

# **Assessing Representation of Remote Sensing Derived Forest Structure and Land Cover Across a Network of Protected Areas**

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Protected areas (PA) are an effective means of conserving biodiversity and protecting suites of valuable ecosystem services. Currently, many nations and international governments use proportional area protected as a critical metric for assessing progress towards biodiversity conservation. However, this and other common metrics do not assess the effectiveness of PA networks, nor do they assess how representative PA are of the ecosystems they aim to protect. Topography, stand structure, and land cover are all key drivers of biodiversity within forest environments, and are well suited as indicators to assess the representation of PA. Here we examine the protected area network in British Columbia, Canada, through these drivers derived from freely available data and remote sensing products across the provincial biogeoclimatic ecosystem classification system. We examine biases in the protected area network by elevation, forest disturbances, and forest structural attributes, including height, cover, and biomass by comparing a random sample of protected and unprotected pixels. Results indicate that PA are commonly biased towards high elevation and alpine land covers, and that forest structural attributes of the park network are often significantly different in protected vs unprotected areas (426 out of 496 forest structural attributes found to be different;  $p < 0.01$ ). Analysis of forest structural attributes suggests that establishing additional PA could ensure representation of various forest structure regimes across British Columbia's ecosystems. We conclude that these approaches using free and open remote sensing data are highly transferable, and can be accomplished using consistent datasets to assess PA representations globally.

## **1 Introduction**

2 Protected areas (hereafter PA) are an integral component of biological conservation, designed to preserve  
3 ecosystem services and biodiversity both inside the PA and in some cases the surrounding regions (Chape  
4 et al. 2005, Watson et al. 2014). In recent decades, there has been a growing consensus of the need to  
5 conserve varying portions of the terrestrial area of the globe, with areal goals increasing over time (CBD  
6 2004, 2010). In the 2010s, the Aichi biodiversity target sought to protect 17% of the entire globe (CBD  
7 2010). Nationwide, the Canadian government has set the goal of protecting 25% of Canada's terrestrial  
8 area by 2025 (ECCC 2021). While increasing proportional ecosystem protection does in turn aid  
9 conservation, it does not guarantee the representativeness of the entire ecosystem, nor that all biodiversity  
10 within the PA will be effectively conserved (Hazen and Anthamatten 2004).

11 Many conservation goals, both global and regional, are commonly based on the proportion of area  
12 protected, at least partly due to its ease of use and calculation (Brooks et al. 2004, CBD 2010). However,  
13 while the area protected is a simple metric to report, other metrics can be more informative, with the  
14 potential to convey how effective a given PA is for protecting the inherent ecosystem services or  
15 biodiversity in the area (Chape et al. 2005, Butchart et al. 2015, Maxwell et al. 2020). Beyond areal extent,  
16 it is also relevant to consider the biases in PA placement, which are frequently located in fiscally cheaper,  
17 low productivity regions both globally (Joppa and Pfaff 2009, Venter et al. 2014, 2018) and regionally, as is  
18 the case in British Columbia (BC), Canada (Hamann et al. 2005, Environmental Reporting BC 2016, Wang  
19 et al. 2020). The area metric heavily underestimates the global protected area required to adequately  
20 protect biodiversity, which research indicates is up to 50% of each ecoregion (Dinerstein et al. 2017,  
21 Dinerstein et al. 2019).

22 In response to the proportion protected approach, a number of other methodologies have been developed  
23 to evaluate the effectiveness of PAs before these larger global targets have been met (Parrish et al. 2003,  
24 Gaston et al. 2006, 2008, Hansen and Phillips 2018, Bolton et al. 2019). One recently identified concept in  
25 Canadian park management is ecological integrity. Ecological integrity is defined as an ecosystem having  
26 the expected “living and non-living pieces for the region,” and where ecological processes occur at the  
27 expected frequency and intensity for the region (Parks Canada 2019). Many potential ecological integrity  
28 indicators have been examined to capture biodiversity related processes within PA (Hansen and Phillips  
29 2018, Hansen et al. 2021). These indicators can then be interpreted manually or automatically, most often

30 through examining temporal trends within the PA or by comparing the indicators to areas in known  
31 healthy reference ecosystems (Woodley 1993).

32 Frequently, comparisons between PA and unprotected areas (UA) have been drawn in order to assess PA  
33 performance and health (Defries et al. 2005). This allows for the PA or PA network to be taken in context  
34 of surrounding and/or similar ecosystems (Wiens et al. 2009). There are, however, challenges associated  
35 with comparing the effectiveness of a PA network directly with UA. It can be difficult to identify suitable  
36 UA for comparison due to the increased prevalence of human pressure in UA (Geldmann et al. 2019), and  
37 the bias for PA to be in areas that would not have faced increased human pressure due to their remoteness  
38 (Joppa and Pfaff 2009).

39 Ferraro (2009) prescribes the use of the counterfactual - comparing what has happened post-PA  
40 implementation with what would have happened if the PA were not implemented. The counterfactual  
41 method has recently been adopted in the literature as a more accurate method for assessing protected area  
42 management effectiveness (Ribas et al. 2020). This method is frequently employed using matching  
43 methods to select UA which directly correspond to the PA being analyzed, often matching based on  
44 topography, climate, land cover, and other variables (Coad et al. 2015, Eklund et al. 2019, Geldmann et al.  
45 2019). Collecting field data across both the PA and its counterfactual UA can often be time-and-cost  
46 prohibitive. The increasing prevalence of freely available imagery has led to satellite remote sensing  
47 becoming an essential tool for PA monitoring (Nagendra et al. 2013).

48 The opening of the Landsat archive in 2008 (Wulder et al. 2012a) has played a significant role in the use of  
49 satellite imagery in conservation monitoring (Nagendra 2008, Turner et al. 2015). The availability of 30-m  
50 spatial resolution data since 1984 allows for assessment of temporal trends in satellite derived indicators  
51 (Nagendra et al. 2013, Hansen and Phillips 2018, Bolton et al. 2019), while the global coverage allows for  
52 comparisons between similar and differing ecosystems (Nagendra 2008, Wulder et al. 2012a). Leveraging  
53 free and open-source optical remote sensing data products has allowed users to increasingly undertake  
54 comparisons across an entire jurisdiction's PA network (Fraser et al. 2009, Soverel et al. 2010, Pôças et al.  
55 2011, Bolton et al. 2019, Skidmore et al. 2021), comparing them to ecologically similar UA (Turner et al.  
56 2015, Buchanan et al. 2018). These comparisons allow for an assessment of the effectiveness of a given PA  
57 or the entire PA network at representing regional biodiversity trends (Soverel et al. 2010, Turner et al.  
58 2015, Bolton et al. 2019).

