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Modelling the ecosystem indicators of British Columbia using Earth observation data and terrain indices

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ABSTRACT

Remotely sensed data plays a critical role by acquiring data on ecological conditions over broad spatial scales, providing important information for mapping landscape-scale ecosystem characteristics. The goal of our research is to employ a robust clustering algorithm to provide a transparent method of integrating remotely sensed datasets into homogeneous ecosystem units for conservation planning and monitoring ecosystem condition and change. Using a suite of ecosystem characteristics derived from digital elevation and remotely sensed data at 1 km spatial resolution, we classify the 94 million ha within the province of British Columbia (BC), Canada, into 16 terrestrial ecosystem regions (and a water category) using a two-step clustering approach. Initially, 10 metrics representing the physical environment (elevation and soil wetness potential), available energy (solar insolation and snow melt) and vegetation production (fraction of photosynthetically active radiation) were considered for ecosystem classification, which were reduced to six after analyzing variable inter-correlations. The results provide ecologically unique terrestrial regions: ten of which describe the Northern Boreal, Coastal Mountains and Southern Interior Mountains, and six the coastal lowlands, Georgia Depression, interior, Boreal Plains and Taiga Plains. Analyzing the spatial interaction between the cluster categories revealed that highly dispersed ecosystem types occur most often in the intermediate elevation zone, moderate dispersion at the highest elevations, and homogeneity in the lowland areas where elevation remains relatively constant. When overlaid with BC's standard biogeoclimatic ecosystem classification zones the newly developed regions represent similar ecosystem ranges in the coastal, Taiga and Boreal Plains. However, overall our delineation exhibits a greater level of diversity in the alpine environment, and greater homogeneity in the central and southern interior. The quantitative regionalization approach we present offers a broad-scale assessment of British Columbia's ecosystem diversity that can be used as a supplement to traditional in situ biodiversity assessments to provide detail in under-sampled regions of BC or areas experiencing landscape change.

1. Introduction

Globally, anthropogenic activities have increased habitat loss and environmental degradation (Gaston, 2000), fragmenting or removing large areas of temperate, broadleaf and mixed type forests (Wade et al., 2003). As a response to this, and similar degradation, vertebrate populations have decreased on average 31% since 1970 (see Butchart et al., 2010). In Canada, habitat loss caused by agricultural activity and urbanization is thought to be the most prominent threat to endangered species (Venter et al., 2006). In the province of British Columbia (BC), landscape change is occurring due, in part, to extended growing season (Gayton, 2008) and widespread tree mortality created by the range expansion of mountain pine beetle populations (Robertson et al., 2009), with the ramifications of these impacts not yet known. Changes to BC's climate are projected to continue leading to marked shifts in the biogeoclimatic ecosystem classification (BEC) zones (Hamann and Wang, 2006).

To mitigate environmental degradation, management agencies need to consider both tree growth and ecosystem management,

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creating a need for scientifically rigorous and unbiased broad-scale biodiversity monitoring systems (Boutin et al., 2009). However, species-specific objectives, limited spatial and temporal scales, and inconsistent data collection and reporting beset current biomonitoring practices (Franklin, 1993; Boutin et al., 2009; Hyde et al., 2010). For example, BC's biogeoclimatic zones, established in the 1970s, have a forest management and climax equilibrium focus (Haeussler, 2011). Consequently, there is an opportunity to develop more comprehensive monitoring systems by building on Earth observation data for broad-scale ecosystem and biodiversity assessments (e.g., Nagendra, 2001; Duro et al., 2007; Boutin et al., 2009; Coops et al., 2009a) to supplement existing classification systems. Earth observation data provides spatially consistent, repeatable datasets considered appropriate for broad-scale, annual modelling of ecosystem diversity (Nagendra, 2001; Kerr and Ostrovsky, 2003; Turner et al., 2003; Duro et al., 2007; Gillespie et al., 2008). If Earth observation ecosystem modelling is repeated on a systematic time step, methods can ensure a cost effective, non-subjective regionalization approach (Hargrove and Hoffman, 2004) with sufficient spatial detail and consistency to identify potential changes or shifts in ecosystem diversity (Duro et al., 2007; Coops et al., 2008, 2009a).

Recent reviews have synthesized geospatial biomonitoring into two main categories of data, direct and indirect indicators, and three environmental features, the physical environment, vegetation productivity, and available energy (Turner et al., 2003; Duro et al., 2007; Gillespie et al., 2008). In a biomonitoring context, direct indicators capture information on individual species and land cover types, while indirect indicators often represent broad-scale landscape patterns understood to affect biodiversity (Turner et al., 2003). Such as, digital terrain data, satellite derived estimates of landscape productivity, and cover types, which have been used to predict avian species richness (Coops et al., 2009b). Significant positive correlations have also been found between Landsat-derived Normalized Difference Vegetation Index (NDVI) and in situ sampled vascular plant richness (Levin et al., 2007).

At the ecosystem level, biodiversity indicators can be represented in the form of landscape patterns, types, and/or process (Noss, 1990). For instance, digital elevation models capture landscape structural patterns (physical environment) in the form of topographic indices (Franklin, 1995). Remotely derived vegetation indices provide data appropriate for modelling landscape types and seasonal variations in landscape greenness (vegetation productivity) (Coops et al., 2008). Furthermore, biophysical ecosystem processes (available energy) can be represented by monitoring snow cover changes (Farmer et al., 2010), modelling annual average incoming solar radiation (i.e., insolation) (Kumar et al., 1997), and estimating moisture availability using topographic wetness indices (Franklin, 1995).

The goal of our research is to demonstrate methods to characterize BC's ecosystem diversity using indirect indicators of biodiversity derived from Earth observation data. To meet our goal, we will address the following objectives. First, we provide background on biodiversity indicators suitable for application over large areas. Second, we assess the monotonic correlation between variables to reduce redundancy and apply a two-step multivariate clustering method to delineate BC's ecosystems at a 1 km spatial resolution. Third, we analyze the potential to hierarchically aggregate our regionalization by assessing spatial pattern of the clustered pixels. Fourth, we compare and contrast our ecosystem regions to the established static BC biogeoclimatic zones to demonstrate how our approach can integrate with legacy ecosystem mapping schemes. Last, we discuss the contributions of our model to the broader objective of systematically monitoring ecosystem diversity over broad spatial scales.

2. Biodiversity indicators

Ecosystem characteristics are both static (i.e., at decadal time scales or longer) and dynamic. Static ecosystem components represent the landscapes potential to sustain species (Wright et al., 1998), while dynamic characteristics relate the effects of climatic variation and anthropogenic impacts on the landscape (Wallington et al., 2005).

Topography is a relatively static structural ecosystem component, with elevation gradients determining species distributions (Sarr et al., 2005), vegetation productivity (Franklin, 1995) and patterns of disturbance (Dorner et al., 2002). Elevation correlates with soil moisture, where productivity levels peak on low, cool, and moist slopes or high, warm, and dry slopes (Allen et al., 1991). Together, elevation and latitude play a critical role in temperature and moisture dynamics and thus shape vegetation composition and function (Franklin, 1995; Duro et al., 2007).

