USING BIOCLIMATIC ENVELOPE MODELLING TO INCORPORATE SPATIAL AND TEMPORAL DYNAMICS OF CLIMATE CHANGE INTO CONSERVATION PLANNING

by

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Abstract

Current and predicted trends in climate are diverging from historic norms, thereby compromising the equilibrial basis of our resource management frameworks. This study investigates the impacts of climate change on biodiversity in the context of conservation planning for British Columbia's Central Interior. I used bioclimatic envelope modelling and a climate interpolation and general circulation model downscaling tool to assess 73 rare plant species, 103 biogeoclimatic variants, and 30 terrestrial ecosystem units. I mapped areas projected to support climate suitable for the persistence of those conservation targets through to the 2080s. Results illustrate the potential for disruptive change; only 12% (24) of the 206 targets are projected to experience persistent climate at their current locations. Although strong overlap among locations projected to persist for different targets was not found, and those areas meeting multiple objectives (including value independent of climate change) are clear priorities for protection. This methodology can function as a valuable tool for conservation planners and resource managers.

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Acronyms

Acronym	Definition
ANHIC	Alberta Natural Heritage Information Centre
B.C.	British Columbia
BEC	Biogeoclimatic ecosystem classification
BEM	bioclimatic envelope modelling
BGC	biogeoclimatic
CDC	Conservation Data Centre
CGCM3	Canadian General Circulation Model Generation 3
COSEWIC	Committee on the Status of Endangered Wildlife in Canada
CSIRO	Australian Commonwealth Scientific and Industrial Research Organization
DEM	digital elevation model
ERAP	ecoregional assessment process
GBIF	Global Biodiversity Information Facility
GCM	general circulation model
GIS	geographic information system (computer mapping program)
ILMB	Integrated Land Management Bureau
IPCC	Intergovernmental Panel on Climate Change
NCC	Nature Conservancy of Canada
PCC	persistent climate corridor
PCM	US Department of Energy's Parallel Climate Model
PRISM	Parameter Regression of Independent Slopes Model
SCS	suitable climate space
SRES	Special Report on Emissions Scenarios
TEU	terrestrial ccological unit
TNC	The Nature Conservancy (U.S.A.)
UBC	University of British Columbia
UNBC	University of Northern British Columbia
UVIC	University of Victoria

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Chapter 1 - Introduction: Conserving biodiversity in a changing climate

Abstract

The ecological repercussions of this century's anthropogenic climate change are expected to devastate the environment. Climate change is driving species to extinction and altering life-sustaining ecosystem processes. These changes are happening at a rate that exceeds the physiological capabilities of most ecological units and consequently, the ability to effectively manage these resources is hampered. In response to these changes, ecologists and resource managers are starting to incorporate the spatial and temporal dynamics of ecosystems into their planning frameworks. A number of tools are available to assist with this transition and there is evidence that a dynamic, non-equilibrium approach to ecosystem management is emerging. Using the Nature Conservancy of Canada's Central Interior ecoregional assessment as a case study, this research explores the identification of persistent climate corridors as a means of addressing the spatiotemporal dynamics of climate change on the landscape and its subsequent impact on conservation planning.

Introduction

Climate has shaped the structure and function of ecosystems and is partly responsible for the existing character and distribution of plant and animal species. However, the current rate of climate change is unprecedented (Leemans and Eickout 2004; IPCC 2007; McKenney et al. 2007b) and will likely exceed the ability of many species to respond (Schwartz et al. 2006). When considered on a geological scale, the impacts of contemporary climate change are immediate, as demonstrated by the mountain pine beetle (*Dendroctonus ponderosae*) epidemic in central B.C. (Carroll et al. 2003) and by global changes in the geographic ranges of many butterfly species (McCarty 2001).

According to the Intergovernmental Panel on Climate Change (IPCC 2007), the primary force driving this century's climate change is anthropogenic, and is expected to cause extreme weather events, global changes in temperature and precipitation, and increases in sea levels. In the same report, IPCC (2007) identified ecosystems, water resources, food security, settlements and society, and human health as the primary systems most vulnerable and highly impacted by anthropogenic climate change. From a biodiversity perspective, the impacts of climate change on ecosystems can include an increase in the magnitude of local extinctions of plant and animal species (Schwartz et al. 2006), as well as an increase in the incidence of species invasions (BCMFR 2006a; Gayton 2008). These impacts will lead to major changes in ecosystem structure and function, ecological interactions and species distributions. Overall, these changes have predominantly negative consequences for biodiversity and the provision of ecological services (McCarty 2001). Anthropogenic drivers of other aspects of global change, such as resource exploitation, and land conversion and degradation are also expected to intensify the consequences of climate change (Hansen et al. 2001; Hannah et al. 2002b).

Individually these impacts will have harmful effects on the environment, but interaction of climate change with other global changes will have a far greater synergistic impact on biodiversity (Dale et al. 2001; Hijmans and Graham 2006). Invasive species, for example, are a serious problem for many indigenous species and biotic communities, and their projected increase is expected to exacerbate current extirpation rates as they outcompete and replace native species (Hansen et al. 2001; Malcolm et al. 2002). Coupled with climate driven changes to natural disturbance regimes, the increase in invasive species is expected to create a positive feedback, which will continue to drive the introduction and establishment of invasive species and intensify natural disturbances such as wildfire (BCMFR 2006a). More intense and frequent fires will change successional trajectories through changes to community structure and composition, such as the difference between native and exotic grass fire cycles which are responsible for woodland conversion to grasslands in the Sonoran woodland deserts and the shrub and steppe habitat in the Great Basin of North America (D'Antonio and Vitousek 1992).

The purpose of this thesis is to explore how climate change will impact biodiversity through changes in species distribution. It will also explore the ability of managers and ecologists to mitigate these changes and develop new adaptive conservation strategies. Specifically the objectives of this thesis are to develop bioclimatic envelopes for three groups of conservation targets (i.e., rare plant species, terrestrial ecological units and B.C. biogeoclimatic variants), and to introduce the concept of persistent climate corridors and their application to the site selection and prioritization of a network of protected areas. The utility of this concept is demonstrated by identifying potential persistent climate corridors for each target which I will argue represent superior priority areas for conservation.

Species and Ecosystem Migration

In response to the anticipated adversities associated with climate change, species must adapt to or evolve with the new climate, migrate to new more suitable areas, or go extinct. Individual species are expected to respond idiosyncratically, which will lead to a redistribution of individual species and widespread re-organization of ecological communities (Shafer et al. 2001; Hamann and Wang 2006; Hijmans and Graham 2006).

A species' response to climate change is a function of its physiological and life history characteristics, such as reproductive biology and phenology (Berry et al. 2003), phenotypic plasticity and genetic adaptation (Hamann and Wang 2006; McKenney et al. 2007b), resilience to disturbance (Fitzpatrick et al. 2008), dispersal ability, biotic interactions and abiotic factors (Hansen et al. 2001; Pearson and Dawson 2003; McKenney et al. 2007b). Human activities will also impact how species will respond to climate change. Land uses such as urban development may create barriers to dispersal and species may become trapped and unable to a move to more suitable areas (Hansen et al. 2001; Williams and Jackson 2007).

At the community level, change is a function of direct and interacting global changes including the impact of invasive species, biochemical changes in the atmosphere, differential species dispersal, and changes to natural disturbance regimes, land use and interspecific interactions (Hansen et al. 2001). Asynchronous responses of individual taxa within a community will have significant ecological consequences for current community dynamics and the persistence of ecological communities, and are likely to result in novel species associations (Shafer 2001; Williams and Jackson 2007).

Inevitably, these idiosyncratic responses within a community will lead to the creation of new ecological communities without current analogues (Suffling and Stocks 2002; Lemieux and Scott 2005; Williams and Jackson 2007). According to Schweiger et al. (2008), one of the potential consequences of differential species responses within a community is spatial mismatching of trophically interacting species. For example, it has been noted that *Boloria titania* (Purple Bog Fritillary), a monophagous butterfly, and its host plant *Polygonum bistoria* (bistort) have a pronounced mismatch of the future geographic ranges projected for their climatic niches (Schweiger et al. 2008). A small area of spatial overlap occurs among the projected areas characterized by their suitable bioclimatic envelopes, which leads to the conclusion that interspecies interactions and species-specific dispersal characteristics will contribute to some dynamic responses to climate change.
Collectively these responses are expected to express themselves on the landscape as 1) poleward migrations (Pearson and Dawson 2003; Parmesan and Yohe 2003); 2) contractions of lower latitudinal biomes and plant communities (Malcolm et al. 2002; Pearson and Dawson 2003; Schwartz et al. 2006); 3) the encroachment or replacement of higher latitude biomes, such as open taiga, with closed forests (Bachelet et al. 2005); and 4) elevational migrations and losses (McCarthy 2001; Walther et al. 2002). The effects of climate change are expected to be strongest in northern sub-boreal, boreal and subarctic ecosystems (Scott et al. 2002; Hamann and Wang 2006). However, this is not a simple conclusion, and there are a number of issues associated with these predictions; for example, species at the southern limit of their range, and the suite of "at risk" species which are sensitive to environmental perturbations face the likelihood of local extinction (Honnay et al. 2002; Parmesan and Yohe

2003; Schwartz et al. 2006). Table 1.1 describes how a variety of different plant species and ecosystems are expected to respond to climate change.

Table 1.1. A summary of predicted geographic responses to climate change of biomes, plant communities

Ecosystem or plant species	Geographic location	Geographic Response	Reference
Hot Desert Ecosystems	Global	Remain stable relative to other ecosystems	Leemans and Eickhout 2004
Alpine Biome	Coterminous United States	Disappear from western mountains and replaced by forests	Hansen et al. 2001
Fynbos Biome	South Africa	Projected loss of area (51-65%) which equates to the loss of a 1/3 of fynbos associated species	Mideley et al. 2002
Grassland Biome	Coterminous United States	Expand into southwest deserts	Hansen et al. 2001
Tundra Biome	Canada	6 climate change scenarios predict a loss of suitable habitat	Scott et al. 2002
Temperate Forests	Canada	Increased representation	Scott et al. 2002
Arctic-Alpine/montane heath	Britain	Highly sensitive; projected loss of suitable habitat.	Berry et al. 2002
Beech Woodland Ecosystems	Britain	Sensitive; projected loss of suitable habitat in southern Britain.	Berry et al. 2002
Lowland raised bog	Europe	Vulnerable; susceptible to summer drying, many species would lose suitable habitat	Berry et al. 2003
Lowland Proteaceae species	South Africa	Projected to experience rapid loss of range	Hannah et al. 2005
Acer saccharum (sugar maple)	North America	General poleward increase.	McKenney et al. 2007b
Pseudotsuga menziesii (Douglas-fir)	British Columbia, Canada	Overall increase in frequency across B.C. with the largest decrease in the Ponderosa Pine zone	Hamann and Wang 2006
Banksia spp. (Proteaceae)	Western Australia	Varied in degree; a general range contraction is projected	Fitzpatrick et al. 2008
Potamogeton filiformis (slender leaved pondweed)	Europe	Losing suitable climate space	Berry et al. 2003
Ranunculus scleratus (cursed crowfoot)	Europe	Gaining valuable climate space	Berry et al. 2003
Lecanora populicola (rim lichen)	Northern Britain	Overall increase in the likelihood of occurrence in eastern and northeastern Scotland.	Ellis et al. 2007
Pinus albicaulis (whitebark pine)	Yellowstone National Park	Modest changes; suitable climate is expected to decline	Bartlein et al. 1997
Quercus gambelii (Gambel oak)	Yellowstone National Park	Currently not present but suitable climate is projected to exist	Bartlein et al. 1997
Pinus virginiana (Virginia pine)	Eastern United States	Projected decrease in suitable habitat and a fairly small northward migration	Iverson et al. 1999
Fagus grandifolia (American beech)	Eastern United States	Projected 90% reduction in suitable area	Iverson and Prasad 2002
Scleranthus perennis (perennial knawel)	Europe	Dramatic area reductions and redistribution	Bakennes et al. 2002
Ilex aquifolium (European holly)	Europe	Northward and northeastward range expansion	Walther et al. 2005
Artemisia tridentata (big sagebrush)	North America	Projected to migrate northward accompanied by a significant contraction of its current range	Shafer et al. 2001

Range shifts are also determined by other environmental factors, including edaphic and hydrological conditions and topography (Hamann and Wang 2006), and constraints such as geographic barriers and lack of sufficient dispersal opportunities (Costa et al. 2008). These overall results will further impact future distributional patterns and consequently biodiversity and its associated ecological processes and services (Hansen et al. 2001; Berry et al. 2003).

Management perspectives: Protected area planning in a changing climate

Managing natural resources for economic or ecological values is a challenging task given the dynamic character of heterogeneous environments. Many government agencies and environmental non-profit organizations are developing innovative management strategies with the objectives to prepare for, mitigate and adapt to the potential impacts of climate change. The B.C. Ministry of Forests and Range (BCMFR), for example, is developing a proactive strategy to address the short- and long-term consequences of climate change on forest and range resources. The recommended actions outlined in this strategy consist of improving the Ministry's ecological knowledge through increasing analysis and research, reviewing current operational policies and practices, as well as building awareness and capacity within and outside the Ministry. Some of the challenges of this adaptive approach include the uncertainty in the magnitude and timing of climate change impacts, the difficulty of balancing multiple values (and hence management objectives), and a variety of institutional and policy barriers. Factors which influence adaptive management in a changing climate include scale of the area of interest, target species, landscape processes, natural disturbance and societal values (Hannah et al. 2002a; Spittlehouse 2005).

Many global change ecologists agree that climate change poses one of the greatest threats to native biodiversity (McCarty 2001; Bakkenes et al. 2002; Berry et al. 2002;

Hannah et al. 2005; Ellis et al. 2007; Fitzpatrick et al. 2008; Gayton 2008). The large-scale, cascading consequences of climate change are bringing current conservation practices into question. The current conservation management paradigm emphasizes equilibrium between biotic communities and their abiotic environment (including soils, terrain and climate), and assumes that this abiotic environment is essentially stable. Consequently, exercises such as ecosystem mapping place static boundaries on an inherently dynamic system, but as plant species migrate in response to climate change this paradigm's flaw becomes apparent (Hijmans and Graham 2006; Leroux et al. 2007). Parks and protected area networks, for example, are unlikely to maintain their conservation objectives as climate driven changes re-assemble and re-organize ecosystems (Scott et al. 2002; Araújo et al. 2004; Leemans and Eickhout 2004).

This classical paradigm of ecological stasis is based on the assumption that ecosystems have discrete, recognizable boundaries and that recovery from disturbance follows a linear progression to a stable or climax state. In contrast, the modern non-equilibrium paradigm states that ecosystems are open and heterogeneous, spatially and temporally variable, and their interactions on the landscape influence the mechanics of other ecosystems (Hannah and Salm 2005; Wallington et al. 2005). Emphasizing the temporal and spatial dynamics of ecological systems is fundamental to the successful integration of a non-equilibrium approach to conservation (Suffling and Stocks 2002; Lemieux and Scott 2005). By closing the gap between ecological theory and practical application, current policy and practice may begin to reflect emerging scientific perspectives and lead to more effective resource management (Wallington et al. 2005; Shultis and Way 2006; Scott and Lemieux 2007). One example of such an application is re-assessing representation and persistence criteria in order to develop a dynamic network of protected areas. By tracking the temporal and spatial dynamics of parks and reserves, managers can more effectively ensure that suitable habitat is continuously available (Leroux et al. 2007; Rayfield et al. 2008). Other strategies that are recommended to address the contradiction between ecosystem dynamics and conserving ecological values include floating reserves (Cumming et al. 1996; Rayfield et al. 2008) and the provision for dispersal corridors (Williams et al. 2005).

A paradigm shift in our conservation management practices would require a more multidisciplinary approach, which involves incorporating biogeography, conservation biology and practical resource management. The fundamental goal of process-integrated conservation strategies is to account for changes in species distribution, and consequently persistence and vulnerability to global changes (Margules and Pressey 2000; Hannah et al. 2002a; Araújo et al. 2004; Botkin et al. 2007). A number of general recommendations and considerations for conserving biodiversity in a changing climate have been proposed:

- Focus on ecosystem pattern with consideration of ecological process (Hannah et al. 2002b; Scott and Lemieux 2007);
- Direct conservation efforts towards preserving areas where species are projected to persist (Shafer et al. 2001; Miller et al. 2007; Fitzpatrick et al. 2008);
- Manage a percentage of the current habitat area as a reserve until populations are established elsewhere (Hansen et al. 2001);
- Consider trans-boundary or potential range shifts (Hamann and Wang 2006; Lee and Jetz 2008);
- Conserve and maintain habitats in an appropriate condition in order to facilitate the migration of species (Halpin 1997; Berry et al. 2003);
- Prioritize the creation of northward and upslope migration corridors (Hansen et al. 2001; Gayton 2008);
- Identify and protect core areas within the ranges of targeted species (Miller et al. 2007; Fitzpatrick et al. 2008);
- Place greater emphasis on longer term ecological monitoring in order to determine the success of stated conservation goals (Welch 2005; Gayton 2008);
- Establish seed banks and nurseries for species at risk (Hansen et al. 2001);
- Help avert species extinction and keep up with climate change using mitigative measures, such as assisted migration (BCMFR 2006a; Schwartz et al. 2006; Van der Veken et al. 2008);
- Manage the surrounding matrix, including stressors, in order to alleviate their exacerbating effect on climate stress (McCarty 2001; Hannah and Salm 2005);

- Coordinate conservation actions across political boundaries and agency jurisdictions (Hannah et al. 2002b; Hannah and Salm 2005; Lee and Jetz 2008); and
- Increase redundancy (representation) of conservation targets and the buffers around them (Halpin 1997; Miller et al. 2007).

These general recommendations can be grouped into different categories of management actions including the selection of redundant reserves and reserves that provide habitat diversity and management for buffer zone flexibility, landscape connectivity and habitat maintenance. In order to maximize the efficacy of these actions, managers must identify the goals and objectives of their projects and prioritize them according to ecological principles (Halpin 1997; Botkin et al. 2007; Miller et al. 2007).

The use and development of bioclimatic envelope models

The responses of species and ecological communities to climate change are difficult, if not impossible, to predict with certainty, but there are a variety of tools available to assist global change ecologists with predicting the probable response of target species and communities. Bioclimatic envelope modelling (BEM) is one technique used to predict species dynamics and community formation (McKenney et al. 2007a; Williams and Jackson 2007). Bioclimatic envelope modelling is used to describe the present and potential future distribution of a species based on defining a set of suitable climate conditions (Thuiller 2003, 2004). Other species distribution modelling strategies use environmental and ecological data other than (or in addition to) climate, such as vegetation type (Segurado and Araújo 2004), geology (Zaniewski et al. 2002) and ecological processes such as competition and succession (Austin 2002). Different modelling strategies utilize a variety of data types including presence-only, presence/absence and abundance estimates, and are analyzed using general linear models, general additive models, classification and regression trees or artificial neural networks (Heikkinen et al. 2006) to predict where plant species should be able to establish and persist.

Bioclimatic envelope modelling has its conceptual underpinnings in Hutchinson's ecological niche theory (Hutchinson 1957), which describes a species' fundamental niche as a conceptual space occupied by a species, the multidimensional axes of which are described by environmental factors. This space, also termed a hypervolume, defines the range of a species' physiological tolerances and its position in the ecosystem. The realized niche, a subset of the fundamental niche, is the functional space a species actually occupies, as constrained by biotic factors such as predation and competition (Pearson and Dawson 2003; Beaumont et al. 2005). In principle, bioclimatic envelopes are larger than fundamental niches because they only consider climatic limitations, which at a global level are typically the dominant influence controlling plant species' establishment, growth and survival. It is for this reason that a bioclimatic envelope is often referred to as a species' "climatic niche" (Pearson and Dawson 2003; Hannah et al. 2005; McKenney et al. 2007a). Overall, BEM provides a practical tool that allows for a relatively quick first assessment to address ecological objectives such as the following (Berry et al. 2002; Kadmon et al. 2003; McKenney et al. 2007b):

- Estimating the spread of invasive species;
- Evaluating potential planting areas;
- Identifying climate-based disease expression in plant communities;
- Mapping wildlife habitats;
- Identifying potential areas for endangered species re-introductions; and
- Investigating potential responses of species to climate change.

BEM is often criticized for its exclusion of important ecological dynamics including biotic interactions (e.g., competition and predation), dispersal ability, evolutionary adaptation and the influence of additional abiotic factors (e.g., local topography, soil conditions) and human pressure on the landscape. Proponents of bioclimatic envelope modelling recognize these shortcomings, and argue that this strategy is typically undertaken as a first step in climate impact projections rather than for precise habitat suitability assessment, employed at a coarse scale where climate is the dominant factor controlling species distributions (Pearson and Dawson 2003; Heikkinen et al. 2006; Ellis et al. 2007).

Bioclimatic envelope modelling is particularly useful for ecologists in the fields of ecological restoration, conservation planning and plantation forestry where managers are interested in matching species to suitable environments (Hamann and Wang 2006). Other advantages of bioclimatic envelopes include a valuable cost-benefit ratio from the perspectives of data availability and budgetary constraints. For example, BEM can typically be conducted on the basis of collection records associated with voucher specimens deposited in museums and herbaria, providing a feasible alternative to field surveys and their high and often prohibitive costs. They also have the potential to provide the only method of estimating the current potential and future distributions of poorly understood or under-researched species. Finally, a large number of datasets such as online herbarium records provide collection locations but no abundance information; such presence-only data are not suitable for many statistical approaches, but are ideally suited for bioclimatic envelope modelling (Kadmon et al. 2003; Beaumount et al. 2005).

Bioclimatic envelopes are developed by associating current species occurrences with a set of climate variables or through an understanding of a species' physiological relationship with climate. When identifying a plant species' climatic space those variables which most limit successful survival, growth and reproduction are ideally used. Typical climate variables (which must be available or calculated from standard meteorological records) include mean annual temperature (MAT), mean temperature of the warmest month (MWMT), mean temperature of the coldest month (MCMT), precipitation in the warmest season, and precipitation in the coldest season (Berry et al. 2002; Thuiller 2003, 2004; McKenney et al. 2007a,b).

Ideally, occurrences from across the entire range of a conservation target are needed to fully describe its bioclimatic envelope. However, this information is not always achievable, especially when dealing with rare or uncommon species. There does not appear to be a consensus regarding a minimum number of records required for developing bioclimatic envelopes. However, Bakkenes et al. (2002) and Fitzpatrick et al. (2008) used a minimum of 20 occurrence records per target to describe bioclimatic envelopes for Europe's higher plants and Kadmon et al. (2003) used a minimum of 50 records to analyze the general performance of climatic envelope models.

Persistent climate corridors: Collapsing the fourth dimension in conservation biology

The Nature Conservancy of Canada (NCC) is a large non-profit organization dedicated to the conservation of native biodiversity (http://www.natureconservancy.ca). To achieve its goals, NCC participates in the acquisition of ecologically valuable parcels of land with specific conservation intentions, (e.g., stewardship programs, conservation covenants or easements). It also assists (or sometimes leads) governments in the process of planning for the designation of protected area networks, through development of a rigorous, multi-stakeholder conservation plan called an ecoregional assessment process (ERAP). NCC and its American counterpart, The Nature Conservancy (TNC), have completed ecoregional assessments for over 45 American and 14 Canadian or trans-boundary terrestrial ecoregions.

In 2007, the B.C. chapter of NCC launched the Central Interior Ecoregional Assessment (Nature Conservancy of Canada 2007b).

The NCC's ecoregional assessments are an example of conservation planning designed to identify priority areas for the protection of biological diversity. A system of ecoregional planning is used to create a conservation blueprint, which attempts to incorporate natural processes, including species migration, predator/prey relationships, and species' response to a variety of disturbances in order to identify and document a portfolio of sites desired for protection (e.g., a reserve network). If conserved, this portfolio should secure the long-term survival of viable native species and community types currently found in the region. NCC takes a "multi-filter approach" to conservation planning, attempting to provide fine-filter protection for individual rare elements, and a full range of representative habitats for coarse-filter ecosystem conservation (Scott et al. 1993).

The ecoregional assessment is carried out by NCC's conservation science and planning team, which consists of conservation planners, geographic information system (GIS) technicians, and ecologists who specialize in aquatic and terrestrial vertebrates, invertebrates, and plants, as well as the ecological processes which drive these ecosystems. These ecoregional assessments are carried out in collaboration with a wide range of government agency and environmental organization partnerships, and provide the rationale for making science-based, strategic investments in the conservation of biodiversity. The products of this process provide the information from which stakeholders can determine optimal conservation outcomes for proposed resource development projects (NCC 2007a,b). The steps to an ecoregional assessment are:

1. Identify conservation targets;
2. Assemble information on the locations or "occurrences" of targets;
3. Determine how to represent and rank target occurrences;

4. Set goals for each target;
5. Rate suitability of each part of the ecoregion for conservation;
6. Assemble draft conservation portfolios using reserve network design algorithms;
7. Refine the portfolios through expert review; and
8. Prioritize the potential conservation sites.

Marxan, an optimal reserve selection algorithm, is currently a fundamental tool used in the NCC's ecoregional assessment process. According to the developers (Ball and Possingham 2000), Marxan,

> "*... receives spatially-explicit data generated through GIS and applies spatial optimization algorithms to achieve a reasonably efficient solution to the problem of selecting a system of spatially cohesive reserves that meet a suite of multiple conservation targets (both coarse and fine filter) simultaneously.*"

Marxan is a greedy, heuristic, simulated annealing algorithm that prioritizes site selection based on the least cost (weighted sum of area and boundary length) for the most benefit. This particular algorithm is used because it identifies a large number of near-optimal solutions (termed "portfolios") to a set of stated objectives, which are based on user-defined parameters, (e.g., size, connectivity, representativeness and complementarity). Portfolios are refined using expert knowledge, and include recommended conservation-based prescriptions, as well as maps of the various Marxan outcomes. These final products are then used by planners and researchers to explore multiple scenarios when designing conservation networks (Ball and Possingham 2000).

The research described in this thesis is specific to the issue of biodiversity persistence and conservation network design, and may provide a framework applicable to the NCC's ERAP and to other protected area agencies, such as Parks Canada and B.C. Parks. The general purpose of this research is to explore the capacity of existing inventories and climate projection tools to identify priority areas for conservation having good prospects for relatively persistent climate over time. To address the impacts of climate change on the management of biodiversity, the concept of a "persistent climate corridor" is developed. A persistent climate corridor is the intersection of a target's current distribution with locations projected to remain within its bioclimatic envelope as projected into the 2080s. This intersection identifies areas where a particular climate zone (as uniquely defined for each conservation target) is expected to persist, based on the best available information of target distribution and localized expectations of climate change (Hannah et al. 2005). Areas so identified represent candidate areas for particular management practices, such as conservation prioritization and assisted migration of target species.

The identification of areas estimated to meet the requirements of particular bioclimatic envelope coincidence across different timeframes is becoming a popular tool in the field of conservation biology and climate change. For example, Berry et al. (2003) used the overlap between current and projected future species distributions based on bioclimatic envelopes to describe the degree of vulnerability a species might face in a changing climate. Overlap analysis may also prove to be a useful tool for exploring the role of competitive interactions or other influences on species distributions (Costa et al. 2008). Vos et al. (2008) combined bioclimatic envelope overlap with dispersal models to identify areas of spatial cohesion for successful colonization of new climate space.

Conservation Targets

The conservation targets used for my research were B.C. biogeoclimatic variants found in the Central Interior (103), NCC defined terrestrial ecological units (30) and "at risk" plant species (73). Rare plant communities or associations were not included in this analysis because the B.C. Conservation Data Centre (CDC) did not have any occurrence records for the Central Interior study area. These conservation targets represent a combined fine and coarse filter approach, which constitutes a basic component of the NCC's ecoregional assessment. An important part of this research is the exploration of how a species' biology affects its response to climate change. The identification of persistent climate corridors for Neck's Teas and B.C. BGC variants will offer insight into how spatial and temporal scales might influence the distribution and availability of suitable climate for particular coarse-scaled conservation targets. The resulting distribution of suitable climate space and any resulting persistent climate corridors should help support the decision-making components of the ERAP. The research will also identify important gaps in our knowledge, as well as aspects of our planning and management practices, which still need to be identified and addressed.

B.C. Biogeoclimatic Ecosystem Classification (BEC): Variants

The B.C. ecosystem classification system is a framework that groups ecosystems at regional, local and successional levels. At the regional level, vegetation, soil type and topography are used to infer the regional climate and identify areas (biogeoclimatic units) with relatively uniform climate. Locally, ecosystems are classed into site units according to relatively uniform areas of soil, vegetation and topography (Pojar et al. 1987).

In order to arrange these levels of integration (regional, local, successional) into a practical tool, the BGC framework combines vegetation, climate (zonal) and site characteristics and sometimes seral stage into a hierarchical classification system. Table 1.2 provides a summary of how each characteristic is used to classify ecosystems into progressively smaller, more site specific units.

In terms of the BGC classification system, this research focused on BGC subzones and any affiliated variants within the study area because they are the smallest units where climate is still the dominant control over ecosystem distribution. The B.C. BGC classification framework also provided one of the foundations for the classification of the terrestrial ecological units for the study area.

Table 1.2. The environmental characteristics used to classify terrestrial ecosystems (BCMFR 2009).

Classification	Description and Method
Vegetation	• Describes the vegetation of a mature ecosystem • Units are determined by grouping plot data and comparing results in a series of vegetation tables • The result is hierarchical: Class → Order → Alliance → Association (basic unit, differentiated by diagnostic species)
Climate (Zonal) e.g., Montane Spruce	• Regional (macro) climate that influences an ecosystem over an extended period of time, as well as prevailing soil processes • Geographic extent inferred by climax or late seral plant communities, less influenced by local topography or soil properties
Subzones e.g., Montane Spruce Dry Very Cold	• Basic unit of climatic classification • May include significant climatic variation marked by changes in vegetation (which are divided into variants, e.g., wetter, snowier, colder) • Derived from relative precipitation and temperature or continentality
Variants e.g., Montane Spruce North Thompson Dry Mild	• Represents a geographic name given to a relative location or distribution within a subzone • Often have distinctive biogeographic elements within the subzone
Site	• The basic unit is an association followed by series and type • Based on edaphic features (soil moisture and nutrients)
Seral or Successional	• Poorly described due to limited sampling • Incorporates complex interactions associated with disturbance history and ecosystem recovery • May span several variants and structural stages

NatureServe's Terrestrial Ecological Unit (TEU) Classification

The classification of the terrestrial ecological units was based on NatureServe's International Vegetation Classification (Comer et al. 2003), and as such reflects a standard methodology employed for ecosystem classification across North America. NatureServe defines an ecological system as "a group of plant communities that tend to occur within landscapes with similar ecological processes, substrates and/or environmental settings" (Comer et al. 2003). This classification system is based on a multiple criteria framework, which incorporates biotic composition (species abundance), environmental settings (moisture regime) and dynamic ecological processes (fire, flooding). Comer et al. (2003) describe the ecological concepts governing their classification framework as:

1) An ecosystem unit is explicitly scaled to represent spatial scales of tens to thousands of hectares and temporal scales of 50 to 100 years;
2) The variability in the system is explicitly described in terms of a consistent list of abiotic and biotic criteria, and by linking ecological systems to plant community types, which describe community variation;
3) Long-term sustainability and local stability are considered by mapping and evaluating the occurrence of ecological systems at local and regional levels; and
4) Population processes are not considered as explicit system dynamics, but through knowledge of the component plant communities.

This framework is based on recurring groups of biological communities that are found in similar habitats and are influenced by similar ecological processes, such as natural disturbance. Ecological factors termed diagnostic classifiers are integrated into this framework to further define and evaluate each classification unit, and to explain the spatial co-occurrence of plant associations. These diagnostic classifiers are described in Table 1.3 (Cromer et al. 2003).

In terms of the Central Interior study area, the classification of the terrestrial ecological units (TEU) was based on the B.C. BGC variant and site series classifications, as well as the B.C. CDC provincial classification of forested and non-forested units (Gwen Kittel *pers. comm.)*. Ecological characteristics (e.g., species composition and abundance, seral stage) refined these ecosystems into manageable units were obtained from the Prince Rupert, Prince George and Cariboo Forest Region guidebooks (Banner et al. 1993; Delong et al. 1993; Steen et al. 1997; Delong 2003) and BCMFR's Vegetation Resource Inventory (VRI) (Gwen Kittel, *pers comm*), which is essentially a forest cover map.

Table 1.3. A summary of the diagnostic classifiers used to describe ecological systems in NatureServe's International Vegetation Classification system (Cromer et al. 2003).

Diagnostic Classifier	Description
Ecological Divisions	Continental bioclimate, phytogeography, biogeography
Bioclimatic Variables	Regional bioclimate
Environment	Landscape position, hydrogeomorphology, soil characteristics, specialized substrate
Ecological Dynamics	Hydrological and fire regimes
Landscape Juxtaposition	Upland-wetland mosaics
Vegetation	Physiognomy, spatial pattern and patch type, composition and abundance of plant associations
Other	Soil chemical and physical properties, natural disturbance

To create the TEU map of the study area, NCC commissioned a reclassification of an existing map of the BGC variants into a different set of ecological systems. Vegetation data were augmented with VRI forest inventory data and leading species polygons using ArcMap® overlay analysis. No new line work was created in this mapping exercise. The final name of each TEU is a combination of regional distribution, environmental setting, and vegetation structure and composition, e.g., the North Pacific Sub-boreal (Ecodivision – regional distribution) Mesic (environmental setting) Hybrid Spruce Forest (vegetation structure and composition).

B.C. Conservation Data Centre (CDC) plant species

The target plant species for this research were selected based on the occurrence records found in the CDC data warehouse. Their conservation status and level of protection varies across the study area and are summarized in Appendix A, Tables A1 and A2. These species are designated "of conservation concern" for a variety of reasons such as habitat loss and low population numbers. Unlike BGC variants and TEUs these rare plants are designated by point occurrences (which may be incomplete) and often have ranges outside of B.C. As noted in Table A1, many of these species are more abundant elsewhere, and central B.C. populations are often marginal or incidental to the total range of a species.

Study Area

The Nature Conservancy of Canada's Central Interior ecoregion corresponds with the Central Interior and Sub-boreal ecoprovinces of Environment Canada's Ecological Classification system (Ecoregions Working Group 1989). The study area is approximately 246,000 km^2 (24.6 million hectares) and its geographic location ranges from 50.868° to 57.408 °N latitude and 131.166° to 119.987 °W longitude. The Central Interior includes several physiographic systems including the Chilcotin, Cariboo, Nechako and McGregor plateaus, the Chilcotin Ranges west to the centre of the Pacific Ranges, the southern portion of the Northern Rocky Mountain Trench, the Bulkley, Tahtsa and Hart Ranges, and the southern Muskwa Ranges and their associated foothills. The southern Skeena and Omineca Mountains are also included in the study area (Demarchi 1995; Figure 1.1).

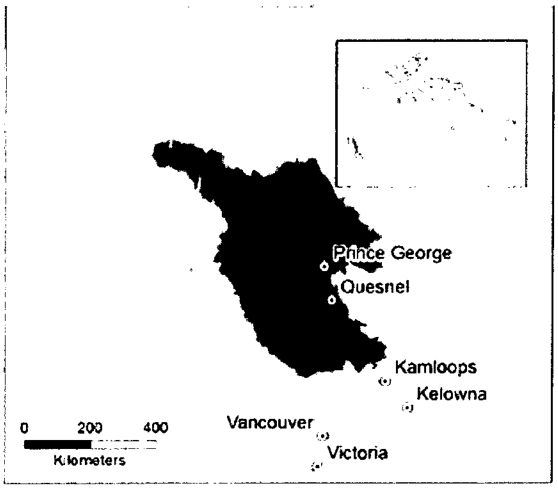


Figure 1.1. A map of the Central Interior study area (NCC 2007b).

Climate

The study area has a continental climate characterized by cold winters and warm summers. The influence of the topography and climate is typified by the Sub-boreal Spruce (SBS) and Interior Douglas-Fir (IDF) biogeoclimatic zones, which dominate much of the study area. The other biogeoclimatic zones, more fully described in Meidinger and Pojar (1991) are:

- Bunchgrass (BG),
- Alpine Tundra (AT),
- Engelmann Spruce-Subalpine Fir (ESSF),
- Montane Spruce (MS),
- Spruce-Willow-Birch (SWB),
- Sub-Boreal Pine-Spruce (SBPS),
- Boreal White and Black Spruce (BWBS) and
- Interior Cedar-Hemlock (ICH)

Wildlife

The Central Interior ecoregion supports a diversity of wildlife, including over 50% of the bird species that live and breed in B.C. This area also supports many ungulate species including *Alces alces* (moose) and *Odocoileus hemionus* (mule deer), as well as some of North America's fiercest predators, e.g., *Ursus arctos* (grizzly bear) and *Felis lynx* (lynx).

Soils and Land Use

According to the Soil Landscapes of British Columbia (B.C. Ministry of Environment, 1985), the soils in this area are dominated by Grey Luvisols with pockets of Humo-Ferric Podzols, Eutric and Dystric Brunisols, and Dark Brown and Dark Grey Chernozems, and provide opportunities for rangeland, agriculture, and forestry activities. Other resource-based industries include oil and gas exploration and development, and mining for base metals. According to the Protected Areas Strategy for B.C. (Ministry of

Environment, Land and Parks 1993), significant conservation and recreational features of Central Interior ecoregion include:

- Douglas-fir (*Pseudotsuga menziesii*) dry forest and scrub grassland habitats;
- Largely undisturbed subalpine spruce-fir forests and alpine tundra;
- Populations of the federally endangered woodland caribou (*Rangifer tarandus caribou*), present as both mountain and northern ecotypes;
- Deep fjord-like lakes with natural hydrology;
- Large unregulated rivers, with important salmonid spawning habitat for Fraser, Skeena, and Nass River runs;
- Lake-headed (warmer, more productive) rivers supporting sockeye salmon spawning habitat;
- Historic trails utilized by First Nations and fur traders; and
- Recreation corridors on both land and water.

Uncertainty

The sources of uncertainty are plentiful in ecology and the climate sciences, and often have a cumulative effect on the research as it progresses from the collection and generation of data to the analysis. The challenge of obtaining occurrence records which span a species' full range is one of many limitations that contribute to the uncertainty associated with BEM. Given their ubiquity, addressing all sources of uncertainty is impossible; however, an attempt should be made to identify and account for those uncertainties which will directly influence final results and ultimately final policy decisions. Some of the uncertainties associated with studying the effects of climate change on species distributions are summarized in Table 1.4.

