

**Forecasting Impacts of Climate Change on Indicators of British Columbia's
Biodiversity**

by

Keith Richard Holmes
B.Sc., University of Victoria, 2008

A Thesis Submitted in Partial Fulfillment
of the Requirements for the Degree of

MASTER OF SCIENCE

in the Department of Geography

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ABSTRACT

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Understanding the relationships between biodiversity and climate is essential for predicting the impact of climate change on broad-scale landscape processes. Utilizing indirect indicators of biodiversity derived from remotely sensed imagery, we present an approach to forecast shifts in the spatial distribution of biodiversity. Indirect indicators, such as remotely sensed plant productivity metrics, representing landscape seasonality, minimum growth, and total greenness have been linked to species richness over broad spatial scales, providing unique capacity for biodiversity modeling. Our goal is to map future spatial distributions of plant productivity metrics based on expected climate change and to quantify anticipated change to park habitat in British Columbia. Using an archival dataset sourced from the Advanced Very High Resolution Radiometer (AVHRR) satellite from the years 1987 to 2007 at 1km spatial resolution, corresponding historical climate data, and regression tree modeling, we developed regional models of the relationships between climate and annual productivity growth. Historical interconnections between climate and annual productivity were coupled with three

climate change scenarios modeled by the Canadian Centre for Climate Modeling and Analysis (CCCma) to predict and map productivity components to the year 2065. Results indicate we can expect a warmer and wetter environment, which may lead to increased productivity in the north and higher elevations. Overall, seasonality is expected to decrease and greenness productivity metrics are expected to increase. The Coastal Mountains and high elevation edge habitats across British Columbia are forecasted to experience the greatest amount of change. In the future, protected areas may have potential higher greenness and lower seasonality as represented by indirect biodiversity indicators. The predictive model highlights potential gaps in protection along the central interior and Rocky Mountains. Protected areas are expected to experience the greatest change with indirect indicators located along mountainous elevations of British Columbia. Our indirect indicator approach to predict change in biodiversity provides resource managers with information to mitigate and adapt to future habitat dynamics. Spatially specific recommendations from our dataset provide information necessary for management. For instance, knowing there is a projected depletion of habitat representation in the East Rocky Mountains, sensitive species in the threatened Mountain Hemlock ecozone, or preservation of rare habitats in the decreasing greenness of the southern interior region is essential information for managers tasked with long term biodiversity conservation. Forecasting productivity levels, linked to the distribution of species richness, presents a novel approach for understanding the future implications of climate change on broad scale biodiversity.

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ACKNOWLEDGMENTS

I am extremely fortunate. Over the past two years I have been privileged to research a subject that I am passionate about in an environment that is challenging and supportive. None of this would be possible without my supervisor Dr. Trisalyn Nelson. Trisalyn exemplifies a truly amazing person and I cannot thank her enough for letting me be part of her team. The support from Dr. Nicholas Coops and Dr. Mike Wulder have been indispensable in making my research a success; their knowledge and support have meant a lot to me and I am honored to have had the opportunity to work with them.

Thank you James Hiebert and Hailey Eckstrand for the technical assistance you provided which made the daunting task of coding and working with climate models rewarding. I am thankful for all the SPAR lab mates for your advice, support, and great ideas that have helped me immensely. My incredible friends have been so important in making the past two years more fun than I would have ever expected with all our amazing adventures. A special thank you to my family who have always supported my strange fixation with maps and the outdoors; I could not have done this without your support. Thank you to all my fellow graduate student friends and lastly David, Karen, Jessica and Jacob for helping me keep my stick on the ice. My mind and heart are truly full.

CO-AUTHORSHIP STATEMENT

This thesis is the combination of two scientific manuscripts for which I am the lead author. The project structure was developed with Dr. Trisalyn Nelson, Dr. Nicholas Coops, and Dr. Michael Wulder to forecast broad indirect indicators of biodiversity into the future using climate change scenarios. For these two scientific manuscripts, I led all research, data preparation, data analysis, result interpretations and writing. Dr. Nicholas Coops and Dr. Michael Wulder provided guidance in developing research questions and contextualizing research results. Dr. Trisalyn Nelson provided support with research structure and methodological considerations. Dr. Trisalyn Nelson, Dr. Nicholas Coops and Dr. Michael Wulder supplied editorial comments and suggestions incorporated into the final manuscript.

1.0 INTRODUCTION

1.1 Research Context

Unprecedented global climate change has been a result of multiple natural and anthropogenic activities which are rapidly altering temperature and precipitation normal. Changes to climate are directly impacting species diversity, abundance, and geographic ranges of species (IPCC, 2007). Anthropogenic sources of climate change include greenhouse gasses such as carbon dioxide (Cox et al., 2000) which as of August 2012 have reached a record 392.4 parts per million (National Oceanic & Atmospheric Administration, 2012) contributing to the global warming effect (Cramer et al., 2001; Solomon et al., 2009). The rate of climate change may be amplified by feedback loops such as melting permafrost and the release of methane (O'Connor et al., 2010) and the diminished albedo effect in the Arctic sea (Lindsay and Zhang, 2005).

The term biodiversity is defined by the multiple scales and components of biological diversity from the genetic level to species, ecosystems, and landscapes (DeLong, 1996). Biodiversity is valuable in supporting functioning ecosystems and is intricately related to chemical, climatological, and ecological systems in nature (Sala, 2000; Cramer et al., 2001). Given that climate strongly influences the amount of biodiversity a habitat can sustain (Holdridge, 1947), climate change will alter the abundance, diversity, and geographic range of species (Huston, 1979; Woodward and Williams, 1987; Hebda, 1998). Climate is a controlling factor in where and how a species will survive which ultimately dictates the type of biodiversity a habitat can sustain. The decline of biological heterogeneity deteriorates the functionality of resilient and healthy environments

resulting in irreversibly destabilized ecosystems (Walker, 1992) which is why maintaining present day biodiversity is so critical to preserving stable habitats.

Global depletion of biodiversity is currently being observed (Butchart et al., 2010) as is evident by the projected extinction of up to 50% of species within 50 years (Pimm and Raven, 2000; Koh et al., 2004). The pandemic loss in species diversity and abundance has caused the international community to take action. International biodiversity conservation agencies include the Millennium Ecosystem Assessment (United Nations Environment Programme, 2005), Species 2000 (Species 2000, 2012), and The Global Biodiversity Assessment (World Resources Institute, 1995). The most notable commitments to preserve biodiversity are The International Union for the Conservation of Nature, and the Convention on Biological Diversity. The mandates of these organizations is that signatories, including Canada, commit to conserve, identify and monitor biodiversity components, and to manage threats (Barton, 1992) including climate change. Biodiversity conservation achievements have been successful at preserving localized biodiversity through the use of protected areas, invasive species control, sustainable resource management, and discrete species conservation efforts (Butchart et al., 2010). Utilizing a knowledge based approach is important to address the threat of climate change on our biodiversity in order to effectively preserve it. Proactive management strategies require tools to predict possible impacts and make informed recommendations.

1.2 Research Focus

British Columbia's biodiversity is threatened by climate change (Hebda, 1998; Gayton, 2008; Wang, et al., 2012). Projected impacts to British Columbia's biodiversity

include an upward shift in treeline, shrinking alpine ecosystems, impairment to native species survival rates, increased invasive species (Gayton, 2008), and large shifts in ecosystem distributions (Wang, et al., 2012). The most notable effort to model biodiversity elements in British Columbia came from Hamann and Wang, (2006) and Wang, et al., (2012) which predict a major reorganization of forest ecosystems in the province through the use of both field collected data (forest plots) and remote sensing based information. Foresight into how climate change may impact biodiversity is imperative in order to effectively manage our natural resources. Considering the cost benefits of conservation strategies is a reality in present day management efforts (Walker, 1992), and understanding the spatial rate of change and vulnerability of habitats is a valuable tool to efficiently delegate climate change adaption strategies.

Biodiversity forecasting efforts are numerous and are widely criticized (Davis et al., 1998; Heikkinen et al., 2006; Thuiller, 2007). Forecasting methodology depends upon the predictor variable type, the extent of the study site, and the distribution model. Our approach will use remotely sensed indirect indicators of biodiversity sourced through the AVHRR satellite fPAR productivity metrics (Fontana et al., 2012). Annual fPAR data from 1987-2007 will be used to extract three biodiversity indicators. The three metrics, greenness, seasonality, and minimum cover represent various ecosystem functions. Given metrics are based of measurements of photosynthetic absorption within the plant canopy they can be used to interpret vegetation greenness, productivity, and biomass (Coops et al., 2009). Remotely sensed biodiversity indicators can therefore represent broad ecological processes and the ability of a habitat to sustain species (Hawkins et al., 2003; Turner et al., 2003).

1.3 Research Goals and Objectives

The goals of this thesis are to forecast shifts in indirect biodiversity indicators due to climate change and apply our findings to the parks and protected areas network. Our rich data sets are used to characterize broad indicators of biodiversity through the use of remote sensing data, topographically adjusted climate information, future climate scenarios, and parks. Our aim of using a remotely sensed DHI biodiversity indicator approach allows for finer spatial resolution, repeatable modelling, and a complete spatial coverage of our large dynamic study area. The impact of climate change on British Columbia's biodiversity will be evaluated by accomplishing the following objectives:

1) The first objective is to assess how climate change is impacting biodiversity in British Columbia. Our approach utilizes archived remote sensing and up-sampled climate information to understand bio-climate relationships for all terrestrial ecosystems in British Columbia. Project the bio-climate relationships into future scenarios of biodiversity indicators using climate model information and regression tree methodologies. Finally, an assessment of change in biodiversity indicators will detail risk to habitat dynamics.

2) The second objective is to assess future biodiversity indicator conditions in parks and protected areas in British Columbia. By exploring our knowledge of projected changes to DHI with protected area information we can investigate the critical aspects of protected areas such as changes in representation, finding conservation gaps, rank impacts to species assemblages, and highlight high risk protected areas.

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2.0 MODELING THE IMPACTS OF CLIMATE CHANGE ON INDICATORS OF BRITISH COLUMBIA'S BIODIVERSITY

2.1 Abstract

Understanding the relationships between biodiversity and climate is essential for predicting the impact of climate change on broad-scale landscape processes. Utilising indirect indicators of biodiversity derived from remotely sensed imagery we present an approach to forecast shifts in the spatial distribution of biodiversity. Indirect indicators, such as remotely sensed plant productivity metrics, representing landscape seasonality, minimum growth, and total greenness have been linked to species richness over broad spatial scales, providing unique capacity for biodiversity modeling. Our goal is to map possible impacts of climate change on British Columbia's habitats by modeling productivity shifts in seasonality, minimum cover, and cumulative vegetative growth. Using an archival dataset sourced from the Advanced Very High Resolution Radiometer (AVHRR) satellite from the years 1987 to 2007 at 1km spatial resolution, corresponding historical climate data, and regression tree modeling, we developed regional models of the relationships between climate and annual productivity growth. Historical interconnections between climate and annual productivity were coupled with three climate change scenarios modeled by the Canadian Centre for Climate Modeling and Analysis (CCCma) to predict and map productivity components to the year 2065. Results exhibit a warmer and wetter environment, which may lead to increased productivity in the north and at higher elevations. Overall, seasonality is expected to decrease and minimum cover is expected to increase in productivity. The Coastal Mountains and high elevation edge habitats across British Columbia are forecasted to experience the greatest

amount of change. This type of approach to predict change in biodiversity provides resource managers with information to mitigate and adapt to future habitat dynamics. Forecasting productivity levels, linked to the distribution of species richness, presents a novel approach for understanding the future implications of climate change on broad scale biodiversity.

2.2 Introduction

Species abundance and diversity, also referred to as biodiversity, are vulnerable to climate change (Running et al., 2004) with shifts in atmospheric conditions caused by both natural and anthropogenic impacts leading to substantial alterations in regional environments (Houghton et al., 1996; IPCC, 2007). Due to the intricate relationship between climate and the spatial distribution and abundance of species (Holdridge, 1947; Woodward and Williams, 1987; Bakkenes et al., 2002), this change is expected to cause ecosystem shifts (Hamann and Wang, 2006; Gayton, 2008) and as such, there is a need to understand the future spatial distribution of biodiversity, extent of expected change, and nature of the transformations to habitats. To address these challenges, baseline information on biodiversity conditions is required, as are trends in changes from these captured conditions. Archival sources of remotely sensed data provide opportunities for the generating biodiversity indicator data, providing new opportunities to monitor past conditions and to support model-based predictions of future changes to species richness and biodiversity.

Indirect indicators of biodiversity are widely used in ecological research (Running and Nemani, 1988; Nemani et al., 2003; Slayback et al., 2003; Xiao and Moody, 2005) and are a useful tool for forecasting shifts to habitat dynamics due to climate change.

Utilizing remote sensing based biodiversity indicators compliments past modeling efforts. Biodiversity indicators are practical for long term monitoring of habitat shifts and are becoming an increasingly viable methodology due to improved spatial resolutions and the temporal depth of archived satellite data (Kerr and Ostrovsky, 2003). Remote sensing based indirect indicators of productivity provide high spatial resolution information over a long time series and can incorporate a broad ecosystem approach to gain information on landscape dynamics and vegetation productivity which has been shown to be statistically linked to biodiversity parameters (Hawkins et al., 2003; Coops et al., 2009; Field et al., 2009; Andrew et al., 2011).

The Dynamic Habitat Index (DHI), proposed by Mackey et al. (2004) and later developed by Berry et al., (2007) and Coops et al. (2008), provides a tool for indirect mapping of biodiversity from archived remote sensing data. The DHI utilizes Advanced Very High Resolution Radiometer (AVHRR) data to create three biodiversity indicator metrics based on fPAR (fraction of Photosynthetically Active Radiation) which measures the amount of radiation absorbed by the plant canopy at the 400-700nm wavelength (Asrar et al., 1984). Acting as a proxy for landscape vegetation primary productivity, fPAR has been demonstrated as a surrogate measure for biodiversity (Xiao and Moody, 2005). Generally, higher productivity habitats sustain a greater level of biodiversity than low productivity areas (Dallmeier and Comiskey, 1998; Chase and Leibold, 2002). By observing trends in productivity indicators over time it is possible to map changes in the carrying capacity available to support species diversity (Chase and Leibold, 2002). Greater primary productivity environments can sustain greater species abundance and variety; therefore, by modeling indicators of habitat productivity we can infer potential

changes to biodiversity (Kerr et al., 2001; Nagendra, 2001; Turner, Spector, Gardiner, Fledeland, et al., 2003; Nilsen et al., 2005). The DHI generates a broad-scale spatial representation of habitat productivity dynamics which act as a metric for assessing change to species richness and variety (Duro et al., 2007; Andrew et al., 2011). Natural ecosystems function in a bottom up approach with primary productivity controlling higher order ecosystem functions (Loreau et al., 2001), which indicate the degree of species richness and variability a habitat is capable of sustaining (Chase and Leibold, 2002). Every habitat has dominant limiting factors controlling productivity and species diversity such as the tundra (temperature), desert (precipitation), tropical forests (solar radiation) and boreal forest (soil temperature) (Waide et al., 1999). Tundra vascular plants for example, are shown to have a significantly higher productivity and diversity with increased temperatures (Arft et al., 1999) and climate change is expected to increase the growing season, increase soil nutrient cycling, and enhance energy to the environment which will in turn allow primary productivity and species diversity to flourish (Waide et al., 1999).

Three fPAR metrics are used in the DHI: cumulative greenness, coefficient of variation, and minimum cover. Cumulative greenness represents the total annual radiation absorbed by the canopy; low greenness values indicate barren land with no productivity while high values indicate more productive habitat. The coefficient of variation indicates the seasonality of plant productivity; high values indicate seasonal habitats, like alpine environments, while low seasonality values indicates vegetation regimes that do not change significantly throughout the year, such as a coastal evergreen forest. Finally, minimum cover represents baseline levels of recurrent vegetation cover (Coops et al.,

2009); high minimum cover values indicate a stable year-round productive habitat, such as a coastal valley forests, while a low values indicate a more barren habitat, such as a glacier. By assessing habitat indicators for total greenness, seasonality, and baseline greenness, several components of landscape dynamics are simultaneously considered. As an indirect indicator of biodiversity, once combined the DHI acts as a composite metric for habitat productivity at a high spatial resolution with complete spatial coverage. The composite DHI provides a three dimensional view of changes to complex habitat shifts by displaying the three productivity metrics weighted evenly in a red-green-blue color gun as detailed in previous work by Coops et al. (2008).

The foundation of our approach to modelling the spatial distribution of future DHI is the strong relationship between climate and productivity (Boisvenue and Running, 2006; Latta et al., 2009) and between productivity and biodiversity (Hawkins et al., 2003; Field et al., 2009; Andrew et al., 2011). Climate change will impact plant phenology, productivity, and ultimately biodiversity. With overall temperatures and precipitation levels increasing a number of outcomes to productivity dynamics can be hypothesized. We anticipate mid to high elevation forests may be impacted the most by increases in greenness (Mote et al., 2003). Coefficient of variation indicates the expected seasonality of habitats. We expect seasonality to decrease especially in high elevation environments due to climate change causing earlier spring green-up dates and more mild winter conditions (Mote et al., 2003; Badeck et al., 2004). Minimum cover represents year-round stable productive habitats. Low elevation evergreen forests and overall rich habitats are highlighted by a high minimum cover metric. We anticipate minimum cover

may increase throughout the province especially in low elevation forests environments (Coops et al., 2009).

Bio-climate relationships vary spatially and it is expected that in northern regions temperature based variables typically cause the greatest shifts in biodiversity indicators compared with hybrid and precipitation variables (Kawabata et al., 2001). Hybrid climate variables such as evapotranspiration and climate moisture deficit detect habitat moisture availability which can be a limiting factor for productivity (Latta et al., 2009) and can indicate climatological limiters such as drought stress. Precipitation based variables are important driving factors in forecasting productivity and although typically weaker than temperature based variables, are important to accurately forecast complex remote sensing based research (Notaro et al., 2006). The landscape variable elevation interacts with temperature and precipitation variables and significantly determines a habitat's ability to sustain life (Daly et al., 2008).

The goal of this research is to model and map impact of climate change on British Columbia's biodiversity, as represented by current and future projections of DHI components. To meet this goal we utilize archived remotely sensed data to extract DHI components from 1987 to 2007. We characterize bio-climate relationships observed over time and space by relating archived climate information to the DHI components using regression trees. Future climate information is then used to predict and map possible scenarios of DHI components to the year 2065. Finally, the forecasted DHI components are synthesized into a composite indirect indicator of biodiversity and change analysis used to highlight areas expected to experience the greatest shifts in habitat and biodiversity.

We hypothesize that our predictions will show cumulative greenness and minimum cover increasing and seasonality will decrease due to climate change. Changes to DHI components will follow the response of vegetation to predicted increased temperatures causing primary productivity in vegetation to accelerate. Plant phenology is temperature dependant (Badeck et al., 2004) and therefore increases in available energy may result in more greenness.

2.3 Methods

2.3.1 Study Area

The province of British Columbia spans 944,735 km² and has a variety of landscapes and ecosystems due to its large size, diverse topography, and climate (Austin et al., 2008; Murdock and Burger, 2010). The province can be divided by climatological forcing caused by proximity to the Pacific Ocean, Rocky and Coast Mountains, and continental air masses. In British Columbia regions of similar climate and ecology are represented by biogeoclimatic regions: ecozones, ecoprovinces, and ecodistricts (from largest to smallest) (B.C. Ministry of Forests, 2009). To support model development and increase classification accuracy, the study area (the entire province of British Columbia) was partitioned into six regions of similar size based on British Columbia biogeoclimatic ecozones and ecoprovinces (B.C. Ministry of Forests, 2009). The regional approach to DHI classifications improved the predictive strength of the regression tree models by reducing heterogeneity. Within each region, remote sensing and climate data were represented by 106 ecodistricts. Aggregated input data into ecodistricts enabled a more appropriate spatial grain for analysis of broad scale processes. The six ecoregions and number of ecodistricts in each are as follows: Taiga Plain (18), Boreal Cordillera (11),

Mountain Cordillera (13), Pacific Maritime (24), Okanagan Caribou (22), and Kootenay (18) (Figure 1).