59 Optical remote sensing technologies have offered a key approach to deriving indicators (Nagendra 2008,

60 Fraser et al. 2009, Soverel et al. 2010, Burkhard et al. 2012, Pereira et al. 2013, Bolton et al. 2019) and  
61 detecting key terrestrial processes (Turner et al. 2003) to assess PA effectiveness at conserving ecological  
62 integrity (Nagendra 2001, Nagendra et al. 2013). These indicators derived from remote sensing  
63 technologies can be categorized and monitored at broad spatial extents and across temporal scales.  
64 Commonly used indicators include land cover proportion (e.g., forest type, wetland, and unvegetated,  
65 Parmenter et al. 2003, Olthof et al. 2006), tree species (Nagendra 2001), habitat classification (McDermid  
66 et al. 2005, Lucas et al. 2011), spectral information (Feeley et al. 2005, Gillespie 2005, Nagendra et al.  
67 2010), spectral heterogeneity (Rocchini et al. 2010), and ecosystem structure (Cohen and Goward 2004,  
68 Goetz et al. 2007, Soverel et al. 2010, Pôças et al. 2011) and function (Skidmore et al. 2021). Moreover,  
69 remote sensing technologies enable the monitoring of terrestrial processes, such as natural and  
70 anthropogenic disturbance regimes (Kerr and Ostrovsky 2003, Alsdorf et al. 2007, Hermosilla et al. 2015b,  
71 Bolton et al. 2019), alongside biogeochemical cycles (Myneni et al. 2001), vegetation productivity  
72 (Running et al. 2004), and vegetation dynamics (Zhang et al. 2003). Diversity in forest structural attribute  
73 measurements, often derived from light detection and ranging (lidar) is also a strong indicator of  
74 biodiversity, providing habitat, influencing food quality, and mediating microclimates (Gao et al. 2014,  
75 Guo et al. 2017).

76 Lidar enables the accurate characterization of treed vegetation structure (e.g. canopy height, canopy cover,  
77 basal area) across forested areas by measuring the time it takes for an emitted pulse of light to return to the  
78 sensor (Lim et al. 2003). While the natural variation in vertical and horizontal forest structure has been  
79 extensively explored using lidar, comparisons between PA and UA have been less frequently drawn using  
80 these methods when compared to optical remote sensing (Nagendra et al. 2013). The lack of previous  
81 comparisons has likely been due to the frequently limited extents of lidar acquisitions, a problem which  
82 has recently been solved by generating wall-to-wall metrics. These wall-to-wall metrics can be created by  
83 combining lidar data with times series of Landsat data, generating forest structural attributes across large  
84 regions and even entire countries (Wulder et al. 2012b, Matasci et al. 2018a).

85 As Canada progresses towards the national goal of 25% of terrestrial area protected by 2025, there is a  
86 growing need to better understand how PA compare to UA with respect to location, ecological  
87 classifications, elevations, productivity, and forest structure. In this study, we (1) examine the hypothesis  
88 that BC's PA network is biased towards high-elevation, low-productivity regions of the province using free  
89 and open remote sensing data products, and (2) identify underrepresented forest structures in PA in the

90 province. To accomplish this, we examined the bias in PA placement by comparing ecoregional PA  
91 coverage and land cover classes by elevation, and disturbances by latitude across protected and UA in BC.  
92 We examine representative forest structural attributes by comparing the distribution of key indicators by  
93 ecological zone to determine the differences between PA and UA to find the most and least similar  
94 represented forest structures throughout the network. We conclude by highlighting the usefulness of these  
95 globally available, high quality, consistent, and transferable datasets and methods for assessing PA  
96 effectiveness.

## 97 **Methods**

### 98 **Study Area**

99 The province of British Columbia, Canada, covers 94.4 million ha, of which approximately 64% is forested  
100 (BC Ministry of Forests 2003), and encapsulates a wide variety of biomes and ecosystems. This diversity of  
101 ecosystems is in part due to the large area as well as variations in topography and climate. The existing  
102 Biogeoclimatic Ecosystem Classification (BEC) system disaggregates BC ecosystems into zones (Pojar et al.  
103 1987). The broadest classification delineates 16 zones, which are further broken down into subzones,  
104 variants, and phases based on microclimate, precipitation, and topography (Pojar et al. 1987, Meidinger  
105 and Pojar 1991). As a result, BEC zones vary widely in size (ranging from 0.25 million ha to 17.5 million  
106 ha), and in number of subzones (from 1 to 43; see Table 1).

107 Both the BC (BC Parks 2012) and Canada-wide (Government of Canada, 2019) PA mandates commit to  
108 conserving ecological integrity across the network. The PA network in BC is designed to serve both  
109 ecological conservation and human recreation aims (BC Parks 2012) and consists of a network of PA and  
110 PA complexes (multiple nearby PA which share the same conservation goals), with large variations in size,  
111 ranging from 0.02 to 987,899 ha (fig. 1).

112 [Figure 1 about here.]

113 **Data**

114 **Biogeoclimatic Ecosystem Classification and Protected Areas**

115 Boundaries for BEC zones and subzones were acquired using the **bcmaps** R package (Teucher et al. 2021).  
116 Two BEC subzones were entirely subsumed by PA (Boreal White and Black Spruce - Very Wet Cool and  
117 Spruce – Willow – Birch - Very Wet Cool Shrub), whereas the Sub-Boreal Pine – Spruce - Moist Cool  
118 subzone has no PA representation.  
119 Boundaries for all PA in BC were obtained from the Canadian Protected and Conserved Areas Database  
120 (available from [https://cws-scf.ca/CPCAD-BDCAPC\\_Dec2020.gdb.zip](https://cws-scf.ca/CPCAD-BDCAPC_Dec2020.gdb.zip)), current as of December 2020,  
121 and includes the International Union for Conservation of Nature (IUCN) classification for each PA. PA  
122 were selected for analysis following the criteria outlined in Bolton et al. (2019). Only parks which  
123 belonged to IUCN classes Ia, Ib, II, and IV were selected, as these categories are considered strictly  
124 protected. Protected areas < 100 ha in size were also excluded from the analysis, as these mainly occurred  
125 in urbanized areas. After selection, 745 suitable parks managed under various jurisdictions (provincial,  
126 federal, NGOs), comprising 15.4% of the total terrestrial area of British Columbia, were studied  
127 (Environmental Reporting BC 2016). An equal sample of pixels equal to the area of PA or UA - whichever  
128 was lower - was randomly selected from both PA and UA for each BEC subzone. This sampling regime  
129 accounts for bias in topography, climate, and climax species due to the methods used to delineate BEC  
130 zones and subzones (Pojar et al. 1987).

131 **Digital Elevation Model**

132 The Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) digital elevation model  
133 (GDEM V2, 30 m) was used to examine biases in protected area land cover and ecological classification by  
134 elevation (Tachikawa et al. 2011).

135 **Landsat derived datasets**

136 Land cover, forest disturbances, and forest structural attributes for BC were derived from the annual  
137 Landsat best-available-pixel (BAP) composites from 1984 to 2019 at 30-m spatial resolution generated  
138 using the Composite2Change (C2C) approach (Hermosilla et al. 2016). These composites are generated by

annually selecting the optimal observations, free from atmospheric effects (haze, clouds, cloud shadows), for each pixel from the catalog of available Landsat-5 Thematic Mapper (TM), Landsat-7 Enhanced Thematic Mapper Plus (ETM+), and Landsat-8 Operational Land Imager (OLI) imagery acquired during Canada's growing season using the scoring functions defined in White et al. (2014). The annual BAP composites are further refined by applying a spectral trend analysis over the Normalized Burn Ratio (NBR) at pixel level in order to remove unscreened noise, detect changes and fill data gaps with temporally-interpolated values, resulting in annual, gap-free, surface-reflectance image composites (Hermosilla et al. 2015b). During this process, forest disturbances are detected, characterized and attributed to a disturbance agent (i.e., wildfire, harvest, non-stand replacing disturbances) using a Random Forests classification model via the object-based analysis approach (Hermosilla et al. 2015a) with an overall accuracy of 92%  $\pm$ 2% (Hermosilla et al. 2016).