Despite the uncertainty associated with combining climate change projections and bioclimatic envelopes to project potential future ranges for various species or ecosystems, the results can provide valuable biogeographic information, so long as model behaviour is well understood (Pearson et al. 2006). The performance of BEM is partially influenced by ecological and geographic characteristics of the distribution pattern of conservation targets including area and extent of occupancy, marginality, niche breadth and prevalence (rarity). The area and extent of occupancy relates to the geography of where a species is found on the landscape, which may be partially defined in terms of latitudinal or elevational limits that reflect strong climate limitations (Heikkinen et al. 2006). Understanding the role of these characteristics and how they impact model performance will help to reduce uncertainties, and improve the ability to differentiate between statistical artefacts and inherent biogeographic or ecological differences in the potential distribution of species (Heikkinen et al. 2006).

Conclusions

The concepts of bioclimatic envelopes, suitable climate space, and persistent climate corridors provide a simple and powerful tool kit for conservation planning under a changing climate, pertinent to the development and application of variety of management strategies. For example, the Nature Conservancy of Canada will use the final outcomes of this research as a pre-processing layer in their conservation plan for the Central Interior ecoregion in British Columbia. Government agencies such as the B.C. Ministry of Forests and Range can use the concept of persistent climate corridors in the development of monitoring programs and strategies for facilitating the expected migration of valuable tree provenances and species. As research continues to reveal the impacts of climate change on ecological systems, the need to develop and adapt new management strategies becomes increasingly urgent. Persistent climate corridors have the potential to assist managers as they cope with the challenges presented by climate-driven changes to the world's ecosystems.

Table 1.4. A summary of the sources of uncertainty pertinent to the use of bioclimatic envelopes to project ecological responses to climate change.

Source of Uncertainty	Description	References
Species response to climate and to climate change	• There are often key ecological features of species that remain unknown or have limited information: ecological plasticity, capacity for genetic adaptation, dispersal barriers and migration ability.	Hansen et al. 2001, Honnay 2002, Malcolm et al. 2002, Parmesan and Yohe 2003, Pearson and Dawson 2003
	• Acquiring this knowledge is hampered by complex interactions and processes, e.g., inter- and intra-species interactions such as predation and competition.	Hannah et al. 2002b Malcolm et al. 2003, Parmesan and Yohe 2003, Pearson and Dawson 2003, Botkin et al. 2007
	• Co-evolved species associations will not adapt synchronously, and these new associations will have unknown impacts on ecosystem function and structure.	Hannah et al. 2002b, Pearson and Dawson 2003, Botkin et al. 2007, Williams and Jackson 2007
	• Describing the climate across the known range of a species is constrained by the distribution of weather stations, how complete their records are, and by the limitations of tools designed to interpolate climatic conditions between those weather stations.	Hijmans et al. 2005, Wang et al. 2006
Source data	• Uncertainties arise from: insufficient or incomplete distribution data, poor or low quality data, and lack of or under-developed methodologies for quantifying certain types of information.	Johnson and Gillingham 2004, and Winte 2005, Moilanen et al. 2006, Botkin et al. 2007, Guisan et al. 2007
	• Failure to validate data can lead to erroneous assumptions about data accuracy and invalid output.	Pearson and Dawson 2003, Moilanen et al. 2006
	• Factors leading to uncertainties include lack of funding, disagreement among multiple sources, vague concepts and imprecise terms, lack of expertise, interpersonal dynamics and how data are solicited.	Hansen et al. 2001, Johnson and Gillingham 2004
Validity of predictions based on general circulation models (GCM)	• GCMs are subject to substantial uncertainty due to assumptions from difficult to measure parameters, ecosystem and atmospheric processes and interactions, and socio-economic conditions, e.g., the effects of land use/conversion on the atmosphere.	Malcolm et al. 2003, Kueppers et al. 2005, Pyke et al. 2005, Pyke and Fischer 2005
	• Different GCMs (e.g., CGCM, CSIRO, Hadley) and different scenarios for future carbon emissions result in different projections of future climate, with no limited indications as to which is most realistic for a given area.	Araújo and New 2006, IPCC 2007,
	• Current GCMs have a limited ability to resolve the spatial distribution of climate and vegetation in regions of complex topography.	Bartlein et al. 1997, Hamann and Wang 2006, Daly et al. 2000, 2002
	• Interpolation from a coarse scale model (e.g., GCM) to the landscape scale of a study area or an even finer scale of an occurrence record introduces cumulative errors.	Pyke et al. 2005, Pearson et al. 2006
Time lags	▪ A biogeographic lag exists between climate change and biome response, (i.e., changes in distribution or composition.) Time lags are very difficult to measure.	Malcolm et al. 2002, Parmesan and Yohe 2003, Leemans and Eickhout 2004, Hannah et al. 2005
Magnitude of error	▪ The difficulty in quantifying or assessing the degree to which uncertainties impact results as well as the direct impact of climate change	Kadmon et al. 2003, Araújo et al. 2005, Heikkinen et al. 2006

Chapter 2 - Proof of concept: Using bioclimatic envelopes to identify persistent climate corridors in support of conservation planning [*]

Abstract

Current and expected shifts in climate are threatening global biodiversity and are forcing managers to re-evaluate how they manage natural resources. Using the third generation of the Canadian general circulation model and ClimateBC, bioclimatic envelopes were developed for eleven Interior Cedar Hemlock biogeoclimatic variants, a North Pacific Interior Lodgepole Pine-Douglas-fir Woodland and Forest ecosystem type, and uncommon (B.C. blue-listed) lichen, *Nephroma occultum.* The geographic distribution of the resulting envelopes was projected for four timeslices, and then overlaid using ArcMap GIS software. The resultant intersection of areas is presumed to indicate locations of suitable climate over the study's timeframe. Next, the current distribution of the species or ecological unit was overlaid with its suitable climate space; the intersection of these points is considered the target's "persistent climate corridor." Current locations with persistent climate are thus expected to provide climatic continuity over time, sufficient to sustain the conservation target. The identification of such locations facilitates prioritization of sites for the designation of protected areas, and provides guidance on where other management policies can persist. The notion of persistent climate corridors is conceptually simple, yet this can be a powerful tool with many potential applications to assist natural resources managers in a rapidly changing environment.

[*] A slightly modified version of this chapter has been published as "Using bioclimatic envelopes to identify temporal corridors in support of conservation planning in a changing climate" Forest Ecology and Management 258 (Suppl.1):S64-S74.

Introduction

Climate is one of the dominant influences on plant species distribution over large areas, such as an ecoprovince or forest region. Understanding its mechanics and subsequent manifestation on the landscape is critical to the successful management and conservation of forest resources (Spittlehouse 2005). Integrating a greater understanding of climate into our management practices is becoming increasingly important as the impacts of climate change on the sustainability of natural resources become more apparent. Some potential climate-driven impacts include the extirpation or even extinction of rare and specialized species (Hansen et al. 2001; Schwartz et al. 2006), an increase in invasive species (Dale et al. 2001; Hannah et al. 2002b), and more frequent and intense forest fires (Flannigan and van Wagner 1990; He et al. 2002) and insect outbreaks (Volney and Fleming 2000; Bale et al. 2002). As a consequence of idiosyncratic adaptations to climate, species displacement and community re-organization will complicate current ecosystem knowledge and subsequent management practices (Suffling and Scott 2002).

As a result of the multitude of individual and interacting species' responses to climate change, large-scale changes in plant species distribution are expected (Thuiller et al. 2005). As our understanding of how ecosystems respond to climate change improves, it is becoming increasingly important to review current paradigms of ecosystem inventory and management, which tend to apply static boundaries to dynamic systems (Margules and Pressey 2000; Walther et al. 2002; Spittlehouse 2005). The dynamic nature of ecosystems, communities and populations is gradually being recognized and accommodated, as indicated by the development of climate prediction tools (Beaumont et al. 2005; Hannah et al. 2005), and the advent of innovative planning tools such as floating reserves (Cumming et al. 1996; Rayfield et al. 2008) and provision for dispersal corridors (Williams et al. 2005). The importance of re-evaluating the current "static ecosystem" paradigm is illustrated with current networks of protected areas. For example, as species respond individualistically to climate change and new ecological communities emerge, parks may no longer be able to support the values for which they were originally designed (Suffling and Scott 2002; Scott and Lemieux 2005).

The purpose of this chapter is to explore the capacity of existing inventories and climate projection tools to identify candidate areas (for conservation or other management objectives) that have good prospects for relatively persistent climate over time. The ecological foundation for this research is supported by niche theory, as well as concepts well established in conservation biology, namely the value of habitat connectivity and the use of gap analysis in conservation planning. Central to this process is the well-developed concept of the bioclimatic envelope, and the novel concept of the persistent climate corridor.

Bioclimatic envelope modelling

Bioclimatic envelope modelling is used to describe the present and future distribution of ecological elements, whether individual species or entire life zones, based on suitable climate conditions. The model's development and subsequent application is supported by niche theory (Vandermeer 1972; Austin 2002; Leibold 1995), which describes the climatic niche as a functional or conceptual space defined on multiple axes of climatic variables (Figure. 2.1). The climatic niche is one aspect of an organism's or ecosystem's fundamental niche, excluding several admittedly important environmental constraints based on soils, topography, and biotic interactions such as competition or predation. Furthermore, the climatic niche is assumed to remain static and does not take dispersal ability or evolutionary adaptation into consideration when extrapolating from current distributions to future potential distributions (Pearson and Dawson 2003; McKenney et al. 2007b). Despite their inability to account for these key ecological processes, bioclimatic envelopes are appropriately employed at regional scales where climate has a dominant influence on species distribution (Pearson and Dawson 2003). Geographically calibrated bioclimatic envelopes are an inherently conservative tool for habitat modelling in that there is no danger of identifying 'false positives' for climatically suitable habitat; they allow firm identification of *some* known acceptable climates, even if the definition of *all* acceptable climates (which could be occupied by the target but are not) is incomplete. Furthermore, this modelling strategy is ideally suited to presence-only data, a characteristic of most conservation targets (Kadmon et al. 2003; Beaumont et al. 2005).

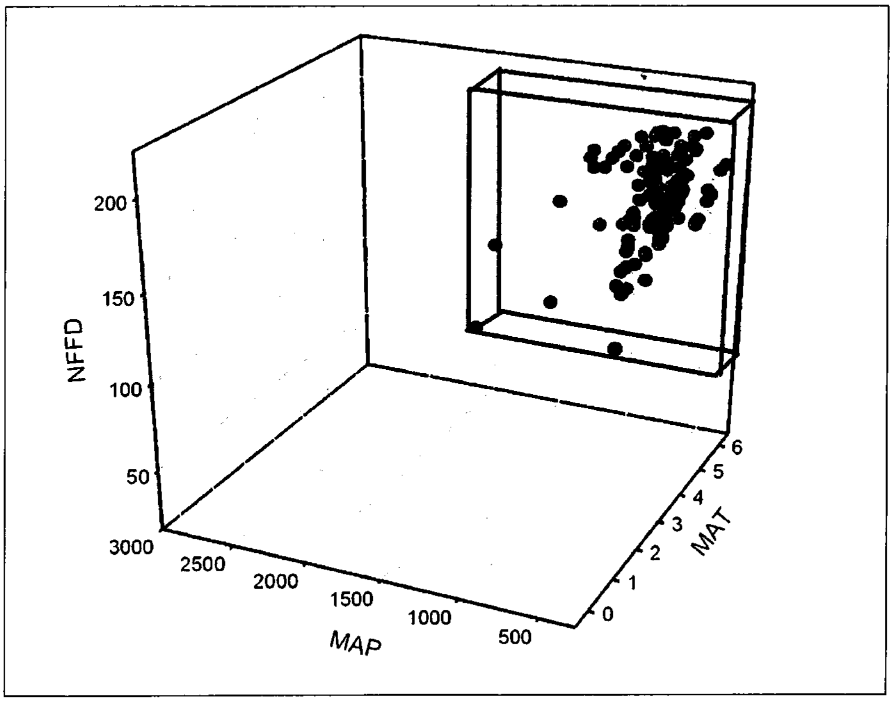


Figure 2.1. An example of the conceptual or functional space describing the bioclimatic envelope of the dainty moonwort fern, *Botrychium crenulatum* Wagner. Axes shown here represent the B.C.-wide range for mean annual precipitation (MAP, mm), mean annual temperature (MAT, °C), and number of frost free days (NFFD), with only a subset of each being suitable for this species. The bioclimatic envelope for a specific conservation target can be further narrowed by consideration of additional or alternative climate attributes.

There is a vast array of methods available for generating bioclimatic envelopes. Most of these methods use one of the following statistical approaches: general linear models (GLM), general additive models (GAM), artificial neural networks (ANN), ecological niche factor analysis (ENFA), or classification and regression tree (CART) analysis. More recently, innovation in the field of statistical modelling has generated an exponential distribution model using maximum entropy (MAXENT), and a multivariate adaptive regression splines modelling approach (MARS) that combines linear regression, the mathematical construction of splines, and binary recursive partitioning to produce a model with linear and non-linear relationships (Guisan and Zimmermann 2000; Heikkinen et al. 2006). Examples of bioclimatic envelope models include BIOCLIM (Busby 1991), HABITAT (Walker and Cocks 1991) and DOMAIN (Carpenter et al. 1993). For a detailed summary of these modelling approaches, including the well described ENVELOP approach, see Guisan and Zimmermann (2000). Shortcomings of the bioclimatic envelope approach include the misrepresentation of suitable climate (commission and omission errors; Guisan and Zimmermann 2000; Heikkinen et al. 2006), the exclusion of possible interactions and partial substitutions, a propensity for autocorrelation and multi-collinearity, and problems with model validation (Kadmon et al. 2003; Araújo et al. 2005; Beaumont et al. 2005).

It has also been recommended that bioclimatic envelopes be coupled with process-based models for a more refined projection of climate change impacts on biodiversity. For example, Pearson et al. (2002) coupled bioclimatic envelope models with a climatic-hydrological process model to predict the potential distribution of *Protea* species under climate change scenarios. Pyke and Fishcer (2005) also incorporated hydrological variables into their bioclimatic representation of fairy shrimp (*Anostraca* species) vernal habitat in the Central Valley ecoregion of California. Other studies exploring the impacts of climate change on plant species and community distribution coupled GCM output with dynamic vegetation models (Burton and Cumming 1995; Malcolm et al. 2002; Scott et al. 2002; Lenihan et al. 2003; Lemieux and Scott 2005). Coupling dynamic models with bioclimatic envelopes is beyond the scope of the preliminary analysis and proof of concept reported here. These projections will be used in conjunction with The Nature Conservancy of Canada's large scale multi-filter ecoregional assessment (as outlined in Chapter 1), which uses expert knowledge and stakeholder input to address some of the shortcomings associated with any one modelling approach.

Persistent climate corridor modelling

To address the impacts of climate change on the management of biodiversity, the concept of a "persistent climate corridor" is developed. A persistent climate corridor extends the theoretical basis for landscape (spatial) corridors to provide continuity in time as a fourth dimension. In general, the purpose of landscape corridors is to provide continuity in geographic space. Maintaining genetic and habitat diversity support species persistence over time (Shafer 1990; Primack 2006). Consequently, the inclusion of climatic continuity over time in conservation planning enhances the decision making process and improves the prospects for resource sustainability.

A persistent climate corridor is identified through the intersection of an ecological feature's current distribution with locations expected to remain within that feature's bioclimatic envelope as projected for the foreseeable future. This intersection identifies areas where a particular climate is expected to persist, based on the best available information of the feature's distribution and downscaled prediction of climate change. Areas so identified represent candidate areas for particular management practices, such as conservation prioritization or the assisted migration of target species. Persistent climate corridors only indicate that certain locations are less at risk from climate change than other locations, and do not address other threats such as habitat destruction or displacement by invasive species.

The idea for my thesis developed from the post-doctoral work of Drs. A. Hamann and T. Wang (2004, 2006), who used bioclimatic envelopes to project future distributional changes to biogeoclimatic zones. These zones represent landscape units based on climatic and physiographic features, and provided a valuable stepping-stone towards the conceptualization of persistent climate corridors. From here I moved to finer-scaled targets for which I hoped to refine my methods and develop a decision support tool which could more fully describe a target's potential future distribution. This chapter is offered as a proof of concept in applying these tools to three different types of conservation targets. It can serve as a template by which researchers and managers can begin to practically address the challenge of a changing climate.

Methods

The primary tools used to identify persistent climate corridors were the 3rd Generation of the Canadian general circulation model (CGCM3; Environment Canada 2008) and ClimateBC and ClimatePP climate downscaling and interpolation software (Hamann 2008). The identification of persistent climate corridors comprises the following four steps: 1) the development of bioclimatic envelopes for management targets; 2) the identification of locations projected to have future climates within each target's bioclimatic envelope for four timeslices ("current," defined as 1961 to 1999; the 2020s; 2050s and 2080s); 3) the overlay and intersection of these four timeslices using ArcMap® 9.2 GIS software (the identification of locations with a suitable climate space); and 4) a final overlay of suitable climate with a target's current distribution. In order to illustrate the development and application of the persistent climate corridor concept, the following three management targets found in the Central Interior and Sub-Boreal ecoprovinces of B.C., Canada, were used in this analysis:

- Biogeographical variants of the Interior Cedar-Hemlock (ICH) biogeoclimatic zone (Ketcheson et al. 1991);
- The North Pacific Interior Lodgepole Pine-Douglas-fir Woodland and Forest vegetation type, as defined by the Nature Conservancy of Canada; and
- An uncommon (B.C. blue-listed) lichen, *Nephroma occultum* Wetm.

These management targets are a subset of those used in the Nature Conservancy of Canada's Central Interior Ecoregional Assessment process for protected area planning. This project area, constituting the Central Interior and Sub-Boreal ecoprovinces, served as the study area defining the spatial extent of the conservation targets explored here. Some conservation targets considered in that planning process are rare plant species or plant communities with individual locations of known occurrence, while other targets represent broad vegetation or ecosystem types, mapped over relatively large areas. The full set of persistent climate corridors identified in this study (of which only some are presented here) will be used in a site prioritization and selection process as part of the Nature Conservancy of Canada's ecoregional assessment, which is expected to provide fine-filter protection for those rare elements, and a full range of representative habitats for coarse-filter conservation as well (Noss 1987; NCC 2007).

Defining bioclimatic envelopes for different conservation targets

The selection of modelling and projection tools is dependent on research goals (e.g., to project species distribution, abundance, habitat suitability, probability of occurrence, or vulnerability), data type (absence and/or presence, relative abundance), data quality or reliability, and sample size. The ENVELOP-type modelling approach (Guisan and

Zimmerman 2000) employed for this research was chosen because it is well suited for presence-only data, which were largely obtained from online herbaria and conservation and natural heritage data warehouses and from pre-existing map polygons. ClimateBC was used for climate interpolation and projection because it is easily accessible and calibrated for the study area (Hamann and Wang 2004, 2006; Spittlehouse 2006), it generates data amenable to this modelling approach, and it includes a wide selection of general circulation model (GCM) outputs from which to chose for future climate scenarios (Hamann 2008).

Occurrence data (longitude, latitude, elevation) were collected for each conservation target. Since there were two types of distribution data (area-based and point-based), two separate methods were devised to capture the data necessary for the development of bioclimatic envelopes. Mapped coverages of the Interior Cedar-Hemlock (ICH) variants and The Nature Conservancy of Canada's North Pacific Interior Lodgepole Pine-Douglas-fir Woodland and Forest were each overlaid with a 1-km grid covering their entire range in B.C. A simple overlay of these coverages using ArcMap® produced a layer of points, which provided latitude, longitude and elevation values representing each 1-km^2 of the target's current mapped range. In contrast, point locations for all documented locations of populations of the rare *Nephroma occultum* lichen were collected from a variety of conservation data centres, online sources and university herbaria. This extensive search for all possible species occurrence data (including locations beyond our study area) ensured that the resulting bioclimatic envelope was described as fully as possible. The bioclimatic envelope for *Nephroma occultum* was generated using 86 unique locations from across the geographic range covered by ClimateBC and ClimatePP including as far south as Idaho and as far east as Ontario. The four known locations of this species in the B.C. Central Interior study area were then evaluated in terms of their potential to support persistent climate corridors.

ClimateBC and ClimatePP (Mbogga et al. 2009) were used to describe current (1961 to 1990) and projected future climates (based on the A2 scenario of the CGCM3 model) for each point. Climate data interpolated or estimated for each target point consisted of 19 variables, which were narrowed down to four orthogonal indicators to reduce collinearity:

- Mean annual temperature (MAT, in °C);
- Continentality, or temperature differences (TD, the difference in mean temperature of the warmest month and mean temperature of the coldest month, in °C);
- Annual heat moisture index (AHM, calculated as (MAT+10)/(mean annual precipitation in mm/1000)); and
- Precipitation as snow (PAS, in units of mm water equivalent).

The variables selected to define bioclimatic envelopes were the most strongly correlated with the first four principal components of a simple principal components analysis, and explained >95% of the variance in current province-wide climate. A Pearson's covariance matrix of the province-wide climate data verified that MAT, TD, AHM and PAS were the least correlated, and therefore represent a set of largely orthogonal variables that can describe most of the variation in B.C.'s climate.

In order to capture the core range of targets, devoid of anomalous and possibly erroneous data, the 5th and 95th percentiles of these variables were calculated for each target's current climate using PROC MEANS (SAS Institute 2004). Collectively, these values describe a target's current bioclimatic envelope.

Identifying a target's persistent climate corridor

Locations expected to be within the current bioclimatic envelope of each management target were projected for the current, 2020s, 2050s and 2080s timeslices using a 1-km grid for the province as a whole, or for just the Central Interior and Sub-Boreal ecoprovinces. A series of conditional statements in SAS was used to query each 1-km grid point to ascertain whether it was within the envelope (5^{th} to 95^{th} percentiles for each of the four selected climate variables) for a given conservation target in each timeslice. Maps portraying locations projected to be suitable, as defined by the target's current envelope are described as envelope areas; the envelope areas for each timeslice were then overlaid using the "Overlay-Intersect" tool in ArcMap. Where the intersection of these timeslices identifies locations of suitable climate for all four timeslices, I infer that those locations are expected to remain adequately constant for the specified conservation target over the 75-year planning period; collectively, those locations are referred to as the "suitable climate space". Locations where the current distribution of a target and the locations of suitable climate space coincide designate a persistent climate corridor, and therefore represent priority candidate areas for management or conservation. Given the uncertainties inherent to original location information, recorded to the nearest minute, any point within 500 m of a target location projected to have a persistent climate was considered to be within its persistent climate corridor. The approach is illustrated by providing mapped output and area-based tabular summaries for some coarse (e.g., biogeoclimatic zones) and fine (e.g., individual rare plant species) conservation targets.

Results

Biogeoclimatic Zones and Interior Cedar-Hemlock (ICH) variants

The overlay-intersection method was initially applied to the biogeoclimatic zones in B.C. In addition to portraying important contractions in the geographic distribution of these broad ecological zones, the analysis of climatic envelopes, suitable climate space and persistent climate corridors permits a simple summarization of expected range shifts, thereby providing an illustration of the potential magnitude of climate change impacts for a given area. Despite the inherent uncertainty, the findings presented in Tables 2.1 and 2.2 (based on the zonal projections published by Hamann and Wang 2006) show a general shift poleward of biogeoclimatic zones, as well as an average shift from low to higher elevations.

The overlay and intersection procedures possible through the use of GIS utilities greatly aids in the visualization and analysis of projected conditions over multiple timeslices. Such overlay work is central to any sort of gap analysis in support of regional conservation planning. Figure 2.2, for example, shows B.C.'s current parks and protected area network overlaid with the persistent climate corridors for the biogeoclimatic zones of the province (derived from projections published as Figure 2.2 of Hamann and Wang (2006), and summarized here in Tables 2.1 and 2.2). The fact that there is little temporal climatic connectivity for many parks and protected areas illustrates a flaw in treating conservation areas as fixed and static. It is probable that the distribution of persistent climate corridors across the landscape is also restricted by the complex topography of B.C.'s landscape, providing very little opportunity for climatic stability and spatiotemporal connectivity.

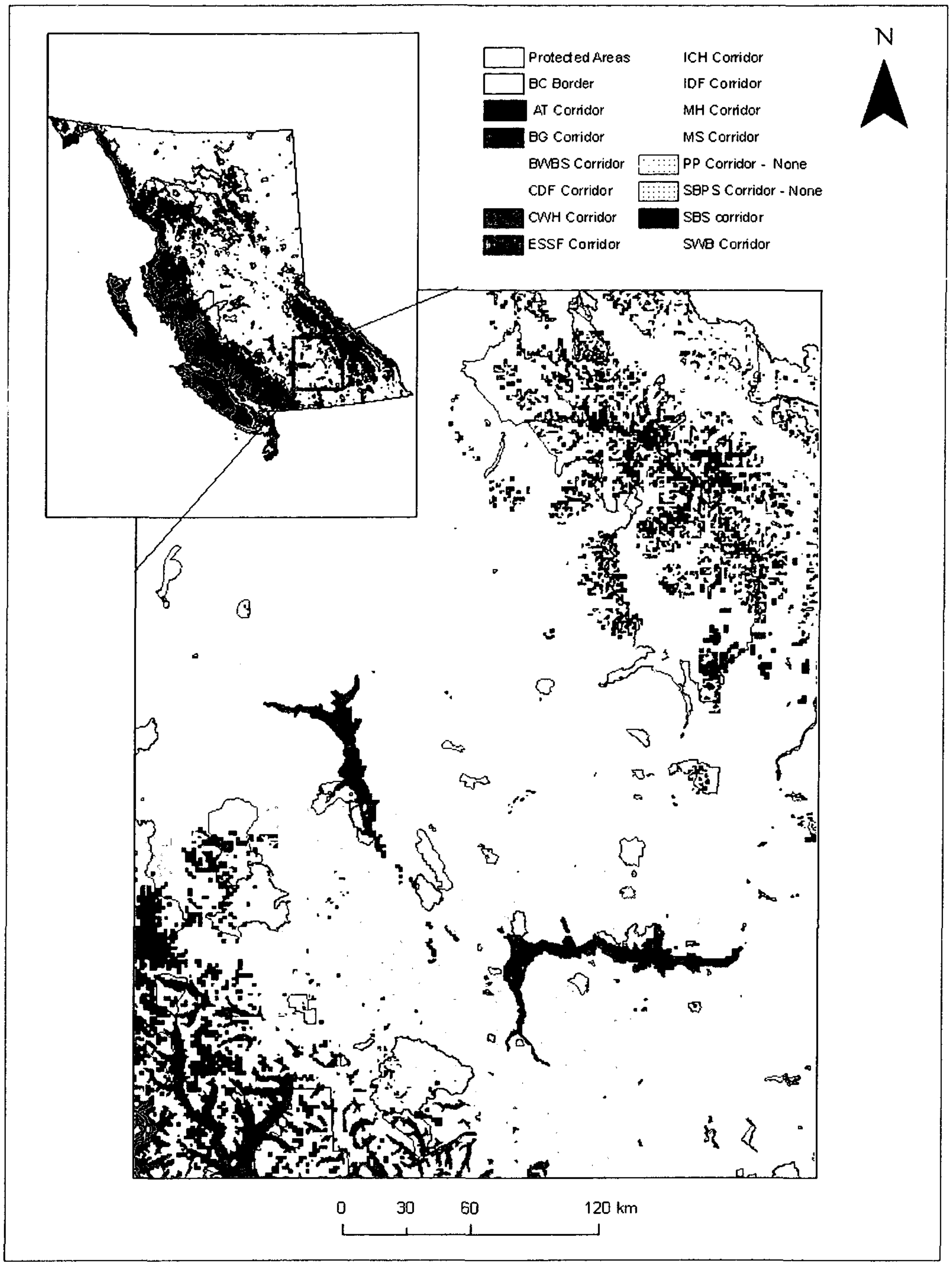


Figure 2.2. Graphical gap analysis showing the locations of persistent climate corridors projected for the biogeoclimatic zones of south-central British Columbia and for the province as a whole relative to the distribution of existing parks and protected areas. Abbreviations for the biogeoclimatic zones are defined in Table 2.1 and 2.2.

Table 2.1. A summary of the mean values and standard deviations for elevation (m) and latitude (°N) of the bioclimatic envelope area for each B.C. biogeoclimatic zone for all four timeslices and its associated persistent climate corridor (PCC)

Biogeoclimatic Zones	Base (1960-1990)		020		2050		2080		Persistent Climate Corridors		
	Mean Latitude	Mean Elevation	Mean Latitude	Mean Elevation	Mean Latitude	Mean Elevation	Mean Latitude	Mean Elevation	Mean Latitude	Mean Elevation	% of Current Area
AT, Alpine Tundra	55.47	1844	55.69	1819	55.30	1844	55.11	1825	60.00	1844	1.68
	(-2.16)	(-327)	(-3.18)	(-427)	(-3.35)	(-480)	(-3.3)	(-518)			
BG, Bunchgrass	50.62	593	50.90	702	50.90	773	50.83	838	51.97	526	69.41
	(0.77)	(199)	(1.06)	(237)	(1.13)	(248)	(1.25)	(266)			
BWBS, Boreal White and Black Spruce	58.16	706	58.29	768	58.62	786	58.86	926	60.01	601	26.98
	(1.39)	(208)	(1.40)	(277)	(1.11)	(318)	(1.01)	(395.30)			
CDF, Coastal Dougls-fir	49.04	37	49.08	74	49.67	73	50.22	74	49.99	37	25.76
	(0.37)	(56)	(0.52)	(113)	(1.19)	(106)	(1.67)	(101.84)			
CWH, Coastal Western Hemlock	51.64	348	51.77	550	51.89	636	51.99	724	58.82	360	26.29
	(2.05)	(314)	(2.12)	(484)	(2.15)	(522)	(2.18)	(555)			
SSF, Engelmann Spruce Sub-alpine Fir	53.32	1552	55.18	1573	55.83	1625	56.39	1700	60.00	1727	1.24
	(2.61)	(347)	(3.11)	(360)	(3.04)	(355)	(2.88)	(347)			
ICH, Interior Cedar Hemlock	51.99	942	52.97	1096	53.15	1177	53.24	1288	57.17	1059	4.64
	(2.29)	(341)	(2.29)	(329)	(2.49)	(351)	(2.78)	(404)			
IDF, Interior Douglas-fir	50.83	1004	51.90	1062	53.55	979	54.33	1077	52.43	1210	62.70
	(-0.91)	-242	(-2.18)	(-295)	(2.33)	(284)	(2.58)	(264)			
MH, Moutain Hemlock	52.79	1085	53.30	1224	53.63	1360	53.98	1520	58.84	1127	1.19
	(2.44)	(265)	2.327	406.4567	(2.30)	(368)	(2.45)	(366)			
MS, Montane Spruce	50.88	1424	53.14	1358	54.53	1358	55.82	1457	52.23	1621	0.22
	(1.20)	(165)	(3.03)	(378)	(3.16)	(357)	(3.22)	(361)			
PP, Ponderosa Pine	49.96	636	50.17	786	52.66	823	55.77	787	0.00	NA*	0.00
	(0.58)	(188)	(0.67)	(193)	(2.70)	(231)	(2.67)	(228)			
SBPS, Sub-boeal Pine Spruce	52.37	1143	52.76	1256	52.77	1394	52.80	1575	0.00	NA*	0.00
	(0.56)	(139)	(1.57)	(163)	(1.80)	(180)	(1.00)	(96)			
SBS, Sub-boreal Spruce	54.37	889	54.65	940	56.06	1089	55.43	1284	59.94	1052	0.91
	(1.26)	(167)	(2.03)	(224)	(3.11)	(233)	(3.33)	(219)			
SWB, Spruce Willow Birch	58.54	1273	58.89	1448	58.80	1661	58.62	1716	59.72	488	0.03
	(0.88)	(219)	(1.21)	(265)	(0.77)	(354)	(0.73)	(519)			

* These values are not applicable because a persistent climate corridfor doesn't exist for these zones

Table 2.2. Summary of the area (km^2) within the bioclimatic envelope for each of the B.C. biogeoclimatic zones and their projected changes over time, their associated persistent climate corridors and the current representation of those persistent climate corridor.

Biogeoclimatic Zone	Basline	2020	2050	2080	Persistent climate Corridor (PCC)	% PCC of Current Area	km^2 PCC protected	% PCC Protected
AT, Alpine Tundra	187,644	73,385	44,879	33,065	31,613	2.0	7,679	24
BG, Bunchgrass	3,299	13,215	26,427	44,452	2,290	6.0	258	11
BWBS, Boreal White and Black Spruce	163,056	163,182	139,873	88,246	43,993	27.0	1,860	4
CDF, Coastal Douglas-Fir	14,140	6,072	10,355	16,015	3,642	26.0	164	5
CWH, Coastal Western Hemlock	398,503	155,633	169,175	179,100	104,758	26.0	1,178	1
ESSF, Engelmann Spruce - Subalpine Fir	148,087	192,225	187,228	132,339	1,834	1.0	588	32
ICH, Interior Cedar-Hemlock	53,502	127,350	152,346	184,827	2,483	5.0	891	36
IDF, Interior Douglas-Fir	44,410	61,722	139,625	111,565	2,765	63.0	324	12
MH, Mountain Hemlock	36,558	26,117	16,486	7,232	435	1.0	61	14
MS, Montane Spruce	28,098	27,302	23,736	17,254	62	0.0	8	13
PP, Ponderosa Pine	3,567	9,257	21,734	14,0657	0	0.0	0	0
SBPS, Sub-Boreal Pine Spruce	24,050	14,369	5,048	489	0	0.0	0	0
SBS, Sub-Boreal Spruce	103,012	81,336	28,687	14,139	934	1.0	44	5
SWB, Spruce-Willow-Birch	74,944	18,964	4,529	750	21	0.0	14	67

Of the eleven ICH variants in the study area, only two are expected to have persistent climate corridors. Table 2.3 summarizes the extent of the each variant's current distribution, its associated suitable climate and persistent climate corridor, as well as the percentage of the current distribution represented by the PCC. Figure 2.3 maps the locations in which climate suitable for ICHmc1 is expected to remain suitable, and thus the locations where this BGC variant can be expected to exhibit a PCC. Despite a relatively large current distribution, there is little overlap with the locations expected to show persistent climate; consequently, the ICHmc1 persistent climate corridor is expected to represent only approximately 4% of its current distribution. In contrast, the ICHvc experienced the only increase in its suitable climate space of the eleven ICH variants. More interestingly, this increase is expected to result in a potential range covered by suitable climate that is approximately 9.25 times its current distribution in the study area (Table 2.3). Overlaid on its current distribution, this expected expansion of persistent climate contributed to identification of a persistent climate corridor (182 km^2), constituting approximately 13% of this variant's current distribution.

Table 2.3. Selected Interior Cedar-Hemlock biogeoclimatic variants found in British Columbia, and their expected persistence.

Variant	Description	Current Area (km^2)	Persistent Climate Range (km^2)	Persistent Climate Corridor (PCC) (km^2)	Current area represented by PCC (%)
ICHdk	Interior Cedar-Hemlock, dry cool	351	0	0	0
ICHmw3	Interior Cedar-Hemlock, Thompson moist warm	3,541	0	0	0
ICHmk2	Interior Cedar-Hemlock, Thompson moist cool	891	0	0	0
ICHmk3	Interior Cedar-Hemlock, Horsefly moist cool	1,072	0	0	0
ICHmc1	Interior Cedar-Hemlock, Nass moist cold	5,343	3,677	203	4
ICHmc2	Interior Cedar-Hemlock, Hazelton moist cold	3,276	0	0	0
ICHwk2	Interior Cedar-Hemlock, Quesnel wet cool	2,038	0	0	0
ICHwk3	Interior Cedar-Hemlock, Goat wet cool	943	0	0	0
ICHwk4	Interior Cedar-Hemlock, Cariboo wet cool	1,425	0	0	0
ICHvk2	Interior Cedar-Hemlock, Slim very wet cool	2,834	0	0	0
ICHvc	Interior Cedar-Hemlock, very wet cold	1,449	13,403	182	13

North Pacific Interior Lodgepole Pine – Douglas-fir Woodland and Forest

The extent of suitable climate for the North Pacific Interior Lodgepole Pine -Douglas-fir Woodland and Forest under current climate conditions is estimated to occupy some 57,000 km^2 of the study area, though only 11,828 km^2 of this area is currently occupied by this ecosystem unit (Figure 2.4). A large area (22,661 km^2) covered by such suitable climate is expected to persist, but the current distribution of this relatively warm and dry vegetation type means that the persistent climate corridor is projected to occupy only 1,131 km^2, which would represent only 10% of its current area.

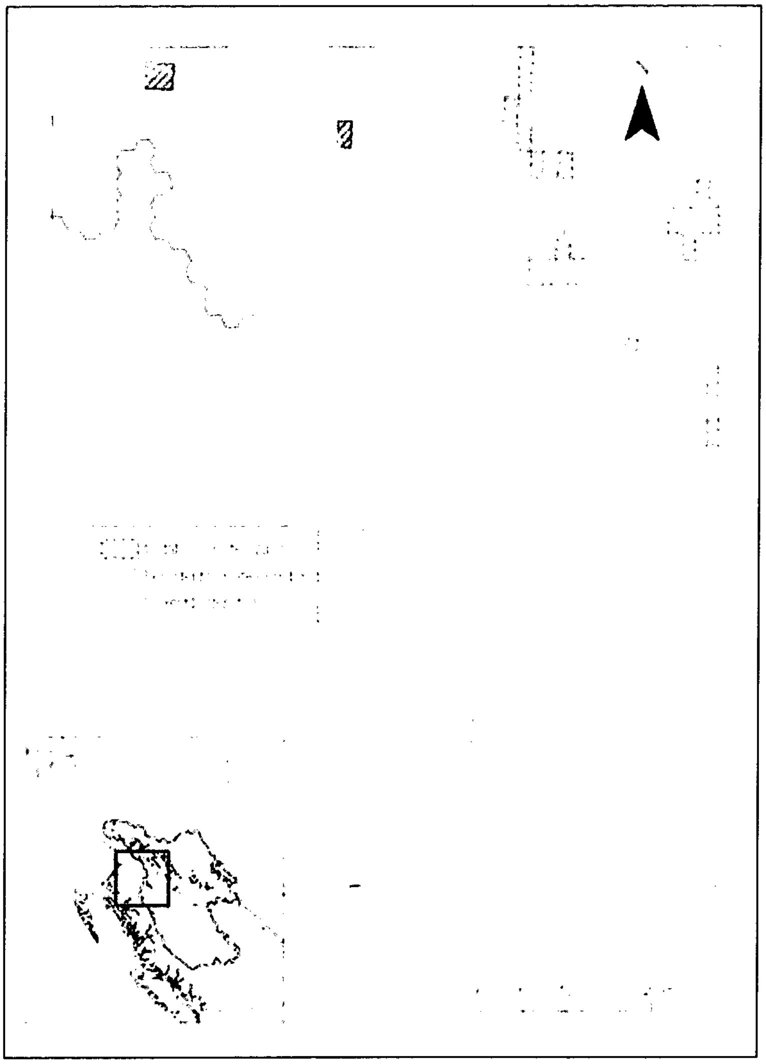


Figure 2.3. Locations of persistent climate corridors projected for the Nass Moist Cold Interior Cedar-Hemlock (ICHmc1) biogeoclimatic variant.

