# Final Technical Report

## Forest Science Program Project # Y093061

**Development and analysis of forest health databases, models, and economic impacts for BC: Spruce bark beetle & spruce; western spruce budworm and Douglas fir**

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## Abstract

The impact of projected climate change on spruce and Douglas fir forests in British Columbia was assessed using bioclimatic envelope models. Present and future climatic suitability was modelled for Douglas fir, Engelmann spruce, hybrid spruce, and white spruce. A correlative modelling technique based on principal component analysis was employed to determine climatic suitability throughout British Columbia. The models were developed using elevation-adjusted interpolated records of the 1961-1990 climate baseline. Future suitability was modelled using climate data from six projections derived from five different Global Climate Models (GCMs) under three emissions scenarios. All projections indicate a shift in suitability for both spruce and Douglas fir to higher elevations and latitudes than their current range. However, significant differences exist between the projections with regard to the pace, extent and fine-scale details of these changes. This uncertainty was investigated by comparing individual projections to each other and presenting results of agreement between models. The effect of spatial resolution was also investigated. The impact of pest suitability was assessed with a simple climate envelope method based on empirically derived climate thresholds affecting locations of historical pest outbreak occurrence of western spruce budworm (WSBW) and spruce bark beetle (SBB). Future projections show increased outbreak risk in central and northwestern British Columbia for two climate scenarios and both pest species. By the end of the century, considerable portions of the Province have no analogue to past outbreak conditions.

The tree suitability and pest suitability results were processed together with forest inventory data by an economic model that considers major stand-level harvest decisions such as greenup constraints, preserves large tracts of old-growth forest, and an even flow of harvest. The model was solved using an iterative spatial optimization method that has good convergence properties. The model was applied to data for the Okanagan TSA and for the entire Province of BC. The results (based on climate influence on tree species and pest outbreaks for Douglas fir/WSBW and spruce/SBB only) show that the economic impact of climate change is a modest improvement or no change, depending on climate scenario, for the Province overall, but that there is a negative economic impact for the Okanagan TSA in all cases.

## Preface

It was unexpected to discover the Pine Beetle infestation and that such a small change in climate could trigger changes of such magnitude. Of course, other factors also contributed to the devastation, such as the pine monoculture and the uniform young age of the stand. However, experts in forestry saw this coming.

Therefore, it is now prudent to examine future climate conditions to ask about the habitat of both tree species and the forest pests that are not held in equilibrium. This Final Report of Forest Science Program Project # Y093061 conducted at the Pacific Climate Impacts Consortium (PCIC) documents the work that was undertaken to assemble databases and investigate methods for the projection of future impacts of climate change on forest health. Work conducted during three years of the project is referred to including methods that were used for final results. The results and discussion sections are limited by results available up to the end of the 2008/2009 fiscal year. The analysis will continue and be made available through the PCIC website, journal publications, and as a subsequent PCIC report on final results and interpretation.

## Acknowledgements

This project is the first multi-year externally funded project of the Pacific Climate Impacts Consortium to reach completion. Its success depended on a multi-disciplinary team located at BC Ministry of Forests and Range, Pacific Forestry Centre (Natural Resources Canada), and University of Victoria: Dave Spittlehouse, Steve Taylor, Richard Hebda, Rene Alfaro, Vince Nealis and Kees Van Kooten. Advice from Greg O'Neill, Jennifer Burleigh, Tongli Wang, Andreas Hamman, Ian O'Connell and participants in the October 2007 workshop was also extremely valuable to ensuring relevance and applicability of project results. Several PCIC staff contributed to the project: Harry Swain, Dave Bronaugh, Cassbreea Dewis, Harpreet Jaswal and Katrina Bennett. This project depended on research conducted by Ph.D. candidate Hamish Aubrey and post-doctoral researchers Alvaro Montenegro, Alan Mehlenbacher, and Kirstin Campbell. Finally, we wish to acknowledge the financial support of the BC Forest Investment Account – Forest Science Program and the administrative support of the University of Victoria.

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## 1. Introduction

This report describes the results of a three year study conducted by the Pacific Climate Impacts Consortium to assemble databases related to forest health, investigate methods for projecting climate impacts on tree and pest species, and to assess future climate impacts on tree species and pest risk, including economic impacts. The study was funded by the BC Forest Investment Account – Forest Science Program projects Y071321, Y071061, Y082061, and Y093061.

BC's climate is already changing (Rodenhuis et al., 2007), and evidence is visible of the ecological impacts of climate change in British Columbia (Gayton, 2008) and across the globe (Parmesan, 2006; Parmesan and Yohe, 2003; Walther et al., 2002). Future projections of climate change indicate increasing temperatures (Figure 1) in all seasons, increasing winter precipitation, and decreasing summer precipitation over much of BC (Rodenhuis et al., 2007). The changes projected to occur over the coming century are comparable to or larger than trends that have occurred already (Rodenhuis et al., 2007).

Bioclimatic envelope models are a practical tool for assessing the potential impacts of climate change on species distributions. These models use historical climate data to define the climatic envelopes that in large part determine species' geographic distributions at broad spatial scales. Bioclimatic envelope models are constructed using climate data only, and therefore do not account for other limiting environmental factors, such as soil types, nor for the ability of species to migrate into newly climatically suitable areas. Therefore, these models cannot be used to predict the actual locations of forests in the future, but they can be useful for assessing potential climatic impacts on forest health and for making decisions regarding assisted migration of species to new, more climatically suitable areas (O'Neill et al., 2008; Pearson and Dawson, 2003).

In this study, present and future climatic suitability was modelled for Douglas fir (*Pseudotsuga menziesii*), Engelmann spruce (*Picea engelmannii*), hybrid spruce (*Picea engelmannii* x *glauca*), and white spruce (*Picea glauca*). These are economically important species which are present throughout significant portions of North America (Figure 2). Two climate envelopes were constructed, one for Douglas fir and one for the three spruce species combined, using a correlative principal components analysis (PCA) based modelling method based on the model described in (Robertson et al., 2001). PCA-based modelling methods can define climate envelopes using any number of predictor variables, even if these variables are highly correlated with each other. Because this PCA method requires only location data for the presence of a species, it is especially useful for regions or species with a lack of high-quality absence data.

Adaptation of forest practices in order to consider future climate change will require not only the selection of climatically suitable tree species and seedlots for planting, but also climate impacts on other disturbances. In particular, climate is expected to influence pest disturbances and wildfire. In this project, a workshop was held of North American experts in forests and pests. The top four in a ranked list of pests that pose the greatest threat to forest values due to climate change according to participants (Abbott et al., 2008) includes spruce bark beetle (SBB), western spruce budworm (WSBW), Douglas-fir bark beetle and western balsam bark beetle.

The possible relationships between climate and two pests (SBB & WSBW) were investigated using dynamical, correlative, and climate envelope approaches. A simple percentiles-based climate envelope approach (not PCA as for tree species) was selected for use in quantifying past and future risk of outbreaks.

The tree species suitability and pest outbreak risk components of this study address two themes of the Future Forests and Ecosystems Initiative (Hamilton and Niemann, 2008) through future projections and uncertainty. The third theme, *Managing in the Face of Uncertainty*, requires a systems approach that integrates the results of climate impacts on components of the ecosystem such as tree species and pest risk, and tracks the economic value of biophysical impacts over the coming century.

In this study, a moving frame spatial optimization bio-economic model (Figure 3) was developed following a thorough literature review. The model was developed to determine economic impacts resulting from the bio-physical impacts of climate change projected for tree species and forest pests. The final result is a proof of concept that spatial bio-economic modelling can be implemented to incorporate future projections of biophysical impacts on forests. In order to use results for decision-making, further work is required in order to investigate the validity of assumptions and to incorporate additional ecological impacts such as other species, impacts of climate variability, and wildfire.

## 2. Methods

Methods used in each of the three major components of investigation (tree species suitability, risk of pest outbreaks, and bio-economic modelling) are described in their own sub-section below. In addition, an important part of the overall methodology was to gather required datasets at the outset of the project, assess various potential modelling methods available for use, and to obtain feedback from research scientists and stakeholders on the planned approach in a workshop setting (Abbott et al., 2008; Flower and Murdock, 2008). Numerous databases of climatic, biological, and topographic variables have been compiled as part of the project. A full list of these databases is available online[i]. Use of tree species, pest outbreak, and climate data in particular are described in their respective sub-sections below.

### 2.1. Tree species suitability

#### Tree species distribution data

Species presence records were obtained for British Columbia in the form of Biogeoclimatic Ecosystem Classification (BEC) vegetation survey plots from the British Columbia Ministry of Forests and Range (BC Ministry of Forests and Range, 2007a). BEC vegetation survey plots are located strategically throughout the Province in undisturbed areas (Meidinger and Pojar, 1991). Records from similar vegetation plot surveys were obtained for Alberta, Washington, and the Yukon Territory. To help compensate for the scarcity of vegetation plots in the north, a set of known locations of spruce plots was obtained from the International Tree-Ring Data Bank (National Climatic Data Center Paleoclimatology Program, 2008). Species distribution data was also obtained in the form of aerial survey records from the Vegetation Resources Inventory (VRI) (BC Ministry of Forests and Range, 2007b). The VRI records were not used in building the models due to concerns regarding their accuracy and the fact that they are not restricted to undisturbed landscapes, but were instead utilized for visual verification of the model results.

#### Climate data

High-resolution climate data is required to adequately represent the diverse local climatic conditions across British Columbia's high-relief, mountainous landscape. The software program ClimateBC version 3.2.1 (Wang et al., 2006) was utilized to obtain climate records downscaled to 4-km and 600-metre resolutions. ClimateBC uses a combination of bilinear interpolation and elevation corrections to downscale Parameter-elevation Regression on Independent Slopes Model (PRISM) climate records (Daly et al., 2002). Eight biologically relevant climate variables were extracted from ClimateBC and included in the models. Temperature was represented by mean annual temperature (MAT), mean warmest month temperature (WMT), mean coldest month temperature (CMT), and temperature difference (TD) between WMT and CMT (i.e., continentality). Precipitation was included in the form of mean annual precipitation (MAP) and mean annual summer (May - September) precipitation (MSP). Annual and summer heat to moisture indices (AHM and SHM, respectively) were also included.

[i] http://pacificclimate.org/tools/data/

### Climatic envelope methods

A number of mechanistic and correlative modelling methods were initially explored for analyzing climatic suitability for the host tree species. Correlative modelling approaches were deemed more appropriate than mechanistic models because the research was designed to estimate the species' responses to climate change, not to explore the physiological response of a species to climate. Various correlative methods were considered, including General Linear Models (GLMs), General Additive Models (GAMs), and Random Forests classification. Methods that require both presence and absence records of the host were ruled out due to concerns regarding the quality and availability of absence records. A correlative principal component analysis based bioclimatic envelope modelling method was chosen for the purposes of this study.

### Principal Components Analysis

The eight climate variables listed in the previous section were extracted from ClimateBC for the exact locations of all available presence-records for each species (Figure 4). PCA was carried out on the climate variables associated with the presence-records for each species. All components with eigenvalues greater than one were retained as significant for inclusion in the bioclimatic envelope model. The loadings of the principal components on each climate variable were examined and interpreted to assess the relative importance of each variable in the model and the associations between variables.

To define the current climatic suitability for each species, a predictive dataset was created using the same eight climate variables. Values of these climate variables were extracted from ClimateBC for the entire Province at a spatial resolution of 4-km. Each variable was standardized using the mean and standard deviation calculated for the presence records of that variable. This was done to centre the predictive dataset on the origin of the climatic envelope (Robertson et al. 2001). The standardized climate variables were multiplied by the component loadings to calculate a score for each grid-cell in the predictive dataset on each principal component. The models' component scores represent a spectrum of climatic conditions, with values near the centre of the spectrum interpreted as the ideal conditions for the species being analyzed. The new component scores were standardized by dividing by the associated eigenvalue. The standardized component scores were squared and summed. The square-root of the sums was taken to calculate the Euclidian distance of each predictive point from the centre of the climatic envelope. These steps were repeated for each climate projection to calculate projected future suitability.

For ease of interpretation, the Euclidian distances were converted into percent suitability values by dividing by the maximum distance value from the baseline model and then subtracting the resulting value from one. A detailed example of this process is given in Appendix A. For analyses requiring a binary suitable/unsuitable categorization, a threshold of 90% suitability was subjectively chosen based on a visual comparison of different threshold values and the actual current distribution of the species. The modelled suitability values from all climate projections were combined by simple averaging to calculate mean predicted suitability values. Additional technical details regarding tree species suitability are available in FY0708 deliverables (Campbell, 2008) and in Appendix A.

## 2.2. Pest suitability

The relationship between climate and occurrence of outbreaks of spruce bark beetle (SBB) and western spruce budworm (WSBW) was examined using three different approaches. Several methods for quantifying and modelling climate-pest dynamics were considered, including correlation analysis, spectral analysis, and logistic regression models. In addition, two climate envelope methods were investigated.

