Research Report

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Persistent climate corridors: The identification of climate refugia in British Columbia's Central Interior for the selection of candidate areas for conservation

Nancy-Anne Rose[1] and Philip J. Burton[2]

Abstract

Climate-driven change is catalyzing the global re-distribution of species and ecosystems and is threatening their persistence. These changes undermine the current conservation paradigm that has a static approach to a dynamic system. Conservation planning agencies, such as the Nature Conservancy of Canada, recognize this quandary and have started to incorporate the potential (though uncertain) impacts of climate change into its planning framework. As a component of the Conservancy's Central Interior Ecoregional Assessment, we identified bioclimatic envelopes for 206 conservation targets (103 biogeoclimatic variants, 30 terrestrial ecological units, 73 British Columbia Conservation Data Centre plant species) using ClimateBC and ArcMap software. Using ClimateBC interpolations of current and expected future climatic conditions, locations projected to meet the 5th through 95th percentile requirements of a target's bioclimatic envelope were identified for four timeslices. The points of coincidence between these areas were identified as a target's projected suitable climate space; locations or areas of a target's current distribution that coincided with its climate space were identified as the target's persistent climate corridor (PCC). Our results projected PCCs to exist for only 10% (10/103) of the biogeoclimatic variants, 20% (6/30) of the terrestrial ecological units, and 10% (7/73) of plant species under the CGCM3 general circulation model using the A2 scenario. When comparing the projected results with those derived for three different general circulation model and scenario combinations, it is clear that the existence and locations of PCCs are subject to great uncertainty. Nevertheless, we argue that the identification of climate refugia should be an important consideration in the site selection and prioritization of candidate areas for conservation.

KEYWORDS: *biogeoclimatic variants; Central Interior Ecoregional Assessment; climate change; climate refugia; conservation planning; persistent climate corridors; suitable climate space; terrestrial ecological units.*

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Introduction

The impact of this century's changing climate is altering the environment at a rate and magnitude beyond our current understanding. In particular, climate change is driving the loss of global biodiversity, making the preservation of genetic, species, and ecosystem diversity a formidable challenge to conservation biologists (Halpin 1997; Lemieux and Scott 2005). Climate change will lead to the creation of new non-analog climates and likely will result in the displacement of current ecological communities and species associations (Suffling and Scott 2002; Williams and Jackson 2007). The consequences of these changes will cascade through biomes and ecosystems, altering natural processes and directly affecting our ability to manage for biodiversity as constrained by something as static as a park boundary (Scott et al. 2002; Suffling and Scott 2002; Lemieux and Scott 2005). A changing climate coupled with shifting ecosystems has important implications for ecosystem-based resource management systems, such as British Columbia's biogeoclimatic ecosystem classification system. The zonal component of this system is based on climate and provides the foundation for resource management in the province (B.C. Ministry of Forests and Range 2009).

To mitigate the loss of biodiversity and effectively protect species, ecological communities, and critical ecosystem services, ecologists are taking a more dynamic, process-based approach to ecosystem management. Evidence of this progression is demonstrated by the advent of innovative planning tools such as floating reserves (Cumming et al. 1996; Rayfield et al. 2008), the provision for dispersal corridors (Williams et al. 2005), and climate-proof reserve networks (Vos et al. 2008). These approaches are facilitated by the development of climate projection tools such as BIOCLIM (Beaumont et al. 2005) and SPECIES (Pearson et al. 2002).

Bioclimatic envelope modelling (Pearson and Dawson 2003; Hamann and Wang 2006) and the concept of climatic constraints provided the foundation for the development of the theory of persistent climate corridors (PCC, also known as "temporal corridors;" Rose and Burton 2009) or climate refugia as candidate areas for conservation. A bioclimatic envelope constitutes the climatic component of a species' fundamental niche (i.e., the environmental variables affecting a species' distribution) and it is based on the assumption that on larger scales (e.g., British Columbia's Central Interior), climate is the dominant factor controlling species and ecosystem distribution. In this study, a suitable climate space denotes areas projected to sustain climatic conditions suitable for a conservation target (Berry et al. 2003; Pearson et al. 2006), and PCCs are locations where a target's current location is coincident with its suitable climate space, making them important candidate areas for conservation. Key limitations of this modelling process are its exclusion of species interactions, dispersal ability, evolutionary adaptability, and a suite of abiotic influences such as local topography and human pressure (Pearson and Dawson 2003; McKenney et al. 2007a, 2007b). Proponents of this scientific approach do not dismiss the importance of these other factors to species distributions, rather they argue that bioclimatic envelope modelling provides a valid first approximation of ecological potential, such as estimating the spread of invasive species, evaluating potential planting areas, mapping wildlife habitats, and investigating potential responses of species to climate change (Berry et al. 2002; Kadmon et al. 2005; McKenney et al. 2007a, 2007b).

Bioclimatic envelope modelling and the concept of climatic constraints provided the foundation for the development of the theory of persistent climate corridors or climate refugia as candidate areas for conservation.

The purpose of the research reported here is to identify bioclimatic envelopes and subsequently map PCCs for 206 Central Interior conservation targets. These targets included 103 biogeoclimatic variants, 30 Nature Conservancy of Canada-defined terrestrial ecological units, and 73 British Columbia Conservation Data Centre plant species, as fully documented in Rose (2010). A minor component of this study was a simple analysis illustrating the variability in projected results among different general circulation models and climate change scenario assumptions.

The Central Interior encompasses an area of 246 000 km^2 and corresponds to Environment Canada's Central Interior and Sub-Boreal Interior ecoprovinces. It includes a diversity of landscape features including the Chilcotin, Cariboo, Nechako, and McGregor Plateaus as well as the Chilcotin Ranges west to the centre of the

