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Corroboration of biogeoclimatic ecosystem classification climate zonation by spatially modelled climate data

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Abstract

The biogeoclimatic ecosystem classification (BEC) method for distinguishing areas of reasonably homogeneous macroclimate has been used in British Columbia for over 20 years. Because of the paucity of actual long-term climate data, the method used other means to map climate. We tested how well the BEC climate units could be discriminated from one another using spatially modelled climate data. We tested the ability of climate data to distinguish three units for each of four climatically different zones at two levels of the climatic classification using discriminant analysis. For each analysis, 60 points were randomly selected from within the boundaries of the mapped unit and climate data were generated by ClimateBC. Even at the finest level of the mapping, over 70% of the randomly selected points were correctly classified according to the mapped unit based on selected climate variables. A large proportion of the misclassified points were within 1 km horizontal distance or 100 m elevation of the boundary and are typically climatically transitional areas. We recommend that the BEC climate unit should form the basic unit for examining climate change at multiple scales from the provincial scale to the scale of watersheds or basins, and that further analysis be conducted to both improve biogeoclimatic unit mapping and climate models.

KEYWORDS: *biogeoclimatic ecosystem classification, ClimateBC, climate change, discriminant analysis.*

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Introduction

The biogeoclimatic ecosystem classification (BEC) system has been widely used for the characterization of ecosystems in British Columbia since the early 1980s (Pojar et al. 1987). The classification deals primarily with three ecosystem elements: climate, vegetation, and site (including topography and soils). Climate has an overarching influence on vegetation and is therefore a critical component of understanding species and ecosystem distribution. Climate is very complex in the province because of the wide latitudinal range, mountainous topography, and strong maritime–continental gradient. Long-term climate stations are sparsely distributed and so indirect methods are required to map climate zones at a scale useful for management. In addition, biologically relevant climatic zonation is required to understand climatic thresholds for important plant species. For both of these reasons, the BEC system applies an approach to climatic zonation that uses vegetation communities to define regions of similar climate. The BEC approach uses a classification of zonal ecosystems to define areas of similar climate (i.e., biogeoclimatic units). The zonal ecosystem is a mature vegetation community that occurs on "zonal sites"—areas with average soil and site conditions—that best reflect the regional climate (Pojar et al. 1987). The basic working unit of this climatic or zonal classification is the "subzone," which circumscribes land areas where zonal sites have the same characteristic combination of plant species or zonal ecosystem (Figure 1). Subzones are often subdivided into "variants" where small differences in zonal vegetation are felt to reflect relatively minor differences in climate. Subzones are also grouped into "zones" at a higher level of the hierarchy to reflect broad climatic areas characterized by climax tree species that dominate in mature forest stands on zonal sites.

To delineate the boundaries of subzones and variants, experienced vegetation ecologists observe zonal vegetation across latitudinal, longitudinal, elevational, and topographical gradients and assign it to a plant association or sub-association that determines its subzone or variant membership. In some cases, ecological plot data are used to develop empirical rules, which are based primarily on elevation and aspect, to map boundaries between biogeoclimatic units.

Since the establishment of the BEC system in the 1980s, the ClimateBC model (Wang et al. 2006) has been developed. This model allows characterization of the climate at a relatively fine spatial resolution. It combines bi-linear interpolation and elevation adjustment techniques to downscale gridded climate data from the PRISM model (Daly et al. 2002) and to produce high resolution spatial climate normals that cover western Canada (Wang et al. 2006). The PRISM model creates gridded surface estimates (4-km resolution) of climate normals based on point climate measurements, digital elevation models, and expert knowledge of complex topographical influences on climate, such as continentality and rain shadows (Daly et al. 2002). ClimateBC generates monthly, seasonal, and annual temperature and precipitation normals (30-year averages) as well as derived variables (e.g., frost-free period, continentality, growing-degree days, and heat-moisture index) for user-provided latitude, longitude, and elevation locations.

In this paper, we examine the use of discriminant analysis at the regional level of the biogeoclimatic ecosystem classification system to determine how well the mapped units are defined by their climate space.

Hamann and Wang (2006) showed that mapped biogeoclimatic zones could be successfully classified using discriminant analysis of PRISM climate data. We want to further examine the use of discriminant analysis at finer (regional) levels of the BEC system—the biogeoclimatic subzone and variant levels—to determine how well the mapped units are defined by their climate space.

In this paper, we wish to examine how well existing mapped subzones and variants are discriminated from one another based on recent climate data. The objectives are to:

- assess the ability of the BEC approach to distinguish climatic differences;
- gain insights about which climate variables are important for differentiation within different macroclimates; and
- identify any consistent attributes of misclassified points.

