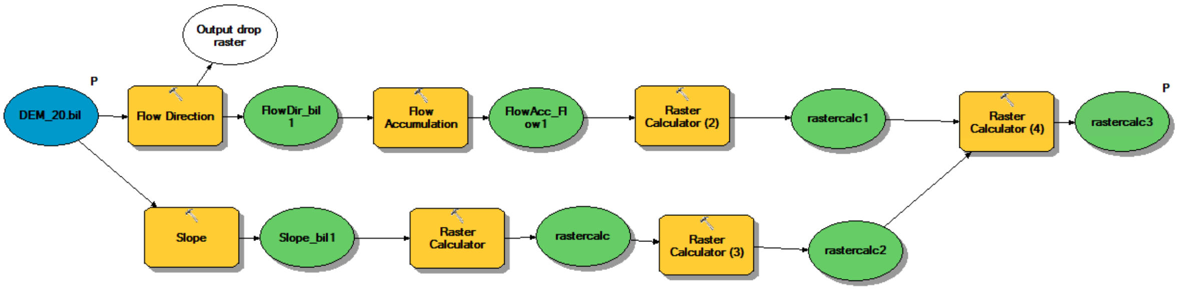

Figure 6.11 ArcMap pipeline for the development of a wetness index as a proxy for water provision. In this model, wetter areas are expected to have higher potential for water provision.

6.4. Random forest results:

In Table 6.5, I listed the five most important prediction variables, LiDAR metrics, for each old-growth model. For the model chosen and utilized in this study, the most important variables were all height-derived metrics, where the maximum height, proxy for dominant tree height, was the most important metrics for old-growth definition. The standard deviation of height, appointed as one important metric for the differentiation between forest successions, was also in between the five most important metrics.

Table 6.6 Ranking of importance of LiDAR metrics

	First	Second	Third	Fourth	Fifth
AGE_CLASS	AHR_Std	STH4_Com	AHR_Max	VERCOMP	H95PercT
KOGA+AGE	STH4_Den	AHR_Dns	H95PercT	AHR_Max	STH4_Cov
KOGA	STH4_Den	AHR_Dns	AHR_Max	H95PercT	STH4_Cov
RFOGA+AGE	AHR_Max	H95PercT	AHR_Std	AHR_Qva	STH4_Cov
RFOGA	AHR_Std	STH4_Cov	AHR_Dns	AHR_Avg	AHR_Qva
AGE	AHR_Max	AHR_Std	AHR_Qva	H75PercT	H95PercT
OGA+AGE	AHR_Max	AHR_Std	AHR_Qva	H75PercT	H95PercT
OGA	AHR_Max	AHR_Qva	H75PercT	H90PercT	AHR_Std

6.5. Fragmented versus contiguous reserves:

Planning unit selections resulting from simple objective functions often result in solutions that are highly fragmented and widely dispersed, yet spatial aggregation of planning units may be desirable for both ecological and management reasons. The ecological justification for aggregation often relates to the ‘single large or several small’ (SLOSS) debate (Diamond 1975), species-area relationship, and population viability. Researches indicate that bigger reserves, more circular with a shorter distance between each other and with habitat corridor links are better than otherwise (Diamond 1975). Determining the strength of the aggregation of compactness effect is a subjective decision that can be usefully visualized by trade-off curves (Beyer et al. 2016). Thus, different clumpiness levels were visually tested to determine the clumpiness level that better approximates the current OGMA’s design (Figure 6.10). Also, timber extraction is the primary management strategy in the landscape. Thus, timber harvesting may occur in all areas outside OGMAs.