2.3.2 Data

Climate

We used high spatial resolution topographically corrected climate information for British Columbia sourced from the Climate Western North America database version 4.60 (CWNA) (Wang et al., 2010). CWNA utilises the Parameter-elevation Regressions on Independent Slopes Model (PRISM) approach (Daly et al., 2008; Oregon State University, 2011) and uses up-sampling of climate models using topography, climate stations, wind patterns, and rain shadow information to provide a continuous coverage of climate data for the province. Annual climate data for 1987-2007 was compiled with subsequent annual indirect biodiversity data in ecodistrict spatial units in order for the regression tree process to learn the relationship between climate and indicator response. Four datasets were used to represent present and future time periods. The thirty year data spanning 1961-1990 was used to represent “present day” climate. The three future climate scenarios were based on the Canadian Centre for Climate Modelling and Analysis (CCCma) B1, A1, and A2 scenarios for the thirty year average 2050-2080 (2065). The range of future scenarios were: B1 (AR4 - R1) represents the least extreme scenario, A1 (AR4 – R1) represents the business as usual scenario, and A2 (AR4 – R4) represents the most extreme scenario. Model selection was based on using the full range of possible scenarios that were available from respected institutions and were recommended by the Pacific Climate Impacts Consortium (Murdock and Splttlehouse, 2011).

Indirect Indicators of Biodiversity

Archived satellite based terrestrial vegetation information provides an important source of spatial-temporal data to understand relationships between climate and terrestrial biodiversity. Biodiversity indicator metrics sourced from remote sensing platforms have been successfully utilized to monitor broad ecosystem dynamics (Nagendra, 2001; Duro et al., 2007; Latta et al., 2009). Recent progress in data processing techniques and enhanced dataset size has allowed for the twenty one year Advanced Very High Resolution Radiometer (AVHRR) remote sensing biodiversity indicator dataset to be available. Fontana et al. (2012) explains the various correction processes conducted on the AVHRR dataset to minimize errors caused by cloud cover, poor sensor calibration, geolocation accuracy, and spectral response inconsistency. The AVHRR dataset used in this study has once daily temporal resolution from 1987 to 2007 with a spatial resolution of 1x1Km (Latifovic et al., 2005; Fontana et al., 2012). The AVHRR satellite has been operating since 1978 (Kidwell, 1998), but due to sensor error, and data gaps, the year 1987 was used to start analysis. Long-term datasets like the AVHRR are valuable sources of spatiotemporal information which can be used to understand physical processes and the impacts of climatic change on habitats (Latifovic et al., 2005). Remotely sensed indicators of habitat productivity provide valuable metric for species richness and variety (Nagendra, 2001) since the amount of landscape productivity is linked to biomass (Lu, 2006), food availability (McNaughton et al., 1989), and habitat complexity (Nemani and Running, 1997; Kerr and Ostrovsky, 2003) all of which dictate the degree of biodiversity a habitat can sustain (Coops et al., 2009). Remotely sensed ecosystem based metrics

therefore provide an excellent source of broad scale biodiversity information in order to model future trajectories of change due to climate variability.

Disturbance

Urban development and other anthropogenic activities have altered climate-vegetation relationships due to a number of factors such as roads and buildings impacting the non-pervious surface layer, irrigation and fertilizers altering vegetation growth, and a change in the abundance and management of non-native species. To ensure the model captures relationships between climate and biodiversity, anthropogenic landscapes were excluded from analysis. The baseline thematic mapping (BTM) land cover classification dataset was used to delineate and extract highly disturbed landscapes and ensure our model will not be skewed by anthropogenic environments (Ministry of Sustainable Resource Management, 2001). We excluded agriculture and urban land cover types (Franklin, 1995).

Climate variables

A literature review of the climatological drivers of species abundance and diversity indicates forecasting efforts require variables that are temperature based (Running and Nemani, 1988), precipitation based (Slayback et al., 2003; Potter et al., 2007), a hybrid of both (Carey, 1996; Hamann and Wang, 2006), and represent landscape dynamics (Daly et al., 2008) (Table 1). Selected temperature based variables consisted of mean annual temperature, temperature difference, growing degree days, number of frost free days, mean coldest month temperature, Julian data on which frost free period begins (green up date). Hybrid climate metrics consisted of climate moisture deficit and evapotranspiration. Precipitation variables were mean annual precipitation, precipitation

falling as snow, and mean summer precipitation. Finally, the landscape indicator was elevation, sourced from a 1km spatial resolution digital elevation model.

Considerations for climate variable use are determined using correlation between variables and their relationship with DHI indicators. Correlations will guide analysis by indicating strong bio-climate relationships and ensure each region is well represented by ensuring appropriate climate variables are used. Climate variables showing high correlation with DHI indicators were chosen because they best represent bio-climate relationships and would improve model performance.

2.3.3 Regression Trees

Regression trees, which are increasingly being used in ecological studies (Carpenter et al., 1993; Iverson and Prasad, 1998; Berry et al., 2002; Thuiller, 2003; Rounsevell et al., 2005; Prasad et al., 2006), were used to predict the future scenarios of biodiversity. Unique regression trees were generated for each of the six regions (Taiga Plain, Boreal Cordillera, Mountain Cordillera, Okanagan-Caribou, Kootenay, and Pacific Maritime) using data represented at the ecodistrict level. Mean DHI and climate information was generated and organized within these ecodistricts resulting in 106 regions with 21 years of data (N= 2,226). The use of regions was necessary for optimal model performance and to extract higher accuracy classification results. To test for intercorrelation between climate variables we computed the correlation coefficient both across the entire province, as well as within ecoregions. Some variables had poor correlations and therefore were not used in regression tree analysis such as extreme minimum temperature; these variables were often superseded by mean annual temperature, elevation, and growing degree days. Stronger correlations typically result in

a greater importance in forecasting (dominant splits), while lesser correlation variables represented the root node of regression trees. In order to quantify the regional bio-climatic relationships in British Columbia an ANOVA regression tree analysis was implemented. ANOVA regression trees use hierarchical recursive partitioning to classify explanatory variables (e.g., climate) and their subsequent responses (e.g., biodiversity indicators) (Heikkinen et al., 2006). Regression trees were run using the “rpart” tool (Therneau and Atkinson, 1997) which uses binary split classification trees to create nodes of minimized residuals using variables with the highest explanatory power. The regression tree process accounts for data collinearity (Venables W.N. and Ripley B.D., 1999) and therefore data redundancy will not impact model performance. The rpart tool is adept at incorporating multiple variables and non-linear datasets which are common for complex bio-climatic relationships (Austin, 2002). To assess regression tree accuracy, a complexity parameter is produced for each tree which is a cross-validated error to show how well each regression tree has minimized the residuals and therefore indicates model confidence (Venables W.N. and Ripley B.D., 1999). The complexity parameter ranges from 0 (weak relationship) to 1 (strong relationship). The rpart prediction function was used with the regression tree results and future climate scenario data to model future remote sensing indicators of biodiversity. The predict function provided forecasted metrics of biodiversity according to the node value for each of the eighteen regression trees.

2.3.4 Model Confidence

Testing the coefficient of determination between the observed remote sensing data and expected modelled data provides regression confidence for each DHI indicator in the

model. The resulting R^2 value determines the overall strength of the bio-climate relationship with zero representing a poor relationship and one being a strong relationship. To assess the quality of the model spatially, pixel differencing was performed to compare the 21 year average remote sensing DHI findings with the modeled results. The modeled results are produced by using the *predict* function in rpart with the present day (1961-1990) averaged climate data and uses the model to represent current DHI components. By comparing observed and modeled DHI components we can map spatial variability in model quality. Over-modeled results would exist if the modeled DHI values were predicted to be higher than observed and under-modeled results from the model DHI values being lower than observed. Since the differences were found to be normally distributed, two standard deviations were used on the error histograms to determine directionality of above, below, and near expected model results. We expect a quality model to show some variation from the measured, resulting in evenly scattered deviations throughout the province. Areas of concern are highlighted when spatial clusters of over or under modeling performance occurs. Spatially random deviations are expected due to disturbances including harvesting, wildfires, insect outbreaks, and other non-climate related variables.

2.3.5 Predicted Changes in Biodiversity

To characterize the spatial distribution of change in indirect indicators of biodiversity we differenced the forecasted 2065 A1 scenario with the present day data (that is, mean 1961-1990 conditions). Using the 1961-1990, 30 year average dataset is standard in climate forecasting to represent current conditions (IPCC, 2007; Murdock and Splttlehouse, 2011). The future components all use the thirty year average for 2050-2080

(2065) with varying degrees of climate forcing. The A1, business as usual scenario, was the representative climate scenario used to compare the degree of change occurring to biodiversity indicators from current conditions to 2065. The A1 scenario was chosen because it has an intermediate amount of change compared to the A2 (extreme) and B1 (conservative) scenarios. The differencing highlights clusters of change and spatial shifts expected in each DHI component.

Observing a composite DHI better reflects the true dynamic shifts in long term biodiversity trends that is more reflective of the complex interrelationships that occur in nature (Zhang et al., 2007). Some regions observed high variation between scenarios indicating that these regions may be the most vulnerable to climate change and minor shifts in climate patterns may cause major changes to biodiversity indicators.

2.4 Results

2.4.1 Regression Trees

Using three DHI indicators and six representative ecological regions resulted in 18 unique regression trees to represent bio-climate relationships in British Columbia (Table 2). The dominant split or root nodes for each regression tree indicate which variable best determines the response DHI variable. Important variables include growing degree days, precipitation as snow, number of frost free days, evapotranspiration, and elevation. Complexity parameter results showed highest confidence in the southern regions where bio-climate relationships are most evident. Less productive environments in the North tend to have poorer bio-climate relationships due to other non-climatic variables having an increased impact on DHI indicators resulting in less accurate results compared to southern temperate regions. Cumulative greenness was the strongest

performing biodiversity indicator followed by coefficient of variation, and lastly by the minimum cover. Trends in regression tree branches showed that northern regions like the Boreal and Taiga resulted in models with a larger number of branches (18 to 30) while southern regions such as the Pacific had fewer (8 to 14). Pruning regression trees did not improve model performance but rather overly simplified classifications to regression trees that already achieved minimized residuals in the rpart process. Branch complexity indicates that our prediction results are more confident in the Pacific Maritime, Okanagan, and Kootenay regions because complex trees are a result of less straightforward and multifaceted bio-climate relationships. Regression tree residuals and complexity parameters also display the ability of our forecasting technique (0= weak relationship, 1= strong relationship) to accurately predict future biodiversity indicators by receiving provincial complexity parameters of .46 (greenness), .48 (seasonality), and .41 (minimum cover).

The future spatial distributions of biodiversity indicators, using climate scenarios B1, A1, and A2 for 2050-2080 (2065) are shown in Figure 2. Cumulative greenness is shown in green (high greenness) and yellow (low greenness); interpreting the outcomes province-wide, overall the greenness is increasing. The coefficient of variation is shown in red (high variability) and blue (low variability); trends show a decrease in seasonality. Minimum cover is shown from dark green (high minimum cover) to white (low minimum cover); shifts indicate an increase in minimum cover. Trends between present day and future DHI scenarios indicate increased greenness and minimum cover and decreased seasonality. Increased greenness occurs along the Coast Mountains and central interior; coefficient of variation transitions throughout the province except for the Boreal region;

and minimum cover steadily increases along the coast, central interior, and Okanagan. Aspect of biodiversity such as birds, insects, and plants are expected to move northward in the continental regions and eastward in the Pacific Maritime. By assessing the various scenarios from best case (B1) to worst case (A2) we quantified predicted mean change in DHI components for the province and each region (Figure 3). Regional change graphs show the greatest change is expected between present day and 2065 B1 scenario and typically a linear change in DHI follows between B1, A1, and A2. Non-uniform responses in mean regional DHI occurred with cumulative greenness in the Okanagan and with the coefficient of variation in the Boreal which will be discussed in detail below in a dedicated sub-section. Simultaneous display of all three DHI components through the climate scenarios allows for better interpretation of shifts to habitats throughout the study area (Figure 4). Dynamic interactions between biodiversity indicators highlight the complex and spatially explicit relationships climate has on the landscape.

2.4.2 Model Confidence

Coefficient of determination calculation provided confidence in our prediction model by assessing observed and modeled results with R^2 values of .92 (cumulative greenness), .89 (coefficient of variation), and .72 (minimum cover). Further analysis differencing the 21 year average DHI values with the modelled DHI displayed spatially scattered residuals (Figure 5). Variance in our results provides evidence that no patterns emerged from differencing showing that no one region or landscape has been poorly modeled. Some areas of model deviation were shown to be disturbed landscapes subject to active forest management activities (harvesting) in the southern Pacific Maritime and central interior regions or a significant stress such as drought in the North Taiga region.

Each DHI component had similar model confidence with near expected results provincially: cumulative greenness receiving 89.4%, coefficient of variation 90.0%, and minimum cover 89.4%. Similarly, directionality of model confidence was between 4.6% and 6.0% above and or below expected values.

Spatial variation in model confidence varied throughout the province. One area of disagreement was the southern Mountain Cordillera region, which experienced noticeable clusters of deviation from the observed for all three DHI indicators. These areas showed the model slightly below expected greenness and minimum cover and above expected seasonality.

2.3.3 Predicted Changes in Biodiversity

Provincially, mean DHI change between present and A1 scenario future was greatest in minimum cover (50.0%) followed by seasonality (-22.0%), and greenness (11.0%). Regional shifts from current to 2065 A1 scenario are shown in Figure 6. An evenly weighted DHI change analysis composite map (Figure 7) highlights the relative degree of change projected for an A1 scenario. In general, trends showed greatest overall DHI change along the coast through an elevation band from the 500 to 1500 m. Also, change analysis on climate scenario variability shows the differences between scenarios B1, A1, and A2 which is discussed below.

Greenness

The mean provincial greenness indicator for British Columbia is projected to increase from 9376.5 to 10411.9, resulting in an 11.0% increase in greenness for the A1 scenario. Cumulative greenness showed minimal change in lower elevation coastal and

mid elevation interior regions. Mean changes observed between regions highlight that clusters of change in biodiversity indicators are concentrated along Pacific Maritime highlands, Mountain Cordillera, southern Boreal, and Kootenay highland regions. Regions such as the Mountain Cordillera may experience an increase of greenness between 13.8% (B1) and 18.5% (A2) which can impact forest growth and a myriad of other interconnections.

Directionality of change in cumulative greenness emphasizes that changes in climate may not have a linear biodiversity indicator response and that each habitat type will likely have a unique change trajectory. For example, when comparing cumulative greenness changes between the Okanagan and Pacific Maritime regions, the latter has an expected response of higher greenness (23.5 %). Though general greenness may increase, some slight decreases in projected greenness are observed in lower elevations of the Okanagan and North East Boreal regions, where increased temperatures are anticipated to cause moisture deficits for the Okanagan grasslands or drought stress for northern Boreal shrub woodlands. For example, the projected temperatures increases in the Okanagan may cause variable responses such as the 100 mile house ecodistrict which has a reduction in productivity (-10.1%). Observed decreases in greenness may be attributed to climatic limitations like evapotranspiration or climate moisture deficits which are associated with drought conditions.

Overall, the mean rates of change to provincial cumulative greenness remain constant across scenarios, however spatial differences can be observed at the finer, ecodistrict, level. For example, as cumulative greenness shifts from scenarios B1, A1, and A2 there is a shift in greenness. Greenness increases to higher elevations along the

coast, as well as increasing greenness in the interior forests and north into the Boreal region. The greatest differences in greenness across the future scenarios were observed in the mid to high elevation (500-1500m) Pacific Maritime region followed by the Mountain Cordillera and high elevation Kootenay regions. The Pacific Maritime is predicted to have an increase in greenness of 17.8% (B1), 23.5% (A1), and 32.9% (A2); indicative of increased productivity. This increase in productivity can be beneficial to generalist species that can survive and adapt to a variety of habitat types. The smallest change in greenness between scenarios was observed in the dryer south central Okanagan region. Spatial variations were observed in the Okanagan and mean values showed greenness to shift from 2.0% (B1), 1.0% (A1), and 0.0% (A2). Although the climate is warming in the Okanagan, other limiting factors such as water availability may restrict greenness from changing at a significant rate. At the ecodistrict level, the Terrace Skeena River ecodistrict on the North West of BC is projected to change considerably from the B1 to A2 scenario with a 28.0% increase in the greenness indicator, while the Williams Lake ecodistrict in the Central Okanagan-Caribou region has a decrease of - 10.1% greenness.

Seasonality

The mean provincial change in seasonality metric shifted from 668.2 to 547.6, resulting in a decrease of -22.0% using the A1 scenario. The seasonality metric depicts landscapes with high change in productivity between warm and cold times of the year. Highly seasonal environments have large differences between summer and winter plant productivity. Seasonality is projected to have the greatest decrease in high elevation landscapes. The most change was observed in edge forest environments like the Coast Mountains, low elevation Taiga forests, Vancouver Island highlands, the Mountain

Cordillera and to a lesser extent the Kootenay highland forests. Little change in seasonality was predicted for the southern lowlands, most of the Okanagan Caribou, and the Boreal regions. Slight increases in seasonality were observed in the Stikine forests which are high elevation edge environments within the Southern Taiga region.

Seasonality showed the largest spatial differences between scenarios. Trends between scenarios B1, A1, and A2 show clusters of decreased seasonality in the Coast Mountains and North West and clusters of increased seasonality in the North East. The Pacific Maritime region may observe the greatest decrease in seasonality through the scenarios from -19.1% (B1), -25.8% (A1), and -35.2% (A2). Regions like the Boreal Cordillera show different trends with projected decreases of -4.0% (B1), -3.2% (A1), and -1.2% (A2) which indicates a lesser and less consistent change in seasonality when compared across the province. At the ecodistrict level, the Fort Nelson Boreal ecodistrict showed a projected increase in seasonality of 8.1% between the B1 and A2 scenario. In contrast, the South Coast Mountains ecodistrict had a mean decrease of seasonality of 27.0% between the B1 and A2 scenarios.

Minimum Cover

Provincially, the most substantial changes observed in our model were the minimum cover DHI metric. Minimum cover is projected to have a mean provincial change from 79.7 to 119.6, resulting in an increase of 50.0% using the A1 scenario. Regions of greatest change are the Pacific Maritime and interior mid to low elevations (Okanagan Caribou, Mountain Cordillera, and Southern Boreal) which indicates more continual productivity throughout the year for these regions. Minimum cover changed little in the North West of the province, and in low (Coastal Vancouver Island) and high

elevations (Rocky Mountains). Small patches of decreased minimum cover were observed in the lower mainland, Haida Gwaii, and Vancouver Island. The Pacific Maritime is projected to have an increase of minimum cover from 46.3% (B1), 64.4% (A1), and 89.4% (A2). The Kootenay region has the least amount of forecasted minimum cover with increases of 22.7% (B1), 28.5% (A1), and 35.6% (A2); these increases are primarily in the low lying valleys and although the regional mean increase may be lesser, the impact may be significant in low elevation landscapes. The ecodistrict level showed the Kispiox River ecodistrict in the Pacific Maritime to have a projected increase of 88.7% minimum cover between B1 and A2 scenarios. Comparatively, it is projected the ecodistrict of East Prince George has a decrease of -21.9% between scenario B1 and A2.

2.5 Discussion

Providing a basis for our analysis, the availability of contemporary climate and remote sensing data allowed us to model, and then validate the DHI under current climate conditions. Results showed the prediction of the DHI under current climate conditions was close to the observed values with some differences clustered in the central interior of British Columbia. Differences indicate lower or higher DHI indicators are observed when compared to the modeled, so an area with lower cumulative greenness for example could be disturbed by logging taking away the natural vegetation regime and therefore less energy is being absorbed by the plant canopy resulting in a lower than expected greenness value. Some possible explanations for this difference could be related to the impact of the mountain pine beetle infestations which have occurred in this region since 1999 (B.C. Ministry of Forests, 2012), resource extraction or other disturbances, or from climatological vectors such as drought stress (Barber et al., 2000; Shafer et al., 2001).