Annual land cover information for Canada was produced using the BAP composites following the Virtual Land Cover Engine framework (Hermosilla et al. 2018). This framework integrates post-classification probabilities, forest disturbance information and forest successional knowledge with a Hidden Markov Model to ensure logical land cover transitions between years. The classification comprises 12 land cover classes organized as either non-vegetated or vegetated. Non-vegetated classes included water, snow/ice, rock/rubble, and exposed/barren land. Vegetated land cover classes discriminated among non-treed and treed vegetation (land-cover level). Vegetated non-treed classes comprised bryoids, herbs, wetland, and shrubs. Vegetated treed land cover classes included wetland-treed, coniferous, broadleaf, and mixed wood. Independent validation of the land cover maps indicated an overall accuracy of 70.3%  $\pm$  2.5%.

Wall-to-wall, 30-m forest structure metrics (i.e., Lorey's height, total aboveground biomass, elevation covariance, and canopy cover) were also annually derived from the BAP composites using the imputation method described in Matasci et al. (2018b, 2018a). This method uses lidar and field plot data to estimate forest structure metrics from topographic and Landsat spectral predictors, using a k-Nearest Neighbor approach. Reported accuracy for the structure metrics indicated a RMSE% ranging from 24.5% to 65.8% and a R<sup>2</sup> ranging from 0.125 to 0.699 (Matasci et al. 2018a).

Forest cover classes (deciduous, broadleaf, mixed-wood, and wetland-treed) were used to generate land cover masks to restrict the comparison of forest structural attributes to treed pixels. Pixels with harvest activity disturbances detected post-1985 were also removed from forest structural attribute rasters in both PA and UA, in order to restrict analysis to non-anthropogenically disturbed areas. All datasets are

169 displayed in fig. 2.

170 [Figure 2 about here.]

## 171 **Analysis**

172 To determine bias in ecosystem representation in BC's PA network, we compared BEC zone, land cover,  
173 and disturbance proportions within and outside the PA network. We employ counterfactual thinking by  
174 examining BEC zone, and land cover as a function of elevation, and secondly compiled disturbance rates  
175 on a latitudinal gradient across the province. Forest structural attributes were then examined at a finer  
176 ecosystem classification level, statistically comparing PA vs UA across similar ecosystems. Forest  
177 structural means across BC zones were calculated to determine which forest structures need additional  
178 representation in the current BC PA network. All data manipulation and analysis was conducted in the **R**  
179 (**R Core Team 2021**) or **Python** programming languages.

## 180 **Ecosystems, Land Cover, and Disturbances**

181 BEC zones and land cover classifications were aggregated to both PA and UA in order to determine the  
182 proportion of each zone under the protected classifications, to examine progress towards the Aichi  
183 biodiversity targets. In this analysis, zones were used to examine categorical data (land cover and  
184 disturbance) for the period of 1984-2019. Land cover and BEC zones were further examined along an  
185 elevation gradient, at 50m increments. Histograms of area by elevation were generated in order to  
186 examine the areal magnitude alongside the proportional coverage of land cover and BEC zones. This  
187 allows us to examine the amount of area protected at each elevation, as well as the differences between PA  
188 and UA. Forest disturbances (including harvesting) were aggregated along a latitudinal gradient at  
189 increments of 0.5°.

## 190 **Forest Structural Attributes**

191 T-tests for PA vs UA were conducted on all pixels selected for analysis by BEC subzone and forest  
192 structural attribute for 2015, and the Bonferroni correction was applied. The Bonferroni correction avoids  
193 spuriously significant results in multiple comparison tests by dividing the significant p-value (0.01) by the

number of tests (Bonferroni 1936). Within each BEC zone, higher proportions of significant tests will indicate dissimilar subzones in each forest structural attribute. The mean values for PA and UA forest structural attributes were calculated, in order to examine the differences in their distribution and determine which structures and zones differ between PA and UA. Values were also converted into z-scores to determine the greatest standardized vector magnitude when comparing canopy cover, elevation covariance, and forest height between PA and UA.

## Results

### Ecosystems, Land Cover, and Disturbances

British Columbia's ecosystems are protected at varying rates across the province (fig. 3). Of the 16 ecosystems present in BC, seven are protected at rates above the Aichi biodiversity target (17%). Only two zones (Boreal Altai Fescue Alpine and Interior Mountain-heather Alpine) are currently protected at rates above the Canadian 2025 protection targets (25%). Zones with Douglas-fir (*Pseudotsuga menziesii*) as dominant old-growth components (Coastal Douglas-fir and Interior Douglas-fir) are the least proportionally represented zones in British Columbia, with 4.9% and 6.4% protected, respectively (fig. 3).

[Figure 3 about here.]

As elevation increases in BC, increasing terrestrial area is protected within the PA network until ~4000m, upon which all terrestrial area is protected (fig. 4). When comparing between PA and UA, zones are protected at differing proportions. Zones commonly found at high elevations, such as the Boreal Altai Fescue Alpine, are predominantly located in protected areas, however, little terrestrial area is found at these elevations. In low elevations, proportions of area protected also differ, with Coastal Western Hemlock having a large proportion of coverage in PA, while in UA, Boreal Black and White Spruce are underrepresented. Generally, the remaining ecosystems are found at similar rates in both PA and UA (fig. 4).

[Figure 4 about here.]

Protected land cover also varies by proportion (fig. 5). Non-vegetated classes of snow/ice, exposed/barren land, and rock/rubble have higher than average proportions protected while mixed wood and broadleaf

220 land cover classes are underrepresented. All other classes are found at rates similar to the overall  
221 proportion of the province protected (~15%; fig. 5).

222 [Figure 5 about here.]

223 Similar to BEC zones (fig. 4), land cover also varies with elevation (fig. 6). Expectedly, snow/ice make up a  
224 large proportion of PA at higher elevations. At lower elevations in UA, mixed wood forest is a more  
225 common forest type than in PA, while wetland classes (wetland, wetland-treed) are less frequent in the  
226 400-900m elevation range in UA compared to PA.

227 [Figure 6 about here.]

228 Examining the elevation distributions of BEC zones and land cover classes shows elevation variation in  
229 some classes and ecosystems (fig. 7). Generally, BEC zones are found at similar elevation profiles in both  
230 PA and UA. Alpine BEC zones (Interior Mountain-heather Alpine, Boreal Altai Fescue Alpine, and  
231 Coastal Mountain-heather Alpine) are found at similar elevations across PA and UA, while other zones  
232 such as Sub-Boreal Pine – Spruce, Ponderosa Pine, and Bunchgrass vary in their elevation profiles. Land  
233 cover classes show differences in the wetland, wetland-treed, and mixed wood classes. The wetland  
234 classes are found at lower elevations in PA than UA, while the mixed wood class has more variation in PA.

235 [Figure 7 about here.]

236 Overall, the burned area of forested cells is similar between PA (2.5% overall) and UA (2.3%), while  
237 harvesting is much higher in UA (7.2%) than in PA (0.33%). Harvesting is more common at lower latitudes  
238 in UA than at higher latitudes. Fire shows similar, but not identical patterns across varying latitudes, with  
239 higher wildfire proportions at high latitudes and between 51-53°N (fig. 8).

240 [Figure 8 about here.]

## 241 **Forest Structural Attributes**

242 fig. 9 shows the subzonal proportional significance ( $p < 0.01$ ) grouped by ecosystem for the 496  
243 comparisons of forest structural variables. Higher percentages confirm ecosystems which had increased

244 number of dissimilar subzones for the specific indicator, and shows that at least half of all subzones in  
245 each ecosystem are significantly different (the exception being Ponderosa Pine, which consists of a single  
246 subzone that is not significantly different in canopy structure). Median proportional significance values  
247 for canopy height, canopy cover, and aboveground biomass are universally significantly different between  
248 PA and UA within the same ecosystem.