### Pest outbreak and climate data

The *Forest Inventory Dataset* was provided by the Pacific Forestry Centre (PFC) of the Canadian Forest Service. This dataset consists of pest impact data digitized from aerial photography surveys at 400-metre resolution. Observations covered the period from 1905 to 2005 for WSBW and 1950 to 2005 for

SBB. Due to quality concerns with the earlier observations, only impacts after 1950 were analysed. The pest outbreak records cannot be considered continuous time series due to concerns regarding the quality of absence records; years with no recorded outbreak might actually represent years in which outbreaks occurred but were not observed due to small size of outbreak or incomplete spatial coverage of observations.

The pest outbreak investigation utilized the ClimateBC data described above as well as gridded climate time series from University of East Anglia Climatic Research Unit (Mitchell and Jones, 2005) and Environment Canada (Zhang et al., 2000).

### Biological spatial statistical modelling

A model of western spruce budworm development and Douglas fir budflush was implemented (in the BioSIM software environment). The model was based on historical weather data, optimal phenology, emergence, first tree flush day, flight, last day zero, pre-March 12 average minimum, average temperature by stage, days with precipitation by stage, and total duration. Preliminary results of the model were tested at three stations within BC (Hope, Pemberton, and Saanichton). Extensive testing and calibration with historical observations is required for further use. Subsequently, biological modelling is expected to provide detailed projections of future outbreak against which the envelope projections developed in this project can be compared and to provide additional site-specific modelling of use in decision-making. Additional technical details and results regarding the BioSIM model of western spruce budworm and Douglas fir budflush are available in the FY0607 deliverables (Ford and Taylor, 2007).

### Lagged climate-outbreak correlations

This stage of analysis utilized visual examination of scatterplots to compare outbreak records with monthly and seasonal records of temperature and precipitation anomalies from the CRU and CANGRID climate datasets described above. Anomalies were calculated with respect to the 1902-2002 mean. Analysis included consideration of lags between climatic events and pest outbreaks by averaging anomalies over a 5, 10, 15, 20, 25 or 30 year period before the occurrence of a pest outbreak. Analysis was also undertaken using windowed anomalies computed for a 17-year window centered at 10, 15, 25 or 35 years before the outbreak occurrence.

This method tested the concept that climate might provide the initial conditions that set in place the origins of the outbreak, but that, with the increase in insect population, other factors start to weight in and climate conditions become less important in determining the occurrence or not of an outbreak. Relationships did appear to exist in certain seasons, more strongly with precipitation than temperature. However, these relationships were considered too weak to be developed further under the scope of this project. Additional technical details and results of lagged climate-outbreak correlations are available in the FY0708 deliverables (Montenegro, 2008).

### Climate envelope of outbreak climatology

Following the investigation of dynamical and lagged correlative approaches, a climate envelope approach was used. Although this method is of the same category as that used for tree species suitability, and a variety of climate envelope modelling methods were considered, the use of climate envelopes for pest outbreak risk was limited by the need to consider thresholds for pest outbreaks rather than similarity to optimal climate as for tree species.

A relatively simple percentiles-based method was identified as the option that would allow for preparation of projections that would be suitable as input data for the bio-economic model. This method allows for the inclusion of absolute thresholds, making it well suited to insect species. Relevant climate variables were selected by comparing the frequency of occurrence of pest outbreaks at a given value of a climate variable to the frequency of occurrence of the host species at that same value. If the frequency of pest outbreaks was identical to the frequency of the host, no climatic influence on outbreak occurrence could be assumed and that variable was excluded. If, however, there was an offset between the frequency of occurrence of pest outbreaks and host trees, such as in relatively cold areas where many hosts may grow but few outbreaks have occurred, then that variable was inferred to impact the likelihood of pest outbreaks. The climate data analysed were 30-year normals for the period 1961-1990. Fourteen climate variables were initially considered for inclusion in the bioclimatic envelope models, but only six were included in the final WSBW model, and seven in the final SBB model (Table 1). The following variables were investigated but not used as thresholds for either SBB or WSBW: warmest month temperature, Degree Days > 18°C, Degree days < 5°C, Degree days > 5°C, Date when degree days > 5°C = 100.

**Table 1: Variables used for pest outbreak envelopes**

| Variable | SBB | WSBW |
|---|---|---|
| **Mean annual temperature (MAT)** | X | X |
| **Coldest month temperature (CMT)** | X | X |
| **Annual temperature range (TD)** | X | X |
| **Mean annual precipitation (MAP)** | X | |
| **Mean summer precipitation (MSP)** | | X |
| **Annual heat to moisture index (AHM)** | X | |
| **Summer heat to moisture index (SHM)** | | X |
| **Degree days < 0°C (DDlt0)** | X | X |
| **Degree days < 18°C (DDlt18)** | X | |

To create the bioclimatic envelope models, the 1961-1990 baseline climate of the selected variables were extracted for all locations where pest outbreaks occurred between 1961-1990. Percentiles were calculated for each variable to define the climate envelopes. Climate data was then extracted for the entire Province at 4-km resolution. Areas with climatic conditions identical to those at the locations where 90% (the 5th to 95th percentiles) of all pest outbreaks occurred were labeled as high risk areas. Areas with climatic conditions identical to those at the locations where the remaining 10% of pest outbreaks occurred were labeled as medium risk. Locations with climatic conditions outside of those in which historical pest outbreaks have occurred were labeled as low risk.

To determine future risk of pest outbreaks, climate projections covering the Province at a resolution of 4-km were compared to the range of climate values associated with the previously defined classes of risk of outbreak. As before, areas with climatic conditions falling within the range that 90% of historical pest outbreaks occurred under were labeled as high risk and areas with climatic conditions falling outside of the high risk range but within the range that 100% of historic outbreaks occurred under were labeled as medium risk. Areas with future climate conditions outside the range in which pest outbreaks have historically occurred were labeled as undefined. These undefined risk areas have climates with no direct historical analogue, and risk of outbreaks can therefore not be confidently assessed with this threshold-based envelope method where there is no analogous historical data. Further details regarding the methods used to assess risk of outbreak can be found in Appendix B.

## 2.3. Bio-economic modelling

### Literature review

A thorough literature review of methods used for modelling the economic impacts of climate change was conducted including stochastic models, dynamic programming, computable general equilibrium, Ricardian models, multiagent systems, and Bayesian networks. Stand Establishment Decision Aids and Growth and Yield Models were also reviewed to seek a decision-making tool that could utilize the results of the economic modelling. Although none were found at the project outset, it is now expected that a new decision-making tool being developed at the BC Ministry of Forests and Range could incorporate results from this project (Hamilton and Niemann, 2008).

Three modelling methods were chosen for trial runs. A non-spatial optimization method was attempted but rejected due to the importance of spatial information for making harvesting decisions. Two models were implemented: spatial cellular automata and spatial optimization. The latter was chosen for further development of economic impacts on the timber supply areas (TSAs) in British Columbia.

### Data

The bio-economic modelling uses as input the tree species suitability and pest outbreak risk projections prepared in the other components of this study. In addition, the VRI species coverages are used to determine harvestable timber volume. Temperature and precipitation climate data from ClimateBC at 600-m and 4-km resolutions are used for the 1961-1990 baseline, the 2020s, 2050s, and 2080s time slices from two GCMs (CGCM3 A2 run 4 = Warm/Wet, HadGEM A1B run 1 = Hot/Dry). In addition, data for volume equations was obtained from (Van Kooten and Bulte, 1999) and (Krcmar et al., 2005), and data for economic values were obtained from (Krcmar and van Kooten, 2008), (Van Kooten and Bulte, 1999), and the BC Ministry of Forests and Range Log Market Reports.

### Spatial optimization

Development of a spatial optimization model was completed, incorporating feedback from external peer review. The optimization method simulates forest management decisions such as accounting for greenup and grow, clustering preserved forest in large tracts, and achieving a relatively even-flow of harvest for steady employment and revenue in the forest industry. This method involves competing objectives with local constraints, neighbourhood constraints, and global constraints over a large geographic area. Since this type of problem is too large and complex to be solved directly, an heuristic method was developed.

The heuristic method optimizes over a grid that covers a TSA or the Province by partitioning the grid into disjoint subsets, called frames, solving the problem for each frame, then integrating the results over several passes. Global constraints for even harvest flow are applied at each pass. The model was designed to be run separately for each of the Timber Supply Areas (TSAs) or for the entire Province. For the Okanagan TSA, training using host-climate and pest-climate relationships has been completed at 4-km and 600-m resolutions. Additional technical details regarding the economic modelling are available in the FY0708 deliverables (Mehlenbacher, 2008) and in Appendix C.

## 2.4. Future climate projections

A suite of climate projections was selected to represent a range of potential future temperature and precipitation conditions in order to address the uncertainty inherent in climate projections. Monthly and annual temperature and precipitation values, averaged across British Columbia, were compared to all available IPCC AR4 projections (~140). Six projections from five Global Climate Models (GCMs) using three different emissions scenarios were selected for analysis. These projections cover much of the range of temperature and precipitation values represented by the AR4 projections (Figure 5; Table 2). The British HadGEM1 model projection represents a hot, dry future, with temperatures changes above the 90$^{th}$ percentile and precipitation changes below the 10$^{th}$ percentile of all AR4 projections. A wet, moderately warm future is indicated by the Canadian CGCM3 model, with temperatures changes near the 75$^{th}$ percentile and precipitation changes above the 90$^{th}$ percentile. The German ECHAM5 and British HADCM2 projections both portray a middle-of-the-road future, with temperature and precipitation changes near the median value for all AR4 projections. The Japanese CGCM2.3.2A projection shows a future in which relatively little change has occurred.

**Table 2 - Projected 2050s BC average temperature and precipitation for the six climate projections used.**

| Climate Model | Emissions scenario / run | BC 2050s Temperature change (°C) | BC 2050s Precipitation change (%) |
|---|---|---|---|
| Meteorological Research Institute of Japan: MRI_CGCM2.3.2A | B1 – run 5 | 0.8 | 3 |
| Hadley Centre Coupled Model: UKMO_HADCM3 | B1 – run 1 | 1.7 | 6 |
| European Centre Hamburg Model: MPI_ECHAM5 | B1 – run 3 | 1.9 | 7 |
| Canadian Global Climate Model: CCCMA_CGCM3 | A2 – run 5 | 2.5 | 15 |
| Canadian Global Climate Model: CCCMA_CGCM3 | A2 – run 4 | 2.7 | 14 |
| Hadley Centre Global Environmental Model: UKMO_HadGEM | A1B – run 1 | 3.7 | 0 |
| All SRES AR4 – $90^{th}$ percentile | | 3.0 | 13 |
| All SRES AR4 – median | | 2.0 | 6 |
| All SRES AR4 – $10^{th}$ percentile | | 1.3 | 2 |

## 3. Results

Selected results and interpretation are available online[ii]. Each figure displayed online is reproduced below for the purposes of discussion. Additional results and interpretation will be made available in a PCIC report and a journal article, each to be published before the end of the calendar year.

### 3.1. Tree species suitability

#### Principal Component models

The Douglas fir model has two significant (eigenvalues ≥ 1) Principal Components (PC; Figure 6). The first principal component primarily represents a southwest-northeast precipitation gradient, and closely follows the spatial variability in mean annual precipitation (Figure 7). This component can be interpreted as reflecting the differences in the precipitation regimes of the coastal maritime climates and the interior continental climates. The second principal component primarily represents a temperature gradient and strongly resembles the spatial variability in mean annual temperature (Figure 8). This component can be interpreted as reflecting elevation and latitude gradients between warmer valley bottoms (and coastal areas) and colder mountainous and northern interior regions. The majority of Douglas fir presence records are located in climates drier than the centre of the climatic envelope; the tail of the distribution extends into negative values on the first principal component, indicating that these plots are located in wetter climates, i.e. the coastal Douglas fir populations (Figure 9). The distribution of BEC plots with regard to temperature (second PC – vertical axis of Figure 9) shows a more even split.

The spruce model has three significant Principal Components (Figure 10). The higher number of principal components with eigenvalues greater than one in the spruce model than in the Douglas fir model can be explained by the larger geographic range of the species, the wider range of climatic conditions that spruce grows in, and is partly the result of the fact that this model is based on data for three separate spruce species. Although the presence records of spruce are associated with a relatively wide spread of component scores, there is still an almost even split between negative and positive scores on each component. The first principal component primarily represents a summer moisture gradient and bears a strong resemblance to the spatial variations in the summer heat to moisture index (Figure 11). This component can be interpreted as reflecting the differences between the dry, hot summers of interior valleys (and eastern Vancouver Island and Haida Gwaii) and the wet, cool summers of high-elevation and most coastal locations. The second principal component represents a southwest-northeast gradient between maritime and continental winter climates, and resembles the spatial variations in annual temperature ranges (Figure 12). This component can be interpreted as reflecting the differences between the cold, dry winters of lower elevations in northern British Columbia and the wetter and/or warmer winters of the rest of the Province. The third principal component primarily represents a summer temperature and precipitation gradient and bears some resemblance to the spatial variations in mean warmest month temperature, except in the far-west where consistently high precipitation overshadows the temperature gradient (Figure 13). This component can be interpreted as reflecting the differences between the warm and/or wet summers of both coastal areas and lower elevations in the interior and the cooler and/or drier summers of higher elevations in the interior. Although both represent a combination summer temperature and precipitation gradients, the third component differs from the first component in that it loads more strongly on temperature than on precipitation.