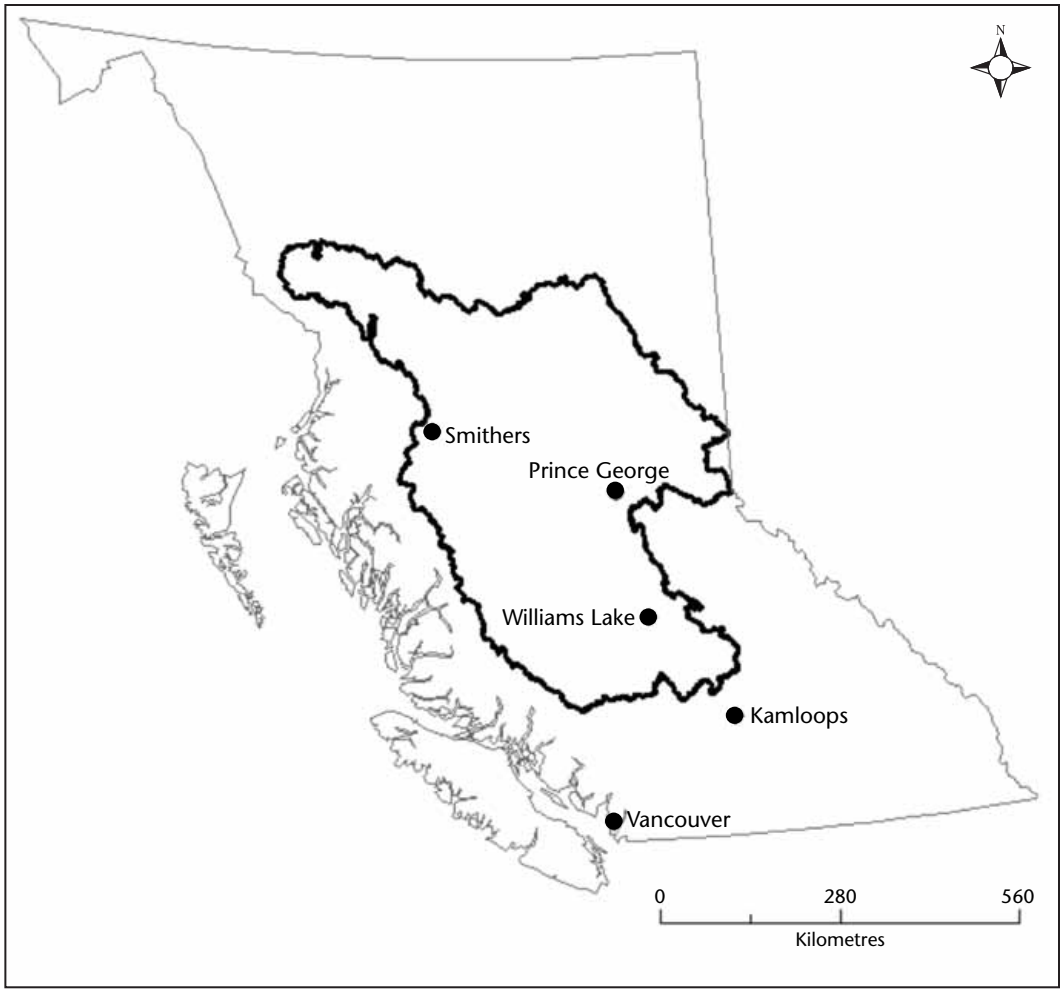

FIGURE 1. The Central Interior study area.

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 (Figure 1).

The elevation of the study area ranges from approximately 70 m to 3300 m above sea level and its climate is 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 (Rose 2010).

Methods

As more fully described by Rose and Burton (2009) and Rose (2010), the identification of suitable climate space is a three-step process that involves:

1. the definition of a bioclimatic envelope for each conservation target, based on its current distribution;
2. the mapping of locations interpolated to meet the requirements of each target's bioclimatic envelope for the baseline (1960s–1990s) and projected 2020s, 2050s, and 2080s time periods; and
3. the intersection of these locations in all four timeslices to determine the points of coincidence.

A target's PCC is the area of coincidence between a target's suitable climate space and its current distribution or known point locations.

The necessary tools used in this process are a geographic information system, a climate interpolation tool capable of addressing elevational differences and differentially weighted weather station data, and detailed projections of future climatic conditions

downscaled to the same resolution as the climate interpolation tool. We used ArcMap® 9.2 software, ClimateBC for climate interpolation and general circulation model downscaling (Mbogga et al. 2009), with emphasis on the third generation of the Canadian general circulation model "business as usual" A2 scenario (CGCM3 A2; Canadian Centre for Climate Modelling and Analysis 2008). Developing bioclimatic envelopes involves collecting occurrence records or mapped distributions of a target's range and generating climate variables at each location with ClimateBC. For a brief description of these variables and the ClimateBC program, please see Spittlehouse (2006).

Quantifying a target's bioclimatic envelope

The key to identifying a target's bioclimatic envelope is to capture the full extent of its current distribution. To accomplish this, the spatial distribution of terrestrial ecological units that extended into adjacent ecoregional assessment areas, as well as the province-wide distribution of biogeoclimatic variants was used. To generate the climate associated with these distributions, the spatial coverages of individual targets were overlaid with a 1-km grid of the study area where each point was associated with a latitude and longitude co-ordinate and an elevation. Occurrence data for rare plant species were obtained from various sources including conservation and natural heritage data centres and online herbaria. Given their rarity, plant occurrence data must be considered incomplete and in all cases the sample sizes are low. The grid locations for area-based targets and occurrence data for rare plant species were organized into a comma-separated value file and run through ClimateBC in batch mode to generate 19 climate variables interpolated for those locations.

As many of the ClimateBC variables are highly correlated, we used a Pearson's correlation matrix and the eigenvalues of a principal components analysis to identify those variables that explained 95% of the variance in current province-wide climate (Hamann and Wang et al. 2006; Mbogga et al. 2009). We then defined bioclimatic envelopes on the basis of the first four climate variables outlined in Table 1.

The definition of a target's bioclimatic envelope is arbitrary, and has variously been defined to include the minimum and maximum values, or (for the core envelope) the 25th and 75th percentiles for local climate attributes. For our purposes, the target's bioclimatic envelopes were defined as the 5th and 95th percentiles of those variables across the range of the target in order to remove the effects of unusual microsites and potential errors on documenting collection locations (Kadmon et al. 2005; Beaumont et al. 2005; Wang et al. 2006; McKenney et al. 2007a, 2007b).

