Development of a Climate Change Index of Stress Using Future Projected BEC: Proof of Concept for the Nadina TSA

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February 2013

Abstract

As the climate changes, some species within existing plant communities will become maladapted to local conditions. Immigration of climatically-suited species is unlikely to keep pace. This study investigated methods of using 1) community similarity between current and projected future plant communities as an indicator of ecosystem stress due to climate change, and 2) geographic distance to climatically-suited species as an indicator of potential recovery. We analysed potential shifts in plant communities under three climate-change scenarios in the Nadina Forest District in Central BC, focusing on the SBSdk, SBSmc2 and ESSFmc biogeoclimatic variants.

Patterns arising from analyses of community similarity, changes in species pools and geographic distance corresponded: a Slightly Warmer scenario (<2°C increase in temperature) likely poses low stress to all variants; a Warmer and Wetter scenario (+2.6°C) may pose higher stress to the drier SBSdk than to SBSmc2 and ESSFmc variants; a Much Warmer scenario (+3.5°C) likely poses high stress to all variants, with low potential for recovery. Geographic distance between variants was correlated with community similarity. At the site scale, analysis suggested that the wettest and driest ecosystems may experience highest stress. Challenges to analysis included a necessity to consider multiple scales, data uncertainty, difficulty in interpreting geographic distance, and limitations of climate projections (e.g. lack of consideration of extreme events). We do not suggest that climate projections can predict future ecosystems, but we suggest that analysis can estimate relative stress to ecosystems.

The pilot study points to the most fruitful avenues to explore for analyses expanded to consider the entire province, including communication of potential ecosystem stress by drawing trajectories on ordinations of similarity, estimating stress related to a broader suite of scenarios, investigating the relationship between geographic distance and community similarity and investigating the relationship between similarity and soil moisture regime.

1 Introduction

As the climate changes, some species within existing plant communities will become maladapted to local conditions (Johnson et al. 2010). Emerging climatic conditions may exceed environmental tolerances and change competitive advantages, leading to extirpation, or reduced abundance and range. Declining biodiversity can affect ecosystem function, resilience and susceptibility to weeds and pests (Hooper et al. 2012, Reich et al 2012, Peterson et al. 1998). Immigration of climatically-suited species could lead to recovery, but is not expected to keep pace with climate change (Aitken et al. 2008, McLachlan et al. 2005), thus future plant communities may remain depauperate for some time in comparison to present-day analogs. Hence, the difference between current and projected future plant communities could be a useful indicator of ecosystem sensitivity to climate change, at least during the period of adaptation. This report describes a pilot study designed to test methods of comparing plant communities across different climate-change scenarios.

As a conceptual basis, we assume that current plant communities are well matched to the current climate and that community/climate mismatches indicate stress to an ecosystem and concomitant decrease in function. Specifically, we assume that the level of stress is related to the dissimilarity between current and projected future plant communities (depth of the trough in Figure 1). Less extreme climate change means that the trough will be shallower. The width of the trough represents recovery, which we assume depends on the availability of climate-adapted species. If suitable species exist nearby, successful community restructuring is more likely. Conversely, increased immigration time may result in dominance by generalist weedy species, lower diversity and lower resilience (Chapin III et al. 2000, Fischer et al. 2006). Ecosystem stress will remain high, and the probability of maintaining ecological function in this situation, even given climate stabilisation, will likely be lower on average and more variable (dotted line on Figure 1). If future climates are less predictable (Table 3.2 in IPCC 2007; Hansen et al. 2012), cumulative effects may lead to even wider fluctuations.

In this paper, we use percent community similarity to represent ecological distance between current and potential future ecosystems, and hence ecological stress, and geographic distance to potential immigrant species pools to represent recovery. We emphasise that we are not concerned with predicting future communities, but with using projected future communities as indicators of ecological stress.

Because community similarity may not be symmetrical, we also look at the number of “stressed” species (those potentially extirpated from the current pool) and “recovery” species (those present in the projected future, but not current, species pool; Figure 2). In Scenario A, many current species are not found in the future species pool and thus face extirpation stress. Conversely, most of the future species occur in the current community; thus it is theoretically possible to create a future community that is known to function in current analog climates, without immigration. Hence Scenario A creates high-stress and easy recovery. In Scenario B, representing low-stress and difficult recovery, the current plant community faces minor climate stress and may retain its composition. However, this community may not function well in the future climate because many species associated with predicted functioning ecosystems of the future climate are absent. In this case, recovery of ecological function likely depends on immigration. The final two scenarios in Figure 2, where both current and future species pools have unique and shared species, are likely most common. High overlap of species pools (scenario D) represents lower stress and quicker recovery.

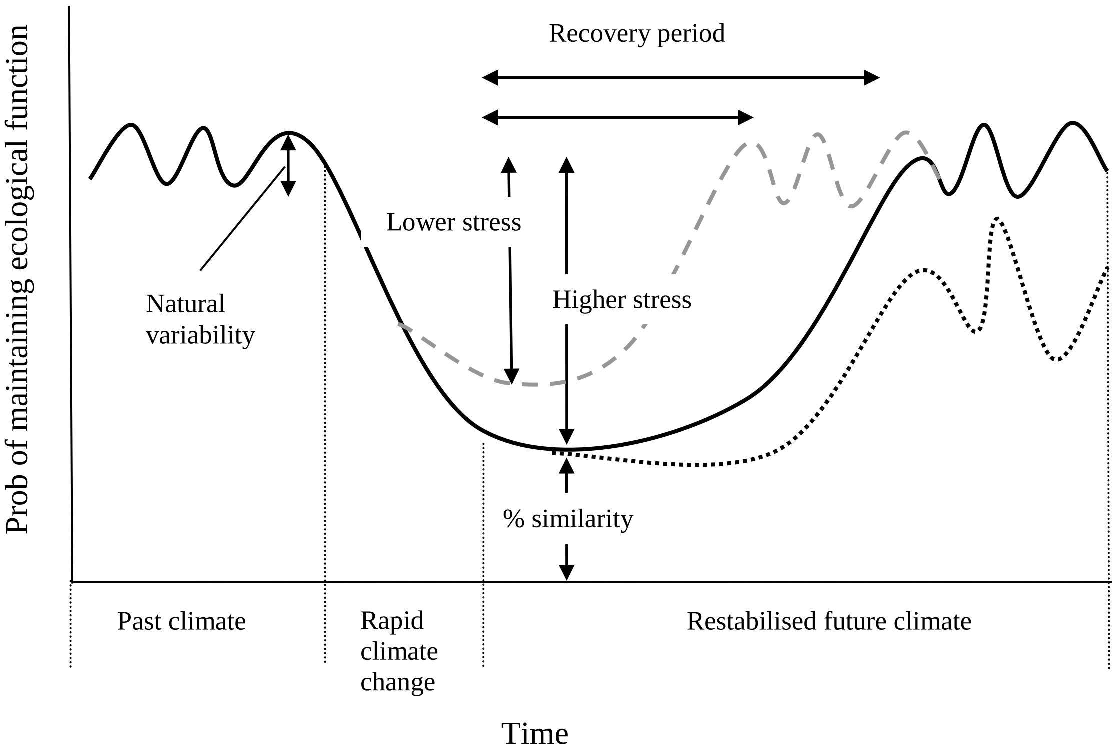


Figure 1. Change in probability of maintaining ecological function over a period of rapid climate change. The depth of the trough, indicating stress, is a function of ecological distance, indicated by community similarity. The breadth, indicating recovery, depends on the geographic distance to climatically-suited species as well as trough depth. The dashed line represents a less extreme climate change scenario. The dotted line shows a less resilient ecosystem (perhaps with invasive species) or an ecosystem with geographically distant future species without full recovery and increased variability.

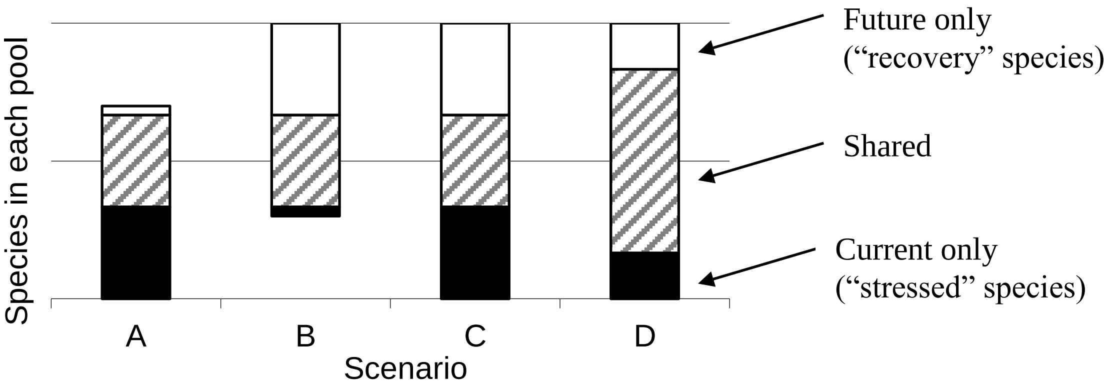


Figure 2. Hypothetical overlap between current and projected future species pools. Scenario A represents a high-stress/easy-recovery scenario; scenario B shows low-stress/difficult recovery; for symmetrical scenarios, C shows high stress and D represents low stress.

Because less dramatic changes in species abundance may also indicate ecological stress, particularly for long-lived and/or structural species such as trees, we examine changes in species abundance as well as species presence/absence. We investigate plant communities at three scales: forest district, biogeoclimatic variant and sites within variants.

2 Methods

2.1 Study Area

We analysed potential shifts in plant community in the Nadina Forest District in Central BC (Figure 3). We used the most common currently-occurring biogeoclimatic variants to define the study area. In the Nadina, three variants—SBSdk (dry, cool sub-boreal spruce), SBSmc2 (moist, cold sub-boreal spruce), and ESSFmc (moist, cold Engelmann spruce subalpine fir)—cover most of the total area. We defined a Nadina core area to include these three variants as well as portions of other variants that fell inside the contiguous unit (ESSFmcp, BAFAun, ESSFmv3, and ESSFmv1).

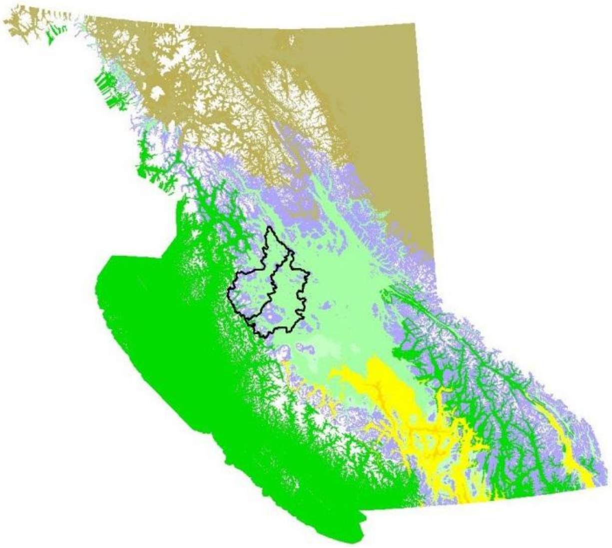


Figure 3. Nadina Forest District study area. Colours represent current biogeoclimatic zone classification.

2.2 Climate Projections

Tongli Wang, UBC Faculty of Forestry, provided climate envelope projections for the study area (Wang 2010), based on methodology described in Hamann and Wang 2006 and Wang et al. 2012. He used three climate projections recommended for BC spanning a range of temperature and precipitation shifts (Table 1, Figure 4). He “downscaled” global projections to describe regional variation in climate better and then used the random forest model to project BEC-based climate envelopes for the 2020s, 2050s and 2080s. We selected the 2050s (actually 2040 – 2070) as a meaningful time horizon for resource management and within the human lifespan, but sufficiently far in the future to represent a real shift. Current biogeoclimatic distributions date from 1990; hence the time span used in our comparisons is 50 – 80 years.

