SYSTEMATIC CONSERVATION PLANNING OF OLD-GROWTH VALUES

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Highlights

• We integrated a systematic conservation planning tool to the design and assessment of old-growth forests reserves.

• The machine learning tequinique, "Random forest", generated strong ecosystem services models from LiDAR metrics and field estimates.

• The estimated gain in old-growth representation in optimum old-growth reserves was not sigficant, indicating a lack of scope for shifting current old-growth management areas (OGMAs).

• An increase in OGMAs areas are not likely to affect timber harvesting before 28% of the study site is set-aside for old-growth conservation.

• There should be different goals for riparian and old-growth conservation to avoid tradeoffs between these two 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 a 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.

Keywords: conservation of old-growth forest; sustainable forest management; community forest; forestry

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-users 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 2017).

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. 2009, 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.

2. Material And Method:

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 2017). 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 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.

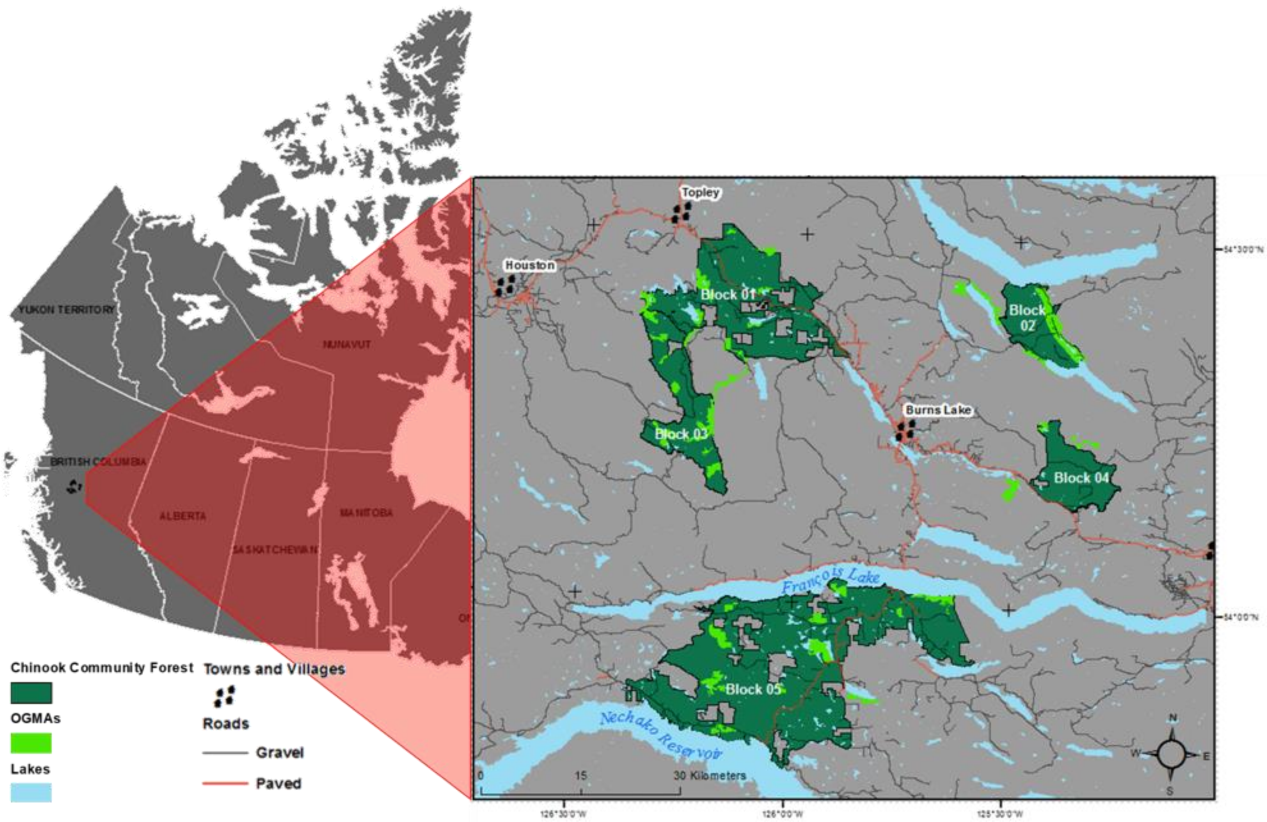

Figure 1 Location of Chinook community forest tenure areas and distribution of Old-growth management areas (OGMAs).

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). These services were timber volume (m^3), carbon storage (Mg), tree diversity (Shannon diversity index), and water values (wetness index) (Figure 2). 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 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 Appendix 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. 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. 2009). 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 4). 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 a OGMAs’ designing tool. Thus, while the accuracy of the individual inputs is important, they do not limit the study.