#### Historical baseline

The modelled baseline (1961-1990) climatic suitability for Douglas fir is shown in Figure 14. Modelled suitability based on a 90% suitability threshold matches the actual distribution of Douglas fir (Figure 15) in the interior quite well, but very poorly along the coast, due to the predominance of interior Douglas fir populations in the model-building dataset.

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[ii] http://pacificclimate.org/resources/climateimpacts/forests/

The PCA baseline matches well with other bioclimatic envelope methods. In particular, the Douglas fir baseline is qualitatively comparable to that computed using Canonical Discriminate Analysis (Hamann and Wang, 2006) and a simpler quantiles-based envelope method (McKenney et al., 2007), including the modeled suitability in northern coastal valleys where Douglas fir has not been observed but climate appears to be suitable according to all three methods. A draft presence-absence method of suitability – random forests – (Tongli Wang, pers. comm.) does not exhibit suitability at these most northerly locations and historical coastal suitability is more successfully modelled by this method.

In the case of spruce, the modelled baseline (1961-1990) suitability (Figure 16) compares well with the actual VRI distribution throughout much of the Province (Figure 17). However, the north-eastern portion of the Province, east of the Rocky Mountains, and some far-northern valleys exhibit a pattern of underprediction of climatic suitability, with very low modelled suitability values in areas where spruce forests currently exist. This is likely due to the relative scarcity of spruce presence records in the north. Some over-prediction of suitability is also apparent at high elevations in the north and in low valleys in interior southern British Columbia.

The Spruce baseline is comparable to the overlap between the two envelopes for *Picea engelmannii* and *Picea glauca* modeled separately by McKenney (McKenney et al., 2007). The PCA baseline is also comparable to the modelled baseline according to Canonical Discriminate Analysis (Hamann and Wang, 2006). All three approaches show the strong influence of local-scale topographic features on the distribution of spruce, and portray the same core area of high climatic suitability for spruce in central British Columbia. The most notable disagreement with both of these other approaches is the deficiency in modelling suitability in Northeastern BC in the PCA method used here. However, this deficiency is likely related to the distribution of presence records used to the build the models than to the modelling methods themselves.

## Projected future changes

Average projected climatic suitability for Douglas fir through the 21$^{st}$ century (Figure 18) shows a large expansion in suitability to higher latitudes and elevations, while suitability decreases on lower valley slopes and in coastal regions. An analysis of areas projected to lose or gain suitability using a 90% suitability threshold (Figure 19) shows a considerable area of lost suitability in southern interior valleys and a dramatic increase in the area suitable for Douglas fir in northern and high elevation areas by the end of the 21$^{st}$ century. According to the average of all six climate projections, 24% of the area that was suitable in the baseline period is no longer suitable by the 2080s, but an area equivalent in size to 150% of the baseline suitable area becomes newly suitable by the 2080s. In comparison to other bioclimatic envelope modelling approaches, the PCA-based model's projected changes appear more similar to simple envelope method results[iii] and Canonical Discriminate Analysis (Hamann and Wang, 2006) than to preliminary results from random forests (Rehfeldt, 2009), which exhibits less future change (Tongi Wang, pers. comm.).

For spruce, average projected climatic suitability indicates a decrease over the next century at lower elevations in the south, where temperatures become too warm for spruce, and at some higher elevations in the north, where precipitation increases beyond the level suitable for spruce (Figure 20). Analysis of areas projected to lose or gain suitability using a 90% suitability threshold shows little change by the 2020s, but a considerable loss of suitability in southern and central interior British Columbia is apparent by the 2080s (Figure 21). Based on the average of all six climate projections, 26% of the area that was suitable for spruce in the baseline period is no longer suitable by the 2080s, while an area equivalent in size to only 5% of the baseline suitable area becomes newly suitable by the 2080s. The PCA-based projection

[iii] https://glfc.cfsnet.nfis.org/mapserver/phmapper/map.phtml?LAYERS=61355,2700,2701,4240,2057&title=Pseudotsuga+menziesii

exhibits less change in future suitability than simpler envelope methods[iv]. Random forest results are not currently available for comparison.

## Agreement between GCM and RCM climate projections

The level of agreement between projections of future climatic suitability for Douglas fir based on different GCM projections reveals a moderate amount of variability between projections during the 2020s (Figure 22), with different projections indicating that anywhere from 21% to 37% of the Province will be suitable for Douglas fir. The level of agreement decreases considerably by the 2050s (Figure 23), with predictions ranging from 28% to 53% of the Province being suitable for Douglas fir. The different climate projections diverge further by the 2080s (Figure 24), with 36% to 58% of the Province predicted to be suitable for Douglas fir, and with much less agreement about where these suitable areas will be located.

Compared to Douglas fir, there is a notably higher level of agreement between predictions of future climatic suitability for spruce based on different GCM projections. Projections of climatic suitability for spruce based on different climate projections are almost identical during the 2020s (Figure 25), with predictions indicating suitable conditions in 69% to 75% of the Province. The different climate projections begin to diverge from each other by the 2050s (Figure 26), with predictions indicating that 59% to 75% of the Province will be suitable for spruce. The surprisingly high level of agreement between climate projections vanishes by the 2080s (Figure 27), with predictions now ranging from 31% to 74% of the Province being suitable for spruce.

In spite of the significant differences, all six climate projections agree that conditions are either suitable or unsuitable in 80% of the Province during the 2020s (Figure 28; Table 3). All six projections agree in their classification of suitable/unsuitable areas in only 55% of the Province by the 2050s (Figure 28; Table 3). By the 2080s, all six projections agree in only 40% of the Province (Figure 28; Table 3). A much higher level of agreement between climate projections is apparent for the spruce model, with all six climate projections agreeing that an area is either suitable or unsuitable in 88% of the Province during the 2020s (Figure 29; Table 3). In the 2050s all six projections agree on their classification of suitable/unsuitable areas in 81% of the Province (Figure 29; Table 3). By the 2080s, all six projections agree in only 54% of the Province (Figure 29; Table 3).

**Table 3: Percentage of the Province in which climate projections agree that climatic conditions will be either suitable or unsuitable for Douglas fir in the 2020s, 2050s, and 2080s.**

| | Douglas fir | | | Spruce | | |
|---|---|---|---|---|---|---|
| | 2020s | 2050s | 2080s | 2020s | 2050s | 2080s |
| **Six** | 80% | 55% | 40% | 88% | 81% | 54% |
| **≥ Five** | 88% | 80% | 66% | 97% | 95% | 76% |

The importance of climate model resolution was investigated by comparing suitability according to projections downscaled using ClimateBC from the Canadian Regional Climate Model v4.1.1 and from the GCM that forced it (CGCM3 A2 run 4). Figures 30 and 31 show that when the projected suitability is converted to a binary suitable/unsuitable classification, the results obtained for the 2050s using the Regional Climate Model (RCM) projection are almost identical to those calculated with from the GCM that forced it. This indicates that the resolution of the climate projections does not have a large impact on final projections of climatic suitability for tree species.

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[iv] https://glfc.cfsnet.nfis.org/mapserver/phmapper/map.phtml?LAYERS=8685,2700,2701,4240,2057&title=Picea+glauca

The difference in suitability between two climate model projections differing only in GCM initial conditions (CGCM3 following A2 runs 4 and 5) indicates the uncertainty due to non-linearity of the climate system. This is shown by the middle and right maps of Figure 31. Differences in suitability between the two are very small, but slightly larger than the difference between using CRCM4.1.1 or the forcing GCM (CGCM3 A2 run4).

## 3.2. Pest suitability

### Historical climate envelopes for pests and hosts

Comparison of the frequency of occurrence of outbreaks with the percentage of the host population occurring under a given range of climatologies revealed that WSBW outbreaks are more likely to occur in areas that are, on average, drier during the summer and warmer throughout the year than the mean climatology of Douglas fir forests. Compared to the average climatology of Douglas fir forests, WSBW outbreaks have historically occurred in areas with higher MAT and lower CMT, TD, and DDlt0, which indicate warmer conditions. WSBW outbreaks have historically occurred in areas that also have lower MSP and higher SHM values, indicating drier conditions (Figure 32). This means that there are currently Douglas fir populations occupying areas that are too wet and/or too cold for WSBW outbreaks to occur under current climatic conditions.

In the case of SBB outbreaks, comparison of the frequency of occurrence of outbreaks with the percentage of the host population occurring under a given range of climatologies revealed that SBB outbreaks usually occur in areas that are, on average, warmer and wetter than the mean climatology of spruce forests. SBB outbreaks have historically occurred in areas with higher MAT and lower CMT, TD, DDlt0, and DDlt18 than the average climatology of spruce forests, indicating that outbreaks occur under warmer conditions. Outbreaks also tend to have occurred in wetter areas with lower MAP and AHM index values compared to the average climatologies of spruce forests (Figure 33). Hosts now living at the colder or drier limits of the distribution of spruce trees will therefore likely become more susceptible to spruce bark beetle outbreaks in areas where climate is projected to become warmer and wetter in the future.

The baseline risk for outbreaks is shown in Figure 34. This risk classification is based on the selected parameters as described above (Table 1). All locations in which outbreaks occurred during the 1961-1990 period are contained within the medium and high risk classes. There are many areas which were historically climatically suitable for pest outbreaks to occur, but which did not experience a pest outbreak during the historical period due to the limiting influence of other factors such as availability and vulnerability of host trees, interactions with other pest species, and internal pest population dynamics.

### Projected future changes

The relatively warm, wet future represented by the Canadian CGCM3 A2 run 5 climate projection shows a future in which the risk of WSBW outbreaks increases considerably in central and northwestern British Columbia, while gradually decreasing from high to medium risk in many of the interior southern valleys over the next century (Figure 35). For SBB outbreaks, this climate projection indicates small areas of decreased risk of outbreak in central British Columbia and small areas of increased risk in the northwestern portion of the Province during the 2020s and 2050s (Figure 36). By the 2080s, a considerable area of undefined risk is apparent in the central valleys as climatic conditions change sufficiently to have no analogue within the historical range of SBB outbreaks.

The hot, dry future portrayed by the British HadGEM1 A1B run 1 climate projection indicates a smaller area with increasing risks of WSBW outbreaks than was seen under the CGCM3 climate projection. This climate projection portrays such rapid and dramatic changes in climate that a considerable portion of the Province has no historical analogue climate by the 2080s (Figure 37). Risk of SBB outbreaks shows small increases and a shift to undefined, no analogue climates at an ever quicker pace and bigger scale than WSBW (Figure 38).

## 3.3. Bio-economic Modelling

Bio-economic modelling results (Appendix C - Figure 14) based on climate change impacts on two tree species (Douglas fir and spruce only) shows an economic loss in the Okanagan TSA of 2.6% for CGCM3 A2 run 4 (Warm/Wet) and 4.5% for HadGEM1 A1B run 1 (Hot/Dry). For the Province as a whole (Appendix C - Figures 14 and 16), there is a slight benefit (0.5%) in the Warm/Wet scenario and no change in Hot/Dry. Additional results of bio-economic modelling are presented in Appendix C (attached).

## 4. Discussion

The PCA method of computing tree species suitability has been shown to be comparable to other climate envelope methods (Hamann and Wang, 2006; McKenney et al., 2007). Although the method appears more sensitive than preliminary results from random forests modelling (Tongli Wang, pers. comm.), it is well suited in cases where absence records are unavailable. The PCA method was not applicable to pest outbreak risk due to the importance of thresholds. A simpler climate envelope method of thresholds based on percentiles of historical occurrence was developed and used to project future pest outbreak risk.

Both methods for projecting tree suitability and pest outbreak used in this project are limited by assumptions in which there is room for future improvement. In particular, both methods are based on 30-year means. This means that relationships between climate and forest health modeled here are only those based on the affects of changes in average conditions on adult trees and mature pest outbreaks. Early in the project, there was a concern that the PCA model should not be based on 1961-1990 climate because the trees in BEC plots are of various ages, in most cases much older than the 1961-1990 period, and it is the climate during seedling growth that might be expected to be more influential than the recent climate. For this reason, the model was recomputed using the 1901-1930 in the Okanagan TSA. Because the component loadings were nearly identical (not shown), it was determined that 1961-1990 would serve as a suitable baseline. Improvement would be expected, however, with a model that is able to consider climate and tree species as a time series – if sufficient data were available for such an approach.