Table 1. Selected climate projections

Projection name	*Model and scenario*	*Relative change in mean annual temperature**	*Relative change in mean annual precipitation*
Slightly Warmer	Hadley Centre Circulation Model version 3 (HadCM3; U.K.) http://www.metoffice.gov.uk/climatechange/science/hadleycentre/; high emission scenario (A2); model run 1.	+1.7°C	+1%
Warmer and Wetter	Coupled Global Climate Model, 3rd generation (CGCM3; Canada). http://www.ec.gc.ca/ccmac-cccma/; high emission scenario (A2); model run 4.	+2.6°C	+13%
Much Warmer	Hadley Centre Global Environmental Model (HadGEM1; U.K.) Builds on HadCM3; intermediate emission scenario (A1B); model run 1.	+3.5°C	-1%

* Mean annual change for projected period (2040-2069) relative to baseline period (1961-1990); Pacific Climate Impacts Consortium Regional Analysis Tool (http://pacificclimate.org/tools-and-data/regional-analysis-tool).

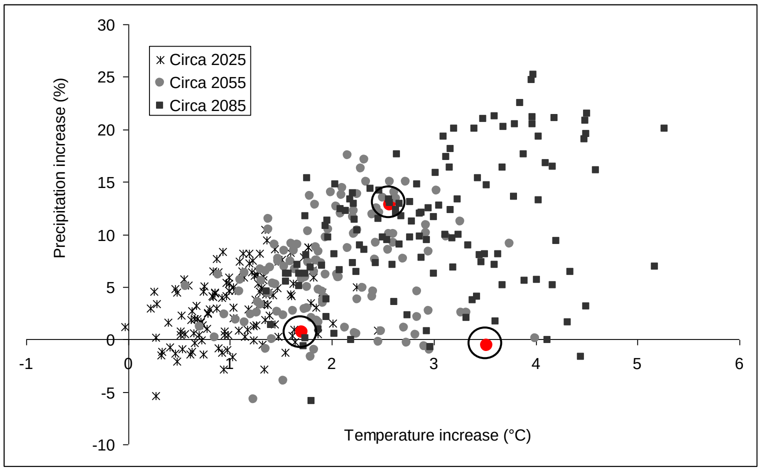


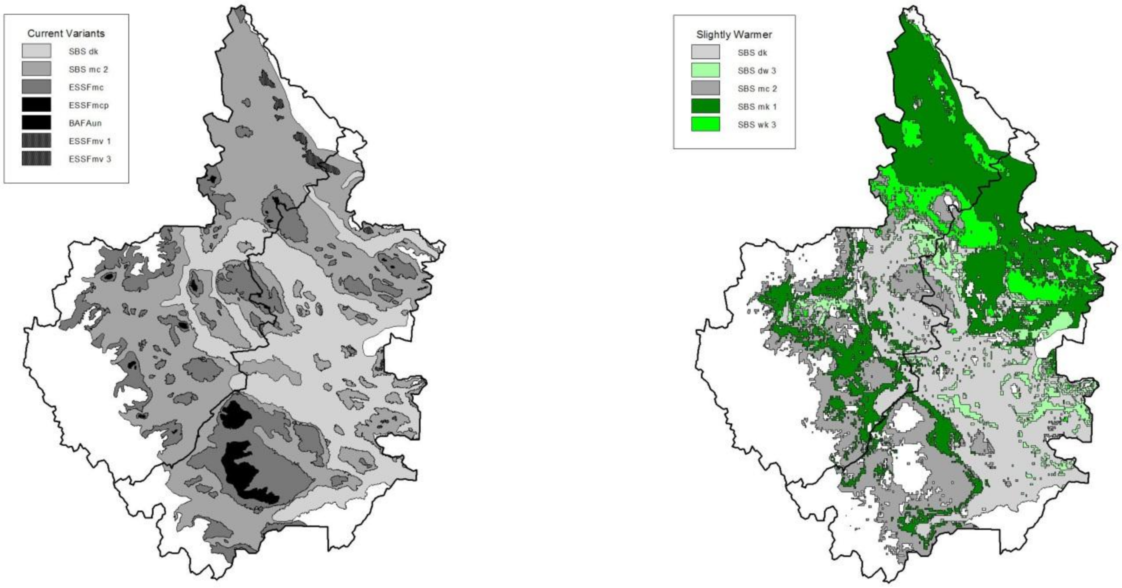
Figure 4. Projected increase in mean annual temperature and precipitation for a range of different climate models and emissions scenarios (A1, A2 and B1 scenarios). Data come from Pacific Climate Impacts Consortium Regional Analysis Tool for the approximate location of the Nadina Forest District. Circled larger symbols show the three projections used in analyses.

2.3 Projected Ecosystems

Each translated climate model provides the variants associated with the projected climate for the area (Figure 5). We compared current and projected ecosystems at three spatial scales: in the complete Nadina core area, in each of the three common variants (SBSdk, SBSmc2, ESSFmc), and in sites within each variant.

Current Climate

Slightly Warmer



Warmer and Wetter

Much Warmer

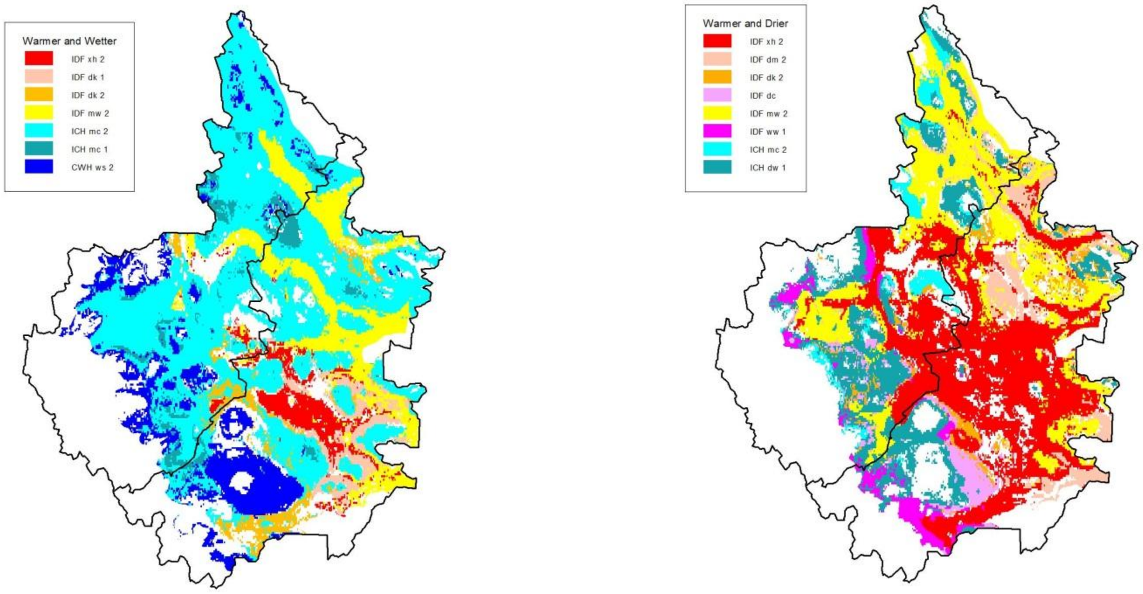


Figure 5. Current BEC variants that dominate the Nadina Forest District (core area) and projected climate envelopes for three climate change scenarios circa 2055 (downscaled data provided by Tongli Wang). Projected variants that cover < 3% of the core area are not shown. Grey = current communities; green = projected SBS communities; blue = wetter communities (ICH, CWS); yellow-red = drier communities (IDF).

2.3.1 Nadina Core Area Scale

After inspecting maps and data, at the broadest scale, we selected projected variants within the Nadina core that each accounted for more than 3% of the area (Table 2). Small fragments may be slivers of larger variants, beyond the border, or projection errors. At this scale, we analysed the complete species pool present in the core.

Table 2. Current and projected variants (covering > 3% of the area) for three climate scenarios at the broadest scale (Nadina core area).

Scenario	*Variant*	*Area (x10^3 ha)*	*Proportion*
Current	SBSmc2	1,222	0.50
	SBSdk	665	0.27
	ESSFmc	476	0.20
Slightly Warmer	SBSmk1	720	0.30
	SBSdk	681	0.28
	SBSmc2	443	0.18
	SBSwk3	187	0.08
	SBSdw3	147	0.06
Warmer and Wetter	ICHmc2	1,146	0.47
	IDFmw2	294	0.12
	CWHws2	291	0.12
	IDFxh2	108	0.04
	IDFdk1	102	0.04
	IChmc1	99	0.04
	IDFdk2	94	0.04
Much Warmer	IDFxh2	701	0.29
	IDFmw2	278	0.20
	ICHdw1	343	0.14
	IDFdm2	157	0.06
	IDFww1	85	0.03
	ICHmc2	82	0.03
	IDFdc	77	0.03
	IDFdk2	68	0.03

When variants are summed across the core area, the Slightly Warmer scenario is projected to be suitable for SBS, the Warmer and Wetter scenario is projected mostly to be suitable for wetter zones (ICH and CWS), with about a quarter suitable for drier IDF, and the Much Warmer scenario is projected to be mostly suitable for drier IDF with some ICH (Figure 6).

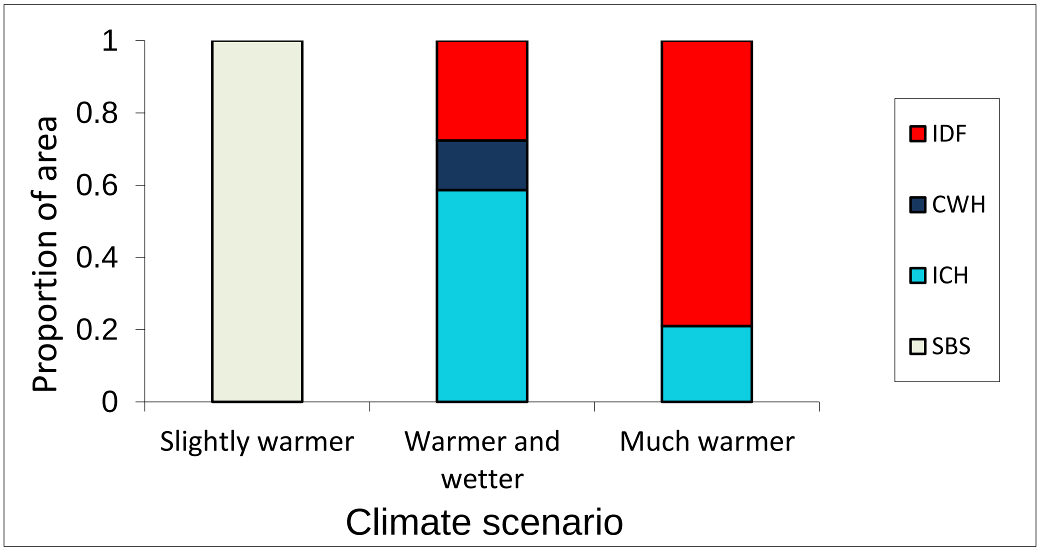


Figure 6. Projected zones for three climate scenarios over the Nadina core area.

2.3.2 Variant Scale

Most analyses focused on this scale. At this intermediate scale, we examined projected changes to the communities of each focal variant. We ranked projected variants by percent overlap with each current Nadina variant and selected the set of variants projected to cover at least two-thirds of a current variant (for all except the ESSF Much Warmer projection which had many projected variants covering a small area; Table 3). This cut-off limited the number of comparisons and focused effort on the most likely shifts.

Table 3. Projected variants for three climate scenarios at the variant scale.

	SBSdk			***SBSmc2***			***ESSFmc***		
Scenario	*Variant*	*Area (x10^{3} ha)*	*Prop'n*	*Variant*	*Area (x10^{3} ha)*	*Prop'n*	*Variant*	*Area (x10^{3} ha)*	*Prop'n*
Slightly Warmer	SBSdk	389	0.58	SBSmk1	547	0.45	SBSmc2	256	0.54
	SBSmk1	133	0.20	SBSdk	271	0.22	SBSwk3	62	0.13
Warmer and Wetter	IDFmw2	226	0.34	ICHmc2	845	0.69	CWHws2	191	0.40
	ICHmc2	169	0.25				ICHmc2	122	0.26
	IDFxh2	102	0.15						
Much Warmer	IDFxh2	446	0.67	IDFmw2	405	0.33	ICHdw1	116	0.24
				IDFxh2	234	0.19	IDFdc	61	0.13
				ICHdw1	208	0.17	ICHmc2	47	0.10
							IDFdk2	40	0.08

2.3.3 Site Scale

At the smallest scale, we examined ecosystems with different relative soil moisture regimes (SMR) within each focal variant. Biogeoclimatic variants are broad and include a variety of plant communities. Within climatically-driven variants, different site series represent different soil moisture and nutrient regimes driven in part by topography. We assume that relative soil moisture will not change topographic position under climate change; for example, receiving sites and steep slopes should remain so. Hence, in our analyses, we assumed that relative soil moisture class would remain the same rather than analysing absolute moisture. Within a variant, we considered assessing potential stress to communities classed by biogeoclimatic site series (drier, mesic, wetter) as well as by SMR. However, the uncertainty associated with estimating the transition among site series seemed too high to warrant further analysis. In addition, data classified by site series were less useful because they only included mature forest plots and hence did not include seral species.