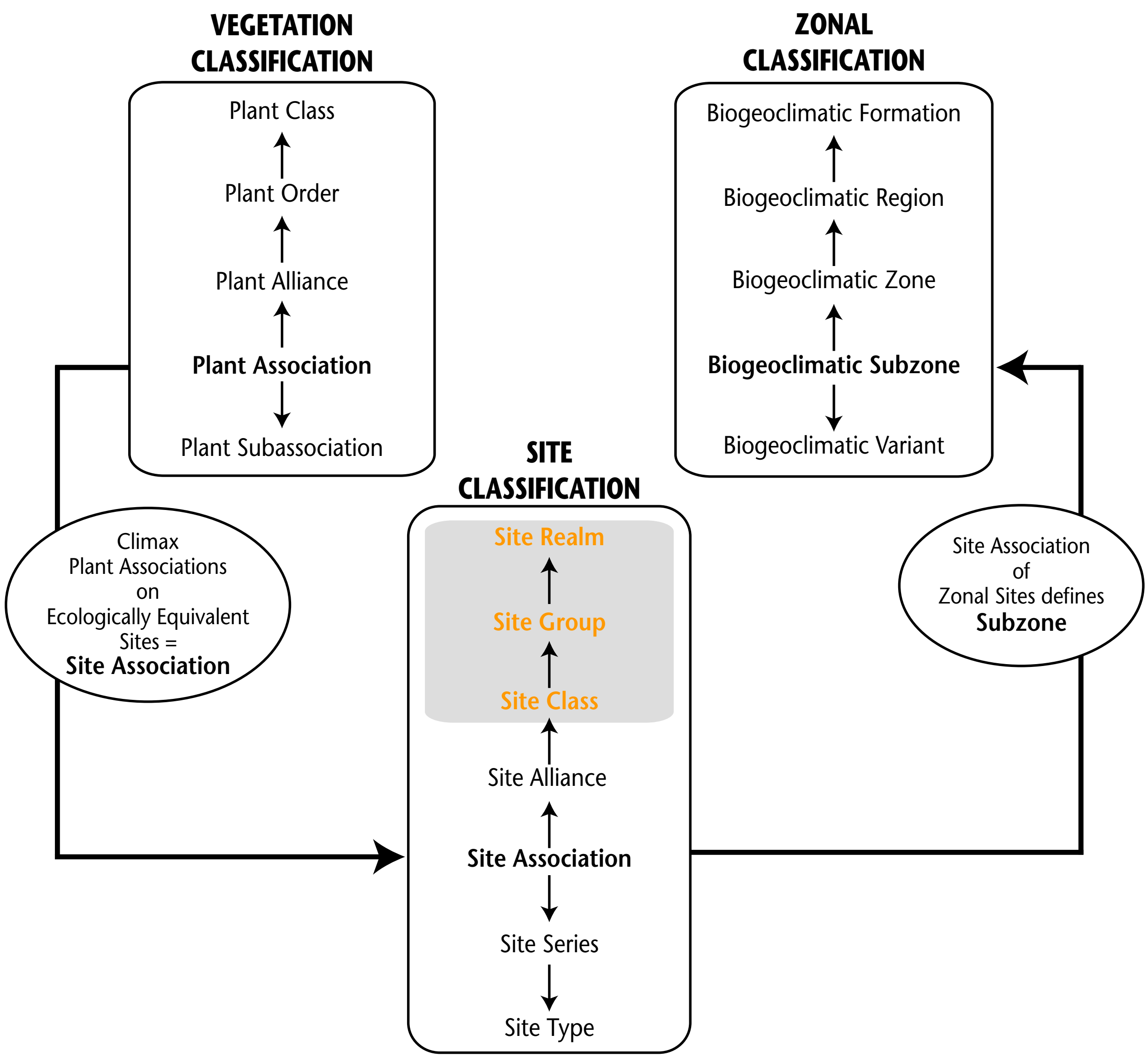

FIGURE 1. Components of the biogeoclimatic ecosystem classification.

Methods

To test the universality of the vegetation on zonal sites used to map climatic units, we examined three biogeoclimatic units from each of four biogeoclimatic zones with contrasting climates. We chose the Interior Douglas-fir (IDF) zone to represent a relatively dry climate, the Interior Cedar–Hemlock (ICH) zone to represent a wet climate, the Boreal White and Black Spruce (BWBS) zone to represent a northern climate, and the Engelmann Spruce–Subalpine Fir (ESSF) zone to represent a high-elevation climate.

Based on data from long-term climate stations, the IDF climate is characterized by warm, dry summers, a relatively long growing season, and cool winters (Hope et al. 1991). The ICH zone has a snowy climate with cool, wet winters and dry, warm summers (Ketcheson et al. 1991). The BWBS zone has a northern continental climate with long, very cold winters and a short but relatively productive growing season owing to long day length (DeLong et al. 1991). The ESSF zone has a cold, moist, and snowy climate typical of high elevations although precipitation is highly variable (Coupé et al. 1991) (Table 1).

TABLE 1. Basic climatic characteristics of four biogeoclimatic zones chosen for analysis.

	IDF	ICH	BWBS	ESSF
Mean annual precipitation (mm)	300–750	500–1200	330–570	400–2200
Precipitation as snow (%)	20–50	25–50	35–55	50–70
Mean annual temperature (°C)	1.6–9.5	2–8.7	–2.9 to +2	–2 to +2
Months average temperature below 0°C	2–5	2–5	5–7	5–7
Months average temperature above 10°C	3–5	3–5	2–4	0–2