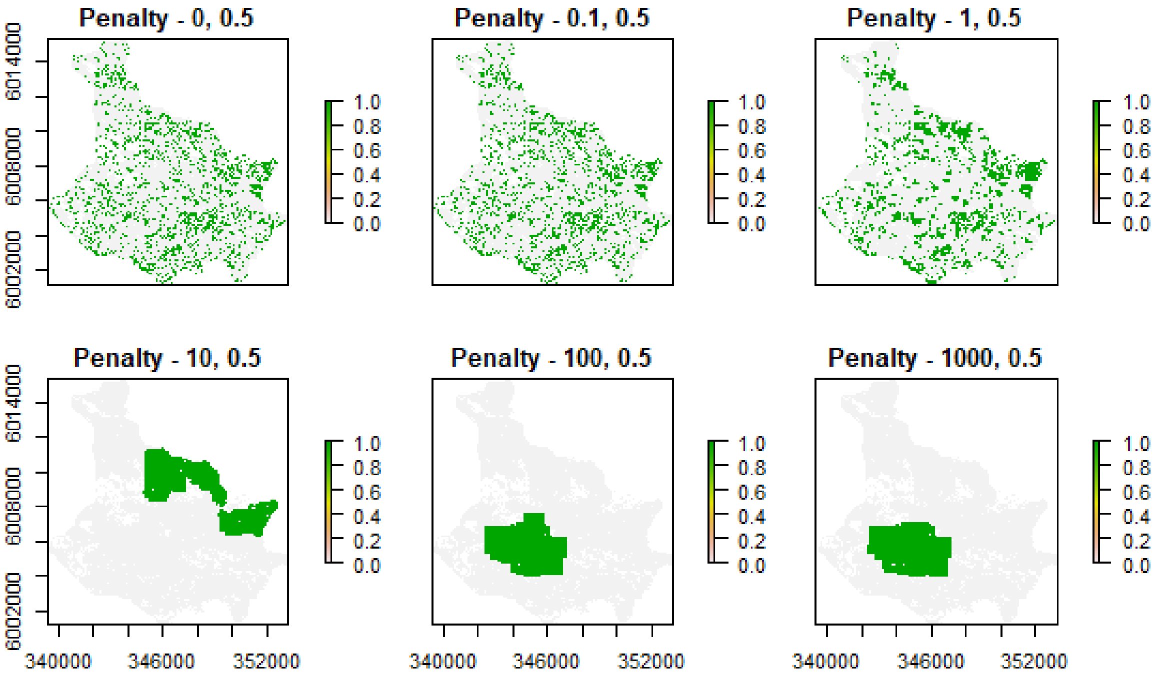

Figure 6.12 Test with multiple boundary length penalties to visually select between OGMAs designs that are extremely fragmented or overly contiguous.

In Figure 6.10, I compare scenarios of increased clumpness (reduction in fragmentation) and increase in area sizes with the current OGMAs network. I assumed that doubling and tripling the current OGMAs areas would result in double and triple of ecosystem services representation in order to get a baseline for comparison. The results in the image are the percentage different between proposed scenarios and the baseline created here. The scenarios demonstrated that more fragmented networks can target better the areas that offer the greatest amount of ecosystem services. Thus, for low clumpness scenarios, all ecosystem services provisioning were mostly above baseline, except for tree diversity and water prioritization. Scenarios with medium and high clumpness were closer to baseline values, which indicate a more linear relationship with area. Most scenarios have higher tree diversity representation than the current OGMA network. In addition, area and feature representation are not linear. In other words, doubling area of OGMA does not mean, representing the double of ESs.