Furthermore, the decision tree models performed the poorest in the Boreal region, potentially due to the situation that the DHI and climate values were less heterogeneous (Hamann and Wang, 2006) in these northern regions and other non-climatic forces like soil composition may be more influential compared to the southern regions because of the limiting factors such as soil structure and nutrients necessary for vegetation to grow (Xiao and Moody, 2005). Despite these issues however, complexity parameters also confirm our model results were defensible with provincial parameters all above .41 and coefficient of determination parameters all above .72 showing that the climate DHI interrelationship is strong and our model performed well (Therneau and Atkinson, 1997).

Using three scenarios of climate change severity we mapped a number of predictions of expected shifts in biodiversity indicators. The scenarios B1, A1, and A2 indicate progressive shifts in the indicators especially in the Pacific Maritime and Mountain Cordillera regions for all DHI indicators.

The composite DHI of present to future scenarios highlights that across the province overall seasonality is decreasing and greenness and minimum cover is increasing, however, trends vary spatially. For instance, some parts of the Taiga have decreases in seasonality, greenness, and minimum cover and do not show typical reactions to increases in temperature, highlighting the fact that each habitat type has complex reactions to change (Pearson and Dawson, 2003). The high spatial resolution and composite DHI allows for more intimate analysis of site specific changes that can be applicable to understanding more than regional trends. Possible site specific applications include: interpretation with endangered species locations, protected areas monitoring, and resource management strategies.

Cumulative greenness is also projected to increase, which indicates a shift to more productive terrestrial habitats. Increased productivity may result in greater capacity for accumulation of biomass and available food which may feedback to a habitats' ability to sustain larger populations and diversity of plants and animals (Boisvenue and Running, 2006). Vegetation may grow at a more rapid rate, so species such as Douglas fir or coastal hemlock can grow to harvestable size in less time (Latta et al., 2009), which is highly relevant to resource managers. Increased productivity, especially along sensitive high elevation habitats can impact sensitive species due to succession and extirpation of species (Bakkenes et al., 2002; Hamann and Wang, 2006). Greenness responses however are also spatially unique throughout the province with some landscapes having rapid increases in greenness while others decrease slightly. For example, the reduced greenness in the Okanagan grasslands highlight the importance of using regional non-linear relationships between habitat indicators and climate variables to ensure the unique interactions between the numerous landscapes of the province are modeled effectively and spatial variation in relationships identified. Okanagan grasslands, or bunchgrass environments, are an example of a habitat that may benefit from climate change, becoming increasingly spatially abundant due to favorable climatic conditions (Hamann and Wang, 2006). Increases in greenness may also result in forest species spreading to the North and growing at faster rates. Increase in greenness can impacts primary producers as well as a myriad of interconnection bottom up effects on all the species in the region (Pearson and Dawson, 2003).

The DHI coefficient of variation (or seasonality) was predicted to change substantially, but not uniformly across the province under changing climate. Changes to

seasonality may further fragment high elevation sparsely treed and or low vegetation habitats. Higher elevation habitats may become less spatially contiguous and patchier. For instance, habitats such as alpine heather meadows may be encroached by successional tree species that can now survive at higher elevations due to warming (Brink, 1959). Mountain-heather alpine habitats sustain a variety of complex and unique vegetation regimes that include sedge meadows, heaths, forb meadows, and flowering plants that are unique to harsh mountain conditions (Brink, 1959). The alpine heather may follow (similar to (Huntley et al., 1989)) their favored climatic regions, shifting to capricious higher elevation environments. Consequently species may shift and establish themselves in more fluctuating habitats and depending on the landscape could become more fragmented or squeezed out. Impacted areas include environment that are found at the fringe or edge of the viable growing landscapes such as high elevation lichens, flowering plant, shrubs, grasses in and around the tree line of mountains (Hebda, 1998). Our models indicate alterations may occur to vegetation along edge environments which are sensitive to climatic change (Thuiller, 2007) which is especially evident in the coast mountains around the 500 to 1500 m elevations. High elevation species are particularly vulnerable due to their slow growth, restricted viable habitat, and limited ability to adapt and migrate (Bakkenes et al., 2002). Seasonality, representing changes in resources throughout the year, is a key limiting factor for many species, will decrease in mid to high elevations (Bunn, 2005) which may lead to increased species succession into higher elevation habitats. Succession into new habitats may be beneficial to generalist species however, detrimental to species of limited habitat range (Algar et al., 2009) which are of particular interest to conservation efforts. Predicted changes indicate that high elevation

habitats, like alpine meadows, may degrade by encroachment, attenuation, and by becoming increasingly fragmented.

As with other studies, our maps of predicted change of indirect indicators highlight that as climate changes, habitat spatial distributions may alter the interaction between species. An example is the vulnerable plant species whitebark pine (*Pinus albicaulis*), which is projected to have substantial shifts in habitat. Whitebark pine is found on the Coast Mountains and is often the only conifer species found at high elevations; it is slow growing and is projected to have a 98% reduction in abundance due to climate change (Hamann and Wang, 2006). Species like whitebark pine are susceptible to change, as slow growth and limited seed dispersal inhibit adaptation. Impacts on the whitebark pine can influence other species as it is considered a keystone species for grizzly bears and several songbirds (McLane and Aitken, 2012). As climate changes, historical whitebark pine habitats are increasingly encroached by other generalist species like mountain hemlock. Our models indicate that the habitat of whitebark pine may become increasingly productive and therefore more favorable to competition from other species.

Sensitive animal species such as the Vancouver Island Marmot (*Marmota vancouverensis*) are also vulnerable to climate change impacting their habitat. The Vancouver Island Marmot is Canada's most endangered species and is found in sub-alpine meadow habitat and our models show these high elevation habitats incurring great shifts due to climate change (Hebda, 1998). Projected decreases in seasonality and increases in greenness and minimum cover in the Marmots' current habitat may result in decreases in habitat size, quality, and connectivity. With a projected three degree increase

in mean annual temperature on Vancouver Island, the alpine environment is expected to shift from 1,600 meters to 2,200 meters (Hebda, 1998) which leads to increased species specific habitat fragmentation and increased succession into higher habitats. Climate change may continue to negatively impact the survivability of the marmots by reducing the size and connectivity of their already limited habitat (Brink, 1959; Bryant and Janz, 1996; Hebda, 1998).

Limiting and driving climatic factors have caused the predicted shifts to each DHI. Increases in greenness, decreased variability, and increased minimum cover have been driven by predicted temperature related variables increasing. Minimum cover increases indicates that evergreen species may be more productive and can shift up higher latitudes and elevations (Coops et al., 2008). Increased year round minimum cover indicates that baseline productivity may escalate. Outcomes of this change will likely be increased productivity of forest habitats throughout the region and better growing conditions for generalist species to succeed into new habitats (Algar et al., 2009). The resulting impacts to species due to increased minimum cover are substantial. Since minimum cover indicates year round primary productivity, the projected increase would result in a more productive environment. The phenology of individual species would need to adapt to new climatological conditions and generalist primary productivity species would grow at a faster rate (Badeck et al., 2004). Examples of species that would benefit from an increased minimum cover include tree species such as coastal western hemlock and interior Douglas fir. Species that may suffer from climate change are mountain hemlock, western larch, and subalpine fir (Hamann and Wang, 2006).

British Columbia is a suitable environment for biodiversity assessments due to a diversity of landscapes and unique ecosystems (Hamann and Wang, 2006) provide an opportunity to demonstrate methodologies across a range of terrestrial environments. Successful ecosystem modeling techniques such as the biogeoclimatic zone mapping (B.C. Ministry of Forests, 2009) and ecosystem indicator mapping (Fitterer et al., 2012) highlight the diversity of species and environments found in the province. Past biodiversity forecasting efforts for British Columbia have been successfully applied. For instance, Hamann and Wang (2006) forecasted change to biogeoclimatic zones and individual tree species habitats in British Columbia. In addition to the successful studies already completed, many of which rely heavily on field data, there is an opportunity to use remotely sensed data sets to indirectly map biodiversity with data that have complete spatial coverage and are collected through time, and as such can be used to support monitoring (Condes and Millan, 2010). Monitoring can be better supported by using our methodology which provides detailed spatial biodiversity metric information with complete coverage in an efficient and cost effective method.

Mapping future scenarios for DHI indicators provides insights into habitat shifts in the province and provides a new perspective on how habitat shifts may impact species abundance and diversity with spatial variability across the province. Climate change will continue to drive phenological shifts in habitats (Badeck et al., 2004). Expected temperature and precipitation changes will be a vector for productivity and therefore biodiversity shifts (Araújo and Rahbek, 2006). Our understanding of the spatial changes aids our ability to properly prescribe best practices in conservation and management strategies (Lemieux and Scott, 2005; Gayton, 2008).

Although our prediction method has some benefits, it also has some inherent limitations. Some researchers argue that regression tree based methods are too responsive to slight changes in climate (Guisan and Thuiller, 2005; Iverson and Prasad, 1998) and these types of climate lead predictions are over simplified and do not incorporate sufficient ecological processes into the prediction (Hampe, 2004). Pearson and Dawson argue that the climate determined models are validated by comparing simulated and actual species distributions and it is accepted that for macro (regional to global) studies a climate deterministic approach would account for biodiversity indicator shifts (Hampe, 2004; Hamann and Wang, 2006; McKenney et al., 2007). Climate determined regression trees have been used by many researchers (Franklin, 1995; Iverson and Prasad, 1998; Thuiller, 2003; Harrison et al., 2006) to determine biodiversity shifts at the regional to global scale. The purpose of our research is to forecast spatial shifts to biodiversity indicators due to climate change and does not incorporate species specific ecological principles such as adaptation, migration, and extirpation. Interpretation of our results should therefore show only broad ecosystem shifts to highlight possible directionality of future changes spatially.

Minimum cover, seasonality, and greenness are forecasted to change. Minimum cover increases can result in more year round productive forested habitats, greater biomass, and available food and habitat complexity (Jorgensen and Nohr, 1996). These changes may benefit some species (generalist species) and be a detriment to others (specialized species). Some examples of threatened specialized species where great habitat changes are expected include the Burrowing Owl (*Athene cunicularia*), Indra Swallowtail (*Papilio indra*), Three Lobed Daisy (*Erigeron trifidus*), Carolina Draba

(*Draba reptans*), and Lyall's Mariposa Lily (*Calochortus lyallii*), and Poor Pocket Moss (*Fissidens pauperculus*) (Species at Risk British Columbia, 2012).

Specialist species in high elevation environments are also at higher risk. Given the anticipated changes to seasonality it is likely that high elevation edge environments may continue to shift to higher elevations (Hebda, 1998). More productive habitats (as observed by minimum cover and cumulative greenness increases) can move into the former seasonal habitats and are projected to move up mountain sides especially along the Coast Mountains, Taiga, and Kootenay regions. Consequences of climatic shifts may likely include generalist ecosystems such as pine and spruce forests, interior Douglas fir, and coastal western hemlock moving into the newly favorable environments. Increased pressure is anticipated on specialist ecosystems like mountain hemlock, heather alpine, and other alpine meadow environments (Brink, 1959). Forest ecosystems are projected to become more productive and climate change may act as a vector for species migration (Davis et al., 1998).

2.6 Conclusion

The results of our forecasting efforts provide a promising method to produce high spatial resolution information of possible future shifts to biodiversity indicators which can be used to supplement direct sampling methods. The benefits of our methods are that they do not require direct sampling and therefore is an efficient and inexpensive method to monitor biodiversity. Using indirect indicators of biodiversity sourced from enhanced remote sensing approaches to produce the DHI has provided an improved ecological landscape understanding at a broad spatial resolution. Utilizing climate information at 1 x 1km spatial resolution in forecasting allowed for mapping of spatial variation in shifts of

biodiversity components due to climate change. Our methods can be repeated, enhanced, and updated regularly to give up to date information about the impacts to the terrestrial environment with complete and uniform coverage for large regions. Forecasting indirect indicators of biodiversity compliments past efforts in biodiversity monitoring.

Understanding the nature of possible spatial shifts to biodiversity indicators are important for effectively planning for the future of protected areas, aid conservation strategies, and properly manage natural resources. Our results provide detailed spatial information indicating the impact of climate change on broad ecological indicators. These indicators can be used to infer phenological shifts, species survivability, migration, adaptation, and extirpation. By understanding climate change impacts decision makers can be better informed to properly adapt and mitigate these impacts. Our methods have highlighted expected changes to the Coast Mountain forests, impacts on high elevation environments, and overall greening trends which can have major consequences for making informed long term planning decisions regarding forest resources, habitat conditions, and overall ecosystem dynamics in British Columbia.

Acknowledgements

Our research, was supported by the British Columbia Innovation Council (BCIC) and was undertaken as an extension of the “BioSpace: Biodiversity monitoring with Earth Observation data” project jointly funded by the Canadian Space Agency (CSA) Government Related Initiatives Program (GRIP), Canadian Forest Service (CFS) Pacific Forestry Centre (PFC), and the University of British Columbia (UBC). Technical support was also provided by the Pacific Climate Impacts Consortium (PCIC).

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Table 1 - Regression tree explanatory variables

Explanatory Variable	Details	Reference
Mean annual temperature	Average annual temperature (°C)	(Running and Nemani, 1988; Slayback et al., 2003; Hamann and Wang, 2006; Latta et al., 2009)
Temperature difference	Temperature difference between mean coldest and mean warmest months (°C).	(Algar et al., 2009; Coops et al., 2009)
Growing degree days	Growing degree days greater than 5°C	(Running and Nemani, 1988; Pearson, 2002; Algar et al., 2009)
Number of frost free days	Total number of frost free days (greater than 0 °C)	(Nigh et al., 2004; Hamann and Wang, 2006)
Mean coldest month temperature	Average temperature of the coldest month (°C)	(Running and Nemani, 1988; Pearson, 2002; Algar et al., 2009)
Julian date on which frost free period begins	Spring up date on which frost free period begins (temperatures greater than 0°C)	(Monserud et al., 2006)
Climate moisture deficit	Hargreaves climate moisture deficit; precipitation and temperature metric	(Carey, 1996; Hamann and Wang, 2006; Latta et al., 2009)
Evapotranspiration	Hargreaves reference evapotranspiration; precipitation and temperature metric	(Currie, 1991; Narongrit, 2003; Hamann and Wang, 2006)
Mean summer precipitation	Mean annual summer (May to September precipitation (mm)	(Notaro et al., 2006; Hamann and Wang, 2006)
Precipitation as snow	Average annual snowfall (mm)	(Running and Nemani, 1988; Pettoirelli et al., 2005; Notaro et al., 2006; Potter et al., 2007)
Mean annual precipitation	Average annual precipitation (mm)	(Running and Nemani, 1988; Slayback et al., 2003; Potter et al., 2007; Latta et al., 2009)
Elevation	Landscape topography (m)	(Hamann and Wang, 2006; Daly et al., 2008; Latta et al., 2009)

Table 2 - Regression tree dominant splits, complexity parameters, and coefficient of determination.

Region	Cumulative Greenness		Coefficient of Variation		Minimum Cover	
Pacific Maritime	Number of frost free days, growing degree days, mean annual temperature	0.668	Mean annual temperature and growing degree days	0.671	Number of frost free days, growing degree days, and precipitation as snow	0.514
Okaganan Caribou	Elevation, evapotranspiration	0.478	Precipitation as snow, evapotranspiration	0.680	Precipitation as snow, number of frost free days, date on which frost free period begins	0.509
Kootenay	Elevation, number of frost free days	0.616	Elevation and evapotranspiration	0.508	Elevation and evapotranspiration	0.487
Mountain Cordillera	Growing degree days, evapotranspiration, elevation	0.435	Growing degree days, precipitation as snow, and mean annual precipitation	0.453	Climate moisture deficit, precipitation as snow, and mean annual temperature	0.360
Boreal Plain	Seasonal temperature difference, Julian date on which frost free period begins	0.214	Precipitation as snow, Julian date on which frost free period begins	0.283	Precipitation as snow, julian date on which frost free period begins	0.413
Taiga Plain	Precipitation as snow, evapotranspiration	0.419	Precipitation as snow, mean summer precipitation	0.244	Precipitation as snow, evapotranspiration	0.063
Province	Number of frost free days, evapotranspiration, and precipitation as snow	0.459	Growing degree days and precipitation as snow	0.483	Growing degree days, precipitation as snow, and number of frost free days	0.411
Coefficient of Determination (R²)	0.92		0.89		0.72	

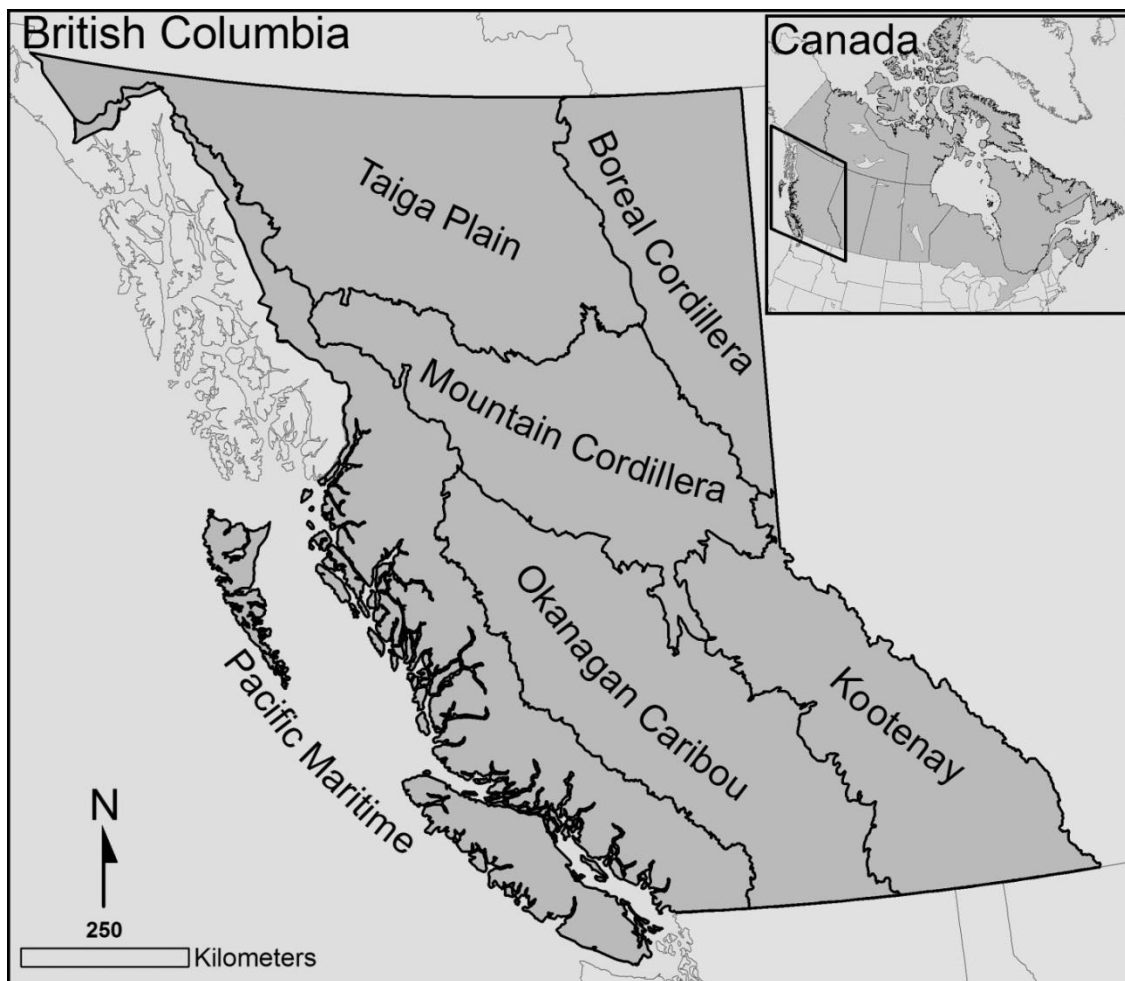


Figure 1 - Study area: British Columbia, Canada and the regional analysis borders.