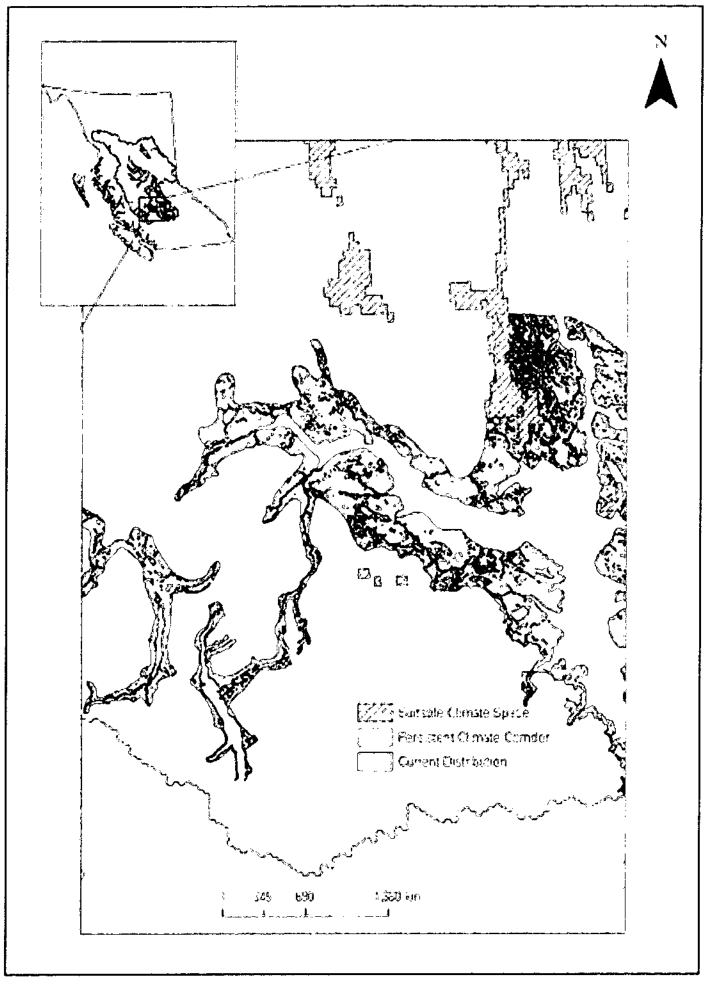


Figure 2.4. The current distribution, locations expected to exhibit persistent suitable climate, and the resulting persistent climate corridors projected for the North Pacific Interior Lodgepole Pine –Douglas-fir Woodland and Forest ecosystem unit in the study area.

<u>Nephroma occultum</u>

For many individual species as well, current climatic envelopes suggest that persistent climate can be expected over large areas, but often where populations are not currently found. This is particularly evident for rare species such as *Nephroma occultum* as shown in Figure 2.5. In this example, there are four occurrences of *Nephroma occultum* in the study area, with only one population located in an area projected to exhibit persistent climate.

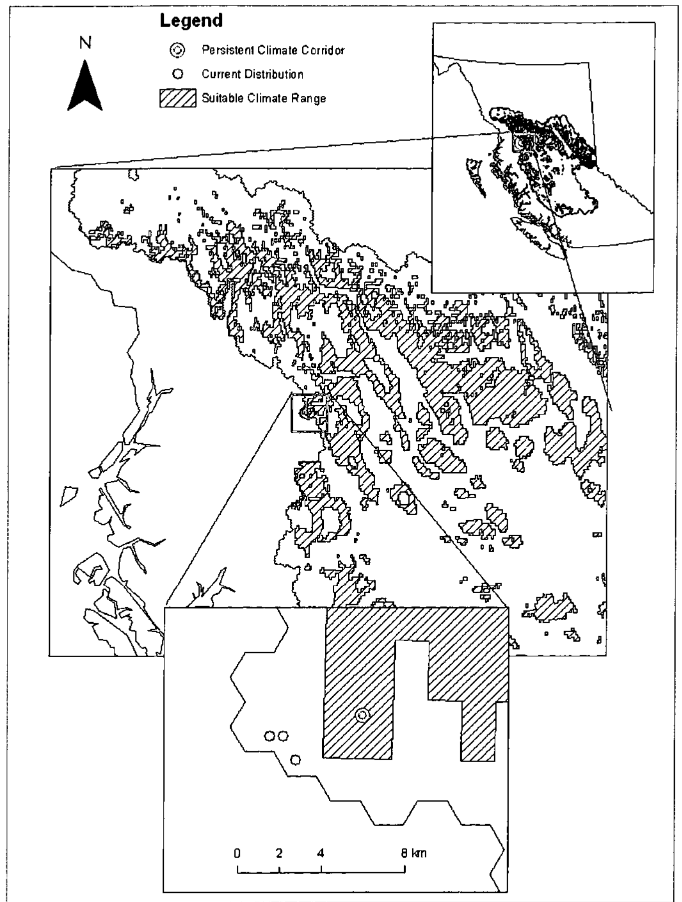


Figure 2.5. Locations of suitable climate space and persistent climate corridor projected for *Nephroma occultum* in the Central Interior study area.

Discussion

Overview

Many caveats apply to the identification of locations expected to have suitable climate space and those having the possibility of providing continuity over time as persistent climate corridors. For all area-based targets, whether biogeoclimatic zones, terrestrial ecosystem units, or plant communities, there is some degree of arbitrary delineation in their definition, as constrained by their current expression under associated climatic and geographic parameters. In other words, how they are distinguished from another similar unit can be very arbitrary, e.g., the Interior Cedar Hemlock (ICH) versus the Coastal Western Hemlock (CWH), or the ICHmc1 versus the ICHmc2 variant. It is also important to recognize that a biogeographic lag exists between climate change and vegetation response such as observable changes in distribution or composition (Parmesean and Yohe 2003; Fitzpatrick et al. 2008). This lag is highlighted by my distinction between locations characterized by persistent climate and those identified as suitable persistent climate corridors: the contradiction of climate change is that there are expected to be larger areas suitable for most of the conservation targets in my study area, however they do not coincide with locations in which these sedentary targets are currently found (Figures 2.2 to 2.5, Tables 2.2, 2.3).

Overall, my results agree with other studies (e.g., Pearson and Dawson 2003; McKenney et al. 2007b) which show that conditions suitable for the persistence of many existing plant species and ecological communities are expected to contract. In my study area, this is shown by the ICH variants (Table 2.3 and Figure 2.3), and the Lodgepole Pine-Douglas-fir Woodland and Forest ecological unit (Figure 2.4). Many rare plant communities (not specifically explored in this thesis) represent unique combinations of climate, soils, floristics and disturbance history, which may not be sustainable under changing climate conditions (Hansen et al. 2001; Gayton 2008; Van der Veken et al. 2008).

The goal of this research was to assist the Nature Conservancy of Canada in refining their ecoregional assessment process to include the impacts of climate change (see http://science.natureconservancy.ca/centralinterior). The concept of persistent climate corridors is designed as an addendum to their fine-filter approaches to conserve individual species which are considered rare or of conservation concern, and coarse-filter approaches to conserve representative ecological communities. The Nature Conservancy of Canada's ecoregional assessment is an intensive data gathering undertaking, which considers multiple inputs (e.g., the range of target animal species, aquatic features, the extent or frequency of natural and anthropogenic disturbance), as well as scientific expertise and priorities of various stakeholders. The climate change component of this ecoregional assessment also incorporates expert knowledge to address the vast uncertainties associated with climate change scenarios and species distribution projections. Recommendations for conservation priorities based on suitable climate and persistent climate corridors will serve as one of many inputs to an iterative, heuristic site selection process using the Marxan reserve selection software (Ball and Possingham 2000).

Trends in my results identifying locations with higher elevations and latitudes (than what is current) as becoming more suitable for lower-elevation and more southerly ecosystems (Table 2.1) likewise concur with the majority of the literature exploring the potential outcomes of climate change (Parmesan and Yohe 2003; Spittlehouse 2005; Hamann and Wang 2006). On the other hand, some of my results may be counter-intuitive to what might be expected. For example, despite an increase in climatically suitable area over time, the Ponderosa Pine (PP) zone and the Sub-Boreal Pine-Spruce (SBPS) zone are not expected to have persistent climate corridors (Figure 2.1). The lack of a persistent climate corridor for the PP zone is particularly ironic given that this zone is characterized by a hot, dry climate (Hope et al. 1991), and thus might be expected to persist and expand under global warming as projected by some models. Unfortunately (from an ecosystem conservation perspective), most of the area expected to be suitable for the characteristic ponderosa pine ecosystem is not currently occupied by those forests or woodlands, while current areas will become so hot and dry that they may only support grassland or sagebrush (BCMFR 2006b).

The lack of identifiable persistent climate corridors for the PP and SBPS zones, plus most of the ICH variants explored in this paper (Table 2.3) presents conservation managers with a number of challenges. For example, if current locations occupied by these identifiable ecosystems are not suitable for sustaining them, should programs of facilitated migration and ecosystem engineering be employed at locations expected to support persistent climate for these conservation targets? The expected loss of nine out of the 11 ICH variants in my study area is particularly disturbing, considering that these inland rainforests are globally unique, with old-growth phases supporting many rare and disjunct lichen species including *Nephroma occultum* (Goward and Spribille 2005).

A number of important questions regarding a conservation target's ecology and its subsequent management arise with the identification of persistent climate corridors. For example, despite an expansion of suitable climate space, *Nephroma occultum* has only one occurrence within the area expected to sustain a persistent climate. Consequently, available information suggests that there can only be one location expected to serve as a persistent climate corridor for this species in my study area. Although protection logically becomes a priority for that location, this result also demonstrates the need to incorporate additional expert knowledge into the conservation planning framework. Using this example, it is reasonable to infer that *Nephroma occultum* is not limited by climate. Rather, its limited distribution depends on old-growth forest habitat, which is threatened by logging, wildfire and defoliation by the hemlock looper (*Lambdina fiscellaria lugubrosa* (Hulst)). Other ecological factors which make *Nephroma occultum* vulnerable are its poor dispersal and competitive abilities (Brodo et al. 2001; COSEWIC 2006). Adapting management practices to maintain or increase its presence in the study area may involve altering timber harvesting practices to encourage the conservation of old- growth forests. Given its rarity and the clustering of current occurrences near the location identified as a persistent climate corridor (Figure 2.5), it may still be prudent to target all known population locations for conservation management.

Expected contractions in the range of conservation targets highlight the utility of identifying persistent climate corridors as potential adaptive strategies for forest management and conservation (Hannah et al. 2005). For example, a target's suitable climate space can provide target areas for the translocation or facilitated migration of plant species or populations which are the target of conservation or management. Facilitated migration represents a degree of active intervention to avoid the extinction of desired species or populations by transporting sensitive or economically important species or populations to more climatically suitable locations (Van der Veken et al. 2008). According to the B.C. Ministry of Forests and Range (BCMFR 2006a), facilitated migration is potentially the most effective and least expensive forest management option to address the effects of climate change on commercially important timber species. A common challenge is that establishment of species or seedlots in locations where they are expected to experience a more favourable future climate depends first on surviving the period of current climate; the mapping of persistent climate corridors gets around this problem. Whether or not a focused program of facilitated migration has applications in the conservation of rare plant communities or ecosystems remains to be seen.

McKenney et al. (2007b) used a similar method to develop new plant hardiness zones for wild and cultivated plant species in Canada. Hannah et al. (2005) used projected bioclimatic envelopes to map areas of overlap in an attempt to protect the remaining distribution of key *Protea* (Proteaceae) species in South Africa. Bioclimatic envelope modelling has also been used to project the distribution of commercial tree species in British

Columbia (Hamann and Wang 2006) and for all of North America (McKenney et al. 2007a). Climatic threats to the persistence of existing habitat, plus the potential for range expansion or range shifts of some biotic elements, were identified in all of these studies.

Sources of uncertainty

All climatic and biogeographic projections are subject to substantial uncertainty, which is largely a function of assumptions that are difficult to validate, parameters difficult to estimate, mechanisms difficult to confirm, and socio-economic conditions difficult to project (Pyke et al. 2005). Therefore, an uncertainty analysis is a critical component of any climate change study. At the very least, possible sources of uncertainty need to be recognized and accounted for. Although a detailed uncertainty analysis is beyond the scope of this chapter, I have summarized some possible sources of uncertainty relevant to this study in Table 1.4.

The uncertainty inherent in the identification of persistent climate corridors is evident at each step in the overlay-intersection process. To begin with, the extent to which the occurrence data represent the full range of some species is questionable given the low number of "calibration points." Due to the challenges of collecting rare occurrence data, such as the difficulty of accurate species identification (especially in reference to varieties and sub-species), plus notoriously incomplete searches in mountainous and roadless terrain, data quality is often questionable (Hannah et al. 2005; McKenney et al. 2007a,b). The ability of general circulation models (GCMs) to accurately predict the relevant changes in future climate, particularly those related to precipitation, are also a significant source of uncertainty. One of the main reasons for this flaw is the large discrepancy of scale between a given study area and the large area covered by a GCM cell (Kueppers et al. 2005). The ability of the CGCM3 model to make realistic projections is also confounded by B.C.'s diverse and mountainous topography, which heavily influences the climate from one area to another. Climate and vegetation both change rapidly over short distances in the mountainous terrain of jurisdictions such as B.C. Consequently, efforts to match and project changes in vegetation with climatic attributes modelled at the scale of GCM cells depend on the calibration and sensitivity of downscaling tools. British Columbia's terrain also constrains the number and placement of weather stations, which heavily influences the outcomes produced by these climate interpolation tools (Pyke et al. 2004; Hannah et al. 2005). Some of these limitations are addressed by the fact that elevational effects and the degree of spatial correlation are incorporated into the spatial interpolation algorithms of ClimateBC and ClimatePP (Daly et al. 2000, 2002; Hamann and Wang 2006).

Conclusions

The concepts of bioclimatic envelopes, suitable climate space, and persistent climate corridors provide a simple and powerful tool kit for conservation planning under a changing climate, pertinent to the development and application of a variety of management strategies. For example, the Nature Conservancy of Canada will use the final outcomes of this research as a pre-processing layer in their conservation plan for the Central Interior of British Columbia. Government agencies, such as the B.C. Ministry of Forests and Range, can use the concept of persistent climate corridors in the development of strategies for facilitating the climate-adapted migration of valuable tree provenances. As research continues to reveal the impacts of climate change on ecological systems, the need to develop and adapt new management strategies becomes increasingly urgent. Persistent climate corridors have the potential to assist managers as they cope with the challenges presented by climate-driven changes to forested ecosystems.

Chapter 3 - Bioclimatic envelopes of selected conservation targets in B.C.'s Central Interior and the identification of candidate areas for conservation in a changing climate

Abstract

One of the threats climate change poses to global biodiversity is a widespread reorganization and redistribution of ecological communities. To address this issue, bioclimatic envelopes were developed to identify persistent climate corridors for 206 conservation targets (30 terrestrial ecological units (TEUs), 103 B.C. biogeoclimatic (BGC) variants, and 73 rare plant species) in B.C.'s Central Interior. Bioclimatic envelopes were developed using ClimateBC, a computer program that interpolates current climate data and downscales general circulation model climate projections. For this research, I chose the 3rd generation of the Canadian general circulation model and a "business as usual" scenario (CGCM3 A2) to generate climate data of the current and potential future distributions of a target. The 5th and 95th percentiles of each target's climate data were used to define the core bioclimatic envelope. Ares were identified which met bioclimatic envelope requirements for 4 timeslices of climate including a baseline (1961-1990s), the 2020s, the 2050s and the 2080s. The identification of areas of coincidence among these envelopes areas revealed a target's suitable climate space (SCS) in which climate suitable for that particular target is expected to persist for the foreseeable future. Subsequently, the intersection of a target's SCS with its current distribution characterized a target's persistent climate corridor (PCC). My analysis produced PCCs for 6 TEUs (20%), 7 plant species (10%) and 10 BGC variants (10%). For those TEUs and BGC variants with PCCs, an average of only 320 km^2 and 19 km^2, respectively, is projected to remain stable through the 2080s, highlighting the severity of climate change impacts to coarse filter biodiversity conservation. Persistent climate

corridors for plant species were scattered around the centre of the study area. It is predicted that rare plant populations will be most strongly limited by reduced snowfall and increased continentality. Persistent climate corridors for the BGC variants were concentrated in the northwest, and TEUs in the southeast and eastern edge of the study area. These areas of persisting suitable climate represent priority areas for conservation as they are projected to provide a degree of climatic refuge. Although this type of analysis is quite sensitive to the choice of models and scenarios for climate change, it represents a reasonable means of incorporating anticipated spatiotemporal ecosystem dynamics into conservation planning.

Introduction

Climate is the dominant abiotic control over large-scale environmental elements such as ecosystems (Pearson and Dawson 2003); and over geological time, climate affects biodiversity through its influence on the dispersal and migration patterns of plant and animal species (Leemans and Eickout 2004; McKenney et al. 2007b). According to the Intergovernmental Panel on Climate Change (IPCC 2007), the existing climate crisis is unequivocal, and global increases in temperatures are due to increases in anthropogenic greenhouse gases. From an ecological perspective, the current rate and magnitude of climate change poses a threat to native biodiversity, a threat considered by some analysts to ultimately be more serious than other anthropogenic activities, such as land use change and resource extraction (Bakkenes et al. 2002; Berry et al. 2002; Ellis et al. 2007; Gayton 2008)

For a variety of socio-economic and scientific reasons, the forces driving climate change are arguably irreversible within our lifetime (Schneider 2004; IPCC 2007). The conservation of biodiversity is one of many resource management objectives demonstrating the need for innovative climate-driven management strategies (Halpin 1997; Hannah et al. 2002b; Spittlehouse 2005). Incorporating foreseeable climate shifts into management practices reflects a paradigm shift to a dynamic, non-equilibrium approach to resource management. The importance of this shift is illustrated with species migrating outside of reserve networks and the complete re-organization and redistribution of ecological communities (Scott et al. 2002; Suffling and Scott 2002; Lemieux and Scott 2005; Hamann and Wang 2006).

At the root of these expected ecosystem changes are species extinctions, extirpations and declines, species invasions, the introduction or proliferation of pests and disease, as well as changes in the frequency and magnitude of natural disturbances such as wildfire and flooding (Dale et al. 2001; Gayton 2008). Individual species are expected to respond idiosyncratically to climate change and current ecological communities are likely to evolve into new communities (Hamann and Wang 2006; Hijmans and Graham 2006; Williams and Jackson 2007). These changes will have cascading effects on community function and consequently important ecosystem services, such as water purification and waste decomposition (BCMFR 2006a).

It is difficult to predict how ecological communities will re-organize themselves because our tools for the analysis and projection of climate predictions and understanding of ecological processes are imperfect. However, there are a variety of technological and conceptual approaches available to approximate the probable outcomes. For this research, I used bioclimatic envelope modelling as a foundation for projecting some potential ecological changes to the Central Interior of British Columbia (B.C.), Canada.

The Nature Conservancy of Canada's ecoregional assessment of B.C.'s Central Interior

The Nature Conservancy of Canada's ecoregional assessment of the Central Interior and Sub-boreal ecoprovinces of B.C. provides a case study to explore the integration of spatiotemporal dynamics into the site selection and prioritization processes of conservation planning (http://science.natureconservancy.ca/centralinterior/central.php. Or Chapter 1). Consequently, the research described here focuses on this geographic area (spanning 50.9 to 57.4 °N latitude and ranging from 131.2 to 120.0 °W longitude) (Figure 1.1), with the goal of aiding the design of a conservation network in the face of impending climate change.

The specific objectives of this chapter are to: 1) define bioclimatic envelopes for three conservation target groups (73 plant species identified as rare by the B.C. Conservation Data Centre (CDC), 30 terrestrial ecological units (TEUs) as defined by the Nature Conservancy of Canada, and 103 subzone variants as mapped under Version 7 of the B.C. Biogeoclimatic Ecosystem Classification; and 2) identify the current locations of each target's suitable climate space and where each target's suitable climate space will persist over a 75-year planning period.

Plant species were selected based on their vulnerability to anthropogenic (e.g., habitat fragmentation, urbanization, invasion of exotic species) and to a lesser extent, natural threats (e.g., herbivory, competition, disturbance). For a description of CDC plant species and their conservation status see Appendix A Tables A1 and A2. The B.C. biogeoclimatic (BGC) variants were selected as conservation targets because they represent climatically homogenous units that correspond to differences in vegetation, soil and ecosystem productivity, and they provide the basis for classification frameworks such as forest management practices and the TEU schema (outlined in Chapter 1) (Pojar et al. 1987). For a complete list of these targets please see Appendix A, Tables A5 and A6 respectively.

In order to meet these objectives, bioclimatic envelopes were developed for each conservation target based on its current documented distribution using climate interpolation and downscaling tools. Geographic information system (GIS) software was used to perform climatic (niche) overlay and gap analysis to identify a target's suitable climate space and the locations where climatic conditions are projected to remain within the limits defined by its bioclimatic envelope. Subsequent analyses of the bioclimatic envelopes were performed to determine the climate variables which most strongly limit the distribution of the conservation targets.

Bioclimatic envelope modelling

Bioclimatic envelope modelling provided the foundation for this study. This modelling strategy is used to predict species dynamics and community formation (McKenney et al. 2007a; Williams and Jackson 2007), and to describe the current and possible future distribution of a conservation target (e.g., a rare plant species) based on a set of suitable climate conditions defined by target-specific physiological tolerances (Thuiller 2003, 2004). More information about bioclimatic envelope modelling is found in Chapter 1 and the feasibility of this approach for each type of conservation target has been demonstrated in Chapter 2.

Development of bioclimatic envelopes - Data collection and amalgamation

The first step in the development of bioclimatic envelopes is to collect occurrence data for each conservation target. The approach to the data gathering process depended on whether a target's occurrence data were point-based (i.e., individual plant species occurrences) or area-based (i.e., consisting of pre-existing spatial coverages of TEUs and BGC variants). In order to fully describe a species' bioclimatic envelope, a variety of online databases, conservation data centres and university herbaria were accessed. Ideally, occurrences from across the entire range of a conservation target are needed to fully describe a target's bioclimatic envelope (Bakkenes et al. 2002; Kadmon et al. 2003; Fitzpatrick et al. 2008). For this research, the development of a target's bioclimatic envelope was based on the climate across Canada, including the territories and northern portions of Washington, Idaho and Montana using ClimateBC and ClimatePP. In general, the occurrence records for the plant species were predominately found east and south of the study area. Their presence in the study area appears to represent marginal populations relative to their distributions outside of ClimateBC and ClimatePP (see http://www.plants.usda.gov).

Target species occurrence data collection

The data sources and herbaria which were accessed to collect as many records of species occurrence as possible are summarize in Table 3.1. These records are typically based on physical voucher specimens deposited in herbaria and identified (or their identity confirmed) by expert plant taxonomists. In some CDC and Natural Heritage Program records, conservation specialists recorded populations of rare species without a corresponding voucher specimen deposited at a herbarium. Although additional information on soils, topography, elevation, plant community, etc., is usually associated with those occurrence records, the analysis reported here depended only on the precise identification of latitude and longitude. All synonyms for each scientific name were searched for; however, any other subspecies or variety other than the listed taxon were excluded from this search. See Appendix A, Table A3, for a list of the species synonyms used in the data collection. This decision was based on the lack of clear universally recognized taxonomic standards and that rarity (and hence my analysis) was specific to the subspecies or variety in some cases. *Allium geyeri* var. *teneri*, for example, is considered imperilled or of special concern and is found sporadically across B.C. On the other hand, *A. geyeri* var. *teneri* is not recognized to occur in Alberta; however, *Allium geyeri* occurs but is unlisted in Alberta and most of the western states in its range (Issac et al. 2004; Haig et al. 2006). The ability to successfully protect rare taxa is a challenging goal in itself, but it is made more difficult by a lack of clearly defined taxonomic standards (Issac et al. 2004; Haig et al. 2006; Garnett and Christidis 2007).

Terrestrial Ecological Unit and Biogeoclimatic variant spatial coverages - Area-based data collection

In order to collect occurrence data for area-based target groups (BGC variants and TEUs), spatial GIS coverages of their current distribution were obtained from the B.C. Integrated Land Management Bureau (ILMB) and the B.C. Chapter of the Nature Conservancy of Canada, respectively. A 1-km grid of B.C., where each point represented a latitude and longitude coordinate and elevation, was overlaid with each of those coverages using ArcMap® 9.2. To ensure that the bioclimatic envelopes of these conservation targets were described, the climate prevailing across the range of those area-based targets was determined from province-wide distributions rather than for the study area only. Climate data generated for the BGC variants

were derived from their province-wide distribution and applied to the variants which occurred in the study area. Climate data for the TEUs were derived from coverages provided by the Nature Conservancy of Canada, including the TEU coverage for the adjacent Okanagan Ecoregional Assessment (NCC 2007a).

Data Amalgamation

Occurrence data were amalgamated in an Excel file and organized according to target group and data source. ClimateBC and ClimatePP (Mbogga et al. 2009) are two climate interpolation and downscaling software programs which can be used to generate 19 climate variables for both historical conditions and a number of future climate change scenarios (Table 3.2).

Table 3.1. Data sources accessed for rare plant occurrence data.

Name of Dataset	Type of data	Reference
Alberta Natural Heritage Centre	Element occurrence records and status report	John Rintoul, (780) 427-6639 Email: john.rintoul@gov.ab.ca
B.C. Conservation Data Centre	Element occurrence records and status report	http://www.env.gov.bc.ca/cdc/
Idaho Conservation Data Centre	Element occurrence records and status report	http://fishandgame.idaho.gov/cdc/
Montana Natural Heritage Centre	Element occurrence records and status report	http://mtnhp.org.
Washington Natural Heritage Centre	Element occurrence records and status report	http://www.dnr.wa.gov/ResearchScience/Topics/NaturalHeritage/Pages/amp_nh.aspx.
Eflora	database	/index.shtml.
Global Biodiversity Information Facility	Occurrence data from a wide variety of sources*	www.gbif.org.
University of Victoria Herbaria	Occurrence data	Email: herb@uvic.ca or 250- 21-7097
University Northern B.C. Herbaria	Occurrence data	Email: reav@unbc.ca
Yukon Biodiversity Database	Occurrence data, area-specific articles	http://www.aina.ucalgary.ca/yb/

*Sources include UBC and Canadian Museum of Natural History

Table 3.2. Description of annual climate variables produced by ClimateBC and ClimatePP. For a more detailed review of these variables, see Spittlehouse (2006).

Climate Variable	Description
MAT	Mean annual temperature (°C)
MWMT	Mean temperature of the warmest month (°C)
MCMT	Mean temperature of the coldest month (°C)
TD	Continentality - difference between MWMT and MCMT (°C)
MAP	Mean annual precipitation (mm)
MSP	Mean May to September precipitation (mm)
AH:M	Annual heat: moisture index (MAT + 10)(MAP/1000)
SH:M	Summer (May to September) heat: moisture index (MWMT)(MSP/1000)
DD<0	Degree days below 0 °C (chilling degree days)
DD>5	Degree days above 5 °C (growing degree days)
DD<18	Degree days below 18 °C (heating degree days)
DD>18	Degree days above 18 °C (cooling degree days)
NFFD	Number of frost free days
FFP	Frost free period (days)
bFFP	Beginning of frost free period (days)
eFPP	End of frost period
PAS	Precipitation as snow (mm)
DD5_100	Day of the year on which DD>5 reaches 100, date of budburst
EXT_Cold	Extreme minimum temperature over 30 years (°C)

Variable selection

Nineteen variables provide the user of ClimateBC and ClimatePP with the opportunity to explore a variety of climate-based hypotheses. However, many of the climatic attributes listed in Table 3.2 are strongly correlated with each other. The presence of collinearity suggests that there is some degree of overlap or redundancy among variables which might lead to a loss of statistical power and make it difficult to interpret the results. In order to reduce collinearity and maximize the predictive power and reliability of my model, I selected four largely orthogonal variables from the original dataset. Variable selection for the development of target bioclimatic envelopes was based on principal components analysis (PCA) using the SAS PROC PRINCOMP procedure (SAS Institute 2004) followed by a Pearson's correlation analysis (SAS PROC CORR; SAS Institute 2004) based on province-wide climate data. From the PCA, I selected the variables most strongly correlated with the first four principal components, which resulted in MAT, AHM, TD and PAS being the strongest contributors to the eigenvalues (Table 3.3a). I confirmed my variable selection with a Pearson's correlation matrix to make sure that none of the stated variables were highly correlated (Table 3.3b). A brief review of the literature further confirmed that these selected variables are considered to be critical for plant survival and reproductive success (Araújo et al. 2005; McKenney et al. 2007a; Fitzpatrick et al. 2008).

The baseline climate data for ClimateBC and ClimatePP were derived from commercially available coverages that were generated using PRISM (Parameter Regression of Independent Slopes Model (Oregon State University Corvallis, Oregon, USA) (Daly et al. 2000, 2002). According to Hamann and Wang (2006), the available PRISM datasets at 2-km and 4-km resolution were insufficient for B.C.'s complex terrain and ultimately led to the overestimation of the changes to future climates. The biased distribution of weather stations which generally excludes difficult to reach, higher altitude mountainous areas also confounds and distorts inferred bioclimatic envelopes. Using high-resolution digital elevation models, Wang et al. (2006) developed simple elevation adjustment formulas that facilitated the intelligent downscaling of the PRISM model (Daly et al. 2000, 2002). Climate change components are incorporated into ClimateBC and ClimatePP with the provision of outputs from a number of general circulation models for the user to choose from. The third generation of Canadian General Circulation Model (CGCM3) was selected for this study because it was easily accessible and internationally recognized (IPCC 2007; McKenney et al. 2007b). The A2 "business as usual" scenario (Environment Canada 2008) was chosen to take a conservative approach and provide the worst possible circumstances (i.e., to follow the precautionary principle). ClimateBC was chosen because it was developed specifically for B.C.'s complex terrain; other climate interpolation tools such as ANUSPLIN (The Fenner School of Environment and Society, The Australian National University) lack the ability to incorporate the influences of complex terrain on climate (Daly et al. 2000, 2002).

Determining a conservation target's bioclimatic envelope

Once the target group's occurrence data were amalgamated, the latitude, longitude and elevation of each occurrence were run through ClimateBC and ClimatePP with the CGCM3 A2 scenario to generate climate variables at each location. The resulting dataset was refined to include the selected variables (i.e., MAT, TD, AHM, PAS), and the target's bioclimatic envelopes were limited to a more certain range defined by the 5^{th} and 95^{th} percentiles of each climate variable (as recommended by Kadmon et al. 2003; McKenney et al. 2007a). Using the 5^{th} and 95^{th} percentiles to capture the core of a target's bioclimatic envelope excluded any anomalous data such as species persistence in regionally peculiar microsites which might skew the results (Walker and Cocks 1991; Carpenter et al. 1993; Beaumont et al. 2005).

Table 3.3. a) The standardized loadings from the top 4 principal components (PC) and b) a partial summary of the Pearson's Correlation Matrix of provincial climate data used to select climate variables for the development of bioclimatic envelopes

a) Principal Component Analysis

		Factor Loadings (Pearson's Correlation, r)						
Loading	**Eigenvalue**	**MAT**	**AHM**	**TD**	**PAS**	**MWMT**	**MSP**	**MAP**
1	0.5135	**0.3437**	0.0092	-0.2106	-0.0591	0.2361	0.0840	0.1597
2	0.3168	0.0300	**0.3945**	0.2807	-0.3417	0.2764	-0.3621	-0.3571
3	0.0692	-0.0672	-0.1063	**0.4246**	0.2810	0.3018	0.4071	0.2780
4	0.0465	0.0746	0.3234	-0.1459	**0.5556**	-0.0842	0.0279	0.1265
	0.9694							

b) Pearson's Correlation Matrix

Variable	MAT	AHM	TD	PAS	MWMT	MSP	MAP
MAT	1	0.1136	-0.5769	-0.1975	0.7022	0.1526	0.3810
AHM		1	0.4669	-0.6072	0.5126	-0.6727	-0.6742
TD			1	-0.2929	0.1616	-0.4747	-0.6563
PAS				1	-0.5088	0.6832	0.6689
MWMT					1	-0.2186	-0.1024
MSP						1	0.9070
MAP							1

NB: Prior to this selection process bFFP, eFFP, DD5_100 were eliminated because they were not always available for each location and they denote Julian days of the year, the particular identity of which is not usually relevant to the persistence of a conservation target.

To determine the locations meeting the requirements of a target's current bioclimatic envelope in the study area, a SAS® 9.1.2 (SAS Institute 2004) program consisting of conditional statements (e.g., Equation 1) was written to determine whether or not each datum in the 1-km grid of the study area fell within the target's core envelope. Locations that satisfied all four variable conditions were considered to meet the requirements of a target's bioclimatic envelope. The resulting dataset of mapped envelope areas provided the locations in the study area where the climatic conditions are suitable for a given target.

Equation 1. IF $MAT \geq MAT^{5th}$ and $MAT \leq MAT^{95th}$, THEN MAT_calc = 1; ELSE MAT_CALC = 0;

where MAT_CALC denotes the suitability (if 1) or unsuitability (if 0) of that location for its climate falling within the 5^{th} to 95^{th} percentiles of MAT (mean annual temperature) derived for locations currently occupied by that target

This procedure was repeated for four timeslices (1961-1990s, 2020s, 2050s and 2080s) using a 1-km grid across the B.C. Central Interior study area. A timeslice simply represents the projected climate for a predefined time in the future. The purpose of projecting a target's bioclimatic envelope over four timeslices is to assess the continuity of a target's suitable climate space over time. Chapter 2 provides a more detailed account of my rationale for multiple timeslices and the need for the continuity of suitable climate space.

Determining a conservation target's suitable climate space and persistent climate corridor

In order to identify a target's suitable climate space, the locations meeting the requirements of a target's bioclimatic envelope for the baseline (1961 to 1990s), 2020s, 2050s and 2080s timeslices were overlaid. Collectively, the points of intersection in which target envelope conditions were predicted to be satisfied in all four timeslices are termed 'suitable climate space' (SCS), and represent the locations where tolerable climatic conditions are expected to persist over the study's timeframe. Next, a target's current distribution was overlaid with its suitable climate space, and the coinciding locations were considered a target's "persistent climate corridor" (PCC) and represent priority areas for conservation. Figure 3.1 illustrates the steps and results for this procedure with *Nephroma occultum* (Cryptic Paw) as the target.

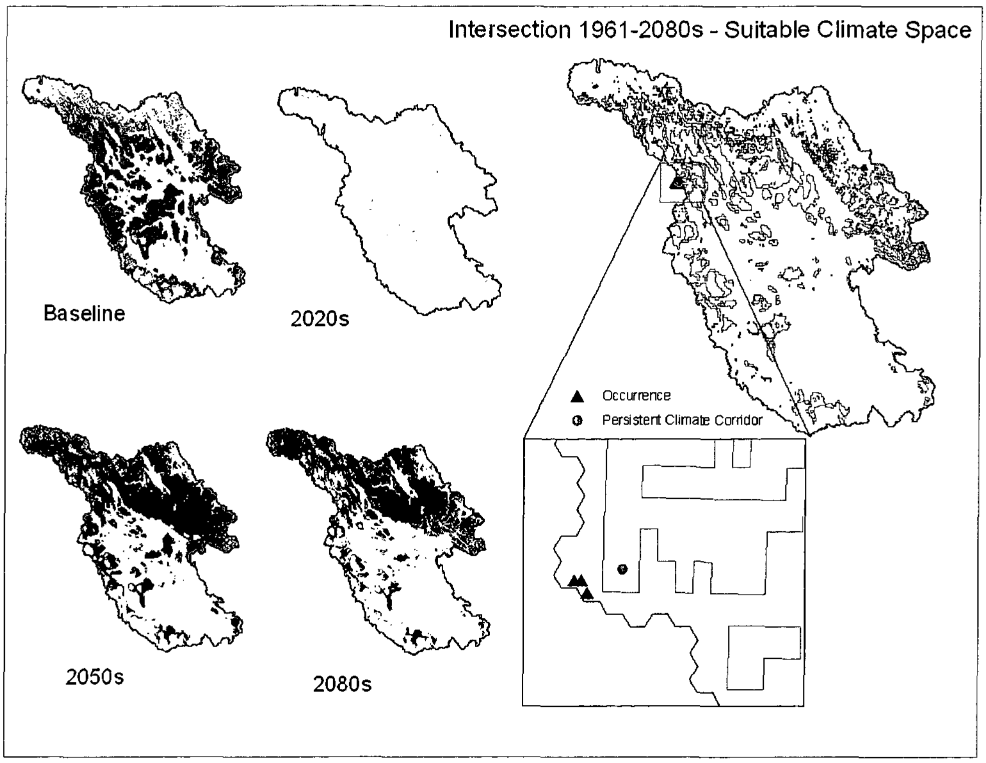


Figure 3.1. An illustration of the intersect-overlay process used to identify candidate areas for conservation of *Nephroma occultum*.

Like its spatial counterpart, which provides *in situ* connectivity, a persistent climate corridor denotes a place where an existing population or ecosystem can expect to experience temporal connectivity in the form of climatic continuity or persistence over time.

Determining climate constraints of conservation targets

The purpose of this analysis was to determine why the occurrences of some species were completely or partially excluded from their bioclimatic envelopes. I used SAS® 9.1.2 (SAS Institute 2004) to determine which of the four selected variables (i.e., MAT, TD, AHM, PAS) at each species' location fell within the 5th and 95th percentiles or core of its distribution. If the climate data at a particular location was outside its core, that location was classed as either "too high" or "too low". Climate constraints were generated for all of the occurrences which did not fall within the 5th and 95th percentiles, and therefore did not result in persistent climate corridors. I determined the climate constraints for all four timeslices (i.e., baseline, 2020s, 2050s, 2080s) and calculated the average number of times a variable was deemed too high or too low.