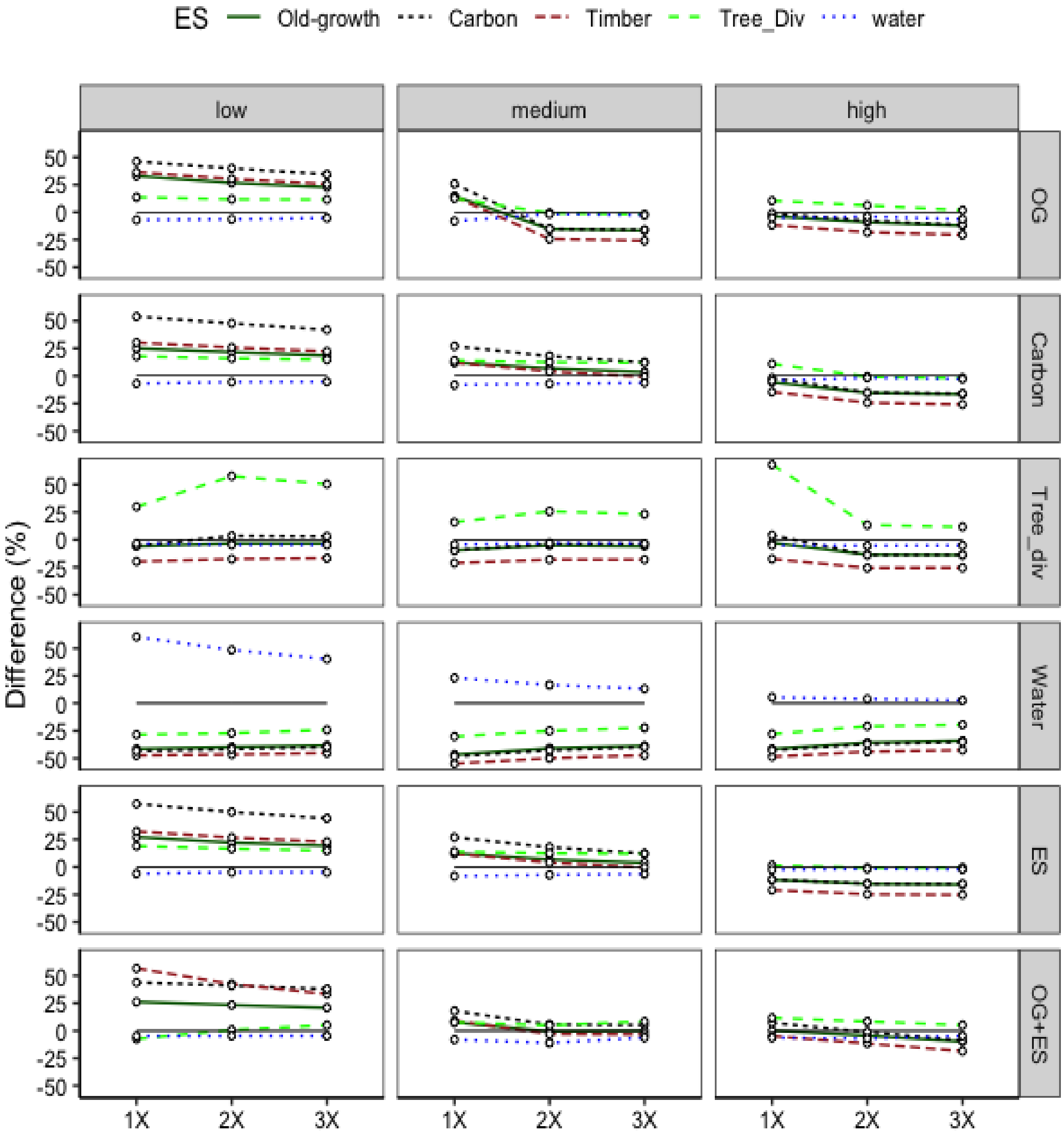

Figure 6.13 Comparison between three different levels of clumpness, from more fragmented to more contiguous reserves networks, and three different reserves network sizes (1X= current OGMA size, 2X= double the current size, and 3X=triple).

A higher level of clumpiness limits the fragmentation and edge effect. However, low levels of clumpiness (more fragmented networks) achieve higher representation of ecosystem services and old-growth values than high clumpiness for the area. The boundary penalties for high clumpiness forces “prioritizR” to achieve contiguous reserves’ networks at the expense of selecting low-value pixels. As a consequence, contiguous networks have less ESs representation with the same amount of set-aside planning units. Even with the smaller feature representation than highly fragmented scenarios, an intermediate clumpiness is more relevant in CCF for two reasons: it better corresponds to the current OGMA design in terms of shape and area, and it allows for a reduced edge effect. Also, bigger OGMAs have a higher chance to accommodate disturbances than small fragmented ones. Bigger reserves allow for multiple different forest succession to occur within the same OGMA and reduce the risk of succession being reset throughout by a single event such as a wildfire (Pickett and Thompson 1978). The reduced edge-to-area ratio may incur more viable populations and ecological processes, crucial for biodiversity and other ecosystem services provisioning. In general, edges between priority areas and cleared or degraded areas are unfavourable ecologically, although, for some species of conservation concern, edges are favourable (Fahrig 2002). On the other hand, when highly clumped, OGMAs’ network might not be separated from an appropriate geographic distance to protect species in multiple places, which might increase the risk of extinction due to a catastrophic event (e.g. wildfires, disease outbreaks)(Game et al. 2008).