Elevation data can also be used to represent biophysical ecosystem processes. For instance, Rich et al. (1994) developed a hemispherical viewshed algorithm to model direct and diffuse solar radiation from topographic data which provides information on a sites microclimate including soil, surface and air temperatures, the sensible heat flux, and evapotranspiration (Kumar et al., 1997), all of which can ultimately influence plant growth. Similarly, studies have found that solar radiation correlates well with forest vegetation patterns (Davis and Goetz, 1990) and provides predictive power for modelling the spatial distribution of vegetative species in alpine environments (Guisan et al., 1998). In addition to solar radiation models, elevation data also provides an opportunity to estimate potential steady state topographic wetness. Topographic wetness indices (TWI) consider the surrounding topography to describe a location's ability to become saturated (Sørensen et al., 2006), and correlate well with soil attributes including horizon depth, silt percentage, and organic matter (Moore et al., 1993). TWI has also been used as a predictor variable of forest health conditions (Zirlewagen et al., 2007).

Snow distribution at the landscape-scale is also an important variable controlling patterns of ecosystem diversity from limiting species establishment and occurrence to driving vegetation seasonality (Walker et al., 1999; Wipf et al., 2009). The presence or absence of snow has either positive or negative effects on evaporation and run-off regimes respectively (Karl et al., 1993). Within the alpine environment, vegetation has adapted to rely on snow cover for protection from extreme weather and provide moisture in the summer (Billings and Bliss, 1959). Therefore, variations in plant diversity and abundance are largely governed by snow presence and melt rate (Kudo, 1991; Walker et al., 1999), making it a critical ecosystem characteristic in mountainous regions such as BC.

Mapping coarse scale vegetation diversity is also important for ecosystem monitoring because highly productive areas provide more resources to distribute between species and are theorized to support higher levels species richness (Walker et al., 1992). Research also indicates that productive ecosystems are more resilient and recover faster from disturbance (Stone et al., 1996). Studies have effectively integrated annual Moderate Resolution Imaging Spectroradiometer (MODIS) fraction of photosynthetically active radiation (fPAR) metrics representative of annual minimum vegetation, annual cumulative growth and annual vegetation seasonality to characterize broad scale ecosystems characteristics (Mackey et al., 2004; Coops et al., 2008, 2009a). By integrating vegetation dynamics with physical structure and available energy, ecosystem regions can be displayed over broad spatial scale and topographically complex rugged environments (Duro et al., 2007).

Table 1
Summary of the freely available geospatial datasets considered for our broad-scale ecosystem regionalization.

Biodiversity metric	Source data	Spatial resolution	Ecological relevance
Elevation	Canadian Digital Elevation Data	25 m	Elevation gradients, determine species distributions, vegetation production levels and patterns of disturbance (Franklin, 1995; Dorner et al., 2002)
Topographic Wetness Index	Canadian Digital Elevation Data	25 m	Steady state topographic wetness indices correlate well with soil attributes such as horizon depth, silt percentage and organic matter (Moore et al., 1993) and thereby provide a good indication of site productivity (Franklin, 1995)
Solar Insolation	Canadian Digital Elevation Data	25 m	Solar radiation effects microclimatic processes (Kumar et al., 1997), ultimately influencing the growth activity of plants
Spring Snow Cover (Max, Min, Chg.)	Daily Fractional Snow Cover (MOD10A1)	500 m	Snow distribution dictates species establishment and occurrence (Walker et al., 1999) with snow melt rates influencing vegetation growth patterns and seasonality (Kudo, 1991; Walker et al., 1999)
fPAR Indices (Max, Min, Sum, CV)	8-day Maximum fPAR (MCD15A2)	1000 m	Highly productive vegetated areas provide more resources to partition between species (Walker et al., 1992) and highly productive ecosystems are considered to be more resilient and recover faster from disturbance (Stone et al., 1996)

3. Methods

3.1. Study area

British Columbia covers over 940,000 km^2 and is a highly diverse mountainous environment subject to a variety of disturbance regimes (e.g., Masek et al., 2011; Safranyik et al., 2010). The physiography and climate are largely controlled by the Pacific Ocean to the west, continental air masses in the interior plateaus, and Rocky Mountains to the east (Austin et al., 2008). The central interior is composed predominantly of lodgepole pine forests. BC is experiencing an epidemic infestation of mountain pine beetle, due to factors including fire suppression and changing climate (Safranyik et al., 2010). The on-going infestation has contributed to an increase in forest fragmentation (through increased harvesting aimed at mitigation) and effects vegetation productivity (Coops and Wulder, 2010). Rapidly changing landscapes such as those in BC require robust techniques for large-area ecosystem mapping.

3.2. Datasets

Ten variables were considered to represent BC's ecosystems including topographic wetness, elevation, average solar radiation, three spring snow cover dynamics and four vegetation indices (Table 1). We selected to analyze remotely sensed data on productivity and snow cover characteristics using 2006 acquisition, post the annual peak tree mortality caused by mountain pine beetle infestations (Province of British Columbia, 2011) and representing average growing conditions with the provincial average temperature lying close to the 17 year median and the precipitation amount falling between the 25th and 50th percentile (only 89.5 mm lower than the provincial 17 year median) (Fig. 1). Therefore, 2006 can be taken as representative of current ecological conditions in BC, while also representing wide-area disturbance conditions. Prior to analysis, all raster datasets were converted to the same extent and a 1 km spatial resolution, partitioning the province into a grid of 1 km × 1 km cells.

3.2.1. Elevation

The Canadian Digital Elevation Data Product (CDED), extracted from the National Topographic Database at scales of 1:50,000 and 1:250,000 source data (GeoBase, 2007), was resampled twice using a bilinear technique, once from 25 m to 100 m spatial resolution for topographic modelling purposes and once from 25 m to 1 km spatial resolution for clustering (Fig. 2).

3.2.2. Topographic Wetness Index

The Topographic Wetness Index ($\ln(a/\tan\beta)$) (Beven and Kirkby, 1979), a well established index for relating soil moisture indices in support of hydrological modelling (Kopecký and Čížková, 2010), was calculated from the 100 m elevation product. In pre-processing all sinks and pits were removed from the Digital Elevation Model (DEM). Next, flow direction and flow accumulation (a) layers were derived using the D8 flow algorithm and the slope degree (β) was calculated and converted to radians. Results were resampled to 1 km spatial resolution and a focal mean filter was applied to smooth linear trends associated with the non-dispersive flow algorithm (for more details on topographic wetness modelling see Tarboton, 1997) (Fig. 2).

3.2.3. Annual solar insolation

To characterize BC's available energy, a solar radiation model was created using 25 m CDED product and a hemispherical viewshed model developed by Rich et al. (1994) (for details on calculation see Wulder et al., 2010). The algorithm uses a hemispherical viewshed and irradiance lookup tables, from each sky direction, to calculate direct and diffuse radiation (Rich et al., 1994). For each cell, a viewshed model was calculated and stored in the hemispherical coordinate system, then lookup values from all unobstructed sky directions were summed to estimate total irradiance, and a cosine correction accounted for the angle of incidence (Rich et al., 1994). To produce the most accurate results annual insolation calculations were conducted over two hour intervals for a single mid-day each month and monthly values were averaged to create annual solar insolation estimate (see Kumar et al., 1997) (Fig. 2).