249 [Figure 9 about here.]

250 Forest structural attributes vary between PA and UA in BC (fig. 10). The largest differences between PA  
251 and UA are found in canopy structure in the Coastal Douglas-fir BEC zone, with the protected area having  
252 much higher canopy structure values. As shown in fig. 9, forests are commonly significantly different  
253 when comparing PA vs UA across all attributes. When examining the forests on an BEC zone level, only  
254 one BEC zone has a >5% difference in vertical forest structure (co-efficient of variation in vegetation  
255 returns), six BEC zones have >5% difference in canopy cover, and five BEC zones have a >5% difference in  
256 canopy height. Ponderosa pine has large differences in canopy cover and canopy height (>5%), but minor  
257 differences in elevation covariance (only 0.25%; Table 2). PA in the Ponderosa Pine, Interior Mountain  
258 Heather Alpine, and Coastal Douglas-fir have more aboveground biomass than in UA in corresponding  
259 areas (fig. 10).

260 [Figure 10 about here.]

## 261 Discussion

262 The recent global availability of freely available, open-source, consistent, and accurate remote sensing data  
263 products allow researchers to examine issues of representation of PA compared to UA, and regional  
264 ecosystems in novel ways (Soverel et al. 2010, Hansen and Phillips 2018, Bolton et al. 2019). Additionally,  
265 the capacity to track forest structural attributes, a key indicator of forest biodiversity (Guo et al. 2017),  
266 across wide swaths allows for informed decisions on potential locations of new PA which capture  
267 previously underrepresented forest structure conditions (Noss 1999). By applying this analysis to an entire  
268 PA network across BEC zones (or other ecological classifications), it becomes possible to determine not  
269 only which BEC zones need additional representation (the proportional metric), but also what types of

270 forest structures should be represented to ensure adequate biodiversity protection (Lemieux and Scott  
271 2005).

272 Internationally, biodiversity preservation targets aim to protect a proportion of the total terrestrial area  
273 (CBD 2010). Frequently, new protected areas are placed in high-elevation, low-productivity ecosystems  
274 both globally (Joppa and Pfaff 2009, Venter et al. 2014, 2018), and in BC, as confirmed by our analysis of  
275 ecosystem (fig. 3) and land cover (fig. 5) proportions. Alpine ecosystems are more commonly protected  
276 (fig. 3), as are the land covers commonly present within them (rock/rubble, snow/ice, exposed/barren  
277 land; fig. 5). As elevation increases, these ecosystems and land covers begin to dominate the proportional  
278 representation (see fig. 4 and fig. 6). Differences between elevation profiles in land cover classes and BEC  
279 zones were also found, with the starker difference being that wetland classes were found at lower  
280 elevations in PA (fig. 7)

281 In high elevation ecosystems, Boreal Altai Fescue Alpine dominates the PA proportions above 3000m,  
282 replacing the Coastal Mountain-Heather Alpine ecosystem found in UA (fig. 4). These zones were both  
283 protected at rates above the average (fig. 3), and above the Aichi biodiversity targets. Interior  
284 mountain-heather alpine had large differences in canopy cover and canopy height, while Boreal Altai  
285 Fescue Alpine only showed large differences in height. The Coastal Mountain-heather Alpine did not any  
286 have large forest structural attribute differences (Table 2).

287 Distribution of disturbances followed a similar pattern to that reported by Bolton et al. (2019). Thus, the  
288 area affected by wildfires is comparable between PA and UA and at mid latitudes (51-53°N), while  
289 harvesting activity is more prevalent in UA and at low latitudes (fig. 8).

290 Our analysis shows that the majority of structural attributes were significantly different between the  
291 protected and unprotected forest stands across BEC subzones (fig. 9). In the south, Coastal Douglas-fir, a  
292 zone with a single subzone, had the large variation between PA and UA in two of four forest structural  
293 attributes examined. The unprotected forests were significantly less tall, had significantly less canopy  
294 cover, and significantly higher elevation covariance (vertical forest structure; fig. 10). In addition, it was  
295 the least protected BEC zone by area, with only 4.9% of the total terrestrial area protected. In this specific  
296 BEC zone, not only does additional area need to be protected to meet national goals, different forest  
297 structures need to be included in new protected areas (Paillet et al. 2010).

298 Utilizing this information on the proportion of BEC zones protected (fig. 3), as well as their forest

299 structural attributes (Table 2), it is possible to identify which forest structures need to be added to the PA  
300 network in BC. Those BEC zones with large differences (identified as being >5% change from PA to UA)  
301 suggest additional protection is needed to encapsulate these underrepresented forest structures. For  
302 example: the forests in the Bunchgrass zone have large differences in both canopy cover and canopy  
303 height, with the PA having larger values in both attributes (Table 2). New PA in this BEC zone should  
304 contain forests with shorter and more open forests. A future avenue of research could be to incorporate  
305 forest structural attributes into spatially optimized PA placement approaches (Christensen et al. 2009).

306 The advent of free and open-source global datasets can allow for the monitoring of protected area health  
307 across the globe (Nagendra et al. 2013). Analyzing large amounts of free and open-source data using  
308 open-source software approaches offers previously unseen perspectives into protected area  
309 representativeness. There are some challenges associated with this, namely: optical imagery archives  
310 being scarce in some regions due to imagery acquisition policies (Wulder et al. 2016), clouds and  
311 atmospheric interference, lack of aerial lidar data available, and varying hierarchies of land cover  
312 classifications in differing regions. New data and satellite missions are being introduced that can meet  
313 these challenges at a spatial resolution of 30 m or less such as Landsat-9 and Sentinel-2, as well as  
314 spaceborne lidar such as GEDI (Dubayah et al. 2020) and ICESat-2 (Neuenschwander et al. 2020), which  
315 can provide global coverage of various forest structural attributes (Potapov et al. 2021) through similar  
316 imputation methods to Matasci et al. (2018a), global land cover maps (Potapov et al. 2020, Zanaga et al.  
317 2021), and forest disturbance maps (Hansen et al. 2013). These novel datasets provide clear opportunities  
318 for regional to global analyses of PA vs UA to be conducted concerning forest structure.

319 Future research monitoring protected area health using satellite remote sensing could focus on  
320 implementing essential biodiversity variables (Pereira et al. 2013) into their monitoring scheme.  
321 Advancing research towards these variables would not only benefit PA monitoring projects, but also  
322 biodiversity monitoring projects across the globe. Beyond this, examining the recovery of forest structural  
323 attribute following disturbances in both PA and UA could assess the effectiveness of PA for promoting  
324 regeneration.

325 **Conclusion**

326 In conclusion, we identified biases in the BC PA network for PA to be placed in high-elevation BEC zones,  
327 commonly dominated by low-productivity land covers. We examined the disturbance regimes of PA vs UA  
328 by latitude, finding that wildfires are similar, while harvesting differs across the province. We then  
329 compared the forest structural attributes across all BEC subzones, finding that the majority of subzones  
330 have significantly different forest structures. Beyond this, we identified BEC zones with large variation in  
331 mean forest structural attributes. When new PA locations are decided upon in BC, they should take forest  
332 structure into consideration, as wall-to-wall coverage of forest structural attributes becomes available.  
333 Novel datasets can allow this methodology to be applied across large regions, in order to identify PA biases  
334 and underrepresented forest structures.