Identifying suitable climate space and persistent climate corridors

A program in SAS® 9.1.2 for Windows (SAS Institute 2004) was written using ClimateBC output to evaluate whether each location in the study area (on a 1-km grid) met the requirements for each target's bioclimatic envelope under current and projected climates. Each point within each timeslice that satisfied a target's bioclimatic envelope was assigned a "1" or a "0," accordingly. Those locations from all four timeslices were overlaid using ArcMap and the suitable locations (i.e., those assigned a "1") coinciding across all four timeslices were termed suitable climate space. Suitable climate space is presumed to persist over the defined time frame, thereby providing temporal and climatic

TABLE 1. Maximum and minimum values of selected variables for the study area

	Climate variable				
	Mean annual temperature (MAT, °C)	**Seasonal temperature differential (TD°C)[a]**	**Annual heat moisture index (AHM)[b]**	**Precipitation as snow (PAS, mm)**	**Mean annual precipitation (MAP, mm)[c]**
Maximum	6.9	28.3	51.1	2790	4032
Minimum	–6.7	14.5	1.4	84	288

[a] Continentality MWMT – MCMT, where MWMT is the mean temperature of the warmest month and MCMT is the mean temperature of the coldest month.
[b] (MAT +10)/(MAP)/1000, where MAP equals mean annual precipitation, expressed as a ratio.
[c] Not used in envelope definition.

connectivity. Next, a target's current distribution was overlaid with its suitable climate space and the areas where these two coverages coincided were identified as PCCs, or climate refugia. Locations where conservation targets are currently found and where climate conditions are expected to remain within tolerable limits arguably represent prime areas for conservation, and therefore those conservation targets are more likely to persist than areas outside of identified PCCs.

Addressing general circulation model variability

The results generated by the CGCM3 general circulation model and A2 scenario are one of many possible outcomes of climate simulation assumptions and socio-economic expectations for the coming century. Other general circulation models produce importantly different projections for the climate of British Columbia. To address the variability among different model projections, our methods were repeated using the models and scenarios incorporated in the ClimateBC options, which showed the widest range in conditions compared to those predicted by the CGCM3–A2 combination. The Australian Commonwealth Scientific and Industrial Research Organization (CSIRO) model with the A2 scenario projects even greater changes in temperature and precipitation than the CGCM3–A2 output, whereas the U.S. Department of Energy's Parallel Climate Model (PCM) B1 scenario projects the least amount of change. For simplicity, only those conservation targets that had suitable climate space locations projected by the CGCM3–A2 combination (i.e., stable locations of bioclimatic envelopes from the baseline through to the 2080s) were selected for this analysis. This subset included 30 target plant species, 16 biogeoclimatic variants, and 8 terrestrial ecological units. In particular, the projected proportional change in suitable climate space from the baseline to the 2080s was compared among the three sets of general circulation model projections. A cursory analysis of randomly selected "B scenarios" from these models (in which environmental stewardship effectively mitigates climate change) was also performed to demonstrate model outcomes for the aforementioned terrestrial ecological units and biogeoclimatic variants under even the more optimistic forecasts.

Identifying areas of high conservation value

Protected areas can be difficult to secure, often involving long negotiations with several levels of government, First Nations, industry, local communities, and various stakeholders. Consequently, conservation planners will give priority to areas with multiple socio-ecological values. To identify areas with PCCs for multiple conservation targets, the spatial data of all PCCs were intersected to identify areas to which a higher collective conservation value could be assigned under expected climate change.

Results

Our results revealed a general paucity of climatic continuity for each of the conservation target groups. In total, 12% (23/206) of the conservation targets had persistent climate. This included 10% (10/103) of the biogeoclimatic variants, 20% (6/30) of the terrestrial ecological units, and 10% (7/73) of the Conservation Data Centre-listed plant species (B.C. Ministry of Environment 2007). The areal extents of persistent climate for biogeoclimatic variants and terrestrial ecological units were 19 km^2 and 320 km^2, respectively, and there was a total of 14 species PCCs, all limited to very restricted locations. With a 1-km^2 resolution, these PCCs collectively represent only 0.14% of the 246 000 km^2 Central Interior study area.

British Columbia biogeoclimatic variants

The biogeoclimatic variants (Table 2) are expected to experience a range of projected climatic characteristics in the future, resulting in variant-specific changes to each one's suitable climate space and whether its climate will persist into the future. The proportional change in the area meeting envelope requirements between the historic and the 2080s timeslices ranged from an increase of 3182% (for the Coastal Western Hemlock Dry Submaritime variant) to a decrease of 99.7% (for the Boreal Altai Fescue Undifferentiated and Parkland). This range is a function of the differences between the areal extents of the current distribution and the projected suitable climate space of each biogeoclimatic variant. A high level of percentage representation did not always correlate with a large bioclimatic envelope area for a target. For example, the Engelmann Spruce–Subalpine-fir Wet Very Cold variant (ESSFwv) had the highest projected PCC of 3337 km^2, as well as a proportionate loss (–93.1%) in the area suitable for its bioclimatic envelope (Figure 2a). The PCC of the Coastal Mountain-heather Alpine Undifferentiated and Parkland variant (CMAunp) is projected to represent 38.5% of its current distribution accompanied by a decline (–67.2%) in its bioclimatic envelope area (182 km^2) (Figure 2b).

TABLE 2. Biogeoclimatic variants in the British Columbia Central Interior study area expected to retain suitable climate space through the 2080s, with associated projections for persistent climate corridors (PCCs)

Description of biogeoclimatic variant	Current area (km^2)	Change in envelope area, baseline to 2080 (%)	Suitable climate space (km^2)	Persistent climate corridor (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	1396	182	0.37
Coastal Western Hemlock Central Dry Submaritime (CWHds2)	816	3182.34	352	64	7.84
Coastal Western Hemlock Wet Maritime (CWHwm)	5359	386.09	2702	0	0.00
Engelmann Spruce–Subalpine Fir Moist Warm (ESSFmw)	2664	210.49	357	16	0.60
Engelmann Spruce–Subalpine Fir Wet Very Cold (ESSFwv)	1933	–93.05	3337	1233	63.79
Interior Cedar–Hemlock Nass Moist Cold (ICHmc1)	5343	–13.81	3677	203	3.80
Interior Cedar–Hemlock Very Wet Cold (ICHvc)	1449	–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)	1198	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)	1195	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)	2243	287.35	31	0	0.00
Mountain Hemlock Undifferentiated (MHun)	4579	–64.37	3172	4	0.09
Total	***180338***	***–9.63***	***29368***	***1936***	***1.07***