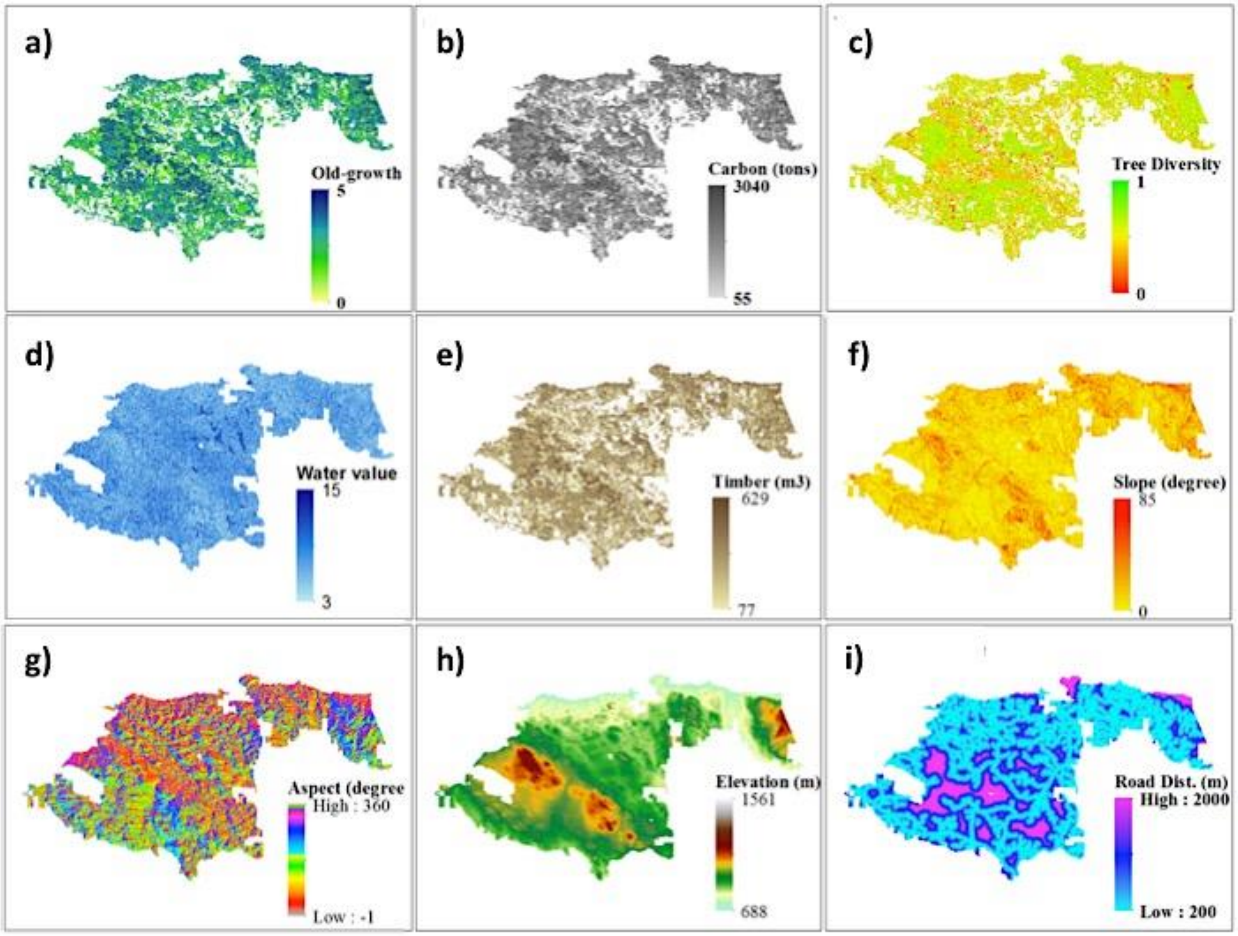

Figure 2 Ecosystem Services and landscape features utilized in the development of "prioritizR" scenarios. A "random forest" framework was applied to generate the a) old-growth index and to estimate b) carbon, c) tree diversity, e) timber for the study site. The d) water value and landscape features f) to i) were developed with surface analysis in ArcMap.

2.3. Systematic Conservation for Old-Growth Values

As a conservation planning tool, we utilized "PrioritizR" to simulate optimum reserves' networks for the provision of old-growth and multiple ecosystem services (Table 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 5. 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 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 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 0 Conservation planning scenarios for OGMA design with "prioritizR"

Prioritizing Feature	PrioritizR Models	Same area Scenarios Percentage	Same area Scenarios Measure	Increase Area Scenarios Percentage	Increase Area Scenarios Measure
	Current OGMAs	5.39%	3541 ha	1 - 50%	1% = 669 ha
Old-growth	Priori:Old-Growth	5.39%	3541 ha	1 - 50%	1% = 669 ha
Carbon	Priori:Carbon	5.39%	3541 ha	1 - 50%	1% = 669 ha
Tree diversity	Priori:Diversity	5.39%	3541 ha	1 - 50%	1% = 669 ha
Water value	Priori:Water	5.39%	3541 ha	1 - 50%	1% = 669 ha
All Features	Priori:All	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. Results:

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 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 1 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 b) with landscape (Figure 3 a). On the other hand, tree diversity has a much lower correlation with old-growth inside OGMAs compared to the landscape, 0.09 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.

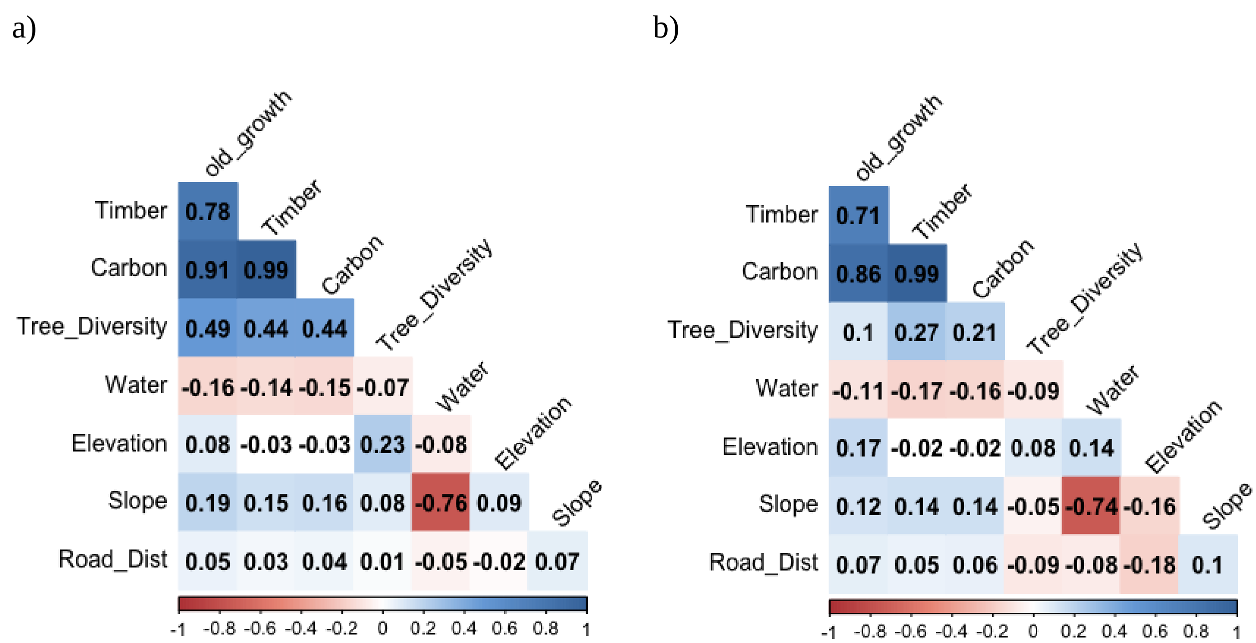

Figure 3 Correlation analyses of ecosystem services and landscape variables a) in the whole landscape, and b) within OGMAs. Values in the grid correspond to the correlation direction and strength between the variables, and the color scale, in the x axis, represents the significance level (p-value<0.01)