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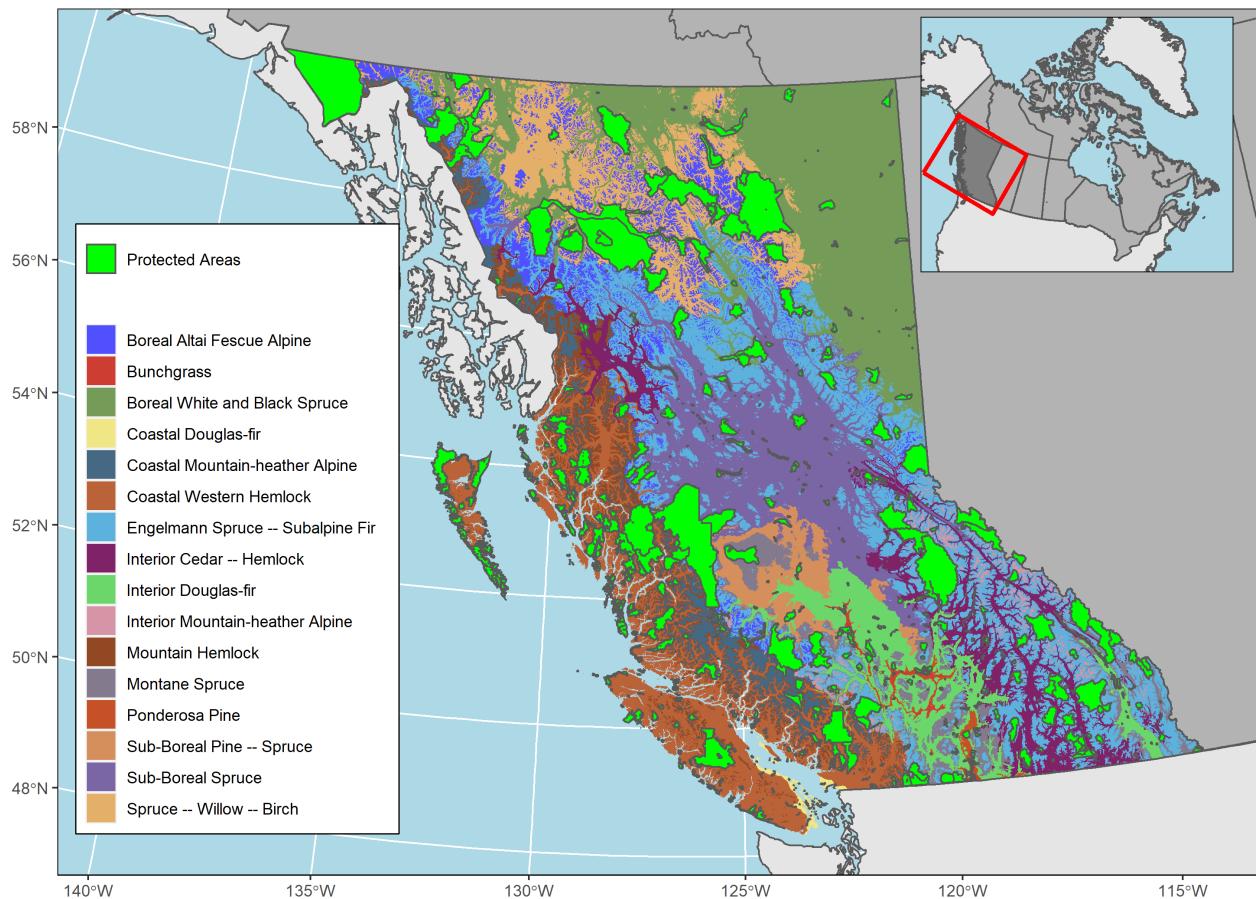


Figure 1: Terrestrial British Columbia including BEC zones and the location of PA selected in this study.

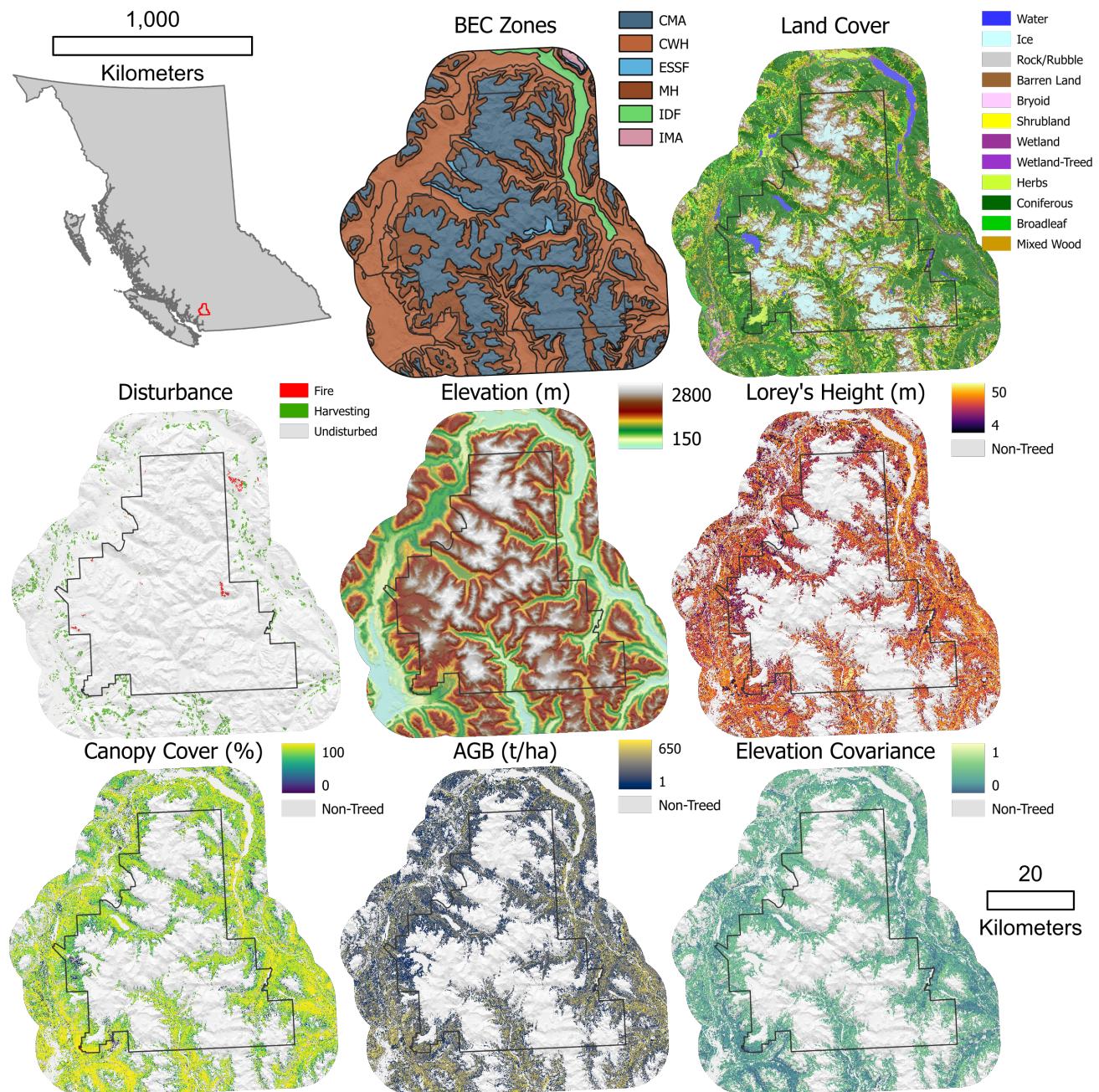


Figure 2: Visualizations for all layers included in the analysis for Garibaldi Park and surrounding region (red outline) in BC for 2015.