Another potential limitation that was investigated is whether photoperiod or elevation could be influential directly. Versions of the PCA models were computed using both elevation and latitude (the latter to represent photoperiod). Both seemed to represent temperature and provide little additional information, so neither was retained in the final model. Spruce already occurs at the highest latitudes of BC, so photoperiod should not be a limiting factor in assisted migration for this species. In the case of Douglas fir, the absence of photoperiod from the model suggests that the projected increases in future suitability north of the present extent could be exaggerated, and that photoperiod should be taken into account when making decisions regarding assisted migration of this species.

The influence of spatial resolution was explored; for binary classification of climate suitability for these two tree species, downscaling with ClimateBC from an RCM projection provided little or no additional difference to projected suitability compared to its driving GCM despite differences between temperature and precipitation projections between the RCM and GCM (Rodenhuis et al., 2007). This is due to a combination of insensitivity of the binary suitability to small differences in climate change projections and to the effect of the ClimateBC downscaling on the RCM and GCM projections. Output resolution was also investigated. The 4-km resolution is informative at a Provincial scale and, while additional local detail is apparent at 600-m, this detail may be spurious in light of the range of uncertainty inherent to the GCM projections (Figures 22 to 29).

It is important to note that while the bio-economic model assumes a relationship between suitability and volume, this is an assumption of the economic modelling and does not imply that increased suitability is equivalent to increased volume. As revealed by preliminary correlation analyses (results not shown), suitability is not necessarily directly correlated with any particular physically meaningful measure such as frequency of species occurrence, tree health, tree size, or forest productivity. However, a t-test indicates a relationship between suitability and site index (si): si is higher on average where the climate suitability for the dominant tree species is above 90% than where it is below 90% suitability. The suitability values represent what would be the relative suitability for a species if climate were the only factor controlling tree health and species distributions. Other factors, such as soil, competition with other species, etc. also influence the distribution of a species. Future research into possible correlations between relative climate suitability and forest productivity/forest health would be valuable.

Similarly, the bio-economic model assumes a relationship between pest outbreak risk and productivity. Not only do the same caveats apply as listed above for tree species, but in this case it should be noted that the outbreak risk envelopes used here are constructed such that outbreak risk is assumed to be identical in future as it was in similar climates in the past. In reality, transient effects of climate change along with unknown thresholds not contained in historical observations may mask much larger potential risks, particularly over the short term. In addition, this approach is limited by past climates and in some cases, the projected future climate results in conditions never observed in the past. In some of these locations, the assumption in the bio-economic model that there is no risk of outbreak will lead to an underprediction of outbreak risk.

Several gaps in knowledge that prevent more explicit modelling of factors important to forest health were identified at the October 2007 workshop (Abbott et al., 2008): understory, co-evolution of forests and pests, cumulative impacts, extremes, and pest biology. Advancement in each of these areas is required in order to move from projected changes in forest health related as 30-year means into changes based on projected climate variability and extremes.

## 5. Conclusions and management implications

The results of this project were specifically designed to make progress towards management implications. With respect to tree species suitability, a method was implemented that is more sophisticated than the simplest climate envelope methods but does not depend on absence data. Results are consistent with other presence-only envelope methods. Similarities and differences between PCA results and presence-absence methods (such as random forests) could be used to prioritize locations in which to start assisted migration trials and provenance tests. During the 21$^{st}$ century, new areas of climatic suitability for Douglas fir are projected in Northern BC and at higher elevations where this species does not grow today, but the most productive and economically important areas of current Douglas fir growth in southern and central interior valleys become climatically unsuitable (Figures 18 and 19). New areas of projected climatic suitability for spruce are limited to a few high elevation coastal and northern locations. Climate is projected to become unsuitable for spruce in most of the southern interior, the valleys of the central interior, and additional areas of the coast and north-eastern BC by the end of the century (Figures 20 and 21).

In order to explore uncertainty in future projected suitability, a suite of six Global Climate Model (GCM) scenarios was used (Figures 22 to 27). The resulting maps of agreement between projections (Figures 28 and 29) show the locations where more confidence can be placed in projected loss or gain of suitability. Despite considerable differences in geographical patterns of changes between models (in particular between warm/wet and hot/dry models), all six projections agree on whether or not a given location is suitable or not at 40% of locations in BC for Douglas fir and 54% for spruce by the 2080s.

Modelling the future risk of pest outbreaks requires dynamic modelling of pest life cycles. However, simple climate envelope models give a rough estimate of future risk of pest outbreaks based on 30-year climatologies. Pest outbreak risk was computed based on similarity of climate thresholds (whereas tree species suitability is based on nearness to optimal conditions). The future pest outbreak projections represent a modest estimate of future risks; areas with climatic conditions outside of the range of conditions that pest outbreaks are known to have historically occurred under are labeled as undefined risk (Figures 35 to 38). Risk of WSBW outbreaks is projected to increase considerably in central and northwestern British Columbia, particularly under the Warm/Wet scenario. The Hot/Dry scenario results in such rapid and dramatic changes in climate that a considerable portion of the Province has undefined risk by the end of the century. SBB outbreak risk decreases in central British Columbia and increases in the northwestern portion of the Province under both scenarios. By the 2080s, a shift to undefined, no-analogue climates occurs at a larger scale than WSBW in both scenarios.

A bio-economic model was developed as a proof of concept that the tree species suitability and pest risk projections could be used in a quantitative way to inform decision making. Several methods were investigated and a preliminary model was developed. Several key assumptions – such as relationships between suitability and volume – need further analysis. Additional factors, such as soil, wildfire risk, and influence of climate variability need to be considered in order to use the bio-economic modelling for decision-making. Furthermore, pest outbreak risk is likely an under-estimate in that the model assumes that pest outbreaks will never occur in locations with undefined risk, i.e. climates other than those in which they occurred during 1961-1990. This first preliminary version of the bio-economic model suggests that for the Province as a whole, assisted migration as an adaptation to climate change can turn a negative economic impact for Douglas fir and spruce into a positive or neutral one, depending on climate scenario but that in certain regions (Okanagan TSA in particular), a net negative economic impact is expected even with assisted migration for both climate scenarios.

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## Figures

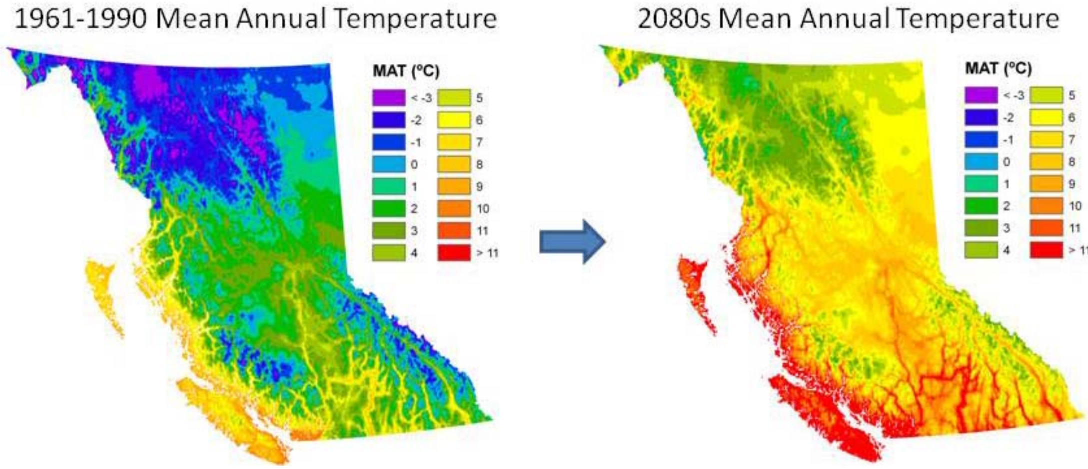


**Figure 1 – Baseline (1961-1990) Mean Annual Temperature (MAT) as compared to 2080s projected MAT from the British HadGEM1 Global Climate Model following A1B emissions scenario, run 1.**

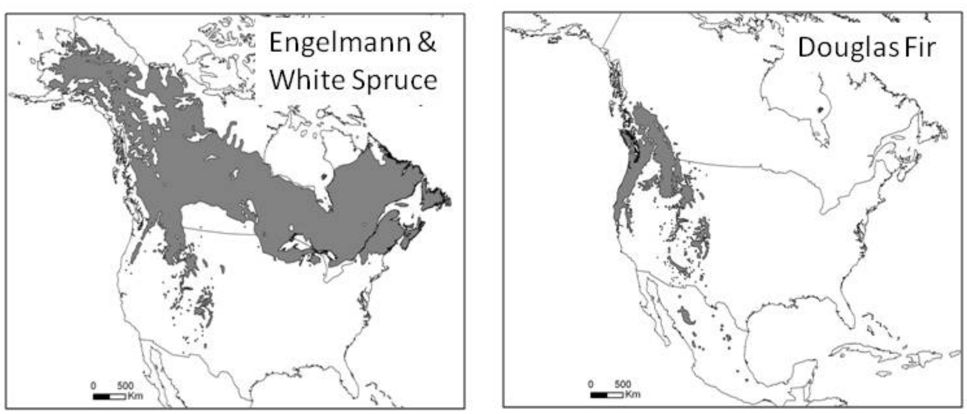


**Figure 2 – Historical distributions of Engelmann & White Spruce, and Douglas fir. Distribution data from Little (1971).**

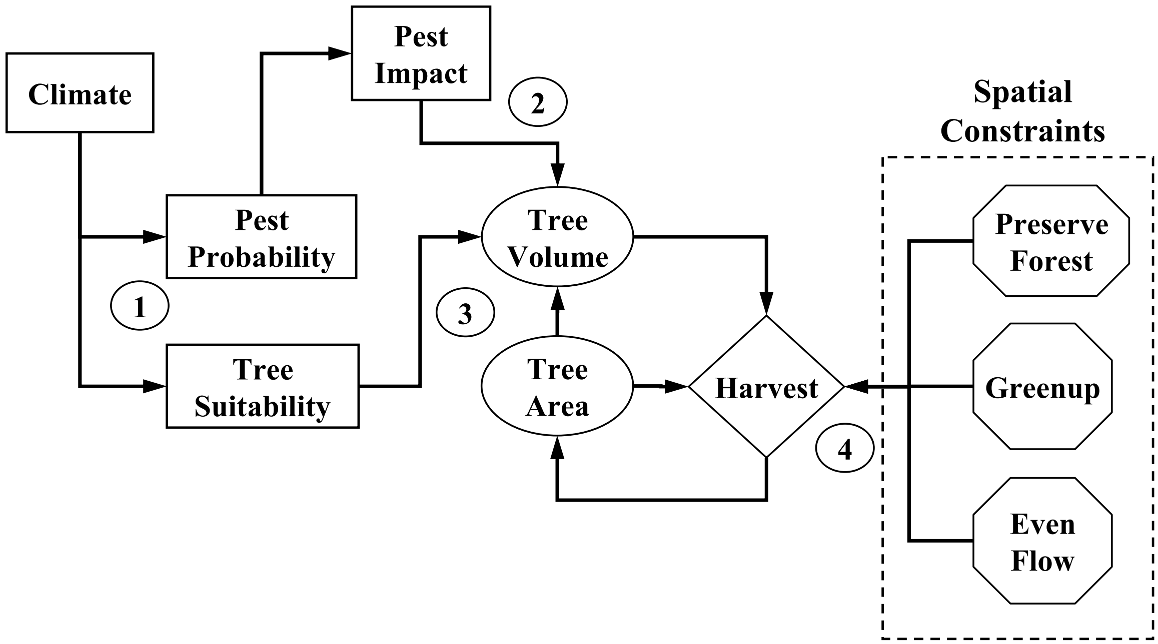


**Figure 3 - Conceptual framework of bio-economic model. The model is spatial in order to realistically model stand management decisions. Numbers in circles denote the following relationships: (1) Climate affects the probability of pests and trees in an area, (2) Pests have different impacts on tree volume through effects on tree growth and mortality, (3) Tree suitability has an impact on tree volume, (4) The decision to harvest a stand is complex and affected by legislative requirements for even flow and greenup of adjacent stands as well as requirement to preserve large contiguous forest area for nontimber benefits.**