3.2. Systematic conservation planning applied to OGMAs

The difference between the percentages of each ES reserved in each alternative OGMAs' network was quite small (Figure 4). For old-growth representation, only OGMAs designed to prioritize water values, Priori:Water = 1822.63 (+/- 284.75), were significantly different from current OGMAs, 2014.64 (+/- 120.12). The only value Priori:Water significantly outperformed current OGMAs was the water value representation, 5219.38 (+/- 222.34) and 4224.70 (+/- 264.49) for Priori:Water and Current OGMAs respectively. Priori:Carbon had significantly higher carbon storage than current OGMAs, 43.88 (+/-1.37 MgC) and 34.06 (+/- 4.40 MgC) respectively. However, Priori:Carbon set aside higher timber volume than current OGMAs, 222882.18 (+/-7624.68 m^3) and 164279.26 (+/- 24018.63 m^3). As well, Priori:Diversity significantly outperform current OGMAs in term of tree diversity. When all features were prioritized simultaneously, there was no significant difference with current OGMAs for none of the values.

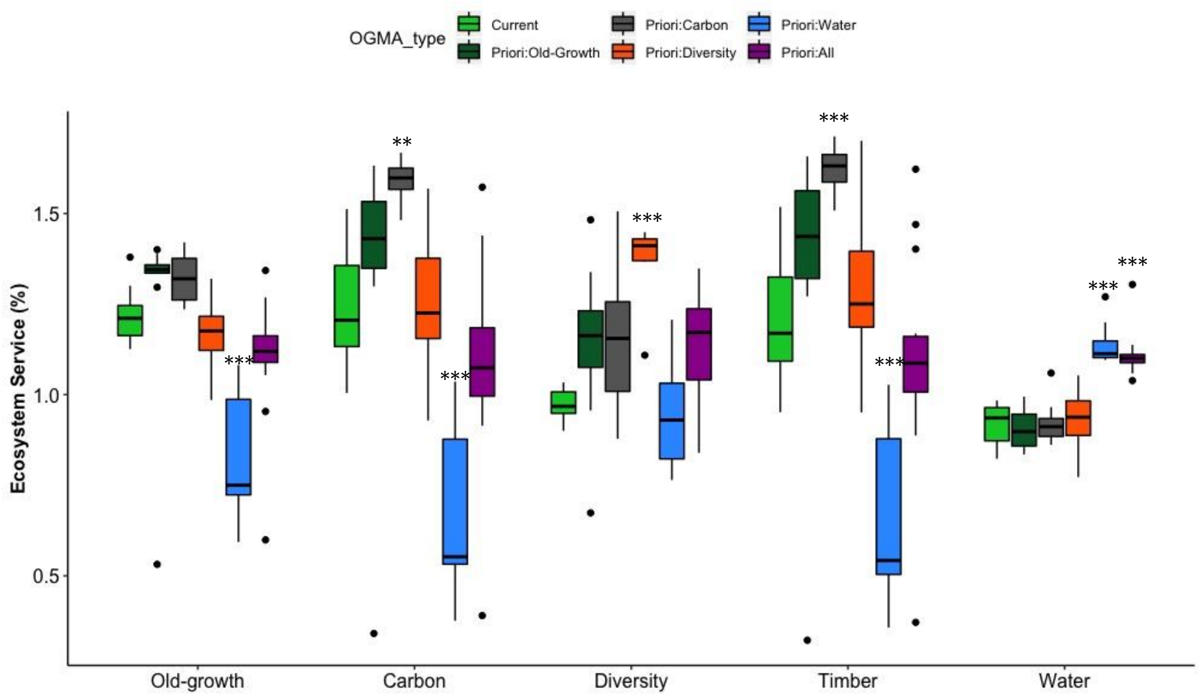

Figure 4 Ecosystem service provisioning represented (%) in current old-growth reserve and each "prioritizR" model. Percentages are the sum of the ecosystem services value within each reserve in the reserve network in relation to the total amount of the ecosystem in the whole landscape. Results from ANOVA and TUKEY mean comparison are summarized in appendix. Results are represented by the significance codes: 0'***' 0.001 '**' 0.01'*' for models that are significantly different from current old-growth reserves.

Only a fraction of the priority areas for the conservation of old-growth and other ecosystem services are currently inside OGMAs (Figure 5) (See also Appendix 6). While each OGMA design displayed different arrangement in the landscape, there was no significant deference between the size distribution of OGMAs for each alternative OGMA network (Df=5, F value= 1.98, p-value= 0.08). 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. 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 not significant. 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%). 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. 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 5 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). 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 5 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.