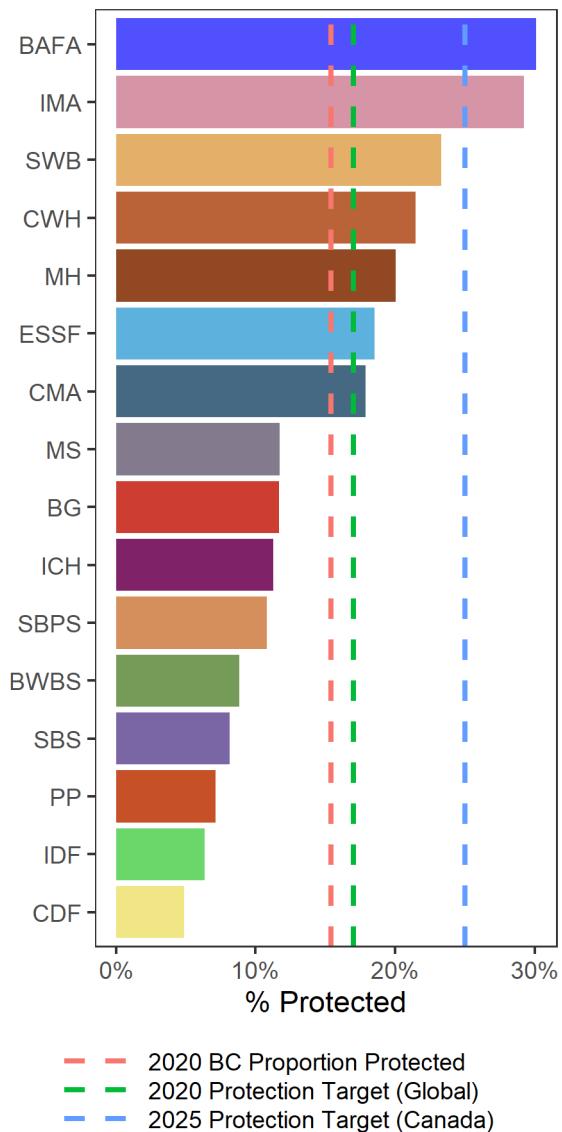


Figure 3: Areal proportion of biogeoclimatic ecosystem classification (BEC) zones protected in British Columbia (See Table 1 for full BEC zone names).

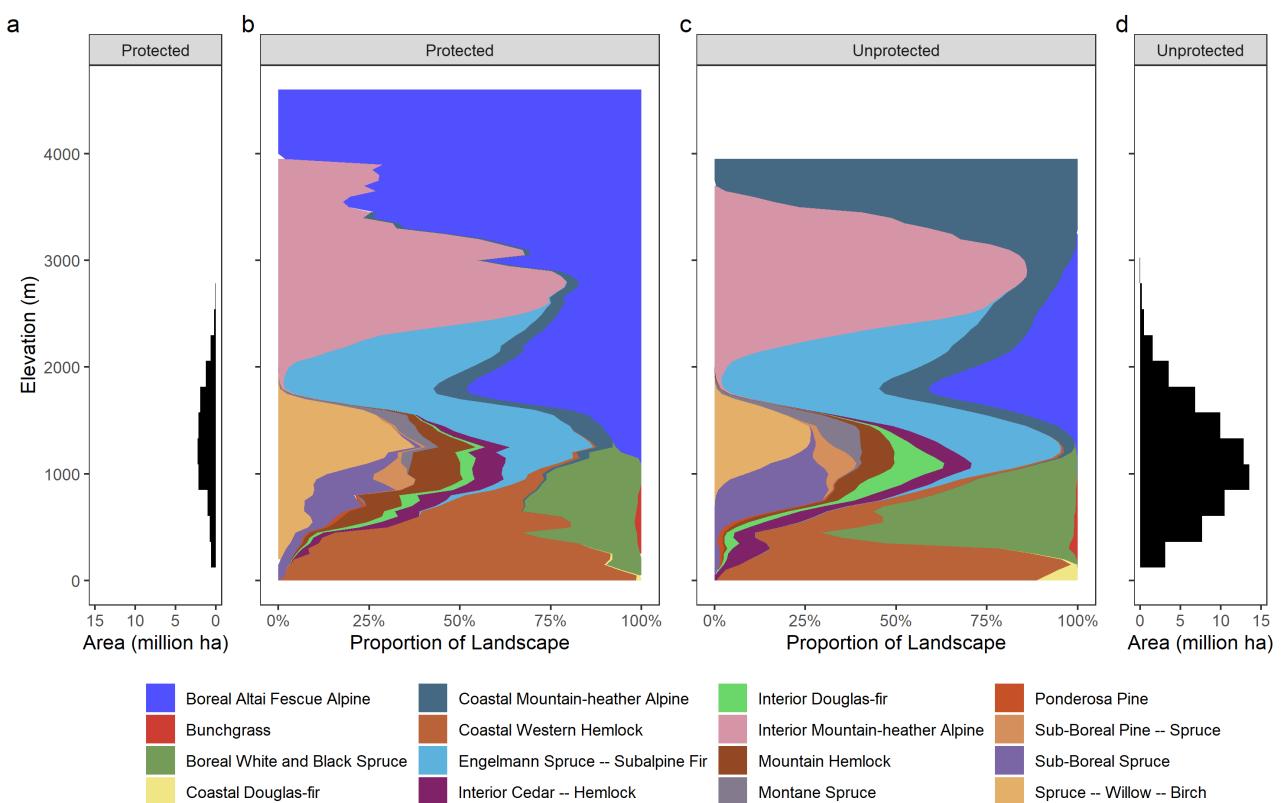


Figure 4: Histogram of area protected in British Columbia by Elevation (a). Proportion of Biogeoclimatic Ecosystem Classification (BEC) zone by elevation for both protected areas (b), and unprotected areas (c). Histogram of area unprotected in British Columbia by Elevation (d).

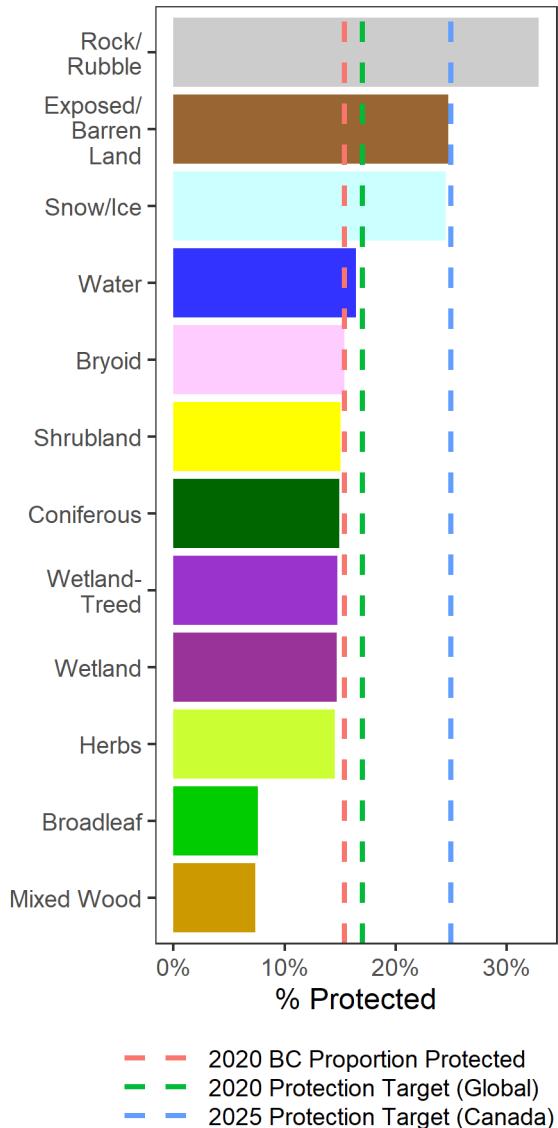


Figure 5: Areal proportion of land cover classes protected in BC.