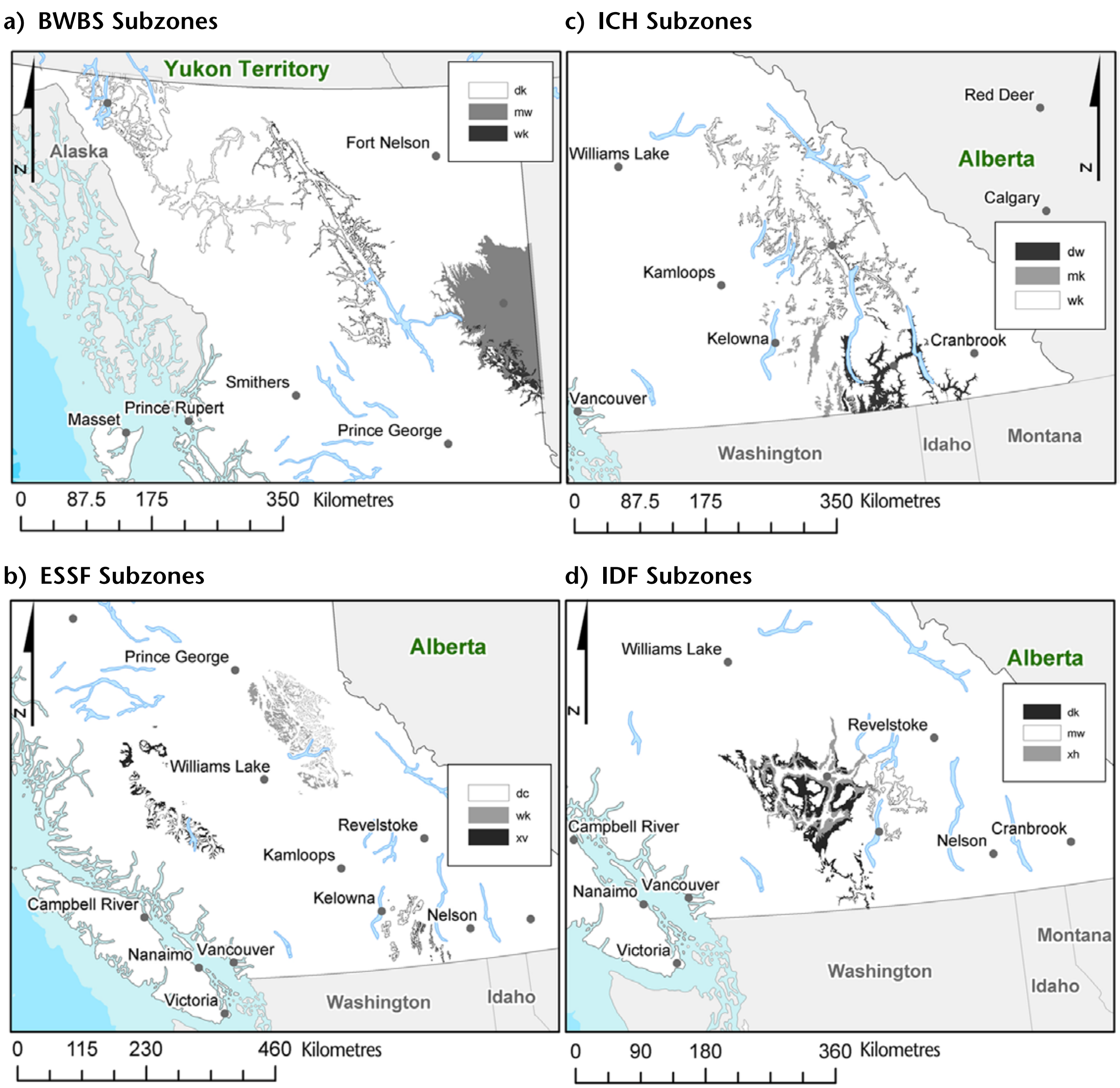

FIGURE 2. Distribution of biogeoclimatic subzones used for discriminant analysis of the BWBS, ESSF, ICH, and IDF zones in British Columbia.

The biogeoclimatic units we chose for each of these zones represent the range in relative precipitation and temperature for the zone. We also avoided units that cover small areas (< 150 000 ha) to prevent heavy clustering of the randomly selected points compared with other units in the analysis. Because variants represent a conveniently valid subset of a subzone, we used one to characterize the whole subzone. In all cases, at least two of the units under analysis were not disjunct and shared common boundaries across at least a portion of the range. This enabled a better test of climate variables to discriminate the units because climate is more likely to be similar between units from the same geographic area versus ones geographically disjunct.

Figure 2 shows the distribution of the biogeoclimatic units chosen for analysis. For the IDF zone, we chose the Thompson variants of the very dry hot subzone (IDFxh2), the dry cool subzone (IDFdk1), and the moist warm subzone (IDFmw2). For the ICH zone, we chose the West Kootenay variant of the dry warm subzone (ICHdw1), the Kootenay variant of the moist cool subzone (ICHmk1), and the Shuswap variant of the wet cool subzone (ICHwk1). For the BWBS zone, we chose the Stikine variant of the dry cool subzone (BWBSdk1), the Peace variant of the moist warm subzone (BWBSmw1), and the Murray variant of the wet cool subzone (BWBSwk1). For the ESSF zone, we chose the West Chilcotin variant of the very dry very cold subzone (ESSFxv1), the Okanagan variant of the dry cold subzone (ESSFdc1), and the Cariboo variant of the wet cool subzone (ESSFwk1).

To test how well climate data differentiate biogeoclimatic units at the finest level of the climate classification (i.e., the biogeoclimatic variant), we chose three variants from the dry cool subzone of the IDFdk (i.e., the Thompson [IDFdk1], the Cascade [IDFdk2], and the Fraser [IDFdk3]) and the dry warm subzone of the ICHdw (i.e., the West Kootenay [ICHdw1], the Boundary [ICHdw2], and North Thompson [ICHdw3]) (Figure 3).

Data analysis

We used discriminant analysis to determine how well the biogeoclimatic units were discriminated based on climatic variables. Discriminant analysis is a multivariate technique that predicts the membership of an individual within multiple predefined groups based on a set of predictors (Wilkinson et al. 1996). In our case, this analysis predicted to which biogeoclimatic unit (within a zone or subzone) a particular geographic point belonged based on the point's average climate conditions. We used SPSS v16.0 for Windows (SPSS 2009) to create two linear discriminant functions for each biogeoclimatic zone (for the subzone-level analysis) and subzone (for the variant-level analysis). The first discriminant function maximized the differences between the groups and had the highest discriminating power. The second function (orthogonal to the first) accounted for the remaining variance in the data. Discriminant analysis uses the discriminant

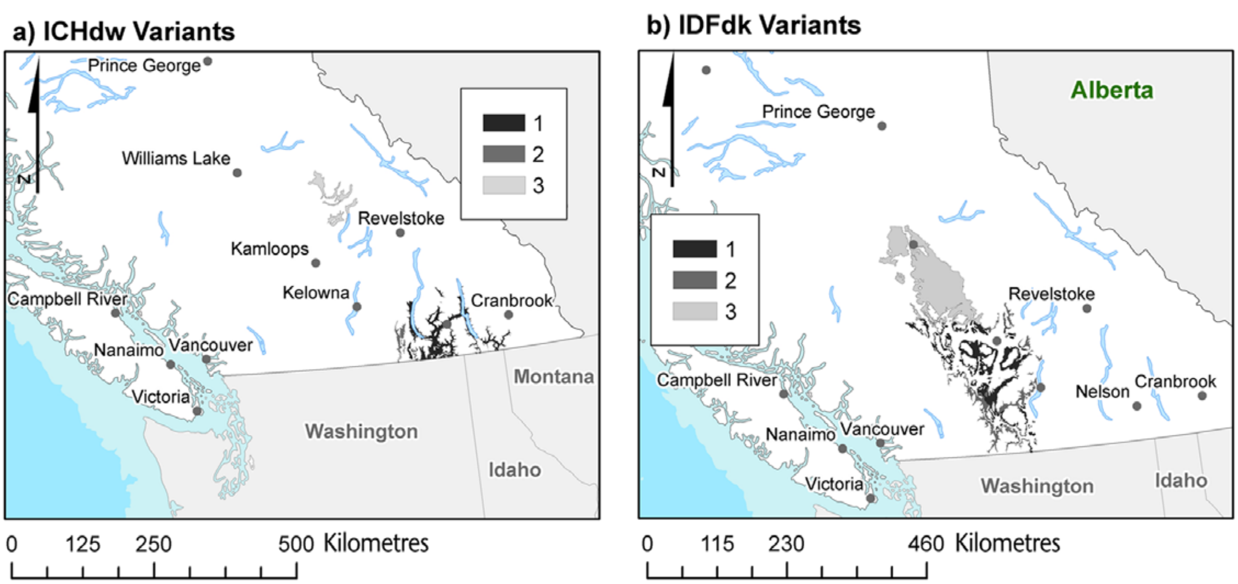

FIGURE 3. Distribution of biogeoclimatic variants used for discriminant analysis of the ICHdw and IDFdk subzones in British Columbia.

functions to predict group membership based on the Mahalanobis distance between the site's discriminant score and the mean vector of the closest group. We determined classification success rates by comparing the discriminant analysis classification to actual group membership using a "jackknifed" classification matrix. Jackknifing procedures systematically omit a single data point and run the classification on the remaining points to provide a cross-validated classification matrix. We also generated standardized coefficient matrices to determine each climate variable's unique (partial) contribution to predicting group membership.