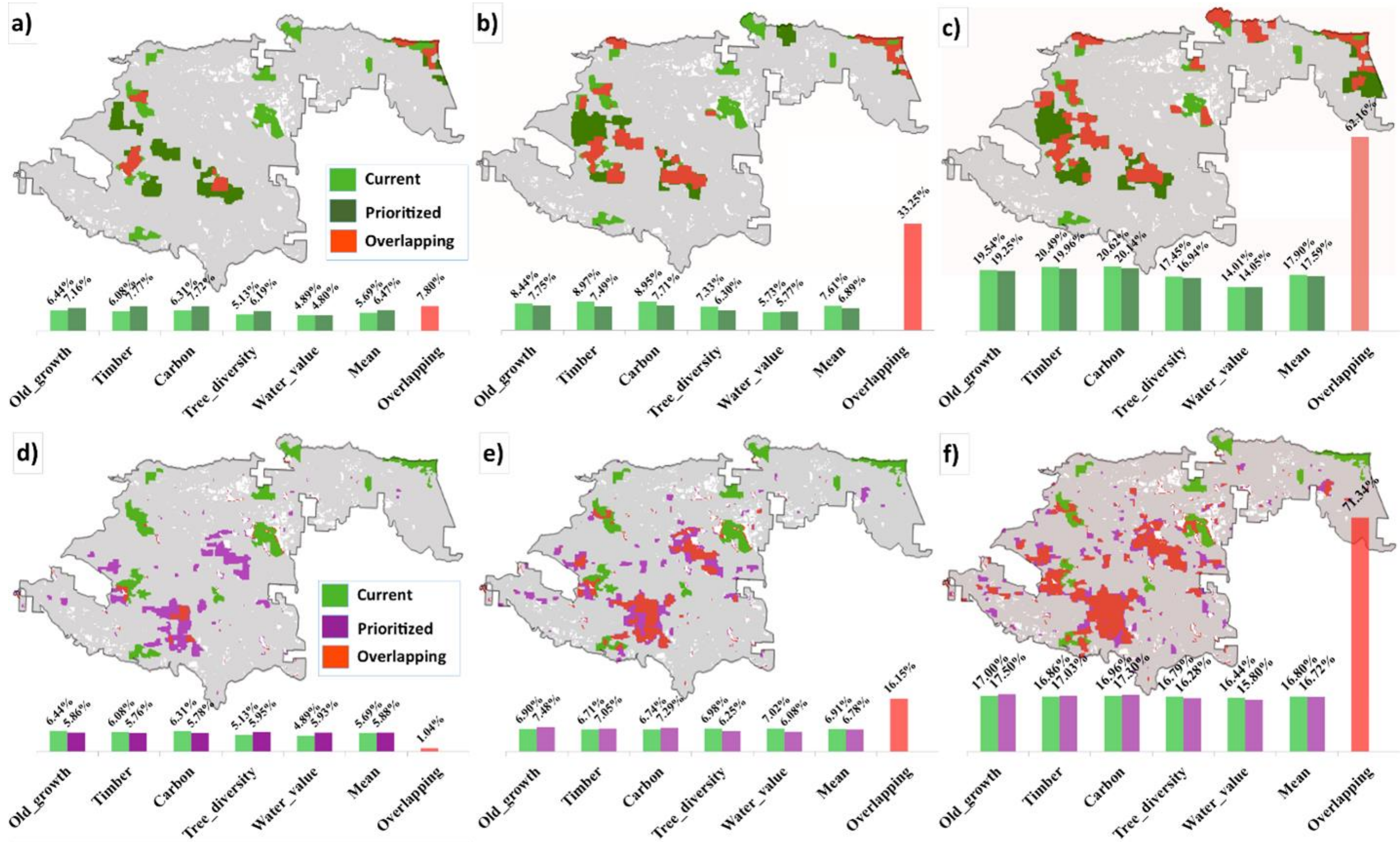

Figure 5 Comparison between increase in OGMAs' areas starting from current OGMAs and OGMAs designed to prioritize each individual ecosystem services and all features together. Old-growth prioritization is represented in figures from a) to c), where a) represents scenarios with current OGMAs size (0% 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 6 b). Besides, despite the low correlation between timber and water (-13%) and timber and tree diversity (42%) (Figure 6), these two values were strongly affected by timber harvesting (Figure 6 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 6 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 6 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.