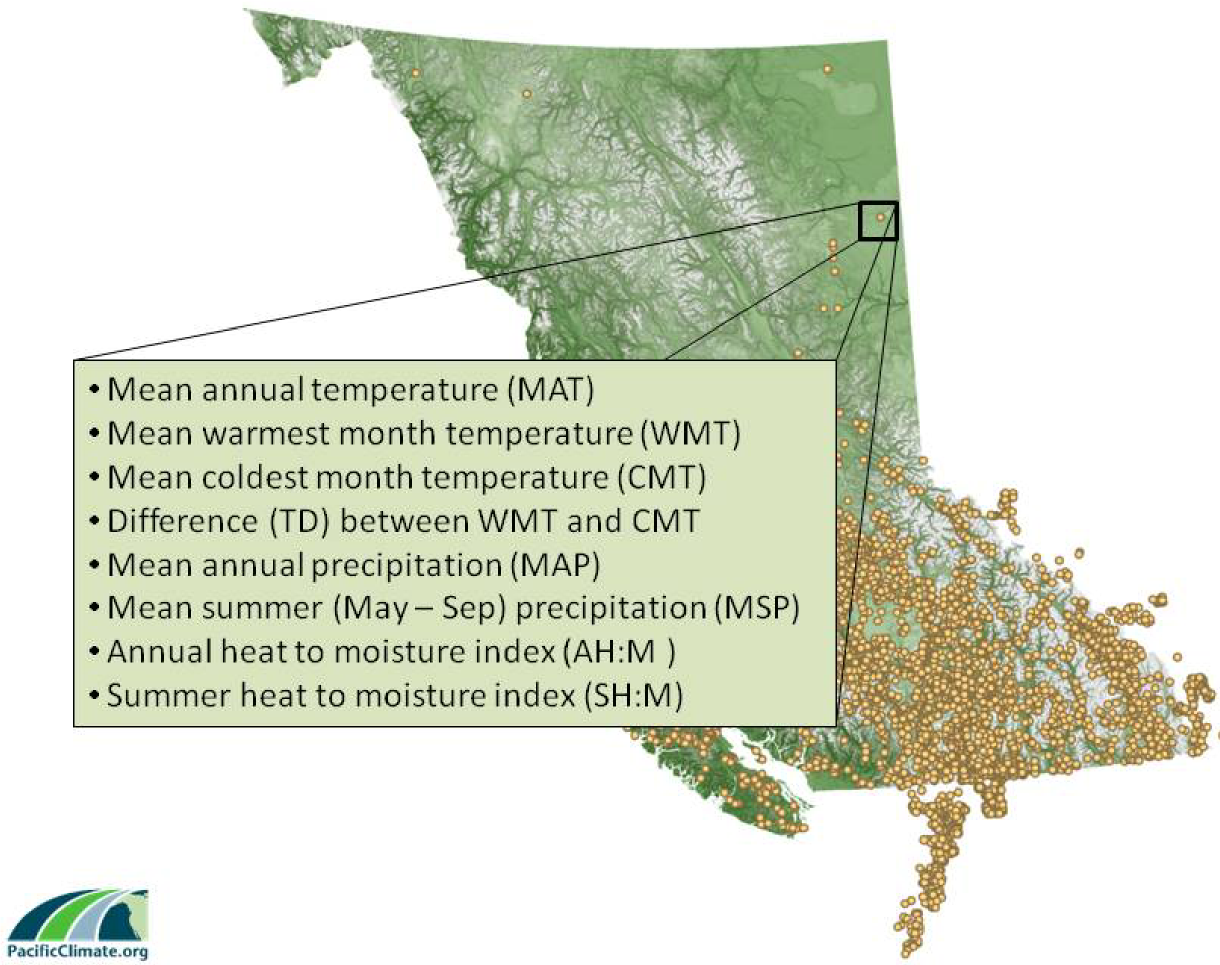


**Figure 4 – Illustration of extraction of climate variables from ClimateBC at BEC plot locations for Douglas fir. (Identical method followed for Spruce).**

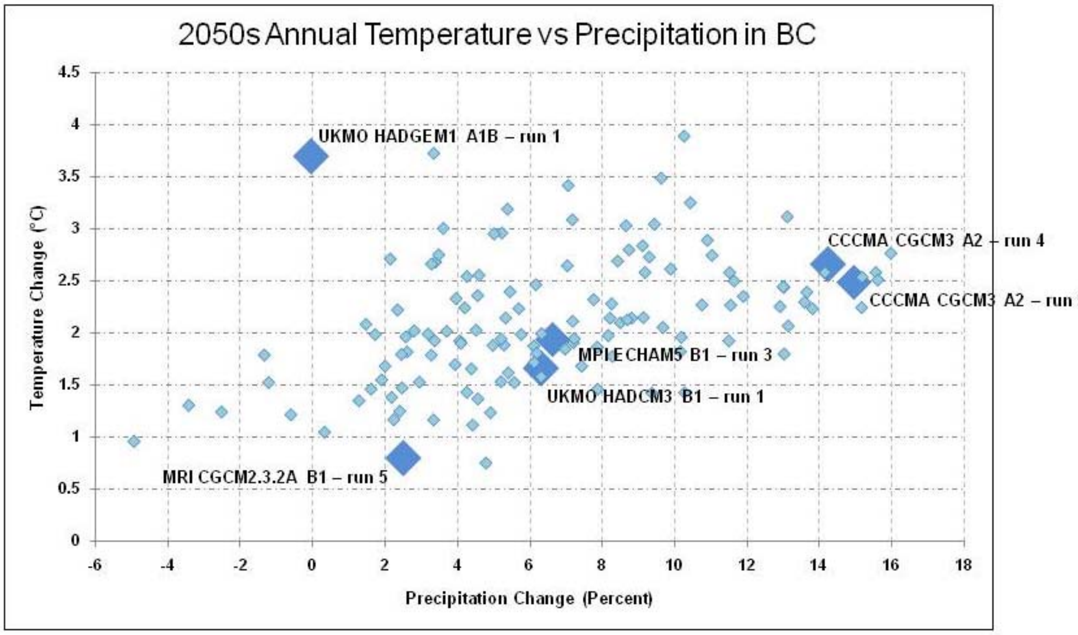


**Figure 5 – Projected 2050s BC average change in temperature and precipitation for the six climate projections used in this study.**

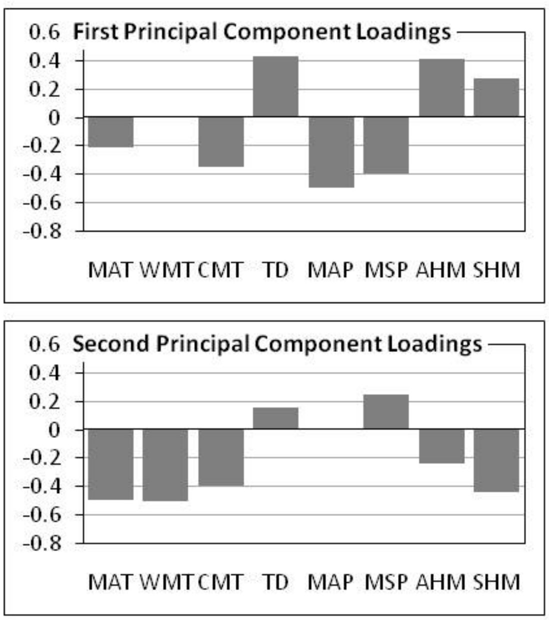


**Figure 6 – Douglas fir model Principal Component loadings.**

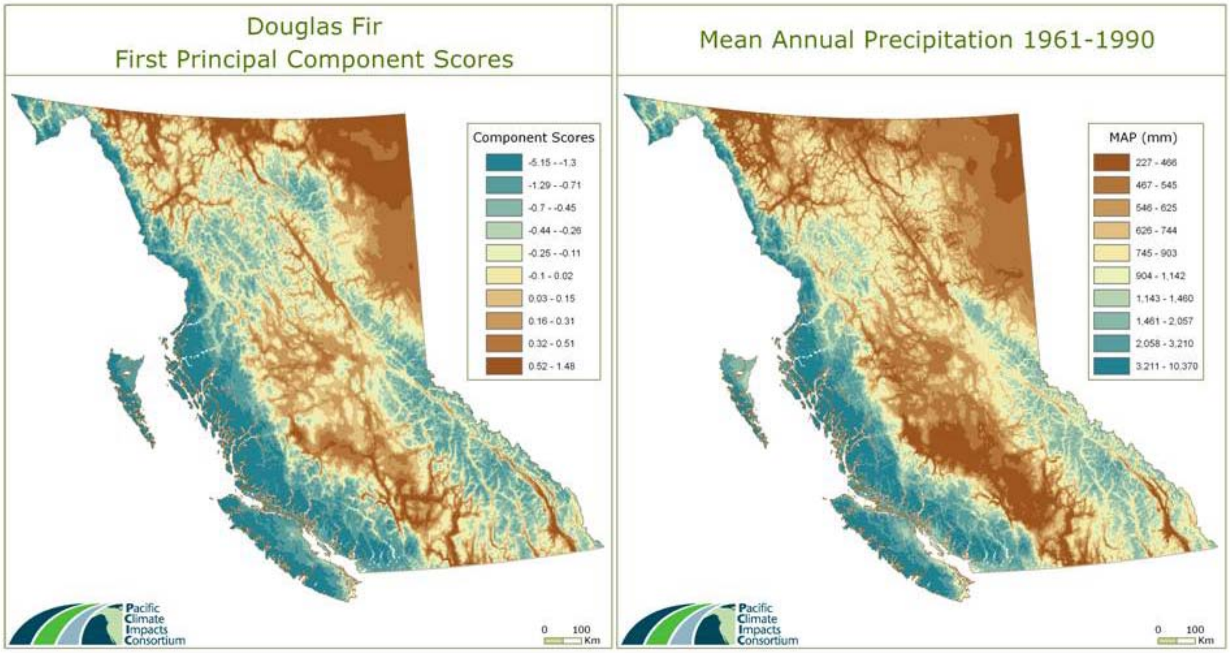


**Figure 7 – Douglas fir model first Principal Component (PC 1) scores compared to Mean Annual Precipitation (MAP).**

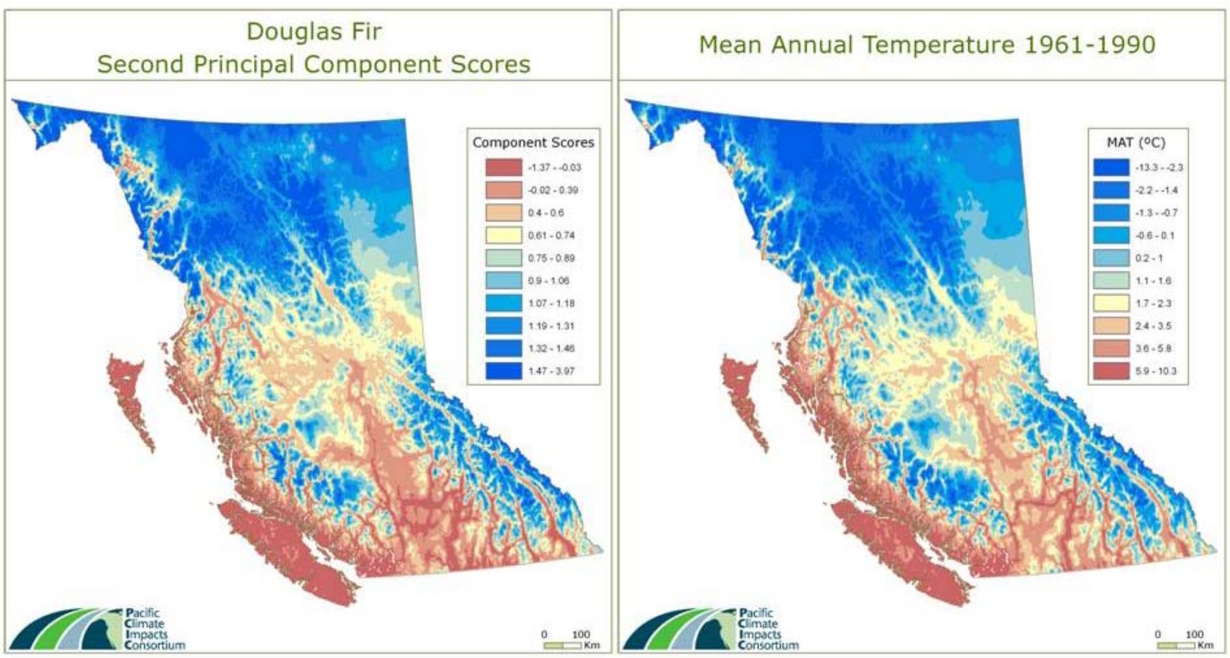


**Figure 8 - Douglas fir model second Principal Component (PC 2)scores compared to Mean Annual Temperature (MAT).**

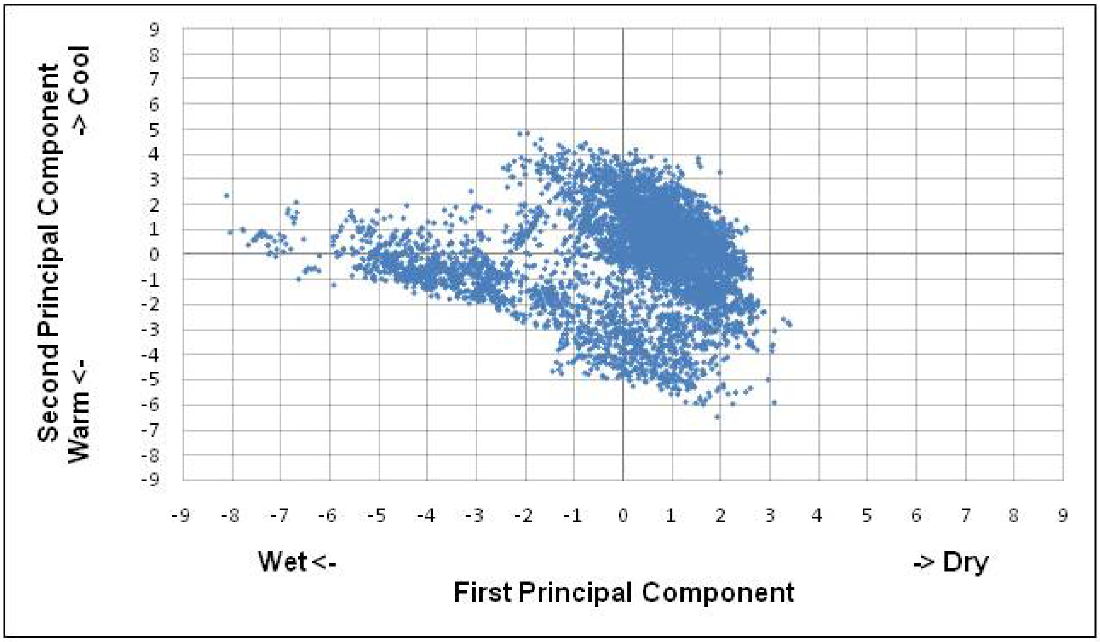


**Figure 9 – Douglas fir Principal Component scores plotted against each other (PC 1 vs. PC 2) for all Douglas fir location records.**