3.2.4. Snow cover

Spring fractional snow cover layers were developed to represent regions experiencing high moisture availability. Source data were collected from 2006 MODIS Terra product (MOD10A1), which uses the normalized difference snow index to provide daily observation of snow cover, snow albedo and fractional snow cover at 500 m spatial resolution (Hall et al., 2006). Daily fractional snow cover datasets were downloaded from NASA DAAC for March, April and May 2006 conditions. Imagery was mosaicked and projected from sinusoidal grid to BC Albers Projection and resampled using a bilinear technique to 1 km resolution. Daily fraction snow cover dataset were used to create maximum and minimum fractional snow cover composites. The three month time period was selected to minimize the capture of cloudy winter images and ensure representation of spatial variability in spring snow cover melt as BC snow cover runoff regimes typically reach average flow by May (e.g., Stewart et al.,

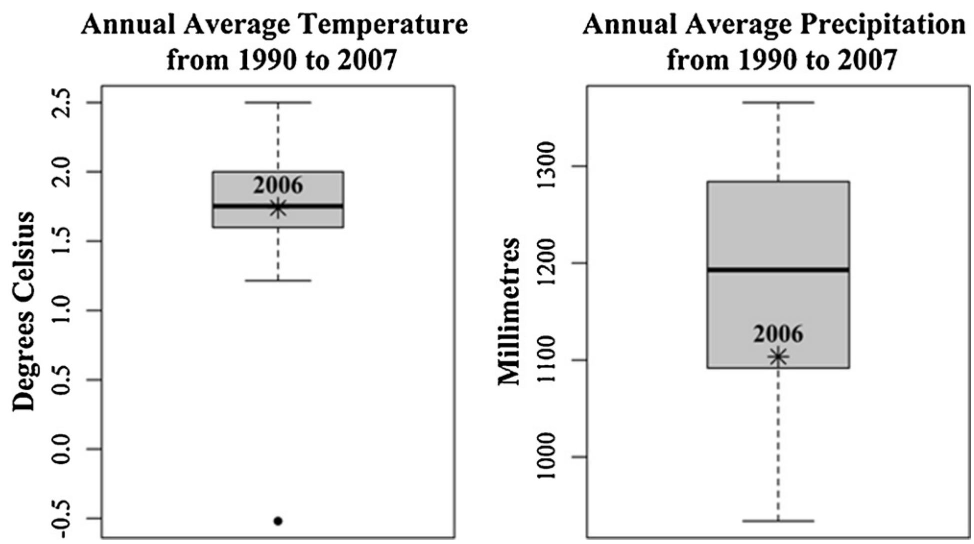

Fig. 1. British Columbia's annual average temperature and precipitation estimates from 1990 to 2007. Data were derived from Climate Western North America program which provides PRISM modelled climate data, in this case, using the Shuttle Radar Topography Mission 1 km Digital Elevation Model (see Wang et al., 2006 for additional modelling details).

2004). The average maximum percentage of snow cover derived from the 1 km daily composites was 92% and the average minimum fractional snow cover was 24%. To estimate the spatial variability of snow cover change (i.e., melt) over the province we subtracted the minimum snow cover values from maximum snow cover composite image (Fig. 2).

3.2.5. Vegetation productivity

Vegetation productivity estimates were derived from 2006 combined MODIS Terra and Aqua 8-day fPAR product (MCD15A2). The fPAR retrieval algorithm takes into account sun angle, background reflectance and view angles using the Bidirectional Reflectance Distribution Function (BRDF) at spectral bands between 400 and 700 nm (Tian et al., 2000). Values range from 0%, signifying barren land or snow cover, to 100%, representing dense vegetation cover (Coops et al., 2008). Images were also mosaicked, projected from sinusoidal grid to BC Albers Projection, and resampled using a bilinear technique to 1 km spatial resolution. Following the methodology proposed by Mackey et al. (2004) and implemented in Canada by Coops et al. (2008), 24-day fPAR maximums were calculated to help reduce the effects of cloud cover and null values within the 8-day maximum datasets (Coops et al., 2008). Using the calculated 24-day maxima, 2006 annual maximum, minimum, cumulative sum and coefficient of variation layers were developed. Each layer provides an indication of the annual vegetation productive levels. To describe the layers, annual maximum fPAR displays climax productivity conditions and ultimately signify phenological variation (i.e., alpine areas provide a much lower fPAR value than highly productive coastal evergreen forests) (Fig. 2). In contrast, annual minimum fPAR relates to the landscapes permanent vegetation cover. Vegetation seasonality is modelled by the coefficient of variation (Fig. 2) and cumulative sum respectively are dictated by topography, species type, and land cover uses (Coops et al., 2009a). High coefficient of variation values are representative of extreme climates or rotational agricultural practices (Coops et al., 2009a). Conversely, sites with low seasonality values represent evergreen forests, barren land or consistently irrigated lands (Coops et al., 2009a).

3.2.6. Ancillary datasets

The 2006 MODIS Terra and Aqua (version 005, University of Maryland) land cover (MCD12Q1) was also acquired to describe the dominant land cover characteristics within the developed ecosystem regions. This land cover product delineates 14 different land cover types from spectral data at 500 m spatial resolution (Friedl and Tan, 2011). Classes include five forest types, two shrub categories, two savannah classes, grassland, cropland, urban, barren or sparsely vegetated, and water.

Existing ecosystem data were obtained from the BC Ministry of Forests version 7 BEC zones, which divides BC into 16 ecosystems using in situ plant associations (and sub-associations) combined with elevation and aspect empirical rules created from ecological plot data (Austin et al., 2008; DeLong et al., 2010). The biogeoclimatic zones are well established and have provided BC's ecosystem characterization for the past 20 years by focusing on relatively permanent ecosystem characteristics such as mature vegetation type, soils and topography to represent homogeneous macroclimates and are most often used in a forest management context (DeLong et al., 2010).

3.3. Statistical analysis

A two-step clustering method was selected to agglomerate the ecosystem metrics into homogeneous regions. The algorithm provides a robust clustering technique, which is able to accommodate large datasets and mixed-type attributes (SPSS, 2001). Two important factors were considered before clustering these data. First, the correlation between variables was assessed to ensure data independence, because although each indicator has been shown to influence ecosystem diversity (Section 2) highly correlated variables can dominate cluster results (Parks, 1966). Secondly, data were standardized to *z*-scores to eliminate the impact of data units on the a-spatial distance measure used in clustering (Bacher et al., 2004).

A Spearman's correlation test was selected to evaluate the monotonic relationship between indirect indicators of ecosystem diversity. After assessment of the correlation matrix, which will be presented in the results, six variables were retained for clustering: annual maximum fPAR (Max. fPAR), annual vegetation seasonality (CV fPAR), the percent change in spring snow cover (Chg. Snow), elevation (Elev.), topographic wetness index (TWI), and annual solar insolation (Solar Rad.).