Testing a range of general circulation model (GCM) and scenario assumptions

In order to test the range of GCM and scenario assumptions, I used ArcMap's Hawth Tools to generate a random spatial sampling of 1000 points (geographic locations with the study area) for the 2080s timeslice. Next, I projected the climate of this random sample for the 2080s using 16 different GCM and scenario pairings and calculated the maximum, minimum, median and mean values for the mean annual temperature of each model (Table 3.5). These 16 models represent a subset of GCMs that are currently available with ClimateBC. In order to simplify this procedure the newest generation of a particular GCM was used (e.g., the HadCM3 was chosen over HadCM2).

Each scenario family (i.e., A1, B1, A2, and B2) represents two divergent tendencies or storylines (A and B) with one set varying between strong economic and strong environmental values, and the other between increasing globalization and regionalization (IPCC 2000) (Table 3.4).

The Australian Commonwealth Scientific and Industrial Research Organization (CSIRO) A2 scenario generated the highest MAT prediction and the US Department of Energy's Parallel Climate Model (PCM) B1 scenario represented the lowest MAT prediction compared to CGCM3 A2.. Therefore, the CSIRO A2 (high) and PCM B1 (low) output were chosen to illustrate the potential uncertainty in climate change projections. This test of the range of assumptions was carried out for those conservation targets which had suitable climate space projected by the CGCM3 A2 combination. This subset included 30 target plant species, 16 B.C. BGC variants and eight terrestrial ecological units.

Table 3.4. A summary of the four storyline and scenario families representing two divergent tendencies, one set varying between strong economic and strong environmental values and the other between increasing globalization and regionalization (IPCC 2007)

Storyline and scenario family	Description
A1 (including A1F1)	• A future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and rapid introduction of new and more efficient technologies. • A1F1 represents a fossil fuel intensive scenario.
A2 (including A2x)	• A very heterogeneous world with continuously increasing global population and regionally oriented economic growth that is more fragmented and slower than in other storylines. • A2x is a custom scenario based on the average output of the A2 scenarios
B1	• A convergent world with the same global population as in the A1 storyline but with rapid changes in economic structures toward a service and information economy, with reductions in material intensity, and the introduction of clean and resource-efficient technologies.
B2	• A world in which the emphasis is on local solutions to economic, social, and environmental sustainability, with continuously increasing population (lower than A2) and intermediate economic development.

Table 3.5. Maximum, minimum, median, mean and standard deviation (SD) for the mean annual temperature (MAT,°C) from 16 GCM and scenario combinations, as projected for 1000 random points in the study area.

General Circulation Model	Minimum (°C)	Maximum (°C)	Median (°C)	Mean (°C)	SD* (°C)
CSIRO2 A2	**-6.10**	**3.80**	**0.70**	**0.48**	**1.61**
HADCM3 A1F1	-5.50	3.40	0.70	0.53	1.48
CSIRO2 A1F1	-6.60	3.20	0.20	-0.04	1.59
CSIRO2 B2	-6.90	3.10	-0.10	-0.28	1.63
HADCM3 A2	-6.60	2.30	-0.30	-0.51	1.48
HADCM3 A2x	-6.50	2.30	-0.30	-0.44	1.45
CSIRO2 B1	-7.40	2.00	-0.90	-1.11	1.52
PCM A1F1	-7.00	2.00	-0.80	-0.95	1.44
CGCM3 A2	**-7.20**	**1.80**	**-1.00**	**-1.13**	**1.47**
PCM A2	-7.70	1.30	-1.40	-1.59	1.44
HADCM3 B2	-7.70	1.20	-1.50	-1.65	1.48
HADCM3 B1	-7.90	1.00	-1.70	-1.89	1.47
PCM B2	-8.80	0.20	-2.55	-2.70	1.46
ECHAM4 B2	-8.70	0.20	-2.60	-2.72	1.44
ECHAM4 A2	-8.80	0.00	-2.70	-2.82	1.43
PCM B1	**-9.10**	**-0.10**	**-2.90**	**-3.01**	**1.46**

*Implications of bold – combinations are explored in the Results

Results

The final results describing the projected bioclimatic envelopes of each target group are summarized in Appendix A, Table A4-A6. For purposes of brevity and simplicity, the data pertinent to those targets with projected suitable climate space are provided in the following text. Many conservation targets are expected to experience large areas of suitable climate space. All conservation target groups are projected to have some examples of persistent climate corridors but usually over a minority of their current range.

Conservation Target Groups

B.C. Biogeoclimatic (BGC) Variants

Only sixteen (16%) of the 103 variants had suitable climate space and only 10 (9%) had any PCCs (Table 3.6, Appendix Table A4). The Coastal Mountain-heather Alpine Undifferentiated and Parkland (CMAunp) and the Engelmann Spruce Subalpine-fir Very Wet Very Cold (ESSFwv) variants provide excellent examples of how climate change might impact the bioclimatic envelope features (i.e., suitable climate space, PCC) of particular targets (Figure 3.2). The CMAunp variant experienced an increase in suitable climate space relative to its current distribution, while the ESSFwv variant experienced an overall greater proportional increase from the baseline to 2080s timeslice. The resulting bioclimatic envelope areas of some other targets are illustrated in Figure 3.3. Overall, the CGCM3 A2 projections generated very low levels of PCC representation for the variants with suitable climate space. Persistent climate corridors were scattered in the northwestern and southeastern corners and eastern edge of the study area. The total area for all variant PCCs was projected to be 1936 km^2.

Nature Conservancy of Canada Terrestrial Ecosystem Units (TEU)

The results for the Nature Conservancy of Canada TEUs are also highly variable (Table 3.7). Please refer to Appendix A Table 5A for projected dynamics of all 30 TEUs. The contraction of the TEUs with suitable climate space and persistent climate corridors represent a reduction of approximately 90% of their cumulative current area. The greatest increases of a TEU's current distribution to its projected suitable climate space TEU5 (1372%) followed by TEU3 (91%) and TEU8 (76%). Despite a near doubling of its current distribution, TEU8 has a relatively small PCC which represents a mere 4% of its current distribution (Figure 3.4). At first glance, the suitable climate space illustrated in Figure 3.4 appears smaller in area, however; the current distribution of TEU8 is linear and represents a riparian ecosystem, while the SCS is nonlinear and represents climate irrespective of topographic features. The current distributions and PCCs of TEUs 1, 2, 5 and 6 are illustrated in Figure 3.5 and demonstrate the concentration of PCCs in the northwestern and southeastern corners, and eastern edge of the study area. The total area of the PCCs for the TEUs is 2561 km^2.

B.C. Conservation Data Centre (CDC) Listed Plant Species

Climate change is expected to influence the distribution of bioclimatic envelopes of most of the rare plant species I evaluated. Overall, 130 out of 162 (80%) plant species occurrence records did not yield PCCs (Table 3.8, Appendix A6). Fourteen of the 162 rare plant occurrences are expected to experience climate conditions suitable for their persistence through the 2080s. Many species are projected to have large envelope areas and suitable climate space (Table 3.8). The low percentage of species with PCCs is largely a function of the low number of species' occurrence records in the study area, and the fact that many of the Central Interior B.C. occurrences are already on the margin of their range.

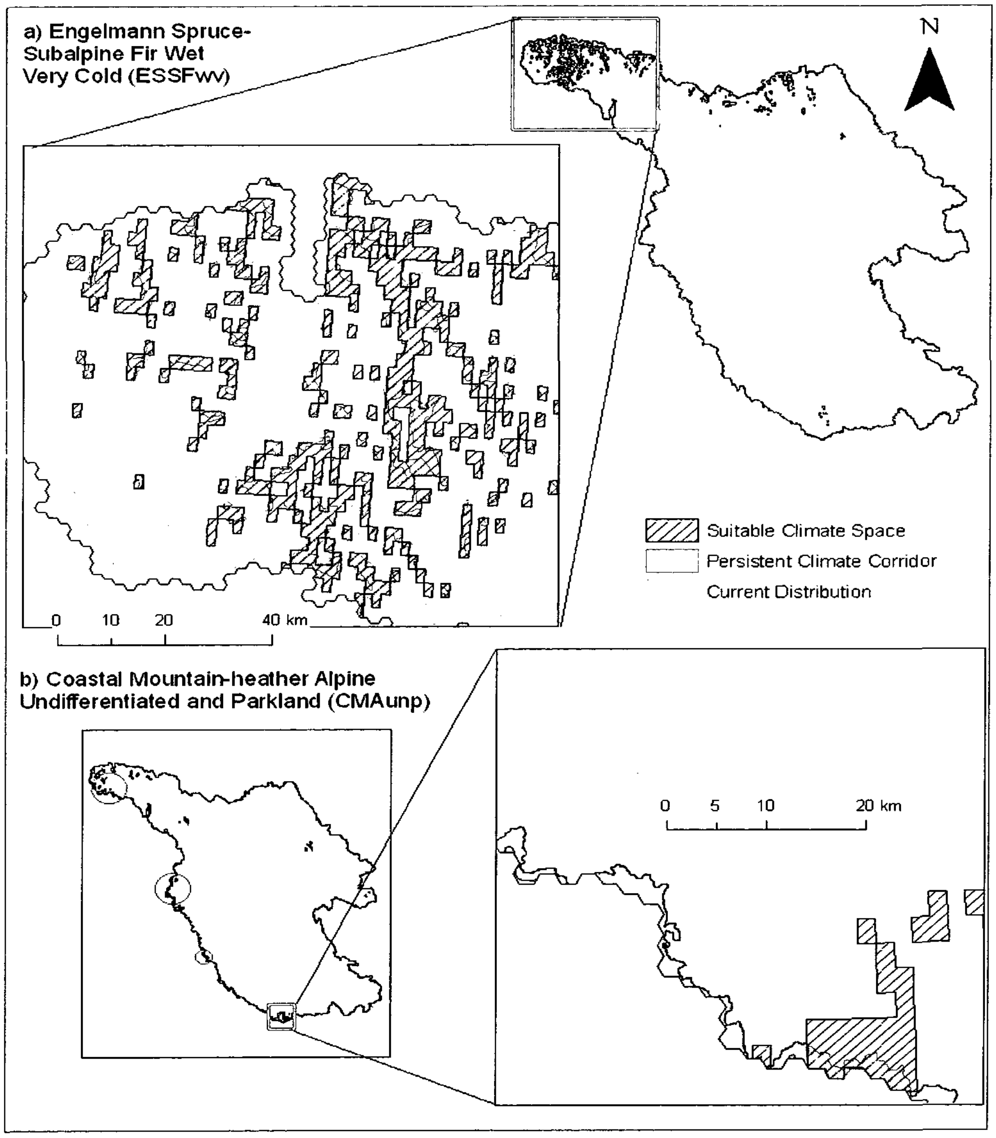


Figure 3.2. Maps of the current distribution, suitable climate space (SCS) and resulting persistent climate corridor (PCC) of a) Engelmann Spruce-Subalpine Fir Wet Very Cold and b) Coastal Mountain-heather Alpine Undifferentiated and Parkland. The circled areas represent other locations of suitable climate space in the study area.

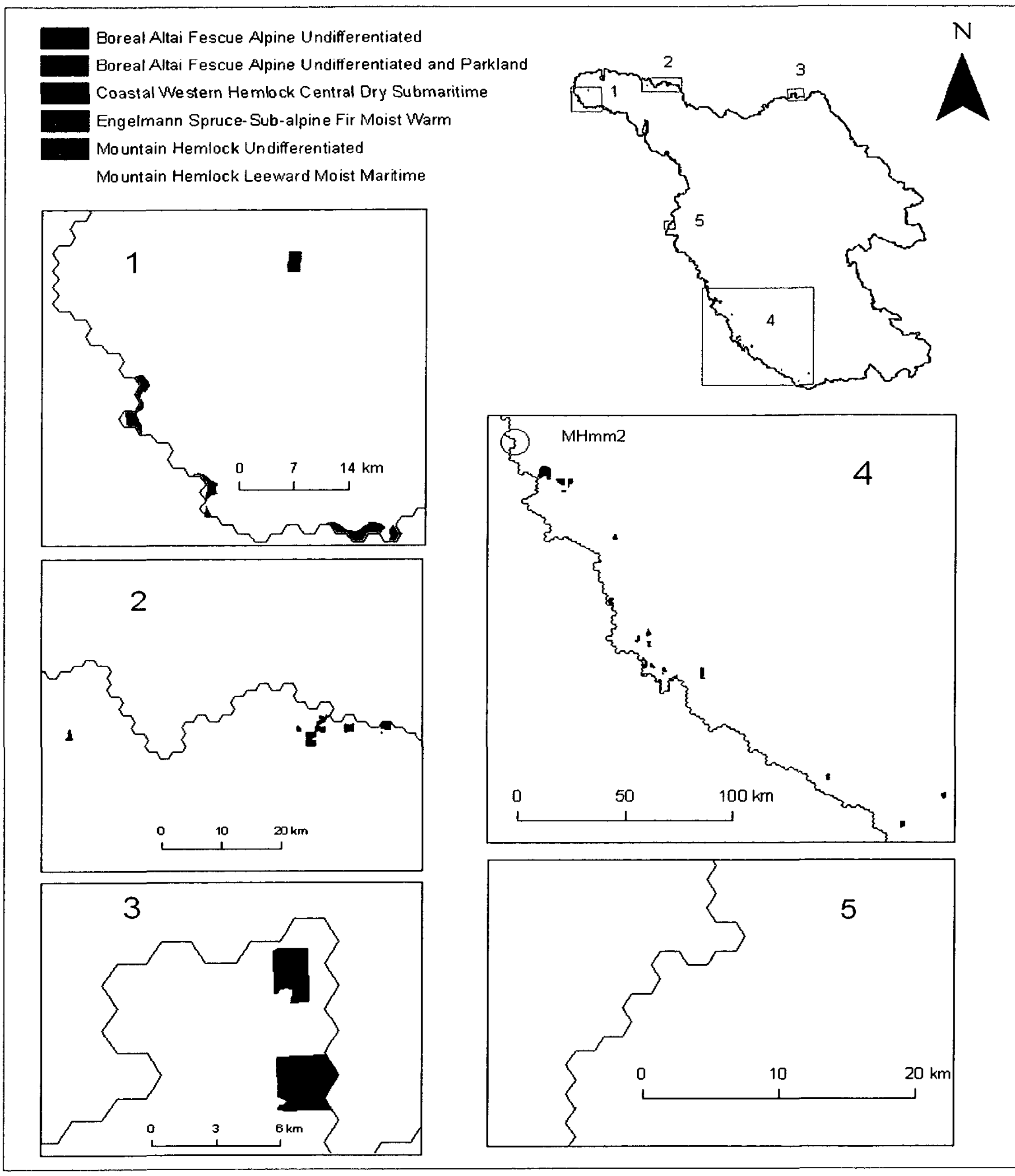


Figure 3.3. Maps of persistent climate corridor (PCC) of Boreal Altai Fescue Undifferentiated and Parkland and Mountain Hemlock Undifferentiated (1) Boreal Altai Fescue Undifferentiated (2, 3) Coastal Western Hemlock Central Dry Maritime and Engelmann Spruce Subalpine fir Moist Warm (4), Mountain Hemlock Leeward Moist Maritime (5). The circled area in 5 represents a very small portion of the MHmm2 persistent climate corridor which is south of those locations shown in the fifth inset.

Table 3.6. Biogeoclimatic variants, currently found in the study area, that are predicted to have suitable climate space (SCS), and the area and degree of change associated with persistent climate corridors (PCCs) based on CGCM3 A2 projections and ClimateBC downscaling.

Description of Biogeoclimatic Variant	Current Area (km^2)	% Change in Envelope Area, Baseline to 2080	SCS (km^2)	PCC (km^2)	% Current Area Represented by PCC
Boreal Altai Fescue Alpine Undifferentiated (BAFAun)	31,255	-97.07	184	34	0.11
Boreal Altai Fescue Alpine Undifferentiated and Parkland (BAFAunp)	46,386	-99.72	10	9	0.02
Coastal Mountain-heather Alpine Undifferentiated and Parkland (CMAunp)	49,788	-67.17	1,396	182	0.37
Coastal Western Hemlock Central Dry Submaritime (CWHds2)	816	3182.34	352	64	7.84
Coastal Western Hemlock Wet Maritime (CWHwm)	5,359	386.09	2,702	0	0.00
Engelmann Spruce-Subalpine Fir Moist Warm (ESSFmw)	2,664	210.49	357	16	0.60
Engelmann Spruce-Subalpine Fir Wet Very Cold (ESSFwv)	1,933	-93.05	3,337	1,233	63.79
Interior Cedar Hemlock Nass Moist Cold (ICHmc1)	5,343	-13.81	3,677	203	3.80
Interior Cedar Hemlock Very Wet Cold (ICHvc)	1,449	-38.15	13,403	182	12.56
Interior Douglas-fir Dry Cold (IDFdc)	745	0.01	123	0	0.00
Interior Douglas-fir Wet Warm (IDFww)	1,198	2578.77	96	0	0.00
Interior Mountain-heather Alpine Undifferentiated (IMAun)	12,991	-97.94	9	0	0.00
Interior Mountain-heather Alpine Undifferentiated and Parkland (IMAunp)	1,195	1.23	413	0	0.00
Mountain Hemlock Leeward Moist Maritime (MHmm2)	12,394	322.65	106	9	0.07
Mountain Hemlock Moist Maritime Parkland (MHmmp)	2,243	287.35	31	0	0.00
Mountain Hemlock Undifferentiated (MHun)	4,579	-64.37	3,172	4	0.09
Totals	180,338	6,398	29,368	1,936	1.07

*A detailed account of the results for the Interior Cedar Hemlock (ICH) including figures and tables is found in Chapter 2.

Table 3.7. A summary of the suitable climate space (SCS), persistent climate corridors (PCCs) and percent of the current area represented by projected PCCs for eight terrestrial ecosystem units.

	Nature Conservancy of Canada - Terrestrial Ecological Unit (TEU)	Current Area (km^2)	% Change in Envelope Area, Baseline to 2080	SCS (km^2)	PCC (km^2)	% Current Area Represented by PCC
1	Boreal Alpine Fescue Dwarf Shrubland and Grassland	17,748	-95.61	715	549	3.09
2	North Pacific Dry and Mesic Alpine Dwarf-Shrubland, Fell-field and Meadow	3,604	-93.23	347	46	1.28
3	North Pacific Interior Lodgepole Pine - Douglas-Fir Woodland and Forest*	11,866	-33.63	22,661	1,131	9.53
4	North Pacific Interior Wetland Composite	7,558	-98.86	200	0	0.00
5	North Pacific Montane Riparian Woodland and Shrubland	1,294	-70.61	19,053	133	10.28
6	North Pacific Sub-Boreal Mesic Subalpine Fir - Hybrid Spruce Forest	47,680	-94.06	1,205	611	1.28
7	North Pacific Sub-Boreal Mesic Subalpine Fir - Hybrid Spruce Parkland	9,259	-93.73	3,005	0	0.00
8	Northern Rocky Mountain Lower Montane Riparian Woodland and Shrubland	2,433	-89.26	4,278	91	3.74
	TOTAL	**91,170**	**-668.99**	**51,264**	**2,561**	**2.81**

*For a more detailed account of the projected outcomes for North Pacific Interior Lodgepole Pine - Douglas-Fir Woodland and Forest (TEU3) see Chapter 2

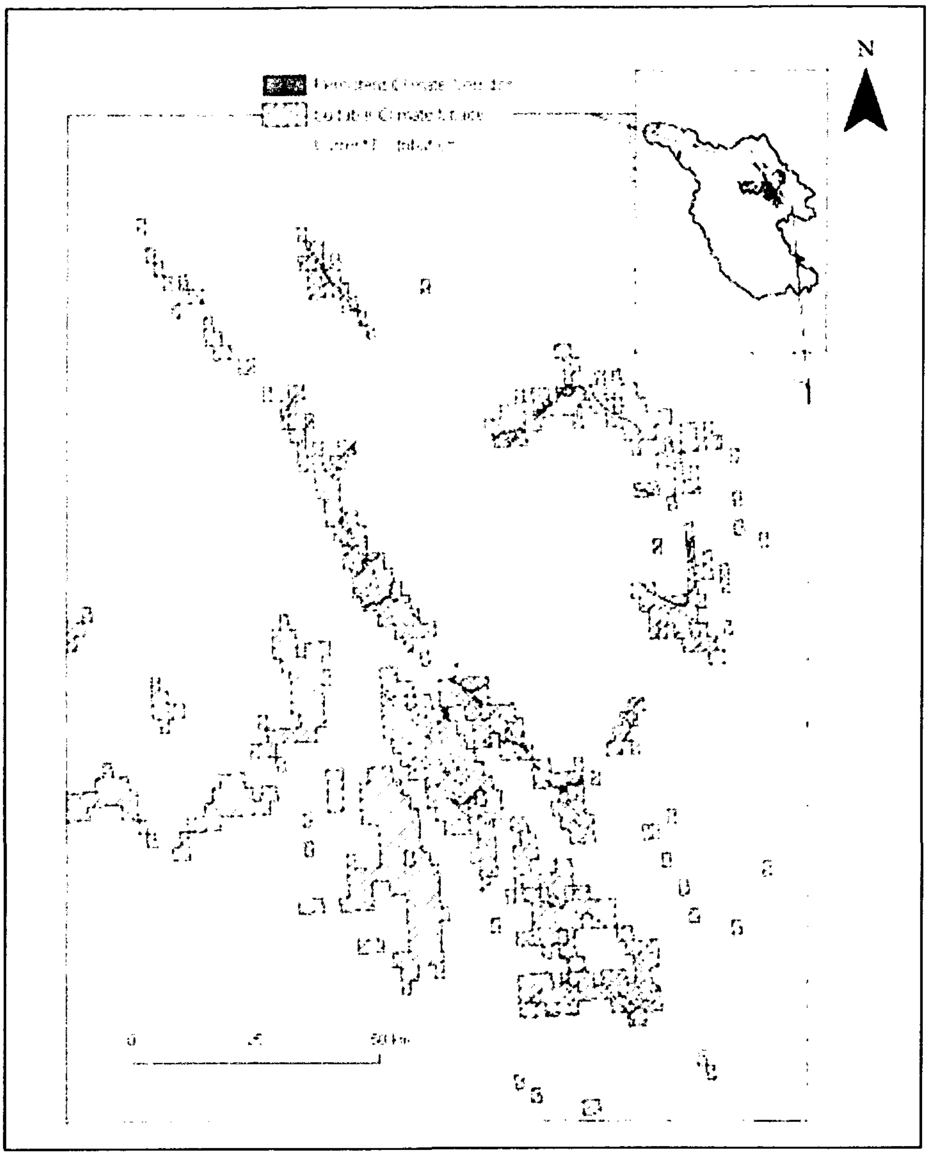


Figure 3.4. An illustration of the current distribution, suitable climate space and persistent climate corridor projected for the Northern Rocky Mountain Lower Montane Riparian Woodland and Shrubland terrestrial ecological unit.

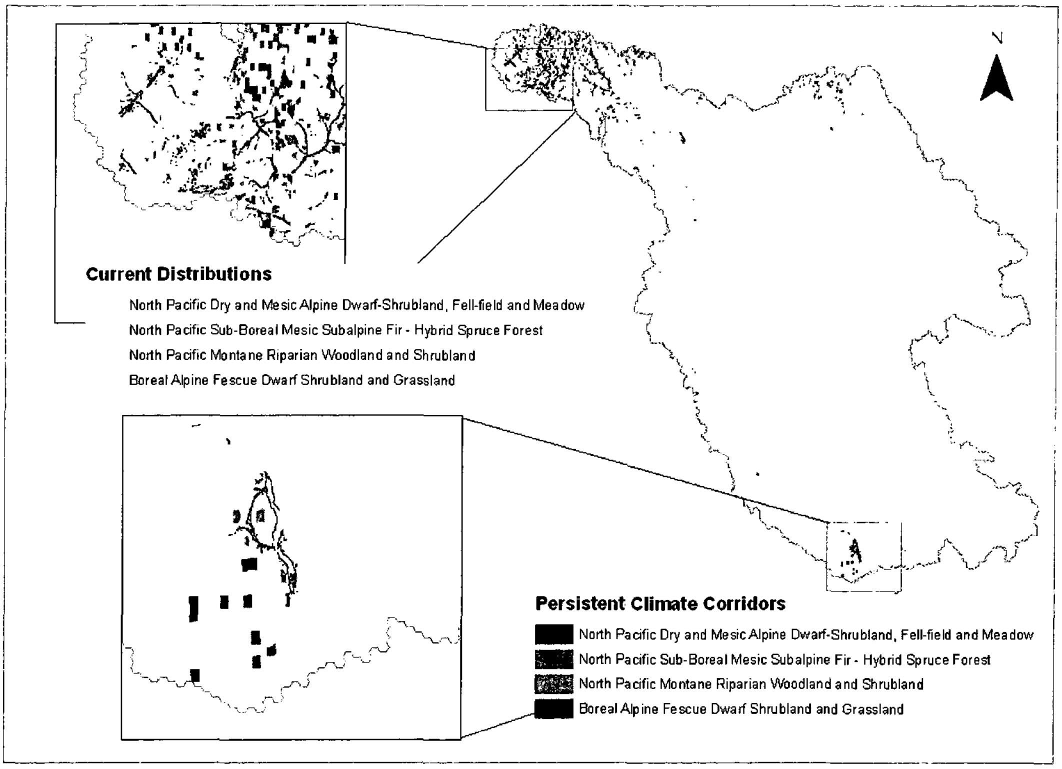


Figure 3.5. A map illustrating the current distributions and persistent climate corridors of Boreal Alpine Fescue Dwarf Shrubland and Grassland, North Pacific Dry and Mesic Alpine Dwarf-Shrubland, Fell-field and Meadow, North Pacific Montane Riparian Woodland and Shrubland and North Pacific Sub-Boreal Mesic Subalpine Fir-Hybrid Spruce Forest.

Table 3.8. A summary of the suitable climate space, persistent climate corridors (PCC) and percent PCC representing the current distribution of 30 rare plant species.

B.C. Conservation Data Centre Plant Species	# in Study Area	Calibration Points	Proportion Change Baseline to 2080	SCS (km^2)	PCC (km^2)	% PCC Representing Current Area
Allium geyeri var. tenerum	1	13	-100.00	11,965	0	0.00
Botrychium simplex	3	34	-1.84	5,993	0	0.00
Carex heleonastes	4	28	-93.76	53	0	0.00
Carex lenticularis var. *dolia*	3	50	-6.86	178,348	1	2.00
Carex scoparia	1	12	0.19	810	0	0.00
Carex sychnocephala	1	34	-82.62	6,175	0	0.00
Carex tenera	7	24	-18.50	49,081	2	8.33
Chenopodium atrovirens	2	25	-1.52	55,356	0	0.00
Draba ruaxes	2	13	-44.06	1,751	0	0.00
Draba ventosa	1	22	-97.30	49,941	0	0.00
Dryopteris cristata	1	91	-16.47	17,356	0	0.00
Epilobium halleanum	2	10	0.35	25	0	0.00
Epilobium leptocarpum	2	25	-11.71	97,321	0	0.00
Juncus albescens	3	27	-61.95	19,529	0	0.00
Juncus arcticus ssp. *Alaskanus*	2	18	-15.75	7,549	0	0.00
Juncus stygius	2	24	-17.27	80,991	1	4.17
Koenigia islandica	2	25	308.70	34,669	1	4.00
Malaxis paludosa	2	34	-14.73	92,612	2	5.88
Minuartia austromontana	2	7	-13.42	1,651	0	0.00
Montia chamissoi	2	4	71.75	17	0	0.00
Muhlenbergia glomerata	4	22	-65.29	26,043	0	0.00
Nephroma occultum *	4	86	-12.31	11,585	1	1.16
Nymphaea tetragona	5	20	0.35	158,015	5	25.00
Potentilla nivea var. *pentaphylla*	1	4	57.94	654	1	25.00
Salix boothii	9	157	-97.09	2,973	0	0.00
Salix serissima	1	21	3.68	6,196	0	0.00
Saxifraga nelsoniana ssp. *Carlottae*	1	15	-36.31	2,166	0	0.00
Sparganium fluctuans	1	11	4.04	590	0	0.00
Stellaria umbellata	1	16	-20.86	241	0	0.00
TOTAL	72	872	2.81	919,656	14	19.44

* For more details concerning the projections for *Nephroma occultum* please see Chapter 2

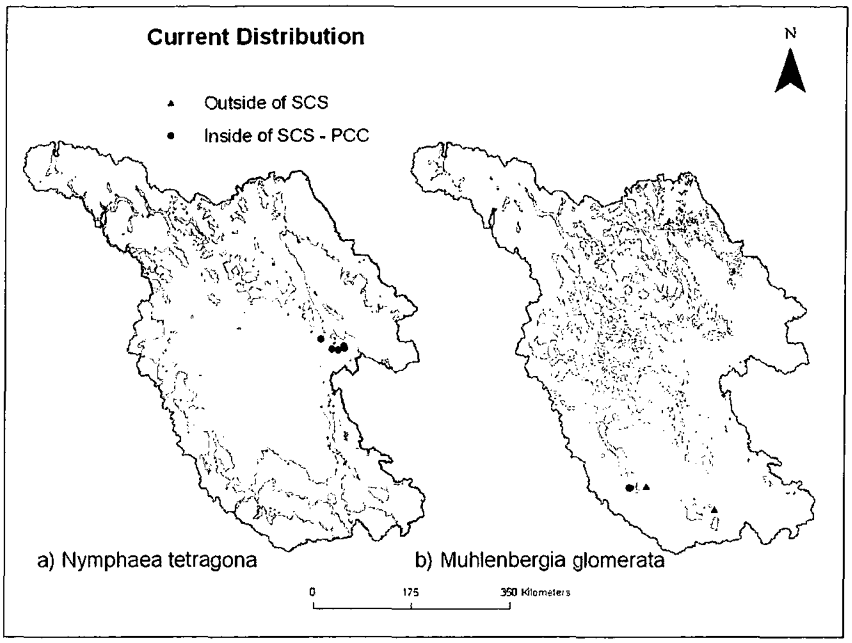


Figure 3.6. An illustration of the current distribution, suitable climate space (coloured polygons) and persistent climate corridors projected for a) *Nymphaea tetragona* (White-Pygmy water lily) and b) *Koenigia islandica* (Iceland purslane).

Climatic constraints to conservation targets

Out of 73 rare plant species, only *Malaxis paludosa, Potentilla nivea* var. *pentaphylla* and *Nymphaea tetragona* were free of climatic constraints and all of their occurrences resulted in PCCs (Appendix A7a, b). Precipitation as snow (PAS) was most often the factor limiting the distribution for many plant species throughout the planning period, followed by continentality (TD) and mean annual temperature (MAT) (Figure 3.8). Many of the plant species were constrained by the same climate variables within each timeslice and in general the climatic constraints remained relatively consistent. At the same occurrence locations, species are predicted to be constrained in a single timeslice which excluded it from an otherwise suitable climate space and consequently prevented the occurrence from serving as a PCC. For example, *Allium geyeri* var. *tenerum* were constrained in the baseline timeslice by a high PAS and a low TD value, and *Epilobium leptocarpum* was constrained by a high TD value. *Juncus stygius* and *Nephroma occultum* were constrained in the 2080s timeslice by high values of AHM and MAT, respectively.

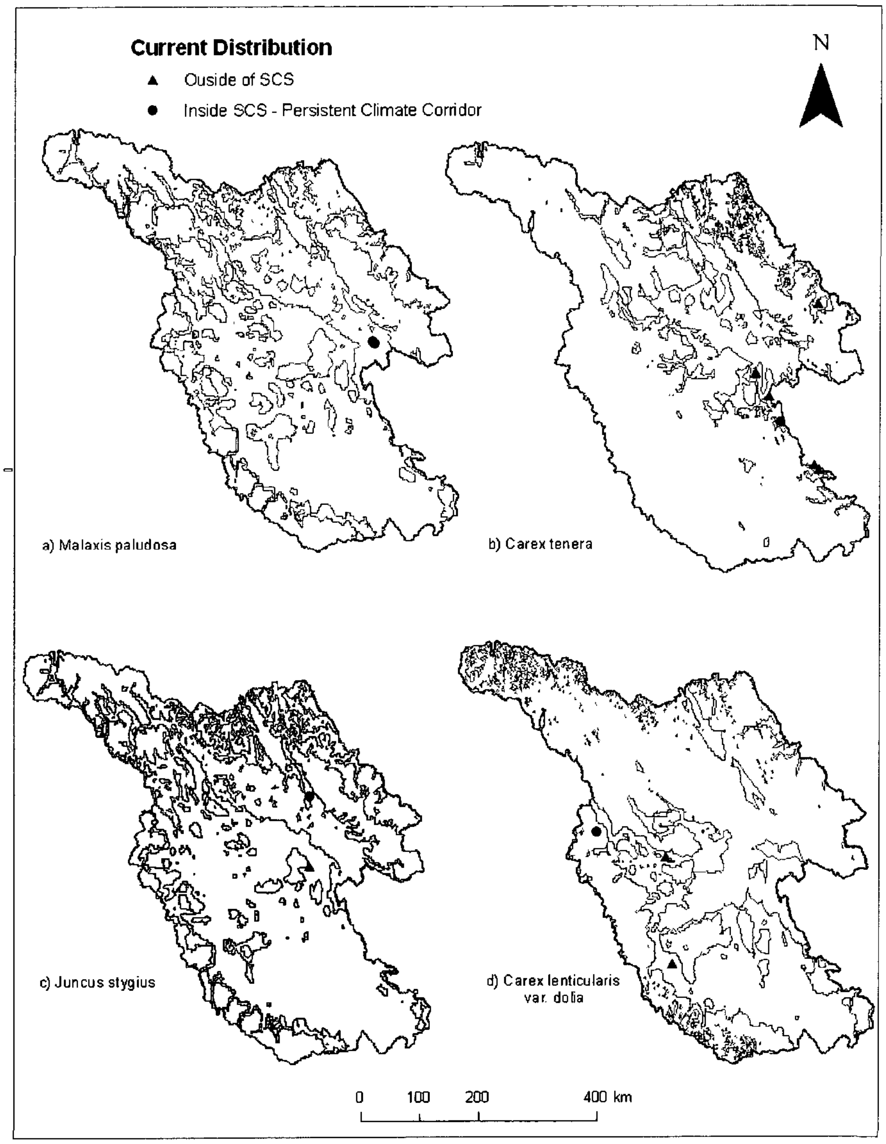


Figure 3.7. An illustration of the current distribution, suitable climate space (coloured polygons) and persistent climate corridors projected for a) *Malaxis paludosa* (bog adder's-mouth orchid), b) *Carex tenera* (quill sedge), c) *Juncus stygius* (moor rush), and d) *Carex lenticularis* var *dolia* (Enander's sedge).

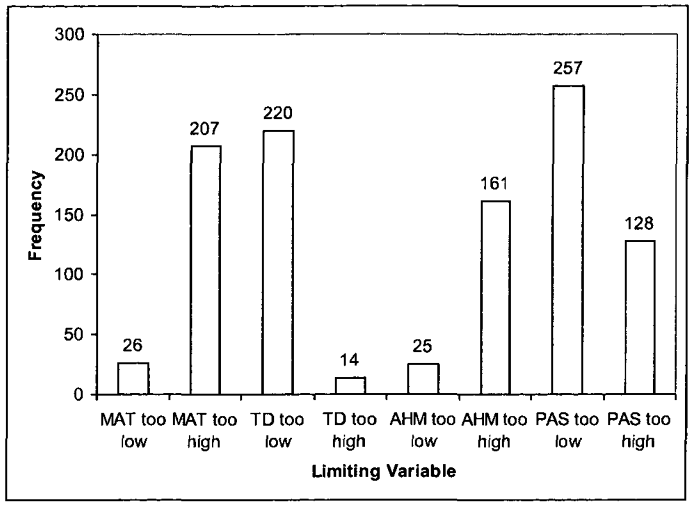


Figure 3.8. The frequency (across all four timeslices) that a variable prevented a species' location from meeting the conditions defined by its bioclimatic envelope.

Species response according to habitat

To explore theories that predict habitat-based climate driven changes to plant species distribution (e.g., expansion or contraction of suitable climate), I categorized the CDC plant species into four broad habitat types (i.e., alpine/subalpine, conifer forests, grasslands and wetlands) and evaluated the proportion change (%) in the areas of the bioclimatic envelope from the baseline to the 2080s timeslices (Appendix A Table A8). The bioclimatic envelopes for 14 of the 18 alpine/subalpine species are expected to contract (Figure 3.9). The remaining species which are expected to experience an expansion of suitable climate space (a positive proportional change) included *Allium geyeri* var. *tenerum* (+432%), *Delphinium bicolor* ssp. *bicolor* (+2560%) and *Draba lonchocarpa* var. *vestita* (+30%), while that for *Polemonium boreale* remained the same (0%). Fifty percent of conifer forest plant species were expected to expand with *Chamaesyce serpyllifolia* ssp. *serpyllifolia* experiencing the greatest proportional change (860%). Of the grassland species, 19 out of 26 experienced a loss of suitable climate. With the exception of *Silence drummondii* var. *drummondii* (+206%)

and *Koenigia islandica* (+309%), a significant increase in suitable climate was not necessarily reflected in the proportional change of suitable climate space from the baseline to the 2080s. Similarly, the majority (14 out of 19) of the wetland species are also projected to contract. The remaining wetland species, including *Megalodonta beckii* var. *beckii* (+183% in envelope area) and *Montia chamissoi* (+72% in envelope area) are projected to experience increases in suitable climate area, while *Nymphaea tetragona* was one of the few species occurrences expected to have persistent climate corridors.