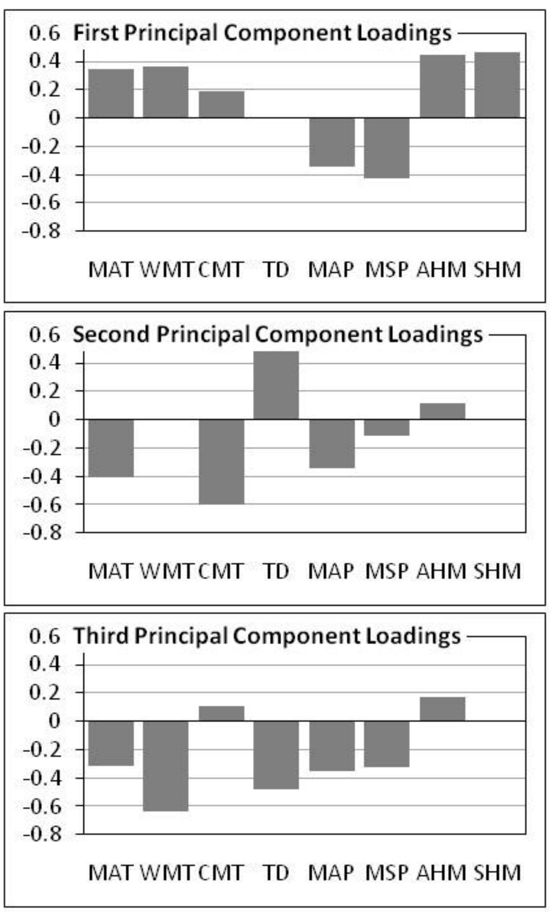


**Figure 10 – Spruce model Principal Component Loadings**

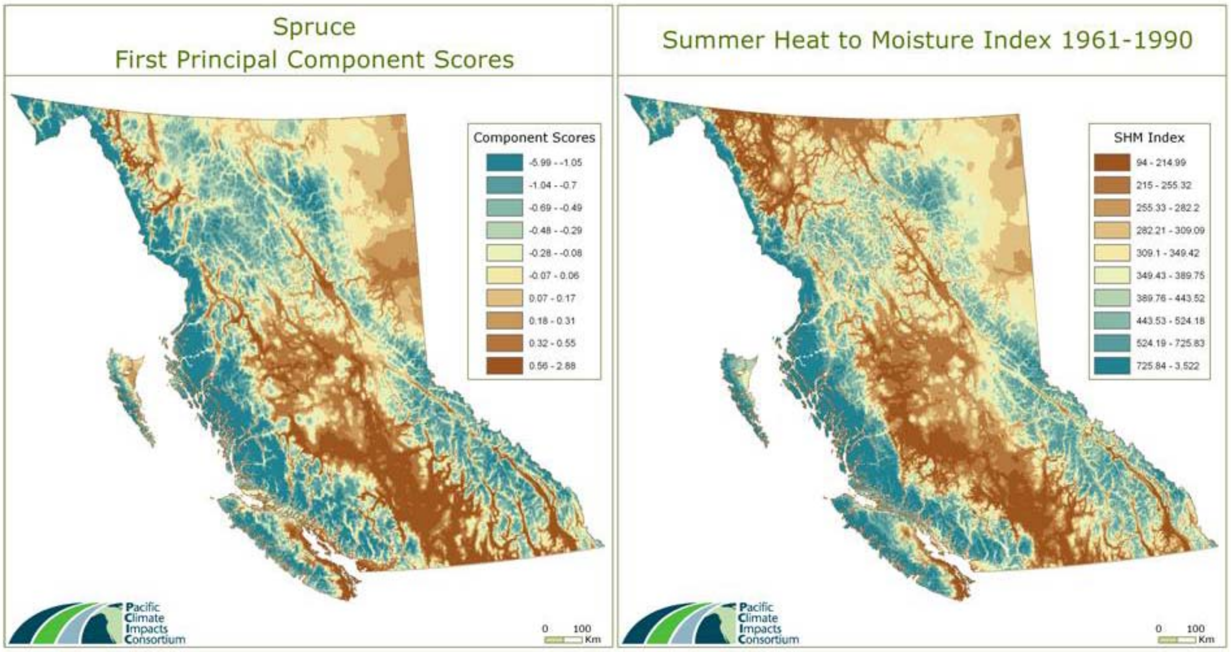


**Figure 11 – Spruce model First Principal Component (PC 1) scores compared to Summer Heat to Moisture Index (SHM).**

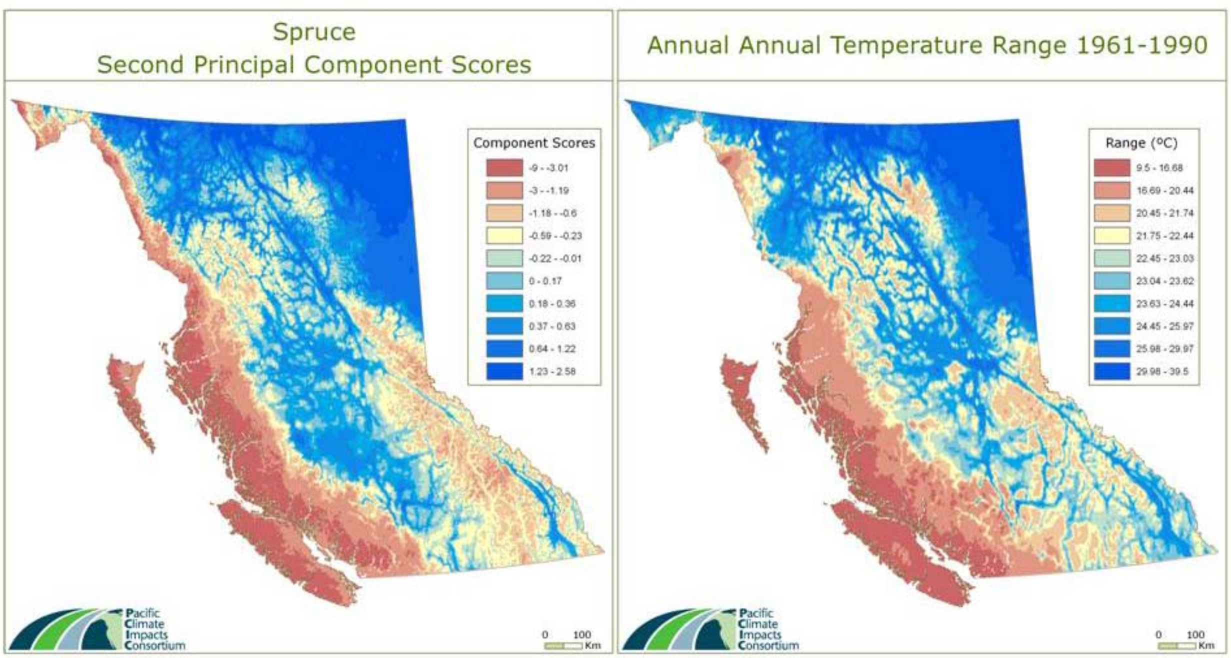


**Figure 12 – Spruce model Second Principal Component (PC 2) scores compared to Average Annual Temperature Range (TD).**

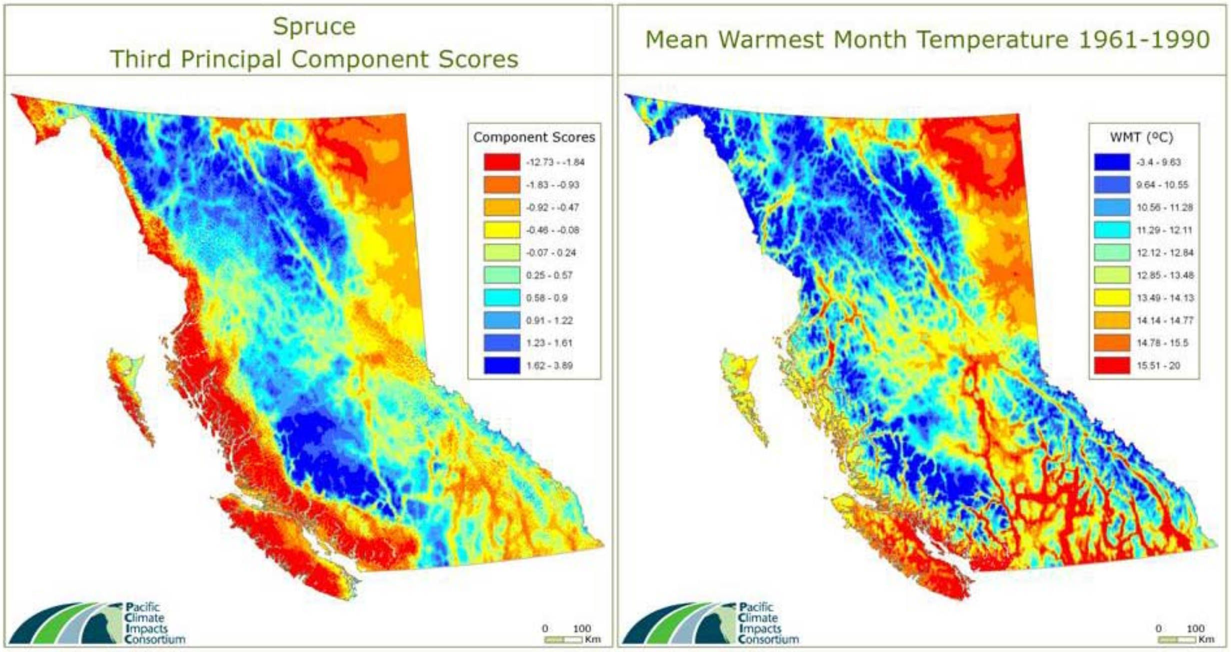


**Figure 13 – Spruce model Third Principal Component (PC 3) scores compared to Mean Warmest Month Temperature (WMT).**

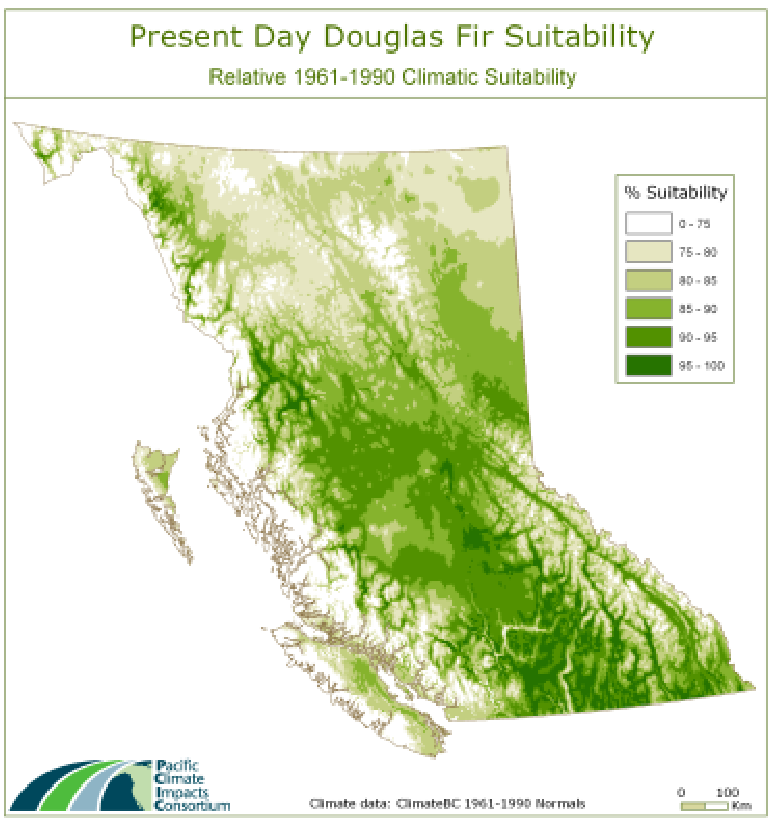