These remaining indicators were clustered into 17 statistically homogeneous ecosystem regions in two stages (16 terrestrial

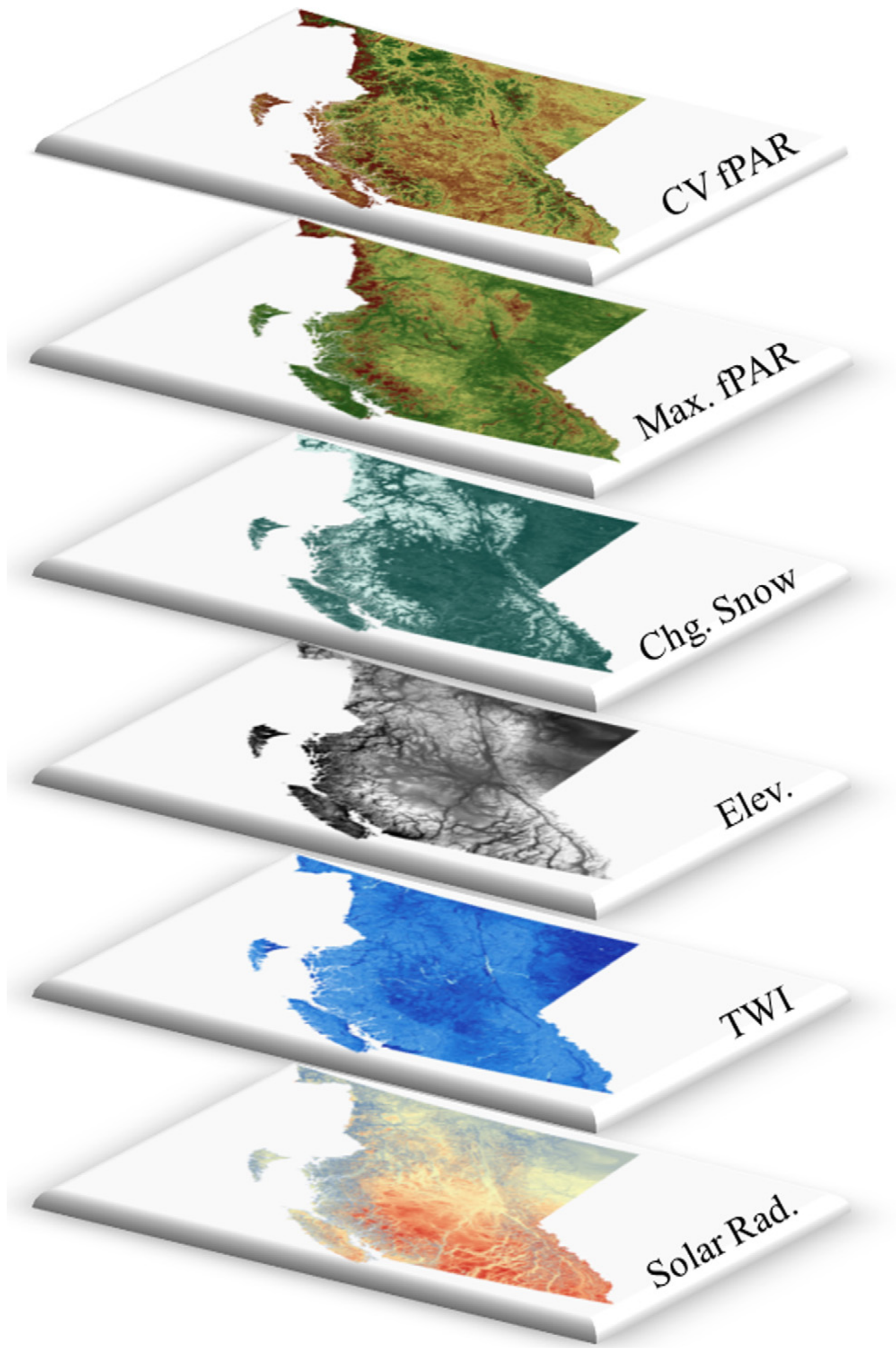

Fig. 2. Six independent biodiversity indicators used for ecosystem modelling.

classes and one water/wetland class). A 17-class system was selected in order to compare our regionalization results to BC's Ministry of Forests (version 7) BEC zones, which describes, at the coarsest scale, 16 ecosystems to describe BC's regional ecosystem diversity (Austin et al., 2008). The first stage of the clustering algorithm developed a cluster tree with a maximum of 585 nodes reducing the datasets into pre-clusters replacing the raw dataset (SPSS, 2001). Once pre-clustering was complete, the pre-clusters were grouped using an agglomerative hierarchical clustering method and a log-likelihood distance measure to monitor the decrease in log-likelihood as one cluster was grouped with another (SPSS, 2001).

The ecological uniqueness of each cluster was assessed by comparing each region's average indicator value using a one-way ANOVA and Dunnett T3 post hoc test. ANOVA provides an empirical method to ensure at least one of the region's variable means is statistically different from the others. Furthermore, because the Levene's test statistic revealed unequal variances (p-value < .001) and the region's samples sizes are unequal a Dunnett T3 test was selected for post hoc pair wise comparisons (Field, 2009). In

Table 2
Categories used to rank the average ecosystem indicator value per region.

Variables	Categories		
	Low	Medium	High
Max. fPAR (%)	0–32	32–73	73–100
CV fPAR	0–.34	.34–.76	.76–2.14
Chg. Snow (%)	0–35	35–76	76–100
Elev. (m)	0–809	809–1437	1437–3534
TWI (ln(%))	5.4–12.1	12.1–13.7	13.7–23.5
Solar Rad. (Wh/m^2)	41643–857797	857797–1040432	1040432–1497022

addition to the formal statistical evaluation, the variable mean of each region was ranked using a three-class system. Low, medium and high categories were defined using a natural breaks classification (Table 2). Following statistical analysis, regionalization results were imported into a geographic information system for display.

In addition to analyzing the separability of the ecosystem clusters, we characterized the spatial interaction of clusters as a means of developing a method for aggregating clusters hierarchically. To characterize the spatial distribution of cells that compose each cluster, we created a Rook's case first order cell contiguity adjacency matrix to assess the percentage of like adjacencies for each cluster category. Adjacencies are converted to a percentage where the number of like adjacencies involving the region category is divided by the total number of cell adjacencies possible for each category. Adjacencies percentages equal 0% when every cell in the cluster is surrounded by cells classified to a different cluster(dispersed) and approach 100% when the cells of a cluster are spatially contiguous (homogeneous). The metric includes edge pixels of each region, but does not include adjacencies located at the provincial extent.

3.4. Cluster characterization

We described each ecosystem region by average indicator value, which were ranked into classes of low, medium and high. To provide a more detailed description of the landscape we quantitatively determined the first and second most frequently occurring MODIS land cover classes and BEC zones and populate BC's BEC zones with our regions. The results of the analysis were also used to qualitatively compare our approach to the BC standard ecosystem units.

4. Results

4.1. Correlation

Reviewing the correlation matrix (Table 3), strong positive relationships were exhibited between annual maximum, minimum and cumulative sum fPAR variables (r_s = .83, .89, .61, p-value < .001). Therefore, maximum annual fPAR was selected to represent vegetation productivity to reduce data redundancy and provide an intuitive measure of landscape greenness. Maximum annual fPAR also provided the maximum separability between the ecosystem indicators values for each region and provided spatial homogeneity when compared to using a combination of fPAR metrics or fPAR cumulative sum. The fPAR coefficient of variation showed moderate to weak associations with other fPAR variables (r_s = −.43, −.11, −.50, p-value < .001) providing additional information regarding vegetation dynamics (seasonality). Spring snow cover matrices also displayed strong negative relationships between minimum snow cover and the change in snow cover (r_s = −.78, p-value < .001), therefore the change in spring snow cover was selected to represent moisture potential. The change in snow cover was selected over the minimum as it provided information on both the capacity of a pixel to retain a snow pack as well as identify which regions experience seasonal snow cover. Together these two factors influence variations in plant diversity and abundance (Kudo, 1991; Walker et al., 1999). Maximum snow cover is uncorrelated with the change in spring snow cover (r_s = −.07, p-value < .001), but strongly correlated with minimum snow cover (r_s = .62, p-value < .001). Despite its low correlation with snow cover change it was not included in the cluster analysis because maximum snow cover was moderately correlated with elevation (r_s = 49, p-value < .001), maximum fPAR (r_s = .47, p-value < .001) and fPAR coefficient of variation (r_s = .44, p-value < .001); thus, most of the variance within the dataset was captured by other ecosystem variables.