2.4 Statistical Methods

We used "BECMaster" databases provided by Will MacKenzie (MFLNRO, Smithers) for all analyses. At all scales, we analysed species pools between current and projected future communities. We limited analysis to plants identified to the species level, and combined interior Picea species and hybrids (excluding black spruce) into a single unit. We looked at entire communities and at patterns within already-defined lifeforms (e.g. coniferous trees, deciduous shrubs, grasses). Some analyses focus on trees and shrubs as these lifeforms are long-lived, potentially important structural species, often with relatively low dispersal potential (Aitken et al. 2008, McLachlan et al. 2005).

2.4.1 Changes in Species Pools

We analysed changes to species pools using presence/absence data at the Nadina core and variant scales. We identified each species as either present in both ecosystems (“shared” species), present in the current and absent from the projected (“stressed” species potentially facing extirpation) or absent from the current and present in the projected ecosystems (“recovery” species). At the variant scale, we also looked at patterns within lifeforms.

Because of high variation in the number of species, we calculated the proportion of stressed species with current species pool as the denominator, and proportion of recovery species with projected species pool as the denominator. Where the area occupied by one current variant is projected to be suitable for several variants in the future, we used area-weighted means. We defined stress classes: 0 – 20% stressed or recovery species = low stress; 20 – 40% = moderate stress; 40 – 60% = high stress; > 60% = very high stress.

2.4.2 Community Similarity

We analysed community similarity at variant and site scales. We used Bray-Curtis similarity to define the symmetrical resemblance between the community compositions of every pair of samples (where samples are variants or soil moisture regimes depending upon scale). The Bray-Curtis coefficient is widely used in ecology because it satisfies several desirable criteria: value = 100 when two samples are identical; value = 0 when two samples are mutually exclusive; value is unchanged by species that are jointly absent; inclusion of a third sample does not impact value (Clarke and Warwick 2001). Similarity scores use the total pool of species in both current and projected ecosystems as the denominator.

Similarity indices based on abundance data can be dominated by a small number of very abundant species; hence transformation of abundance data is desirable. We used prominence scores as abundance metrics. These scores combine measures of plant cover and frequency of occurrence (Banner et al. 1993). They essentially transform abundance data to reduce the weight of common species, rendering further transformation unnecessary. We also analysed community similarity based on presence/absence data (a more extreme transformation that weights rare species equally to common species). Bray-Curtis similarity calculated on presence/absence data is equivalent to the Sorensen metric.

We represented community similarity graphically with two ordination techniques: non-metric multi-dimensional scaling (NMDS) and classical principal components analysis (PCA). NMDS is an ordination technique that plots samples such that the relative distances apart are in the same rank order as the relative dissimilarities of the samples. Hence, points that are close together are similar in community composition; points that are distant are dissimilar. If the technique has difficulty placing points appropriately on 2-d space, the statistical “stress” value is high, and plots are unreliable. We considered stress values under 0.15 as reliable. We used PCA to chart the contribution of each species to an ordination. We used PRIMER v6 (PRIMER-E 2006) software to calculate both ordinations.

We used hierarchical agglomerative clustering to group samples by similarity class. We considered similarity of > 60% as low stress, 40 – 60% as moderate stress and < 40% as high stress. We selected 50% similarity contours to represent a moderately high level of similarity on ordination graphs. We chose this level after investigating the similarity among communities in different soil moisture regimes (SMR) within variants. Within a variant, adjacent mesic SMR classes have a similarity of 60 – 70%. These communities can be considered as ecologically “very similar”. We selected 50% as representing most (i.e. 70% of 70%) of the similarity present between adjacent SMR classes. These 50% contour lines plotted on the NMDS ordination graphs show relative scale, helping interpretation on the non-metric graphs.

Finally, at the variant scale, we identified which species are most responsible for patterns of community dissimilarity using the SIMPER routine in PRIMER. This analysis decomposes average Bray-Curtis dissimilarities between all pairs of samples into percentage contributions from each species.

2.4.3 Geographical distance

We measured potential migration distance for recovery species very coarsely as straight-line distance, with no consideration of geographical barriers. We created 100-km buffers around the Nadina core area and created a list of variants within each distance class based on the closest point to the Nadina (Figure 7). We defined variants within the Nadina District but outside the Nadina core area as “in Nadina”. We then identified the shortest distance class for each recovery species (species typically occur in several variants). We also looked at the distance that stressed species within the Nadina would have to travel to reach areas projected to have more hospitable climates.

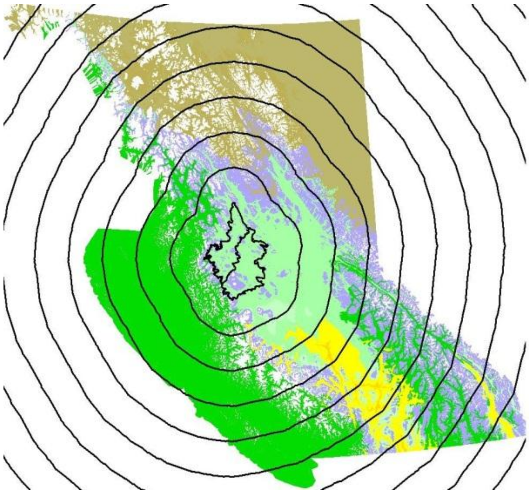


Figure 7. 100-km distance bands measured from the Nadina core area over current biogeoclimatic zones.

As an independent data source, we used the eFlora database to locate individual records for a small group of plant species and measured the distance from the nearest record to the centre of the Nadina core.

3 Results

3.1 Changes in Species Pools

3.1.1 Nadina Core Area Scale

Over 1,000 species are listed in the current core Nadina database. In the Slightly Warmer scenario, the great majority of these species (nearly 90%) are shared between the current and projected variants. However, in both the Warmer and Wetter and Much Warmer scenarios, fewer than 50% of species are shared, with about a fifth subject to extirpation stress and nearly half of projected "recovery" species absent from the current species pool (Figure 8). Hence, in the Slightly Warmer scenario, at this scale, stress is very low, and recovery easy; in the more extreme scenarios, current stress remains low (about 20% of species projected to be stressed), but recovery may be difficult.

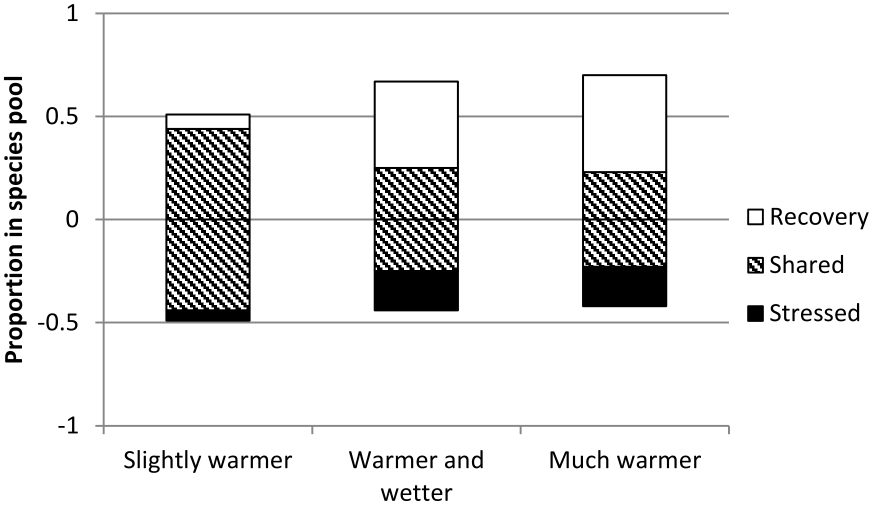


Figure 8. Proportion of species shared between species pools, stressed (i.e. present in current variants; absent from projected variants) or recovery (i.e. absent from current variants; present in projected variants) in the Nadina core for each climate projection. Proportions do not sum to 1 because denominators differ.

3.1.2 Variant Scale

Analysis at the variant scale increases resolution and reveals more patterns. For example, the proportion of shared species in the SBSdk drops drastically from the Slightly Warmer to Warmer and Wetter scenarios, while the proportion of shared species in the SBSmc2 is similar (Figure 9). The pattern is intermediate in the ESSFmc. In the Slightly Warmer scenario, the SBSdk faces the least stress and easiest recovery. In 2055, a large proportion of this area is projected to remain appropriate to support a SBSdk community; hence no species are projected to be stressed (although the area of SBSdk will be reduced and hence loss could occur due to species-area relationships; Thomas et al. 2004, He and Hubbell, 2011). The remaining SBSdk area is projected to be suitable for the SBSmk1. Only 8% of species in the SBSmk1 are not in the SBSdk; hence very little immigration would be necessary to achieve a known functioning ecosystem. The more severe scenarios, however, pose much higher stress to the SBSdk. A large proportion of species would need to immigrate in both scenarios, and more than half of the current species are projected to be stressed.

The Slightly Warmer scenario poses moderate stress and moderately difficult recovery to the ecosystems of the SBSmc2 and ESSFmc. The Warmer and Wetter scenario poses moderate stress to the SBSmc2 and high stress to the ESSFmc with more than half of the species stressed. The Much Warmer scenario brings high stress and a difficult recovery everywhere, with current variants missing a high proportion of recovery species, those present in variants consistent with the warmer, drier climate.

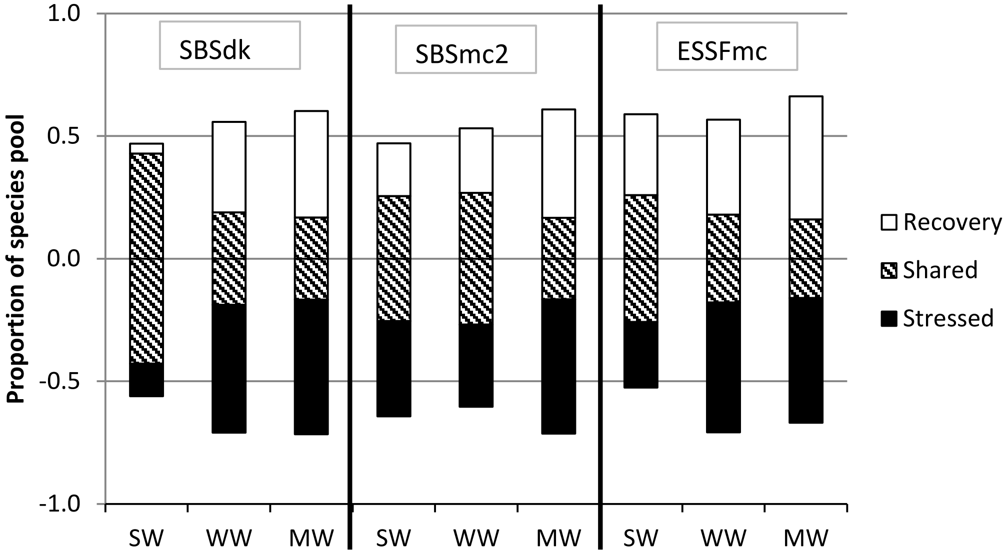


Figure 9. Proportion of stressed, shared and recovery species for each current variant and climate projection (SW = Slightly Warmer; WW = Warmer and Wetter; MW = Much Warmer). Proportions are based on weighted mean similarities from each pair of current and projected future variants. They do not sum to 1 as they are based on different denominators.

Changes in the proportions of particular lifeforms can indicate the types of stress an ecosystem might undergo. Figure 10 illustrates potential lifeform shifts within the current SBSdk ecosystems under the Much Warmer scenario. In addition to a low proportion of shared species, there are large shifts within lifeforms. For example, this transition could involve a loss of 70 – 80% of liverwort and dwarf shrub species, with no replacement by other species. Most evergreen shrub species are unique to one or the other ecosystem (note the low proportion shared), and a complete variant shift would mean a loss of 4 of 6 species and a concurrent gain (assuming successful migration) of three different species. Such shifts in lifeform could possibly be used to infer broader ecological shifts assuming that other organisms depend on particular lifeforms (e.g. foundation species).