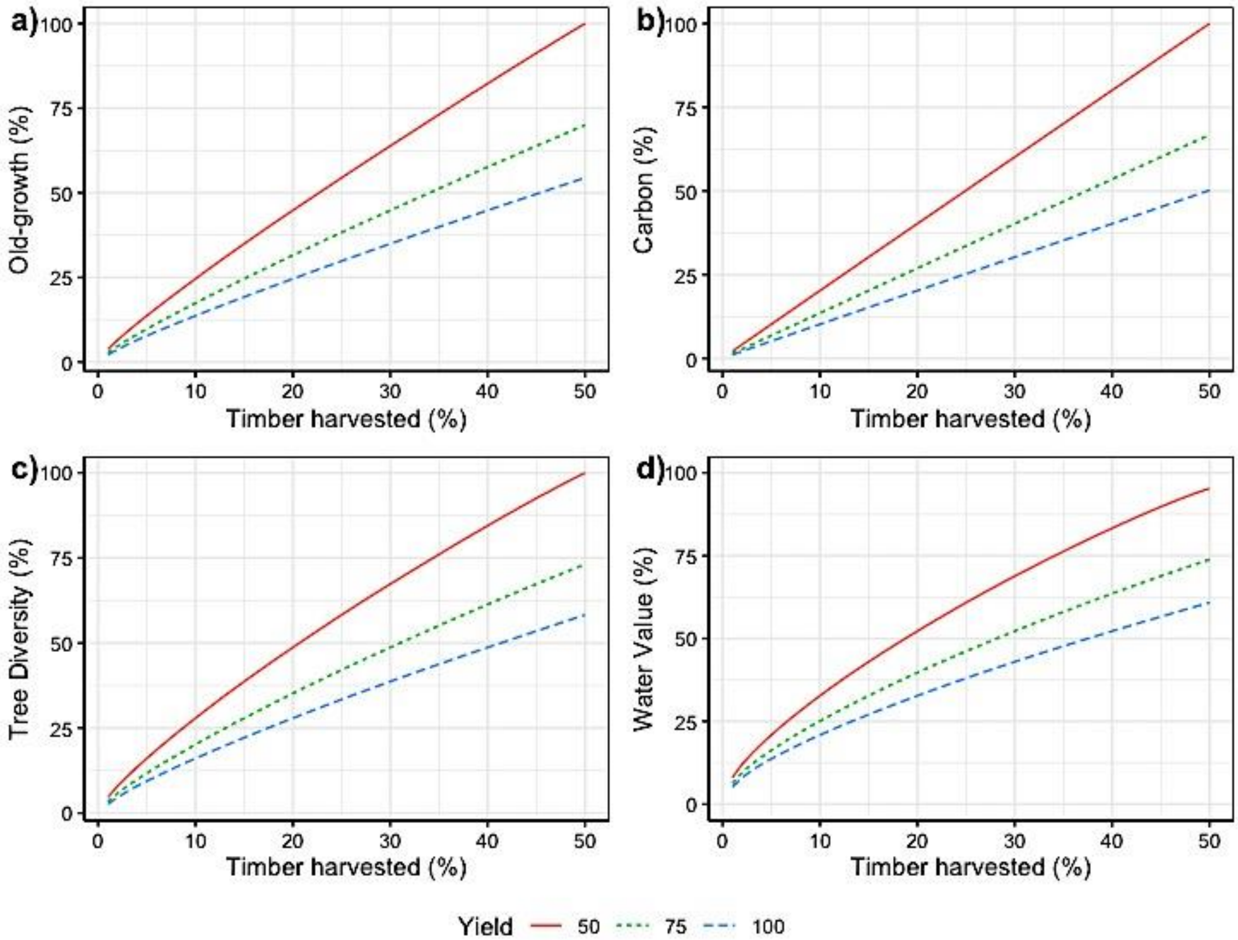

Figure 6 Trade-off between provision of ecosystem services and timber for harvesting. Images depict the effect of timber availability on the amount of representation of each ecosystem service that is removed together with timber. A) old-growth value removed from the landscape for harvesting scenarios 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 7). 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 7 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 7 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.

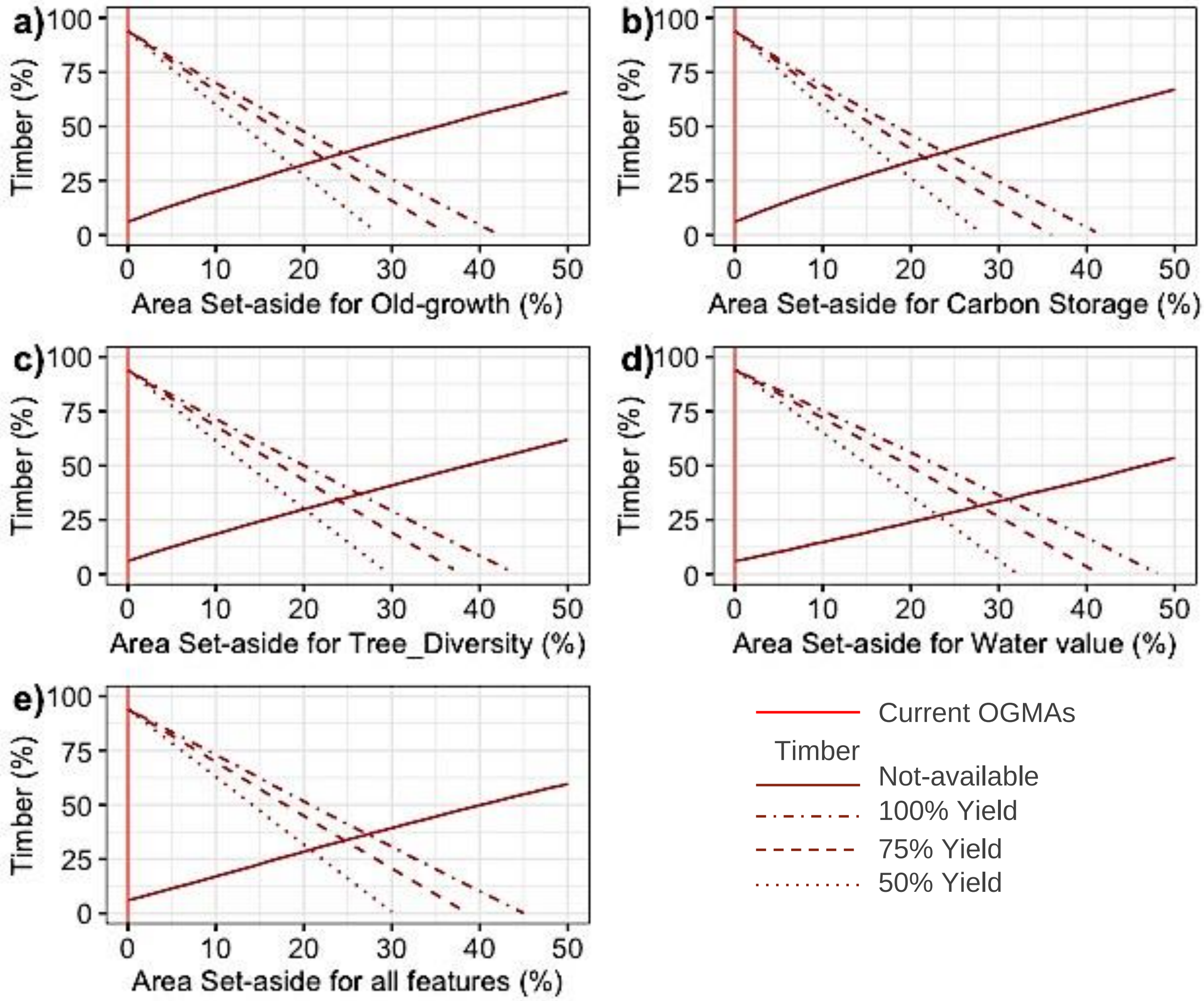

Figure 7 Trade-off curve between timber harvesting and setting aside areas for the provision of a) old-growth, b) carbon, c) tree diversity, d) water value, and e) all features together. Scenarios were designed to have a starting point at the current OGMAs network. Thus, 1% increase means that an additional of 1% of the landscape was set-aside and included in the current OGMAs' area network.

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 a lack of scope for altering OGMAs location and 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. 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 2017), 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).

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.

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 significantly 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.

Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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APPENDICES

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 2 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 0.2 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;

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

2.1. Volume-Height, DBH

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

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

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 3 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

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)

$$ratio = \exp\left(p_1 + p_2/d\right) \quad (4)$$

Where

ratio = ratio of component biomass to total aboveground biomass

exp = exponential function

d = DBH

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

Table 4 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

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 5 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

3. 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 6 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

4. Water value:

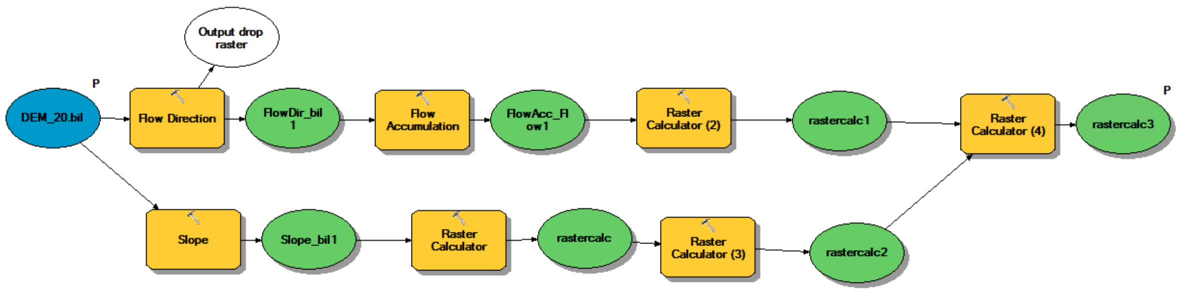

Figure 0.3 ArcMap pipeline for the development of a wetness index as a proxy for water provision. In this model, wetter areas are expected to have higher potential for water provision.

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.

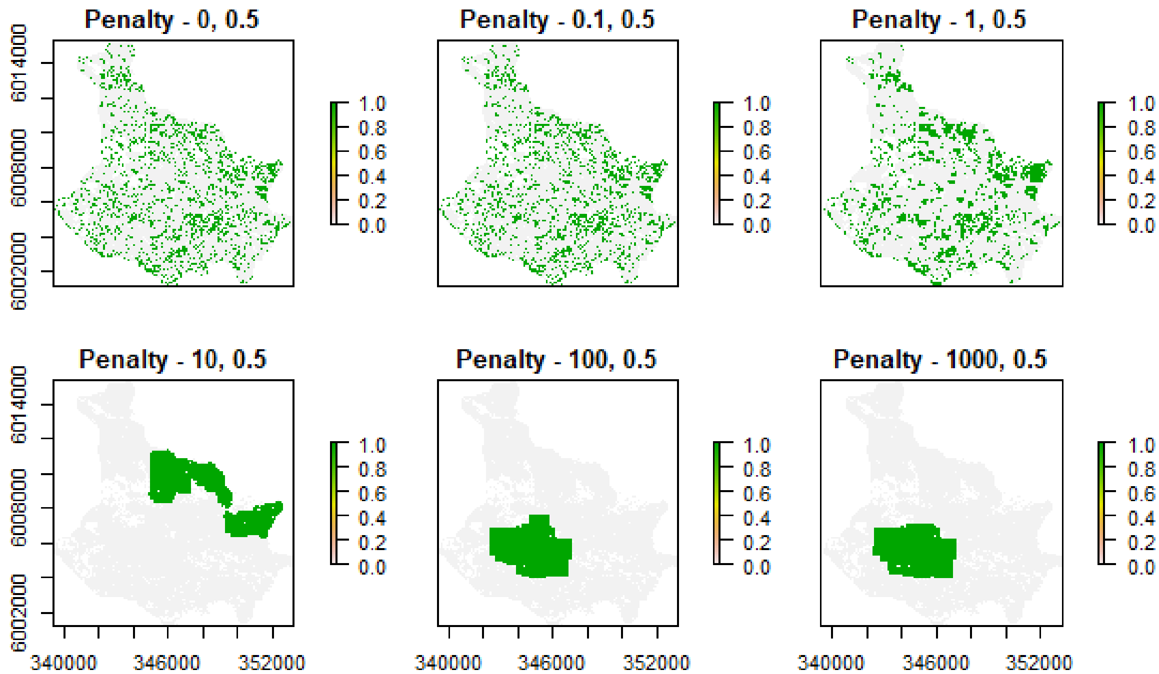

Figure 0.4 Test with multiple boundary length penalties to visually select between OGMAs designs that are extremely fragmented or overly contiguous.

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.