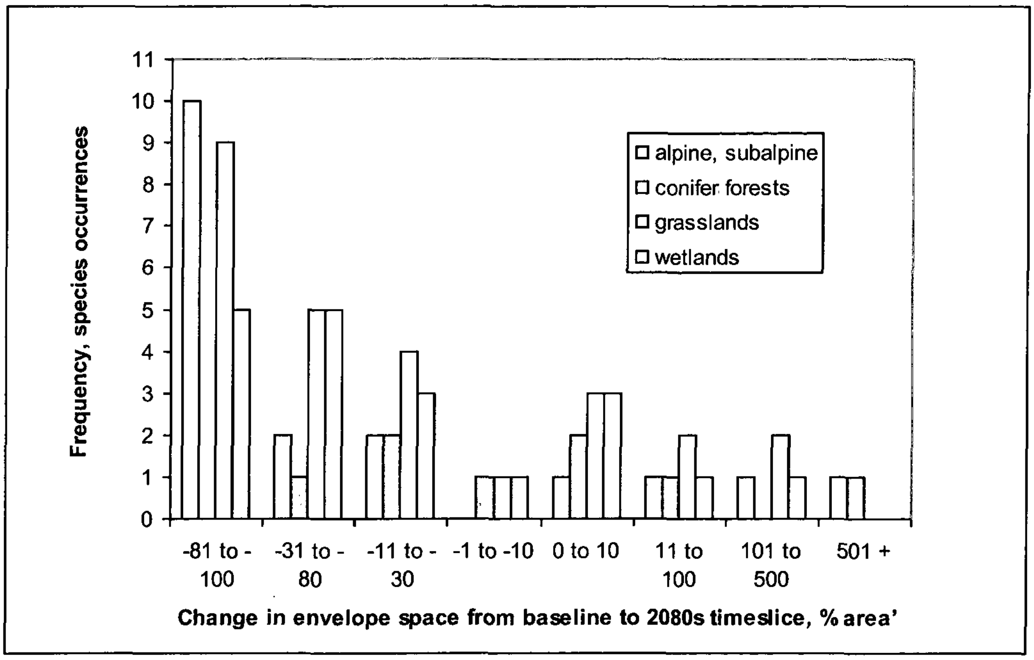


Figure 3.9. A comparison of the frequency of different degrees of change in the area covered by suitable climate space (SCS) of rare species grouped by four broad habitat types.

Testing a range of GCM and scenario assumptions

There were strong discrepancies among the three selected GCMs in terms of their implications to suitable climate space and persistent climate corridors (i.e., PCM B1, CGCM3, CSIRO A2; Figures 3.10 and 3.11). The differences between projected persistent climate corridors are based on a subset of conservation targets, which had suitable climate space projected by the CGCM3 A2 (Figure 3.10). A sampling of target species were selected to illustrate the percent change in current area represented by persistent climate corridors in Figure 3.11. A full tabulation of the projections from each GCM and scenario combinations are presented for rare plant occurrences in Table 3.10 and for the area-based targets in Table 3.9. Of the 30 species with a suitable climate space under CGCM3 A2, five (*Carex lenticularis* var. *dolia*, *C. tenera*, *Juncus stygius*, *Muhlenbergia glomerata* and *Nymphea tetragona*) had at least one population projected to persist in each model x scenario combination (Table 3.10). In contrast, only three area-based conservation targets are projected to have PCCs under all three combiuations, with the CSIRO A2 projecting the least amount of area meeting envelope requirements through time.

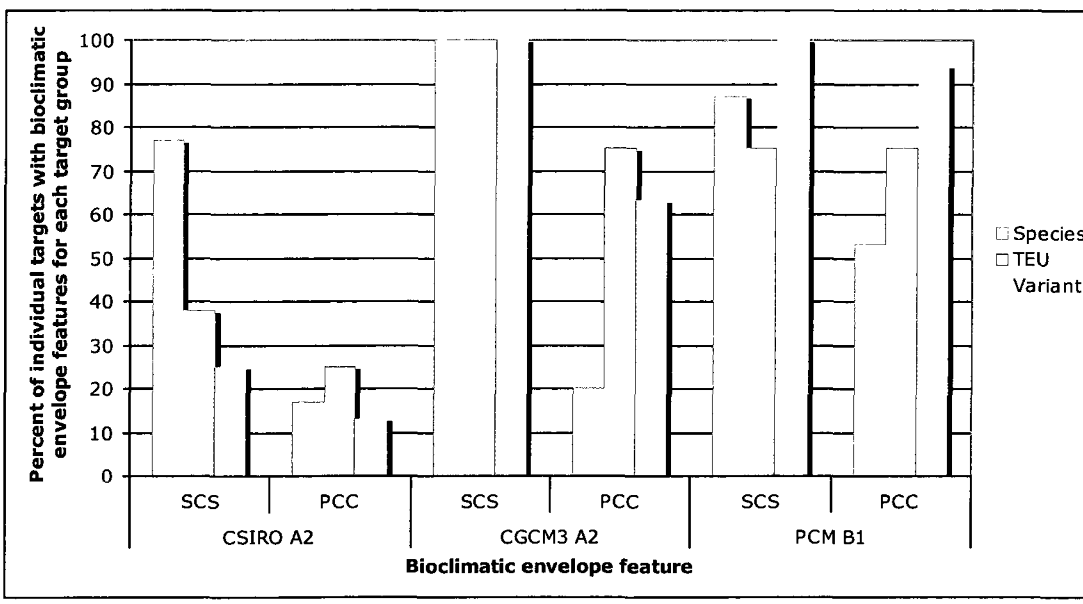


Figure 3.10. A comparison of the number of targets (for each group) with suitable climate space (SCS) and persistent climate corridors (PCCs) as projected by the CSIRO A2, CGCM3 A2 and PCM B1 scenarios.

Given the low number of occurrence records for rare species in the study area, the potential error associated with the actual persistent climate corridor is difficult to assess. Some consistent findings can be acted on, however. For example, the results projected by each GCM for *Carex tenera* and *Nephroma occultum* were noticeably different. On the other hand, the results produced by each GCM for *Juncus stygius* were the same, making planning for the conservation of this species more robust, even though one model scenario combination projects an expansion of SCS and the other two project a contraction (Figure 3.11).

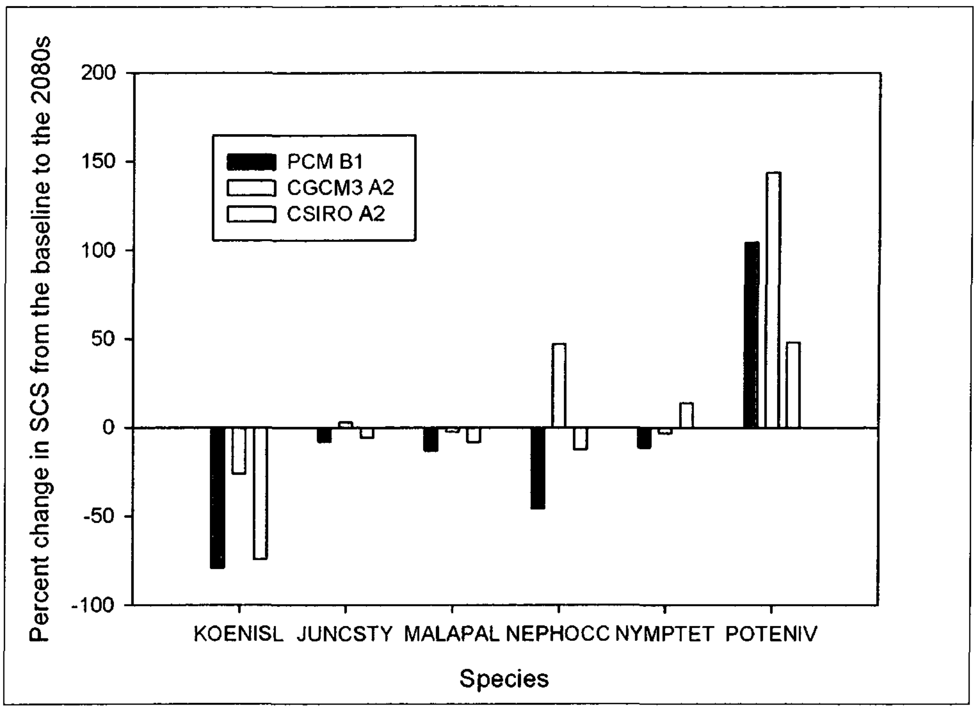


Figure 3.11. A comparison of the percent change in suitable climate space (SCS) for six species as projected by three different scenarios (CSIRO A2, CGCM3 A2, PCM B1) scenarios for *Koenigia islandica* (KOENISL), *Juncus stygius* (JUNCSTY), *Malaxis paludosa* (MALAPAL), *Nephroma occultum* (NEPHOCC), *Nymphaea tetragona* (NYMPTET) and *Potentilla nivea* var. *pentaphylla* (POTENIV).

Table 3.9. A comparison of the percentage current range of biogeoclimatic variants and terrestrial ecological units projected to fall in persistent climate corridors under the assumptions of three different climate model and scenario combinations.

Conservation Target Group	% current area represented by persistent climate corridors		
B.C. Biogeoclimatic Variant	**PCM B1**	**CGCM A2**	**CSIRO A2**
Boreal Altai Fescue Alpine Undifferentiated	7.03	0.11	0.00
Boreal Altai Fescue Alpine Undifferentiated and Parkland	5.73	0.02	0.47
Coastal Mountain-heather Alpine Undifferentiated and Parkland	0.59	0.37	0.00
Coastal Western Hemlock Central Dry Submaritime	19.85	7.84	4.66
Coastal Western Hemlock Wet Maritime	0.21	0.00	0.00
Engelmann Spruce-Subalpine Fir Moist Warm	0.64	0.60	0.00
Engelmann Spruce-Subalpine Fir Wet Very Cold	0.11	6.90	0.00
Interior Cedar Hemlock Nass Moist Cold	29.63	3.80	0.00
Interior Cedar Hemlock Very Wet Cold	35.69	18.94	0.00
Interior Douglas-fir Dry Cold	0.03	0.00	0.00
Interior Douglas-fir Wet Warm	1.00	0.00	0.00
Interior Mountain-heather Alpine Undifferentiated	0.00	0.00	0.00
Interior Mountain-heather Alpine Undifferentiated and Parkland	1.34	0.00	0.00
Mountain Hemlock Leeward Moist Maritime	0.40	0.07	0.00
Mountain Hemlock Moist Maritime Parkland	0.18	0.00	0.00
Mountain Hemlock Undifferentiated	0.44	0.09	0.00
NCC Terrestrial Ecological Units			
Boreal Alpine Fescue Dwarf Shrubland and Grassland	39.90	0.00	0.00
North Pacific Dry and Mesic Alpine Dwarf-Shrubland, Fell-field and Meadow	39.10	1.28	0.00
North Pacific Interior Lodgepole Pine - Douglas-Fir Woodland and Forest	29.25	3.10	0.00
North Pacific Interior Wetland Composite	69.35	1.28	8.36
North Pacific Montane Riparian Woodland and Shrubland	25.02	0.00	0.00
North Pacific Sub-Boreal Mesic Subalpine Fir - Hybrid Spruce Forest	0.00	11.68	0.00
North Pacific Sub-Boreal Mesic Subalpine Fir - Hybrid Spruce Parkland	0.01	41.18	0.00
Northern Rocky Mountain Lower Montane Riparian Woodland and Shrubland	0.00	9.56	0.00

Table 3.10. A comparison of the number of populations (occurrences) of rare plants projected to fall in persistent climate corridors under the assumptions of three different climate model and scenario combinations.

B.C. Conservation Data Centre Listed Plants	**# in Study Area**	**General Circulation Model**		
		PCM B1	**CGCM A2**	**CSIRO A2**
Allium geyeri var. *tenerum*	1	0	0	0
Botrychium simplex	3	1	0	0
Carex lenticularis var. *dolia*	3	2	1	1
Carex scoparia	1	1	0	0
Carex sychnocephala	1	0	0	0
Carex tenera	7	7	1	2
Chenopodium atrovirens	2	2	0	0
Delphinium bicolor ssp. *bicolor*	1	0	0	0
Draba cinerea	3	0	0	0
Draba ruaxes	2	0	0	0
Draba ventosa	1	1	0	0
Dryopteris cristata	1	0	0	0
Epilobium halleanum	2	1	0	0
Epilobium leptocarpum	2	0	0	0
Juncus albescens	3	1	0	0
Juncus arcticus ssp. *alaskanus*	2	0	0	0
Juncus stygius	2	1	1	1
Koenigia islandica	2	1	1	0
Malaxis paludosa	2	2	2	0
Minuartia austromontana	2	0	0	0
Montia chamissoi	2	1	0	0
Muhlenbergia glomerata	4	2	1	2
Nephroma occultum	4	4	2	0
Nymphaea tetragona	5	5	5	1
Potentilla nivea var. *pentaphylla*	1	0	0	0
Salix boothii	9	3	0	0
Salix serissima	1	0	0	0
Saxifraga nelsoniana ssp. *carlottae*	1	0	0	0
Sparganium fluctuans	1	0	0	0
Stellaria umbellata	1	0	0	0

Discussion

B.C. biogeoclimatic (BGC) variant bioclimatic envelopes

There appears to be a general migration or preservation of suitable climate in the northwestern corner of the study area where the persistent climate corridor of the Engelmann Spruce-Subalpine fir wet very cold (ESSFwv) and the Interior Cedar Hemlock very wet cold

(ICHvc) variants are found. These variants are adjacent to each other and are characterized by a colder, wetter climate relative to their southern counterparts and are found across a wide elevational range (Banner et al. 1993). These variants have the greatest range of mean annual temperature compared to other variants in their respective subzones. The ranges for the remaining variables (continentality, annual heat moisture index, precipitation as snow) are less consistently high but lie within the top quartile of the ranges for all other variants. A broader ecological niche may provide bioclimatic flexibility and the ability to persist as the climate changes. Mean annual temperature explained the most variance according to a Pearson's correlation matrix and principal components analysis of province-wide climate data. The Coast Mountain-heather Alpine Undifferentiated Parkland (CMAunp) and the Boreal Altai Fescue Alpine Undifferentiated (BAFAun) constitute minor components of the northwestern corner of the study area. The predominance of PCCs for these four variants (Appendix A Table A4) is contrary to other studies which project contractions of subalpine, alpine or boreal ecosystems (Pearson and Dawson 2003; McKenney et al. 2007a). However, this result might be explained by a projected increase in precipitation, a distinguishing characteristic of these variants in northern B.C. (CGCM3; Environment Canada 2008) as well as an anomaly in relation to the remainder of the province.

A recent re-classification of the Alpine Tundra BGC zone has led to the recognition of three new BGC zones: the CMA, BAFA and IMA (Interior Mountain-alpine). Ice, snow and rock are also characteristic of the alpine tundra zone and remain classified as such despite the fact that these substrates cannot support much of the alpine flora and fauna. However, over the long-term (decades to millennia) the climates and soils of these areas may become more suitable for a greater complement of other species and ecological communities (Figures 4.3, Appendix A Table A4).

Terrestrial ecological units (TEU) bioclimatic envelopes

Persistent climate corridors for the TEUs are found in the southeastern corner and along the eastern edge of the Rocky Mountain Trench within the study area. Physiognomy and elements of ecosystem classification are two possible explanations for this result. For example, at the southeastern corner of the study area, the Cariboo-Quesnel Highlands region is characterized by rolling hills and plateaus and a relatively homogenous climate which is reflected in the vegetation. The greater area of persistent climate corridors for TEUs compared to BGC variants is potentially explained by natural disturbances, such as wildfire (and consequently fire weather) which influence the ecological characteristics of a given ecosystem. In the Central Interior, for example, wildfire maintains the composition and age structure of *Pinus contorta* (lodgepole pine) ecosystems. As such, these ecosystems rarely reach the climax stage which can be tightly tied to climate and their composition remains determined more by the disturbance regime, which results in a comparatively uniform forest composition across several BGC variants.

Plant species bioclimatic envelopes

The low percentage of species with PCCs is largely a function of the low number of species' occurrence records in the study area, and the fact that many of the Central B.C. occurrences are already on the margin of their range. Species that are constrained by climate might be considered marginal because the climate associated with their occurrences is outside of what I have defined as the "core" of their bioclimatic envelope (i.e., the 5^{th} and 95^{th} percentiles). Using the 5th and 95th percentiles to define the core of the bioclimatic envelope is a somewhat conservative measure since I have excluded some populations for consideration as conservation priorities *a priori*. This definition is potentially erroneous because it rejects 10% of species occurrences as unsuitable at the outset, and does not consider a population's genetic diversity or phenotypic plasticity. I chose to define the core as I did in an attempt to address any potential uncertainties associated with rare species occurrence records, such as unlikely record locations or transcription errors in online herbarium records. Ultimately, the choice of how to define a species' core bioclimatic envelope requires a cost-benefit analysis of the trade-offs dependent on project-specific goals and objectives.

The inconsistencies between the distribution of a species' suitable climate and its current distribution in the study area also suggest that factors other than climate are limiting the distribution and establishment of most of these species (Figures 3.6 and 3.7). That is to say, climate is not currently the primary cause of rarity. Rarity of any given species is a function of a number of plausible anthropogenic factors including the loss of valuable habitat to urban and agricultural development (Ledig 1993). Secondary consequences of these activities with deleterious effects on the survival of a species include air and soil pollution (Mosquin 2000; Goward 1994) and the introduction of exotic species for horticultural and commercial purposes (Harper et al. 1993). Natural causes influencing rarity include natural disturbance, insects and pathogens (Harding 1994), a naturally discontinuous or sporadic habitat range (Schofield 1994) or range restriction by northern latitudes (Harper et al. 1993; Harding and McCullum 1997). In some cases a species' physiological and ecological characteristics pose severe challenges to long-term persistence, such as *Nephroma occultum*'s poor competitive and dispersal abilities (Brodo et al. 2001; COSEWIC 2001).

However, climate driven changes to the distribution of certain habitat types may threaten associated plant species. For example, climate change is likely to alter the thermal and hydrological regimes of wetlands, thereby drastically affecting proper ecological function and productivity of wetland species such as *Nymphaea leibergii* and *N. tetragona* (Burkett and Kusler 2000: Johnson et al. 2005; Pittock et al. 2008). According to the literature, the projected impact of climate change on grassland habitat, and consequently grassland plants such as *Juncus*, *Carex* and *Poa* species, varies from one study to another. My results show that the CGCM3 A2 projected a general decrease of suitable climate space for the *Juncus* and *Carex* species and an increase for *Poa fendleriana* ssp. *fendleriana* is projected. However, despite slight decreases in suitable climate space for *Juncus arcticus* ssp. *alaskanus, J. stygius, Carex lenticularis* var. *dolia, C. backii* and *C. bicolor*, the area meeting the requirements of their bioclimatic envelopes is projected to remain relatively constant (Table 3.10, Appendix A, Table A6).

Multi-filter approach to conservation planning

The premise of a multi-filter approach is to first select sites that are supporting single species or communities of conservation concern (fine filter). Larger scale ecological units (coarse filter) are then used to select sites with multiple values such as an ecosystem service, a unique natural feature, or a representative ecosystem or a variety of species or talon (Nature Conservancy 1982; Noss 1987; Groves et al. 2002; Molina et al. 2006). To complement their multi-filter approach and address some sources of uncertainty, the Nature Conservancy of Canada's ecoregional assessment process requires a number of data inputs on anthropogenic and natural attributes, including wildlife species of conservation concern, aquatic features, ecosystem services (e.g., carbon storage, flood mitigation and recreation), land use classifications (e.g., agriculture, urban development), and natural disturbances (e.g., extent of the mountain pine beetle epidemic).

Augmenting these inputs is an intensive expert-based site selection exercise supported by Marxan. See Chapter 1 for a brief description of Marxan and how it is used. For the Central Interior ecoregional assessment, the CDC-listed plant species represent fine filters, while the BGC variants and the TEUs represent coarse filters. Each of these target groups represents a Marxan input that will be included in a decision support tool for resource managers in the study area. The climate change component of the Central Interior ecoregional assessment will be supported by the findings of a climate change working group, which consists of experts from each input group. Through a series of workshops, these experts identified which targets are the most vulnerable to climate change and their probable response. Together with my empirical model, this expert-based approach will provide valuable ecological information from two different methodologies.

A dynamic approach to resource management

The B.C. biogeoclimatic ecosystem classification provides a level of climatic detail that is reflected in differences in plant, soil and ecosystem productivity (MacKinnon et al. 1992). The Nature Conservancy of Canada's terrestrial ecological units, for example, are in part based on the B.C. biogeoclimatic variants. The projected loss of suitable climate for a number of BGC variants (Table 3.5, Figures 3.5 and 3.6) and TEUs (Table 3.6, Figures 3.7 and 3.8) provide a warning of the drastic level of changes that might be expected in ecosystem structure and composition, and the subsequent impact of climate change on future resource management practices (BCMFR 2009). In all likelihood, new ecological communities will emerge; the composition, function and the role of those new species assemblages are difficult to predict, and may displace the familiar communities on which many of our management practices are based.

The efforts to integrate dynamic processes into a management framework are potentially undermined by how ecologists and resource managers classify ecological units. Despite their basis in reflecting relatively uniform ecology (species composition, soil type, and climate), ecosystem classes and mapped ecological zones or regions ultimately reflect a subjective process. Furthermore, these human constructs may have limited flexibility and adaptability because they describe the current expression of some ecological attributes (e.g., climax vegetation) under local climatic and geographic parameters. The delineation of boundaries for ecological units is also subject to interpretation, debate and uncertainty. The sources of uncertainty (and ultimately of error) afflicting projections of bioclimatic envelopes for terrestrial ecological units, for example, include a lack of ground truthing, and the inclusion of information from a range of different sources which differ in their underlying assumptions. In comparison, BGC variants have been more consistently sampled, evaluated, updated and refined to reflect consistent principles and hence represent a reliable source of information (BCMFR 2009).

It is important to consider the biogeographic lag which exists between climate change and vegetation response, and recognize its contribution to landscape heterogeneity (Shafer 1990). These lags are also expected to cause sub-optimal ecological functioning and reduced resilience to natural disturbance (Parmesean and Yohe 2003; Leemans and Eickout 2004; Fitzpatrick et al. 2008). To date, biogeographic lags have not been incorporated into species distribution modelling and their impact on individual species and communities remains unclear (Pearson and Dawson 2003; Thuiller et al. 2005). The potential influence of time lags in this study is evidenced by the widespread distinction between the locations defining a target's suitable climate space and those identified as persistent climate corridors.

Adaptive management: The application of suitable climate space and persistent climate corridors to resource management

Effective adaptive management requires adjustments to our ecological and socio-economic responses to the environment. It should incorporate risk analysis and require resource managers and conservation planners to educate stakeholders, establish future management objectives that consider cost-effective actions and develop monitoring programs that aid in the regular assessment of newly implemented strategies (Spittlehouse 2005; BCMFR 2006a; Millar et al. 2007). Some of the challenges of adaptive management include coordinating conservation initiatives with multiple protected areas and other resource-based activities, incorporating uncertainties, such as time lags and the emergence of new communities into our decision-making frameworks and making improvements to ecological modelling, (e.g., the coupling of GCMs with dynamic process-based simulations) (Hannah et al. 2002a; Spittlehouse 2005; Botkin et al. 2007; Rayfield et al. 2008).

Addressing these challenges requires an emphasis on ecological process rather than structure and composition, and an understanding that no single approach will suit all situations (Millar et al. 2007). The intended purpose of persistent climate corridors is to provide refuge in the form of climatic connectivity or persistence. During the warm stages of Quaternary and Tertiary geological eras, climate refugia fostered speciation; and across topographically diverse areas, climate refugia allowed habitats to persist through shifts in elevation and diverge during periods of climate change. On a small scale such as a planning unit, climate refugia can be important for maintaining the unique floristics of species assemblages which differ from those communities adapted to the dominant climate (Noss 2001; Taberlet and Cheddadi 2002).

The identification of suitable climate space has managerial implications for conservation planning. Facilitated migration, for example, is a proactive management strategy designed to mitigate possible species extinctions by translocating species along expected climate gradients to more suitable climates (Millar et al. 2007; Van der Veken et al. 2008). It is potentially the most effective and economically feasible adaptive management strategy currently favoured by foresters and ecologists (Hannah et al. 2002a; BCMFR 2006a; McKenney et al. 2007b). In general, the identification of a target's suitable climate space allows silviculturalists and foresters to optimize their management of commercially valuable timber species by maximizing their deployment to the best possible growing conditions (i.e., core bioclimatic envelopes).

Other research exploring climate change impacts on natural processes using a similar overlay-intersect approach include the redefinition and projection under climate change of North America's plant hardiness zones (McKenney et al. 2007b), predicting the future distribution of North American trees (McKenney et al. 2007a) as well as key British Columbian tree species (Hamann and Wang 2006), the mapping of candidate areas to protect key Proteaceae species in South Africa (Hannah et al. 2005), exploring the spatial mismatching of trophically interacting species (Schweiger et al. 2008), and identifying hotspots of response to climate change (Post et al. 2009).

Model-based uncertainty

The variability among different general circulation models can significantly compromise the usefulness of the results for guiding policy development and decision making processes. Ideally, an ensemble forecast would address some of the uncertainty-based issues because it is more narrowly defined by several different models across a set of conditions, and model classes and parameters (Araújo and New 2006). In order to address the uncertainties associated with predicting future climates and avoid overly optimistic estimates, model projections would ideally be validated. A variety of validation techniques exist including resubstitution and grouped cross validation, but the best option for bioclimatic envelope modelling is to use independent test data from another region or timeframe. Unfortunately, given the data limitations of projecting future species distributions, validation of most bioclimatic envelope modelling research is rarely performed. Some of the limitations which might hamper a model's predictive ability include the assumption that species response to climate change is immediate, and the potential of climate change to occur more rapidly and at a greater magnitude than experienced in the past (Araújo et al. 2005; Heikkinen et al. 2006).

Conclusions

Bioclimatic envelope modelling provided the foundation for the identification of persistent climate corridors. These corridors represent locations where a conservation target's bioclimatic envelope is expected to be met over a 75-year period, and are designed to assist with the site selection and prioritization process of conservation planning. According to the CGCM3 A2 general circulation model and scenario, 24 (12%) of the 206 conservation targets were projected to have persistent climate corridors. Although a rational and moderate projection, this result is subject to a number of uncertainties including the accuracy and validity of the CGCM3 model and A2 scenario.

The concept of persistent climate corridors provides a simple and powerful tool kit for conservation planning under a changing climate. It is also pertinent to the development and application of a variety of management strategies, including the Nature Conservancy of

Canada Central Interior ecoregional assessment, and federal (Canadian Forest Service) and provincial (BCMFR) strategies for facilitating the climate-adapted migration of valuable tree provenances and seed sources. As the impacts of climate change continue to threaten global biodiversity, the need to develop new proactive management strategies becomes increasingly urgent. Persistent climate corridors give planners and ecologists some priorities for conservation and mitigation as they cope with the challenges presented by climate-driven changes to the protection of valued ecosystems and the ecological services they provide.

Chapter 4 - Synthesis: Dynamic conservation planning and climate change

Abstract

Climate change represents significant and unforeseen changes to the natural environment and subsequently exacerbates the challenge of managing natural resources. Bioclimatic envelope modelling was used to predict the future distribution of suitable persistent climate for three conservation target groups, namely biogeoclimatic (BGC) variants, terrestrial ecological units (TEU) and selected rare plant species. Results from chapter 3 projected persistent climate corridors for 9% of the 103 BGC variants, 20% of the 30 TEUs and 11% of the selected plant species. Of these individual targets, only 4 TEUs and 5 BGC variants coincided to create overlapping areas of persisting suitable climate which equated to 327 km^2 (or 0.13 % of the study area). I consider areas of overlap (coincidence) to be of high conservation value because they theoretically supported the persistence of more than one target. Results were evaluated according to the final scores of one of the outputs generated by Marxan, a reserve selection program set to prioritize areas with low human disturbance. The average scores (conservation value, on a scale of 0 to 100) for the areas of coincidence were 80 (without parks locked in) and 82 (with parks locked in). The identification of persistent climate corridors that also coincide with other high conservation values provides a means of designating areas that can be expected to have greater persistence in a changing climate.

Introduction

The impact of the coming century of climate change will alter the environment at an indeterminate rate and magnitude. A changing climate, in concert with other global pressures, seriously threatens native biodiversity, the protection of which represents a formidable challenge to resource managers (Halpin 1997; Scott and Lemieux 2005). Some of the anticipated threats associated with global warming are shifts in species distributions leading to the displacement and loss of biodiversity (Suffling and Scott 2002; Williams and Jackson 2007). The consequences of these changes are expected to have cascading effects throughout a number of ecosystems and will directly affect Canada's current network of parks and protected areas (Scott et al. 2002; Suffling and Scott 2002; Lemieux and Scott 2005). To mitigate the loss of biodiversity and to effectively protect critical species and ecological communities, ecologists have started to incorporate a more process-based approach to protected area planning. Using the Nature Conservancy of Canada's Central Interior Ecoregional Assessment as a case study, the research reported in this thesis explored the temporal dynamics of a changing climate and their implications to planning processes (Chapter 2). Bioclimatic envelope modelling (Pearson and Dawson 2003; Hamann and Wang 2006) and the concept of a suitable climate space (Berry et al. 2003; Pearson et al. 2006) provided the foundation to develop the concept of persistent climate corridors and their role as candidate areas for conservation (Chapter 2, 3).

In this study, "suitable climate space" represents the spatial distribution of a conservation target as defined by its bioclimatic envelope (Pearson and Dawson 2003), and specifically where it is expected to persist over time (Berry et al. 2003; Pearson et al. 2006). "Persistent climate corridors" (PCCs) are locations where a target's current location is coincident with its suitable climate space. The application reported here sought to 1) identify areas of high conservation value, which in this study were defined by areas with multiple persistent climate corridors; and 2) compare the location of PCCs with areas of high conservation value as denoted by the Nature Conservancy of Canada using Marxan, an iterative reserve selection program (Ball and Possingham 2000).

Methods

As illustrated in Chapter 2 and executed for multiple conservation targets in Chapter 3, the identification of persistent climate corridors is a four-step process. These steps consist of: 1) the development of bioclimatic envelopes for each conservation target for the Central Interior study area (i.e., 103 B.C. biogeoclimatic variants, 30 terrestrial ecological units, 73 plant species); 2) the identification of locations in the study area meeting a target's bioclimatic envelope requirements for the baseline (current), 2020s, 2050s and 2080s timeslices; 3) the intersection of these four timeslices (suitable climate space), and 4) an overlay of a target's current distribution with its suitable climate space. The tools used in this process were ArcMap® 9.2 geographic information systems (GIS) software, ClimateBC (Mbogga et al. 2009) and output from the third generation of the Canadian general circulation model (CGCM3; Environment Canada 2008).

Developing bioclimatic envelopes involved collecting occurrence records or mapped distributions of a target's range and generating climate variables at each location using ClimateBC (Spittlehouse 2006). ClimateBC generated 19 climate variables but due to high collinearity among them, four key discriminators of climate were used: mean annual temperature (MAT), annual heat moisture index (AH:M), continentality (TD) and precipitation as snow (PAS); see Chapter 3. The target's bioclimatic envelopes were limited to a core range defined by the 5th to 95th percentiles of each climate variable (Kadmon et al. 2003; Beaumont et al. 2005; McKenney et al. 2007b).

Within each timeslice, the locations meeting the requirements of a target's core bioclimatic envelope were overlaid using ArcMap; the climate at these intersecting locations was termed suitable climate space and was presumed to persist over the defined timeframe, thereby providing temporal connectivity in climatic conditions (Berry et al. 2003; Pearson and Dawson 2003; see Chapters 2 and 3). Next, a target's current distribution was overlaid with its suitable climate space, and locations where these two coverages coincided were identified as persistent climate corridors. Because these locations already support populations and ecologies of a particular target, and they are expected to undergo less perceptible climate change than elsewhere, they arguably represent priority areas for conservation.

Applying persistent climate corridors to conservation planning

A reserve network that protects many conservation targets in a given area is the optimal solution for which planners and agencies such as the Nature Conservancy of Canada (NCC) strive. To explore this idea in concert with the concept of persistent climate corridors (PCCs), the projected PCCs for different conservation target groups were overlaid singly and in combination to form a single PCC layer. Locations exhibiting high conservation value were then themed to identify areas where one, two or three PCCs were projected.

To illustrate how Marxan and persistent climate corridors can be used together, the aggregate PCC layer was compared with two of NCC's final outputs for the Central Interior study area. Conservation portfolios were created using Marxan, a reiterative reserve selection program (Ball and Possingham 2000; see Chapter 1) which generates a suite of potential protected area networks based on a stable climate and widely accepted conservation values.

Marxan conservation value scores are a function of a number of built-in metrics including a cost threshold penalty, a species penalty factor and a boundary length modifier designed to maximize the benefit of a reserve network at the least cost (Game and Grantham 2008; http://www.uq.edu.au/marxan/index.html?p=1.1.1). Final Marxan scores for the Central Interior were assigned to individual 500-ha hexagons covering the study area and represent a set of conservation targets as defined by expert knowledge. Depending on the conditions or requirements set by NCC's goals and objectives, each hexagon receives a score which represents the number of times that it was selected to be included in one of the Marxan iterations. Each Marxan output was created from 100 runs, each with 1 million iterations.

For this exploratory analysis, NCC provided the Marxan outputs for the suitability index of terrestrial-based conservation targets with and without parks and protected areas "locked in" to the solution. The suitability index was a "cost function" measured in this case by the absence of human impact on the landscape as indicated by low road density and average distance to roads within each hexagon. Hexagons with a high cost receive a low score and are considered less attractive for conservation. For this particular Marxan output, areas with high human influence were thus less likely to be chosen; no other priorities such as rare habitats or endangered ecosystems were included in these Marxan runs. In this procedure each hexagon is scored between 0 and 100, with 100 being the highest value areas (Figure 4.1). When exploring conservation solutions built around existing parks and protected areas, these locations are assigned scores of 100, and so are "locked in" to the solution to more closely approximate a reasonable land use planning process for the region (Sarah Loos, NCC GIS Analyst, *pers. comm.*). To identify high conservation value areas that also are expected to support PCCs, or conversely, PCC locations that have high conservation value, the aggregate layer showing multiple PCCs was overlaid with the Marxan scores with and without fixed parks and protected areas.

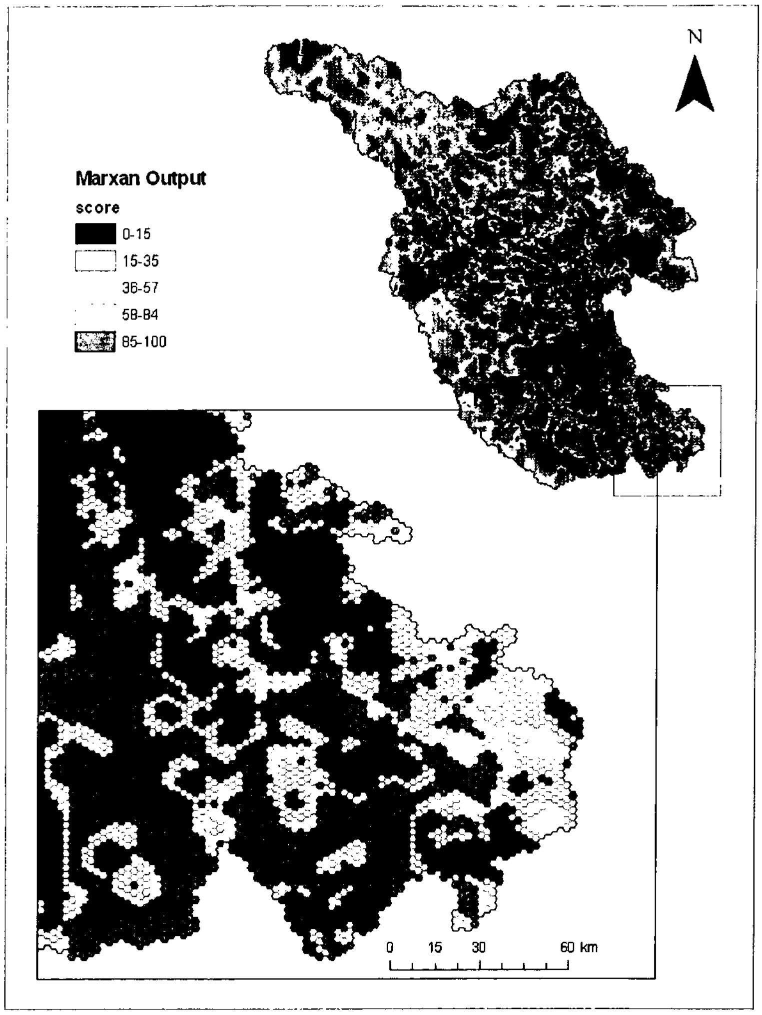


Figure 4.1. Marxan output for the Central Interior study area showing the range of conservation value scores generated from a suitability index without parks "locked in".

Results

Conservation Target Groups

B.C. Biogeoclimatic (BGC) Variants

According to the CGCM3 projections and my overlay analysis (Chapter 3), only 16 of the 103 BGC variants found in the study area had suitable climate space and eight had persistent climate corridors (Appendix A, Table A4). Overall, the resulting projections indicated the potential for a substantial loss in representative climatic regions and vegetation assemblages represented by the BGC variants (Table 3.6).

Terrestrial Ecological Units (TEU)

The results for NCC's TEUs (Table 3.7) were similar to the BGC variants in that there is the potential for a significant loss of valued ecosystem types (Appendix A, Table A5). With CGCM3 projections, only eight of the 30 TEUs currently found in the Central Interior were expected to have suitable climate space and six had PCCs, though still representing only 1-10% of their corresponding current areas. There is projected to be a loss of suitable climate space from the baseline timeslice to the 2080s for some TEUs, even while the suitable climate space for other units was projected to occupy more land than now.

Plant Species listed by the B. C. Conservation Data Centre (CDC)

Most of the rare plant species listed as being found in the Central Interior study area were expected to be threatened by the levels of climate change anticipated over the rest of this century. The CGCM3 projections and associated overlay analysis indicated that 29 of the 73 target plant species evaluated would have suitable climate space, and only nine would be able to persist in one or more of their currently documented locations (Appendix A, Table A6). Because lots of suitable climate space is available for most species under current as well as future climates, these projections imply that the distributions of these species are not limited by climate. However, the low sample sizes available for envelope calibration and point-based climate projections, as well as the exclusion of occurrences outside the 5th and 95th percentiles, undoubtedly affect the probability of a PCC for any particular species. In other words, these are probably very conservative estimates of the potential for the persistence of rare plant populations; several other ones are likely to be suitable too.

Applying persistent climate corridors to conservation planning

The creation of a single aggregate PCC layer identified areas where BGC variants and terrestrial ecological units coincided. Other target group combinations did not result in areas of coincidence (Figure 4.2). Across the study area, the extent of target persistent climate corridors and the locations of coincidence are relatively sparse. The study area is approximately 246,000 km^2, whereas the areas of the BGC variant PCCs, TEU PCCs, and their coincidence (TEU + BGC variant) are 18,108 km^2 (7 %), 2,372 km^2 (0.96 %) and 327 km^2 (0.13 %), respectively. In terms of the CDC plant species, there were only 27 out of a possible 162 (17%) persistent climate corridor locations (based on occurrences of 73 species) for these rare plant species, none of which coincided with the PCCs of other conservation targets. Though potentially alarming from an overall biodiversity conservation perspective, these results nevertheless give strong direction to planners in terms of some priority areas for conservation.