We used the "Create Random Points Tool" within the ESRI ArcInfo® Geographic Information System (Environmental Systems Research Institute, Inc., Redlands, California) to randomly select 60 geographic points for each biogeoclimatic unit using the most recent coverage available (Version 7). These points were submitted to the ClimateBC model version 3.21 (Wang et al. 2006) to generate the climatic data set. For each point, we extracted normals (1971–2000 average) for 18 annual climate variables (Table 2). The climate normal period of 1971–2000 was chosen to use the most currently available data from ClimateBC.

TABLE 2. Mean climate normals (1971–2000) and standard deviations for biogeoclimatic variants used for the subzone-level analysis based on the 60 randomly selected points.

		BWBS			ESSF		
		mw1	dk1	wk1	xv1	wk1	dc1
MAT[a]	mean	1.5	–0.3	2.6	–0.1	1.6	2.0
	sd	0.5	1.2	0.4	0.8	0.5	0.4
MWMT[b]	mean	14.8	12.7	14.3	9.4	12.1	12.9
	sd	0.3	0.9	0.3	0.9	0.6	0.4
MCMT[c]	mean	–13.1	–14.3	–9.4	–9.8	–9.2	–7.9
	sd	1.3	2.8	1.0	1.4	0.4	0.4
TD[d]	mean	27.8	27.1	23.7	19.2	21.4	20.8
	sd	1.4	2.8	0.9	1.5	0.5	0.4
MAP[e]	mean	503.6	493.2	705.3	903.6	936.4	817.1
	sd	47.5	127.2	76.3	286.3	144.7	87.1
MSP[f]	mean	315.5	241.1	388.2	265.8	421.8	345.1
	sd	24.4	57.9	23.5	56.1	47.8	36.6
AH:M[g]	mean	22.9	20.6	18	12	12.7	14.9
	sd	1.8	5.2	1.6	3.5	2.1	1.8
SH:M[h]	mean	47.1	56.1	37	37.4	29.2	37.8
	sd	4.2	14.6	2.4	11.3	3.8	4.5
DD<0[i]	mean	1534	1705	1126	1225	1073	988
	sd	155	316	109	158	63	59
DD>5[j]	mean	1154	785	1106	420	780	832
	sd	63	149	51	119	96	76
DD<18[k]	mean	5815	6478	5432	6384	5771	5640
	sd	195	445	158	299	192	154
DD>18[l]	mean	16	3	11	–3	0	2
	sd	4	4	3	1	1	2
NFFD[m]	mean	154	131	159	88	135	142
	sd	4	15	4	14	7	6
FFP[n]	mean	91	62	95	1	60	63
	sd	11	12	10	10	16	13
bFFP[o]	mean	150	168	150	192	171	175
	sd	2	9	2	7	6	4
eFFP[p]	mean	241	230	245	205	231	238
	sd	2	9	2	14	4	3
PAS[q]	mean	151.5	222.3	225.6	514.6	390.8	366.1
	sd	18.9	64.9	34.6	200	90.6	47.5
DD5_100[r]	mean	135	156	137	185	159	163
	sd	3	8	2	10	7	6

TABLE 2. *(Continued).*

		ICH			IDF		
		wk1	dw1	mk1	dk1	mw2	xh2
MAT[a]	mean	2.7	5.6	3.8	3.7	5.2	4.8
	sd	0.8	1.1	0.7	0.6	1.0	0.8
MWMT[b]	mean	14.1	17.0	14.8	14.4	16.5	15.9
	sd	0.8	1.1	0.7	0.7	1.2	1.0
MCMT[c]	mean	–8.9	–5.9	–7.0	–6.7	–6.7	–6.4
	sd	0.8	1.0	0.6	0.5	1.0	0.7
TD[d]	mean	23.0	22.9	21.8	21.1	23.2	22.3
	sd	0.8	0.6	0.4	0.6	0.5	0.7
MAP[e]	mean	1171.9	823.9	700.6	452.6	561.3	380.9
	sd	280.4	159.3	93.0	66.7	78.6	53.9
MSP[f]	mean	414.0	283.8	294.1	197.2	247.3	173.0
	sd	84.7	45.8	30.2	25.3	34.5	26.6
AH:M[g]	mean	11.6	19.7	20.0	30.9	27.6	39.7
	sd	3.0	4.5	3.0	4.8	4.0	5.9
SH:M[h]	mean	35.8	61.7	51.0	74.2	68.2	94.1
	sd	9.1	12.0	7.0	10.5	11.0	15.8
DD<0[i]	mean	993	598	785	767	665	676
	sd	119	122	88	75	116	97
DD>5[j]	mean	1058	1568	1161	1112	1498	1380
	sd	137	238	121	119	233	182
DD<18[k]	mean	5366	4343	5005	5031	4482	4616
	sd	276	375	239	219	373	299
DD>18[l]	mean	11	78	17	13	61	40
	sd	8	48	10	7	42	23
NFFD[m]	mean	153	188	160	160	182	173
	sd	10	14	9	9	16	13
bFFP[n]	mean	158	140	159	159	142	148
	sd	7	7	6	7	9	8
eFFP[o]	mean	240	255	244	245	252	249
	sd	4	5	4	4	7	6
FFP[p]	mean	82	116	85	86	109	101
	sd	11	12	10	10	16	13
PAS[q]	mean	525.5	273.6	260.4	168.8	170.9	124.0
	sd	161.3	91.2	51.4	34.5	32.1	22.7
DD5_100[r]	mean	144	125	142	143	125	131
	sd	7	9	7	7	9	8

a MAT Mean annual temperature (°C)
b MWMT Mean warmest month temperature (°C)
c MCMT Mean coldest month temperature (°C)
d TD Temperature difference between MWMT and MCMT, or continentality (°C)
e MAP Mean annual precipitation (mm)
f MSP Mean annual summer (May to September) precipitation (mm)
g AH:M Annual heat:moisture index ((MAT+10)/(MAP/1000))
h SH:M Summer heat:moisture index ((MWMT)/(MSP/1000))
i DD<0 Degree-days below 0°C, chilling degree-days
j DD>5 Degree-days above 5°C, growing degree-days
k DD<18 Degree-days below 18°C, heating degree-days
l DD>18 Degree-days above 18°C, cooling degree-days
m NFFD Number of frost-free days
n FFP Frost-free period
o bFFP Julian date on which FFP begins
p eFFP Julian date on which FFP ends
q PAS Precipitation as snow (mm)
r DD5_100 Julian date at which degree days above 5°C (i.e., growing degree days) reaches 100

For the discriminant analysis, we selected a subset of the 18 annual normals output by ClimateBC using the five directly measured variables:

1. mean annual precipitation,
2. mean annual temperature,
3. mean seasonal precipitation (May – September),
4. mean temperature of the warmest month, and
5. mean temperature of the coldest month.