4.2. Statistical analysis of the ecosystem regionalization

Regionalization results, depicting the distribution of BC's ecosystem diversity, are shown in Fig. 3. Reviewing the f-statistic generated from the division of the between group mean squares and within group mean squares it was concluded with greater than 95% confidence that at least one of the regional means for each ecosystem metric are statistically different. Subsequently, the post hoc results (Table 4) compare the ecosystem variables between regions, which did not meet statistical significance to deduce a difference between their means (p-value > .05). To summarize, regions 1 and 2 do not exhibit different annual fPAR coefficient of variation and maximum fPAR characteristics. Regions 3 and 10 and regions 11 and 15 do not display different annual maximum fPAR greenness levels. Regions 3 and 6, 4 and 2, and, 11 and 12 represent similar snow cover seasonality and regions 3 and 6 share comparable potentials to hold soil moisture. In all other cases, the region's mean values for each ecosystem diversity variable are significantly different (p-value < .05). Most notably, elevation and solar radiation provide statistically different variable means between each region. Overall, the regions remain dissimilar if evaluated based on the combination of ecosystem variables and therefore successfully maximize between group variance and within group similarity ensuring our regionalization represents a range of ecological diversity found in the province.

Table 3
Spearman's correlation matrix, monotonic relationships are significant at p-value < .001.

	TWI ln (%)	Elev. (m)	Solar rad. (WH/m^2)	Max. snow (%)	Min. snow (%)	Chg. snow (%)	CV fPAR	Sum. fPAR	Max. fPAR	Min. fPAR
TWI	1									
Elevation	−0.43	1								
Solar Rad.	0.04	0.29	1							
Max. Snow	−0.30	0.49	−0.08	1						
Min. Snow	−0.45	0.57	−0.11	0.62	1					
Chg. Snow	0.35	−0.36	0.06	−0.07	−0.78	1				
CV fPAR	−0.08	0.27	−0.12	0.44	0.30	−0.03	1			
Sum. fPAR	0.36	−0.53	0.10	−0.66	−0.68	0.36	−0.43	1		
Max. fPAR	0.29	−0.52	−0.01	−0.47	−0.57	0.38	−0.11	0.83	1	
Min. fPAR	0.37	−0.41	0.17	−0.61	−0.61	0.31	−0.50	0.89	0.61	1

Correlations were assessed to ensure data independence before applying the two-step cluster.

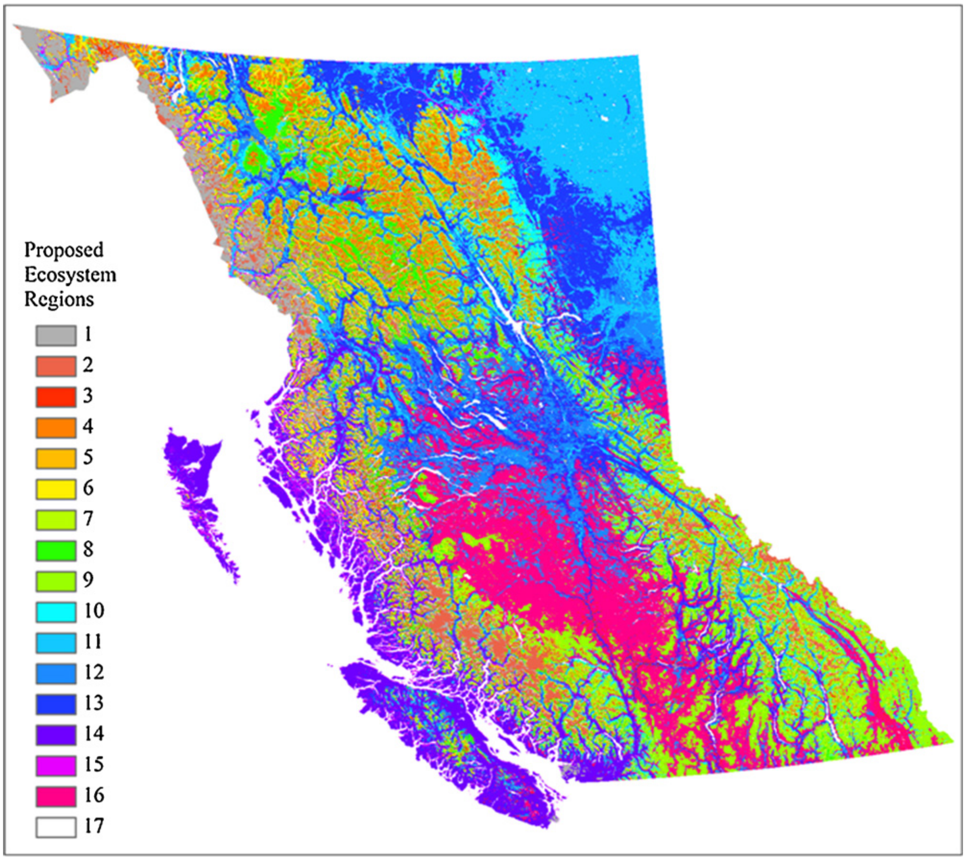

Fig. 3. Geospatial regionalization of BC's ecosystem diversity distinguishing 16 terrestrial ecosystem units (regions 1 through 16) and one water class (region 17). Regions 1 through 10 represent mountainous ecosystems and regions 11 through 16 delineate coastal and lowland areas.

The spatial adjacency matrix (Table 5) indicates that the regions 3, 5, 6, 7, 10, and 17 (water) are relatively dispersed with less than 50% of their adjacencies similar. In contrast, regions 11, 14 and 16 are highly homogeneous with over 70% of the possible adjacencies corresponding to the same regional category. Regions 1, 2, 4, 9, 12, 13 and 15 are moderately homogeneous with 50% to 70% of their adjacencies matching. Generally, the highly dispersed cluster values occur most often in the intermediate elevation zones, moderate dispersion levels at the highest elevations, and homogeneity is found in central interior, coastal and Taiga Plains areas where elevation remains relatively constant (Fig. 2). A threshold for aggregating classes can be determined qualitatively depending on the goals of the aggregation. As an example, if we were to use a threshold of 12% or higher to combine regions based on adjacency similarity alone region 1 and 2, 5 and 10, 6 and 8, 4 and 7, 12 and 13, and 14 and 15 could be aggregated reducing our 16 terrestrial ecosystems to 10 regions (Table 5).