Comparing Marxan suitability indices with persistent climate corridors

The "locking in" of parks into Marxan solutions resulted in a 44% increase in the number of hexagons with scores of 100, which on the landscape means 73,639 km^2 of land with potential for conservation compared to 41,209 km^2 for the solution without parks. In general, the TEUs persistent climate corridors had greater representation across the five score classes than the BGC variants' PCCs and BGC/TEU combinations for both the suitability index with (Table 4.1) and without (Table 4.2) parks locked into the solution. Conversely, the score of a plant species is based on the score of the hexagon where it is located and did not appear to vary too greatly between Marxan outputs (Table 4.3).

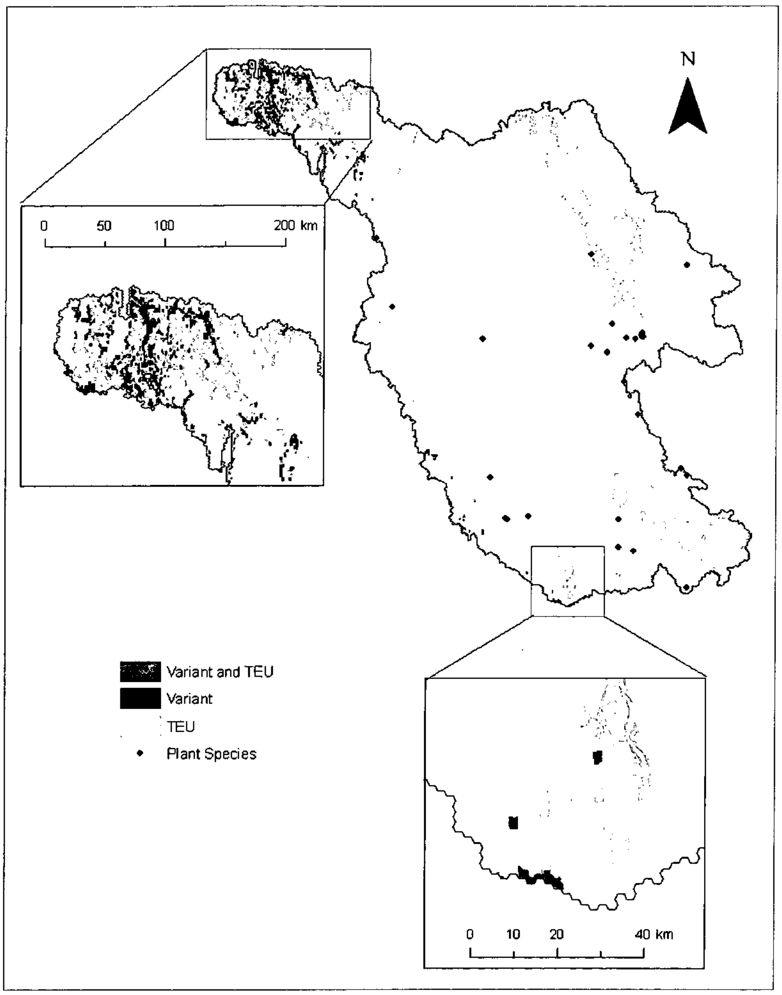
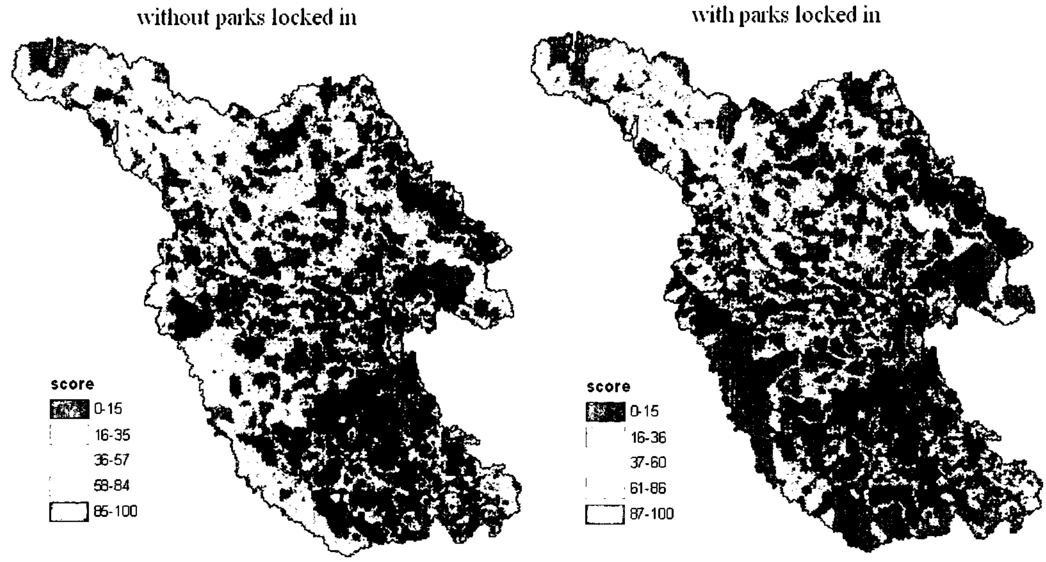


Figure 4.2. A map illustrating the locations in the Central Interior study area with more than one persistent climate corridor. B.C. biogeoclimatic variants and terrestrial ecological units (TEU) were the only target groups with areas of coincidence (red).



Score	with parks locked in (km^2)	without parks locked in (km^2)
0-20	84028	86663
21-40	40064	49064
41-60	28004	37854
61-80	16235	24550
81-100	88523	58724
Total	256854 km^2	

Figure 4.3. A comparative illustration showing the Marxan suitability index output with and without parks "locked in". The area (km^2) of each score class is summarized according to the suitability index with and without parks in the table below the below the maps. (NCC 2009, unpublished).

Discussion

The map in Figure 4.2 illustrates those conservation targets with multiple persistent climate corridors and provides guidance for the selection of areas expected to exhibit relative ecological suitability under a changing climate. From the perspective of a conservation organization and agencies, areas which could potentially conserve more than one target are ideal candidates for protection. The patterns of temporal connectivity or climatic persistence as represented by a target's PCC facilitate the mobilization of a concerted effort for preservation and allocation of resources in these general areas.

Table 4.1. An areal summary (km²) of the scores assigned to the area-based PCCs with parks locked in to the Marxan suitability run.

	Marxan Output score classes (0-100)					Total Area
Conservation Target Group	**0-15**	**16-36**	**37-60**	**61-86**	**87-100**	**(km²)**
Biogeoclimatic (BGC) variants						
Boreal Altai Fescue Alpine Undifferentiated (BAFAun)	0	0	10	30	145	185
Boreal Altai Fescue Alpine Undifferentiated and Parkland (BAFAunp)	0	0	20	10	0	30
Coastal Mountain-heather Alpine Undifferentiated and Parkland (CMAunp)	0	0	135	95	145	375
Coastal Western Hemlock Central Dry Submaritime (CWHds2)	0	0	0	0	260	260
Engelmann Spruce-Subalpine Fir Moist Warm (ESSFmw)	0	0	20	10	140	170
Engelmann Spruce-Subalpine Fir Wet Very Cold (ESSFwv)	60	535	1,160	530	2,150	4,435
Interior Cedar Hemlock Nass Moist Cold (ICHmc1)	15	150	460	185	110	920
Interior Cedar Hemlock Very Wet Cold (ICHvc)	75	80	60	100	425	740
Mountain Hemlock Moist Maritime (MHmm2)	0	0	0	0	50	50
Mountain Hemlock Undifferentiated (MHun)	0	0	10	60	5	75
Terrestrial Ecosystem Units (TEU)						
Boreal Alpine Fescue Dwarf Shrubland and Grassland	5	500	510	200	1,020	2,235
North Pacific Dry and Mesic Alpine Dwarf-Shrubland, Fell-field and Meadow	0	0	0	20	185	205
North Pacific Interior Lodgepole Pine - Douglas-Fir Woodland and Forest	1,665	960	420	120	1,175	4,340
North Pacific Montane Riparian Woodland and Shrubland	2,170	5,560	13,670	4,315	12,085	37,800
North Pacific Sub-Boreal Mesic Subalpine Fir - Hybrid Spruce Forest	100	495	790	430	1,675	3,490
Northern Rocky Mountain Lower Montane Riparian Woodland and Shrubland	8,805	5,465	1,790	255	4,885	21,200
BGC and TEU combination						
BAFAun - Boreal Alpine Fescue Dwarf Shrubland and Grassland	0	0	0	5	60	65
BAFAun - North Pacific Dry and Mesic Alpine Dwarf-Shrubland, Fell-field and Meadow	0	0	0	0	20	20
CMA unp - North Pacific Dry and Mesic Alpine Dwarf-Shrubland, Fell-field and Meadow	0	0	0	5	15	20
ESSFwv - Boreal Alpine Fescue Dwarf Shrubland and Grassland	0	0	0	0	10	10
ESSFwv - North Pacific Montane Riparian Woodland and Shrubland	0	130	145	95	105	475
ESSFwv - North Pacific Sub-Boreal Mesic Subalpine Fir - Hybrid Spruce Forest	0	220	450	195	950	1,815
ICH mc 1 - North Pacific Montane Riparian Woodland and Shrubland	0	0	80	10	0	90
ICH vc - North Pacific Montane Riparian Woodland and Shrubland	0	350	85	5	1,615	2,055
Total area (km²) for score class	12,895	14,445	19,815	6,675	27,230	81,060
Proportion (%) of each score class	16	18	24	8	34	

Table 4.2. An areal summary (km²) of the scores assigned to the area-based PCCs without parks locked in to the Marxan suitability run.

	Marxan Output score classes (0-100)					Total
Conservation Target Group	**0-15**	**16-35**	**36-57**	**58-84**	**85-100**	**Area (km²)**
BGC variants						
Boreal Altai Fescue Alpine Undifferentiated (BAFAun)	0	20	65	40	20	145
Boreal Altai Fescue Alpine Undifferentiated and Parkland (BAFAunp)	0	0	20	10	10	40
Coastal Mountain-heather Alpine Undifferentiated and Parkland (CMAunp)	0	30	145	160	35	370
Coastal Western Hemlock Central Dry Submaritime (CWHds2)	0	10	10	35	85	140
Engelmann Spruce-Subalpine Fir Moist Warm (ESSFmw)	10	10	15	115	20	170
Engelmann Spruce-Subalpine Fir Wet Very Cold (ESSFwv)	0	355	1,500	905	400	3,160
Interior Cedar Hemlock Nass Moist Cold (ICHmc1)	20	95	465	240	70	890
Interior Cedar Hemlock Very Wet Cold (ICHvc)	85	65	70	100	105	425
Mountain Hemlock Moist Maritime (MHmm2)	0	0	15	20	5	40
Mountain Hemlock Undifferentiated (MHun)	0	0	5	45	35	85
TEUs						
Boreal Alpine Fescue Dwarf Shrubland and Grassland	0	530	490	340	895	2,255
North Pacific Dry and Mesic Alpine Dwarf-Shrubland, Fell-field and Meadow	0	70	35	35	50	190
North Pacific Interior Lodgepole Pine - Douglas-Fir Woodland and Forest	2,190	855	215	205	875	4,340
North Pacific Montane Riparian Woodland and Shrubland	3,020	3,755	12,805	7,985	10,235	37,800
North Pacific Sub-Boreal Mesic Subalpine Fir - Hybrid Spruce Forest	35	390	1,090	850	1,125	3,490
Northern Rocky Mountain Lower Montane Riparian Woodland and Shrubland	9,245	5,345	1,380	900	4,330	21,200
BGC and TEU combination						
BAFAun - Boreal Alpine Fescue Dwarf Shrubland and Grassland	0	0	50	25	0	75
BAFAun - North Pacific Dry and Mesic Alpine Dwarf-Shrubland, Fell-field &Meadow	0	0	0	0	20	20
CMAunp - North Pacific Dry and Mesic Alpine Dwarf-Shrubland, Fell-field & Meadow	0	5	15	0	0	20
ESSFwv - Boreal Alpine Fescue Dwarf Shrubland and Grassland	0	0	0	0	10	10
ESSFwv - North Pacific Montane Riparian Woodland and Shrubland	0	5	215	150	105	475
ESSFwv - North Pacific Sub-Boreal Mesic Subalpine Fir - Hybrid Spruce Forest	0	95	650	335	760	1,840
ICHmc1 - North Pacific Montane Riparian Woodland and Shrubland	0	0	80	10	0	90
ICHvc - North Pacific Montane Riparian Woodland and Shrubland	0	5	100	85	1,530	1,720
Total area (km²) for score class	14,605	11,640	19,435	12,590	20,720	78,845
Proportion (%) of each score class	19	15	25	16	26	

Table 4.3. The Marxan output scores for the B.C. Conservation Data Centre plant species PCCs.

Without parks "locked in"	Marxan Output Score (0-100)									Mean Score
	4	16	28	42	64	78	80	86	100	
Carex lenticularis var. *dolia*									1	100
Carex tenera	1									4
Juncus stygius									1	100
Malaxis paludosa						1		1		82
Muhlenbergia glomerata									2	100
Nephroma occultum					1					64
Nymphaea tetragona		1	1	1			1		1	53
Potentilla nivea var. pentaphylla									1	100

With parks "locked in"	Marxan Output Score (0-100)									Mean Score
	3	16	38	42	50	60	74	80	100	
Carex lenticularis var. *dolia*									1	100
Carex tenera	1									3
Juncus stygius									1	100
Malaxis paludosa					1			1		65
Muhlenbergia glomerata									2	100
Nephroma occultum							1			74
Nymphaea tetragona		1	1	1		1			1	51
Potentilla nivea var. pentaphylla									1	100

Given the general paucity of conservation resources and an abundance of issues surrounding multiple stakeholders associated with conservation planning, large areas consisting of more than one PCC are ideal "coarse filter" conservation areas, suitable for the protection of a number of conservation targets. In terms of the overlap with the rare plant species it is especially unfortunate that none of the rare plant persistent climate corridors, indicating priority investments for successful "fine filter" conservation of rare species, overlap with PCCs for either of the area-based conservation targets. They may yet, however, coincide with the locations of other NCC conservation priorities as planning for this ecoregion progresses.

Areas of the Central Interior with multiple persistent climate corridors are concentrated in the northwestern and southeastern corners, and the eastern edge of the study area. Englemann Spruce-Subalpine fir Wet Very Cold (ESSFwv) and the Interior Cedar Hemlock Very Wet Cold (ICHvc) variants are the primary BGC variants found in the northwestern corner, while the Coast Mountain-heather Alpine Undifferentiated Parkland (CMAunp) and the Boreal Altai Fescue Alpine Undifferentiated Parkland (BAFAunp) constitute minor components of the northwestern corner of the study area. The potential expansion by these variants is contrary to the projections of other similar habitat types in that boreal, subalpine and alpine ecosystems are expected to contract (Pearson and Dawson 2003; McKenney et al. 2007a). For this study, their expansion might be explained by a projected increase in precipitation, a distinguishing characteristic of these variants in northwestern B.C. (Woods et al. 2005; Environment Canada 2008) as well as an anomaly for the remainder of the province.

The persistent climate corridors for the terrestrial ecological units were concentrated in the southeastern corner and the eastern edge of the study area. These areas are relatively less diverse and are characterized by rolling hills and plateaus. The climate of these areas is also relatively homogeneous, and targets with broader climate niches might be more flexible and therefore more likely to persist as the climate changes.

The analysis of suitable climate and persistent climate corridors of these conservation targets is based at a scale where climate is generally the dominant factor limiting species distributions (Pearson and Dawson 2003; Heikkinen et al. 2006). Realistically, species distributions are a function of genetics, adaptive capacity, biotic interactions and other abiotic factors such as the natural disturbance regime. Human activities including modern climate change alter these mechanisms and further exacerbate our ability to accurately predict the probable outcomes (McCarty 2001; Gayton 2008). For example, plant species are expected to respond individually to climate change, leading to a widespread redistribution and re-organization of plant communities (Shafer et al. 2001; BCMFR 2006a).

The relatively large area of suitable climate and overall low percentage (17%) of PCCs for most rare plant species occurrences suggests that, as a group, they are not primarily limited by climate at the regional scale of the Central Interior. Although the inclusion of rare plant PCCs will be a useful contribution to an overall conservation strategy, protection and the recovery of any individual plant species requires identification of the threats limiting the distribution of that species in order to recommend pertinent management strategies. Persistent climate corridors which have high Marxan scores (e.g., >80), will be especially important targets for protection in conservation planning, contributing to continuity and high conservation values under current conditions as well has having high probability of persistence in the face of climate change.

The analysis of PCCs in conjunction with two of the Nature Conservancy of Canada (NCC) Marxan outputs was an exploration into the applicability of persistent climate corridors to conservation planning and is by no means complete. The suitability index based on roadlessness with and without parks is one of many outputs which NCC has created and continues to create for the Central Interior study area. Various Marxan outputs and PCCs will be incorporated into a decision support tool designed by NCC for the Central Interior study area. The purpose of this tool is to allow users to create their own conservation portfolio or determine the advantages and disadvantages of any particular reserve network.

A thorough understanding of species and ecosystems is central to successfully predicting their future distribution in a changing climate and subsequently prescribing appropriate conservation strategies. However, the inability to confidently predict ecological responses to climate change reflects a substantial uncertainty originating from a variety of sources (Chapter 1, Table 1.4). These uncertainties are cumulative, difficult to quantify and inevitably lead to error. The probable origins of error in this research include low sample sizes for listed plant species, incomplete occurrence data of a target's range (or distribution) leading to a misrepresentation of a target's suitable climate space and consequently its persistent climate corridor. A number of GCM limitations which introduce error into the analysis include differences in scale, output variability from one model and scenario combination to another, and a generally poor ability to accurately project some climatic features such as cloudiness and the seasonality of precipitation (Chapter 1, Table 1.4) (Hannah et al. 2002; Millar et al. 2007a,b). Finally, it is recognized that many features of the landscape (topography; soils) and species biology (dispersal and competitive abilities) contribute additional factors that further constrain or facilitate the persistence of species and communities in a changing climate. Nonetheless, the identification of locations predicted to meet bioclimatic envelope requirements for the foreseeable future is an important first step for conservation planning in a word now facing some drastic changes.

Conclusions

The addition of a climate change perspective into a conservation planning framework attempts to recognize and account for the spatiotemporal dynamics of an ecosystem and its subsequent manifestation on the landscape. Within the Nature Conservancy of Canada's planning framework, projections of ecological resistance to the climate change component of these dynamics is one of many potential inputs to the planning process, along with considerations such as the distribution and habitat preferences of target wildlife species, natural disturbance regimes, aquatic features and ecosystem services. The results of the research reported here, juxtaposed with the research derived from NCC's Climate Change Working Group, provide some insight into how climate change will impact the Central Interior of B.C. and how some of the impacts can be minimized with careful spatial planning.

This collective effort also demonstrates the adaptive potential of a dynamic-based approach to resource management and conservation.

References

Araújo, M.B., M. Cabeza, W. Thuiller, L. Hannah, and P.H. Williams. 2004. Would climate change drive species out of reserves? An assessment of existing reserve-selection methods. Global Change Biology **10**:1618-1626.

Araújo, M.B., and M. New. 2006. Ensemble forecasting of species distributions. Trends in Ecology and Evolution. **22**:42-47.

Araújo, M.B., R.J. Whittaker, R.J. Ladle, and M. Erhard. 2005. Reducing uncertainty in projections of extinction risk from climate change. Global Ecology and Biogeography **14**:529-538

Austin, M.P. 2002. Spatial prediction of species distribution: an interface between ecological theory and statistical modelling. Ecological Modelling **157**:101-118.

Bachelet, D., J. Leniham, R. Neilson, R. Drapek, and T. Kittel. 2005. Simulating the response of natural ecosystems and their fire regimes to climatic variability in Alaska. Canadian Journal of Forest Research **35**:2244-2257.

Bakkenes, M., J.R. Alkemade, F. Ihle, R. Leemans, and J.B. Latour. 2002. Assessing the effects of forecasted climate change on the diversity and distribution of European higher plants for 2050. Global Change Biology **8**:390-407.

Bale, J.S., G.J. Masters, I.D. Hodkinson, C. Awmack, T.M. Bezemer, V.K. Brown, J. Butterfield, A. Buse, J.C. Coulson, J. Farrar, J.E. Good, R. Harrington, S. Hartley, T.H. Jones, L.R. Lindroth, M.C. Press, I. Symrnioudis, A.D. Watt, and J.B. Whittaker. 2002. Herbivory in global climate change research: direct effects of rising temperature on insect herbivores. Global Change Biology **8**:1-16.

Ball, I.R., and H.P. Possingham. 2000. Marxan (V1.8.2): Marine Reserve Design Using Spatially Explicit Annealing, A Manual. Available from: http://www.uq.edu.au/marxan/. (Accessed January 21 2009).

Banner, A., W.H. MacKenzie, S. Haeussler, S. Thomson, J. Pojar, and R.L. Towbridge. 1993. A field guide to site identification and interpretation of the Prince Rupert Forest District, Land Management Handbook 26. B.C. Ministry of Forests Research Branch, Crown Publications Inc., Victoria, B.C.

Bartlein, P.J., C. Whitlock, and S.L. Shafer. 1997. Future climate in the Yellowstone National Park region and its potential impact on vegetation. Conservation Biology **11**:782-792.

B.C. Ministry of Environment. 1985. Soil Landscapes of British Columbia. Crown Publications Inc., Victoria, B.C.

B.C. Ministry of Environment. 2007. B.C. Conservation Data Centre. Available from: http://www.env.gov.bc.ca/cdc. (Accessed June 17, 2009).

B.C. Ministry of Environment, Land and Parks. 1993. A Protected Areas Strategy for British Columbia. Crown Publications Inc., Victoria, B.C.

B.C. Ministry of Forests and Range. 2006a. Preparing for Climate Change: Adapting to impacts on British Columbia's Forest and Range Resources. Available from: http://www.for.gov.bc.ca/mof/Climate_Change/Preparing_for_Climate_Change.pdf (Accessed January 21, 2009).

B.C. Ministry of Forests and Range. 2006b. The ecology of the alpine zone (Brochure). Available from: http://www.for.gov.bc.ca/hfd/pubs/Docs/Bro/Bro83.pdf. (Accessed September 2, 2009).

B.C. Ministry of Forests and Range Research Branch. 2009. Biogeoclimatic ecosystem classification program. Available from: http://www.for.gov.bc.ca/hre/becweb/system/methods/index.html. (Accessed June 16, 2009).

Beaumont, L.J., L. Hughes, and M. Poulsen. 2005. Predicting species distributions: Use of climatic parameters in BIOCLIM and its impacts on predictions of species' current and future distributions. Ecological Modelling **186**:250-269.

Berry, P.M., T.P. Dawson, P.A. Harrison, and R.G. Pearson. 2002. Modelling potential impacts of climate change on the bioclimatic envelope of species in Britain and Ireland. Global Ecology and Biogeography **11**:453-462.

Berry, P. M., T.P. Dawson, P.A. Harrison, R. Pearson, and N. Butt. 2003. The sensitivity and vulnerability of terrestrial habitats and species in Britain and Ireland to climate change. Journal of Nature Conservation **11**:15-23.

Botkin, D.B., H. Sake, M.B. Araújo, R. Betts, H.W. Bradshaw, T. Cedhagen, P. Chesson, T.P. Dawson, J.R. Etterson, P.D. Faith, S. Ferrier, A. Guisan, A. Skjoldborg, A.S. Hansen, D.W. Hilbert, C. Loehle, C. Margules, M. New, M.J. Sobel, and D.R. Stockwell. 2007. Forecasting the effects of global warming on biodiversity. BioScience **57**: 227-236.

Brodo, I.M., S.D. Sharnoff, and S. Sharnoff. 2001. Lichens of North America. Yale University Press, New Haven.

Burkett, V., and. J. Kusler. 2000. Potential impacts and climate change interactions in the wetlands of the United States. Journal of the American Water Resources Association **36**:313-320.

Burton, P.J., and S.G. Cumming.1995. Potential effects of climatic change on some western Canadian forests, based on phenological enhancements to a patch model of forest succession. Water, Air and Soil Pollution **82**:401-414.

Busby, J.R. 1991. BIOCLIM: A bioclimatic analysis and prediction system. Plant Protection Quarterly **6**:8-9.

Canadian Centre for Climate Modelling and Analysis. 2008. The Third Generation Coupled General Circulation Model. Environment Canada. Available from: http://www.cccma.ec.gc.ca/models/cgcm3.shtml. (Accessed January 5, 2009).

Carpenter, G., A.N. Gillison, and J. Winter. 1993. DOMAIN: A flexible modelling potential distributions of plants and animals. Biodiversity Conservation **2**:67-680.

Carroll, A., S.W. Taylor, J. Régnière, and L. Safranyik. 2003. Effects of climate change on range expansion by the mountain pine beetle in British Columbia. Mountain Pine Beetle Symposium: Challenges and Solutions. Information Report BC-X-399, Canadian Forest Service, Victoria, B.C. Available from: http://www4.nau.edu/direnet/publications/publications_c/files/Carrol_et_al_2003.pdf (Accessed August 24, 2009).

Committee on the Status of Endangered Wildlife in Canada (COSEWIC). 2006. Update COSEWIC Status Report of Cryptic Paw (*Nephroma occultum*) in British Columbia. Environment Canada, Ottawa. Available from: http://dsp-psd.pwgsc.gc.ca/Collection/CW69-14-62-2006E.pdf. (Accessed November 3, 2009).

Committee on the Status of Endangered Wildlife in Canada (COSEWIC). 2008. Recovery Stategy for the Rusty Cordmoss (*Entosthodon rubiginous*) in Canada. Environment Canada, Ottawa. Available from: http://www.env.gov.bc.ca/wld/documents/recovery/rcvrystrat/rusty_cord-moss_rcvry_strat171108.pdf. (Accessed November 3, 2009).

Comer, P., D. Faber-Langendoen, R. Evans, S. Gawler, C. Josse, G. Kittel, S. Menard, M. Pyne, M. Reid, K. Schulz, K. Snow, and J. Teague. 2003. Ecological Systems of the United States: A Working Classification of U.S. Terrestrial Systems. NatureServe, Arlington, Virginia.

Costa, G.C., C. Wolfe, D.B. Shepard, J.P. Caldwell, and L.J. Vitt. 2007. Detecting the influence of climatic variables on species distributions: A test using GIS niche-based models along a steep longitudinal environmental gradient. Journal of Biogeography **35**:637-646.

Cumming, S.G., P.J. Burton, and B. Klinkenberg. 1996. Boreal mixedwood forests may have no "representative" areas: some implications for reserve design. Ecography **19**:162-180.

Dale, V.H., L.A. Joyce, S. McNulty, R.P. Neilson, M.A. Ayres, M.D. Flannigan, P.J. Hanson, Z.C Irland, A.E. Lugo, C.J. Peterson, D. Simberloff, F.J. Swanson, B.J. Stocks, and B.M Wotton. 2001. Climate change and forest disturbances. BioScience **51**:723-734.

Daly, C., W.P. Gibson, G.H. Taylor, G.L. Johnson, and P.A. Pasteris. 2002. A knowledge-based approach to the statistical mapping of climate. Climate Research **22**:00-113.

Daly, C., W.P. Gibson, G.H. Taylor, T.W. Parzybok, G.L. Johnson, and P.A. Pasteris. 2000. High quality spatial climate data sets for the United States and beyond. Transactions of the ASAE **43**:1957-1962.

D'Antonio, C.M., and P.M. Vitousek. 1992. Biological invasions by exotic grasses: The grass/fire cycle and global change. Annual Review of Ecology & Systematics **23**:63-87.

Delong, C. 2003. A field guide to site identification and interpretation of the southeastern portion of the Prince George Forest District. B.C. Ministry of Forests and Range Research Branch, Queens Press, Victoria, B.C.

Delong, C., D.H. Tanner, and D.M. Juli. 1993. A field guide to site identification and interpretation of the southwestern portion of the Prince George Forest District, Land Management Handbook 24. B.C. Ministry of Forests Research Branch, Crown Publications Inc., Victoria, B.C.

Demarchi D.A. 1995. Ecoregions of British Columbia. Fourth Edition. British Columbia Wildlife Branch, Ministry of Environment, Lands and Parks, Crown Publications Inc., Victoria B.C.

Ecoregions Working Group of the Canada Committee on Ecological Land Classification. 1989. Ecoclimatic Regions of Canada, First Approximation. Ecological Land Classification Series, No. 23, Sustainable Development Branch, Canadian Wildlife Service, Environment Canada, Ottawa, Ontario.

Ellis, C. J., B.J. Coppins, and T.P. Dawson. 2007. Predicted response of the lichen epiphyte *Lecanora populicola* to climate change scenarios in a clean-air region of Northern Britain. Biological Conservation **135**:396-404.

Fitzpatrick, M.C., A.D. Gove, N.J. Sanders, and R.R. Dunn. 2008. Climate change, plant migration and range collapse in a global biodiversity hotspot: the *Banksia* (Proteaceae) of Western Australia. Global Change Biology **14**:1-16.

Flannigan, M.D., and C.E. Van Wagner. 1990. Climate change and wildfire in Canada. Canadian Journal of Forest Research **21**:66-72.

Game, E.T., and H.S. Grantham. 2008. Marxan User Manual: For Marxan version 1.8.10. University of Queensland, St. Lucia, Queensland, Australia, and Pacific Marine Analysis and Research Association, Vancouver, British Columbia, Canada. Available from:

http://www.uq.edu.au/marxan/docs/Marxan_User_Manual_2008.pdf (Accessed October 13, 2009).

Garnett, S.Y., and L. Christidis. 2007. Implications of changing species definitions for conservation purposes. Bird Conservation International **17**:187-195.

Gayton, D.V. 2008. Impacts of climate change on British Columbia's biodiversity: A literature review. FORREX Series 23: Forestry Research and Extension Partnership. Kamloops, B.C. Available from: http://ww.forrex.org/publications/jem/ISS48/vol9_no2_art4.pdf. (Accessed December 17, 2008).

Goward, T. 1994. Rare and endangered lichens in British Columbia. Pages 77-80 in Harding and E. McCullum, editors. Biodiversity in British Columbia: Our changing environment. Environment Canada, Ministry of Supply and Services, Ottawa, ON.

Goward, T., and T. Spribille. 2005. Lichenological evidence for the recognition of inland rainforests of western North America. Journal of Biogeography **32**:1209-1219.

Groves, C.R., D.B. Jensen, L.L. Valutis, K.H. Redford, M.L. Shaffer, J.M. Scott, J.V. Baumgartner, J.V. Higgins, M.W. Beck, and M.G. Anderson. 2002. Planning for biodiversity conservation: Putting conservation science into practice. BioScience **52**:499-512.

Guisan, A., and N.E. Zimmermann. 2000. Predictive habitat distribution models. Ecological Modelling **135**:147-186.

Haig, S.M., B.A. Beever, S.M.Chambers, H.M. Draheim, B.D. Dugger, S. Dunham, E. Elliot-Smith, J.B. Fontaine, D.C. Kesler, B.J. Knaus, I.F. Lopes, P. Loschl, T.D. Mullins, and L.M. Sheffield. 2006. Taxonomic considerations in listing subspecies under the U.S. Endangered Species Act. Conservation Biology **20**:1584-1594.

Halpin, P.N. 1997. Global change and natural area protection: Management responses and research directions. Ecological Applications **7**:828-843.

Hamann, A., 2008. ClimateBC and ClimatePP downloads v3: Programs for integrating climate normals, historical data, and GCM predictions for genecology and climate change studies in western Canada. University of Alberta. Available from: http://www.ales2.ualberta.ca/RR/people/hamann/climate/index.asp?page=climate-bc-pp. (January 7, 2009).

Hamann, A., and T. Wang. 2006. Potential effects of climate change on ecosystem and tree species distribution in British Columbia. Ecology **87**:2773-2786.

Hannah, L., G.F. Midgley, G. Hughes, and B. Bomhard. 2005. The view from the Cape: Extinction risk, protected area and climate change. BioScience **55**:231-241.

Hannah, L., G.F. Midgley, T. Lovejoy, W.J. Bond, M. Bush, J.C. Lovett, D. Scott, and F.I. Woodward. 2002b. Conservation of biodiversity in a changing climate. Conservation Biology **16**:264-268.

Hannah, L., and R. Salm. 2005. Protected areas management in a changing climate. Pages 363-371 in T.E. Lovejoy and L. Hannah, editors. Climate change and biodiversity. Yale University Press, New Haven.

Hannah, L., G.F. Midgley, and D. Millar. 2002a. Climate change integrated conservation strategies. Global Ecology and Biogeography **11**:485-495.

Hansen, A.J., R.P. Neilson, V.H. Dale, C.H., Flather, L.R. Iverson, D.J. Currie, S. Shafer, R. Cook, and P.J. Bartlein. 2001. Global change in forests: Response of species, communities and biomes. BioScience **51**:765-779.

Harding, L. 1994. Threats to forest ecosystems in British Columbia. Pages 245-278 in L. Harding and E. McCullum, editors. Biodiversity in British Columbia: Our changing environment. Environment Canada, Ottawa, ON.

Harding, L., and E. McCullum. 1997. Ecosystem response to climate change in British Columbia and Yukon: Threats and opportunities for biodiversity. Pages 9-1 to 9-22 in E. Taylor and B. Taylor, editors. Responding to global climate change in British Columbia and Yukon: Volume 1 Impacts and Adaptation. B.C. Ministry of Environment, Lands and Parks, Victoria, B.C. Available from: http://dsp-psd.pwgsc.gc.ca/Collection/En56-119-1997E.pdf#page=136. (Accessed September 9, 2009).

Harper, W.L., E.C. Lea, and R.E. Maxwell. 1993. Biodiversity Inventory in the South Okanagan. Pages 249-264 in M.A. Fenger, E.H. Miller, J.F. Johnson and E.J.R. Williams, editors. Our Living Legacy, Proceedings of a symposium on biological diversity. Royal British Columbia Museum, Victoria, B.C.

He, H.S., D.J. Mladenoff, and E.J. Gustafson. 2002. Study of landscape change under forest harvesting and climate warming-induced fire disturbance. Forest Ecology and Management **155**:257-270.

Heikkinen, R.K., M. Luoto, M.B. Araújo, R. Virkkala, W. Thuiller, and M.T. Sykes. 2006. Methods and uncertainties in bioclimatic envelope modelling under climate change. Progress in Physical Geography **30**:751-777.

Hijmans, R. J., S.E. Cameron, P.G. Jones, and A. Jarvis. 2005. Very high resolution, interpolated climate surfaces for global land areas. International Journal of Climatology **25**:1965-1978.

Hijmans, R.J., and C.H. Graham. 2006. The ability of climate envelope models to predict the effect of climate change on species distributions. Global Change Ecology **12**:2272-2281.

Honnay, O., K. Verheyen, J. Butaye, B. Jacquemyn, M. Bossuyt, and M. Hermy. 2002. Possible effects of habitat fragmentation and climate change on the range of forest plant species. Ecology Letters **5**:525-530.

Hope, G.D., D.A. Llyod, W.R., Erickson, W.L. Harper, and B.M. Wikeem. 1991. Ponderosa pine zone. In Meidinger, D. and J. Pojar, editors. Ecosystems of British Columbia. Special Report Series 6, British Columbia Ministry of Forests, Victoria, B.C., pp. 139-152.

Hutchinson, G.E. 1957. Concluding remarks: Cold Spring Harbour Symposia on Quantitative Biology 22: 415-427. Accessed on June 16, 2009. Available from: http://artifex.org/~ecoreaders/lit/Hutchinson1957.pdf (Accessed on June 16, 2009).

Intergovernmental Panel on Climate Change (IPCC). 2000. IPCC Special Report on Emissions Scenarios. IPCC Secretariat, Geneva 2, Switzerland. Available from: http://www.grida.no/publications/other/ipcc_sr/?src=/climate/ipcc/emission. (Accessed September 22, 2009).

Intergovernmental Panel on Climate Change (IPCC). 2007. Climate Change 2007: Impacts, Adaptation and Vulnerability. Summary for Policy Makers. IPCC Secretariat, Geneva 2, Switzerland. Available from: http://www.ipcc.ch/ipccreports/assessments-reports.htm. (Accessed January 22, 2009).

Issac, N.B., J. Mallet, and G.M. Mace. 2004. Taxonomic inflation: its influence on macroecology and conservation. Trends in Ecology and Evolution **19**:464-469.

Iverson, L.R., and A.M. Prasad. 2002. Potential redistribution of tree species habitat under five climate change scenarios in the eastern US. Forest Ecology and Management **155**:205-222.

Johnson, C.J., and M.P. Gillingham. 2004. Mapping uncertainty: Sensitivity of wildlife habitat ratings. Journal of Applied Ecology **41**:1032-1041.

Johnson, W.C., B.V. Millett, T. Gilmanov, R.A.Voldseth, G.R.Guntenspergen, and D.E. Naugle. 2005. Vulnerability of northern prairie wetlands to climate change. BioScience **55**:863-872.

Kadmon, R., O. Fraber, and A. Danin. 2005. A systematic analysis of factors affecting the performance of climatic envelope models. Ecological Applications **13**:853-687.

Ketcheson, M.V., T.F. Braumandl, D. Meidinger, G. Utzig, D.A. Demarchi, B.M., and Wikeem. 1991. Interior cedar-hemlock zone. In Meidinger, D. and J. Pojar, editors. Ecosystems of British Columbia. Special Report Series 6, British Columbia Ministry of Forests, Crown Publications Inc.,Victoria, B.C., pp. 167-182.

Kueppers, L.M., M.A. Snyder, L.C. Sloan, E.S. Zavaleta, and B. Fulfrost. 2005. Modelled regional climate change and California endemic oak ranges. Proceedings of the National Academy of Sciences **102**:16281-16286.

Ledig, F.T. 1993. Secret extinctions: The loss of genetic diversity in forest ecosystems. Pages 127-140 in M.A. Fenger, E.H. Miller, J.F. Johnson and E.J.R. Williams, editors. Our Living Legacy, Proceedings of a symposium on biological diversity. Royal British Columbia Museum, Victoria, B.C.

Lee, M. T., and W. Jetz. 2008. Future battlegrounds for conservation under global change. Proceedings of the Royal Society B: Biological Sciences **275**:1261-1270.

Leemans, R., and B. Eickhout. 2004. Another reason for concern: regional and global impacts on ecosystems for different levels of climate change: The benefits of climate policy. Global Environmental Change **14**: 219-228.

Leibold, M. 1995. The niche concept revisited: mechanistic models and community context. Ecology **76**:1371-1382.