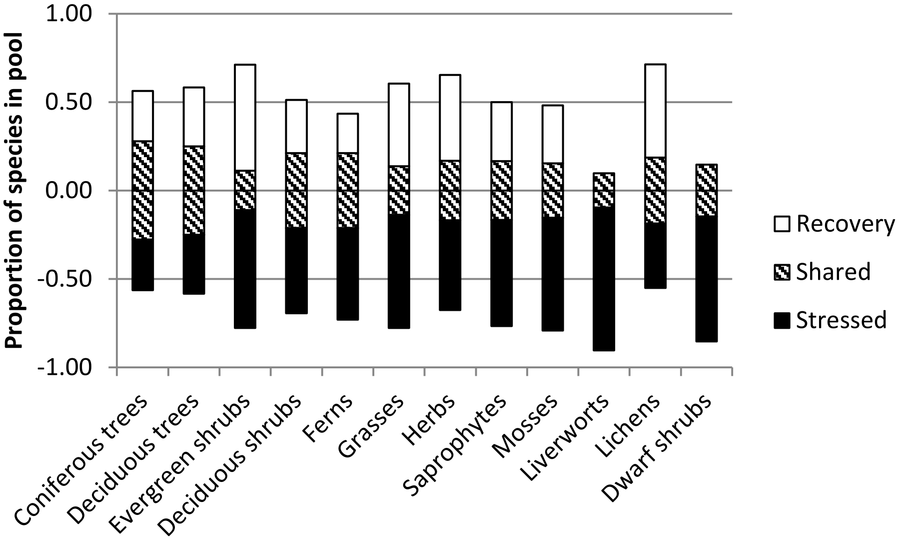


Figure 10. Proportion of recovery, shared and stressed species within lifeforms in current SBSdk under the Much Warmer climate scenario.

Lists of species present in each variant are useful for identifying changes in important species and for picking out patterns within those lifeforms with relatively few species. However, complete species lists are unwieldy due to length. We looked at changes in common species as changes in these species may reflect relatively higher stress, and because data for these species are likely more reliable. At the variant scale of analysis, only 12 "common" species (with prominence scores > 1 in at least one site series within a variant) are projected to be stressed or missing from current variants (Table 4). Of these species, three coniferous trees stand out: *Abies amabilis* is at risk from two scenarios in the SBSmc2, while *Thuja plicata* and *Pseudotsuga menziesii* are missing from at least two current Nadina variants.

Table 4. Common species (prominence > 1) present in current variant and not in projected variant (Stressed Species) and absent from current variant database, but present in projected variant (Recovery Species) for each current variant and climate scenario.

Variant	*Scenario*	*Common Stressed Species*	*Common Recovery Species*
SBSdk	Slightly Warmer	--	*Valeriana sitchensis*
	Warmer and Wetter	--	*Abies amabilis* *Thuja plicata* *Vaccinium alaskaense* *Pseudoregneria spicata* *Valeriana sitchensis*
	Much Warmer	*Tsuga heterophylla* *Oplopanax horridus* *Vaccinium ovalifolium* *Rubus pedatus*	*Thuja plicata* *Pseudoregneria spicata*
SBSmc2	Slightly Warmer and Wetter	*Abies amabilis*	*Pseudotsuga menziesii*
	Warmer and Wetter	--	*Pseudotsuga menziesii* *Thuja plicata* *Vaccinium alaskaense*
	Much Warmer	*Abies amabilis* *Valeriana sitchensis*	*Pseudotsuga menziesii* *Thuja plicata* *Pseudoregneria spicata*

Variant	*Scenario*	*Common Stressed Species*	*Common Recovery Species*
ESSFmc	Slightly Warmer and Wetter	*Vaccinium alaskaense*	*Pseudotsuga menziesii* *Betula papyrifera* *Acer glabrum*
	Warmer and Wetter	--	*Thuja plicata* *Pseudotsuga menziesii* *Betula papyrifera* *Acer glabrum*
	Much Warmer	--	*Thuja plicata* *Pseudoregneria spicata* *Pseudotsuga menziesii* *Betula papyrifera* *Acer glabrum*

3.2 Community Similarity

3.2.1 Variant Scale

Because the proportions of stressed and recovery species are fairly symmetrical with lifeforms combined (Figure 9), examining changes in similarity likely captures most patterns at this scale and simplifies comparisons. For example, plotting [1 – community similarity] against the change in temperature for each scenario gives a picture of relative long-term stress, highlighting the steep increase in stress in the SBSdk moving from the Slightly Warmer to Warmer and Wetter scenario versus the slight decrease in stress for the same scenarios in the wetter SBSmc2 (Figure 11).

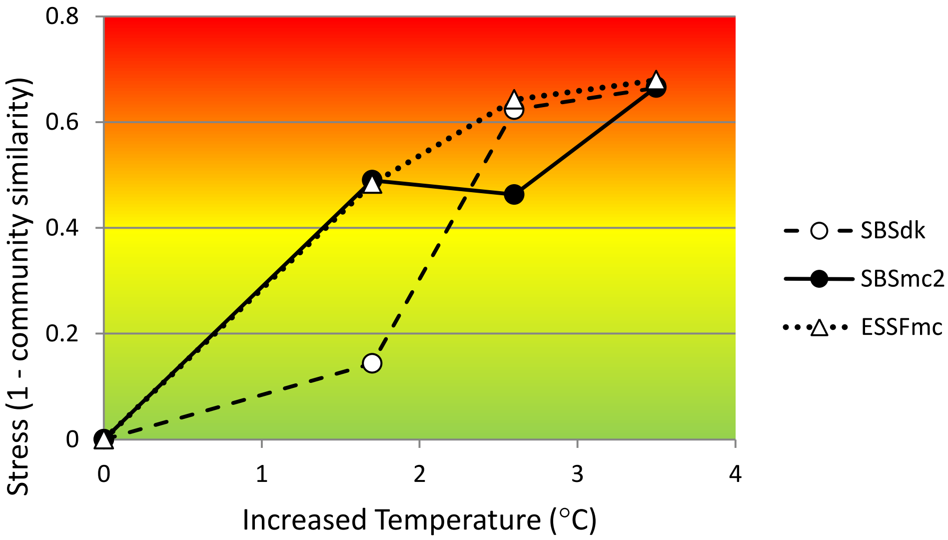


Figure 11. Potential stress associated with three climate scenarios against the temperature increase in each scenario. Background colour represents stress (green = low; yellow = moderate; red = high).

With the current data, Figure 11 confounds temperature and moisture: the middle scenario is wetter than the other scenarios. Increased data points would be useful to tease apart the effects.

Ordination enables easy visualisation of community similarity. Of all current and projected variants analysed at the variant scale, the variants currently making up most of the Nadina district, the SBSdk, SBSmc2 and ESSFmc, cluster together, with more than 60% similarity in community composition (Figure 12). The ICHmc2 lies within the same cluster; hence a shift to ICHmc2 would represent low stress. All SBS variants have a similarity of at least 50%. Similarly, all IDF variants lie within a 50% contour, but outside the SBS cluster. The two ICH variants analysed fall within different clusters and the CWHws is dissimilar to all other variants analysed. Although axis labels are inappropriate on NMDS plots, variants are generally drier and warmer on the left and wetter on the right (Figure 12). Plots based on species presence/absence are almost identical to those based on prominence values and not presented.

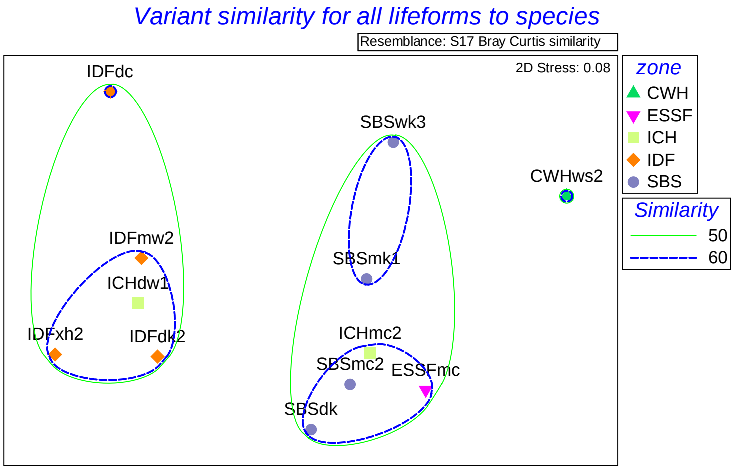
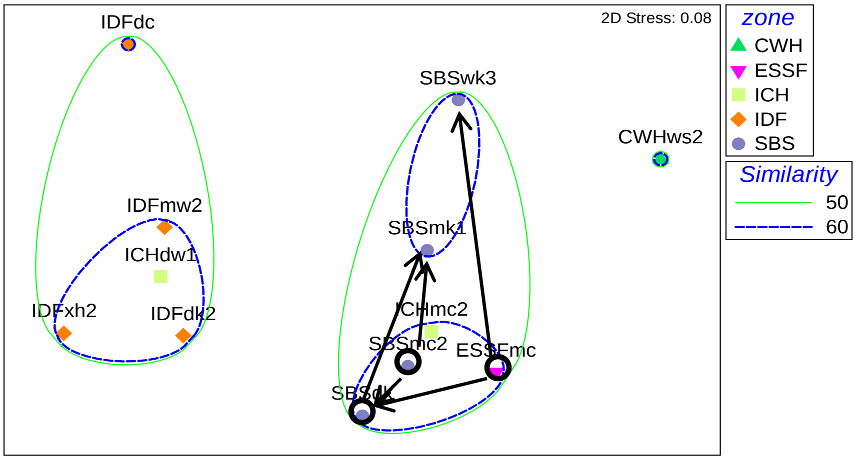


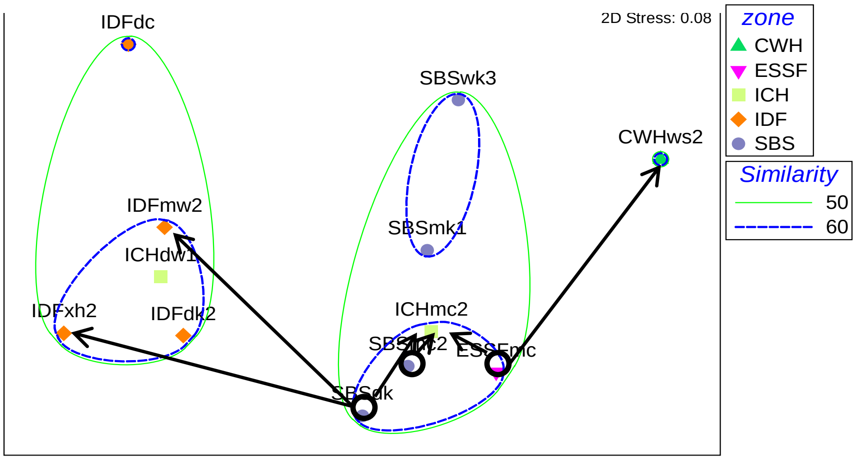
Figure 12. NMDS plot of all variants based on community similarity of all taxa identified to species. Contours show variants with 50% and 60% similarity based on cluster analysis. The plot shows relative similarity across multiple dimensions; hence axis labels are meaningless.

Tracing trajectories from current to projected future variants on the NMDS community similarity plot under different scenarios provides an excellent way to visualise the ecological distance for a climate scenario (Figure 13). This figure is identical to Figure 12, with superimposed arrows indicating transitions from current to projected ecosystems. Longer arrows indicate a transition to a less similar community than short arrows. The Slightly Warmer scenario in the top panel has generally short arrows that are confined to a small area of the graph; the Much Warmer projection on the bottom panel has long arrows pointing uniformly towards the drier variants on the left; and the Warmer and Wetter projection has arrows pointing to both wetter and drier variants.