**Figure 14 – Baseline (1961-1990) Douglas fir relative (%) suitability.**

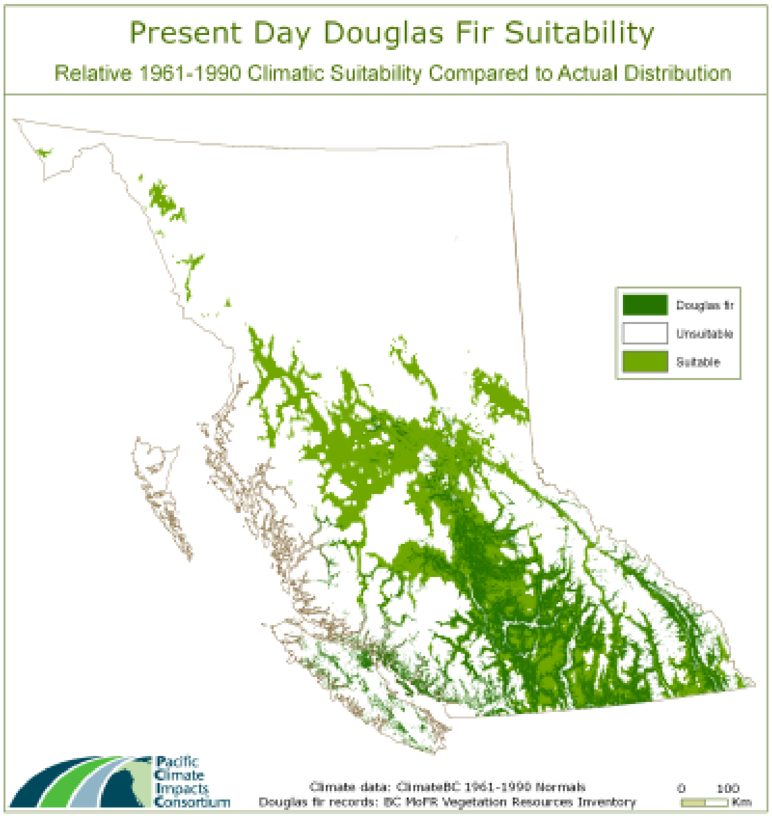


**Figure 15 - Baseline (1961-1990) Douglas fir suitability (90% cutoff) compared with actual distribution (VRI).**

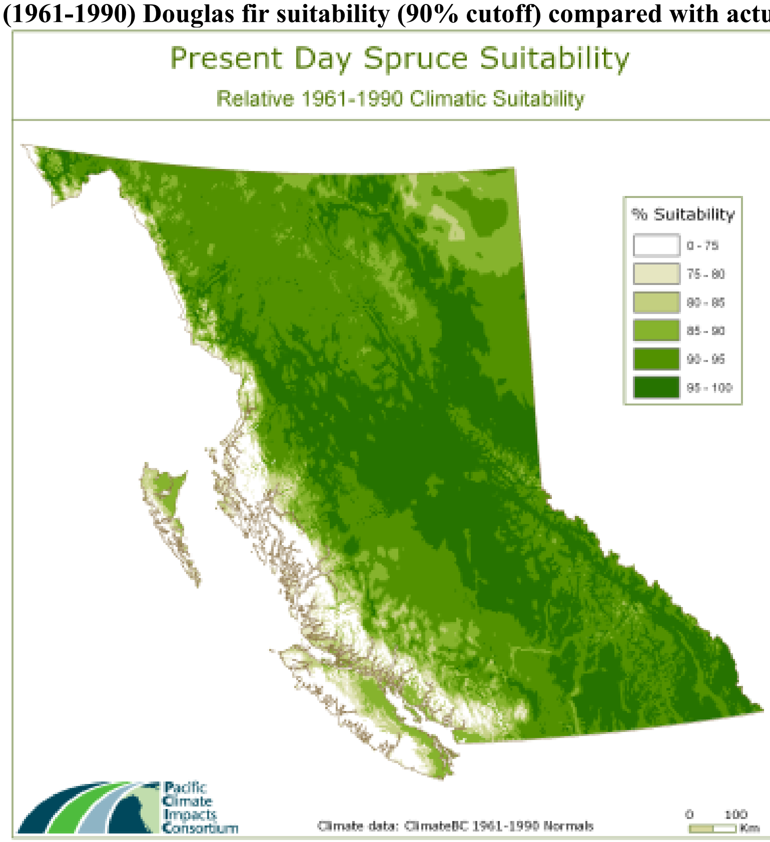


**Figure 16 – Baseline (1961-1990) spruce relative (%) suitability.**

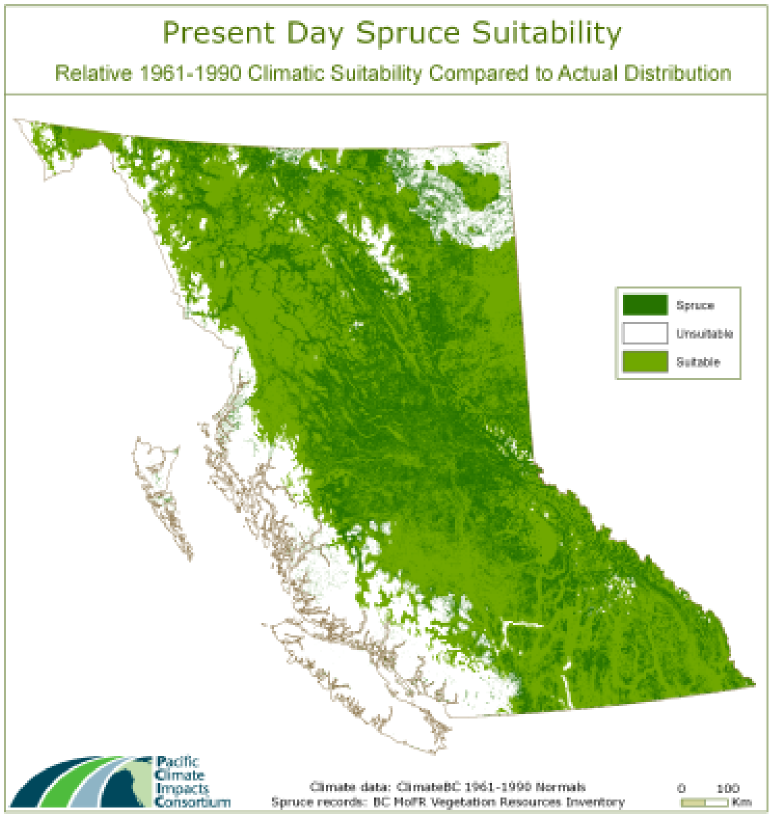


**Figure 17 - Baseline (1961-1990) spruce suitability (90% cutoff) compared with actual distribution (VRI).**

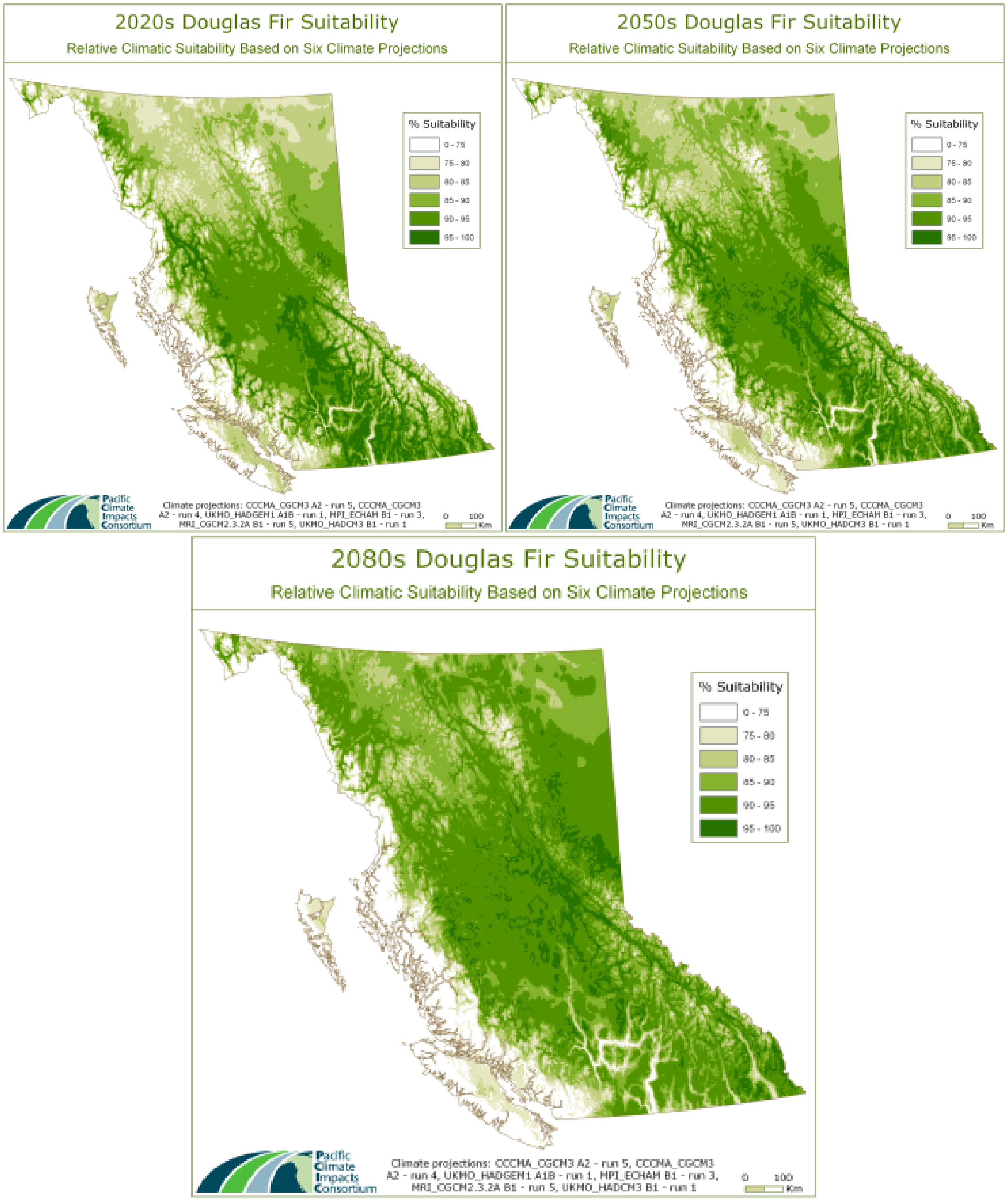


**Figure 18 – Projected Douglas fir suitability based on six climate projections: 2020s, 2050s, and 2080s.**

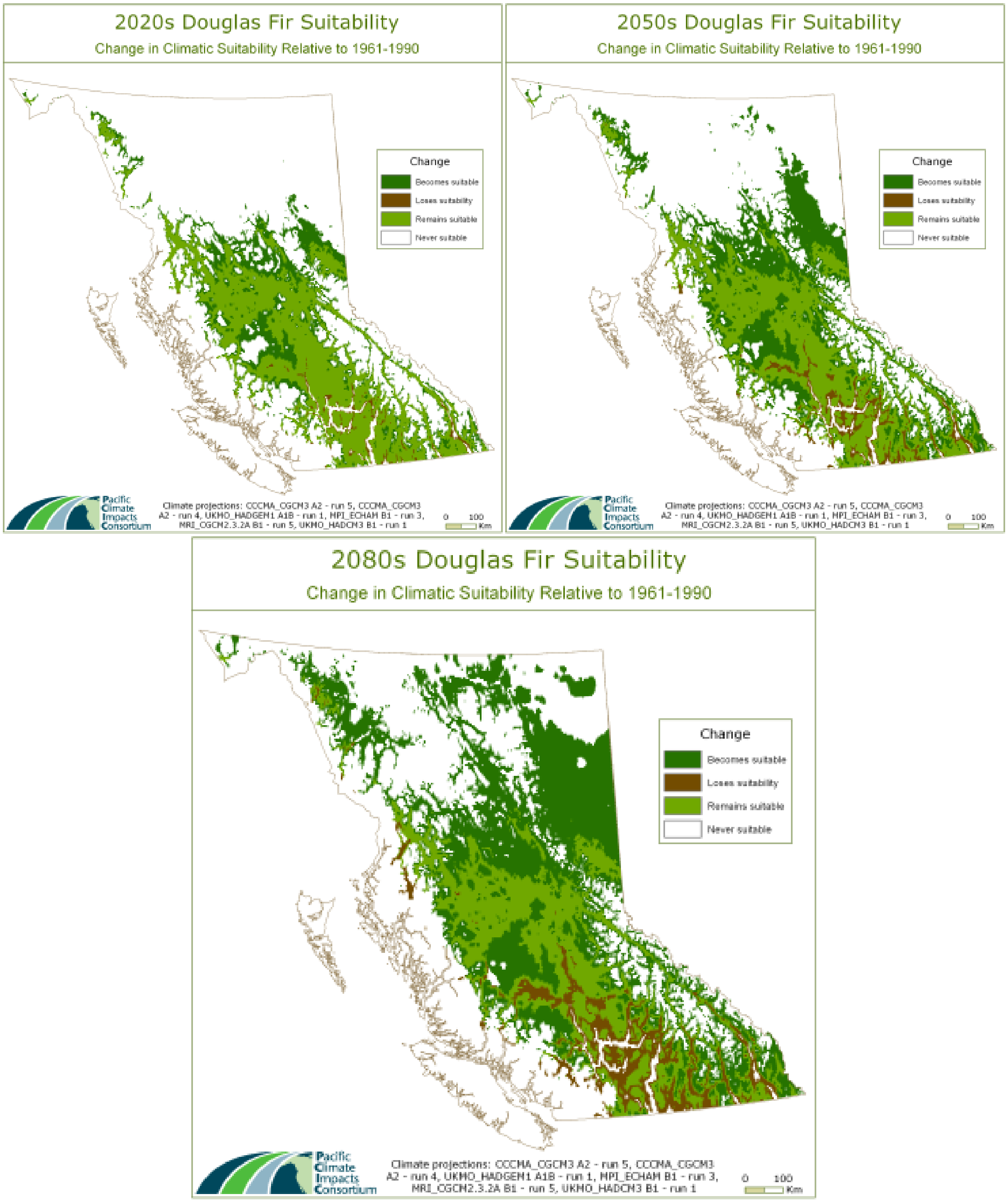