Lemieux, C., and D. Scott. 2005. Climate change and protected area policy and planning in Canada. The Forestry Chronicle **81**:696-703.

Lenihan, J.M, R. Drapek, D. Bachelet, and R. Neilson. 2003. Climate change effects on vegetation distribution, carbon and fire in California. Ecological Applications **13**:1667-1681.

Leroux, S. J., F.K. Schmiegelow, S.G. Cumming, R.B. Lessard, and J. Nagy. 2007. Accounting for system dynamics in reserve dynamics. Ecological Applications **17**:1954-1966.

Malcolm, J.R., A. Markham, R.P. Neilson, and M. Garaci. 2002. Estimated migration rates under scenarios of global climate change. Journal of Biogeography **29**:835-849.

Margules, C.R., and R.L. Pressey. 2000. Systematic conservation planning. Nature **405**:243-253.

MacKinnon, A., D. Meidinger, and K. Klinka, editors. 1992. Use of biogeoclimatic ecosysem classification system in British Columbia. The Forestry Chronicle **68**:100-120.

Mbogga, M., A. Hamann, and T. Wang. 2009. Historical and projected climate data for natural resource management in Canada. Agricultural and Forest Meteorology **149**:881-890.

McCarty, J. P. 2001. Ecological consequences of recent climate change. Conservation Biology **15**:320-331.

McKenney, D.W., J.H. Pedlar, K. Lawrence, K. Campbell, and M.F. Hutchinson. 2007a Potential impacts of climate change on the distribution of North American trees. BioScience **57**:939-948.

McKenney, D.W., J.H. Pedlar, K. Lawrence, K. Campbell, and M.F. Hutchinson. 2007b. Beyond traditional hardiness zones: Using climate envelopes to map plant range limits. BioScience **57**:929-937.

Meidinger, M., and J. Pojar. 1991. Ecosystems of British Columbia, Special Report Series 6. Research Branch, B.C. Ministry of Forests, Victoria, B.C.

Millar, C. I., N.L. Stephenson, and S.L. Stephens. 2007. Climate change and forests of the future: Managing in the face of uncertainty. Ecological Applications **17**: 2145-2151.

Moilanen, A., and B.A. Winte. 2005. Uncertainty analysis favours selection of spatially aggregated reserve networks. Biological Conservation **129**:427-434.

Moilanen, A, B.A.Winte, J. Elith, and M. Burgman. 2006. Uncertainty analysis for regional-scale reserve selection. Conservation Biology **20**:1688-1697.

Molina, R., B.G. Marcot, and R. Lesher. 2006. Protecting rare, old-growth, forest-associated species under the Survey and Manage Program Guidelines of the Northwest Forest Plan.

Mosquin, T. 2000. Status of and trends in Canadian biodiversity. Pages107-136 in S. Bocking, editor. Biodiversity in Canada: Ecology, ideas and action. Broadview Press, Peterborough, ON.

Nature Conservancy of Canada. 2007a. Okanagan Ecoregional Assessment. The Nature Conservancy of Canada. Available from: http://science.natureconservancy.ca/initiatives/blueprints/okanagan_w.php. (Accessed January 22, 2009).

Nature Conservancy of Canada. 2007b. B.C. Central Interior Project, Central Interior Project: Central Interior Ecoregional Assessment. Available from: http://science.natureconservancy.ca/centralinterior/central.php. (Accessed January 2, 2010).

Nature Conservancy (U.S.). 1982. Natural heritage program operations manual. The Nature Conservancy, Arlington, Virginia..

Noss, R. F. 1987. From plant communities to landscapes in conservation inventories: A look at The Nature Conservancy (USA). Biological Conservation **41**:11–37.

Noss, R. F. 2001. Beyond Kyoto: Forest management in a time of climate change. Conservation Biology **15**:578-590.

Parmesan, C., and G. Yohe. 2003. A globally coherent fingerprint of climate change impacts across natural systems. Nature **421**:37-42.

Pearson, R.G., and T.P. Dawson. 2003. Predicting the impacts of climate change on the distribution of species: are bioclimatic envelopes models useful? Global Ecology and Biogeography **12**:361-371.

Pearson, R.G., T.P. Dawson, P.M. Berry, and P.A. Harrison. 2002. SPECIES: A spatial evaluation of climate impact on the envelope of species. Ecological Modelling **154**:289-300.

Pearson, R.G., C.J. Raxworthy, M. Nakamura, and A.T. Peterson. 2007. Predicting species distributions from small numbers of occurrence records: a test case using cryptic geckos in Madagascar. Journal of Biogeography **34**:102-117.

Pearson, R.G., W. Thuiler, M.B. Araújo, E. Martinez-Meyer, L. Brotons, C. McClean, L. Miles, P. Segurado, T.P. Dawson, and D.C. Lees. 2006. Model-based uncertainty in species range prediction. Journal of Biogeography **33**:1704-1711.

Pittock, J., L.J. Hansen, and R. Abell. 2008. Running dry: Freshwater biodiversity, protected areas and climate change. Biodiversity Informatics **9**:30-38.

Pojar, J., K. Klinka, and D.V. Meidinger. 1987. Biogeoclimatic ecosystem classification in British Columbia. Forest Ecology and Management **22**:119-154.

Post, E., J. Brodie, M. Hebblewhite, A. D. Anders, J.A. Maier, and C.C. Wilmers. 2009. Global population dynamics and hot spots of response to climate change. BioScience **59**:489-497.

Primack, R.B., 2006. Essentials of Conservation Biology, 4th Africa. Edition. Sinauer Associates, Sunderland, Massachusetts.

Pyke, C.R., S.J. Andelman, and G. Midgley. 2005. Identifying priority areas for bioclimatic representation under climate change: a case study for Proteaceae in the Cape Floristic Region, South Africa. Biological Conservation **125**:1-9.

Pyke, C.R., and D.T. Fischer. 2005. Selection of bioclimatically representative biological reserve systems under climate change. Biological Conservation **121**:429-441.

Rayfield, B., P.M. James, A. Fall, and M.J. Fortin. 2008. Comparing static versus dynamic protected areas in the Quebec boreal forest. Biological Conservation **141**:438-449.

Rose, N.A., and P.J. Burton. 2009. Using bioclimatic envelopes to identify temporal corridors in support of conservation planning in a changing climate. Forest Ecology and Management **258** (Suppl. 1):S64-S74.

SAS Institute. 2004. Statistical Analysis System (SAS) Release 9.2.1. 2004. Cary, North Carolina.

Schneider, S. H. 2004. Abrupt non-linear climate change, irreversibility and surprise. Global Environmental Change **14**:245-258.

Schofield, W.B. 1994. Rare and endangered bryophytes in British Columbia. Pages 71-76 in E. Harding and E. McCullum, editors. Biodiversity in British Columbia: Our changing environment. Environment Canada, Ottawa, ON.

Schwartz, M.W., L.R. Iverson, A.M. Prasad, S.N. Matthews, and R.J. O'Connor. 2006. Predicting extinctions as a result of climate change. Ecology **87**:1611-1615.

Schweiger, O., J. Settele, O. Kudrna, S. Klotz, and I. Kuhn. 2008. Climate change can cause spatial mismatch of trophically interacting systems. Ecology **89**:3472-3479.

Scott, J. M., F. Davis, B. Csuti, R. Noss, B. Butterfield, C. Groves, H. Anderson, S. Caicco, F. D'Erchia, T.C. Edwards, J. Ullima,n and R.G. Wright. 1993. Gap Analysis: A geographic approach to protection of biological diversity. Wildlife Monographs **123**:3-41.

Scott, D., J.R. Malcolm, and C. Lemieux. 2002. Climate change and modelled biome representation in Canada's national park system: implications for system planning and park mandates. Global Ecology and Biogeography **11**:475-484.

Segurado, P., and. M.B. Araújo. 2004. An evaluation of methods for modelling species distributions. Journal of Biogeography **31**:1555-1568.

Shafer, S.L., B.J. Bartlein, and R.S. Thompson. 2001. Potential changes in the distributions of western North American trees and shrub taxa under future climate scenarios. Ecosystems **4**: 200-215.

Shultis, J.D., and. P.A. Way. 2006. Changing conceptions of protected areas and conservation: Linking conservation, ecological integrity and tourism management. Journal of Sustainable Tourism **14**:223-227.

Spittlehouse, D. 2005. Integrating climate change adaptation into forest management. The Forestry Chronicle **81**:691-695.

Spittlehouse, D. 2006. ClimateBC: your access to interpolated climate data for BC. Streamline Watershed Management Bulletin **9**:16-21.

Steen, O.A., and R.A. Coupe. 1997. A field guide to site identification and interpretation of the Cariboo Forest Region, Land Management Handbook 39. B.C. Ministry of Forests Research Branch, Victoria, B.C.

Suffling R., and D. Stocks. 2002. Assessment of climate change effects on Canada's National Park System. Environmental Monitoring and Assessment **74**: 117-139.

Taberlet, P., and R. Cheddadi. 2002. Quaternary refugia and persistence of biodiversity. Science **297**:2009.

Thuiller, W. 2003. BIOMOD - Optimizing prediction of species distributions and projecting potential future shifts under global change. Global Change Biology **9**:1353-1362.

Thuiller, W. 2004. Patterns and uncertainties of species' range shifts under climate change. Global Change Biology **10**:2020-2027.

Thuiller, W., S. Lavorel, M.B. Araújo, M.T. Sykes, and I.C Prentice. 2005. Climate change threats to plant diversity in Europe. Proceedings of the National Academy of Sciences **102**:8245-8250.

Vandermeer, J.H. 1972. Niche theory. Annual Review of Ecology and Systematics **3**:07-132.

Van der Veken, S., M. Hermy, M. Velland, A. Knapen, and K. Verheyen. 2008. Garden plants get a head start on climate change. Frontiers in Ecology and the Environment **6**: 212-216.

Volney, W.J., and Fleming, R.A. 2000. Climate change and impacts of boreal forest insects. Agriculture, Ecosystems and the Environment **82**:283-294.

Vos, C.C., P. Berry, P. Opdam, H. Baveco, B. Nijhof, J.O. O'Hanley, C. Bell, and H. Kuipers. 2008. Adapting landscapes to climate change: Examples of climate-proof ecosystem networks and priority adaptation zones. Journal of Applied Ecology **45**:1722-1731.

Walker, P.A., and K.D. Cocks. 1991. HABITAT: A procedure for modelling a disjoint environmental envelope for a plant or animal species. Global Ecology and Biogeography **1**:108-118.

Wallington, T.J., R.J. Hobbs, and S.A. Moore. 2005. Implications of curent ecological thinking for biodiversity conservation: A review of the salient issues. Ecology and Society 10: 15. Available from: http://www.ecologyandsociety.org/vol10/iss1/art15. (Accessed June 17, 2009).

Walther, G.R., E. Post, P. Convery, A. Menzel, C. Parmesan, T.J. Beebee, J.M. Fromentin, O. Hoegh-Guldberg, and F. Bairlein. 2002. Ecological response to recent climate change. Nature **416**:389-395.

Wang, T., A. Hamann, D.L. Spittlehouse, and S. N. Aitken. 2006. Development of scale-free climate data for Western Canada for use in resource management. International Journal of Climatology **26**:383-397.

Welch, D. 2005. What should protected areas managers do in the face of climate change? The George Wright Forum **22**:75-93.

Williams, P., L. Hannah, S. Andelman, G. Midgley, M. Araújo, G. Hughes, L, Manne, E. Martinez-Meyer, and R. Pearson. 2005. Planning for climate change: Identifying minimum-dispersal corridors for the Cape Proteaceae. Conservation Biology **19**:1063-1074.

Williams, J.W., and S.T. Jackson. 2007. Novel climates, no-analog communities and ecological surprises. Frontiers in Ecology and the Environment **5**:475-482.

Woods, A., K.D. Coates, and A. Hamann. 2005. Is an unprecedented Dothistroma needle blight epidemic related to climate change? Bioscience **55**:761-769.

Appendix A - Conservation target and climate data for the conservation target groups.

Table A 1. Target plant species names and their conservation status (*See Table A2 for a description of codes describing conservation status).

Scientific Name	Common Name	# of occurrences: Calibration Points*	# of occurrences: Study Area	Status: Global	Status: Provincial	Status: BC List	Status: COSEWIC
Allium geyeri var. *tenerum*	Geyer's onion	13	1	G4G5T3T5	S2S3	Blue	
Anemone canadensis	Canada anemone	19	1	G5	S2S3	Blue	
Apocynum x floribundum	western dogbane	4	3	GNA	S2S3	Blue	
Arabis holboellii var. *pinetorum*	Holboell's rockcress	8	3	G5T5?	S2S3	Blue	
Arabis sparsiflora	sickle-pod rockcress	7 W	3	G5	S1	Red	
Atriplex argentea ssp. *argentea*	silvery orache	4	1	G5T5	S1	Red	
Botrychium simplex	least moonwort	34	3	G5	S2S3	Blue	
Bouteloua gracilis	blue grama	19	2	G5	S1	Red	
Camissonia breviflora	short-flowered evening-primrose	4	2	G5	S1	Red	
Carex backii	Back's sedge	32 S,W	1	G4	S2S3	Blue	
Carex bicolor	two-coloured sedge	18 E,N	2	G5	S2S3	Blue	
Carex heleonastes	Hudson Bay sedge	28	4	G4	S2S3	Blue	
Carex lenticularis var. *dolia*	Enander's sedge	50 W	3	G5T3Q	S2S3	Blue	
Carex scoparia	pointed broom sedge	12 E	1	G5	S2S3	Blue	
Carex simulata	short-beaked fen sedge	8	8	G5	S2S3	Blue	
Carex sychnocephala	many-headed sedge	34	1	G4	S3	Blue	
Carex tenera	tender sedge	24 S,E	8	G5	S2S3	Blue	
Carex tonsa var. tonsa	bald sedge	4	1	G5T4T5	S2S3	Blue	
Carex xerantica	dry-land sedge	18	4	G5	S2	Red	
Chamaerhodos erecta ssp. *nuttallii*	American chamaerhodos	19 W	5	G5T4T5	S2S3	Blue	
Chamaesyce serpyllifolia ssp. *serpyllifolia*	thyme-leaved spurge	8	2	G5T5	S2S3	Blue	
Chenopodium atrovirens	dark lamb's-quarters	25 S	2	G5	S1	Red	
*Delphinium bicolor*ssp. *bicolor*	Montana larkspur	10	1	G4G5T4T5	S2S3	Blue	
Draba alpina	alpine draba	10 E,N,W	2	G4G5	S2S3	Blue	
Draba cinerea	gray-leaved draba	20 N	3	G5	S2S3	Blue	
Draba fladnizensis	Austrian draba	16 S,N	1	G4	S2S3	Blue	

Scientific Name	Common Name	# of occurrences		Status			
		Calibration Points*	Study Area	Global	Provincial	BC List	COSEWIC
Draba glabella var. *glabella*	smooth draba	3	2	G4G5T4	S2S3	Blue	
Draba lactea	milky draba	10 N	1	G4	S2S3	Blue	
Draba lonchocarpa var. *vestita*	lance-fruited draba	9	1	G5T3	S2S3	Blue	
Draba reptans	Carolina draba	5	2	G5	S1	Blue	
Draba ruaxes	coast mountain draba	13	1	G4	S2S3	Red	
Draba ventosa	Wind River draba	22	1	G3	S2S3	Blue	
Dryopteris cristata	crested wood fern	91	1	G5	S2S3	Blue	
Entosthodon rubiginosus	rusty cord-moss	5	2	G1G3	S1	Red	E (NOV 2004)
Epilobium halleanum	Hall's willowherb	10	2	G5	S2S3	Blue	
Epilobium leptocarpum	small-fruited willowherb	25	1	G5	S2S3	Blue	
Eutrema edwardsii	Edwards wallflower	10 E,N,W	3	G4	S2S3	Blue	
Festuca minutiflora	little fescue	25	2	G5	S2S3	Blue	
Glyceria pulchella	slender mannagrass	7 W	2	G5	S2S3	Blue	
Hesperostipa spartea	porcupinegrass	15	3	G5	S2	Red	
Impatiens aurella	orange touch-me-not	27	2	G4?	S2S3	Blue	
Juncus albescens	whitish rush	18 W	2	G5	S2S3	Blue	
Juncus arcticus ssp. *alaskanus*	arctic rush	24	2	G5T4T5	S2S3	Blue	
Juncus stygius	bog rush	25 N	1	G5	S2S3	Blue	
Koenigia islandica	Iceland koenigia	14	2	G4	S2S3	Blue	
Lloydia serotina var. *flava*	alp lily	34 E, W	2	G5T3	S3	Blue	
Malaxis paludosa	bog adder's-mouth orchid	7	1	G4	S2S3	Blue	
Megalodonta beckii var. *beckii*	water marigold	11 S	2	G4G5T4T5	S3	Blue	
Melica bulbosa var. *bulbosa*	oniongrass	7	2	G5TNRQ	S2	Red	
Melica spectabilis	purple oniongrass	4 S,W	4	G5	S2S3	Blue	
Minuartia austromontana	Rocky Mountain sandwort	22 E	4	G4	S2S3	Blue	
Montia chamissoi	Chamisso's montia	86	1	G5	S2S3	Blue	
Muhlenbergia glomerata	marsh muhly	12	5	G5	S3	Blue	
Nephroma occultum	Cryptic Paw	20 E	2	G4	S2S3	Blue	SC (APR 2006)
Nymphaea leibergii	small white waterlily	5	2	G5	S2S3	Blue	
Nymphaea tetragona	pygmy waterlily	9	1	G5	S2S3	Blue	
Platanthera dilatata var. *albiflora*	fragrant white rein orchid	27 N,W	1	G5T3T5	S2S3	Blue	
Poa fendleriana ssp. *fendleriana*	mutton grass	6	1	G5T5	S1	Red	
Polemonium boreale	northern Jacob's-ladder	4	1	G5	S2S3	Blue	

Scientific Name	Common Name	# of occurrences		Status			
		Calibration Points*	Study Area	Global	Provincial	BC List	COSEWIC
Polygonum ramosissimum var. *ramosissimum*	bushy knotweed	4	1	G5T5	S1	Red	
Polypodium sibiricum	Siberian polypody	13 E	1	G5?	SH	Blue	
Potentilla nivea var. *pentaphylla*	five-leaved cinquefoil	5 N	9	G5T4	S2S3	Blue	
Pyrola elliptica	white wintergreen	157 E,N	1	G5	S2S3	Blue	
Sagina nivalis	snow pearlwort	21 W	1	G5	S2S3	Blue	
Salix boothii	Booth's willow	15	6	G5	S2S3	Blue	
Salix serissima	autumn willow	14	4	G4	S2S3	Blue	
Saxifraga nelsoniana ssp. *carlottae*	dotted saxifrage	5	1	G5T3?	S3	Blue	
Senecio plattensis	plains butterweed	11	1	G5	S2S3	Blue	
Silene drummondii var. *drummondii*	Drummond's campion	16	2	G5T5	S3	Blue	
Sparganium fluctuans	water bur-reed	3	4	G5	S2S3	Blue	
Stellaria umbellata	umbellate starwort	11	1	G5	S2S3	Blue	
Woodsia alpina	alpine cliff fern	18 E	1	G4	S2S3	Blue	

* Some additional documented occurrences were available but not within the geographic range of ClimateBC and ClimatePP. These were excluded from use in envelope calibrations with additional distribution in the directions noted.
E = east of 88 °W
N = north of 60.42 °N (if east of 113.02 °W) or north of 70°N (if west of 113.02 °W)
S = in the U.S.A. south of 46.98 °N
W + in Alaska, west of 142.02 °W

Table A 2. A summary of the conservation status codes assigned by the B.C. Conservation Data Centre. Plant species are ranked according to B.C., provincial, global and COSEWIC (The Committee on the Status of Endangered Wildlife in Canada) definitions.

STATUS CODE	STATUS DESCRIPTION (and source for more information)
British Columbia	**(www.gov.bc.ca/atrisk/red-blue.htm)**
RED	Any indigenous species or community that have or are candidates for Extirpated, Endangered, or Threatened status in B.C.
BLUE	Any indigenous species or community considered to be of Special Concern (formerly Vulnerable) B.C.. Taxa of Special Concern have characteristics that make them particularly sensitive or vulnerable to human activities or natural events.
YELLOW	Any species that are apparently secure and not at risk of extinction. Yellow listed species may have Red- or Blue-listed subspecies.
Provincial Code/Global Code	**(www.natureserve.org)**
S1(N1)/G1	CRITICALLY IMPERILLED At very high risk of extinction due to extreme rarity, very steep declines, or other factors.
S2(N2)/G2	IMPERILLED At high risk of extinction due to very restricted range, very few populations, steep declines, or other factors.
S3(N3)/G3	VULNERABLE At moderate risk of extinction due to a restricted range, relatively few populations, recent and widespread declines, or other factors.
S4(N4)/G4	APPARENTLY SECURE Uncommon but not rare; some cause for long-term concern due to declines or other factors.
S5(N5)/G5	SECURE Common; widespread and abundant.
COSEWIC Code	**(www.cosewic.gc.ca)**
E	ENDANGERED. A species facing imminent extirpation or extinction.
SC	SPECIAL CONCERN. A species of special concern because of characteristics that make it is particularly sensitive to human activities or natural events.

Table A 3. Synonym for some of the B.C. Conservation Data Centre "At Risk" plant species investigated in this study. These synonyms were also used in the data collection process.

Species Name	Synonyms*
Acorus americanus	*Acorus calamus* var. *americanus*
Agrostis pallens	*Agrostis diegoensis, Agrostis lepida, Agrostis pallens* var. *vaseyi*
Allium geyeri var. *tenerum*	*Allium geyeri* subs. *tenerum, Allium geyeri* var. *tenerum*
Anemone canadensis	*Anemonidium canadense*
Arabis lignifera	*Boechera lignifera*
Astragalus bourgovii	*Tragacantha bourgovii, Homalobus bourgovii*
Astragalus umbellatus	*Astragalus littoralis, Phaca littoralis, Astragalus alpinus* var. *littoralis, Astragalus frigidus* var. *dawsonensis, Astragalus frigidus* var. *littoralis, Phaca frigida* var. *demissa, Phaca frigida* var. *littoralis*
Atriplex argentea ssp. *argentea*	*Atriplex argentea* subs. *argentea argentea, Atriplex argentea* subs. *typica*
Botrychium crenulatum	*Botrychium dusenii*
Botrychium simplex	*Botrychium tenebrosum, Botrychium simplex var. compositum, Botrychium simplex* var. *laxifolium, Botrychium simplex* var. *tenebrosum, Botrychium simplex* spp. *typicum*
Bouteloua gracilis	*Chondrosum oligostachyum, Chondrosum gracile, Bouteloua oligostachya, Bouteloua gracilis* var. *stricta*
Camissonia breviflora	*Oenothera breviflora, Taraxia breviflora*
Carex backii	*Carex durifolia, Carex durifolia* var. *subrostrata, Carex backii* var. *subrostrata*
Carex lenticularis var. *dolia*	*Carex eurystachya, Carex hindsii, Carex enanderi, Carex plectocarpa*
Carex rostrata	*Carex rostrata* var. *ambigens*
Carex tenera	*Carex tenera* var. *echinodes*
Carex tonsa var. *tonsa*	*Carex umbellata* var. *tonsa, Carex rugosperma* var. *tonsa*
Chamaerhodos erecta ssp. *nuttallii*	*Chamaerhodos erecta var. nuttallii*
Chenopodium atrovirens	*Chenopodium wolfii, Chenopodium aridum, Chenopodium fremontii* var. *atrovirens*
Draba alpina	*Draba pilosa, Draba micropetala, Draba eschscholtzii, Draba alpina* var. *nana*
Draba corymbosa	*Draba macrocarpa, Draba bellii, Draba barbata*
Draba densifolia	*Draba sphaerula, Draba nelsonii, Draba caeruleomontana*
Draba lactea	*Draba allenii, Draba fladnizensis* var. *heterotricha*

Species Name	Synonyms*
Draba reptans	*Draba micrantha, Draba caroliniana, Draba reptans* var. *stellifera, Draba reptans* var. *typica, Draba reptans* var. *micrantha, Draba reptans* spp. *stellifera*
Draba ruaxes	*Draba exalata, Draba ventosa* var. *ruaxes*
Eleocharis kamtschatica	*Scirpus kamtschaticus*
Epilobium halleanum	*Epilobium pringleanum, Epilobium pringleanum* var. *tenue, Epilobium brevistylum* var. *subfalcatum, Epilobium brevistylum* var. *tenue, Epilobium glandulosum* var. *tenue*
Festuca minutiflora	*Festuca ovina* var. *minutiflora, Festuca brachyphylla* var. *endotera*
Galium labradoricum	*Galium tinctorium* var. *labradoricum*
Galium multiflorum	*Galium bloomeri, Galium matthewsii* var. *scabridum, Galium multiflorum* var. *hirsutum, Galium multiflorum forma hirsutum, Galium multiflorum* spp.. *hirsutum, Galium bloomeri* var. *hirsutum*
Hesperostipa spartea	*Stipa spartea*
Juncus albescens	*Juncus conicinnus*
Koenigia islandica	*Macounastrum islandicum*
Malaxis brachypoda	*Malaxis monophyllos* var. *brachypoda, Malaxis monophyllos* spp.. *brachypoda*
Malaxis paludosa	*Hammarbya paludosa*
Melica smithii	*Avena smithii, Bromelica smithii*
Melica spectabilis	*Bromelica spectabilis, Melica bulbosa* var. *spectabilis*
Mimulus breweri	*Minuartia austromontana*
Minuartia austromontana	*Arenaria rossii* var. *columbiana, Arenaria rossii* spp.. *columbiana*
Montia chamissoi	*Crunocallis chamissoi, Claytonia chamissoi*
Muhlenbergia glomerata	*Muhlenbergia racemosa* var. *cinnoides, Muhlenbergia glomerata* var. *cinnoides*
Nymphaea leibergii	*Nymphaea tetragona* var. *leibergii, Nymphaea tetragona* spp.. *leibergii*
Nymphaea tetragona	*Castalia leibergii, Castalia tetragona*
Oxytropis maydelliana	*Oxytropis campestris* var. *melanocephala, Oxytropis campestris* var. *glabrata*
Poa fendleriana ssp. *fendleriana*	*Stipa spartea*
Polemonium occidentale ssp. *occidentale*	*Polemonium occidentale* spp.. *amygdalium, Polemonium occidentale* spp..*typicum*
Potentilla ovina var. *ovina*	*Potentilla ovina* var. *pinnatisecta*
Pyrola elliptica	*Pyrola compacta*

Species Name	Synonyms*
Ranunculus pedatifidus ssp. *affinis*	*Ranunculus pedatifidus* spp.. *affinis, Ranunculus pedatifidus* var. *leiocarpus*
Sagina nivalis	*Sagina intermedia, Spergella intermedia*
Salix boothii	*Salix myrtillifolia, Salix curtiflora, Salix pseudomyrsinites, Salix pseudocordata, Salix novae-angliae, Salix pseudocordata* var. *aequalis, Salix pseudomyrsinites* var. *aequalis, Salix myrtillifolia* var. *curtiflora*
Salix serissima	*Salix arguta* var. *pallescens, Salix lucida* var. *serissima, Salix arguta* var. *alpigena*
Scolochloa festucacea	*Arundo festucacea, Fluminia festucacea*
Senecio plattensis	*Packera plattensis*
Silene drummondii var. *drummondii*	*Melandrium drummondii, Lychnis drummondii, Gastroluchnis drummondii, Wahlbergella drummondii, Lychnis pudica*
Stellaria obtusa	*Alsine washingtoniana, Alsine viridula, Alsine obtusa, Stellaria washingtoniana, Stellaria viridula*
Stellaria umbellata	*Stellaria weberi, Alsine baicalensis, Stellaria gonomischa*
Thermopsis rhombifolia	*Thermopsis arenosa, Thermopsis annulocarpa, Thermia rhombifolia, Scolobus rhombifolius, Drepilia rhombifolia, Cytisus rhombifolius, Thermopsis rhombifolia* var. *rhombifolia, Thermopsis rhombifolia* var. *arenosa, Thermopsis rhombifolia* var. *annulocarpa*
Trichophorum pumilum	*Scirpus rollandii, Baeothryon pumilum, Trichophorum rollandii, Scirpus pumilus, Trichophorum pumilum* var. *rollandii, Scirpus pumilus* var. *rollandii, Trichophorum pumilum* spp. *rollandii, Scirpus pumilus* spp.. *rollandii*
Woodsia alpina	*Woodsia glabella* var. *bellii, Woodsia alpina* var. *bellii*

**According to the Global Biodiversity Information Facility (GBIF) http://data.gbif.org/welcome.htm*

Table A4. A summary of the results using CGCM3 for the B.C. biogeoclimatic variants currently found in the study area. This table provides the resulting areas of suitable climate for each timeslice (number of points, which roughly equate to area in km²), the proportional change from the baseline area to the 2080s area, the area of suitable climate space and persistent climate corridors as well as the percent of the current area represented by the persistent climate corridor.

			Suitable Climate Space						
Description of Biogeoclimatic Variant	Current Area (km^2)	Base (km^2)	2020s (km^2)	2050s (km^2)	2080s (km^2)	Change From Base to 2080s (%)	Suitable Climate Space (km^2)	Persistent Climate Corridor (PCC) (km^2)	% of Current Area Represented by PCC
Boreal Altai Fescue Alpine Undifferentiated (BAFAun)	31,255	24,208	16,234	4,242	710	-97.07	184	34	0.11
Boreal Altai Fescue Alpine Undifferentiated and Parkland (BAFAunp)	46,386	27,025	6,745	993	75	-99.72	10	9	0.02
Bunchgrass Thompson Very Dry Hot (BGxh2)	679	0	19	58	51	0	0	0	0.00
Bunchgrass Fraser Very Dry Hot (BGxh3)	377	306	588	172	0	-100	0	0	0.00
Bunchgrass Alkali Very Dry Warm (BGxw2)	550	143	2,433	3	0	-100	0	0	0.00
Boreal White and Black Spruce Stikine Dry Cool (BWBSdk1)	28,541	23,174	556	0	0	-100	0	0	0.00
Boreal White and Black Spruce Peace Moist Warm (BWBSmw1)	30,769	2,814	18	0	0	-100	0	0	0.00
Boreal White and Black Spruce Murray Wet Cool (BWBSwk1)	3,399	16,885	5,488	13	5	-99.97	0	0	0.00
Boreal White and Black Spruce Graham Wet Cool (BWBSwk2)	3,530	1,052	0	0	0	-100	0	0	0.00
Coastal Mountain-heather Alpine Undifferentiated and Parkland (CMAunp)	49,788	6,671	5,438	3,329	2,190	-67.17	1,396	182	0.37
Coastal Western Hemlock Southern Dry Submaritime (CWHds1)	2,618	42	137	3,323	12,038	28561.9	0	0	0.00
Coastal Western Hemlock Central Dry Submaritime (CWHds2)	816	1,365	17,247	39,326	44,804	3182.34	352	64	7.84
Coastal Western Hemlock Central Moist Submaritime (CWHms2)	1,744	2	4	80	424	21100	0	0	0.00
Coastal Western Hemlock Undifferentiated (CWHun)	16	378	538	215	91	-75.93	0	0	0.00
Coastal Western Hemlock Wet Maritime (CWHwm)	5,359	7,055	19,315	28,469	34,294	386.09	2,702	0	0.00
Coastal Western Hemlock Montane Wet Submaritime (CWHws2)	6,607	83	873	8,522	13,987	16751.81	0	0	0.00
Engelmann Spruce-Subalpine Fir South Thompsom Dry Cold (ESSFdc2)	1,391	2,246	21,633	15,647	945	-57.93	0	0	0.00
Engelmann Spruce-Subalpine Fir North Thompsom Dry Cold (ESSFdc3)	1,351	8,057	18,420	2,108	5,752	-28.61	0	0	0.00
Engelmann Spruce-Subalpine Fir Dry Very Cold Parkland (ESSFdvp)	1,171	5,575	14,618	8,964	3,064	-45.04	0	0	0.00
Engelmann Spruce-Subalpine Fir Dry Very Cold Woodland (ESSFdvw)	707	6,179	23,011	17,047	8,041	-94.48	0	0	0.00
Engelmann Spruce-Subalpine Fir Moist Cold (ESSFmc)	11,678	50,993	19,959	2,042	341	-99.33	0	0	0.00
Engelmann Spruce-Subalpine Fir Moist Cold Parkland (ESSFmcp)	2,413	20,467	5,436	839	42	-99.79	0	0	0.00
Engelmann Spruce-Subalpine Fir Moist Cool (ESSFmk)	1,853	9,326	19,481	13,768	9,121	-2.2	0	0	0.00
Engelmann Spruce-Subalpine Fir Moist Cool Parkland (ESSFmkp)	583	8,322	12,424	7,639	4,378	9.6	0	0	0.00
Engelmann Spruce-Subalpine Fir Raush Moist Mild (ESSFmm1)	3,011	20,590	4,481	245	34	-99.83	0	0	0.00
Engelmann Spruce-Subalpine Fir Raush Moist Mild Parkland (ESSFmp)	3,586	10,943	4,025	848	70	-99.36	0	0	0.00
Engelmann Spruce-Subalpine Fir Nechako Moist Very Cold (ESSFmv1)	1,946	7,431	2,233	27	0	-100	0	0	0.00
Engelmann Spruce-Subalpine Fir Bullmoose Moist Very Cold (ESSFmv2)	6,069	43,899	13,215	507	139	-99.68	0	0	0.00

Description of Biogeoclimatic Variant	Current Area (km^2)	Suitable Climate Space: Base (km^2)	Suitable Climate Space: 2020s (km^2)	Suitable Climate Space: 2050s (km^2)	Suitable Climate Space: 2080s (km^2)	Change From Base to 2080s (%)	Suitable Climate Space (km^2)	Persistent Climate Corridor (PCC) (km^2)	% of Current Area Represented by PCC
Engelmann Spruce-Subalpine Fir Omineca Moist Very Cold (ESSFmv3)	13,981	24,853	1,714	13	4	-99.98	0	0	0.00
Engelmann Spruce-Subalpine Fir Graham Moist Very Cold (ESSFmv4)	7,899	8,315	58	0	0	-100	0	0	0.00
Engelmann Spruce-Subalpine Fir Moist Very Cold Parkland (ESSFmvp)	5,107	19,076	3,186	69	1	-99.99	0	0	0.00
Engelmann Spruce-Subalpine Fir Moist Warm (ESSFmw)	2,664	5,235	17,413	20,588	16,254	210.49	357	16	0.60
Engelmann Spruce-Subalpine Fir North Monashee Wet Cold (ESSFwc2)	6,098	35,601	11,507	1,134	153	-99.57	0	0	0.00
Engelmann Spruce-Subalpine Fir Cariboo Wet Cold (ESSFwc3)	8,749	30,319	9,094	1,354	143	-99.53	0	0	0.00
Engelmann Spruce-Subalpine Fir Wet Cold Parkland (ESSFwcp)	9,111	18,597	7,885	1,926	405	-97.82	0	0	0.00
Engelmann Spruce-Subalpine Fir Wet Cold Woodland (ESSFwcw)	4,775	14,578	5,847	1,625	289	-98.02	0	0	0.00
Engelmann Spruce-Subalpine Fir Cariboo Wet Cool (ESSFwk1)	5,136	8,501	7,564	883	202	-97.62	0	0	0.00
Engelmann Spruce-Subalpine Fir Misinchinka Wet Cool (ESSFwk2)	5,876	30,083	3,986	35	10	-99.97	0	0	0.00
Engelmann Spruce-Subalpine Fir Wet Very Cold (ESSFwv)	1,933	85,218	50,567	12,774	5,924	-93.05	3,337	1,233	63.79
Engelmann Spruce-Subalpine Fir Wet Very Cold Parkland (ESSFwvp)	1,263	13,123	7,095	1,984	460	-96.49	0	0	0.00
Engelmann Spruce-Subalpine Fir Pavillion Very Dry Cold (ESSFxc3)	481	3,112	16,905	14,707	4,489	44.25	0	0	0.00
Engelmann Spruce-Subalpine Fir Okanagan Very Dry Cold Parkland (ESSFxcp)	157	4,984	15,294	11,052	2,620	-47.43	0	0	0.00
Engelmann Spruce-Subalpine Fir Okanagan Very Dry Cold Woodland (ESSFxcw)	208	4,908	19,082	15,834	5,184	5.62	0	0	0.00
Engelmann Spruce-Subalpine Fir West Chilcotin Very Dry Very Cold (ESSFxv1)	2,931	14,208	30,071	14,391	4,175	-70.62	0	0	0.00
Engelmann Spruce-Subalpine Fir Big Creek Very Dry Very Cold (ESSFxv2)	945	11,323	25,216	9,310	1,742	-84.62	0	0	0.00
Engelmann Spruce-Subalpine Fir Very Dry Very Cold Woodland (ESSFxvw)	77	412	424	380	14	-96.6	0	0	0.00
Interior Cedar Hemlock Dry Cool (ICHdk)	351	9,302	7616	284	80	-99.14	0	0	0.00
Interior Cedar Hemlock Nass Moist Cold (ICHmc1)	5,343	40,162	70,213	56,173	34,615	-13.81	3,677	203	3.80
Interior Cedar Hemlock Hazelton Moist Cold (ICHmc2)	3,276	7,265	48,297	67,688	4,887	-32.73	0	0	0.00
Interior Cedar Hemlock Thompson Moist Cool (ICHmk2)	891	21,547	46,434	7,707	1,945	-90.97	0	0	0.00
Interior Cedar Hemlock Horsefly Moist Cool (ICHmk3)	1,072	20,694	28,116	2,217	746	-96.4	0	0	0.00
Interior Cedar Hemlock Thompson Moist Warm (ICHmw3)	3,541	36,092	35,298	7,874	5,987	-83.41	0	0	0.00
Interior Cedar Hemlock Very Wet Cold (ICHvc)	1,449	67,405	90,066	71,740	41,692	-38.15	13,403	182	12.56
Interior Cedar Hemlock Slim Very Wet Cool (ICHvk2)	1,320	10,217	6,224	57	6	-99.94	0	0	0.00
Interior Cedar Hemlock Quesnel Wet Cool (ICHwk2)	2,038	44,295	37,039	3,896	995	-97.75	0	0	0.00
Interior Cedar Hemlock Goat Wet Cool (ICHwk3)	943	18,617	12,812	203	103	-99.45	0	0	0.00
Interior Cedar Hemlock Cariboo Wet Cool (ICHwk4)	1,425	18,638	12,798	421	171	-99.08	0	0	0.00
Interior Douglas-fir Dry Cold (IDFdc)	745	28,937	69,465	63,315	28,941	0.01	123	0	0.00
Interior Douglas-fir Thompson Dry Cool (IDFdk1)	5,165	2,668	19,087	18,195	2,283	-14.43	0	0	0.00
Interior Douglas-fir Fraser Dry Cool (IDFdk3)	10,001	14,711	19,526	1,566	19	-99.87	0	0	0.00