Slightly Warmer (+1.7°C)



Warmer and Wetter (+2.6°C)



Much Warmer (+3.5°C)

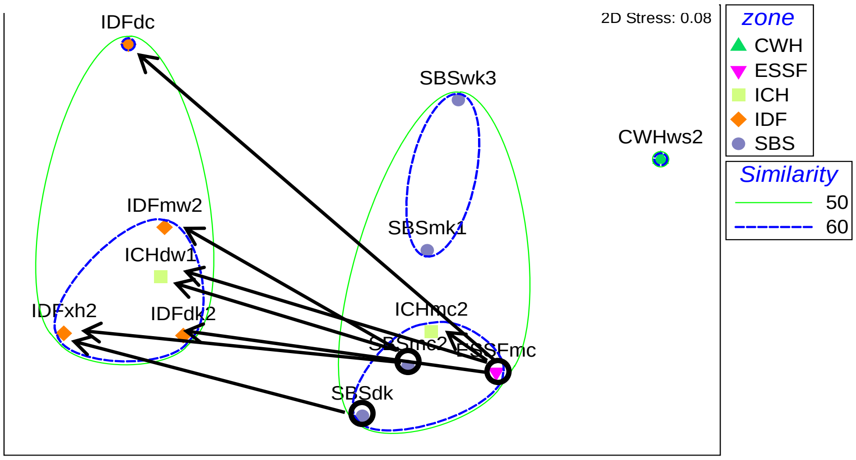


Figure 13. Projected trajectories for SBSdk, SBSmc2 and ESSFmc variants in the Nadina District under three climate scenarios. Circled points are current variants; arrows point to projected variants.

The pattern in community similarity is fairly consistent across lifeforms although clustering is much more evident within some lifeforms than others. For example, coniferous trees and evergreen shrubs form three tight clusters of more than 60% similarity separated by less than 50% similarity, whereas deciduous trees and shrubs form looser clusters, all related by more than 50% (Figure 14).

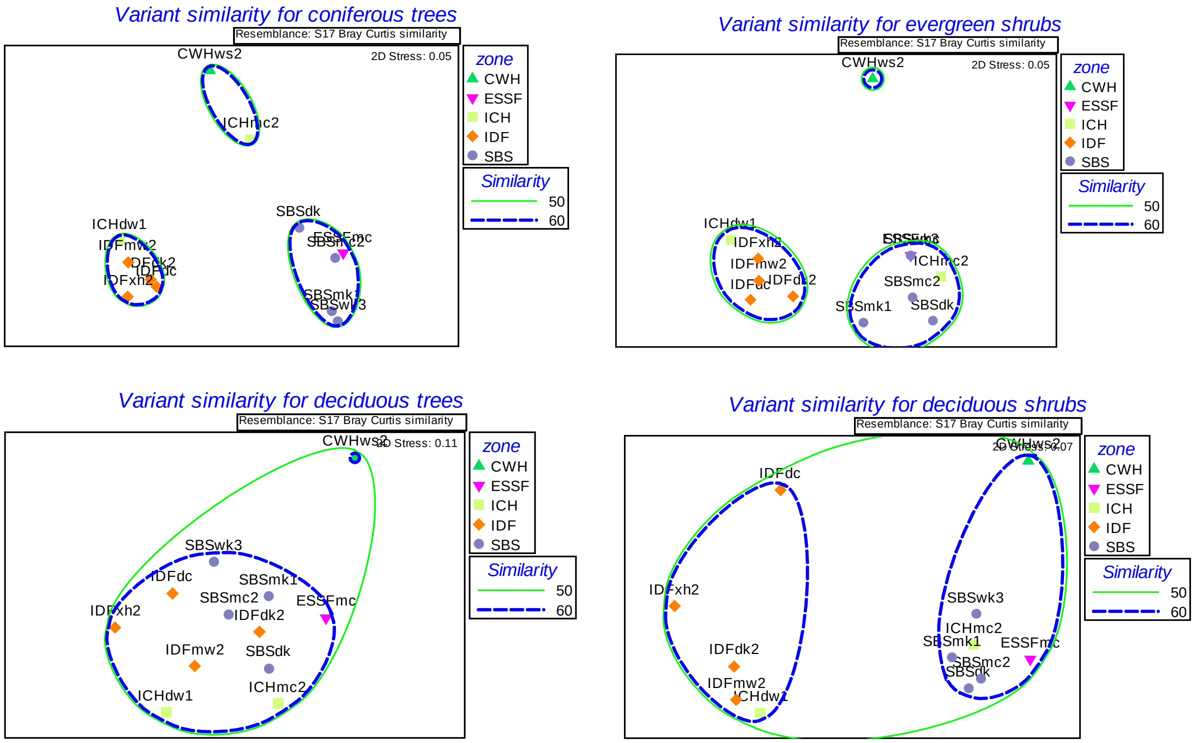


Figure 14. NMDS plots of all variants based on community similarity of trees and shrubs. Contours show variants with 50% and 60% similarity based on cluster analysis.

For the lifeforms with tight clusters, moving from one cluster to another will likely be more ecologically challenging than for the lifeforms with looser clusters. This pattern is reasonably consistent with that shown in Figure 10 above. For example, evergreen shrubs, with tight clusters, have a lower proportion of shared and higher proportions of lost and needed species than deciduous shrubs.

Long-term stress will also be a function of dispersal ability. For example, communities of grasses and allies seem particularly dissimilar among variants (Figure 15). Despite the dissimilarity, grasses disperse relatively quickly; hence recovery may be quick, and stress to this lifeform may be low. For grasses, inconsistencies in identification may also have led to apparently higher dissimilarity (Will MacKenzie personal communication).

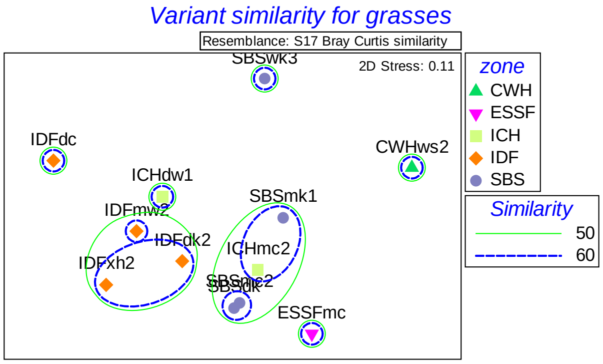


Figure 15. NMDS plots of all variants based on community similarity of grasses and allies. Contours show variants with 50% and 60% similarity based on cluster analysis.

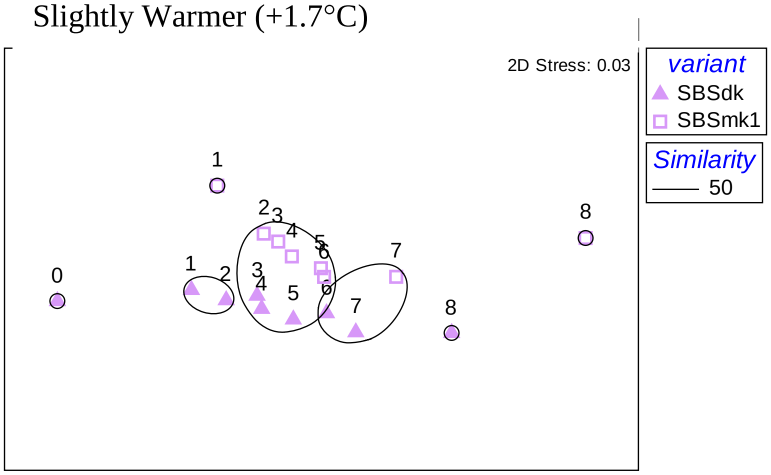
3.2.2 Site Scale

Analysing community similarity at a site scale can estimate which particular ecosystems are most stressed. For the Slightly Warmer scenario, current and projected future mesic communities are more than 50% similar, although the wettest and driest sites are less similar (Figure 16). In the Warmer and Wetter scenario, there is a split, with most of the SBSdk and ICHmc2 communities lying within 50% similarity clusters (and only the SMR 0 and 8 ecosystems sitting alone), but with no IDF ecosystems more than 50% similar to SBSdk ecosystems of similar SMR. In the Much Warmer scenario, the current and projected ecosystems do not share any clusters. In all cases, the SMR 0 and 8 ecosystems are most dissimilar and hence have the potential for highest stress.

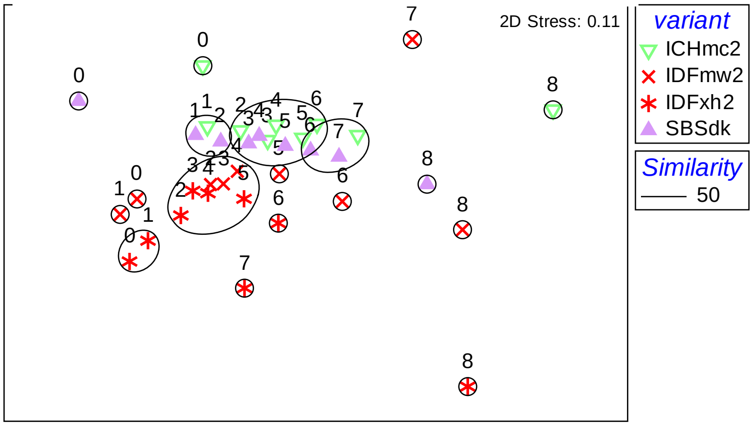
Comparing area-weighted mean across all SMRs and scenarios reveals two patterns. First, the wettest and driest ecosystems differ most between current and projected variants; while mesic ecosystems are most similar (Table 5). This pattern suggests that the wettest and driest sites may be most stressed. While some of the pattern could be due to inconsistent species identification or few sample plots in the extreme sites, it is remarkably consistent overall. Second, stress increases from the Slightly Warmer to Much Warmer scenarios (Table 5). In the Slightly Warmer scenario, all ecosystems except for the wettest and driest have more than 40% similarity. In the Warmer and Wetter scenario, additional wet and dry ecosystems fall below 40%, and in the Much Warmer scenario, all but mesic ecosystems fall below 40% similarity and hence potentially experience high stress.

Analyses at this scale show a much wider range of dissimilarity, and hence stresses, than analyses at the variant scale, because some species are limited to particular soil moisture regimes. Table 5 is based on one-to-one SMR matches (i.e. SMR 0 in current variant compared with SMR 0 in projected variants). Similar analyses that group ecosystems into three levels (mesic, drier than mesic and wetter than mesic), allowing some shift between moisture levels, show similar patterns and are not presented.

Slightly Warmer (+1.7°C)



Warmer and Wetter (+2.6°C)



Much Warmer (+3.5°C)

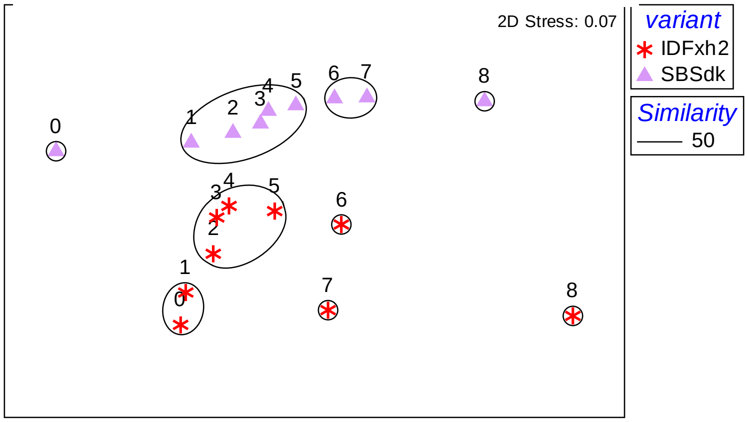


Figure 16. NMDS plots of community similarity for SMR within SBSdk and projected variants under three scenarios. Although the axes are arbitrary, the X-axis is clearly related to moisture.

Table 5. Mean Bray-Curtis similarity between current and projected variants weighted by area for each scenario for relative soil moisture regime classes (0 is driest; 8 is wettest). Colours highlight 20% stress classes (red <20%; orange 20 – 39%; green 40 – 59%; white >60%).

		SMR								
Climate	**Variant**	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Slightly Warmer	SBSdk	74	84	86	89	89	90	90	88	81
Slightly Warmer	SBSmc2	4	48	56	60	64	67	64	59	25
Slightly Warmer	ESSFmc	0	41	47	58	67	60	58	57	13
Warmer and Wetter	SBSdk	23	40	48	50	52	53	42	29	27
Warmer and Wetter	SBSmc2	28	60	59	56	63	62	55	61	20
Warmer and Wetter	ESSFmc	0	31	28	41	49	47	32	39	5
Much Warmer	SBSdk	21	33	38	46	47	44	34	20	22
Much Warmer	SBSmc2	13	30	39	44	47	44	34	16	16
Much Warmer	ESSFmc	0	24	26	38	45	43	32	29	7

3.3 Focal Species Abundance

3.3.1 Variant Scale

Analysing which species contribute most to variant dissimilarity provides additional information, given the assumption that changes in prominence indicate level of potential risk to ecological function, particularly for long-lived species. Table 6 lists trees that contribute most to the dissimilarity between SBSdk and sample projected future variants under the three climate-change scenarios based on analysis using the SIMPER routine in PRIMER.