This subset was chosen deductively because the directly measured variables alone likely capture the climatic variability between the sites. The other annual normals were derived from these or measured daily variables (Wang et al. 2006), and in this case, tended to be redundant (i.e., strongly correlated with the measured annual variables, data not shown). We also completed a separate discriminant analysis using all 18 annual normals (after screening them for multi-collinearity using a tolerance criterion of 0.001) to determine whether the classification rates from the original analysis could be improved using the larger climate data set. Data for the discriminant analysis using all climate output are presented on page 64.

Climate data used in this study violated assumptions of multivariate normality and homogeneity of covariance among groups (not shown); however, tests of assumption were not strictly necessary because we used discriminant analysis as a descriptive, as opposed to a predictive, model (McGarigal et al. 2000; Hamann and Wang 2006). For the IDFdk variant analysis, five climate data points were outliers greater than three times the interquartile range. A preliminary data inspection showed that these outliers did not substantially affect discriminant analysis classifications, and therefore the outliers were retained for final analysis. We characterized all other outliers in the climate data as "mild" (less than three times the interquartile range), and therefore retained them for analysis.

Results

Subzone comparisons

Using the five selected annual climate normals, the best discriminant analysis classification was for the ESSF zone where all points were correctly classified (Table 3). The poorest classification was within the IDF zone where 23 of the 180 points were misclassified; however, the classification was still 88% correct. The percentage of correctly classified points was 94 and 90 for the BWBS and ICH, respectively. When the 18 annual variables were used in the discriminant analysis, the overall

TABLE 3. Classification matrix of biogeoclimatic units for different subzones within four zones comparing jackknifed classification by discriminant analysis of the selected climatic variables with classification based on current mapping.

Zone	Mapped unit	Predicted unit			Accuracy (% correct)
		dk1	**mw1**	**wk1**	
BWBS	**dk1**	57	3	0	95.0
	mw1	0	56	4	93.3
	wk1	0	4	56	93.3
		xv1	**dc1**	**wk1**	
ESSF	**xv1**	60	0	0	100
	dc1	0	60	0	100
	wk1	0	0	60	100
		dw1	**mk1**	**wk1**	
ICH	**dw1**	53	4	3	88.3
	mk1	2	58	0	96.7
	wk1	1	8	51	85.0
		xh2	**dk1**	**mw2**	
IDF	**xh2**	50	9	1	83.3
	dk1	10	50	0	83.3
	mw2	1	1	58	96.7

TABLE 4. Variance explained and standardized coefficients of the climate variables[a] for each biogeoclimatic zone.

Zone	Function[b]	Variance (%)	MAT	MWMT	MCMT	MAP	MSP
ESSF	1	90.4	−3.947	3.452	2.333	−0.923	0.972
	2	9.6	2.695	−1.358	−1.693	0.311	0.663
BWBS	1	89.1	1.058	0.389	−0.841	−0.617	1.402
	2	10.9	−0.038	−0.354	0.584	0.769	−0.344
ICH	1	71.4	−1.884	1.375	1.459	0.391	−0.628
	2	28.6	−0.727	1.674	−0.419	0.741	−0.107
IDF	1	86.8	1.673	0.855	−0.031	0.211	−1.798
	2	13.2	−2.258	0.586	0.157	1.048	0.861

a MAT = mean annual temperature (°C); MWMT = mean warmest month temperature (°C); MCMT = mean coldest month temperature (°C); MAP = mean annual precipitation (mm); and MSP = mean annual summer (May – September) precipitation (mm.)

b Function and variance explained in the original data set by each discriminant function. The contribution of each climate variable to the corresponding discriminant function is quantified by the standardized coefficient; the larger the absolute distance from zero, the stronger the contribution of that variable to the corresponding discriminant function.

classification success rates for the ESSF zone did not change. For the BWBS and ICH zones, success rates increased to 95 and 97%, respectively, and decreased to 87% for the IDF (see "Classification matrices," page 64).

For the BWBS biogeoclimatic units, the first discriminant function and standardized coefficients showed that mean annual summer precipitation and mean annual temperature were the most important variables (i.e., had the highest standardized coefficients), explaining 89.1% of the between-group variance (Table 4). Based on the means for the climate variables predicted by ClimateBC for the 60 randomly selected points, the BWBSdk1 has the driest growing season and the BWBSwk1 the wettest (Table 2). The BWBSdk1 is also the coldest of the units and the BWBSmw1 is the warmest in the summer (Table 2). The BWBSwk1 has the warmest winters also resulting in the highest mean annual temperature (Table 2).

The discriminant analysis misclassified four points within the BWBSmw1 as BWBSwk1, and four points within the BWBSwk1 as BWBSmw1. When the position of these misclassified points was examined geographically, all were near the border between the two biogeoclimatic units (Figure 2). All the elevations of these points, except one, were within 150 m of the general elevation boundary between the two units of 1050 m reported by DeLong et al. (1990). The remaining point, which was mapped as BWBSmw1 but classified as BWBSwk1, was at 862 m and at the southernmost extent of this unit. Three points within the BWBSdk1 were misclassified as BWBSmw1. These points were all at the eastern extent of the BWBSdk1 and had a combination of higher mean annual temperature and higher mean annual summer precipitation (as predicted by ClimateBC) than the correctly classified points. However, summaries of short-term climate station data (1966–1987) from the nearby community of Fort Ware, which were not included in producing ClimateBC, are more similar to BWBSdk1 normals than BWBSmw1 (Table 2) (i.e., mean annual temperature: −0.4°C; mean warmest month temperature: 13.6°C; mean coldest month temperature: −17.2°C; mean annual precipitation: 428 mm; and mean annual summer precipitation: 221 mm; Environment Canada 2008).

None of the points was misclassified for the ESSF. The first discriminant function explained over 90% of the variance between ESSF units, mostly as a result of temperatures (Table 4). The ESSFxv1 has the driest growing season and the ESSFwk1 the wettest (Table 2). The ESSFxv1 was also the coldest unit and the ESSFdc1 was the warmest.