Description of Biogeoclimatic Variant	Current Area (km^2)	Base (km^2)	Suitable Climate Space			Change From Base to 2080s (%)	Suitable Climate Space (km^2)	Persistent Climate Corridor (PCC) (km^2)	% of Current Area Represented by PCC
			2020s (km^2)	2050s (km^2)	2080s (km^2)				
Interior Douglas-fir Chilcotin Dry Cool (IDFdk4)	3,729	23,982	23,161	1,186	5	-99.98	0	0	0.00
Interior Douglas-fir Dry Warm (IDFdw)	1,115	6,650	41,278	33,314	13,692	105.89	0	0	0.00
Interior Douglas-fir Thompson Moist Warm (IDFmw2)	1,943	4,963	18,683	7,252	7,066	42.37	0	0	0.00
Interior Douglas-fir Wet Warm (IDFww)	1,198	2,647	34,727	85,493	70,907	2578.77	96	0	0.00
Interior Douglas-fir Thompson Very Dry Hot (IDFxh2)	3,482	1,414	13,799	24,862	18,928	1238.61	0	0	0.00
Interior Douglas-fir Very Dry Mild (IDFxm)	2,590	6,650	11,195	221	16	-99.76	0	0	0.00
Interior Douglas-fir Very Dry Warm (IDFxw)	445	2,797	5,870	4,026	677	-75.8	0	0	0.00
Interior Mountain-heather Alpine Undifferentiated (IMAun)	12,991	8,137	7,436	1,962	168	-97.94	9	0	0.00
Interior Mountain-heather Alpine Undifferentiated and Parkland (IMAunp)	1,195	6,771	14,376	10,813	6,854	1.23	413	0	0.00
Mountain Hemlock Leeward Moist Maritime (MHmm2)	12,394	1,960	6,297	8,579	8,284	322.65	106	9	0.07
Mountain Hemlock Moist Maritime Parkland (MHmmp)	2,243	1,162	3,456	4,576	4,501	287.35	31	0	0.00
Mountain Hemlock Undifferentiated (MHun)	4,579	30,147	31,017	17,934	10,740	-64.37	3,172	4	0.09
Montane Spruce Tatlayoko Dry Cold (MSdc2)	482	4,093	17,849	12,857	3,890	-4.96	0	0	0.00
Montane Spruce North Thompson Dry Mild (MSdm3)	1,018	6,908	34,168	7,017	1,412	-79.56	0	0	0.00
Montane Spruce Dry Very Cold (MSdv)	283	7,366	11,293	4,127	1,731	-76.5	0	0	0.00
Montane Spruce Undifferentiated (MSun)	93	2,705	15,429	12,970	5,724	111.61	0	0	0.00
Montane Spruce South Thompson Very Dry Cool (MSxk2)	2,277	1,451	16,828	8,333	888	-38.8	0	0	0.00
Montane Spruce Pavillion Very Dry Cool (MSxk3)	1,046	1,469	5,849	5,106	361	-75.43	0	0	0.00
Montane Spruce Very Dry Very Cold (MSxv)	8,789	14,219	9,787	307	4	-99.97	0	0	0.00
Ponderosa Pine Thompson Very Dry Hot (PPxh2)	1,250	195	969	716	131	-32.82	0	0	0.00
Sub-boreal Pine-Spruce Dry Cold (SBPSdc)	4,054	9,796	2,621	31	0	-100	0	0	0.00
Sub-boreal Pine-Spruce Moist Cold (SBPSmc)	3,165	13,567	2,295	52	0	-100	0	0	0.00
Sub-boreal Pine-Spruce Moist Cool (SBPSmk)	4,082	23,254	23,469	981	147	-99.37	0	0	0.00
Sub-boreal Pine-Spruce Very Dry Cold (SBPSxc)	11,353	22,139	12,653	116	1	-100	0	0	0.00
Sub-boreal Spruce Dry Cool (SBSdk)	10,612	23,713	6,333	85	5	-99.98	0	0	0.00
Sub-boreal Spruce Horsefly Dry Warm (SBSdw1)	3,993	25,202	39,179	6,115	1,363	-94.59	0	0	0.00
Sub-boreal Spruce Blackwater Dry Warm (SBSdw2)	5,286	35,588	33,609	3,165	471	-98.68	0	0	0.00
Sub-boreal Spruce Stewart Dry Warm (SBSdw3)	9,718	45,702	25,572	737	184	-99.6	0	0	0.00
Sub-boreal Spruce Moffat Moist Cold (SBSmc1)	516	14,641	34,445	3,503	784	-94.65	0	0	0.00
Sub-boreal Spruce Babine Moist Cold (SBSmc2)	22,112	51,420	16,598	526	94	-99.82	0	0	0.00
Sub-boreal Spruce Kluskus Moist Cold (SBSmc3)	2,613	7,292	1,212	9	0	-100	0	0	0.00
Sub-boreal Spruce Moist Hot (SBSmh)	1,083	5,321	8,832	2,591	2,561	-51.87	0	0	0.00

Description of Biogeoclimatic Variant	Current Area (km^2)	Base (km^2)	Suitable Climate Space 2020s (km^2)	Suitable Climate Space 2050s (km^2)	Suitable Climate Space 2080s (km^2)	Change From Base to 2080s (%)	Suitable Climate Space (km^2)	Persistent Climate Corridor (PCC) (km^2)	% of Current Area Represented by PCC
Sub-boreal Spruce Mossvale Moist Cool (SBSmk1)	13,975	41,785	6,355	3	0	-100	0	0	0.00
Sub-boreal Spruce Williston Moist Cool (SBSmk2)	3,909	11,782	123	0	0	-100	0	0	0.00
Sub-boreal Spruce Moist Mild (SBSmm)	707	7,498	11,496	853	205	-97.27	0	0	0.00
Sub-boreal Spruce Moist Warm (SBSmw)	2,194	17,839	16,259	66,906	263	-98.53	0	0	0.00
Sub-boreal Spruce Very Wet Cool (SBSvk)	5,035	23,162	9,605	138	28	-99.88	0	0	0.00
Sub-boreal Spruce Willow Wet Cool (SBSwk1)	7,858	23,437	14,330	662	241	-98.97	0	0	0.00
Sub-boreal Spruce Finlay-Peace Wet Cool (SBSwk2)	5,090	32,940	1,213	0	0	-100	0	0	0.00
Sub-boreal Spruce Takla Wet Cool (SBSwk3)	4,448	33,423	5,385	8	3	-99.99	0	0	0.00
Spruce-Willow-Birch Moist Cool (SWBmk)	59,663	3,653	3	0	0	-100	0	0	0.00
Spruce-Willow-Birch Moist Cool Scrub (SWBmks)	10,467	3,098	5	0	0	-100	0	0	0.00
Spruce-Willow-Birch Moist Undifferentiated (SWBun)	8,748	23,598	1,291	5	0	-100	0	0	0.00
TOTAL	**626,967**	**1,613,763**	**1,566,818**	**905,958**	**467,464**	**-71.03**	**29,368**	**1936**	**3.09**

Table A5. A summary of the results using CGCM3 for the Nature Conservancy of Canada's (NCC) terrestrial ecological units currently found in the study area. This table provides the resulting areas for each timeslice (number of points, which roughly equate to area in km^2), the proportional change from the baseline area to the 2080s area, the area of suitable climate space and persistent climate corridors as well as the percent of the current occurrences represented by the persistent climate corridor.

			Suitable Climate Space						
Description of NCC's Terrestrial Ecosystem Units	Current Area (km^2)	Base (km^2)	2020s (km^2)	2050s (km^2)	2080s (km^2)	Change From Base to 2080s (%)	Suitable Climate Space (km^2)	Persistent Climate Corridor PCC (km^2)	% of Current Area Represented by PCC
Boreal Alpine Fescue Dwarf Shrubland and Grassland	17,748	33,993	20,162	6,038	1,493	-95.61	715	549	3.09
North Pacific Dry and Mesic Alpine Dwarf-Shrubland, Fell-field and Meadow	3,604	14,997	10,950	4,524	1,015	-93.23	347	46	1.28
North Pacific Interior Dry Douglas-Fir Forest	2,265	7,535	13,920	609	0	-100	0	0	0
North Pacific Interior Dry-Mesic Conifer Forest (Pl, Fd, Sxw, Cw, Bl)	117,031	105,998	80,763	12,404	4,349	-95.9	0	0	0
North Pacific Interior Wet Toeslope/Riparian Hybrid Spruce - Western Red Cedar Forest	4,886	112,397	49,106	1,715	238	-99.79	0	0	0
North Pacific Interior Wet Toeslope/Riparian Mixed Conifer Forest	3,997	60,195	34,442	1,754	622	-98.97	0	0	0
North Pacific Interior Wetland (Swamp, Bog, Fen and Marsh) Composite	7,558	144,621	87,393	5,750	1,647	-98.86	200	0	0
North Pacific Maritime Mesic-Wet Douglas-fir-Western Hemlock Forest	274	2,848	18,012	24,163	22,401	551.47	0	0	0
North Pacific Mesic Western Hemlock-Silver Fir Forest	147	7,583	22,424	24,184	18,554	144.68	0	0	0
North Pacific Montane Riparian Woodland and Shrubland	1,294	110,602	109,618	59,818	32,508	-70.61	19,053	133	10.28
North Pacific Mountain Hemlock Forest	887	15,433	24,014	15,257	9,749	-36.83	0	0	0
North Pacific Mountain Hemlock Parkland	224	10,964	14,404	8,090	10,964	0	0	0	0
North Pacific Sub-Boreal Dry Lodgepole Pine Forest	28,106	61,480	56,202	4,609	647	-98.95	0	0	0
North Pacific Interior Lodgepole Pine - Douglas-Fir Woodland and Forest	11,866	57,219	77,191	50,204	37,977	-33.63	22,661	1,131	9.53
North Pacific Sub-Boreal Mesic Hybrid Spruce Forest	57,165	81,796	25,041	519	109	-99.87	0	0	0
North Pacific Sub-Boreal Mesic Hybrid Spruce-Douglas Fir Forest	18,844	50,244	43,284	4,277	913	-98.18	0	0	0
North Pacific Sub-Boreal Mesic Subalpine Fir - Hybrid Spruce Forest	47,680	79,335	49,476	11,831	4,716	-94.06	1,205	611	1.28
North Pacific Sub-Boreal Mesic Subalpine Fir - Hybrid Spruce Parkland	9,259	67,605	22,834	4,897	4,242	-93.73	3,005	0	0
North Pacific Sub-Boreal Riparian Woodland and Shrubland	531	45,388	33,036	11,931	2,949	-93.5	0	0	0
Northern Rocky Mountain Dry-Mesic Montane Mixed Conifer Forest (Fd and Py)	293	1,976	2,805	0	0	-100	0	0	0
Northern Rocky Mountain Lower Montane Riparian Woodland and Shrubland	2,433	74,119	47,267	15,282	7,963	-89.26	4,278	91	3.74
Northern Rocky Mountain Lower Montane, Foothill and Valley Grassland	773	2,021	3,575	10	0	-100	0	0	0
Northern Rocky Mountain Ponderosa Pine Woodland and Savanna	9	0	0	0	0	0	0	0	0
Rocky Mountain Subalpine Mesic-Wet Spruce-Fir Forest and Woodland	13,323	18,926	56,013	45,303	26,157	38.21	0	0	0
Rocky Mountain Subalpine-Montane Riparian Shrubland	74	48,715	14,248	1,542	178	-99.63	0	0	0
North Pacific Sub-Boreal Wet Toeslope/Riparian Hybrid Spruce Forest	3,795	35,359	13,766	209	75	-99.79	0	0	0
Boreal Open Scrub/Willow Peatland	795	18,030	350	2	0	-100	0	0	0

Description of NCC's Terrestrial Ecosystem Units	Current Area (km^2)	Base (km^2)	Suitable Climate Space 2020s (km^2)	Suitable Climate Space 2050s (km^2)	Suitable Climate Space 2080s (km^2)	Change From Base to 2080s (%)	Suitable Climate Space (km^2)	Persistent Climate Corridor PCC (km^2)	% of Current Area Represented by PCC
Boreal White Spruce Forest and Woodland	6,231	38,228	5,469	7	0	-100	0	0	0
North Pacific Hypermaritime Sitka Spruce Forest	21	2,434	1,107	26	0	-100	0	0	0
TOTAL	**216,249**	**361,113**	**1,310,041**	**936,872**	**314,955**	**-12.78**	**51,464**	**2,561**	**1.18**

Table A6. A summary of the results using CGCM3 for rare plant species listed by the B.C. Conservation Data Centre (CDC) as occurring in the study area. This table provides the resulting areas for each timeslice (number of points, which roughly equate to area in km2), the proportional

change from the baseline area to the 2080s area, the area of suitable climate space and persistent climate corridors, as well as the percent of the current area represented by the persistent climate corridor.

Species Name	Points in Study Area	Base Area (km^2)	Suitable Climate Space 2020s (km^2)	Suitable Climate Space 2050s (km^2)	Suitable Climate Space 2080s (km^2)	Change From Base to 2080s (%)	Suitable Climate Space (km^2)	Persistent Climate Corridor (km^2)	% of Current Points in PCC
Allium geyeri var. *tenerum*	1	35,236	119,633	189,880	187,311	-100	11,965	0	0
Anemone canadensis	1	80320	35,754	4,689	3,518	-95.62	0	0	0
Apocynum x floribundum	3	28,534	19,853	3,019	3,857	-86.48	0	0	0
Arabis holboellii var. *pinetorum*	3	15,912	23,249	8,766	10,056	-36.8	0	0	0
Arabis sparsiflora	3	217,934	231,965	235,327	230,380	5.71	0	0	0
Atriplex argentea ssp. *argentea*	1	385	1,316	45	2	-99.48	0	0	0
Botrychium simplex	3	246,951	250,860	248,935	242,408	-1.84	5,993	0	0
Bouteloua gracilis	2	144,422	142,524	51,330	44,989	-68.85	0	0	0
Camissonia breviflora	2	70,946	113,810	70,736	0	-100	0	0	0
Carex backii	1	149,567	28,869	298	26	-99.98	0	0	0
Carex bicolor	2	218,521	227,063	230,988	228,769	4.69	0	0	0
Carex heleonastes	4	206,697	158,161	40,992	12,894	-93.76	53	0	0
Carex lenticularis var. *dolia*	3	237,767	233,824	224,410	221,445	-6.86	178,348	1	33.33
Carex scoparia	1	227,333	231,205	228,068	227,768	0.19	810	0	0
Carex simulata	8	12,477	5,039	2	0	-100	0	0	0
Carex sychnocephala	1	117,279	85,582	18,458	20,378	-82.62	6,175	0	0
Carex tenera	7	209,132	214,157	181,302	170,450	-18.5	49,081	2	28.57
Carex tonsa var. *tonsa*	1	42,820	6,937	11	8	-99.98	0	0	0
Carex xerantica	4	22,910	36,328	17,698	19,963	-12.86	0	0	0
Chamaerhodos erecta ssp. *nuttallii*	5	33,985	15,094	1,700	2,231	-93.44	0	0	0
Chamaesyce serpyllifolia ssp. *serpyllifolia*	2	9,003	26,470	53,890	86,287	858.42	0	0	0
Chenopodium atrovirens	2	195,832	217,560	204,187	192,848	-1.52	55,356	0	0
Delphinium bicolor ssp. *bicolor*	1	5,201	207,518	173,591	138,341	2559.89	0	0	0
Draba alpina	2	50,065	22,737	4,515	547	-98.91	0	0	0
Draba cinerea	2	147,852	40,110	2,233	381	-99.74	2	0	0
Draba fladnizensis	3	50,318	24,656	4,493	999	-98.01	0	0	0
Draba glabella var. *glabella*	1	40,037	24,211	10,035	2,867	-92.84	0	0	0
Draba lactea	2	25,922	72	2,811	576	-97.78	0	0	0
Draba lonchocarpa var. *vestita*	1	15,800	26,355	24,456	20,481	29.63	0	0	0

Species Name	Points in Study Area	Base Area (km^2)	Suitable Climate Space 2020s (km^2)	2050s (km^2)	2080s (km^2)	Change From Base to 2080s (%)	Suitable Climate Space (km^2)	Persistent Climate Corridor (km^2)	% of Current Points in PCC
Draba reptans	1	8,075	14,177	1,885	37	-99.54	0	0	0
Draba ruaxes	2	174,894	147,033	120,544	97,831	-44.06	1,751	0	0
Draba ventosa	1	54,564	25,844	7,812	1,472	-97.3	49,941	0	0
Dryopteris cristata	1	113,581	157,411	103,736	94,879	-16.47	17,356	0	0
Entosthodon rubiginosus	1	1,534	4,042	53,559	212	-86.18	0	0	0
Epilobium halleanum	2	233,060	242,307	242,771	233,869	0.35	25	0	0
Epilobium leptocarpum	2	188,968	186,451	169,639	166,843	-11.71	97,321	0	0
Eutrema edwardsii	1	18,241	1,991	136	1	-99.99	0	0	0
Festuca minutiflora	2	248,562	244,985	206,844	130,590	-47.46	0	0	0
Glyceria pulchella	1	44,620	1,689	0	0	-100	0	0	0
Hesperostipa spartea	2	132,094	164,058	154,660	133,368	0.96	0	0	0
Juncus albescens	3	247,071	231,794	169,248	94,015	-61.95	19,529	0	0
Juncus arcticus ssp. *alaskanus*	2	171,556	161,157	146,340	144,531	-15.75	7,549	0	0
Juncus stygius	2	175,517	165,874	149,924	145,198	-17.27	80,991	1	50
Koenigia islandica	2	18,010	150,868	92,987	73,607	308.7	34,669	1	50
Lloydia serotina var. *flava*	1	70,424	62,283	53,488	50,112	-28.84	0	0	0
Malaxis paludosa	2	180,154	170,455	155,217	153,612	-14.73	92,612	2	100
Megalodonta beckii var. *beckii*	2	57,387	116,388	150,466	162,566	183.28	0	0	0
Melica spectabilis	1	164,481	212,477	222,392	214,329	30.31	0	0	0
Minuartia austromontana	2	110,415	105,669	95,432	95,602	-13.42	1,651	0	0
Montia chamissoi	2	66,917	127,081	137,620	114,928	71.75	17	0	0
Muhlenbergia glomerata	4	207,655	170,641	75,737	72,075	-65.29	26,043	2	25
Nephroma occultum	4	112,782	146,634	125,213	98,893	-12.31	11,585	1	25
Nymphaea leibergii	1	115,773	10,443	39,179	37,660	-67.47	0	0	0
Nymphaea tetragona	5	235,285	236,629	235,194	236,105	0.35	158,015	5	100
Platanthera dilatata var. *albiflora*	2	41,625	59,744	69,983	77,243	-48.75	0	0	0
Poa fendleriana ssp. *fendleriana*	2	150,717	184,326	198,580	194,740	26.5	0	0	0
Polemonium boreale	1	153,944	77,549	19,566	7,143	-56.62	0	0	0
Polygonum ramosissimum var. *ramosissimum*	1	16,466	27,361	10,095	457	-83.42	0	0	0
Polypodium sibiricum	1	2,757	5	0	0	-100	0	0	0
Potentilla nivea var. *pentaphylla*	1	111,151	181,767	195,584	175,555	57.94	654	1	100
Pyrola elliptica	1	127,258	176,408	204,706	218,649	71.82	0	0	0

Species Name	Points in Study Area	Base Area (km^2)	Suitable Climate Space			Change From Base to 2080s (%)	Suitable Climate Space (km^2)	Persistent Climate Corridor (km^2)	% of Current Points in PCC
			2020s (km^2)	2050s (km^2)	2080s (km^2)				
Sagina nivalis	1	102,329	58,350	15,474	6,168	-93.97	0	0	0
Salix boothii	9	177,641	110,818	16,674	5,176	-97.09	2,973	0	0
Salix serissima	1	185,995	197,075	194,831	192,846	3.68	6,196	0	0
Saxifraga nelsoniana ssp. *carlottae*	1	220,193	198,056	171,507	140,244	-36.31	2,166	0	0
Senecio plattensis	6	72,120	65,045	8,136	1,245	-98.27	0	0	0
Silene drummondii var. *drummondii*	2	36,959	40,546	5,720	112,902	205.48	0	0	0
Sparganium fluctuans	2	108,508	111,763	104,903	112,896	4.04	590	0	0
Stellaria umbellata	1	147,701	136,108	120,828	116,896	-20.86	241	0	0
Torreyochloa pallida	2	3,781	4,585	186	3	-99.92	0	0	0
Trichophorum pumilum	4	95,306	47,510	2,649	315	-99.67	0	0	0
Woodsia alpina	1	2,601	0	0	-100	0	0	0	0
Total	**162**	**7,767,830**	**7,706,309**	**6,486,310**	**5,984,593**	**-88.16**	**919,658**	**16**	**9.88**

Table A7a. A complete summary of the fatal trends to B.C. Conservation Data Centre listed plant populations for the baseline and 2020s timeslices. Cells indicate number of populations constrained by different bioclimatic envelope attributes.

	Occurrences		BASELINE								2020 s							
			MAT		TD		AHM		PAS		MAT		TD		AHM		PAS	
Species	Study Area	Without PCCs	too low	too high	too low	too high	too low	too high	too low	too high	too low	too high	too low	too high	too low	too high	too low	too high
Allium geyeri var. *tenerum*	1	1					1			1								
Anemone canadensis	1	1			1				1				1					1
Apocynum x floribundum	3	3	1					1	3	1		1	1		1	1	2	1
Arabis holboellii var. *pinetorum*	3	3							3								3	
Arabis sparsiflora	3	3							2	1							1	2
Atriplex argentea ssp. *argentea*	1	0	1			1			1						1		1	
Botrychium simplex	3	3					1	1				1			1	1		1
Bouteloua gracilis	2	2						2								2		
Camissonia breviflora	2	2	1			1	1			2			1				1	1
Carex backii	1	1			1		1			1			1					1
Carex bicolor	2	2			1					2		1	2					1
Carex heleonastes	4	0						2					2			2		
Carex lenticularis var. *dolia*	3	2						2								2		
Carex simulata	1	1	1	1		1			6								1	
Carex scoparia	8	8										7	4			2	8	
Carex sychnocephala	1	0					1			1			1		1			1
Carex tenera	7	6			1								1					
Carex tonsa var. *tonsa*	1	1								1		1						1
Carex xerantica	4	4			1			1	4				1			1	4	
Chamaerhodos erecta ssp. *nuttallii*	5	5		1					5			4	1			2	5	
Chamaesyce serpyllifolia ssp. *serpyllifolia*	2	2							2								2	
Chenopodium atrovirens	2	2						1	2							1	1	
Delphinium bicolor ssp. *bicolor*	1	1	1							1								1
Draba alpina	2	2	2		1				2				1					2
Draba cinerea	2	2										1	1					
Draba fladnizensis	3	0	1							3		2						3
Draba glabella var. *glabella*	1	1			1			1		1			1			1		1
Draba lactea	2	2	2		2			2		2		2	2			2		2
Draba lonchocarpa var. *vestita*	1	1								1								1

			BASELINE								2020 s							
	Occurrences		MAT		TD		AHM		PAS		MAT		TD		AHM		PAS	
Species	**Study Area**	**Without PCCs**	**too low**	**too high**	**too low**	**too high**	**too low**	**too high**	**too low**	**too high**	**too low**	**too high**	**too low**	**too high**	**too low**	**too high**	**too low**	**too high**
Draba reptans	1	1			1		1		1				1				1	
Draba ruaxes	2	2								2								2
Draba ventosa	1	1			1								1					
Dryopteris cristata	1	1	1															
Entosthodon rubiginosus	1	1	1						1								1	
Epilobium halleanum	2	2							1									2
Epilobium leptocarpum	2	0				1												
Eutrema edwardsii	1	1							1				1					1
Festuca minutiflora	3	3	1							1		1	1					1
Glyceria pulchella	2	2							2			1	1					1
Hesperostipa spartea	2	2						1	2			1				2	2	
Juncus albescens	3	3		1	1			1				1	1			1	1	
Juncus arcticus ssp.*aAlaskanus*	2	2								2								1
Juncus stygius	2	1																
Koenigia islandica	2	1			1							1	1			1		
Lloydia serotina var. *flava*	1	1						1		1						1		1
Megalodonta beckii var. *beckii*	2	1				1				2								
Melica spectabilis	1	1								1								1
Minuartia austromontana	2	2								2								2
Montia chamissoi	2	2	1					1	1	1						1	2	
Muhlenbergia glomerata	4	2											1			1		
Nephroma occultum	4	3																
Nymphaea leibergii	1	1								1								1
Platanthera dilatata var. *albiflora*	2	2				1				2								1
Poa fendleriana ssp. *fendleriana*	2	2								2		1					2	
Polemonium boreale	1	1			1								1					
Polygonum ramosissimum var. *ramosissimum*	1	1							1			1					1	
Polypodium sibiricum	1	1			1		1			1		1	1				1	
Pyrola elliptica	1	1						1	2								1	

	Occurrences		BASELINE								2020 s							
			MAT		TD		AHM		PAS		MAT		TD		AHM		PAS	
Species	Study Area	Without PCCs	too low	too high	too low	too high	too low	too high	too low	too high	too low	too high	too low	too high	too low	too high	too low	too high
Sagina nivalis	1	1		1			1		1	1		1				1		
Salix boothii	8	8		1				1				3				1	1	
Salix serissima	1	1						1								1		
Saxifraga nelsoniana ssp. *carlottae*	1	1	1					1	1							1	1	
Senecio plattensis	6	6	1		1		1	1	4	1		1	1			2	5	
Silene drummondii var. *drummondii*	4	4	2		2		2	1	4			2	1	1		1	4	
Sparganium fluctuans	1	1						1	1			1				1	2	
Stellaria umbellata	1	3						1								1		
Torreyochloa pallida	2	2		1	1			1	2			2	1			1	2	
Trichophorum pumilum	4	4		1				1	1			2	1			1	4	
Woodsia alpina	1	1		1						1		1	1			1		
Mean			1.20	1.00	1.12	1.00	1.10	1.17	2.11	1.39		1.64	1.20	1.00	1.00	1.29	2.22	1.31

N.B. *Nymphea tetragona* does not appear in this list because each of its occurrences met the conditions of its bioclimatic envelope.

Table A7b. A complete summary of the fatal trends to B.C. Conservation Data Centre listed plant populations for the 2050s and 2080s timeslices Cells indicate number of populations constrained by different bioclimatic envelope attributes.

Species	Occurrences: Study Area	Occurrences: Without PCCs	2050s MAT too low	2050s MAT too high	2050s TD too low	2050s TD too high	2050s AHM too low	2050s AHM too high	2050s PAS too low	2050s PAS too high	2080s MAT too low	2080s MAT too high	2080s TD too low	2080s TD too high	2080s AHM too low	2080s AHM too high	2080s PAS too low	2080s PAS too high
Allium geyeri var. *tenerum*	1	1																
Anemone canadensis	1	1			1					1		1	1					1
Apocynum x floribundum	3	3		1	2		1	1	2	1		1	2		1	1	2	
Arabis holboellii var. pinetorum	3	3			2			2	3			2	2			3	3	
Arabis sparsiflora	3	3						1	1	2						1	1	1
Atriplex argentea ssp. *argentea*	1	0			1				1				1				1	
Botrychium simplex	3	3		3				1		1		3				1		1
Bouteloua gracilis	2	2						2	1			2				2	2	
Camissonia breviflora	2	2		1	1				1	1		2	1				2	
Carex backii	1	1		1	1							1	1					
Carex bicolor	2	2		1	2							2	2					
Carex heleonastes	4	0		2	4			2				3	4			3		
Carex lenticularis var. *dolia*	3	2							2							2		
Carex simulata	1	1							1								1	
Carex scoparia	8	8		8	8			2	8			8	8			2	8	
Carex sychnocephala	1	0			1					1			1					
Carex tenera	7	6			2			2				4	2			2		
Carex tonsa var. *tonsa*	1	1		1	1					1		1	1					1
Carex xerantica	4	4		2	3			1	3			2	3			2	3	
Chamaerhodos erecta ssp. *nuttallii*	5	5		5	5			4	5			5	5			4	5	
Chamaesyce serpyllifolia ssp. *serpyllifolia*	2	2							2								2	
Chenopodium atrovirens	2	2		1				1	1			2				1	2	
Delphinium bicolor ssp. *bicolor*	1	1			1					1			1					1
Draba alpina	2	2		2	1					2		2	1					2
Draba cinerea	2	2		1	1							2	1					
Draba fladnizensis	3	0		2	2					3		2	3					3
Draba glabella var. *glabella*	1	1		1	1			1		1		1	1			1		
Draba lactea	2	2		2	2			2		2		2	2			2		2
Draba lonchocarpa var. *vestita*	1	1						1		1						1		1

	Occurrences		2050s								2080s							
			MAT		TD		AHM		PAS		MAT		TD		AHM		PAS	
Species	Study Area	Without PCCs	too low	too high	too low	too high	too low	too high	too low	too high	too low	too high	too low	too high	too low	too high	too low	too high
Draba reptans	1	1		1	1				1			1	1				1	
Draba ruaxes	2	2								2								2
Draba ventosa	1	1			1								1					
Dryopteris cristata	1	1			1		1						1			1		
Entosthodon rubiginosus	1	1			1				1				1				1	
Epilobium halleanum	2	2						1	2							1	2	
Epilobium leptocarpum	2	0																
Eutrema edwardsii	1	1			1					1		1	1					1
Festuca minutiflora	3	3		1	2					1		2	2					
Glyceria pulchella	2	2		1	1					1		1	1					1
Hesperostipa spartea	2	2		2				2	2			2				2	2	
Juncus albescens	3	3		2	1			1	1			2	2			1	1	
Juncus arcticus ssp. *Alaskanus*	2	2								2								2
Juncus stygius	2	1						1								1		
Koenigia islandica	2	1		1	1			1				1	1			1		
Lloydia serotina var. *flava*	1	1						1		1						1		
Megalodonta beckii var. *beckii*	2	1															2	
Melica spectabilis	1	1								1			1					1
Minuartia austromontana	2	2								1								1
Montia chamissoi	2	2						1	2							1	2	
Muhlenbergia glomerata	4	2			4			2	2				4			2	3	
Nephroma occultum	4	3										3					3	
Nymphaea leibergii	1	1								1		1	1					
Platanthera dilatata var. *albiflora*	2	2						1								1	1	
Poa fendleriana ssp. *fendleriana*	2	2		1					2			1					2	
Polemonium boreale	1	1		1	1							1	1					
Polygonum ramosissimum var. *ramosissimum*	1	1		1	1				1			1	1				1	
Polypodium sibiricum	1	1		1	1					1		1	1					1
Pyrola elliptica	1	1							1								1	

			2050s								2080s							
	Occurrences		MAT		TD		AHM		PAS		MAT		TD		AHM		PAS	
Species	Study Area	Without PCCs	too low	too high	too low	too high	too low	too high	too low	too high	too low	too high	too low	too high	too low	too high	too low	too high
Sagina nivalis	1	1		1				1				1				1	1	
Salix boothii	8	8		7	7			1	1			8	7			1	3	
Salix serissima	1	1		1	1			1				1	1			1	1	
Saxifraga nelsoniana ssp. *carlottae*	1	1						1	1							1	1	
Senecio plattensis	6	6		2	5			2	5			6	5			2	6	
Silene drummondii var. *drummondii*	4	4		4	3			2	4			4	3			3	4	
Sparganium fluctuans	1	1		1				1	2			1				1		
Stellaria umbellata	1	3		1				1				1				1		
Torreyochloa pallida	2	2		2	2			2	2			2	2			2	2	
Trichophorum pumilum	4	4		4	4			1	4			4	4			1	4	
Woodsia alpina	1	1		1	1			1	1			1	1			1	1	
Average				1.94	2.05		1.00	1.41	2.13	1.30		2.21	2.05		1.00	1.53	2.26	1.38

N.B. *Nymphea tetragona* does not appear in this list because each of its occurrences met the conditions of its bioclimatic envelope.

Table A8. A summary of a species' projected suitable climate space (SCS) and the proportional change from the baseline to the 2080s timeslice (Proportional Change) according to 4 broad habitat types (alpine/subalpine, conifer forests, grasslands and wetlands).

Species	Baseline	2080s	Proportion Change Baesline to 2080	Suitable Climate Space	Habitat
Allium geyeri var. *tenerum*	35,236	187,311	431.59	11,965	alpine, subalpine
Delphinium bicolor ssp. *bicolor*	5,201	138,341	2559.89	0	alpine, subalpine
Draba alpina	50,065	547	-98.91	0	alpine, subalpine
Draba cinerea	147,852	381	-99.74	2	alpine, subalpine
Draba fladnizensis	50,318	999	-98.01	0	alpine, subalpine
Draba glabella var. glabella	40,037	2,867	-92.84	0	alpine, subalpine
Draba lactea	25,922	576	-97.78	0	alpine, subalpine
Draba lonchocarpa var. *vestita*	15,800	20,481	29.63	0	alpine, subalpine
Draba reptans	8,075	37	-99.54	0	alpine, subalpine
Draba ruaxes	174,894	97,831	-44.06	1,751	alpine, subalpine
Draba ventosa	54,564	1,472	-97.30	49,941	alpine, subalpine
Lloydia serotina var. *flava*	70,424	50,112	-28.84	0	alpine, subalpine
Minuartia austromontana	110,415	95,602	-13.42	1,651	alpine, subalpine
Polemonium boreale	153,944	7,143	0.00	0	alpine, subalpine
Polypodium sibiricum	2,757	0	-100.00	0	alpine, subalpine
Sagina nivalis	102,329	6,168	-93.97	0	alpine, subalpine
Saxifraga nelsoniana ssp. *carlottae*	220,193	140,244	-36.31	2,166	alpine, subalpine
Woodsia alpina	50,999	0	-100.00	0	alpine, subalpine
Average			**106.69**		
Apocynum x floribundum	28,534	3,857	-86.48	0	conifer forests
Arabis sparsiflora	217,934	230,380	5.71	0	conifer forests
Chamaesyce serpyllifolia ssp. *serpyllifolia*	9,003	86,287	858.42	0	conifer forests
Chenopodium atrovirens	195,832	192,848	-1.52	55,356	conifer forests
Epilobium halleanum	233,060	233,869	0.35	25	conifer forests
Malaxis paludosa	180,154	153,612	-14.73	92,612	conifer forests
Nephroma occultum	112,782	98,893	-12.31	11,585	conifer forests
Pyrola elliptica	127,258	218,649	71.82	0	conifer forests
Average			**102.66**		
Arabis holboellii var. *pinetorum*	15,912	10,056	-36.80	0	grasslands

Species	Baseline	2080s	Proportion Change Baesline to 2080	Suitable Climate Space	Habitat
Bouteloua gracilis	144,422	44,989	-68.85	0	grasslands
Camissonia breviflora	70,946	0	-100.00	0	grasslands
Carex backii	149,567	26	-99.98	0	grasslands
Carex bicolor	218,521	228,769	4.69	0	grasslands
Carex heleonastes	206,697	12,894	-93.76	53	grasslands
Carex lenticularis var. *dolia*	237,767	221,445	-6.86	178,348	grasslands
Carex scoparia	227,333	227,768	0.19	810	grasslands
Carex simulata	12,477	0	-100.00	0	grasslands
Carex sychnocephala	117,279	20,378	-82.62	6,175	grasslands
Carex tenera	209,132	170,450	-18.50	49,081	grasslands
Carex tonsa var. *tonsa*	42,820	8	-99.98	0	grasslands
Carex xerantica	22,910	19,963	-12.86	0	grasslands
Chamaerhodos erecta ssp. *nuttallii*	33,985	2,231	-93.44	0	grasslands
Festuca minutiflora	248,562	130,590	-47.46	0	grasslands
Glyceria pulchella	44,620	0	-100.00	0	grasslands
Hesperostipa spartea	132,094	133,368	0.96	0	grasslands
Juncus albescens	247,071	94,015	-61.95	19,529	grasslands
Juncus arcticus ssp. *alaskanus*	171,556	144,531	-15.75	7,549	grasslands
Juncus stygius	175,517	145,198	-17.27	80,991	grasslands
Koenigia islandica	18,010	73,607	308.70	34,669	grasslands
Melica spectabilis	164,481	214,329	30.31	0	grasslands
Poa fendleriana ssp. *fendleriana*	150,717	194,740	26.50	0	grasslands
Senecio plattensis	72,120	1,245	-98.27	0	grasslands
Silene drummondii var. *drummondii*	36,959	112,902	205.48	0	grasslands
Torreyochloa pallida	3,781	3	-99.92	0	grasslands
Average			**-26.06**		
Anemone canadensis	80,320	3,518	-95.62	0	wetlands
Atriplex argentea ssp. *argentea*	385	2	-99.48	0	wetlands
Botrychium simplex	246,951	242,408	-1.84	5,993	wetlands
Dryopteris cristata	113,581	94,879	-16.47	17,356	wetlands
Entosthodon rubiginosus	1,534	212	-86.18	0	wetlands

Species	Baseline	2080s	Proportion Change Baesline to 2080	Suitable Climate Space	Habitat
Epilobium leptocarpum	188,968	166,843	-11.71	97,321	wetlands
Eutrema edwardsii	18,241	1	-99.99	0	wetlands
Megalodonta beckii var. *beckii*	57,387	162,566	183.28	0	wetlands
Montia chamissoi	66,917	114,928	71.75	17	wetlands
Muhlenbergia glomerata	207,655	72,075	-65.29	26,043	wetlands
Nymphaea leibergii	115,773	37,660	-67.47	0	wetlands
Nymphaea tetragona	235,285	236,105	0.35	158,015	wetlands
Platanthera dilatata var. *albiflora*	41,625	77,243	-48.75	0	wetlands
Polygonum ramosissimum var. *ramosissimum*	16,466	457	-83.42	0	wetlands
Salix boothii	177,641	5,176	-97.09	2,973	wetlands
Salix serissima	185,995	192,846	3.68	6,196	wetlands
Sparganium fluctuans	108,508	112,896	4.04	590	wetlands
Stellaria umbellata	147,701	116,896	-20.86	241	wetlands
Trichophorum pumilum	95,306	315	-99.67	0	wetlands
Average			**-33.20**		