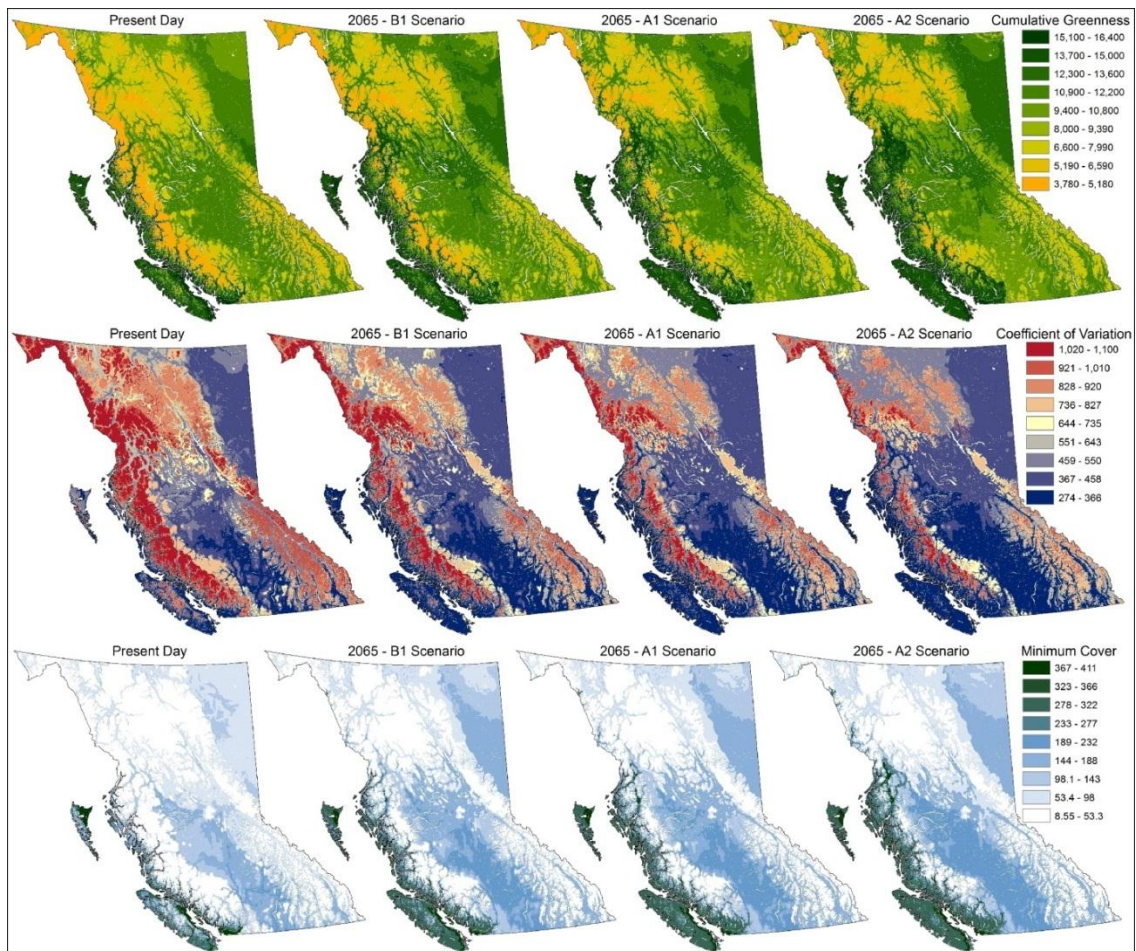


Figure 2 - DHI biodiversity indicator results: present day and 2065 B1, A1, and A2 scenarios.

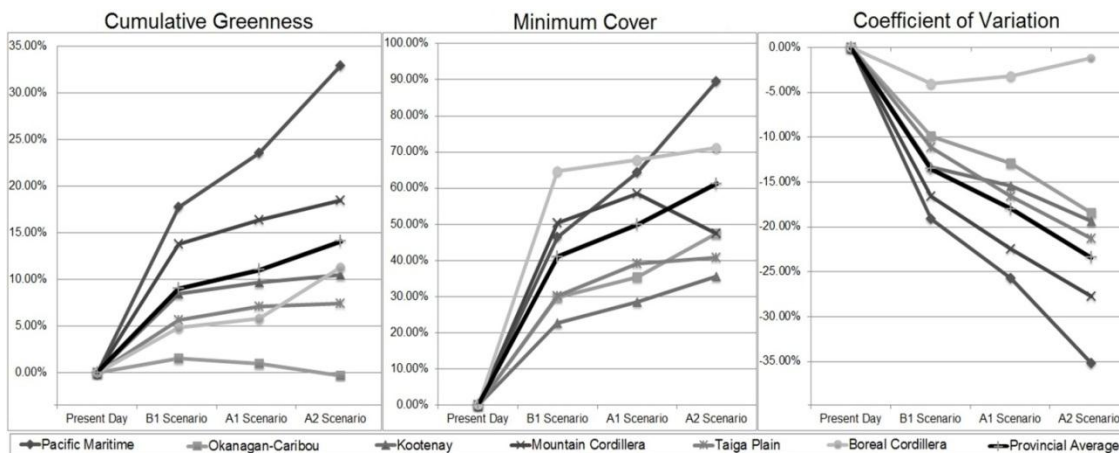


Figure 3 - Regional and provincial percent change in dynamic habitat indicators cumulative greenness, minimum cover, and coefficient of variation from present day to B1, A1, and A2 scenarios.

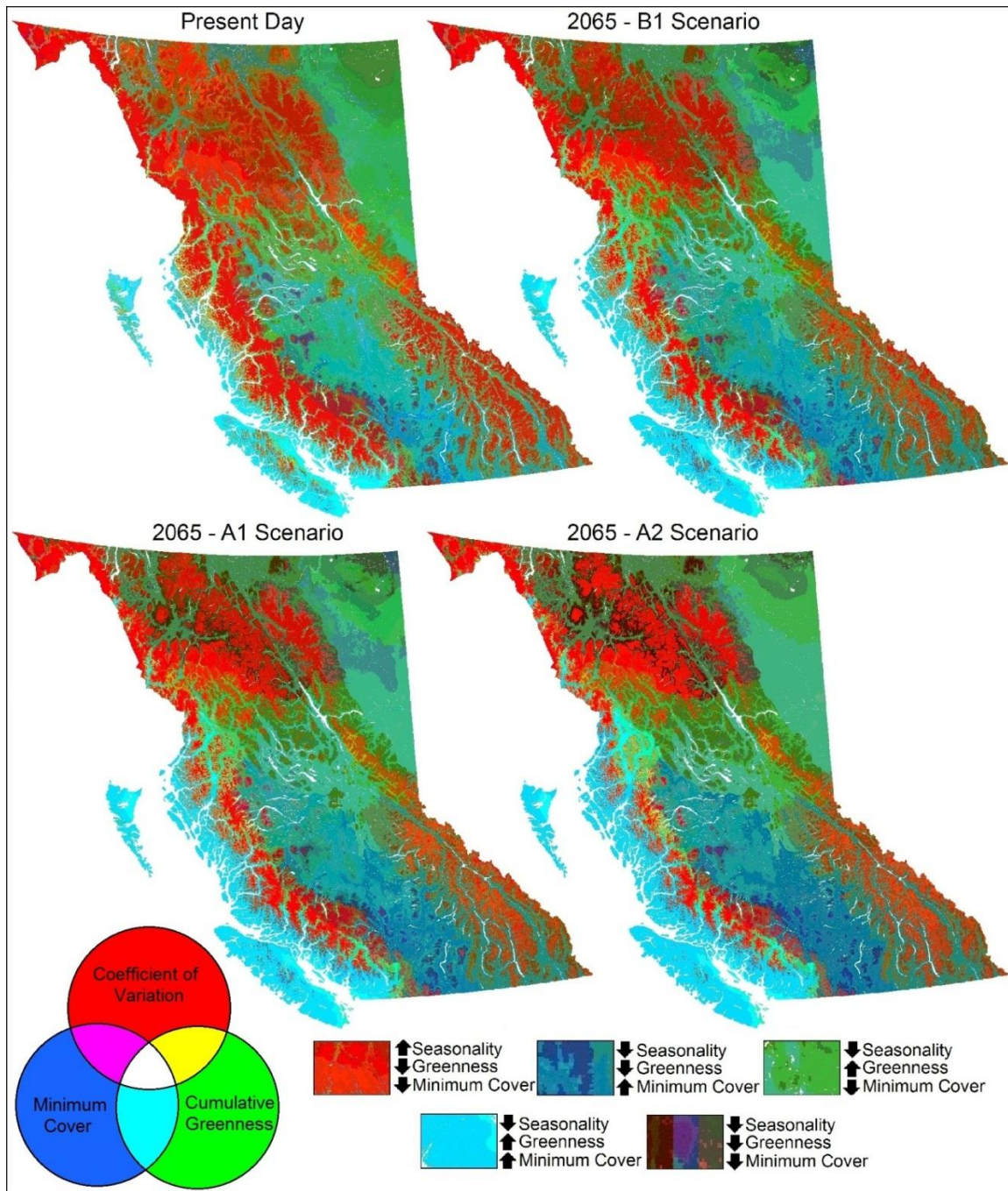


Figure 4 - Composite DHI model results.

Simultaneous display of the spatial distributions of the habitat metrics uses a color gun technique where the red, green, and blue color bands each represent a different DHI component; consequently coefficient of variation is represented by red, cumulative greenness is characterized by green, and minimum cover, blue. The resulting image is a display of all three habitat indicators to be observed at once resulting in a comprehensive view of the spatial shifts occurring to the habitat. Dark colored regions have little of all three DHI while light colored areas have high predicted levels of DHI. Furthermore,

areas of definitive color with little mixing detail the dominant habitat indicator; for example a region that is purely red denotes a highly variable habitat (high coefficient of variation). As indicators shift over time such as when seasonality decreases, other components such as greenness or minimum cover develop to fill into newly favorable habitats. Common DHI blending occurred with light blue, yellow, and darker colorations like purple or dark orange. The light blue regions represent the most productive habitats with high minimum cover, high greenness, and low seasonality; found in coastal and low elevation habitats. Darker purple and orange colorations indicate low productivity, low seasonality, and low minimum cover. Present day through to scenarios B1, A1, and A2 indicate the greening of the province and decreases in seasonality. Observations of the composite DHI allow for more site specific analysis of change. Examples of typical climate driven reactions are shown in sites along the Coast Mountains and central interior where seasonality decreases and greenness increases. Whereas sites alongside mountains in the northern Taiga region display opposing reactions to decreasing seasonality; these sites display decreases in all DHI through the future scenarios.

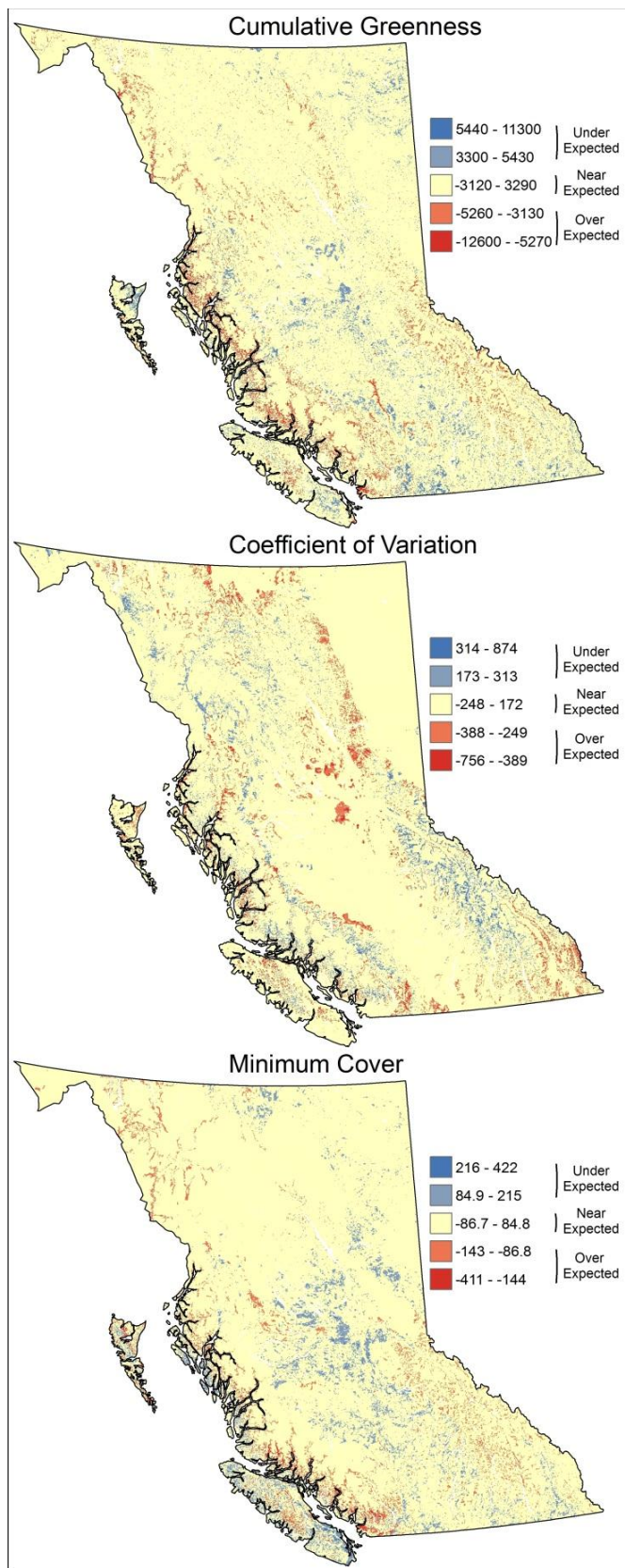


Figure 5 - Model confidence comparing average remote sensing data with modeled data.

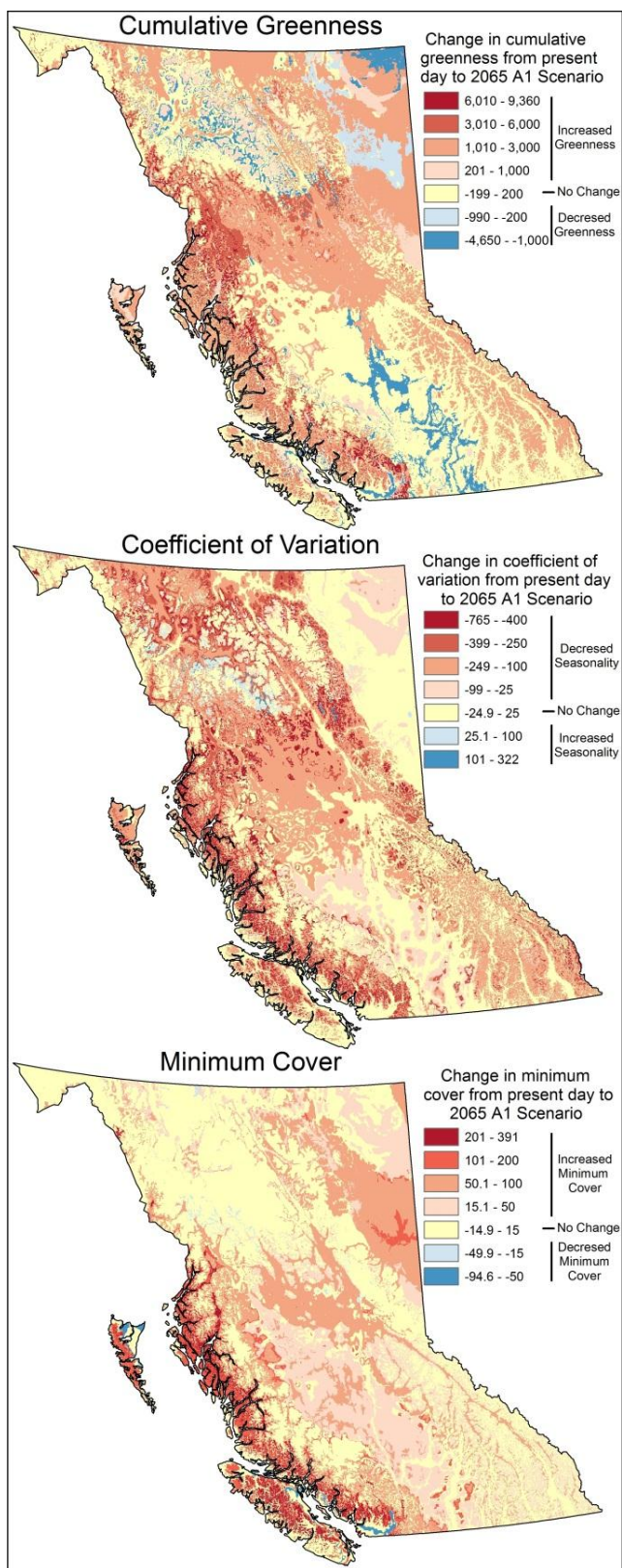


Figure 6 - Change analysis for greenness, seasonality, and minimum cover from present day to 2065 using the A1 scenario.

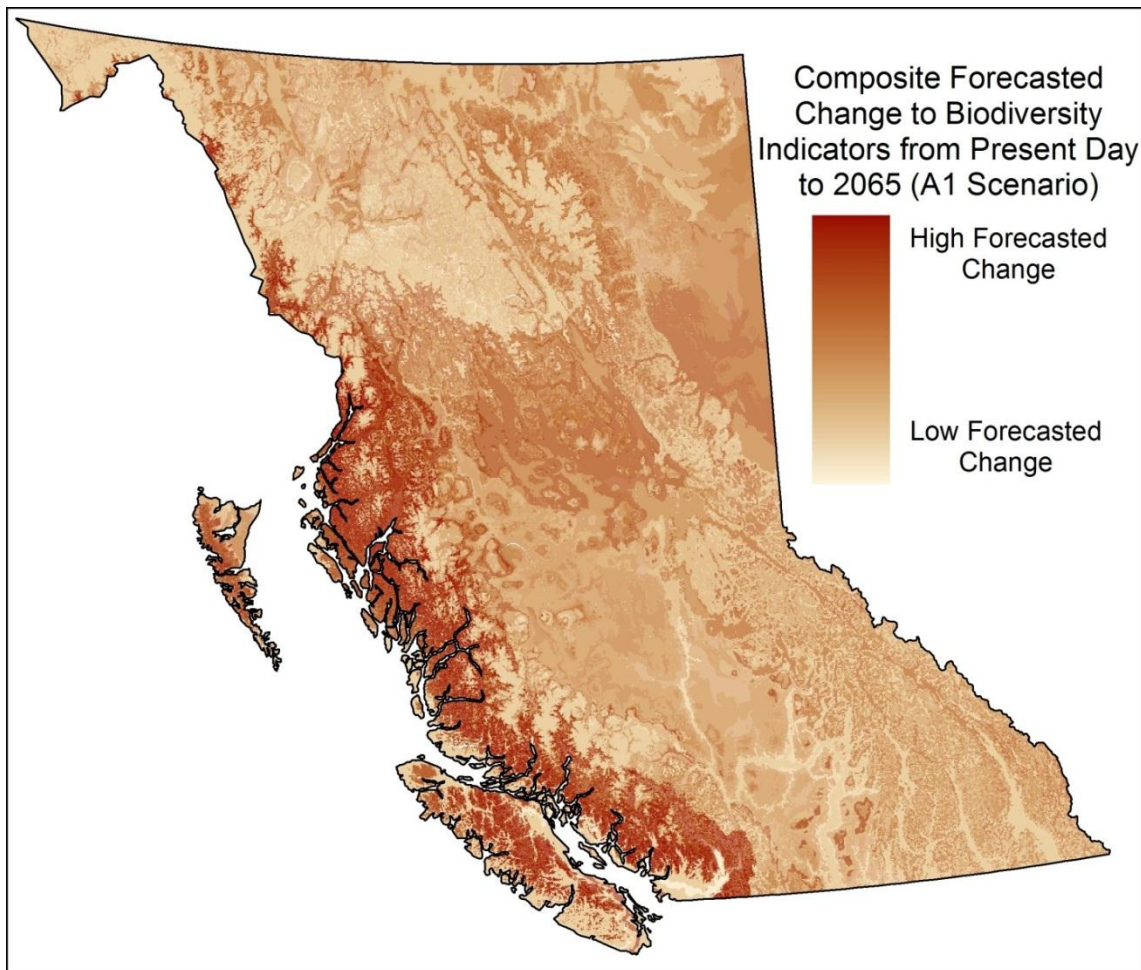


Figure 7 - Composite DHI change map comparing present day to the A1 scenario.