Table 6. Tree species contributing most to dissimilarity between SBSdk and projected variants based on prominence scores.

	Mean prominence	
Species	***Current variant***	***Projected variant***
Slightly Warmer (SBSdk to SBSmk1)		
Pinus contorta	1.8	2.8
Abies lasiocarpa	0.8	2.4
Picea interior hybrid	1.6	2.5
Populus tremuloides	1.8	1.0
Warmer and Wetter (SBSdk to ICHmc2)		
Tsuga heterophylla	0.3	2.8
Thuja plicata	0.0	1.9
Betula papyrifera	0.8	2.2
Much Warmer (SBSdk to IDFxh2)		
Pseudotsuga menziesii	0.8	3.2
Pinus contorta	1.8	0.2
Populus tremuloides	1.8	1.1
Pinus ponderosa	0.0	1.2

PCA plots, with axes selected to demonstrate clearly the difference in variants, provide another way of looking at species that contribute highly to dissimilarity (Figure 17). Frequently, the best axes are not the first two because SMR classes are treated as replicates; hence the first or second axis is closely related to species that indicate moisture levels rather than variants. Species listed on PCA plots are generally similar to those in the SIMPER tables, but do not match perfectly because some species contribute more to one axis and others to a different axis.

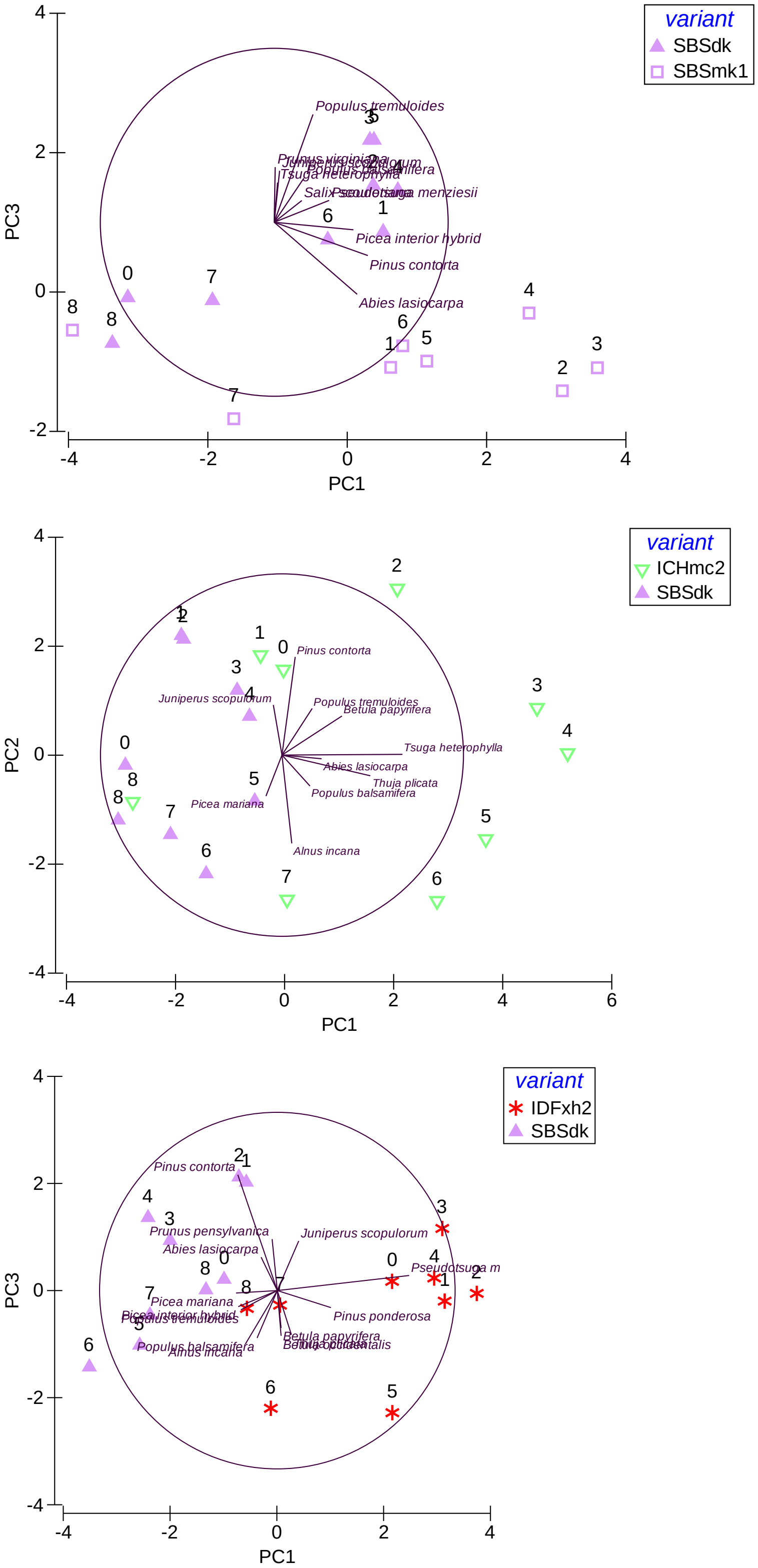


Figure 17. PCA plots for tree species shifts from SBSdk to SBSmk1, ICHmc2 and IDFxh2. Numbers represent soil moisture regime; symbols represent variants.

3.4 Geographic Distance

3.4.1 Variant Scale

Analysis of geographic distance between current and projected variants indicates potential for recovery. Consistent with community similarity measures, projected variants lie closest to the current variants in the Slightly Warmer scenario (Table 7; Figure 18). Existing climate envelopes are essentially projected to shift to higher elevations and all transitions are within 40 km; recovery potential is high. Recovery potential in the Warmer and Wetter scenario is mixed: projected variants lie relatively close to the current SBSmc2 and ESSFmc, but some are more distant from the drier SBSdk. Projected variants are furthest away in the Much Warmer scenario (two variants are more than 600 km away). Climate envelopes can no longer move uphill, and potential for recovery is low.

Table 7. Distance between current location of projected variants and current variants (area-weighted mean for the transitions shown in Table 3).

Scenario	*Distance to SBSdk (km)*	*Distance to SBSmc2 (km)*	*Distance to ESSFmc (km)*
Slightly Warmer	6	15	8
Warmer and Wetter	243	35	26
Much Warmer	370	415	438

Analysis of required migration distance, along a direct path, for recovery species shows the same pattern (Figure 19). In the area currently occupied by SBSdk, few recovery species lie beyond the Nadina District in the Slightly Warmer scenario, but many lie up to 400 km away in the more extreme scenarios. In the current SBSmc2 and ESSFmc ecosystems, no species lie further than 100 km from the Nadina in the Slightly Warmer or Warmer and Wetter scenarios, but some species would need to travel 700 km in the Much Warmer scenario. In the Warmer and Wetter scenario, the SBSmc2 is projected to be suitable for primarily ICHmc2, a nearby variant, and the ESSFmc is projected to be suitable for the ICHmc2 and the CWHws2 which lies within the western portion of the Nadina District.

The velocity of projected climate change over 65 years (1990 – 2055) represents a migration distance varying from about 0.1 km/year in the Slightly Warmer scenario to 7 km/year in the Much Warmer scenario.

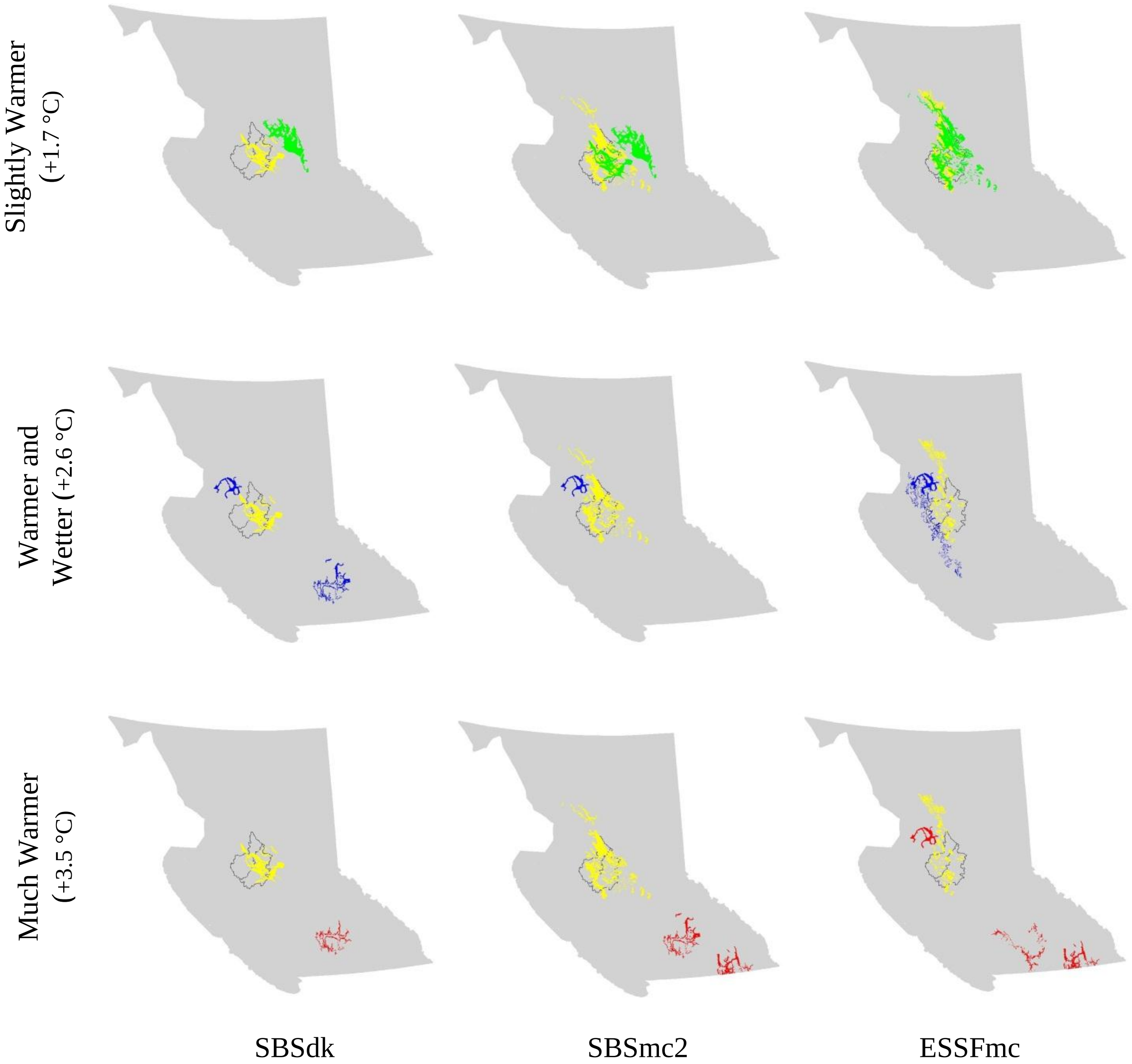


Figure 18. Current location of variants with climate envelopes projected to dominate the Nadina Forest District in the 2050s, under three climate-change scenarios. Current variants (SBSdk, SBSmc and ESSFmc) are shown in yellow. Current locations of projected variants are shown in green for the Slightly Warmer scenario (SBSmk1, SBSdk, SBSmc2, SBSwk3), in blue for the Warmer and Wetter scenario (IDFmw2, IDFxh2, ICHmc2, CWHws2), and in red for the Much Warmer scenario (IDFxh2, IDFmw2, ICHdw1, IDFdc, IDFdk2, ICHmc2). Note that, in the Slightly Warmer scenario, much of the SBSdk is projected to remain as SBSdk. Maps also show an outline of the Nadina Forest District.