4.3. Ecosystem regionalization results

In addition to the statistical analysis, individually comparing the ranks of the ecosystem metrics offers a good indication of landscapes dynamics (Table 6). For example, region 17 represents water or highly saturated ground with low elevations and low vegetation characteristics (Table 6). Commonly, the coastal alpine ecosystems (regions 1 and 2) are characterized with low vegetation production, wetness potential and snow seasonality (Table 6). Region 14 represents the lowland coastal areas of the province displaying highly productive vegetation with low seasonality, moderate snow cover changes, topographic wetness and solar insolation (Table 6).

Table 4
Dunnett T3 post hoc test for unequal variances and samples sizes.

Dunnett T3 post hoc test for 17 ecosystem regions						
Variable	Regions	Mean Difference	Std. Error	Sig.	Confidence interval	
					Lower bound	Upper bound
CV fPAR	1 and 2	0.000	0.000	1.000	−0.001	0.002
Max. fPAR	1 and 2	−0.052	0.032	1.000	−0.174	0.071
Max. fPAR	3 and 10	−0.056	0.129	1.000	−0.518	0.406
Max. fPAR	11 and 15	0.194	0.072	0.617	−0.070	0.458
Chg. Snow	3 and 6	−0.034	0.149	1.000	−0.593	0.526
Chg. Snow	4 and 2	0.249	0.090	0.548	−0.087	0.586
Chg. Snow	11 and 12	−0.075	0.038	0.998	−0.194	0.044
TWI	3 and 6	−0.003	0.007	1.000	−0.029	0.023

Results conclude that the ecosystem regions provide statistically unique combination of the ecosystem indicators.

Table 5
Rook's case first order cell contiguity matrix, showing the percentage of like adjacencies between the ecosystem categories (excludes background value adjacencies found at the provincial extent).

Regions	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
1	63	16	8	4	1	5	2	2	0	0	0	0	0	0	1	0	3
2	11	64	5	1	0	0	7	1	0	0	0	0	0	0	0	0	1
3	6	5	24	5	2	4	8	3	1	1	0	0	1	1	1	2	2
4	6	3	11	52	6	13	16	10	1	1	0	0	0	0	0	0	3
5	1	0	4	5	32	14	2	9	2	10	0	3	1	0	4	0	4
6	4	0	5	8	10	36	0	7	0	2	0	0	0	0	4	0	4
7	2	8	9	9	2	0	41	5	4	0	0	0	0	0	0	0	2
8	2	2	8	11	11	13	10	49	4	2	0	2	0	0	0	0	5
9	0	1	3	1	4	1	10	5	65	10	0	2	0	0	0	5	4
10	0	0	2	1	16	4	1	3	9	49	0	6	4	0	4	2	5
11	0	0	0	0	1	0	0	0	0	0	84	3	4	2	6	0	5
12	0	0	1	0	6	2	0	3	3	9	3	58	9	2	3	7	7
13	0	0	3	0	3	0	0	0	0	7	6	12	68	6	8	5	6
14	1	0	3	0	0	0	0	0	0	0	2	1	3	76	21	1	6
15	1	0	1	0	2	4	0	0	0	1	2	1	1	7	43	0	5
16	0	0	11	0	1	0	0	1	10	4	0	10	6	2	0	77	4
17	2	1	3	2	3	4	2	3	1	2	2	2	1	3	6	1	34

Note that because the regions have different spatial shapes order between the percentage of like adjacencies matters (i.e., the percentage of like adjacencies between region 1 and 2 is different from the percentage of like adjacencies between region 2 and 1). Furthermore, while the percentage magnitudes between like adjacencies of the same class differ the values indicate spatial trends (refer to section 4.2).

Region 16 located in the southern to mid latitude interior exhibits maximum vegetation production with low seasonality, moderate elevation. The region's change in snow cover, potential topographic wetness, and solar insolation are high (Table 6), which contributes to an abundance of available energy for vegetative growth.

Regions 10, 11, 12 and 13 are located in Taiga Plains, Boreal Plains, and Sub-Boreal Interior, all of which have a moderate vegetation seasonality, high maximum productivity and snow cover change, medium to low elevations, and moderate solar radiation conditions (Table 6). Soil wetness potential remains high for regions 11, 12 and 13, but low for region 10 (Table 6). Region 9 is located in the higher elevation regions of the Southern Interior and Southern Interior Mountains, correspondingly the soil wetness potential is low, vegetation seasonality is moderate, but snow cover change, maximum fPAR, and solar radiation values are high.

Regions 3, 4, 5, 6, 7 and 8 depict the mid to high mountainous ecosystems. Towards the north-west coast region 3 has low seasonality and high maximum vegetation characteristics (Table 6). In contrast, regions 4, 5, 6, 7, and 8 exhibit high vegetation seasonality and moderate vegetation greenness (Table 6). Regions 3 through 7 all exhibit low topographic wetness potential while region 8 has a moderate reading (Table 6). With the exception of region 5, these mountainous ecosystems have little change in their spring snow cover values (Table 6). However, regions 3 through 7 have variable average solar insolation values indicative of their latitudinal position and complex topographies. Regions 3, 4, 5, and 8 have moderate solar insolation values, region 6 low and region 7 high (Table 6). In summary, regions 1 through 10 characterize high to middle elevation mountainous ecosystems, and regions 11 through 16 represent lowland, interior and coastal areas (Fig. 3).

4.4. Ecosystem characterization

When compared to BC's standard biogeoclimatic ecosystem classification zones the newly developed regions occupy similar spatial areas in the coastal, Taiga, and Boreal Plains. Region 1, a coastal alpine ecosystem, is characterised by barren land, sparse vegetation and open scrublands. It is dominated by the Coastal Mountain-heather Alpine and Boreal Altai Fescue Alpine BEC zones. Region 2 is a drier coastal alpine region also characterized with low production levels (Table 6). Region 2 is dominated by the Coastal Mountain-heather and Interior Mountain-heather Alpine BEC zones (Table 6).

Region 3 is considerably more productive mountainous region than 1 and 2. It is characterised by evergreen needleleaf forests and open shrublands and is dominated by the Boreal Altai Fescue Alpine and the Engelmann Spruce-Subalpine Fir BEC zones (Table 6). Region 4 has similar elevation, wetness potential and climate characteristics to region 3, but its vegetation contrasts region 3 with high seasonality and open shrublands. However, region 4, like region 3, is dominated by the Boreal Altai Fescue Alpine and the Engelmann Spruce-Subalpine Fir BEC zones (Table 6). Region 5 is situated at a lower elevation level than region 4, and as such, has a moderate change in snow cover. Region 5 is dominated by the Spruce-Willow-Birch BEC zone (Table 6). Region 6 has less solar exposure than region 4 sitting at a lower average elevation; however, it exhibits similar vegetation characteristics (high vegetation seasonality and moderate production) and is also characterized by the Boreal Altai Fescue Alpine and the Engelmann Spruce-Subalpine Fir BEC zones (Table 6).

Regions 7 through 10 representing the moderate to high mountainous zones span high to moderate vegetation seasonality, moderate to high vegetation production levels and low to high snow seasonality respectively. These regions represent evergreen needleleaf forests, open shrublands and woody savannas. Their dominant BEC zone is the Engelmann Spruce-Subalpine Fir. Their secondary dominant zones set regions 7 and 9 apart (Boreal Altai Fescue Alpine and Montane Spruce, respectively) (Table 6).