Terrestrial ecological units

Terrestrial ecological units are projected to experience a relatively uniform reduction in the area suitable for their bioclimatic envelopes from the baseline to the 2080s timeslice (Table 3). As demonstrated by the biogeoclimatic variants, the projected reduction in a terrestrial ecological unit's envelope area did not always correlate with a loss of persistent climate. Alpine and wetland ecosystems are particularly sensitive to climate change and although the projected results vary, a common theme is the potential for drastic ecological changes (Rose 2010). The North Pacific Sub-Boreal Mesic Subalpine Fir–Hybrid Spruce Parkland and North Pacific Interior Wetland Composite units, for example, are projected to experience a reduction in suitable climate relative to their current distribution; further, these units are projected to have no suitable climate space where they are currently located. Alpine ecosystems are also sensitive to a rapidly changing climate as demonstrated by the changes in the bioclimatic envelope area of the

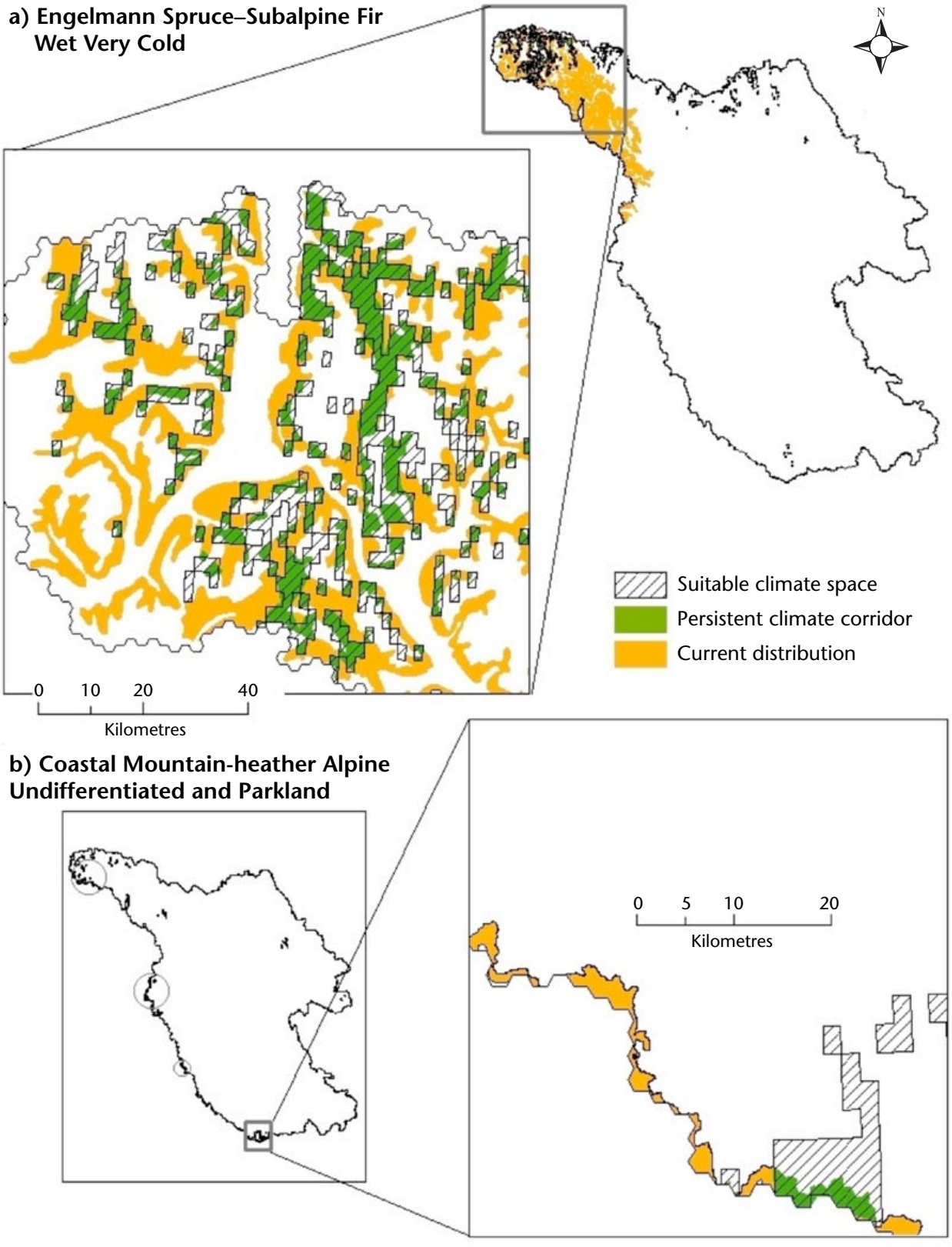

FIGURE 2. Projected locations for climatic characteristics suitable for: (a) the ESSFwv and (b) the CMAunp biogeoclimatic variants through the 2080s.

TABLE 3. Terrestrial ecological units in the British Columbia Central Interior study area expected to retain suitable climate space through the 2080s, with associated projections for persistent climate corridors (PCCs)

	Nature Conservancy of Canada terrestrial ecological unit	Current area (km^2)	Change in envelope area, baseline to 2080 (%)	Suitable climate space (km^2)	Persistent climate corridor (PCC, km^2)	Current area represented by PCC (%)
1	Boreal Alpine Fescue Dwarf Shrubland and Grassland	17748	–95.61	715	549	3.09
2	North Pacific Dry and Mesic Alpine Dwarf-Shrubland, Fell-field and Meadow	3604	–93.23	347	46	1.28
3	North Pacific Interior Lodgepole Pine–Douglas-Fir Woodland and Forest	11866	–33.63	22661	1131	9.53
4	North Pacific Interior Wetland Composite	7558	–98.86	200	0	0.00
5	North Pacific Montane Riparian Woodland and Shrubland	1294	–70.61	19053	133	10.28
6	North Pacific Sub-Boreal Mesic Subalpine Fir–Hybrid Spruce Forest	47680	–94.06	1205	611	1.28
7	North Pacific Sub-Boreal Mesic Subalpine Fir–Hybrid Spruce Parkland	9259	–93.73	3005	0	0.00
8	Northern Rocky Mountain Lower Montane Riparian Woodland and Shrubland	2433	–89.26	4278	91	3.74
	Total	***101442***	***–84.28***	***51464***	***2561***	***2.52***

North Pacific Dry and Mesic Alpine Dwarf-Shrubland, Fell-field and Meadow. The area of climate suitable for this unit was projected to decline by 93.2% from the baseline to the 2080s timeslice, with only 1.3% of its representative climate projected to persist (Figure 3).