3.0 BIODIVERSITY INDICATORS SHOW CLIMATE CHANGE WILL ALTER VEGETATION CONDITIONS IN PARKS AND PROTECTED AREAS

3.1 Abstract

Parks and protected areas help represent and preserve biological diversity. Parks are typically developed in consideration of current biodiversity conditions, not on how these conditions may be altered by climate change. Climate change is having an impact upon biodiversity both directly (such as through changes in disturbance regimes) and indirectly (such as changes in vegetation growth rates and recovery) and there is a need to assess expected changes in protected areas and how representative protected areas will be of environmental conditions in the future. To assess changes in biodiversity, broad ecosystem information can be sourced from indirect remotely sensed indicators. Quantifying biodiversity through indirect indicators allows us to characterize inter-relationships between climate and biodiversity and assess possible implications of climatic change, as the indicators can be modelled based upon future scenarios of spatially explicit climatic conditions. Our goal in this paper is to quantify expected impacts of climate change to British Columbia's parks and protected areas by assessing changes in remotely sensed indicators of biodiversity, which are predicated by relating the measured amount of incoming solar energy used by vegetation with metrics mapping the overall annual energy utilization, variability (seasonality), and latent or baseline energy. To do so we compare current conditions represented by parks and protected areas, to those expected in the year 2065. Findings show protected areas are likely to

become more productive and less seasonal as a result of changes in climate. Future gaps in the vegetation conditions protected by parks are observed in the eastern edge of the Rocky Mountains and the central interior region of British Columbia, which exhibit higher vegetation greenness and moderate seasonality. Protected areas along the Coast Mountains, Vancouver Island highlands, and the Rocky Mountains show the greatest amount of change in the biodiversity indicators, including decreasing seasonality, with the Mountain Hemlock ecozone most at risk. Our methodology informs long-term conservation planning by highlighting protected areas and ecosystems expecting the greatest changes in vegetation conditions and identifying possible gaps in vegetation conditions protected.

3.2 Introduction

Parks and protected areas networks play a key role in conserving biological diversity. Many international and national conservation targets call for 10-12% protection of every ecosystem or habitat type (Barton, 1992). The contentious conservation targets are criticized for their over-simplified and arbitrary values placed on biological elements yet applauded for their effectiveness in achieving a greater global protected areas network. In order for protection to be effective, all habitat types must have representation, resiliency, and redundancy within a protected area network (Svancara et al., 2005). While the allocation of land for conservation is often opportunistic (Andrew et al., 2011) conservation networks should be designed to consider the spatial distribution of biodiversity, ecosystem threats (Pressey et al., 2007), habitat configuration, environmental representation and species at risk (Kerr and Deguise, 2004).

An assumption of protected area planning is that parks offer long term environmental conservation. However, planning does not typically account for anticipated landscape and ecological change that may occur over time (Lemieux and Scott, 2005; Hannah et al., 2007). Parks planning would benefit from a more adaptive planning process that considers change and future spatial distributions of species and biodiversity (Visser, 2008). Planning for future conditions is especially important given climate change which has been shown to potentially cause rapid shifts to species' geographic range, diversity, and abundance (Berry et al., 2002; Midgley, 2003; Harrison et al., 2006). Previous research has predicted that 37-48% of Canada's protected areas could experience a conversion in ecological classification type due to climate change

(Lemieux and Scott, 2005). Climate change threatens global ecosystem functions and protected areas are rapidly losing their intended purpose of preserving natural conditions, indicating a need for prioritization of appropriate policy and /or management response (Halpin, 1997). Many conservation strategies stress the importance of considering climate change impacts to identify areas of concern and ensure effective long-term management of biodiversity (UNEP, 2004; Lemieux and Scott, 2005; Environment Canada, 2006; “Canadian Biodiversity Strategy,” 2010). Information to support the prioritization, revision, or expansion of protected areas most expected to be impacted by climate change is required to inform proactive planning and management.

Climate change has been identified as a threat to the preservation of biological diversity where it is altering environmental conditions at a rate at which species cannot effectively adapt or migrate (Iverson and Prasad, 1998; Fussel, 2007). Considering climate is the main driving and limiting force determining productivity, climate is a key determinant in the amount of species richness and abundance a terrestrial habitat can sustain (Hannah et al., 2002; Hawkins et al., 2003; Midgley, 2003; Araújo and Rahbek, 2006). Species and ecosystem responses to climate change are diverse and complex. Species-specific tolerances and abilities or tendencies for adaptation and migration caused by climatic alterations results in different potential impacts to geographic ranges (Willis et al., 2009). The aim of equally representing all habitat conditions within parks will become increasingly difficult considering ecosystems are unstable and fluctuate with climate (Lemieux and Scott, 2005). Flexible, broad scope monitoring techniques such as remote sensing provide quantitative information for mapping large area ecosystem

dynamics that are difficult to measure and as a result are often assessed indirectly (Nagendra, 2001; Turner et al., 2003).

Over the long term, preserving the full range of biodiversity requires insight on possible shifts in broad scale biodiversity in order to ensure the continued effectiveness of protected areas. Climate models do not portray the complexity of stressed ecosystems. Ecosystem modelling requires a link between climate and biodiversity indicators. Utilizing broad scale indirect biodiversity indicators shows promise in detecting future conditions of sensitive ecosystems and parks ecosystem representation (Hawkins et al., 2003). Extracting information about ecosystem changes and protected areas will allow for an improved assessment of the possible impacts that climate change may have on endangered species, as well as fragile or rare habitats (Shilling, 1997; Algar et al., 2009).

Climate, productivity, and biodiversity have been shown to be related at a broad scale via indirect indicators of biodiversity available from earth observation imagery (Running and Hunt, 1993; Waide et al., 1999; Hawkins et al., 2003; Latta et al., 2009). Satellite based measures of vegetation productivity are examples of indirect indicators of biodiversity. These measures of productivity have been correlated with plant canopy cover (Fitterer et al., 2012) and overall productivity (Nagendra, 2001) in historical (Slayback et al., 2003; Xiao and Moody, 2005; Fontana et al., 2012) and current contexts (Puimalainen et al., 2003; Waser et al., 2004). This relationship between productivity indicators and biodiversity has also been used to assess future spatial distributions of biodiversity (Running and Nemani, 1988; Latta et al., 2009). Remote sensing offers an approach for mapping indirect indicators of biodiversity with complete spatial coverage and is ideal for large complex environments (Buchanan et al., 2009).

Time series of remotely sensed productivity components have been linked with climate data and applied to forecast future indicators of biodiversity (Running and Nemani, 1988; Kawabata et al., 2001; Nemani et al., 2003; Herrmann et al., 2005; Zhang et al., 2007). For example, Latta et al., (2009) predicted future productivity in Washington and Oregon by linking climate data to metrics of Fractional Photosynthetically Active Radiation (FPAR) (a measure for the amount of energy absorbed by the plant canopy). Other studies have used remote sensing productivity indicators to predict climate alterations to ecosystem dynamics such as Churkina and Running, (2000) and Hall et al., (2006). The findings from these studies showed that climate change increases forest productivity and hence will impact biological diversity (Waide et al., 1999).

Our goal in this paper is to examine expected alterations to vegetation conditions in protected areas due to climate change in the province of British Columbia, Canada. By forecasting changes in vegetation conditions within protected areas we can better inform strategies for long-term preservation of biodiversity. To meet our research goal, forecasted changes in biodiversity metrics are quantified to 1) characterize how the frequency of biodiversity indicators in parks and protected areas will change in order to identify possible future gaps in the types of vegetation conditions protected by parks; 2) evaluate expected changes to biodiversity indicators by biogeoclimatic zones in order to identify broad species assemblages and ecosystem types that are most threatened by climate change; 3) rank protected areas by mean level of expected change as a mechanism for identifying parks likely to experience the most change. The research modelling of future indirect indicators of biodiversity based on climate change scenarios

and remotely sensed indicators that were developed by (Holmes, 2012). Future shifts in conditions represented within protected areas are identified by comparing present and future models of indirect biodiversity indicators.

3.2.1 Study Area

British Columbia is positioned in the Pacific Northwest of North America from 49° 00' N to 60° 00' N and spans 944,735 km². Diverse landscapes of temperate rainforest, desert, and tundra exist because of the province's large size, topography, and position within the Pacific Maritime and Rocky Mountain continental climates (Austin et al., 2008). The extensive protected areas network in British Columbia covers 13.7% of the province and contributes to conserve habitats and species from a rapidly changing environment (Ministry of Environment, 2012). Urban and agriculture centers are concentrated in the south of the province juxtaposed with the most biologically rich landscapes (Kerr and Cihlar, 2004). The rural areas of British Columbia are relatively untouched with most disturbances traced to forest resource extraction, mountain pine beetle, droughts, and forest fires (Mote et al., 2003; Coops et al., 2008).

3.3 Data

3.3.1 The Dynamic Habitat Index

Our research uses the Dynamic Habitat Index (DHI) for biodiversity mapping. The DHI is an indirect indicator of biodiversity derived from remotely sensed imagery and is based on annual trends in FPAR. FPAR is a measure of the amount of photosynthetically active energy absorbed by the plant canopy (400nm-700nm) (Coops et al., 2008). FPAR has been shown to represent annual ecosystem dynamics and is

associated with vegetation dynamics, snow cover, butterflies, and avian species richness (Coops et al., 2009; Andrew et al., 2012). Using high temporal resolution sensors, such as AVHRR and MODIS, FPAR can be mapped twice daily and can be used to map intra-annual productivity conditions (Pettorelli et al., 2005). The DHI is a combination of three annual FPAR metrics cumulative greenness (greenness), coefficient of variation (seasonality), and minimum cover.

Each element of the DHI has been linked to broad scale ecosystems characteristics that are indicators of biodiversity. High greenness values indicate landscapes of year-round productivity with stable and temperate climates. Higher greenness equates to more productive habitat (Liu et al., 1999; Berry et al., 2007) and greater species diversity (Huston, 1979; Tilman et al., 1996). Therefore, protected areas with expected increases in greenness may see an increase in species or existing species may become more dynamic. Examples of high greenness habitats include productive coniferous forests at lower elevations. Lower greenness, as observed in some dry interior habitats, may indicate that the environment will become less productive (Los et al., 2001; Coops et al., 2009). For instance, bunchgrass may become more prolific as forested (higher productivity) environments are being extirpated from the region.

High seasonality values indicate seasonal habitats that are often snow covered, high elevation habitats with vegetation growth detectable only in the warm months. Examples of high seasonality environments include high elevation alpine habitats and deciduous forests with ample winter snowfall. Decreasing seasonality indicates less variation in productivity between winter and summer growing seasons. Decreased seasonality is a key factor for species succession and movement in especially high

elevation environments because it can limit nutrient cycles and biomass accumulation and therefore restrict species movement up elevation gradients (Shaver et al., 1986).

High minimum cover indicates habitats of high productivity, densely vegetated and limited snow cover (Coops et al., 2008). An increase to minimum cover can result in the greater forecasted baseline year-round productivity levels and therefore equates to more year round sustainable food supplies and biomass (Coops et al., 2009). High minimum cover environments are often associated with riparian areas and productive coniferous forests throughout the coast and central interior regions of British Columbia.

Prior to this research, our team created a historical archive of DHI (Fontana et al., 2012), quantified relationships between historical DHI and climate data (Holmes, 2012), and integrated quantified relationships with climate change scenarios to map likely future spatial distributions of each DHI element (Holmes, 2012). Historical productivity metrics were generated using archival remote sensing information as processed by (Fontana et al., 2012). Annual (1km x 1km resolution) DHI data from 1987-2007 was linked, via regression trees, with 10 corresponding climate and landscape variables which includes mean annual temperature, mean annual precipitation, temperature difference, growing degree days, number of frost free days, mean coldest month temperature, Julian date on which frost free period begins, climate moisture deficit, evapotranspiration, and mean summer precipitation. Regression tree modeling offers the capacity to manage large datasets (Breiman et al., 1984) and has been successful at predicting ecological processes into the future as was observed in (Iverson and Prasad, 1998).

Observed climate-DHI relationships were projected to the future using climate scenarios to the year 2065. The modelling relationships identified from the recursive

partitioning (Rpart) regression trees were applied to three climate models from the Canadian Centre for Climate Modelling and Analysis (CCCma) derived from Climate WNA version 4.6. (Wang et al., 2010) to forecast future spatial distributions of DHI elements. The future climate models are projected to a thirty year average 2050-2080, hereafter referred to as 2065, and range from B1 (AR4 - R1) represents the least extreme scenario, A1 (AR4 – R1) represents the business as usual scenario, and A2 (AR4 – R4) represents the most extreme scenario. To simplify the comparison between present day and 2065 results the climate model A1 (CCCma A1 – AR4 – R1) was chosen because it was positioned in the middle of the projected precipitation and temperature ranges for mainstream climate models (Murdock and Burger, 2010).

3.3.2 Protected Area and Ecological Classification Data

In order to further analyze the changes to biodiversity indicators additional data were used to assess its influence on changing DHI conditions and biogeoclimatic zones. Protected area data are the basis for much of our analysis and are classified by the International Union for Conservation and Nature (IUCN) as categories I-VI which includes ecological reserves, conservancies, provincial and national parks. British Columbia has achieved 13.7% protection (Ministry of Environment, 2012) and 1008 parks are represented in our study. Parks data were sourced from the government of British Columbia data server last updated in July 2012 (GeoBC, 2012). Zones from BC's provincial Biogeoclimatic Ecosystem Classification (BEC) system (version 8) developed by the BC Ministry of Forests were used to provide more species specific information about protected areas and what species assemblages might be impacted the most. The BEC system categorizes ecosystems hierarchically according to vegetation, soil,

topography, and climate classifications to create homogenous units of similar physical and ecosystem characteristics (B.C. Ministry of Forests, 2009). At the broadest scale, 16 zones have been developed, which provide broad spatial species assemblage information in the province (B.C. Ministry of Forests, 2009).

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3.4 Methods

Current and future scenarios of DHI indicators were intersected with the parks and protected area network to evaluate the future effectiveness of biodiversity protection.

In order to categorize expected change in the DHI characteristics of parks through time, DHI values were classified into nine categories based on even breaks established in our previous work (Holmes, Keith et al., n.d.). The changing area (or number of pixels) in each DHI class, between the present and future (as represented by the modeled year 2065 conditions) DHI maps, indicates how well a current parks' characteristics are likely to be represented by parks in the future.

Gaps in protection are observed when DHI characteristics are currently well represented by protected areas, but not represented in the future. Gaps indicate vegetation conditions that may become minimally or no longer protected by the parks network as climate change impacts ecological processes. Gaps were identified in a multiple part process. First, the current and future DHI values of for protected areas were extracted from each DHI element (cumulative greenness, seasonality, and minimum cover). Second, to emphasize dominant DHI conditions, DHI value categories (nine were defined for each element using natural breaks) with less than 1000 Km² in area were excluded. Thirdly, by DHI element (cumulative greenness, seasonality, or minimum cover) DHI value categories were flagged and mapped if they were not represented by parks in the future. Fourth, within parks flagged locations for all three DHI elements where intersected to define gaps.

To quantify spatial variation in expected broad-scale habitat change, image differencing was used to measure regional change in indicators by BEC zones from present day to 2065. Greenness, seasonality, and minimum cover metrics were each subtracted by pixel to produce a forecasted change map. Change was summarized, as mean change, by BEC zone and ecozones ranked by mean change to identify ecosystems

at greatest risk of climate change. Mean change in each of the DHI indicators was calculated for each park and protected area. Park size was a factor in ranking change since smaller parks had lower sample sizes and could be entirely located within extreme high or extreme low change areas, therefore providing the most wide ranging results. To account for the influence of park size, parks were divided into three categories for ranking, large ($>1000\text{km}^2$), medium ($50\text{-}1000\text{km}^2$), and small ($<50\text{km}^2$) based on natural breaks. Parks were ranked by size and DHI category to highlight the most threatened parks and characterize the nature of expected change.

3.5 Results

Presently, some DHI value categories are more represented across the total province and within parks than others (Figure 1 a,b,c). For instance, generally, the mid-range greenness values are most common in the province (Figure 1a) yet parks tend to occur in locations with low minimum cover (Figure 1c). Forecasted change indicates that in the future the DHI value categories will be more evenly represented by parks as well as throughout the province (Figure 1a,b,c).

Currently greenness values in protected areas favour representation of lower values with minimal protection of the highest greenness values (Figure 1a). In 2065 the frequency distribution of greenness DHI values will likely shift to having higher greenness. The largest change in a class of DHI greenness values is in the lowest value class where a 53.8% drop in area is projected.

Presently, in protected areas high seasonality values are overrepresented, relative to provincial conditions (Figure 1b). Parks in 2065 are likely to be characterized by an increase in lower seasonality and a decrease in high seasonality representation. Evidence

for this change is that the lowest seasonality category increase 319.1.3% in area from present levels to the projected 2065 A1 scenario. High seasonality representation levels drop steadily with the highest value category dropping 39.3% in area.

In protected areas, present day minimum cover values emphasize low seasonality values (Figure 1c). In 2065, minimum cover in protected areas is projected to include more higher values and fewer lower values. Evidence of the change is shown by the major shifts in protected area representation occurring in the low level minimum greenness values changing to increasingly mid-level values. The lowest level minimum cover category is forecasted to decrease by 55.3% in area. The higher minimum cover categories have varied responses as was shown by the highest value category forecasted to decrease in area by 32.0% in protected areas using the A1 scenario.

For the gap analysis, flagged change in greenness occurred in mid-low values to mid-high values and had a total area of 36,327 Km². Locations with flagged greenness occurs along the eastern and central regions of the province and span from the far north to the far south. Locations flagged by seasonality gap analysis are more limited, when compared to greenness, with a mid-value range covering an area of 14,419Km². Locations flagged for change in seasonality geographically range from the Rocky Mountains to the central interior. Locations flagged for change in minimum cover were observed in mid to low level values with a limited range and amount to 20,542 Km². Locations of flagged change in minimum cover stretch the latitudinal length of the province and are situated from the eastern edge of the Coastal Mountains to the valleys of the Rocky Mountains.

When flagged locations of change in greenness, seasonality, and minimum cover were intersected to define DHI gaps, we located 5,105 km² in 81 protected areas that are likely to have substantial change in all three DHI variables (Figure 2). The protected areas associated with the gaps are located along the Rocky Mountains and Central Interior regions and predominantly occur in the Interior Cedar Hemlock, Sub-Boreal Spruce, and Montane Spruce biogeoclimatic zones. Protected areas with the greatest total area of DHI gaps highlight large parks with diminished biodiversity indicator representation. Protected areas with the highest percentage of gap coverage emphasize smaller protected areas that have diminished biodiversity indicator representation. The following protected areas are projected to have the largest total areas of gaps: Wells Gray Provincial Park, Omineca Provincial Park, Carp Lake Provincial Park, and Bowron Lake Provincial Park. Calculating through percentage of gap coverage, many of the smaller parks are highlighted. Protected areas such as Babine Lake Provincial Park and Blackwater Creek Ecological Reserve located in the central interior show that the unique DHI characteristics may not be well represented in the future.

Expected change in ecosystem biodiversity is represented by ranked mean change in ecozones and associated dominant species assemblages (Table 1). The Mountain Hemlock ecozone has 332.0% more change in greenness than the provincial average, followed by Coastal Western Hemlock ecozone (213.2% above average). Interior Douglas Fir was observed to have a decrease in mean greenness of 141.7%, Ponderosa Pine decreasing 110.4%, and Bunchgrass decreasing 148.2%; whereas they did not change considerably in seasonality or minimum cover metrics. BEC zones with the least

amount of change were observed in geographically restricted zones or areas of limited area like the Coastal Douglas Fir, Bunchgrass, and Ponderosa Pine.