6.6. PrioritizR scenarions for increasing areas

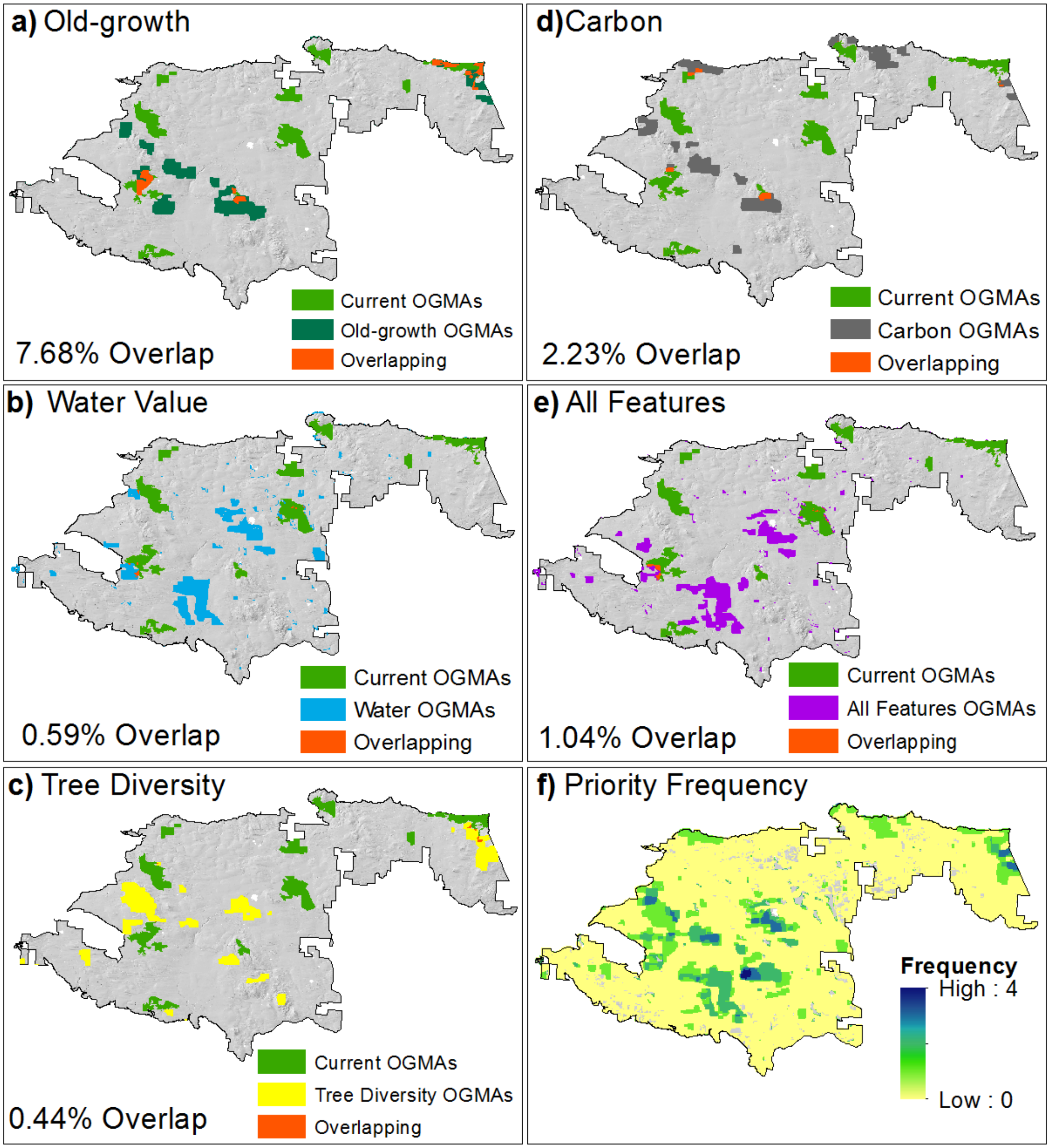

Figure 6.14 Comparison between current OGMAs' network and OGMAs designed to priority a) Old-growth, b) Water value, c) Tree diversity, d) carbon, e) all features. The representation of how many times one planning unit was taken as priority is represented in f).

Managers are not allowed to reduce the current sizes of Old-growth management areas (OGMAs), only shift to a different location or increase their sizes (MFLNRORD 1995).

Thus, I designed increments in OGMAs’ areas from 1-50% of the total landscape starting from current OGMAs’ area (5.39% of the landscape or 3,541 ha) to observe possible synergies and trade-off between ESs. Figure 6.15 depicts the comparison between the increments in OGMAs’ areas starting from current OGMAs’ design and the five alternative networks for ESs’ reserves developed in this study. Scenarios starting from current OGMAs’ design were called “Fixed” because the current OGMAs’ locations were unchanged. The alternative scenarios called “Not-Fixed” because they were individually designed to represent priority areas for the provision of each ES and them all together. The idea of this analysis is to evaluate if, for future OGMA increment, the starting point affects the final ES provision.