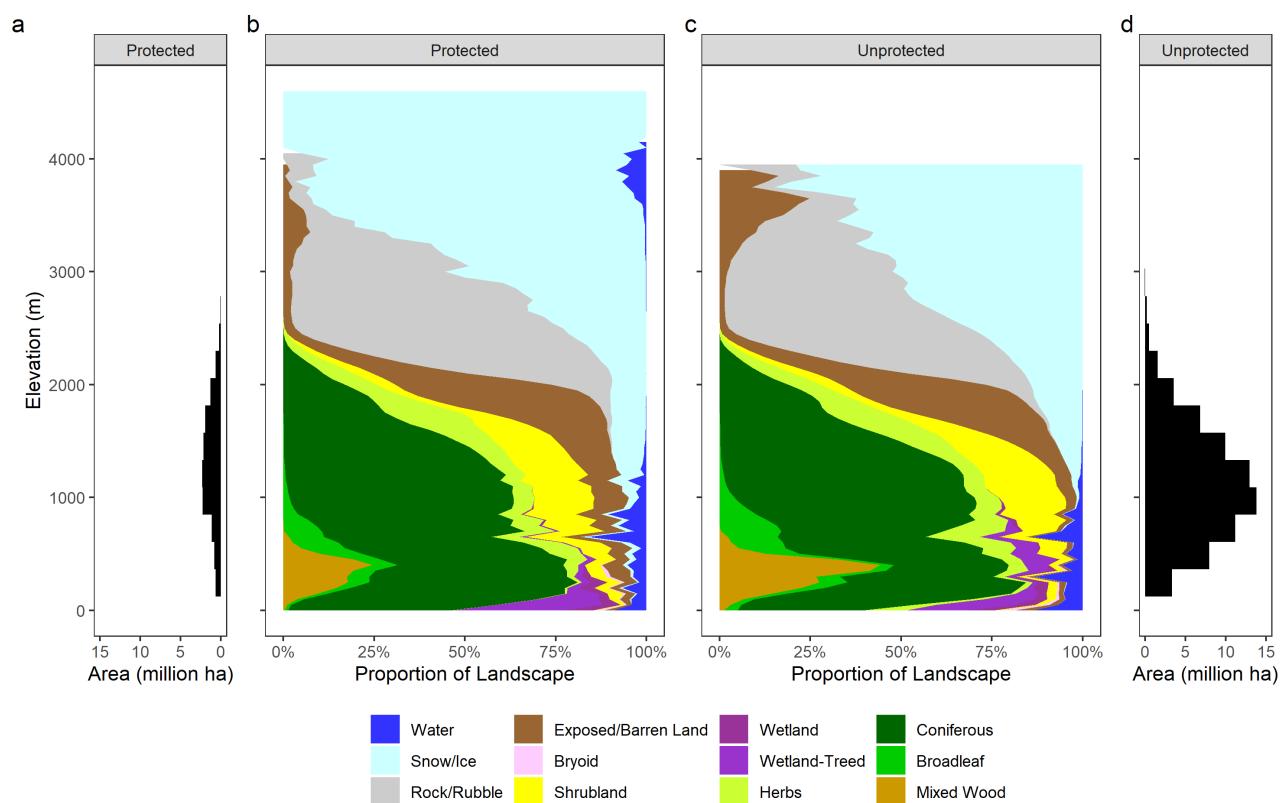


Figure 6: Histogram of area protected in British Columbia by Elevation (a) Proportion of land cover by elevation for both protected areas (b), and unprotected areas (c). Histogram of area unprotected in British Columbia by Elevation (d).

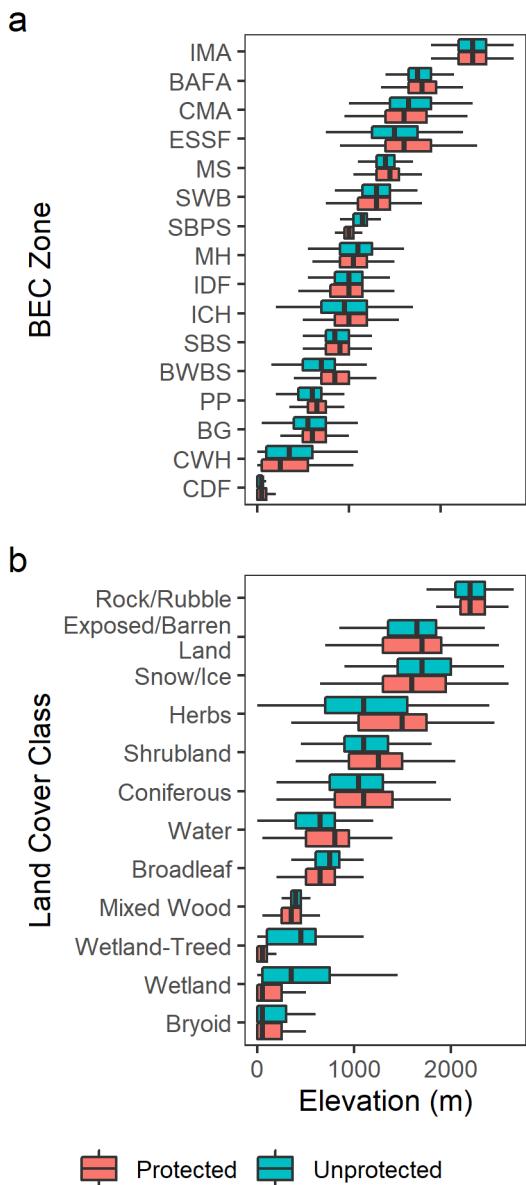


Figure 7: Elevation boxplots for BEC zones (a), and land cover classes (b). Whiskers indicate first quartile minus the interquartile range and third quartile to the interquartile range. Box and interior vertical line indicate first quartile, median, and third quartile, respectively.