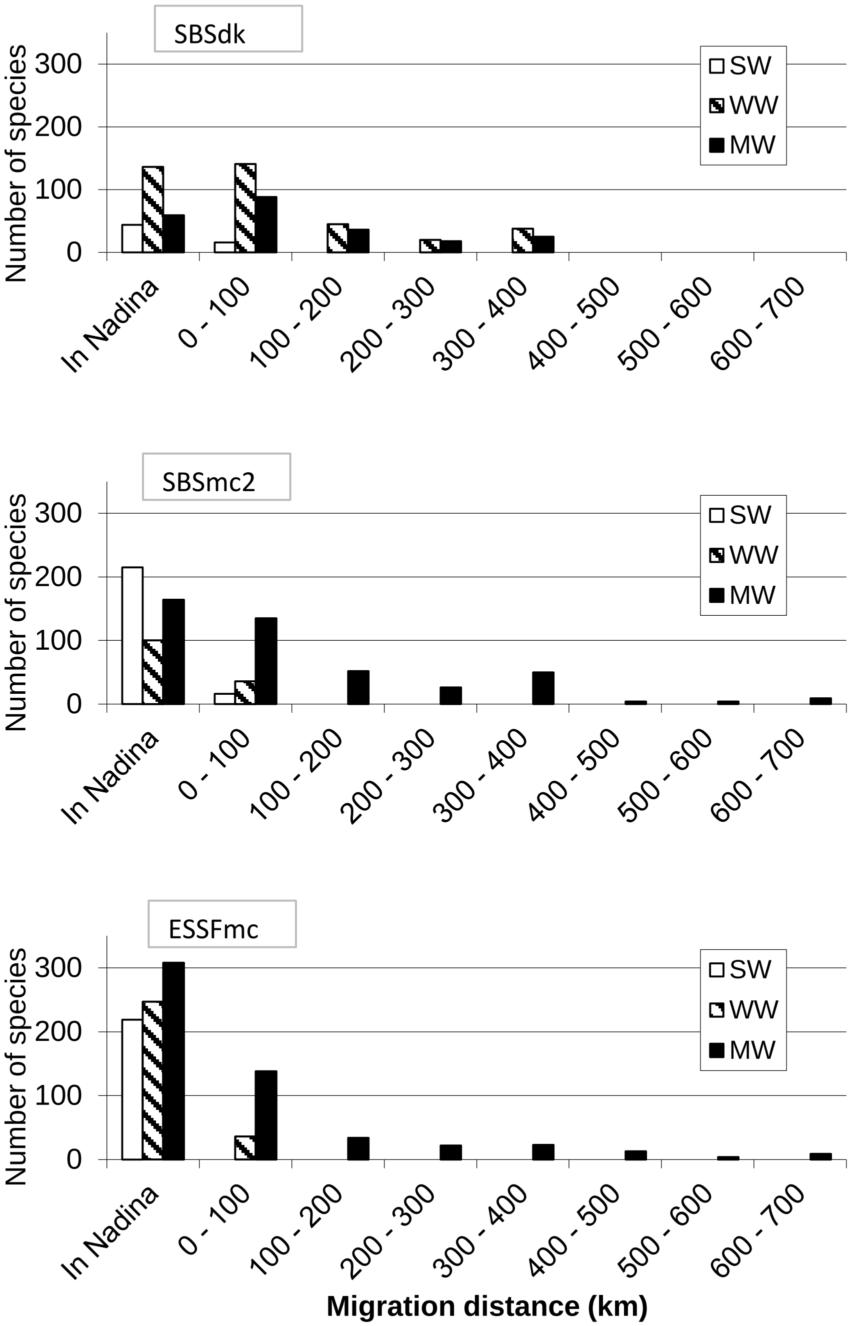


Figure 19. Frequency distribution of migration distances for recovery species to reach the location of current SBSdk, SBSmc2 and ESSFmc variants within the Nadina core area under three climate-change scenarios (SW = Slightly Warmer; WW = Warmer and Wetter; MW = Much Warmer).

3.4.2 Nadina Core Scale

The pattern in migration distance is similar at the broader scale of the Nadina core area (Figure 20). The pattern varies slightly with the threshold selected to include projected variants. Including all variants projected to cover more than 3% of the Nadina core area suggests that variants projected with the Warmer and Wetter scenario lie almost as far distant as those projected with the Much Warmer scenario, whereas including only those variants needed to make up at least 67% of the area shows a greater distinction between the Warmer and Wetter and Much Warmer scenarios that seems to match the pattern at the variant scale more closely.

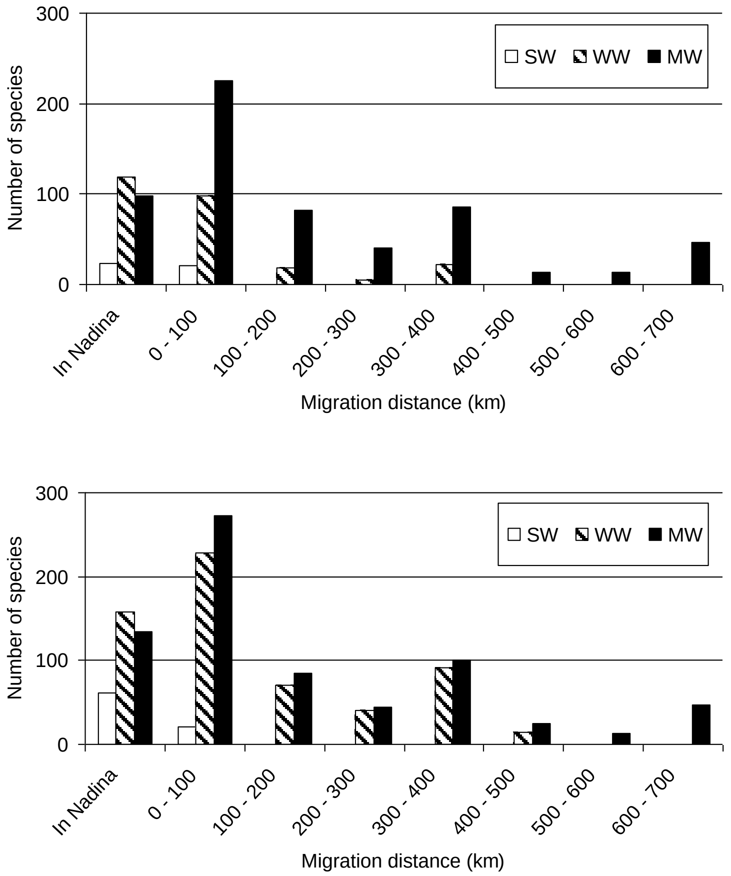


Figure 20. Frequency distribution of migration distances for recovery species to reach the Nadina core area under three climate-change scenarios. The top panel includes variants that are projected to cover more than 3% of the core area; the lower panel only includes variants projected to make up at least 67% of the core area in total.

In the Warmer and Wetter scenario, the ICHmc2, IDFmw2 and CWHws2 variants are projected to cover the first 71% of the area. Two of these ecosystems lie within the first 100 km of the Nadina, while the IDFmw2 lies within 400 km. Including additional ecosystems that each cover at least 3% of the area adds the IDFxh2, IDFdk1, ICHmc1 and IDFdk2 that lie respectively 400, 400, 100 and 500 km from the Nadina and include new suites of species. This difference suggests that care is necessary in choosing which variants to include in analysis.

We compared nearest recorded occurrences (from eFlora maps: www.eflora.bc.ca) for four tree and shrub species with the distances estimated by presence in variants (Table 8). Recorded occurrences are considerably longer than distances to a variant containing the species. For the four example species, *Thuja plicata* and *Mahonia nervosa* are components of the CWHws2 and SBSdw3 variants respectively. A portion of each of these variants lies within the Nadina (though outside the core), although this portion has no records of the species. Both *Pinus ponderosa* and *Acer macrophyllum* are components of the IDFww variant which lies in narrow bands along mountains and reaches further north than other IDF variants.

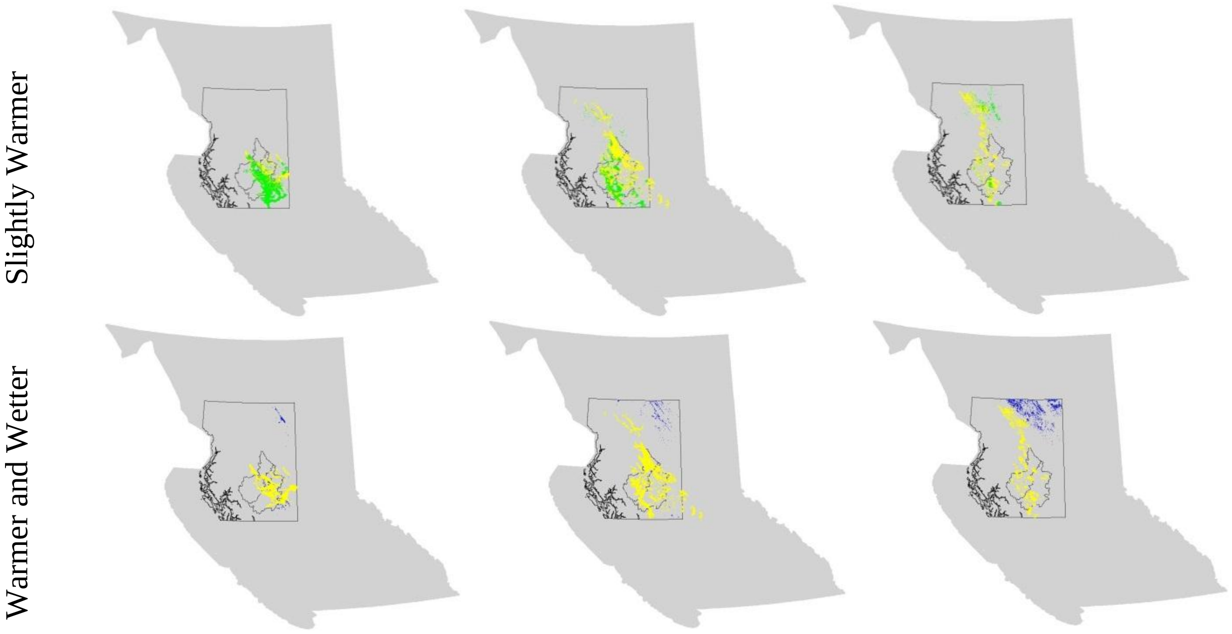
Table 8. Distance that selected tree and shrub species would need to migrate to reach the projected climate envelope in the Nadina. Distance calculated from eFlora occurrence maps measured to the middle of Francois Lake and from an overlay of variants with 100-km buffers around the Nadina Core area; therefore, subtract 100km from the eFlora distances to compare.

Species	*Distance based on species records (km)*	*Distance based on variant location (km)*
Pinus ponderosa	625	< 100
Thuja plicata	215	In Nadina
Acer macrophyllum	550	< 100
Mahonia nervosa	488	In Nadina

The difference between the distance measured by eFlora and the distance between variants suggests that caution is necessary in using geographic distance to indicate recovery potential.

The other side of the migration equation measures the distance that stressed species need to migrate to reach a climatically hospitable area (e.g. stressed species from the Nadina SBSdk would need to move to an area where SBSdk is projected to exist in the future). Measuring the distance from current variant locations to projected future locations is one way to measure this migration potential (Figure 21). We were only able to look at a subset of BC in this way, and hence did not analyse the data quantitatively.

The limited window available suggests that, as in other analyses, the Slightly Warmer scenario has considerable geographical overlap and hence a higher recovery potential than the more severe scenarios. In both of the remaining scenarios, small patches of potentially hospitable climate exist mostly to the northeast, but it is not possible to draw further conclusions.



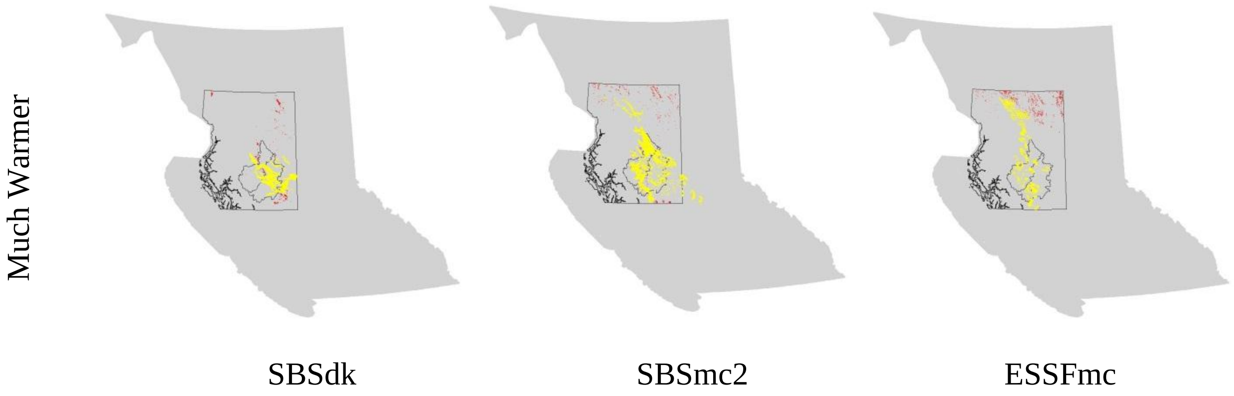


Figure 21. Current BEC variant locations (yellow) and projected locations, circa 2050, of climate envelopes corresponding to the same variant, under different climate change scenarios (green, blue, and red). Rectangular outline shows extent of projections.