British Columbia Conservation Data Centre-listed plant species

The projected responses of plant species listed by the Conservation Data Centre are also highly variable because of numerous factors, most notably low sample sizes. Although the currently suitable climate space is universally greater than current documented ranges, most species are projected to experience a loss of bioclimatic envelope area from the baseline to the 2080s timeslice. This loss most often corresponds to a lack of a PCC (i.e., the locations of a target's bioclimatic envelope change over time) (Table 4). Figure 4 illustrates the suitable climate spaces and PCCs for *Malaxis paludosa* (2/2),[1] *Carex tenera* (2/7), and *Juncus stygius* (1/2).

The locations of a species' suitable climate space in these examples imply that rare species could occupy much of the province; however, factors other than climate are limiting their distribution (see Discussion) and these results are an artifact of bioclimatic envelope modelling (see Introduction). On the other hand, a novel climate may provide the appropriate opportunities for some rare species to flourish and become more widespread (Marris 2010).

Identifying candidate areas for conservation

The overlay of all targets (23/206) with PCCs revealed 19 km^2 and 320 km^2 of biogeoclimatic variants and terrestrial ecological units, respectively, and 14 species'

[1] The fraction in parentheses denotes the number of PCCs per the total number of occurrences.

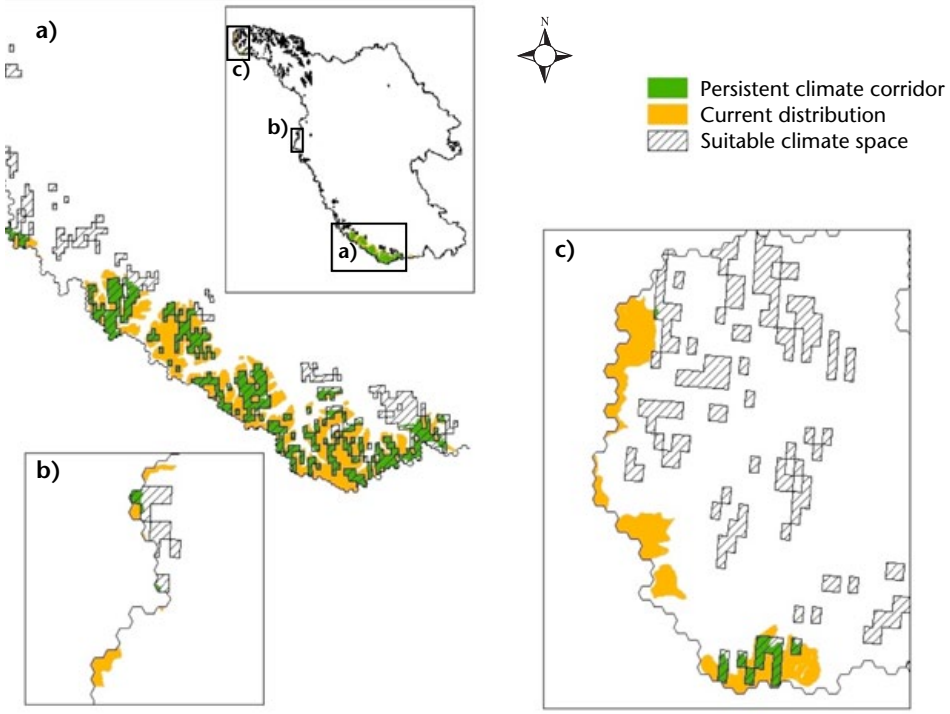

FIGURE 3. The current distribution, expected suitable climate space and persistent climate corridor locations for the North Pacific Dry and Mesic Alpine Dwarf-Shrubland, Fell-field, and Meadow terrestrial ecosystem units through the 2080s.

PCCs. On the premise of preserving climate connectivity or persistence (in the form of climate refugia), the mountainous northwestern corner and scattered locations in the eastern third of the study area should take priority because more than one target has the potential to persist in those locations (Figure 5). Unfortunately, none of the PCCs projected for individual rare plant species coincided with another target's PCC.

Testing a range of assumptions

Our test of assumptions demonstrated variability between two other general circulation models and scenario combinations (CSIRO A2, PCM B1), illustrating the challenges associated with projecting the potential for species and ecosystem response to climate change (Figure 6).

The PCM B1 and the CGCM3 A2 combinations show the least variation when projecting a target's suitable climate space, with slightly more variation exhibited by a target's persistent climate. Interestingly, the percentage of species having a suitable climate space under the CSIRO A2 and the PCM B1 projections are within 10% of each other, whereas with the CGCM3 A2 and CSIRO A2 projections for species' persistent climate are within 5%.

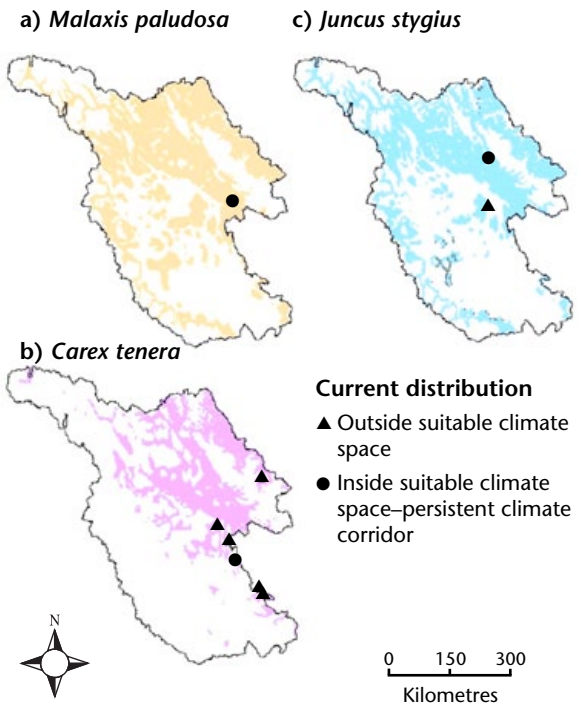

FIGURE 4. Projected suitable climate space (coloured) showing current population locations in (circle) or out (triangle) of this space, for: (a) *Malaxis paludosa*; (b) *Carex tenera*; and (c) *Juncus stygius* in 2080.