The ten top ranking large, medium, and small parks, according to mean level of forecasted change to their greenness, seasonality, and minimum cover, are shown in Figures 3, 4, and 5. Impacts for individual parks are spatially variable with some having consistently high change rankings for all three indirect biodiversity indicators. Protected areas along the Coast Mountains are consistently ranked among the highest changing followed by regions such as the Rocky Mountains and the northern central interior. Protected areas with the least amount of forecasted change are located on low lying coastal zones and leeward interior parks.

Most of the thirty two large protected areas ($>1000\text{Km}^2$) are situated along the Coast Mountains, Rocky Mountains, and northern regions. Examples of large parks with a lot of change include Strathcona, Garibaldi, and Kitlope protected areas and all are forecasted to have above average change, with decreases in seasonality and increases in greenness and minimum cover. Other large parks are impacted by only one indicator, such as the Stitkine River provincial park which is forecasted to have a large decrease in seasonality while attaining low to average levels of change in greenness and minimum cover. Strathcona Provincial Park is as expected to experience a lot of change, with mean greenness changing 173.1% greater than the provincial average, seasonality 242.7% above average levels, and minimum cover change 498.3% above average levels.

High changing medium parks ($50\text{-}1000\text{km}^2$) vary greatly in their rankings between DHI categories, but remain consistently located along the western mountainous region of British Columbia. Among the greatest consistently changing protected areas is

Tetrahedron Provincial Park, Fiordland Conservancy, and Ecstall-Spoksuit Conservancy, all located along the Coast Mountains. For example, Tetrahedron Provincial Park by comparison to mean medium size parks is forecasted to have greenness change 230.4% above average, seasonality change 301.2% above average, and minimum cover change 405.4% above average. In the south central interior, some parks have negative forecasted values. One example is the medium park Kalamalka Lake protected area which is forecasted to have a decrease in greenness of 158.5% below the mean for small parks which is indicative of the complex interrelationships observed in the dryer interior environments.

Like medium parks, small parks (<50km²) with considerable projected change are located in the Coastal Mountains of British Columbia. The rankings for high changing small parks are less consistent between DHI categories resulting in a wide variety of protected areas identified as high risk. Small parks attain the most extreme mean values in changes due to their small extent located entirely in expected high or low change regions. Examples of high changing small parks are Mount Elliot Ecological Reserve, Tsitika Mountain Ecological Reserve, and Williams Creek Ecological Reserve. Small protected areas such as Mount Elliot Ecological Reserve (3.3 km²) on Northern Vancouver Island has a predicted change in the seasonality value decrease of 734.8% above average, greenness value increase of 869.3% above average, and minimum cover value increase 490.3% above small park average. Strategic protected areas such as the Milligan Hills Provincial Park located in the North East Boreal region protects woodland caribou habitat. Milligan Hills has a projected decrease in greenness metric of 47.5%

below the provincial mean for medium parks and an increase in minimum cover of 141.2% above average indicating possible alterations to food supplies.

3.6 Discussion

Our research compliments many international, national, and provincial climate action goals by providing a bio-climate impact assessment for conservation decision makers. For example, the Canadian biodiversity strategy states the need for increased long term comprehensive monitoring of ecosystem changes caused by climate change (“Canadian Biodiversity Strategy,” 2010). British Columbia’s climate change adaptation strategy states its three goals to achieve a more climate resilient province are to build a foundation of knowledge and tools, ensure adaptation is considered in decision making, and assess the risks and prioritize actions for sensitive sectors (Ministry of Environment, 2010). Conservation strategies revolve around maintaining species populations, completing the protected areas network, restoring species and threatened ecosystems, and reducing threats to biodiversity.

How parks represent ecosystems will be altered by climate change (Lemieux and Scott, 2005). The amount, and in some locations, magnitude of areas forecasted to change is considerable. For example, East Redonda Ecological Reserve and Tetrahedron Provincial Park are two similarly sized parks in the south coast with distinct projected changes in DHI conditions. Projected increases in average minimum cover, seasonality and greenness are greater in Tetrahedron Provincial Park than in the East Redonda Ecological Reserve, respectively, 194%, 265% and 1008%. Although these two protected areas are similar the main difference is that Tetrahedron is at a higher elevation that is more susceptible to climate altered biodiversity indicator conditions.

Trends indicate the current parks and protected areas network will favour protection of highly seasonal and lower greenness landscapes. Increased levels of protection were most prevalent in low greenness value areas, associated with barren or high elevation landscapes. Also greenness increased substantially in the highest productivity protected areas such as the mountainous coastal region (e.g., Kitlope Conservancy's mean increase in greenness metric of 336.5% above large area protected area mean) indicating that biomass and productivity may be enhanced (Coops et al., 2009). Provincially low greenness values are currently over-represented in protected areas and high greenness values are under-represented (Andrew et al., 2011); the forecasted shift has potential to create an increasingly balanced representation of greenness landscapes within protected area. However, rapidly shifting environmental conditions (i.e., DHI) may have many unknown consequences since individual species' resilience to change and degradation thresholds are difficult to assess (Food and Agriculture Organization, 2011).

Overall, protected areas in the future will enhance representation of lower seasonality habitats which can sustain greater biodiversity (Shaver et al., 1986). The protected area network is likely to shift to become more representative of provincial seasonality as climate change alters the nature and spatial distribution of seasonality. Protected areas will better represent less seasonal landscapes, such as those observed in the coastal forests. An extensive increase in the lowest seasonality value was observed to occur within 100 km of the coast and the highest seasonality values are forecasted to decrease in mountainous environments. Future representation of seasonality will have

gaps in some mid-value seasonality classes. Mid-level fluctuations in seasonality characteristics may produce gaps in protection.

Currently, protected area representation for present day minimum cover favours low values indicating a bias toward low vegetation or low biodiversity environments as reported by (Andrew et al., 2011). Across the province and in parks, minimum cover observed a unanimous shift to higher values with the most noteworthy increases in the lower value categories. The projected and mapped future changes indicate better representation for higher minimum cover environments such as dense forests and riparian areas that sustain year-round productive habitats. Future gaps in protection were found in locations with mid to low level minimum greenness values, which are found throughout most of interior (i.e., Tweedsmuir and Wells Grey Provincial Parks) and the DHI gap characteristics are associated with lower productivity forests. Although the greatest changes in DHI are observed along the Coast Mountains most of the gaps in protection are observed to be in the interior and Rocky Mountain regions.

In general, future DHI conditions in the province follow the same propensities as future protected areas. The province, similar to protected areas, observes future conditions of increased greenness and decreased seasonality metrics at roughly the same rates. Exceptions to this were found in mid-value greenness where provincial and protected area values diverge. The divergence may result from large forested regions, which in the future have higher greenness values that are not well represented in the protected area network (i.e., the central interior). Comparing future provincial and protected area seasonality values, exception were found in the low seasonality value categories that observe a greater rate of change in protected areas. The more extreme

reaction in protected areas is most likely due to the higher representation of protected areas in high seasonality landscapes. Minimum cover conditions in protected areas in the future remained the most consistent with provincial trends due to its ubiquitous increase throughout the province.

Gap analysis is commonly used for identifying under-represented biological characteristics in existing protected areas networks (Flather and Wilson, 1997). Locations with gaps in all three DHI metrics are likely to be most at risk to climate change. The Rocky Mountains and central interior have gaps quantified in all three DHI characteristics. Gaps had DHI characteristics of high greenness and mid-level minimum cover and seasonality, and were located in BEC zones: Interior Cedar Hemlock, Sub-Boreal Spruce, and Montane Spruce. Other gaps were observed at Wells Grey Provincial Park and appear to be located in the valleys dominated by Interior Cedar Hemlock forests up in elevation to the Engelmann Spruce and Subalpine Fir zones. The Wells Gray Provincial Park master plan states the need to preserve park values of wildlife and ecosystem health (Ministry of Lands Parks and Housing, 1986) and our results indicate this will require assessment of climate change impacts to wildlife and ecosystem health. The unique responses observed using indirect indicators of biodiversity may indicate vulnerable ecosystems that require better protection.

Much of the Coastal Mountains and Rocky Mountains are projected to experience the greatest changes to indirect biodiversity indicators with the most notable projected decreases to seasonality and increases to greenness in the province. Mid to high elevation landscapes are expected to be altered by increased primary productivity and decreased seasonality. Indirect DHI indicators point to possible fewer climate limiters, such as food

availability and harsher climates, resulting in shifting geographic distributions of species diversity and abundance throughout British Columbia. The general observed greening trends in future biodiversity indicator scenarios shows progressive increases in productivity. Indications of productivity increases may lead to increased food availability and biomass which could be understood as positive outcomes of climate change.

Although greenness of parks may increase over time it will not necessarily be positive for all species. For example, small southern parks which host the most endangered species (Kerr and Cihlar, 2004) are less able to adapt to changes to their habitats and a greening effect may have a negative impact on their survivability (Waide et al., 1999). Complex bio-climate relationships exist in leeward interior environments. Ecosystems such as the Boreal (North East Region) and Okanagan (South Central Region) are showing decreasing predicted greenness. Although the interior landscape did not rank amongst the greatest changing region, it did present complex combinations of negative greenness, decreased seasonality, and increased minimum cover which indicates dry forests associated with this unique DHI characteristic may shift northward.

Mountain Hemlock is ranked as the BEC zone forecasted to change the most by 2065 and Coastal Douglas Fir will change the least. Mountain Hemlock is common on the greatest impacted zones of the Coast Mountains between the 407-1428m elevation ranges and thinly located in the transition zone of Coastal Western Hemlock and higher alpine habitats. Mountainous temperate regions are found to be one of the most sensitive landscapes to climate change in the world resulting in rapid changes in ecosystem type (Halpin, 1997). High alpine forests and ecosystems like Mountain Hemlock and Englemann Spruce - Subalpine Fir are sensitive to slight changes in climate since their

distribution is predominately determined by climate and are pressed between competing highly competitive ecosystems (Brink, 1959; Klanderud, 2005). Protected areas closer to the coast are forecasted to have little change in biodiversity indicators; however, the Coastal Western Hemlock zone does border on the highest changing ecosystems and therefore the mean rated change ranks it as one of the highest changing ecosystems. Low elevation coastal zone parks change very little with only increases in minimum cover, while inland Coastal Hemlock zone parks change considerably. Interior BEC zones like Bunchgrass, Interior Douglas fir, and Ponderosa Pine were found to expand due to their forecasted decreases in greenness. Decreased greenness signifies that dryer ecosystems will dominate over wetter forests of the interior like Montane Spruce and Sub-Boreal Spruce. Grasses and dryer forests will therefore spread throughout much of the Southern Interior. Our findings are corroborated by BEC zone forecasting completed by Wang et al., (2012) where warmer and wetter future conditions will lead to species groupings to shift northward and up higher elevations. Wang et al., (2012) forecasts support our findings of stresses to Mountain Hemlock and expansion of dryer interior ecosystems.

Knowledge of possible future scenarios of indirect biodiversity indicators may benefit long-term conservation planning by detailing how DHI metrics and all its macroecological associations may change. For example a large park like Omineca Provincial Park (1359.5 Km²) is ranked as one of the protected areas expected to change the most. It is predicted to undergo large increases in greenness, minimum cover, and decreases to seasonality. Omineca Park is also an important calving location in the spring for the blue listed Northern Woodland Caribou. Caribou favour alpine and mid elevation environments in Omineca Park (Johnson et al., 2004) which are amongst the highest

changing biodiversity indicator types and our predictions show possible increased greenness, primary productivity, and biomass as well as increased minimum cover (year-round productivity) and decreased seasonality. All predicted DHI changes will have positive and negative impacts on individual species and the complex ecological processes cannot be fully understood, such as changes to predator prey relationships. Prioritizing conservation efforts and monitoring should be considered for locations with high ecological value (Freemark et al., 2006) that are also expected to experience high changing to biodiversity indicators.

The southern interior region has a number of parks that are projected to observe a decrease in greenness in the future. The South Okanagan Grasslands protected area for example has a projected decrease in greenness. Decreased greenness in the grasslands region equates to an expansion of dry grassland habitats and less favourable conditions for the megafauna species like the dry forests that have a higher greenness DHI characteristic. The grasslands protected area hosts 15 endangered species such as the red listed Lyall's Mariposa Lily (*Calochortuslyallii*) and the Flat-topped broomrape (*Orobanchecorymbosa ssp. Mutabilis*) (Ministry of Environment, 2003). Many of the endangered plants that thrive in grassland may benefit from expansion of their habitat due to diminished climate limiters that once restricted migration into new regions. Changes to climate may also impact species negatively, such as the bird species that require dry forests for their habitat. Decreased greenness indicates that the dry forests within the Grasslands Protected Area may decline causing red listed species such as the Brewer's Sparrow (*Spizellabreweribreweri*) and the Sage Thrasher (*Oreoscoptesmontanus*) to reduce in population as well. To protect these bird species in the future parks must either

expand into territories where habitats are projected to be more favourable or park conservation efforts should implement strategies to preserve species abundance and diversity within park boundaries.

Small protected areas ($>50\text{Km}^2$) are commonly designed to protect specific species or unique habitats and often protect the most threatened regions (Kerr and Deguise, 2004). The most extreme range in forecasted DHI results were found for small parks because their sample size is smaller and can be often enveloped by regions of strong change. Williams Creek Ecological Reserve (7Km^2) in the northwest of the province represents one of the highest forecasted increases in greenness. Seasonality and minimum cover will also have above average decreases and increases, respectively. The reason for Williams Creek expecting such extreme change in biodiversity metrics is because it is located along the Coast Mountains and is situated at an elevation gradient of 490-1,735m and has the highest changing ecosystems such as Mountain Hemlock and Coastal Mountain—heather Alpine (Ministry of Environment, 2002). Increased greenness will likely result in a push of dominant ecosystem species up elevation gradients. In other words all three dominant ecosystem's climate niches will shift to higher elevations allowing Coastal Hemlock and Sitka Spruce forest to overtake traditional Mountain Hemlock zones and Mountain Hemlock can advance into traditional Alpine environments.

Achieving equal representation of landscape conditions within parks can be difficult, especially for biologically rich environments because of conflicting interests such as resource extraction, urbanization, and agriculture practices (Kerr, 2012). Southern Vancouver Island, for example, has a unique Garry Oak ecosystem with the greatest high

priority species counts in British Columbia (Nature Conservancy, 2009), but protection of this ecosystem is limited by urbanization. Evaluation of present protection coverage shows capricious results with some biological characteristics lacking adequate protection. Biases exist especially in large reserves over 10,000 km², toward protection of more seasonal, higher elevation, lower biodiversity environments (Hamann et al., 2005; Andrew et al., 2011). Critiques of protected areas networks identify a bias toward low biodiversity regions that protect barren or glacial environments (Lemieux and Scott, 2005; Willis et al., 2009; Andrew et al., 2011) rather than southern forests and riparian habitats which host many more species at risk (Species at Risk British Columbia, 2012). Our results for present day reflect these biases and indicate how they could change to become more representative in a future climate. Changes in representation to higher greenness and lower seasonality may negatively impact individual species. Projected alterations to biodiversity indicators can be especially damaging to species vulnerable to change and species with specific habitat requirements (Visser, 2008).

Our method of assessing change to individual parks and ecosystems using remotely sensed biodiversity indicators (i.e., fPAR metrics) provides a broad understanding of the vectors of change. By using indirect indicators of biodiversity we avoid the problems and assumptions associated with species specific niche based modelling (Pearson and Dawson, 2003). It is unrealistic to represent complex ecological processes such as adaptation, tolerance, and migration (Austin, 2002; Heikkinen et al., 2006) over a broad scale. Indirect indicators of biodiversity provide a broad lens for identifying where and how biodiversity is likely to change and should be considered as a tool for strategic level planning and resource prioritization.

3.7 Conclusion

Our remote sensing based approach, modelling indirect indicators of biodiversity, provides spatial climate impact information offering insight into how macroecological processes may shift with future climate scenarios. We have identified protected areas and ecosystem assemblages that are most threatened by climate change. By ranking areas where biodiversity indicators change the most, such as Strathcona Provincial Park or the Mountain Hemlock ecozone, we can indicate what types of environmental changes can be expected. Coast Mountains, Vancouver Island, and southern regions are of particular importance because of their projected large change and the need to preserve the region's high concentrations of endangered species. Overall, trends in biodiversity indicator characteristics represented by protected areas may improve with projected increases in greenness and decreases in seasonality. Parks may preserve habitats with greater productivity and therefore greater carrying capacity which may also improve the biases currently observed in DHI frequency distributions. Although the projections indicate more representative protected areas in the future, these changes are particularly damaging to sensitive habitats and species due to their inability to adapt to changes in climate and ecosystem functions (Visser, 2008).

Projected future gaps in the representativeness of DHI conditions within parks have characteristics of high greenness and mid to low level seasonality and minimum cover which are located in the valleys of the Rocky Mountains and central interior. Planning new protected areas should be focussed around identified gap regions which are associated with Interior Cedar Hemlock and Sub-Boreal Spruce biogeoclimatic zones.

Understanding how and where an environment can change and what pressures may exist will better inform efforts to manage shifting biodiversity landscapes.

With repeated coverage and spatially continuous data, remote sensing based biodiversity indicators provides an excellent tool for characterizing broad macroecological changes to habitats with complete spatial coverage over large areas. Our findings indicate important information useful to management and policy support provided through knowledge for individual protected areas using a simplistic and transparent tool that represents our current and projected future representation conditions. Mapped DHI identifies specific locations of interest and can help decision makers effectively achieve international biodiversity conservation commitments.

Acknowledgments

Our research, was supported by the British Columbia Innovation Council (BCIC) and was undertaken as an extension of the “BioSpace: Biodiversity monitoring with Earth Observation data” project jointly funded by the Canadian Space Agency (CSA) Government Related Initiatives Program (GRIP), Canadian Forest Service (CFS) Pacific Forestry Centre (PFC), and the University of British Columbia (UBC).