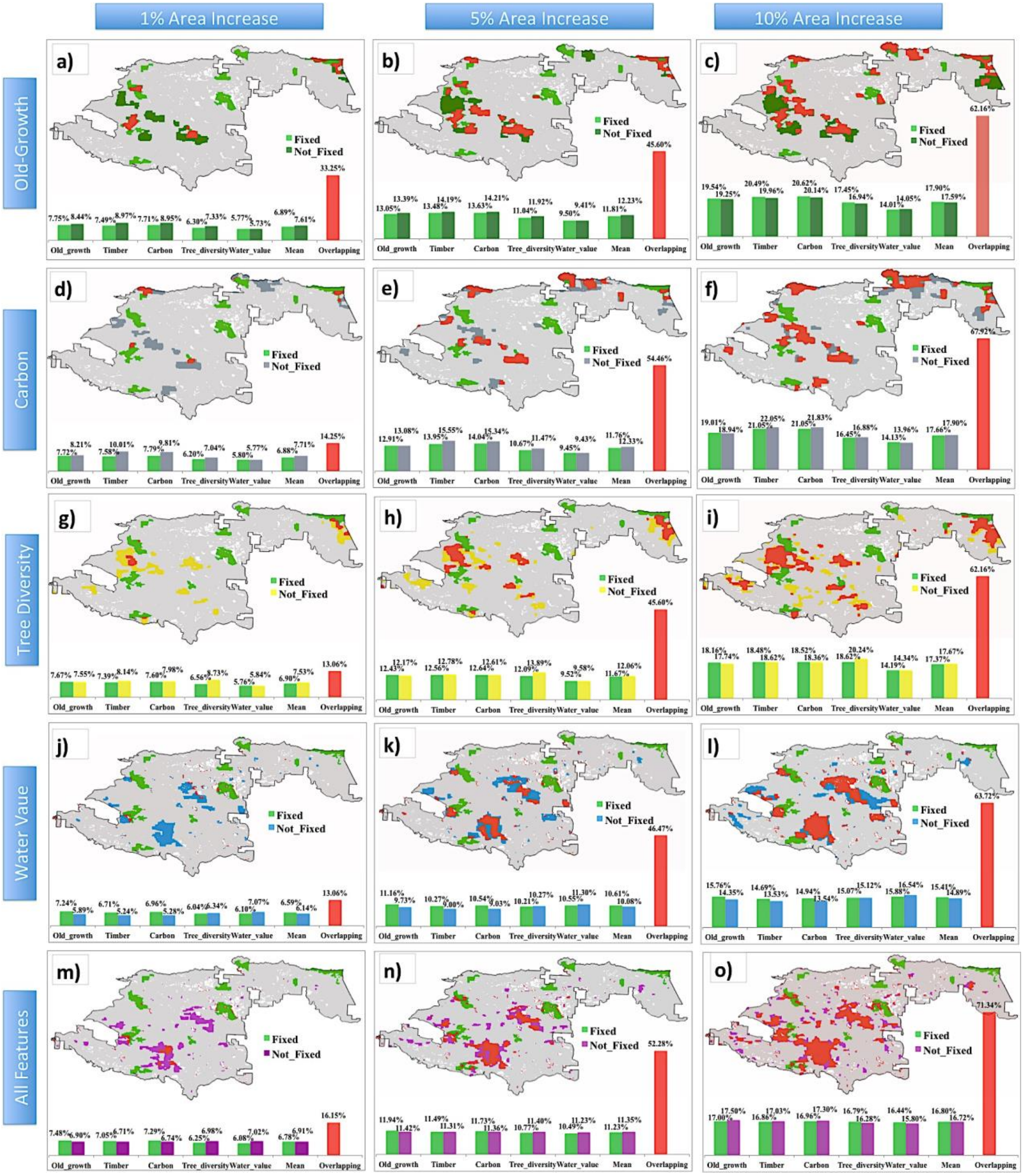

Figure 6.15 Comparison between increase in OGMAs' areas starting from current OGMAs (Fixed) and OGMAs designed to prioritize each individual ecosystem services and all features together (Not-fixed). Old-growth prioritization is represented in figures from a) to c), with areas increase of 1%, 5%, and 10% respectively; carbon prioritization from d) to e), tree diversity from f) to h); water values from j) to l), and all feature from m) to o).