TABLE 4. Rare plant species found in the British Columbia Central Interior study area expected to retain suitable climate space through the 2080s, with associated projections for persistent climate corridors (PCCs), assuming B2 scenarios of GCM (z y +z)

British Columbia Conservation Data Centre plant species	No. in study area	Calibration points	Change in envelope area, baseline to 2080 (%)	Suitable climate space (km^2)	Persistent climate corridor (PCC, km^2)	Current area represented by PCC (%)
Allium geyeri var. *tenerum*	1	13	–100.00	11 965	0	0.00
Botrychium simplex	3	34	–1.84	5993	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	6175	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	1751	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	7549	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	1651	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	2973	0	0.00
Salix serissima	1	21	3.68	6196	0	0.00
Saxifraga nelsoniana ssp. *charlottae*	1	15	–36.31	2166	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***

The B, or "stewardship," family of climate change scenarios is thought to represent a future with greener technology and consequently an atmosphere with lower concentrations of carbon dioxide and other greenhouse gases. As such, it is expected that these scenarios would project less variable or extreme changes in climate. The comparative analysis among the B runs (PCM B1; Hadley Centre Coupled Model, ver. 3, HADCM3 B1; and the Max Planck Institute for Meteorology's ECHAM B2,) revealed a relatively positive outcome (i.e., a conservation of suitable climate) in the projection of biogeoclimatic variants (100%) as well as for the Conservancy's terrestrial ecological units (> 80%); however, the projections of PCCs were variable and open to interpretation. Both analyses in our test of assumptions raise several questions and clearly demonstrate the need for a more sophisticated uncertainty analysis.

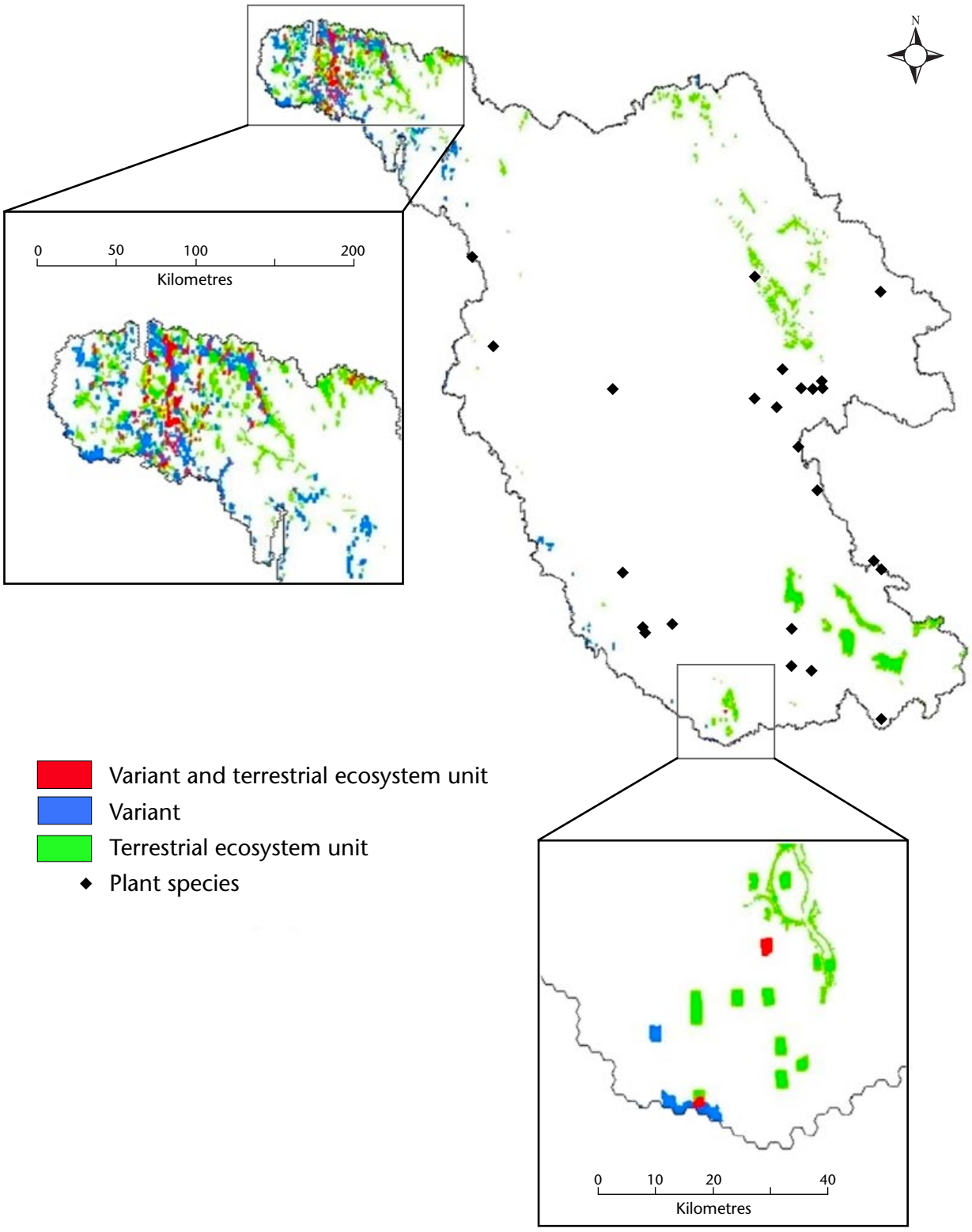

FIGURE 5. Areas of high value represent locations where more than one target's persistent climate corridor exists (red). These areas would be given high priority if climatic connectivity or persistence is considered.