For the ICH biogeoclimatic units, the first discriminant function explained 71.4% of the between-group variance, mostly because of differences in temperatures (Table 4). Based on the randomly selected points, the ICHdw1 was the warmest unit for all temperature variables and the ICHwk1 was the coldest (Table 2). The ICHwk1 was the wettest unit, the ICHmk1 was driest based on mean annual precipitation, and the ICHdw1 was driest based on mean annual summer precipitation (Table 2).

For the ICHdw1, the three points misclassified as ICHwk1 and three of the four points misclassified as ICHmk1 were at higher elevation near the boundary with the moist warm ICH (ICHmw). The other point misclassified as ICHmk1 was near the eastern extent of the ICHdw1 close the boundary of the dry mild ICH (ICHdm). The two points mapped as ICHmk1 but classified as ICHdw1 were both within 1 km of another variant of the ICHdw. These points were at the lower elevation limits of the ICHmk1 and had the highest predicted mean annual temperature of all the ICHmk1 points. Four of the nine points mapped as ICHwk1 but classified as ICHmk1 were near the southern extent of the ICHwk1. All were within 25 km of the ICHmk1 and within 1 km of the ICHmw. The other five points misclassified as ICHmk1 were in the middle of the range of the ICHwk1. Three of the five were less than 1 km from the ICHmw, whereas the other two were over 10 km away from any boundary of the ICHmw and closer to the very wet ICH (ICHvk).

For the IDF biogeoclimatic units, the first discriminant function explained 86.8% of the between-group variance. Mean annual summer precipitation, mean annual temperature, and mean warmest month temperature were the most important discriminating variables (Table 4). The IDFxh2 was the driest unit and the IDFmw2 the wettest (Table 2). The IDFmw2 was the warmest unit based on mean annual temperature and mean warmest month temperature, whereas the IDFdk1 was the coldest (Table 2).

For the IDF zone, 10 points mapped as IDFdk1 were classified as IDFxh2 by the discriminant analysis. Six of these points were within 500 m (horizontal map distance) and none were more than 1400 m from the mapped boundary between the two units. These points were predicted to have a combination of higher predicted mean warmest month temperature and mean coldest month temperature and lower predicted mean annual precipitation and mean annual summer precipitation than other points in the IDFdk1 that were correctly classified. Nine points mapped as IDFxh2 were classified as IDFdk1. Five of these were within 500 m (horizontal map distance) of the mapped boundary and none was greater than 800 m. These points had lower mean warmest month temperature and higher mean annual precipitation than other correctly classified points in the IDFxh2. One point at the northeastern extent of the IDFxh2 was misclassified as IDFmw2 and it had a combination of higher predicted mean annual precipitation and mean warmest month temperature than the correctly classified points. Only two points were misclassified in the IDFmw2. One of these points classified as IDFdk1 was mapped at the southern extent of the IDFmw2 near the boundary with the IDFdk1 and within 100 m of the boundary of the IDFdk2, another variant of the IDFdk. The other point classified as IDFxh2 was near the middle of the IDFmw2 (nowhere near the IDFxh2) and also relatively close to a dry variant of the ICH, a wetter zone. This point was predicted to have a combination of lower mean annual precipitation and mean annual temperature than other correctly classified points in the IDFmw2.

Variant comparison

Using the five annual climate normals, discriminant analysis correctly classified 92% of the points in the ICHdw variant, and 79% of the points in the IDFdk variant. Using the 18 annual climate normals, overall discriminant analysis classification rates increased to 98% for the ICHdw and did not change for the IDFdk (see “Classification matrices,” page 64).

Among ICHdw units, temperature variables had the highest contribution to the first discriminant function, which explained 88.1% of the between-group variance (Table 5). The ICHdw3 is the coldest of the variants, whereas the other two are quite similar in temperature regime (Table 6). The ICHdw2 had the lowest precipitation both annually and over the growing season (Table 6).

The lowest classification rate was 80% for the ICHdw1 (Table 7). All but one of the 12 points mapped as ICHdw1 but classified as ICHdw2 were more than 10 km away from the nearest mapped polygon of ICHdw2. All of these points were less than 5 km from a boundary with the ICHmw. These points were generally near the lower limit of the mean annual precipitation predicted for the points in the ICHdw1. The four points mapped as ICHdw3 but classified as ICHdw2 were all near the southern extent of the ICHdw3 at the lower limits of elevation for this unit. The ICHdw3 and ICHdw2 are disjunct units, being separated by more than 200 km. These misclassified points had predicted temperature variables at the higher end of the range and mean annual precipitation at the low end of the range for the ICHdw3 points.

Similar to the ICHmw variant analysis, temperature variables explained over 90% of the variance among the IDFdk units (Table 7). The IDFdk3 is the coldest of the variants, whereas the IDFdk2 is the warmest (Table 6).

TABLE 5. Variance explained and standardized coefficients for the climate variables[a] for the ICHdw and IDFdk subzones.

Subzone	Function[b]	Variance (%)	MAT	MWMT	MCMT	MAP	MSP
ICHdw	1	88.1	–5.946	3.613	2.920	2.138	–1.848
	2	11.9	4.258	–2.348	–1.925	1.999	–1.550
IDFdk	1	92.4	–2.494	2.392	1.362	0.188	–0.292
	2	7.6	0.192	0.253	–0.307	0.850	0.189

a MAT = mean annual temperature (°C); MWMT = mean warmest month temperature (°C); MCMT = mean coldest month temperature (°C); MAP = mean annual precipitation (mm); and MSP = mean annual summer (May – September) precipitation (mm.)

b Function and variance explained in the original data set by each discriminant function. The contribution of each climate variable to the corresponding discriminant function is quantified by the standardized coefficient; the larger the absolute distance from zero, the stronger the contribution of that variable to the corresponding discriminant function.

The IDFdk1 was the driest during the growing season with the IDFdk3 being the wettest. The IDFdk2 was the wettest based on precipitation over the year (Table 6).

For the IDFdk, the poorest classification rate was 70% for the IDFdk2 (Table 7). The IDFdk1 and dk2 were often confused by the discriminant analysis with a total of 28 misclassified points (Table 7). Ten of these points were within 3 km of a mapped polygon of the other variant, but six points were over 10 km away with the furthest being 27.6 km away. Generally, points mapped as IDFdk1 with predicted mean annual temperature and mean annual precipitation at the high end of the range for the IDFdk1 points were classified as IDFdk2. The reverse was true for misclassified points in the IDFdk2. The eight points that were confused by the discriminant analysis between the IDFdk1 and dk3 were near the north–south boundary between the two variants. Six of these points were within 10 km of the boundary. The one point mapped as IDFdk2 but classified as IDFdk3 was also near the north–south boundary of the two variants. Generally, the points mapped as IDFdk1 or dk2 but classified as IDFdk3 had predicted mean coldest month temperature and mean annual temperature at the lower end of the range for these variants. The reverse was true for the IDFdk3 points misclassified as IDFdk1.