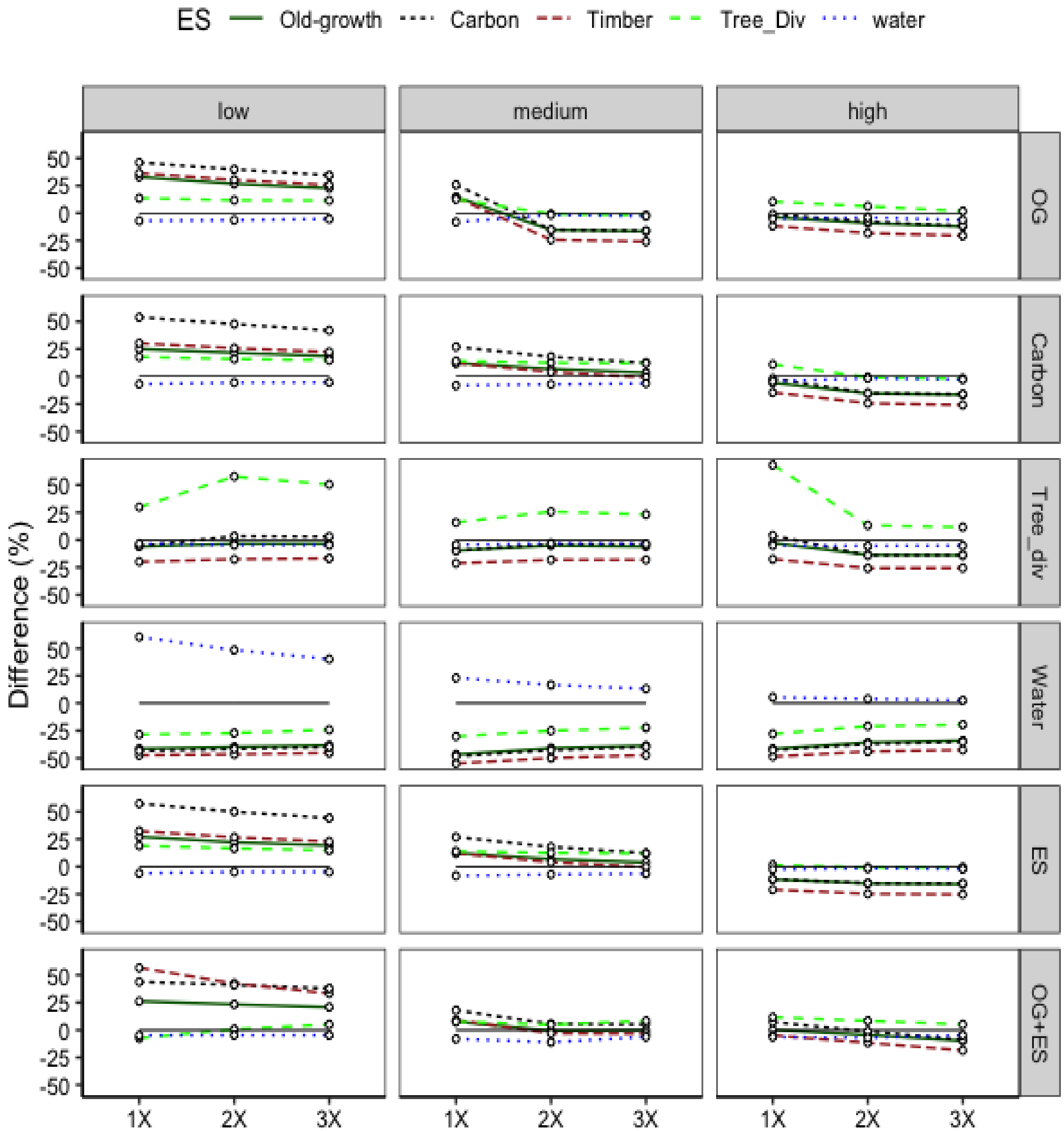

Figure 0.5 Comparison between three different levels of clumpness, from more fragmented to more contiguous reserves networks, and three different reserves network sizes (1X= current OGMA size, 2X= double the current size, and 3X=triple).

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. PrioritizR scenarions for increasing areas

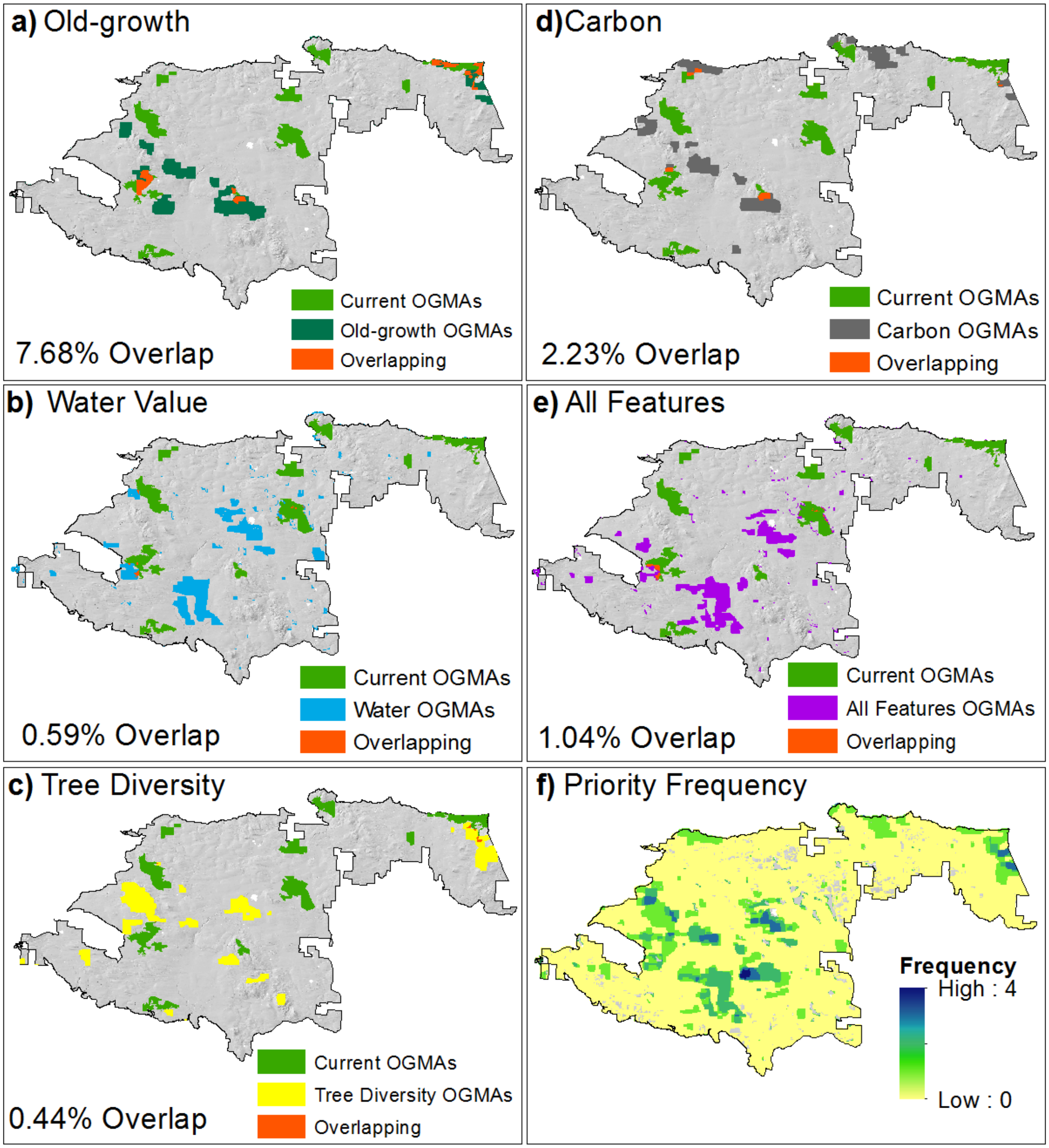

Figure 0.6 Comparison between current OGMAs' network and OGMAs designed to priority a) Old-growth, b) Water value, c) Tree diversity, d) carbon, e) all features. The representation of how many times one planning unit was taken as priority is represented in f).

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.