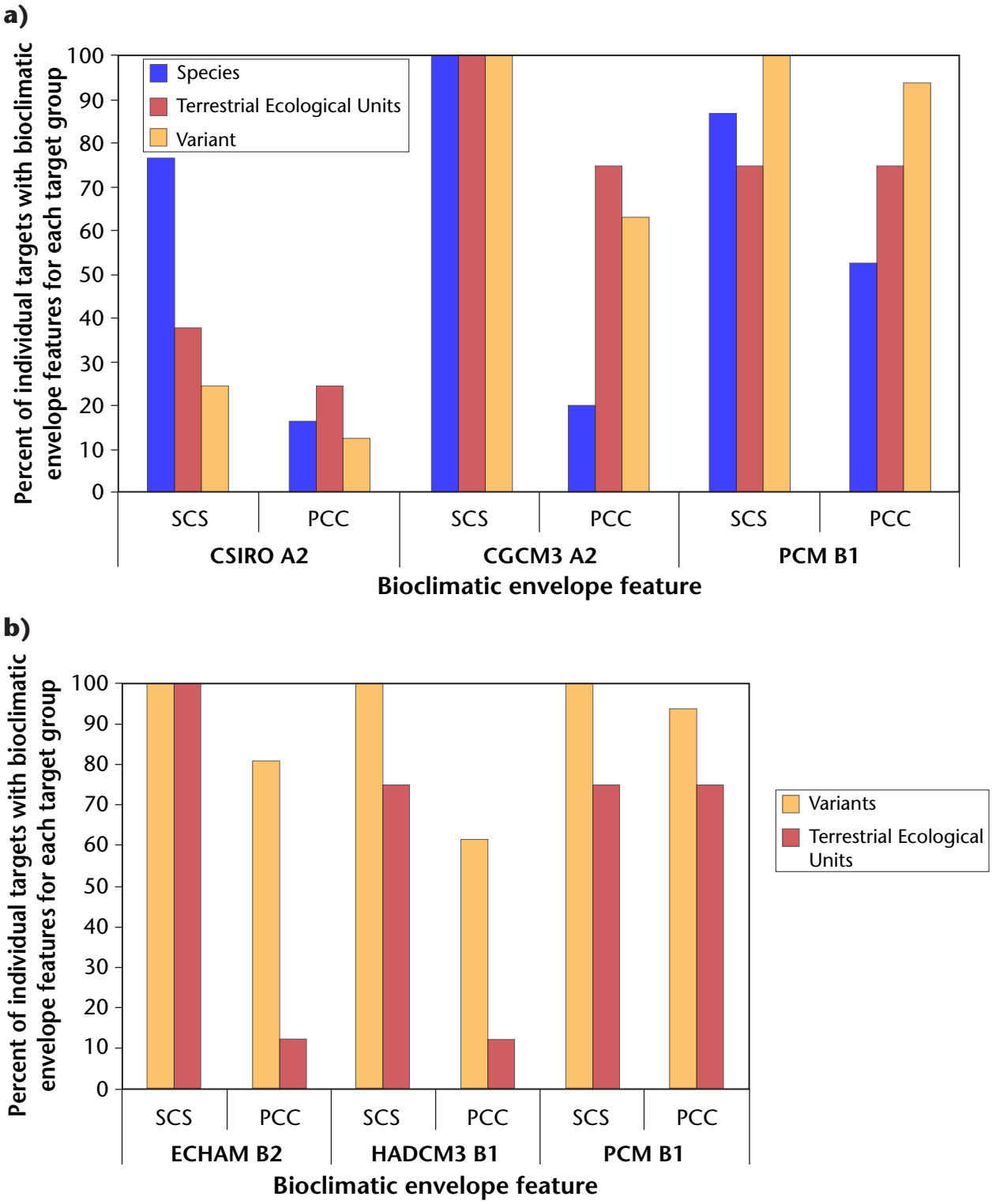

FIGURE 6. Variability in projections stemming from different general circulation models and scenarios as demonstrated by: (a) the models and scenarios with the greatest difference from CGCM3 A2 output (Rose 2010)*; and (b) a set of stewardship or B family scenarios. *The suitable climate space (SCS) projected by the CGCM3 A2 scenario for all three conservation target groups is 100% because the individuals in those groups were used as a subsample to test and compare the projections of the PCM B1 and CSIRO A2 combinations.

TABLE 5. The maximum and minimum values of the selected climate variables as generated for the Central Interior study area by each general circulation model and scenario combination (baseline) used in the two analyses demonstrating variability. Mean annual precipitation (MAP) was included because it tends to be a difficult variable to predict and it is important in the derivation of other variables.

Model/scenario	MAT Max	MAT Min	TD Max	TD Min	AHM Max	AHM Min	PAS Max	PAS Min	MAP Max	MAP Min
CGCM3 A2	10.1	–3.6	25.8	12.4	57	2.1	2708	49	4419	318
PCM B1	8.2	–5.5	26.1	13.5	52.1	1.5	3173	77	4692	309
CSIRO A2	11.2	–2.3	26.6	14.1	58.8	2	2995	43	5510	337
HADCM3 B1	9.6	–4.3	31	17.4	56.1	1.7	3151	79	4851	310
ECHAM B2	8.8	–5	28.5	15.5	54.8	1.7	2877	78	4288	298

To further elucidate the following results and demonstrate the variability among different model and scenario combinations, the maximum and minimum values projected for selected variables are provided in Table 5.

Discussion and management implications

The intended purpose of research on PCCs is to identify target-specific refugia that can be expected to remain robust in the face of climate change. Across geological time, climate refugia fostered speciation; across topographically diverse areas, climate refugia allowed habitats to diverge and form new species associations (Rose 2010). At the regional scale (e.g., the Central Interior), climate refugia have the capability to maintain the unique floristics of species assemblages that differ from those communities adapted to the dominant climate (Noss 2001). A target's suitable climate space also has value for conservation planning as well as for other resource management practices. In particular, the identification of a target's projected suitable climate space is an important component of facilitated or assisted migration. Assisted migration is a proactive strategy designed to mitigate possible extinctions or productivity constraints by translocating species or populations along expected climate gradients to more suitable climates (Millar et al. 2007; Van der Veken et al. 2008). According to the B.C. Ministry of Forests and Range (2006), facilitated migration is potentially one of the more cost-effective and economically feasible management strategies in adapting sustainable forest management to a changing climate.

British Columbia biogeoclimatic variant bioclimatic envelopes

Suitable climate for several biogeoclimatic variants is projected to migrate or remain stable in the northwestern corner of the study area, where the PCCs of the ESSFvc and Interior Cedar–Hemlock Very Wet Cold (ICHvc) variants are found (Figure 5). Possible reasons for their persistence are that they 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 also have the greatest range of mean annual temperature compared to other variants and the ranges for the other three defining variables (i.e., continentality, annual heat moisture index, precipitation as snow). A broader ecological niche (e.g., tolerance to a wide temperature range) may provide bioclimatic flexibility and the ability to persist as the climate changes (Rose 2010).