Discussion

The high degree of success at discriminating between mapped biogeoclimatic units using climate variables predicted by ClimateBC illustrates the effectiveness of the BEC approach, which uses vegetation growing on zonal sites to map climatically distinct areas of the landscape. Even at the finest level of the mapping, the variant level, over 70% of the randomly selected points were correctly classified according to their mapped unit based on selected climate variables. A large proportion of the misclassified points for the subzone-level analysis were within 1 km horizontal distance or 100 m elevation of the boundary and are typically biogeoclimatic transitional areas.

Our study builds on the results of Hamann and Wang (2006) who showed that mapped biogeoclimatic zones could be successfully classified using discriminant analysis. They achieved classification success rates of 91, 72, 60, and 69% for BWBS, ESSF, ICH, and IDF, respectively. The authors suggested that, when distinguishing at the zone level, discriminant analysis has high classification success with biogeoclimatic zones of low topographic relief (e.g., BWBS); it has relatively high errors with zones occupying narrow elevation bands in mountainous terrain (e.g., ICH). We have demonstrated that discriminant analysis can be used successfully at finer spatial scales even in complex terrain. This suggests that climate varies enough over space to differentiate plant communities at relatively fine scales and this is well reflected in the assemblage of vegetation found on zonal sites. Among the subzones analyzed in this study, discriminant analysis was more successful at classifying the coldest zones (i.e., ESSF and BWBS), than the warmest zone (IDF).

Despite the success of using modelled climate data to distinguish ecosystems at various scales, it is important to acknowledge model limitations. For British Columbia, modelling spatial precipitation data from geographic variables is difficult because of elevation differences between climate stations and PRISM tiles, non-uniform climate station coverage, and complicated elevation–precipitation relationships (Wang et al. 2006).

TABLE 6. Mean climate normals (1971–2000) and standard deviations for biogeoclimatic variants used in the variant-level analysis based on the 60 randomly selected points.

		ICH			IDF		
		dw1	**dw2**	**dw3**	**dk1**	**dk2**	**dk3**
MAT[a]	mean	5.6	5.2	4.3	3.7	4.1	3.2
	sd	1.1	0.5	1.0	0.6	0.6	0.6
MWMT[b]	mean	17.0	16.4	15.4	14.4	14.9	14.0
	sd	1.1	0.5	1.2	0.7	0.7	0.8
MCMT[c]	mean	–5.9	–5.9	–7.6	-–6.7	–6.2	–8.4
	sd	1.0	0.3	0.8	0.5	0.6	0.6
TD[d]	mean	22.9	22.2	23.0	21.1	21.0	22.4
	sd	0.6	0.3	0.6	0.6	0.9	1.0
MAP[e]	mean	823.9	627.0	726.1	452.6	606.7	450.4
	sd	159.3	56.2	150.7	66.7	189.0	49.2
MSP[f]	mean	283.8	254.7	307.8	197.2	221.1	240.6
	sd	45.8	19.9	48.9	25.3	40.8	22.3
AH:M[g]	mean	19.7	24.5	20.4	30.9	24.7	29.6
	sd	4.5	2.4	4.2	4.8	5.1	3.5
SH:M[h]	mean	61.7	64.8	51.5	74.2	68.9	58.9
	sd	12.0	5.8	9.3	10.5	11.1	6.4
DD<0[i]	mean	598	608	769	767	709	908
	sd	122	49	112	75	65	68
DD>5[j]	mean	1568	1447	1302	1112	1184	1077
	sd	238	113	221	119	130	131
DD<18[k]	mean	4343	4476	4821	5031	4876	5214
	sd	375	175	377	219	209	219
DD>18[l]	mean	78	48	33	13	18	10
	sd	48	16	28	7	13	7
NFFD[m]	mean	188	178	171	160	168	145
	sd	14	6	15	9	8	10
bFFP[n]	mean	140	146	149	159	155	163
	sd	7	4	9	7	6	7
eFFP[o]	mean	255	251	247	245	248	234
	sd	5	3	7	4	4	6
FFP[p]	mean	116	105	98	86	93	71
	sd	12	7	16	10	9	12
PAS[q]	mean	273.6	198.6	248.6	168.8	230.4	148.7
	sd	91.2	24.6	69.2	34.5	85.9	18.6
DD5_100[r]	mean	125	130	132	143	140	141
	sd	9	5	9	7	7	8

a MAT Mean annual temperature (°C)
b MWMT Mean warmest month temperature (°C)
c MCMT Mean coldest month temperature (°C)
d TD Temperature difference between MWMT and MCMT, or continentality (°C)
e MAP Mean annual precipitation (mm)
f MSP Mean annual summer (May to September) precipitation (mm)
g AH:M Annual heat:moisture index ((MAT+10)/(MAP/1000))
h SH:M Summer heat:moisture index ((MWMT)/(MSP/1000))
i DD<0 Degree-days below 0°C, chilling degree-days
j DD>5 Degree-days above 5°C, growing degree-days
k DD<18 Degree-days below 18°C, heating degree-days
l DD>18 Degree-days above 18°C, cooling degree-days
m NFFD Number of frost-free days
n FFP Frost-free period
o bFFP Julian date on which FFP begins
p eFFP Julian date on which FFP ends
q PAS Precipitation as snow (mm)
r DD5_100 Julian date at which degree days above 5°C (i.e., growing degree days) reaches 100

TABLE 7. Classification matrix of biogeoclimatic units for variants within a subzone from a dry and wet climate comparing jackknifed classification by discriminant analysis of the selected climatic variables with classification based on current mapping.

Zone	Mapped unit	Predicted unit			Accuracy (% correct)
		dw1	**dw2**	**dw3**	
ICH	**dw1**	48	12	0	80.0
	dw2	0	60	0	100.0
	dw3	0	3	57	95.0
		dk1	**dk2**	**dk3**	
IDF	**dk1**	45	11	4	75.0
	dk2	17	42	1	70.0
	dk3	4	0	56	93.3

According to the model developed by Wang et al. (2006), "geographical variables can maximally explain only 65% of the total variation in precipitation (vs. over 90% for temperature variables)" and that "no elevation adjustment was applied to precipitation." This likely explains why mean annual precipitation was never an important discriminating variable and mean annual summer precipitation was only important in distinguishing between the BWBS and IDF, both of which are generally lower-relief zones lacking strong elevational gradients as compared with the ICH or ESSF. Therefore, future application of our methodology to biogeoclimatic units that primarily differ in precipitation, especially if driven by elevation, may yield lower classification success rates.