Table 3 Ranking changes to the Dynamic Habitat Index within each biogeoclimatic

		Rank	Biogeoclimatic Zone	Mean Greenness Change
High Change Zone		1	Mountain Hemlock	3437.4
		2	Coastal Mountain-heather Alpine	2207.7
		3	Interior Mountain-heather Alpine	1781.0
		4	Coastal Western Hemlock	1712.7
		5	Engelmann Spruce - Subalpine Fir	1466.8
		6	Sub-Boreal Spruce	786.9
		7	Boreal White and Black Spruce	759.6
		8	Interior Cedar - Hemlock	676.3
		9	Boreal Altai Fescue Alpine	613.9
		10	Bunchgrass	-498.5
		11	Interior Douglas-fir	-431.6
		12	Spruce - Willow - Birch	407.3
		Low Change Zone		13
14	Ponderosa Pine			-107.4
15	Sub-Boreal Pine - Spruce			53.3
16	Coastal Douglas-fir			0.0
		Rank	Biogeoclimatic Zone	Mean Seasonality Change
High Change Zone		1	Mountain Hemlock	-257.4
		2	Coastal Western Hemlock	-192.4
		3	Spruce - Willow - Birch	-178.9
		4	Engelmann Spruce - Subalpine Fir	-165.4
		5	Coastal Mountain-heather Alpine	-134.1
		6	Interior Cedar - Hemlock	-106.5
		7	Sub-Boreal Spruce	-95.1
		8	Montane Spruce	-87.3
		9	Interior Mountain-heather Alpine	-63.1
		10	Boreal Altai Fescue Alpine	-61.5
		11	Boreal White and Black Spruce	-56.9
		12	Sub-Boreal Pine - Spruce	-48.4
		Low Change Zone		13
14	Ponderosa Pine			-0.3
15	Bunchgrass			-0.2
16	Coastal Douglas-fir			0.0
		Rank	Biogeoclimatic Zone	Mean Minimum Cover Change
High Change Zone		1	Mountain Hemlock	90.8
		2	Coastal Western Hemlock	87.8
		3	Sub-Boreal Pine - Spruce	57.4
		4	Sub-Boreal Spruce	53.9
		5	Coastal Douglas-fir	48.5
		6	Montane Spruce	41.3
		7	Interior Cedar - Hemlock	41.1
		8	Coastal Mountain-heather Alpine	41.0
		9	Boreal White and Black Spruce	40.8
		10	Interior Douglas-fir	39.4
		11	Engelmann Spruce - Subalpine Fir	16.7
		12	Spruce - Willow - Birch	14.7
		Low Change Zone		13
14	Interior Mountain-heather Alpine			7.4
15	Ponderosa Pine			4.3
16	Boreal Altai Fescue Alpine			4.1

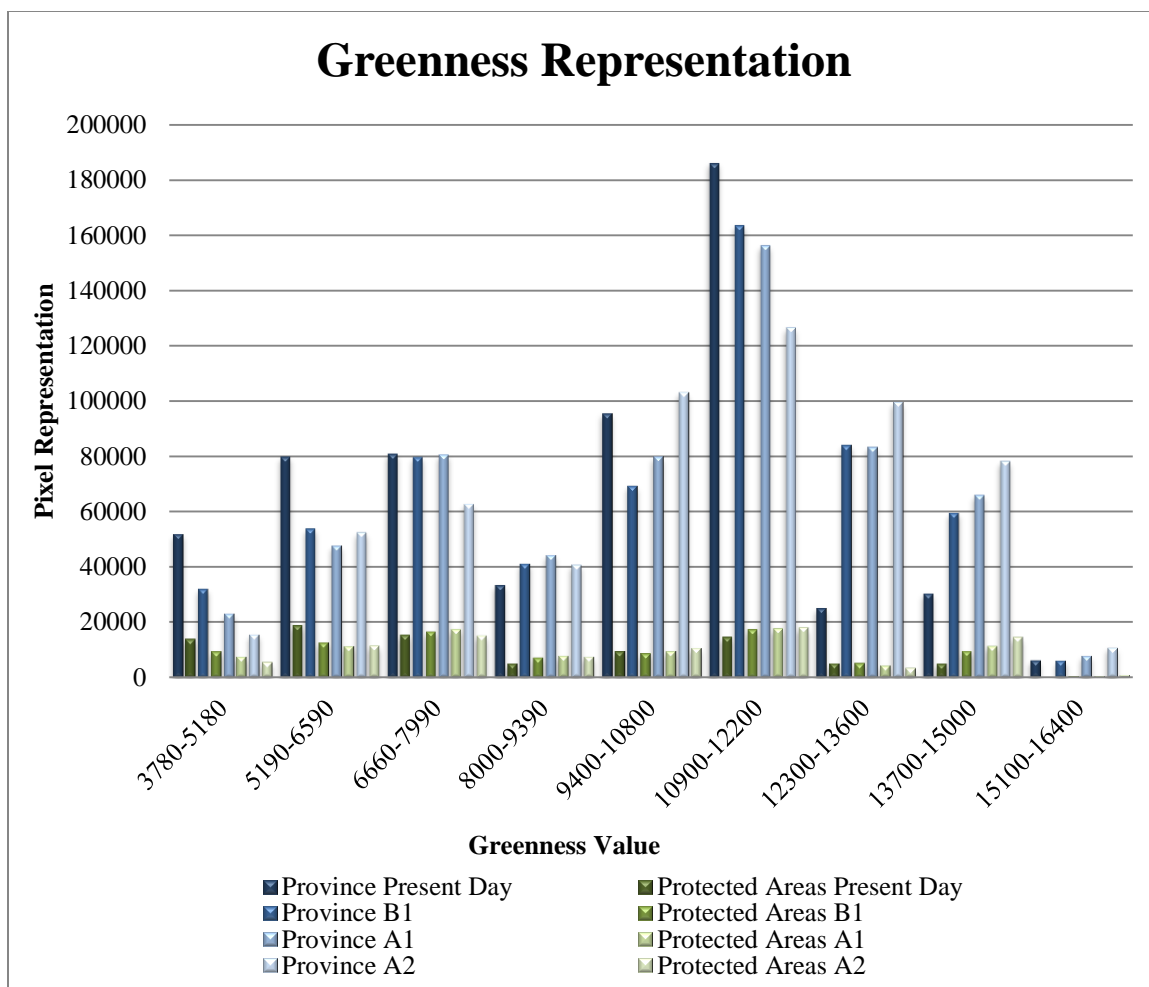


Figure 8 - Changes in greenness representation showing present day, B1, A1, and A2 2065 climate scenarios. Overall changes indicate a better representation for higher greenness due to climate change.

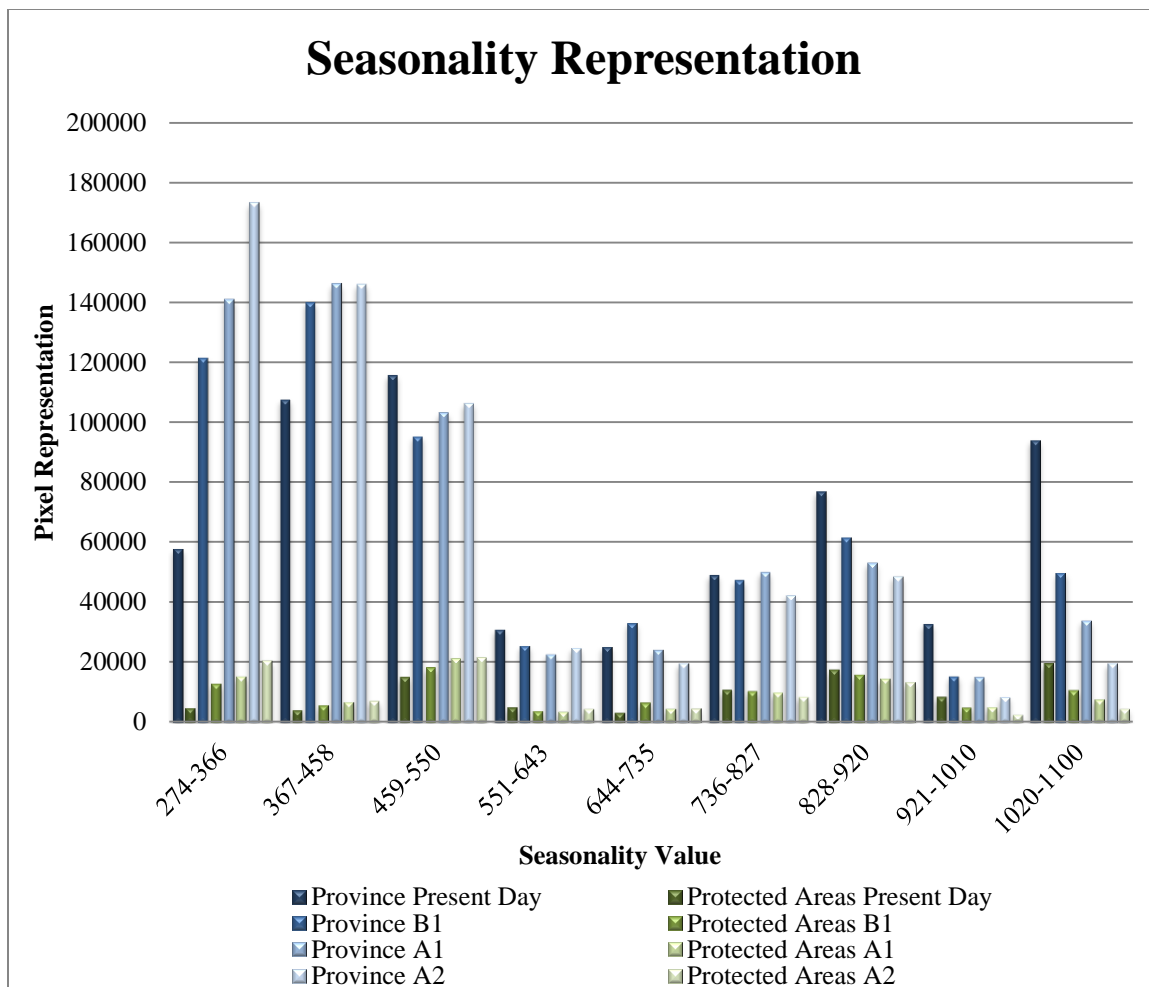


Figure 9 - Changes in seasonality representation showing present day, B1, A1, and A2 2065 climate scenarios. Overall changes indicate a better representation for lower seasonality due to climate change.

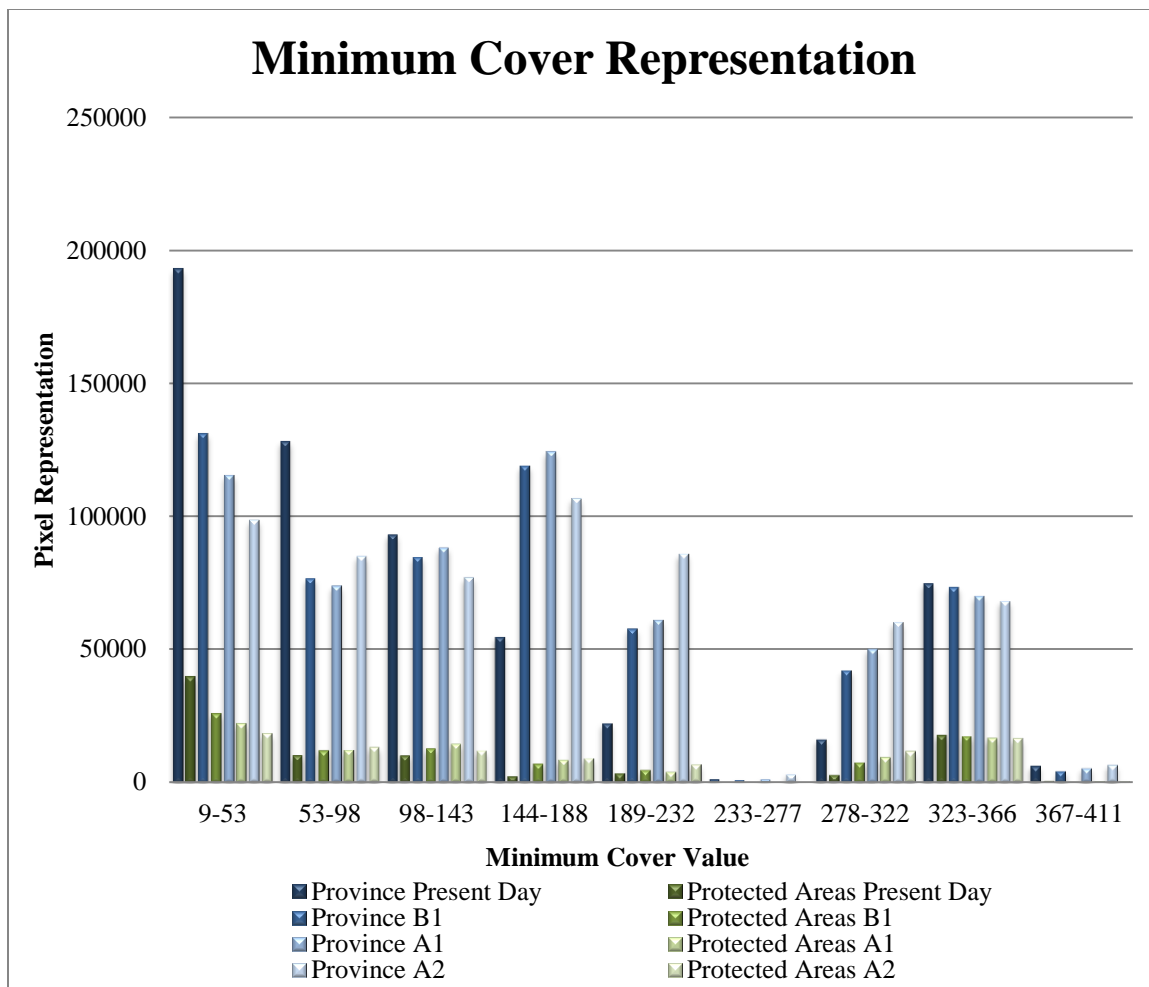


Figure 10 - Changes in minimum cover representation showing present day, B1, A1, and A2 2065 climate scenarios. Overall changes indicate a better representation for higher minimum cover due to climate change.

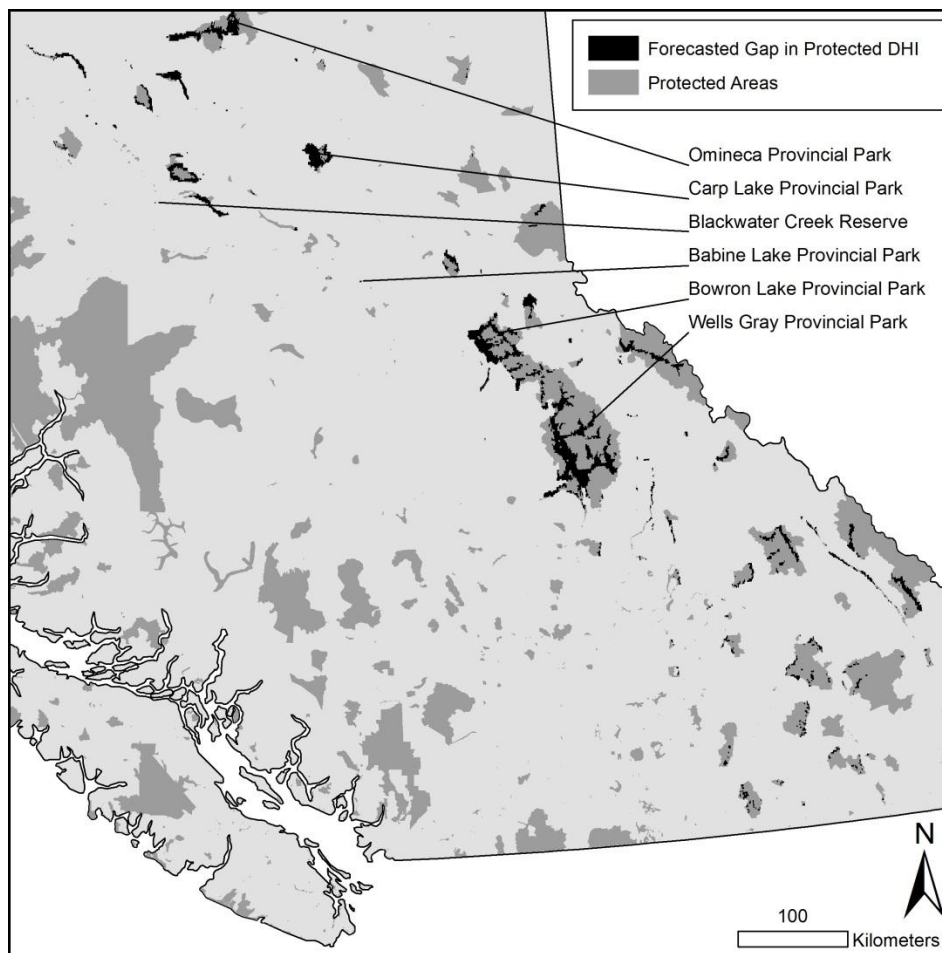
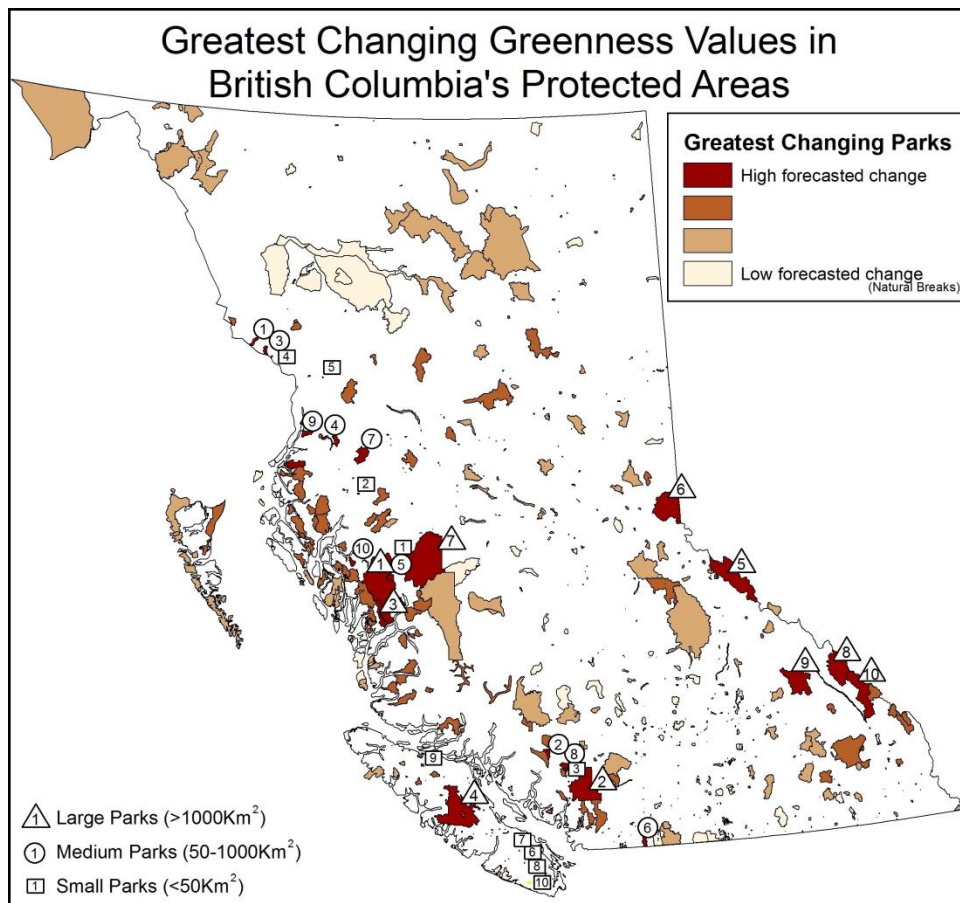


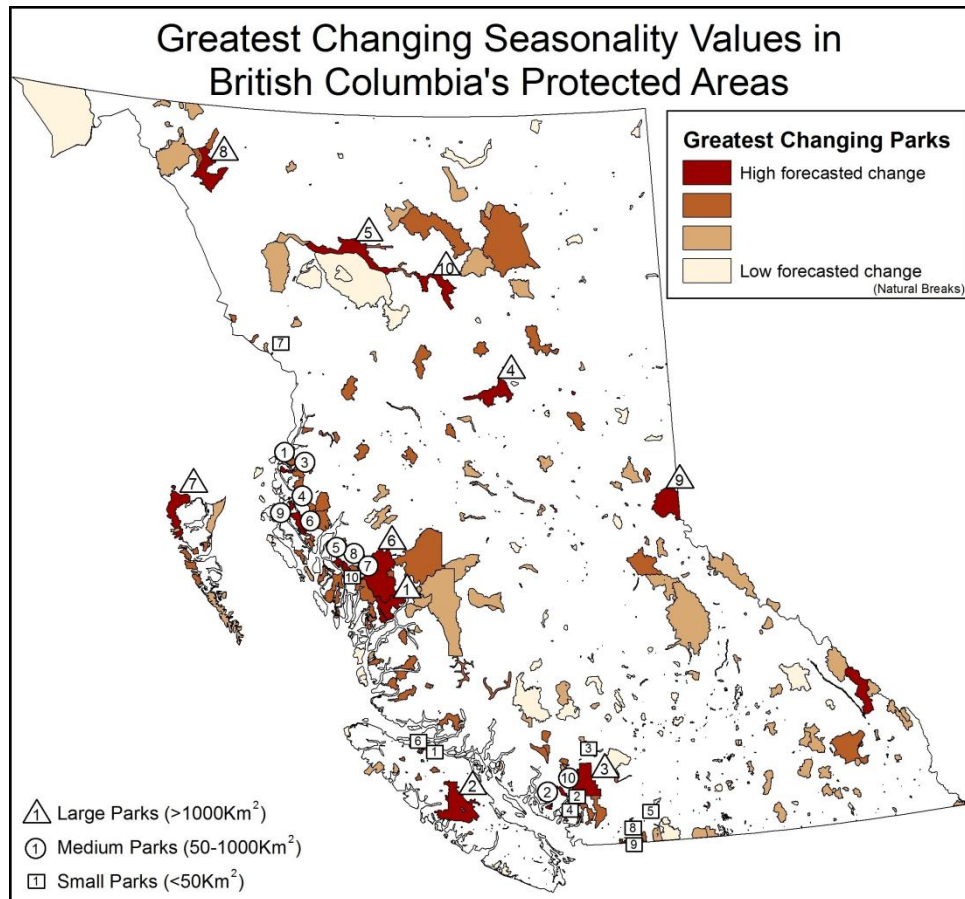
Figure 11 - Sub-set of British Columbia and select parks and protected areas illustrating gaps in DHI representation.