Regions 11, 12 and 13 are highly productive mixed forests with high moisture availability and seasonal snow covers. Region 11 and 13 located in the Taiga and Boreal Plains are dominated by the Boreal White and Black Spruce BEC Zone (Table 6). Region 12 is represented by the Sub-Boreal Spruce ecosystem (Table 6). Coastal regions 14 and 15 are also highly productive, with low to moderate vegetation seasonality and moderate to high changes in snow cover (Table 6). Region 15 is located in land from region 14 which is situated on the coastline. Both regions are dominated by the Coastal Western Hemlock BEC zone; however, their variation in elevation separates their second dominant zones into Interior Cedar-Hemlock (region 14) and Mountain Hemlock (region 15) (Table 6). Region 16 represents the southern to central interior contains evergreen and mixed forests dominated by the Interior Douglas-fir BEC zone and the Sub-Boreal Spruce in the northern parts of the region (Table 6). Populating the BEC zones with our classification we can conclude that our regions exhibit a higher level of homogeneity in coastal low-lands, southern and central Interior,

Table 6
A summary of the ranked ecosystem variables, dominant land cover and biogeoclimatic zone.

Region	% Area	Categorized variable rank comparison						Dominant land cover and ecosystem type			
		CV fPAR	Max. fPAR	Chg. Snow	Elev.	TWI	Solar Rad.	Dominant land cover	Second dominant land cover	Dominant BEC zone	Second dominant BEC zone
1	4	Low	Low	Low	High	Low	Med.	Barren or sparsely vegetated	Open shurblands	Coastal Mountain-heather Alpine	Boreal Altai Fescue Alpine
2	2	Low	Low	Low	High	Low	High	Barren or sparsely vegetated	Open shrublands	Coastal Mountain-heather Alpine	Interior Mountain-heather Alpine
3	2	Low	High	Low	High	Low	Med.	Evergreen Needleleaf Forest	Open shrublands	Boreal Altai Fescue Alpine	Engelmann Spruce – Subalpine Fir
4	5	High	Med.	Low	High	Low	Med.	Open shrublands	Evergreen Needleleaf forest	Boreal Altai Fescue Alpine	Engelmann Spruce – Subalpine Fir
5	4	High	Med.	Med.	Med.	Low	Med.	Evergreen Needleleaf forest	Woody savannas	Spruce – Willow – Birch	Engelmann Spruce – Subalpine Fir
6	3	High	Med.	Low	Med.	Low	Low	Evergreen Needleleaf forest	Woody savannas	Boreal Altai Fescue Alpine	Engelmann Spruce – Subalpine Fir
7	3	High	Med.	Low	High	Low	High	Open shrublands	Evergreen Needleleaf forest	Engelmann Spruce – Subalpine Fir	Boreal Altai Fescue Alpine
8	5	High	Med.	Low	Med.	Med.	Med.	Evergreen Needleleaf forest	Open shrublands	Engelmann Spruce – Subalpine Fir	Spruce – Willow – Birch
9	7	Med.	High	High	High	Low	High	Evergreen Needleleaf forest	Open shrublands	Engelmann Spruce – Subalpine Fir	Montane Spruce
10	6	Med.	High	High	Med.	Low	Med.	Evergreen Needleleaf forest	Woody savannas	Engelmann Spruce – Subalpine Fir	Spruce – Willow – Birch
11	9	Med.	High	High	Low	High	Med.	Evergreen Needleleaf forest	Mixed forest	Boreal White and Black Spruce	Interior Cedar -Hemlock
12	10	Med.	High	High	Med.	High	Med.	Evergreen Needleleaf forest	Mixed forest	Sub-Boreal Spruce	Boreal White and Black Spruce
13	12	Med.	High	High	Med.	High	Med.	Evergreen Needleleaf forest	Mixed forest	Boreal White and Black Spruce	Sub-Boreal Spruce
14	7	Low	High	Med.	Low	Med.	Med.	Evergreen Needleleaf forest	Mixed forest	Coastal Western Hemlock	Interior Cedar -Hemlock
15	3	Med.	High	High	Low	Low	Low	Evergreen Needleleaf forest	Mixed forest	Coastal Western Hemlock	Mountain Hemlock
16	15	Low	High	High	Med.	High	High	Evergreen Needleleaf forest	Mixed forest	Interior Douglas-fir	Sub-Boreal Spruce
17	3	Low	Low	Med.	Low	N/A	Med.	Water	Water	N/A	N/A

The low, medium and high variable ranks were created by utilizing the natural breaks of the ungrouped data. Subsequently, the regional means were described by the appropriate low, medium, or high categories to assist ecological interpretation.

but are considerably more heterogeneous in the mountainous areas (Table 7).

4.5. Discussion

The uniqueness of our regions can be characterized by simultaneously considering the ecological attributes of each region as well as the spatial distribution and interaction between the ecosystems. For example, though regions 1 and 2 have similar ecological characteristics, based on attributes(seen in Table 4), they display a pronounced latitudinal variation, with region 1 separating the south coastal and interior mountains from region 2's north coastal and interior mountains. Regions 3 and 10, and 11 and 15 have similar maximum greenness levels values, (displayed in Table 4), but their spatial separation and statistical properties of the other ecological characteristics set them apart.

Regions 3 and 10 have a maximum like adjacency of only 2% and their vegetation seasonality differs between a low and moderate level respectively, suggesting phenological variations, which are exacerbated by the differences in their change in snow cover with region 3 keeping most of its snow cover into the summer months. Regions 11 and 15 found in the Taiga Plains and in-land south coast areas respectively, share similar vegetation characteristics (presented in Table 4), with moderate vegetation seasonality and high greenness values, but differ vastly in soil wetness potential and solar radiation. Differences between region 11 and 15 are expressed in the dominant species, Boreal Black and White Spruce in region 11 and Coastal Western Hemlock in region 15.

Regions 2, 3, 4, 6 exhibit minimal changes to their winter snow pack and regions 11 and 12 share a similar snow melt season, as seen in Table 4. Although, snow cover melt is an ecologically important factor for moisture availability we would expect similar rates of change between these regions because the variation is a seasonal response to the temperature rising above freezing. Mountainous areas with cooler climates and thicker snow packs keep their snow cover into the winter months. However, vegetation dynamics set mountains ecosystem regions apart. The vegetation in region 6 is seasonal with lower greenness values while region 3 has stable vegetation growth and high maximum absorption of fPAR. Rarely are regions 3 and 6 spatial adjacent with a maximum of 5% of their adjacencies together. Regions 2 and 4 are both situated at higher elevation and have low soil wetness potential; however, region 4's vegetation is seasonally variable with a green up season, moderate greenness level, and solar exposure, while region 2 is relatively barren of green foliage, and has high solar exposure. It seems the only common element between region 2 and 4 is the change in spring snow cover as their spatial extents remain disjoint with region 2 situated in the coastal mountains predominately to the south and region 4 in the Northern Boreal area.

In contrast, regions 11 and 12 are relatively ecologically similar with moderate vegetation seasonality and high maximum photosynthetic absorption (84% and 80%, respectively) representative of their high soil wetness potential. Similarities in ecological attribution are expressed by their corresponding land covers dominated by spruce forests. However, they are spatial separated with only 1% to 3% of their possible adjacencies found together and are spatial separated by region 13. In addition, their elevation levels differ. Region 11 is situated at the lowest provincial elevation level and region 12 at a moderate elevation. Specifically, they exhibit a 386 meter difference in their mean ground elevations and correspondingly have significantly different solar radiation levels (seen in Section 4.2), most likely impacting their species distributions (Franklin, 1995) and patterns of disturbance (Dorner et al., 2002).