The projected climatic characteristics of the CMAunp and the Boreal Altai Fescue Alpine Undifferentiated (BAFAun) variants are contrary to other studies, which project contractions of higher-elevation ecosystems (Pearson and Dawson 2003; McKenney et al. 2007a, 2007b). Nevertheless, our result might be explained by a projected increase in precipitation for this area, a distinguishing characteristic of these variants in northern British Columbia (CGCM3; Canadian Centre for Climate Modelling and Analysis 2008) and a climate anomaly in relation to the remainder of the province (Rose 2010).

Projected changes in potential ecosystem distributions are skewed by incomplete environmental information such as soil type and parent material. For example, most alpine ecosystems (i.e., the Coast Mountain Alpine, Interior Mountain Alpine,

and the Boreal Altai Fescue Alpine zones) are characterized by large areas of ice, snow, and rock that are not distinguished from alpine tundra, even though the former substrates cannot support much of the alpine flora. Over geological time, however, the climates and soils of these zones may become more suitable for a greater diversity of species and ecological communities (Rose 2010).

Terrestrial ecological units bioclimatic envelopes

Bioclimatic envelopes for the terrestrial ecological units with projected suitable climate are expected to persist in the southeastern corner and along the eastern edge of the Rocky Mountain Trench (Figure 2). These areas have homogenous landscapes relative to other parts of the Central Interior, suggesting that landscape-level physiognomy may explain this result. For example, the Cariboo-Quesnel Highlands (in the southeast) are characterized by rolling hills and plateaus accompanied by a relatively homogenous climate (e.g., hot, dry summers), which is expressed by large tracts of similar ecosystem types (Rose 2010). The projected area of climate persistence for terrestrial ecological units in the southeastern and eastern portions of the study area is also potentially explained by wildfire. Wildfire in the Central Interior maintains the composition and age structure of *Pinus contorta* (lodgepole pine) ecosystems. These ecosystems rarely reach a climax stage that can be tied to climate and their composition remains determined more by the disturbance regime, which results in a comparatively uniform forest composition (Rose 2010).

Plant species bioclimatic envelopes

The low percentage of rare plant species with PCCs is largely a function of the low number of species occurrence records and the fact that many of the Central Interior occurrences are already on the northern margin of their range. Our chosen method for defining bioclimatic envelopes is further limited because it excludes 10% of species occurrences as unsuitable at the outset, and does not consider a population's ability to adapt, nor does it consider genetic diversity or phenotypic plasticity. However, we chose to define the core using the 5th and 95th percentile 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 (Rose 2010).

The limited degree to which a rare species currently occupies its suitable climate space confirms that factors other than climate are limiting its distribution. Rarity of any given species is a function of anthropogenic and natural factors including the direct loss of populations and habitat to urban and agricultural development (Ledig 1993), the physiological impacts of air and soil pollution (Mosquin 2000; Goward 1994), the introduction of exotic species for horticultural and commercial purposes (Harper et al. 1993), competition, predation, natural disturbance, insects and pathogens (Harding 1994), a naturally discontinuous or sporadic habitat range defined by substrate or seral stage (Schofield 1994), or range restriction by northern latitudes (Harper et al. 1993; Harding and McCullum 1997).

General circulation model variability

Many uncertainties are associated with the use of bioclimatic envelopes and climate modelling to project the future distribution of ecological entities (Rose and Burton 2009). Our comparison of different climate modelling assumptions is a simple demonstration of the variability generated by various general circulation model and scenario combinations. Inherent uncertainty aside, improving this analysis would involve using more examples and comparing within scenario families, namely several "B" (stewardship) responses, several "A" (business-as-usual) responses, as well as between and among different models (e.g., CSIRO A2 vs. CGCM3 A2, etc.).

Key management considerations

The following is a short outline of conservation management direction and associated caveats that follow from our results.

- The projected loss of suitable climate for a number of biogeoclimatic variants and terrestrial ecological units provides a warning of the drastic level of changes that might be expected in ecosystem structure and composition. New ecological communities are likely to emerge and may displace the communities on which many of our management practices are based (Rose 2010).
- Although uncertain, the expected locations of climate refugia under the CGCM3 A2 projections are more likely to be robust in their ability to sustain conservation targets than areas not so identified. Persistent climate corridors should be given a priority in conservation planning.

- Efforts to incorporate dynamic processes into conservation planning are potentially undermined by how ecological units are classified. Despite their basis in reflecting relatively uniform ecology, these ecosystem units ultimately reflect a subjective process, which may have limited flexibility because the units describe the current expression of some ecological attributes (e.g., climax vegetation) under local climatic and geographic parameters (Rose 2010).
- It is important to recognize that time and biogeographic lags exist between climate change and vegetation response. These lags play an important role in landscape heterogeneity (Shafer et al. 2001).
- Effective adaptation to climate change should incorporate risk analysis and management objectives that consider cost-effective and no-regrets actions, and must include monitoring programs that aid in the regular assessment of newly implemented strategies (Spittlehouse 2005; B.C. Ministry of Forests and Range 2006; Millar et al. 2007).
- The challenges of adaptive management require an emphasis on ecological processes, as well as an understanding that no single approach will suit all situations (Millar et al. 2007).

Conclusions

The addition of a climate change perspective into conservation planning is an attempt to recognize and account for the spatial and temporal dynamics of species and ecosystem distribution. As climate change continues to threaten native biodiversity, the need to develop new adaptative management strategies becomes increasingly urgent. The use of PCCs can help planners and ecologists prioritize their conservation targets as they cope with the challenges presented by climate-driven changes to the protection of valued ecosystems and the ecological services they provide (Rose and Burton 2009).

The use of persistent climate corridors can help planners and ecologists prioritize their conservation targets as they cope with the challenges presented by climate-driven changes to the protection of valued ecosystems and the ecological services they provide.

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Test Your Knowledge . . .

Persistent climate corridors: The identification of climate refugia in British Columbia's Central Interior for the selection of candidate areas for conservation

How well can you recall some of the main messages in the preceding Research Report? Test your knowledge by answering the following questions. Answers are at the bottom of the page.

1. What does the acronym PCC represent?
   A) Persistent climate corridor
   B) Positive climate correlation
   C) Partial climate connectivity

2. What does a PCC represent for any given target?
   A) Extinction
   B) Climate refugia
   C) Complete loss of suitable climate

3. According to this article, areas of conservation value:
   A) Are likely to remain high for the foreseeable future
   B) Can be determined by general circulation models
   C) Can be modelled for persistence in a changing climate

ANSWERS

1. A 2. B 3. C