3.5 Geographic Distance and Community Similarity

Community similarity and geographic distance are correlated, with pairs of distant communities differing more than pairs of close communities (Figure 22; r = -0.67, p = 0.003 Pearson correlation). This pattern can be attributed primarily to higher similarity in communities within 100 km versus those beyond 200 km; there is no pattern among the eight communities lying from 300 – 700 km apart.

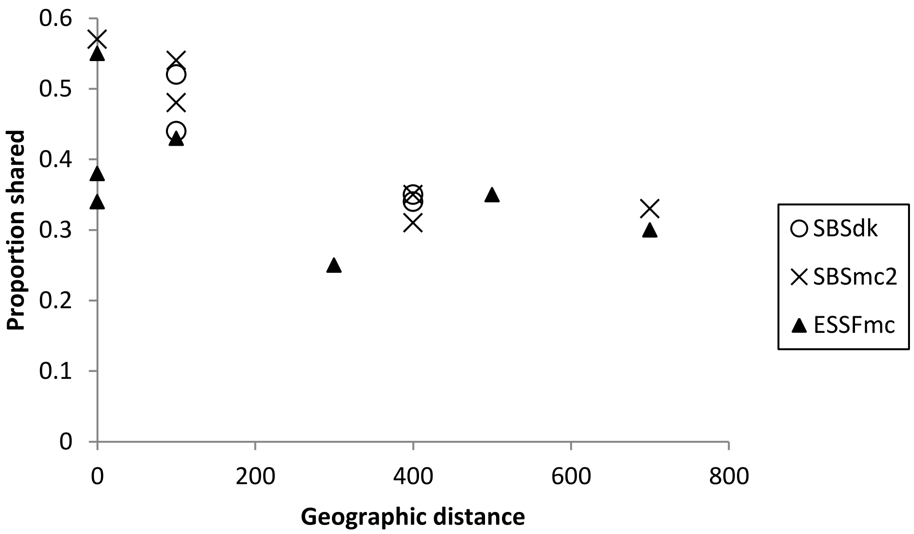


Figure 22. Relationship between community similarity and geographic distance between pairs of variants analysed at the variant scale.

This pattern might be less clear in regions with more relief. For an example in the Nadina region, the high elevation, interior ESSFmc is geographically close to, but ecologically distant from, the low elevation, coastal CWHws2.

4 Discussion

The patterns arising from the analyses of community similarity, changes in species pools and geographic distance correspond well. At all scales and for all variants, the Slightly Warmer climate scenario, with an estimated temperature increase of less than 2°C, seems to pose low stress. In this scenario, climate envelopes are projected to move short distances towards higher elevations. Community similarity is high, particularly in the SBSdk, where a large area is projected to still support SBSdk communities. These results are consistent with a general consensus that substantial or severe climate-related impacts are expected when global mean temperature increases beyond 2°C (Smith et al. 2009).

With more extreme climate projections, analyses suggest that stress increases. At the Nadina scale, both Warmer and Wetter (+2.6°C) and Much Warmer (+3.5°C) scenarios show similar patterns, with low stress (20% species projected to be stressed) but difficult recovery (nearly half of projected species absent). The southerly ICH and IDF variants projected to be suitable to the Nadina have a large combined species pool, leading to the high proportion of recovery species. Variants can no longer just "move uphill". Recovery to known functioning ecosystems is unlikely; uncertainty about future ecosystem function is high.

At the variant scale, patterns vary between the two severe scenarios. All variants are projected to experience high stress with the most extreme scenario. Ecosystems suited to this scenario lie uniformly distant from the Nadina and have low similarity to current ecosystems. However, projected stress to the SBSmc2 and ESSFmc remains low to moderate in the Warmer and Wetter scenario, as ecosystems suited to the moister projected climatic conditions lie nearby. The drier SBSdk , however, potentially experiences higher stress in this scenario, as some potentially suitable IDF ecosystems lie hundreds of kilometres distant; and many species are projected to be stressed or absent. Including smaller fragments in the list of projected variants leads to a prediction for even higher stress in this scenario as many of the smaller units currently exist in southern BC; hence the number of absent species approaches that for the Much Warmer scenario. This result suggests that care is needed in the choice of fragment size to include. Patterns are more consistent between Nadina Core and variant scale analyses with the > 67% total cut-off than with the inclusion of additional units with areas > 3%.

Geographic distance correlates with community similarity to some extent, suggesting that dissimilar ecosystems risk both depauperate plant communities and longer (and hence less likely) recovery.

Site-scale analysis of ecosystems with different soil moisture regimes suggests that the driest and wettest sites will experience the greatest stress in all scenarios, with higher stress expanding towards mesic sites in the more extreme scenarios. Sites at the extremes of relative moisture have higher proportions of unique species; hence community restructuring from nearby may be more difficult. This result is counter to intuition that drier sites should be less stressed as they already include dry-adapted species. Data are less reliable for the wettest and driest sites: species identification may be inconsistent among regions and the smaller sample of plots may have increased apparent dissimilarity (Will MacKenzie personal communication). However, the pattern seems consistent across all scenarios and variants and bears further investigation.

4.1 Analysis Challenges

4.1.1 Scale Considerations

Analysis at multiple spatial scales seems useful. Examining potential migration distances is likely best done at the broadest scale. This scale combines adjacent ecosystems and allows for community restructuring within the ecosystems of the Nadina. However, it is not able to determine which current ecosystems face greatest stress, but can only compare across scenarios. Analysis at the variant scale found different patterns in each variant, with community similarity decreasing considerably moving from the Slightly Warmer to Warmer and Wetter scenario in the SBSdk, while remaining relatively constant in the SBSmc2. Analysis at the smallest scale reveals which particular sites within variants will likely experience most stress. This scale matches well with the scale of forest management. At an even smaller scale, it might be useful to identify specialists with narrow SMR tolerance. These species are limited by area-specific conditions and are likely most at risk because they have little room to move.

Community similarity scores increase at larger scales. At the broadest scale, the species pool in the entire Nadina core area shares about 50% of species with the pool found in variants suitable to Warmer and Wetter and Much Warmer scenarios. At the variant scale, the species pools are about 50% similar in the Warmer and Wetter scenario, but about 35% similar in the Much Warmer scenario. At the site scale, shared species pools drop to about 45% in mesic sites in the most severe scenario, and below 20% in half of the wettest and driest sites across scenarios. Because of the influence of scale on similarity, it is challenging to define stress classes: at the Nadina scale, similarity remains at 50% or above, while at the site scale, it can drop below 20%. We had initially chosen 50% similarity to represent a threshold between high and low stress on NMDS plots by analysis of the similarity of communities in sites with adjacent SMRs, but this definition is likely inappropriate at larger scales.

The species pool analyses assume that a focal region acts as a single community. The spatial scale selected for analysis should reflect the degree of difficulty of internal reorganisation within the focal region. If clumps of species within a region are relatively evenly or randomly distributed, then internal reorganisation should be relatively easy. Conversely, if a region divides into a few widely spread clusters, then reorganisation may be difficult and an invalid assumption. Variants within the Nadina core may lie in a few widely spread clusters. For example, migration from the SBSdk to the ESSFmc may not be “easy”. This effect could be more pronounced in regions with more incised topography.

4.1.2 Data Uncertainty

Any study compiling databases from different areas of BC is fraught with challenges as inventory standards and identification vary. Nadina ecosystems have more recorded information on seral ecosystems and wetland ecosystems than is available in other regions of the province due to completion of special projects. These projects likely explain why the SBSdk database includes more unique species of each lifeform (except lichens) than the southerly IDFxh2 database. Additional complexities include taxonomic issues (e.g. Betula species) that lead to higher predictions of species turnover, as well as errors in identification. We combined all interior hybrid Picea species to remove the effects of multiple hybrids. Data reliability is better for more common species, but very few species met the easily-applied prominence criteria (prominence score >1 in any SMR). It would be useful to screen the original data for inappropriate species (e.g. parkland species within non-parkland variants) and to pull out a more comprehensive set of common species for future analyses.

4.1.3 Interpreting Geographic Distance

Interpreting geographic distance meaningfully is difficult. Simple linear measures of distance are highly uncertain given the incised topography of BC, although no mountain ranges lie between current and projected variants to act as dispersal barriers. The relatively higher elevation interior plateau may hinder dispersal from lower elevations in southern BC. As an added complexity, lifeforms have different dispersal mechanisms and abilities, and prevailing winds partially determine which species will travel furthest. With caution, measuring relative distances might be useful. Distance is somewhat related to community similarity: at least, communities within 100 km of the Nadina have higher similarity than those from 300 – 700 km distant. The discrepancy between distance to nearest variant and distance to recorded occurrence suggests considerable caution, as species are not present throughout variants. Interpreting geographic distance may be even more challenging in more incised regions of the province.

We believe that the geographical data are sufficiently useful to conclude that the rate of migration necessary for some species is not within the documented rates of movement. Fossil pollen data suggest that North American trees can move from 0.1 – 1 km/year (McLachlan et al. 2005; but these data may not account for refugial populations that facilitated recolonisation and thus the rate of spread may be substantially lower < 0.1km/year). At these rates, species will only be able to reach suitable climates in the “Slightly Warmer” scenario.

4.1.4 Climate Projections

We caution that the climate projections are based on mean temperature and precipitation and do not include potentially large changes in climate variability. Climate variability has the potential to fundamentally restructure ecosystems due to unpredictable events (e.g. mountain pine beetle, Dothistroma, shifts in seasonal weather patterns; Haughian et al. 2012). We suspect that such unpredictable (arguably random across variants given our lack of knowledge) changes could swamp the shifts analysed within this paper. Climate variability and extreme weather events have a large effect on population and community dynamics and on species distributions (Parmesan et al. 2000, Parmesan 2006). The topic of climate extremes versus averages is currently an active area of research (IPCC 2011). Changes in mean characteristics, however, likely still indicate relative stress, and could predict resilience in the face of extreme events.

We do not believe that climate projections can be used to predict future ecosystems (Haeussler 2011). However, we do believe that this analysis can estimate relative stress to an ecosystem. They could also potentially inform conservation options. Results can be used to plan reserves to include ecosystems that will likely experience the highest stress (e.g. very wet or very dry). Species that contribute highly to community dissimilarity, particularly those that characterise a projected variant and have broad SMR tolerance, and particularly if they are long-lived and/or structural species, are the best candidates for facilitated migration. In general, the high potential level of stress suggests that increased reservation of ecosystems to represent as much diversity as possible could be beneficial because unfragmented natural ecosystems have increased resilience to change and decreased susceptibility to invasion by weedy species (Noss 2001).

5 Future Analysis

This pilot study suggests several useful avenues for future analyses:

1. Replicate Figure 13 for all variants in BC. This figure would be useful for communication purposes, to illustrate projected transitions from one variant to another,

and could provide a first, rough estimate of relative stress. Community similarity provides the broadest measure of ecological distance. Our results show that analyses performed at higher level of detail (e.g. SMR vs. variant; stressed and recovery vs. shared species; lifeforms vs. entire community) provide additional information. However, over larger geographic areas (e.g. BC), such detail may be overwhelming and simple analyses using community similarity to represent ecological distance may be more useful.

2. Investigate the relationship between geographical distance and community similarity among variants across BC. This analysis is crucial to determine if the patterns in the relatively flat Nadina differ from patterns in more incised terrain.
3. Populate Figure 11 by a) increasing sample of scenarios and b) teasing apart precipitation and temperature. A graph of stress (1 – similarity) for every 0.5°C in increased temperature with two or three precipitation classes would be useful for detecting thresholds in risk.
4. At the site scale, further investigation of the potential relationship between similarity and soil moisture regime would help to determine whether the pattern is real or an artefact of data inconsistencies.

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