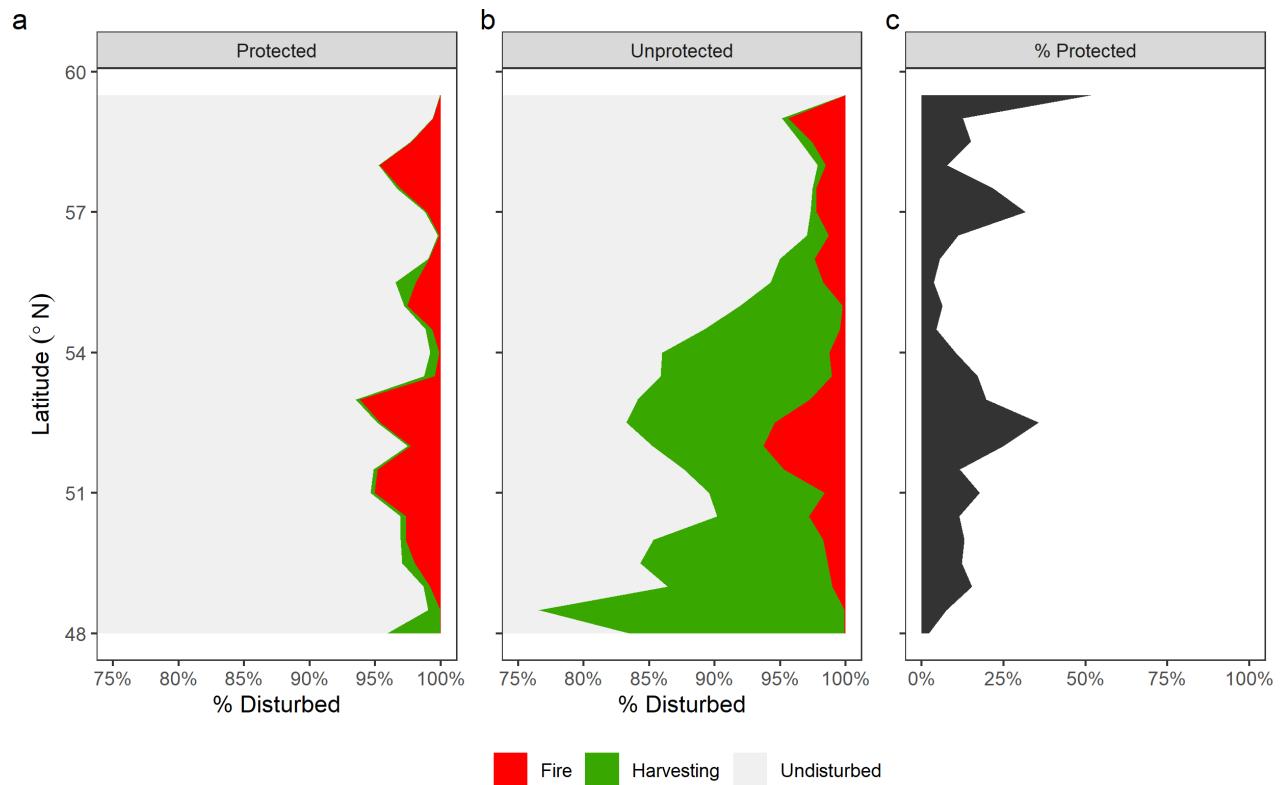


Figure 8: Proportion of area disturbed by latitude from 1984 to 2019 in protected areas (a), and unprotected areas (b). Proportion of terrestrial area that is protected at each latitude (c).

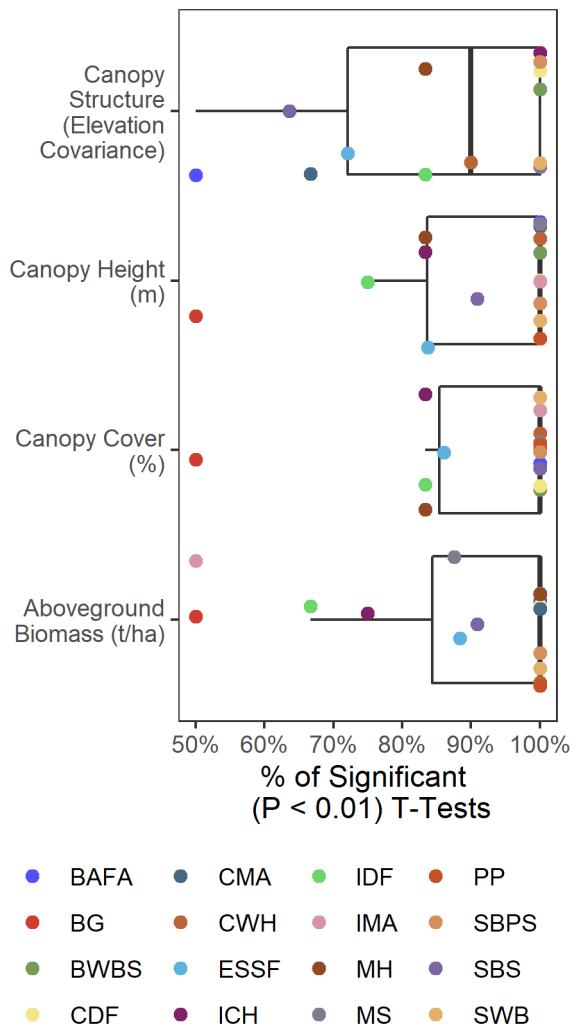


Figure 9: Boxplot of proportion of ecosystem subzone which have significant p-values from a two-tailed t-test with the Bonferroni correction ( $n = 496$ ) applied at a significance level of 0.05. Boxplot vertical lines indicate the first quartile, the median, and the third quartile. The whisker extends from the first quartile to the smallest value no further than  $1.5 * \text{interquartile range}$  from the first quartile.

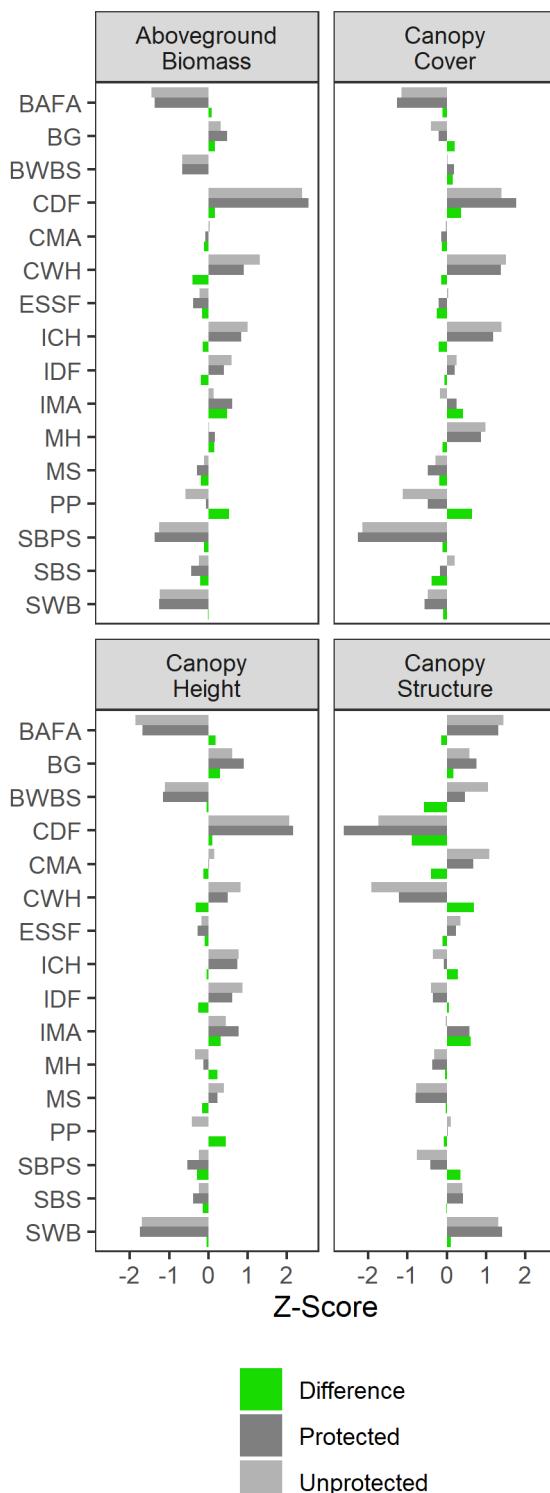


Figure 10: Z-Scores of forest structural attributes in PA, UA, and their differences across BEC zones in BC.