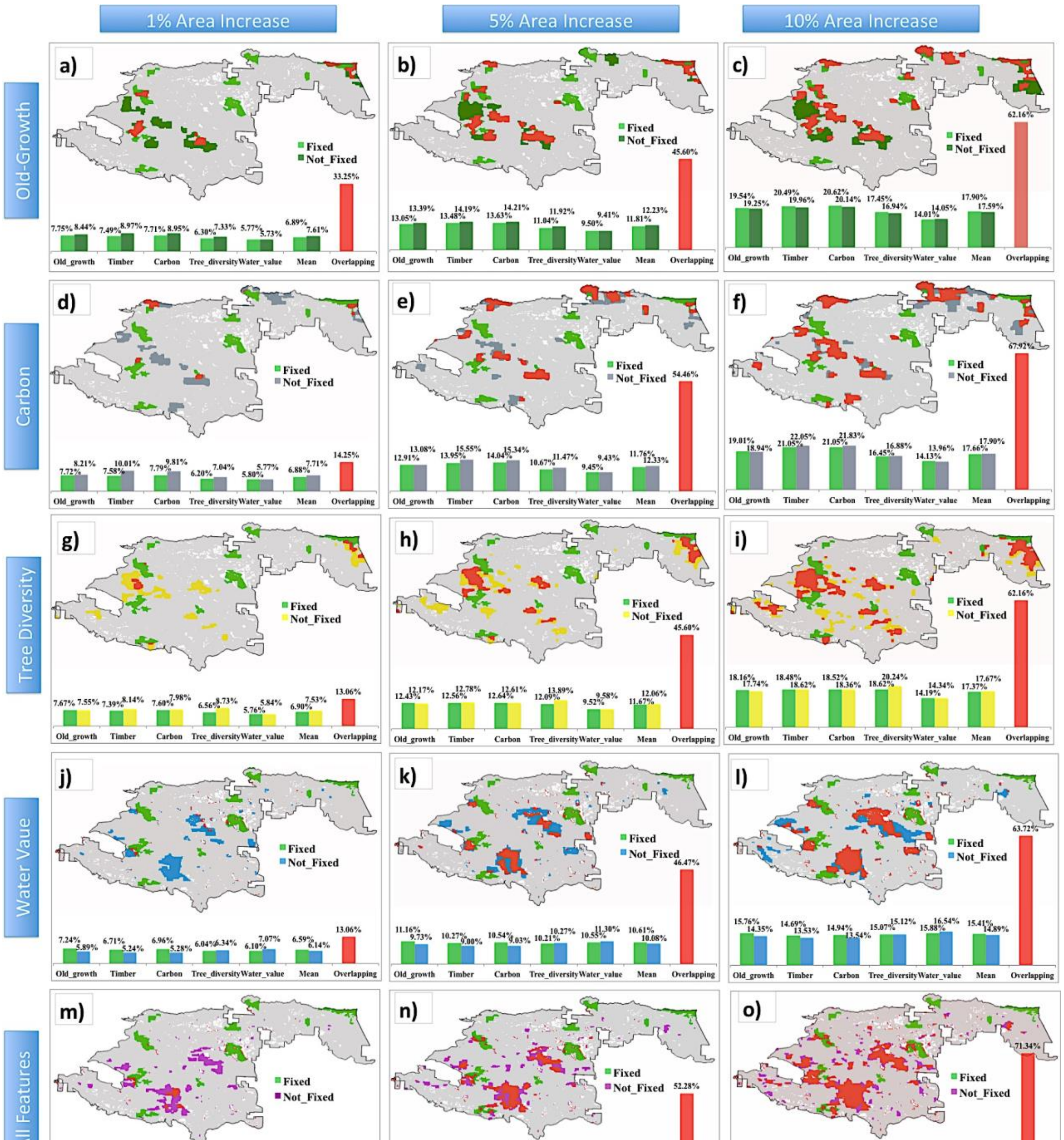

Figure 0.7 Comparison between increase in OGMAs' areas starting from current OGMAs (Fixed) and OGMAs designed to prioritize each individual ecosystem services and all features together (Not-fixed). Old-growth prioritization is represented in figures from a) to c), with areas increase

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).

Table 7 Summary of ANOVA and TUKEY comparison between alternative OGMAs design

Model	Ecosystem_ Service	Ecosystem Service (mean)	Sd	Unit	Sample_ size	p-value
Current	Old-growth	2014.64	120.12	-	12	-
Priori:All	Old-growth	1822.63	284.75	-	14	0.345
Priori:Carbon	Old-growth	2186.36	105.36	-	15	0.454
Priori:Diversity	Old-growth	1933.18	166.15	-	13	0.959
Priori:Old-Growth	Old-growth	2112.04	411.25	-	11	0.928
Priori:Water	Old-growth	1384.70	261.92	-	15	0.000
Current	Carbon	34.06	4.40	MgC	12	-
Priori:All	Carbon	30.12	7.62	MgC	14	0.574
Priori:Carbon	Carbon	43.88	1.37	MgC	15	0.001
Priori:Diversity	Carbon	34.76	5.23	MgC	13	1.000
Priori:Old-Growth	Carbon	37.42	9.71	MgC	11	0.773
Priori:Water	Carbon	18.95	5.91	MgC	15	0.000
Current	Diversity	243.11	11.27	-	12	-
Priori:All	Diversity	286.71	37.68	-	14	0.032
Priori:Carbon	Diversity	288.44	43.13	-	15	0.020
Priori:Diversity	Diversity	347.09	21.91	-	13	0.000
Priori:Old-Growth	Diversity	286.33	52.53	-	11	0.055
Priori:Water	Diversity	234.09	33.45	-	15	0.987
Current	Timber	164279.26	24018.63	m^3	12	-
Priori:All	Timber	150020.72	40701.62	m^3	14	0.872
Priori:Carbon	Timber	222882.18	7624.68	m^3	15	0.000
Priori:Diversity	Timber	177669.11	29265.86	m^3	13	0.905
Priori:Old-Growth	Timber	186837.36	50485.44	m^3	11	0.557
Priori:Water	Timber	92333.00	30703.85	m^3	15	0.000
Current	Water	4224.70	264.49	-	12	-
Priori:All	Water	5100.02	283.37	-	14	0.000
Priori:Carbon	Water	4229.50	230.36	-	15	1.000
Priori:Diversity	Water	4292.92	351.40	-	13	0.988
Priori:Old-Growth	Water	4162.90	251.09	-	11	0.994
Priori:Water	Water	5219.38	222.34	-	15	0.000