In addition to spatial ecological information being useful for describing the uniqueness of regions, we indicate how the spatial pattern/interaction of individual pixels may be used for cluster

Table 7
A summary of the most frequently occurring ecosystems/regions found within each of BC's biogeoclimatic zones.

BEC zone	Ecosystems representing more than 2% of each BEC zone	Dominant region	Second dominant region
Boreal Altai Fescue Alpine	8	4	1
Bunchgrass	6	16	14
Boreal White and Black Spruce	5	11	13
Coastal Douglas Fir	4	14	15
Coastal Mountain-heather Alpine	8	1	2
Coastal Western Hemlock	6	14	15
Engelmann Spruce – Subalpine Fir	11	9	10
Interior Cedar – Hemlock	7	16	13
Interior Douglas-fir	6	16	13
Interior Mountain-heather Alpine	7	2	7
Mountain Hemlock	11	6	8
Montane Spruce	3	16	9
Ponderosa Pine	6	16	14
Sub-Boreal Pine – Spruce	3	16	12
Sub-Boreal Spruce	4	12	16
Spruce – Willow – Birch	7	10	5

aggregation. Aggregating clusters can be useful if fewer clusters are desirable. Ideally, aggregation of clusters should be based on a combination of the ecosystem characteristics and spatial proximity of individual pixels, especially given that British Columbia's elevation gradients typically have marked changes in climatic and vegetation conditions over short distances (Austin et al., 2008). As a suggestion, ecosystems differing in more than two ecological characteristics should not be combined. For example, 16% of Region 5's possible adjacencies are found beside region 10; however, their vegetation characteristics differ (Section 4.2). Region 5 exhibits a higher level of vegetation production and snow cover melt. These regions also have different dominant BEC zones Spruce-Willow-Birch (region 5) and Engelmann Spruce-Subalpine Fir (region 10). In contrast, regions 12 and 13 are spatially adjacent, and have similar high vegetation productivity levels, change in snow cover and moderate solar exposure. Notably, regions 12 and 13 house different BEC zones, including the Sub-Boreal Spruce and Black and White Spruce respectively and provide significant ecological indicator regional means, but their spatial proximity provides them with similar growth conditions. Therefore, at the spatial scale examined; it may be ecologically and spatially suitable to consider combining regions 1 and 2, 4 and 7, and 12 and 13; however, in-field assessment is advised as we draw upon these results by comparing the regional average of the ecological indicators.

We can further contextualize our regions through comparison with the utilized and standard BEC zones. Areas of discrepancy between our classification and the BEC zones are similar to those found by Hamann and Wang (2006) who predicted BEC zones using climate data and discriminant analysis. Similar to our results, they found significantly higher classification success rates in the regions of low topographic relief than the mountainous areas of BC. The variability found between our regionalization and BEC zones in the mountainous and central interior regions may be a result of remotely sensed imagery and terrain indices providing a uniform amount of detail over the province which is too costly for in situ sampling (Duro et al., 2007) which governs the BEC classification program (Pojar et al., 1987; DeLong et al., 2010). Further, the mountainous regions are spatially variable and more complex than the central interior regions, with elevation gradients and different slope aspects leading to both physiographic and vegetation complexity. Within mountainous areas, the selected ecosystem classifiers have the ability to distinguish the natural heterogeneity that characterizes them.

Unlike the BEC ecosystems boundaries which emphasize the patterns of static variables such as landforms, soils and climax vegetation conditions (Pojar et al., 1987) our methods explicit represent temporally dynamic ecosystem characteristics susceptible to anthropogenic effects and climate change by including Earth observation data. For example, the case of the central interior where vegetation greenness has been subjected to wide spread mountain pine beetle infestation (Robertson et al., 2009; Safranyik et al., 2010). Instead of the vegetation dynamics representing the ecosystem's mature vegetation conditions modelled in the BEC zones (Pojar et al., 1987); our regionalization approach includes the current vegetation conditions representing a more homogeneous central interior. By including current conditions we are allowing for the contemporary vegetation status, growth and variability to be represented. In addition by utilising remote sensing datasets which are continuously updated, this proposed approach is potentially useful for monitoring. A variety of remote sensing datasets can be utilised, including long term means, or layers updated annually allowing a much more dynamic representation of the ecoregionalizations to be created as ongoing datasets become available.

At the same time as recognizing the strengths of our regionalization approach, data limitations must also be acknowledged. For instance, MODIS sensors are sensitive to atmospheric attenuation and spectral mixing (Jensen, 2007); therefore, maximum fPAR and fractional snow cover should be considered best approximations. It is possible that cloud cover has masked maximum values and spectral mixing has had an effect on the true spatial variation of the vegetation and snow cover indices. We also recognize that in the mountainous areas of BC shadowing due to topography and atmospheric interference may be a concern (Huete et al., 2011). To reduce this possible source of error we used MODIS quality assessment information and monthly maximum retrievals to develop the indicators used. However, apart from the vegetation and snow cover characteristics that may be effected, solar insolation and TWI derived from ground elevation data remain ecological separable.

Despite data limitations, representing species richness using indirect indicators of biodiversity derived from remotely sensed imagery makes spatially consistent standardized broad-scale ecosystem diversity modelling possible when in-field assessments are limited by resources and time (Franklin, 1993). We considered our biodiversity metrics as components of the ecosystem related to species richness and metrics most effectively represent biodiversity when combined into homogeneous regions, rather than being studied in isolation. We are not suggesting that large-area Earth observation ecosystem modelling could replace in-field or species-specific biodiversity assessments; rather, it should be used as a supplement to target resources for detailed ecosystem monitoring in the most vulnerable areas.

5. Conclusion

Given the ecosystem indicators selected, our methods ensure a robust regionalization system that maximizes the variance between and homogeneity within each ecosystem unit at 1 km resolution. The metrics build upon well-established environmental relationships and suggested modelling practices (e.g., Franklin, 1995; Mackey et al., 2004; Duro et al., 2007; Coops et al., 2008, 2009a) and provide sufficient detail, accuracy and spatial consistency to recognize changes or shifts in ecosystem regions (Coops et al., 2008, 2009a; Hyde et al., 2010). By monitoring ecosystem dynamics researchers are transforming space-time data into a resource management tool. Additionally, by ranking the average indicator value into classes of low, medium and high we provide an intuitive summary of the spatial variability of BC's landscape.

By combining the benefits of systematically and repeatedly collected remotely sensed datasets with a quantitative regionalization approach we have created a baseline model for future ecosystem monitoring. We recommend our approach be used as a supplement to traditional in situ biodiversity assessments (e.g., BC's biogeoclimatic zones) to provide detail in under-sampled regions of BC or areas experiencing landscape change to support adaptive resource management strategies and resource conservation policies aiming to protect the current, and future, biotic diversity present over the province of British Columbia (BC Ministry of Environment, 2011). With anticipated shifts in BC's ecosystem dynamics (Hamann and Wang, 2006) monitoring should be a central priority of British Columbia's conservation initiatives.

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