Top ten protected areas with the greatest forecasted change to greenness due to climate change

Large Parks (>1000 Km ²)			
Rank:	Park / Protected Area Name:	Area: Square Km	Greenness
1	Kitlope Heritage Conservancy	3206.3	3749.9
2	Garibaldi Provincial Park	1883.7	3457.0
3	Cascade-Sutislem Conservancy	1190.3	3393.4
4	Strathcona Provincial Park	2461.5	1929.5
5	Mount Robson Provincial Park	2125.3	1860.5
6	Kakwa Provincial Park	1726.8	1704.2
7	Tweedsmuir North Provincial Park	4470.1	1680.2
8	Yoho National Park	1284.8	1547.7
9	Glacier National Park	1358.0	1525.4
10	Kootenay National Park	1373.0	1455.3
			Mean: 1114.4
Medium Parks (50-1000 Km ²)			
Rank:	Park / Protected Area Name:	Area: Square Km	Greenness
1	Craig Headwaters Protected Area	75.9	5384.5
2	Upper Elaho Valley Conservancy	102.6	5077.9
3	Lava Forks Provincial Park	73.1	4904.9
4	Nisga'a Memorial Lava Bed Provincial Park	178.8	4716.7
5	Upper Kimsquit River Conservancy	105.9	4703.3
6	Chilliwack Lake Provincial Park	97.0	4688.8
7	Seven Sisters Protected Area	392.2	4389.9
8	Upper Soo Conservancy	113.1	4243.5
9	Ksi Xts'at'kw/Stagoo Conservancy	113.7	4070.0
10	Europa Lake Conservancy	89.5	4061.2
			Mean: 1452.5
Small Parks (<50 Km ²)			
Rank:	Park / Protected Area Name:	Area: Square Km	Greenness
1	Tweedsmuir Corridor Protected Area	0.3	9358.0
2	Williams Creek Ecological Reserve	6.9	7683.8
3	Callaghan Lake Provincial Park	26.7	6067.1
4	Border Lake Provincial Park	8.2	5556.8
5	Meziadin Lake Provincial Park	2.2	4994.5
6	Gordon Bay Provincial Park	0.5	4857.8
7	Haley Lake Ecological Reserve	1.1	4857.8
8	Honeymoon Bay Ecological Reserve	0.1	4857.8
9	Mount Elliot Ecological Reserve	3.3	4857.8
10	San Juan Ridge Ecological Reserve	0.9	4857.8
			Mean: 558.8

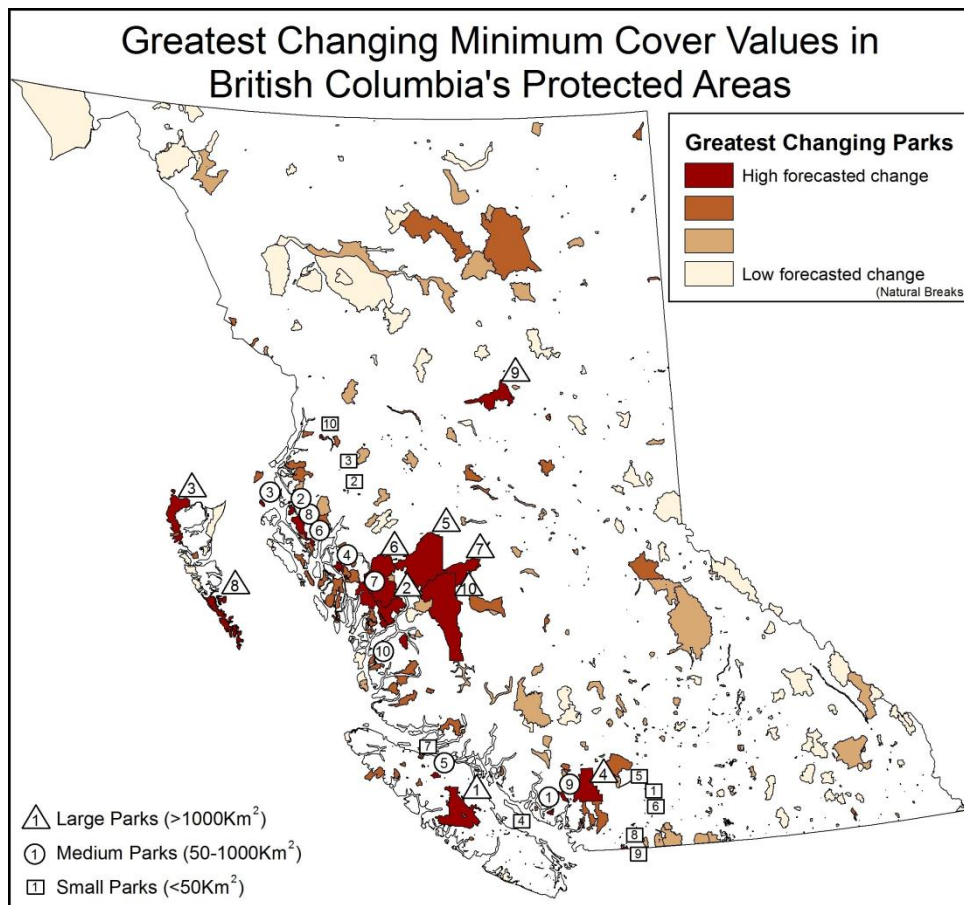
Figure 12 Ranking of highest changing greenness in large, medium, and small protected areas.



Top ten protected areas with the greatest forecasted change to seasonality due to climate change

Large Parks (>1000 Km ²)			
Rank:	Park / Protected Area Name:	Area: Square Km	Seasonality
1	Cascade-Sutislem Conservancy	1190.3	-315.0
2	Strathcona Provincial Park	2461.5	-312.8
3	Garibaldi Provincial Park	1883.7	-221.2
4	Omineca Provincial Park	1359.5	-217.2
5	Stikine River Provincial Park	2120.1	-208.8
6	Kitlope Heritage Conservancy	3206.3	-204.2
7	Duu Guusd Conservancy	1349.1	-203.3
8	Nakina-Inklin Rivers/Yawu Yaa Conservancy	1673.3	-190.1
9	Kakwa Provincial Park And Protected Area	1726.8	-169.8
10	Finlay - Russel Provincial Park	1228.0	-146.5
			Mean: -128.9
Medium Parks (50-1000 Km ²)			
Rank:	Park / Protected Area Name:	Area: Square Km	Seasonality
1	Kts'mkta'ani/Union Lake Conservancy	63.4	-487.6
2	Tetrahedron Provincial Park	60.6	-466.8
3	Khutzeymateen Inlet Conservancy	88.2	-454.2
4	Ecstall-Spoksut Conservancy	100.8	-451.2
5	K'Igaan/Klekane Conservancy	166.8	-448.3
6	Klewngugit Conservancy	67.9	-405.4
7	Fiordland Conservancy	776.2	-396.3
8	Q'altanaas/Aaltanhash Conservancy	173.5	-395.5
9	Ecstall-Sparkling Conservancy	405.8	-366.5
10	Tantalus Provincial Park	113.6	-361.5
			Mean: -155.0
Small Parks (<50 Km ²)			
Rank:	Park / Protected Area Name:	Area: Square Km	Seasonality
1	Mount Elliot Ecological Reserve	3.3	-569.5
2	Murrin Provincial Park	0.2	-569.5
3	Nairn Falls Provincial Park	1.9	-569.5
4	Shannon Falls Provincial Park	0.9	-569.5
5	Silver Lake Provincial Park	1.1	-569.5
6	Tsitika Mountain Ecological Reserve	6.0	-482.7
7	Border Lake Provincial Park	8.2	-445.9
8	Chilliwack River Provincial Park	0.3	-409.6
9	Liumchen Ecological Reserve	21.6	-409.6
10	Green Inlet Marine Provincial Park	0.3	-400.7
			Mean: -77.5

Figure 13 - Ranking of highest changing seasonality in large, medium, and small protected areas.



Top ten protected areas with the greatest forecasted change to minimum cover due to climate change

Large Parks (>1000 Km ²)			
Rank:	Park / Protected Area Name:	Area: Square Km	Minimum Cover Change
1	Strathcona Provincial Park	2461.5	146.5
2	Cascade-Sutsem Conservancy	1190.3	124.3
3	Duu Guusd Conservancy	1349.1	68.6
4	Garibaldi Provincial Park	1883.7	62.1
5	Tweedsmuir North Provincial Park	4470.1	59.4
6	Kitlope Heritage Conservancy	3206.3	56.9
7	Entiako Provincial Park	1218.1	56.8
8	Gwaii Haanas National Park Reserve	1200.3	47.7
9	Omineca Provincial Park	1359.5	45.3
10	Tweedsmuir South Provincial Park	5417.5	40.4
			Mean: 29.4
Medium Parks (50-1000 Km ²)			
Rank:	Park / Protected Area Name:	Area: Square Km	Minimum Cover Change
1	Tetrahedron Provincial Park	60.6	216.1
2	Ecstall-Spoksut Conservancy	100.8	190.6
3	Ksgaxl/Stephens Islands Conservancy	56.5	188.9
4	K'lgan/Klekane Conservancy	166.8	183.7
5	Schoen Lake Provincial Park	89.1	182.3
6	Alty Conservancy	84.7	173.5
7	Hot Springs-No Name Creek Conservancy	227.3	172.2
8	Fiordland Conservancy	776.2	170.6
9	Ecstall-Sparkling Conservancy	405.8	169.9
10	Tantalus Provincial Park	113.6	164.7
			Mean: 53.3
Small Parks (<50 Km ²)			
Rank:	Park / Protected Area Name:	Area: Square Km	Minimum Cover Change
1	Alexandra Bridge Provincial Park	0.6	293.0
2	Hai Lake-Mount Herman Provincial Park	6.8	293.0
3	Kitsumkalum Provincial Park	0.5	293.0
4	Little Qualicum Falls Provincial Park	5.0	293.0
5	Qualicum National Wildlife Area	0.8	293.0
6	Stoyoma Creek Ecological Reserve	0.7	293.0
7	Yale - Garry Oak Ecological Reserve	0.1	293.0
8	Tsilika Mountain Ecological Reserve	6.0	260.0
9	Chilliwack River Provincial Park	0.3	219.0
10	Liumchen Ecological Reserve	21.6	219.0
			Mean: 41.4

Figure 14 - Ranking of highest changing minimum cover in large, medium, and small protected areas.

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4.0 CONCLUSIONS

4.1 Discussion and Conclusions

The preservation of biodiversity is recognized as an international priority (Barton, 1992). Climate change impacts to biodiversity include altering species richness, abundance, and spatial distributions. By 2050 15-37% of species will likely be “committed to extinction” due to climate change (Thomas et al., 2004). Mountainous temperate rainforests, like those in British Columbia, are predicted to experience considerable changes to ecosystems due to climate change (Halpin, 1997). Projected changes in British Columbia include migrating ecosystems (Hebda, 1998), species extinction (Gayton, 2008), and habitat degradation (Wang, Campbell, et al., 2012).

Our biodiversity forecasting research is motivated by the need for decision makers to have map-based, scientific tools to that quantify expected changes to biodiversity and create opportunities to take proactive steps in achieving conservation targets. Our mapped future scenarios of biodiversity distributions deliver geographic information that described the directionality and magnitude of altering macroecological processes.

In Chapter two we link two multifaceted archived datasets in order to quantify and spatially forecast expected changes in biodiversity due to climate change. Twenty one years of annual climate and remotely sensed biodiversity indicator data are used to establish relationships that were projected into the future. The resultant map indicates that climate change is expected to considerably increase minimum cover, decrease seasonality, and increase greenness. The spatial patterns of predicted DHI changes

indicate a greening trend throughout the province and high changing areas are concentrated along the Coast Mountains and mid-to high elevation landscapes like the highlands of Vancouver Island, the Rocky Mountains, or the central interior. The quantification of macroecological changes in the province allows for a spatial assessment of the direction and magnitude of climate change impacts.

In chapter three we explore the impact of expected changes in the spatial distribution and magnitude of biodiversity indicators for protected areas in British Columbia. Utilizing future DHI mapping, from chapter two, allows for an investigation of future protected area representation, analysis of future gaps in protection, and identification of most threatened biogeoclimatic zones and protected areas. Comparing provincial and protected area representation of forecasted DHI scenarios details the directionality and relative severity of changes which impact the proper representation of long term preservation of park values. Protected areas are predicted to have higher greenness and lower seasonality. Gap analysis highlighted regions where DHI characteristics will likely be poorly represented in the future. Gaps in protection exist along the Western edge of the Rocky Mountains to the central interior. The observed conservation gaps are closely associated with the Interior Cedar Hemlock biogeoclimatic zone. The greatest changing biogeoclimatic zone is projected to be the Mountain Hemlock zone. The highest changing protected areas are found between 407-1428 meters and are concentrated along the Coast Mountains (e.g., Tweedsmuir Provincial Park), Vancouver Island (e.g., Strathcona Provincial Park), and the Rocky Mountains (e.g. Kootenay National Park).

4.2 Research Contributions

The principal contribution from this thesis is a novel product for assessing future impacts to biodiversity indicators due to climate change. This valuable forecasting tool contributes to climate change science and has a variety of decision making and management applications. The methodology of predicting indirect biodiversity indicators is advantageous because it produces mapped information that is spatially continuous, scientific, and relatively easy to interpret. Contributions to climate change science include the use of high spatial resolution climate models to produce a knowledge based tool that can be applied to multiple scientific platforms. The utility of remote sensing science is highlighted by interconnecting indirectly collected data with climate information to produce a tool with the capacity to quantify and effectively monitor biodiversity.

Providing easily interpretable tools may motivate pre-emptive planning by enhancing the capacity to inform public and decision maker's knowledge on the issues of climate change and its impacts on biodiversity. However, since the prediction data are organized within a geographic information system, data can be integrated with a number of ancillary spatial datasets to answer research and management questions. Some examples of applications include furthering research in species intactness and land cover change. The tool illustrates vectors of change to DHI that may cause modifications to land cover and species interactions. Predicted DHI data can also be related to gross primary productivity data which can be used to calculate carbon sequestration (D. P. Turner et al., 2003) which has important policy implications in society. Agricultural practices may also be informed by investigating alterations in climate, crop yield

capacities, and new locations for viable local food production. All these examples highlight the enhanced capacity to understand major consequences to our environment through the use of the projected biodiversity indicators and may improve society's ability to react and adapt to change.

Both the methods developed and maps produced are tools that support management of expected ecosystems changes in British Columbia due to climate change. Benefits include a better understanding of the risks to protected areas, identifying high impact ecosystems, and provide a general tool to inform broad landscape alterations. Considering the value placed on natural resources, biodiversity, and the protected area in society, our enhanced method of gathering science based knowledge of threats to British Columbia's biodiversity provides necessary information for long term planning. Foresight into broad ecosystem changes will lead to several management opportunities including better knowledge of tree regeneration rates for forest resource managers (Latta, Hailemariam, & Barrett, 2009), forest replanting efforts (Wang et al., 2012), ecosystem preservation (Lemieux & Scott, 2005), and endangered species conservation efforts (G. F. Midgley & Thuiller, 2010).

We have contributed new knowledge specifically in British Columbia and have provided insights into climate change impacts generally as well as at local scales on species such as the Whitebark pine (*Pinus albicaulis*)(McLane & Aitken, 2012), Vancouver Island Marmots (*Marmot vancouverensis*), Northern Woodland Caribou (*Rangifer tarandus caribou*) (Johnson, Parker, Heard, & Seip, 2004), and red listed avian species (Species at Risk British Columbia, 2012). Examples of broad studies include examining ecosystem shifts (Wang et al., 2012), post glacial succession rates (Hebda,

1998), and climate change modelling (Murdock & Splittlehouse, 2011). The far reaching applications of the forecasting product benefit multiple aspects of society, research, and can greatly bolster management capabilities in order to combat climate change impacts.

4.3 Research Limitations

The nature of forecasting research has a number of limitations and inherent uncertainties (Thuiller, 2003). Uncertainty in climate scenario choice and modelling technique were concerns for our work. The climate scenarios chosen provided a wide range of possible climate outcomes and were representative of likely changes to occur (Murdock & Splittlehouse, 2011). Although the climate model information is decisive in the model result, it is important to note that our results provide a continuous relative metric. Our aim was to observe main directionality and relative magnitude of biodiversity indicators rather than predict species specific or species assemblage movements. The emphasis of our research was not to explore modelling approaches but to choose a method that produced quality results and could handle large and complex datasets.

4.4 Research Opportunities

There are many research opportunities using remote sensing biodiversity indicators for climate change impact analysis. Since the inception of climate change and biodiversity modelling, rapid advancements have been made in the accuracy, modelling methodology, spatial resolution, and range of information researched (Midgley & Thuiller, 2010; Turner et al., 2003). Six future opportunities have been identified that may both improve the scope and accuracy of results.

1) Enhance the geographic range of the research area by analyzing larger regions and datasets. Our analysis can be applied to larger areas from the regional, continental, and global scale. Since the AVHRR or analogous MODIS satellite data covers global terrestrial environments the broader scope of research may be beneficial.

2) Improve input datasets by including newer and more advanced data types. Over time, archived remote sensing datasets will become even more robust by attaining greater sample sizes (J. Kerr & Ostrovsky, 2003). Larger sampling size will aid in improving the accuracy of results by providing more data which will improve the confidence and diminish the effects of outlier data in the results. Climate models are also improving with greater accuracy and spatial resolutions (Daly et al., 2008). Using agglomerated climate models as observed in Wang et al., (2012) may also improve future climate representation. Remote sensing data is ever changing and being updated. Calibration techniques (Toutin, 2004) and automated updating of remote sensing data is possible (Coppin, Pol & Bauer, Marvin, 1996) and will improve long term utility and accuracy of indirect biodiversity monitoring programs.

3) Include a larger variety of data types in analysis that may better reflect complex ecosystem functions. Soils data, for example, play an important ecological role and can limit how natural processes and rates of change (Franklin, 1995). Including soils information could bolster a model's ability to mimic nature since it has the potential to limit succession, migration, and extirpation of species due to climate change (L. R. Iverson & Prasad, 1998). Results can also be compared to important data on rare species and habitat locations. The spatial relationship between ecologically important areas and threat level would provide important information to specific conservation efforts.

4) Experiment with other modelling techniques to assess which type reflects the most accurate environmental conditions in the study area. Although our regression tree approach was successful, there are a number of other methods used in literature such as Random Forests (Breiman, 2001; Prasad, Iverson, & Liaw, 2006), artificial neural networks (Berry, Dawson, Harrison, & Pearson, 2002; Pearson, 2002), generalized linear models (Lehmann, Overton, & Leathwick, 2002; Thuiller, 2003), and generalized additive models (G. Midgley, 2003). These 4 alternative modelling techniques could be explored more fully and may result in improved accuracy in forecasting biodiversity indicators.

5) Link DHI with species information by ground truthing indirect biodiversity indicators to field based habitat information. Linking specific DHI arrangements with field sampled species information or habitat characteristics may better detail how ecosystems alter due to climate change. Remote sensing information could be better linked with biodiversity by understanding how each DHI value equates with a particular species assemblage or habitat type. Considering one of the key interrelationships in our forecasting technique is the connection between biodiversity and remotely sensed indicators, it would be valuable to strengthen our knowledge of the relationship.

6) Create increasingly regionalized models based on a larger number of more homogenous ecosystems. Our regression tree approach used six ecozones to define homogenous ecosystems in order to specialize results for each region and increase classification accuracy. Using a greater number of regions would specialize and improve accuracy further. Regions could be based off the 16 zones from either Fitterer et al.,

(2012) or the BEC zones (B.C. Ministry of Forests, 2009) which are landscapes with similar biogeographic characteristics.

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