Further model limitations need to be considered. Using the 1971–2000 climate normals may introduce potential errors to the climate data because these normals are adjusted from the baseline period of 1961–1990 from which the PRISM and ClimateBC were developed (Mbogga et al. 2009). PRISM and ClimateBC temperature data is generated from weather station measurements at 1.5 m above ground, which may not best replicate the microclimate conditions necessary to represent biogeoclimatic units (Wang et al. 2006). A more detailed description of the limitations inherent in the climate data can be found in Daly et al. (2002), Wang et al. (2006), and Mbogga et al. 2009). As well, the misclassification of some points may be attributable to the delineation of the ecosystem boundaries themselves—as discussed in the introduction, ecosystem delineation is a somewhat subjective procedure.

The largest discrepancies between locations of misclassified points relative to the range of the correct biogeoclimatic unit were for the ICH at both the subzone and variant level. Many of the misclassified points were more than 10 km away from the boundary of the two units confused by the discriminant analysis. In some cases, the predicted climate statistics for a misclassified point did not correspond well with the mapped biogeoclimatic units in the area. For instance, all the points mapped as ICHdw1 but classified as ICHdw2 were closer to areas mapped as a wetter subzone (the ICHmw) than to anything drier, even though these points had predicted precipitation variables at the low end of the range for ICHdw1.

Climate data from Fort Ware, in the vicinity of the points mapped as BWBSdk1 but misclassified as BWBSmw1, fit better with the bounds of the BWBSdk1 climate space than the BWBSmw1 climate space. The Fort Ware station was likely not used to parameterize the PRISM model according to the criteria in Wang et al. (2006) owing to gaps in the data. Such areas may be examples of where the ClimateBC model makes inaccurate predictions.

The least successful discriminant analysis classification was at the variant level between the IDFdk1 and dk2. These units occur in the same geographic area over a similar elevation range and have relatively similar zonal vegetation (e.g., lack of *Chimaphila umbellata* [L.] Bart. and *Paxistima myrsinites* [Pursh] Raf. on zonal sites in the IDFdk1), so it is not unexpected that the climate differences are equivocal.

With a rapidly changing climate, it is unlikely that the vegetation expressed on a zonal ecosystem will continue to be an accurate reflection of the current climate, although it is unclear how quickly this may occur. Because areas of similar macroclimates are defined by relatively permanent atmospheric and geographic factors (e.g., the position of large water bodies, orthographic influences, and the amount of solar radiation received) (Demarchi 1996), we anticipate that the boundaries of surrounding areas with similar past climate may be retained but will just have a differing climate within these boundaries. This makes the current mapped biogeoclimatic units extremely useful in understanding climate parameters of forest regions and examining the potential climate change implications to ecosystem processes at the landscape scale.

The high quality of the climatic unit mapping and description of site or climatic potential is likely without compare worldwide and puts British Columbia in a lead position to study the implications of climate change at this scale.

Recommendations

The biogeoclimatic unit should continue to form the basic unit for examining climate change at multiple scales from the provincial scale to the scale of watersheds or basins. These units accurately represent areas of relatively homogenous macroclimate that are well differentiated from one another. The high quality of the climatic unit mapping and description of site or climatic potential is likely without compare worldwide and puts British Columbia in a lead position to study the implications of climate change at this scale.

A further analysis following the methods outlined in this article can be used to improve both biogeoclimatic unit mapping and ClimateBC models. Undersampled regions where mapped units disagree with ClimateBC discriminant analysis prediction should be priority areas for field visits to assess correct biogeoclimatic designation. Areas where unit designation is confirmed by fieldwork but is contradicted by the ClimateBC discriminant analysis are prospective areas for improvements to the PRISM model through model adjustment or collection of additional climate measurements.

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Classification matrices

Classification matrix of biogeoclimatic units for different subzones within four zones comparing jackknifed classification by discriminant analysis of the 18 climatic variables with classification based on current mapping.

Zone	Mapped unit	Predicted unit			Accuracy (% correct)
		dk1	mw1	wk1	
BWBS	dk1	57	3	0	95.0
	mw1	0	56	4	93.3
	wk1	0	2	58	96.7
		xv1	dc1	wk1	
ESSF	xv1	60	0	0	100
	dc1	0	60	0	100
	wk1	0	0	60	100
		dw1	mk1	wk1	
ICH	dw1	58	2	0	96.7
	mk1	1	59	0	98.3
	wk1	1	1	58	96.7
		xh2	dk1	mw2	
IDF	xh2	49	9	2	81.7
	dk1	11	49	0	81.7
	mw2	1	1	58	96.7

Classification matrix of biogeoclimatic units for variants within a subzone from a dry and wet climate comparing jackknifed classification by discriminant analysis of the 18 climatic variables with classification based on current mapping.

Zone	Mapped unit	Predicted unit			Accuracy (% correct)
		dw1	dw2	dw3	
ICH	dw1	56	4	0	93.3
	dw2	0	60	0	100.0
	dw3	0	0	60	100.0
		dk1	dk2	dk3	
IDF	dk1	40	15	5	66.7
	dk2	13	46	1	76.7
	dk3	4	0	56	93.3

Test Your Knowledge . . .

Corroboration of biogeoclimatic ecosystem classification climate zonation by spatially modelled climate data

**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. For which biogeoclimatic zone were the mapped units most poorly differentiated based on climate variables?
   A) Boreal White and Black Spruce zone
   B) Interior Cedar–Hemlock zone
   C) Interior Douglas-fir zone

2. Which climate variable was most useful at differentiating between the mapped biogeoclimatic units?
   A) Mean annual temperature
   B) Mean annual precipitation
   C) Mean seasonal precipitation

3. What were the general conclusions of this study?
   A) Mapped biogeclimatic units poorly represent areas of homogenous climate and will not be useful in climate change research
   B) Mapped biogeoclimatic units appear to represent areas of relative homogeneous climate very well but have little value for climate change research
   C) Mapped biogeoclimatic units appear to represent areas of relative homogenous climate very well and are a useful aid in carrying out climate change research

ANSWERS

1. B 2. A 3. C