**Figure 19 – Changes in Douglas fir suitability relative to baseline (1961-1990) period, based on a 90% suitability threshold.**

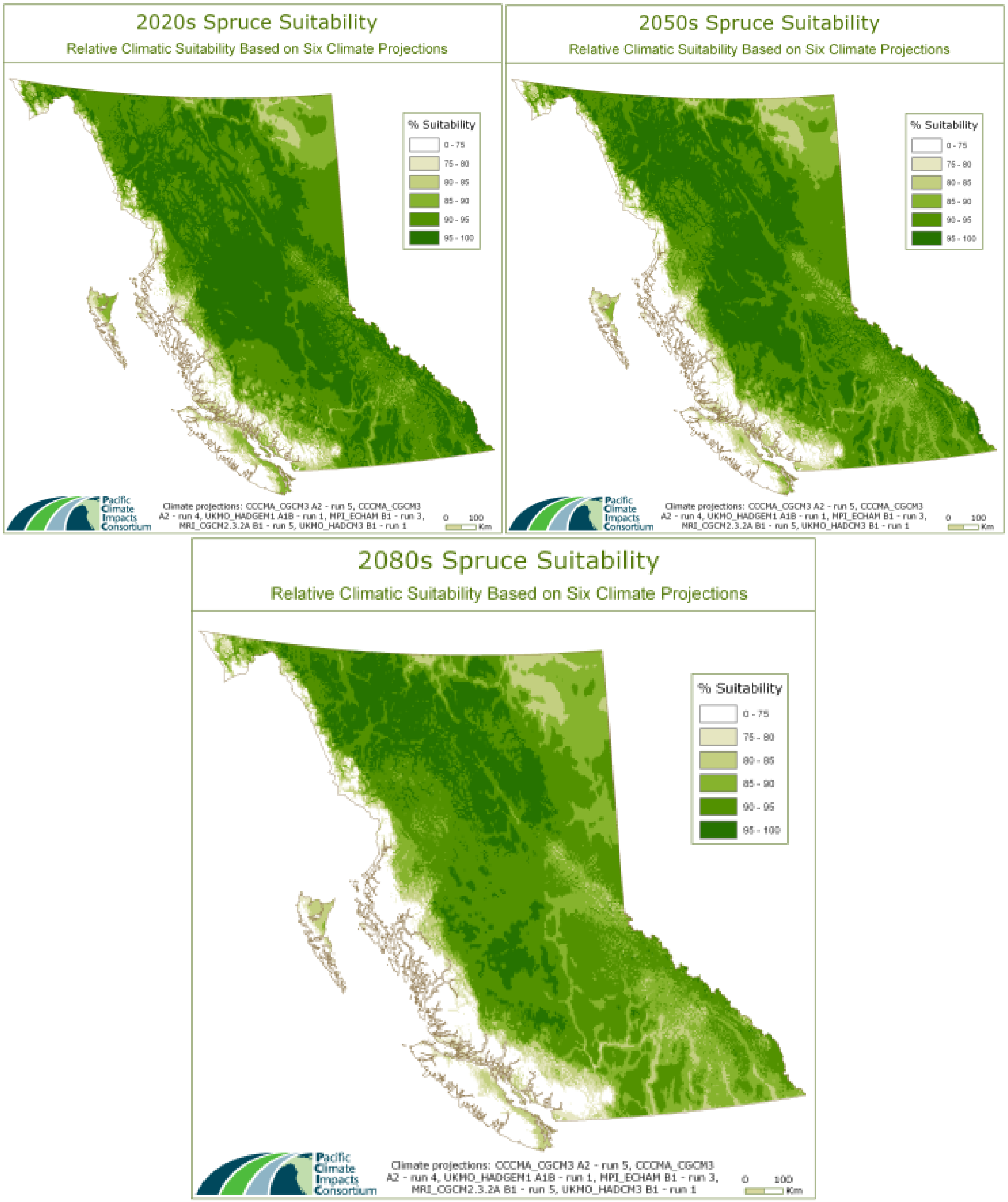


**Figure 20 – Projected spruce suitability based on six climate projections: 2020s, 2050s, and 2080s.**

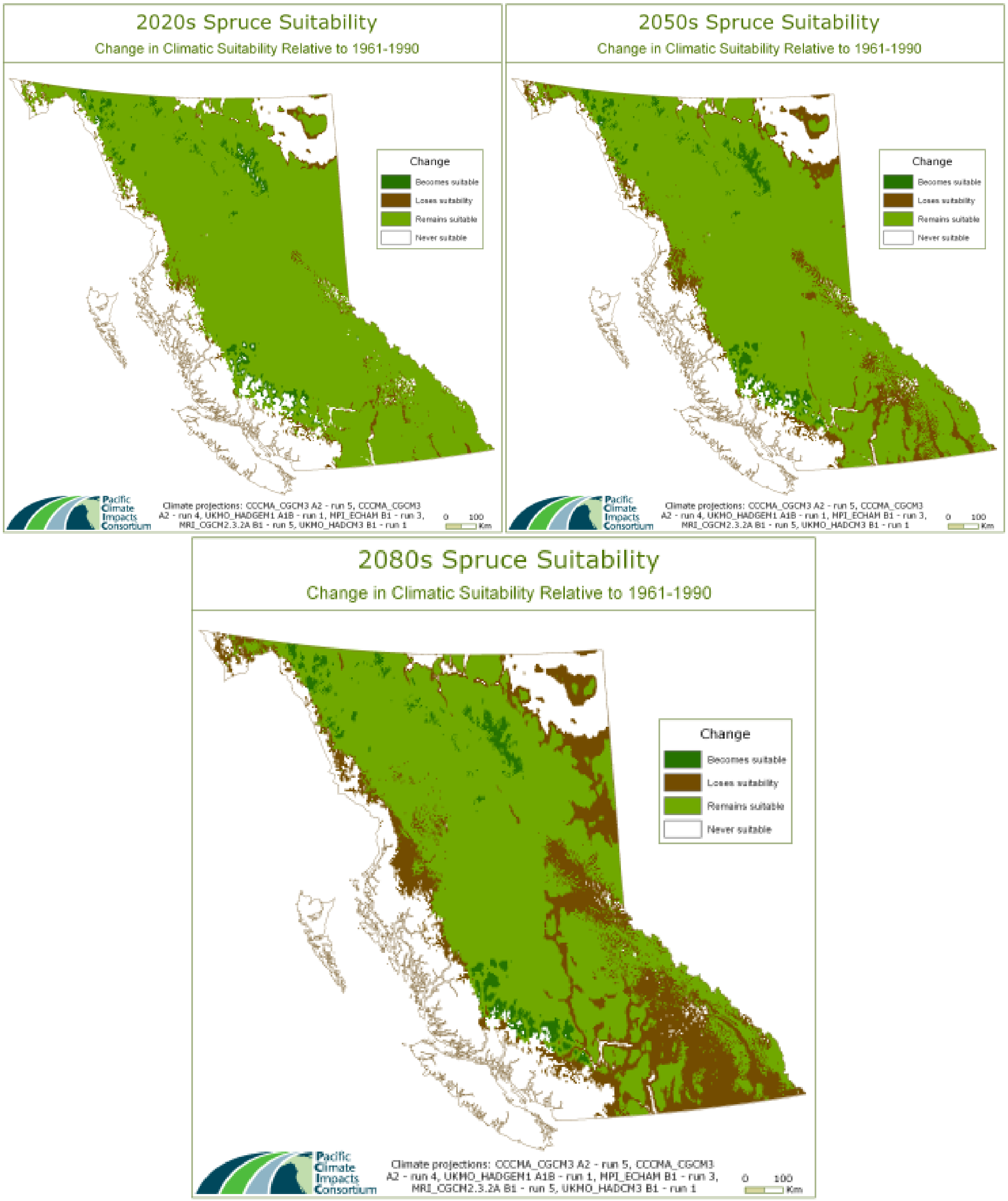


**Figure 21 - Changes in spruce suitability relative to baseline (1961-1990) period, based on a 90% suitability threshold.**

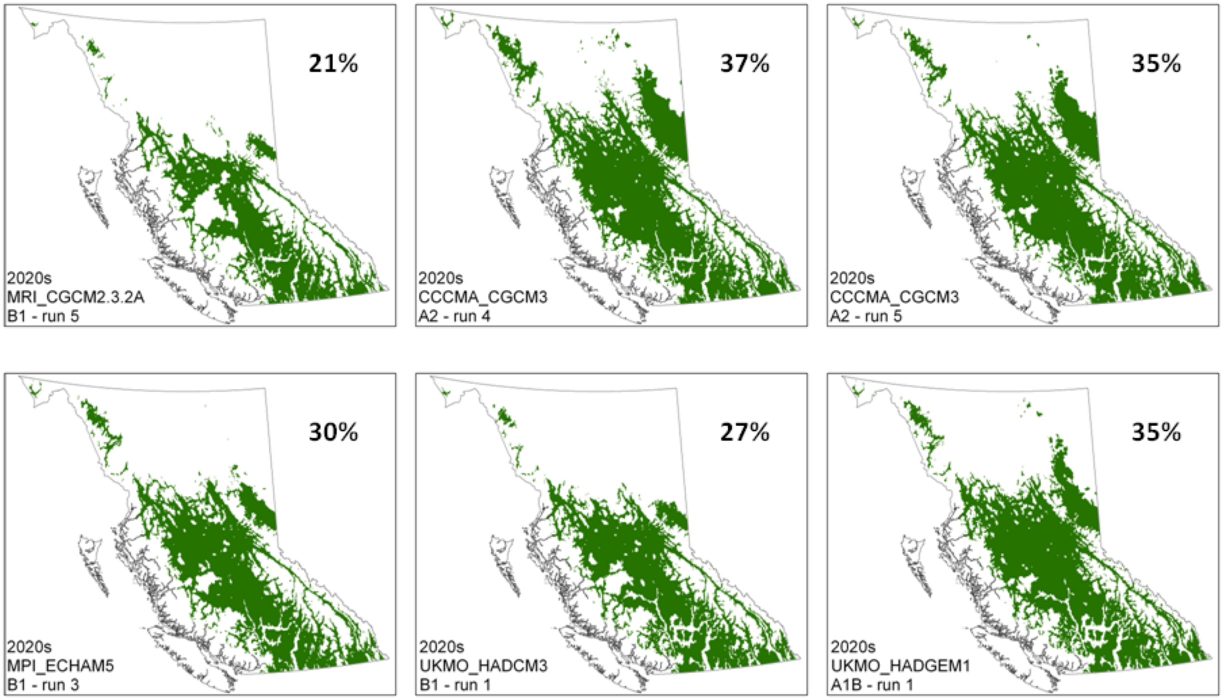


**Figure 22 – Agreement between GCM projections for Douglas fir suitability (defined using a 90% suitability threshold) in 2020s, with percent of the Province predicted to be suitable (in upper right corner).**

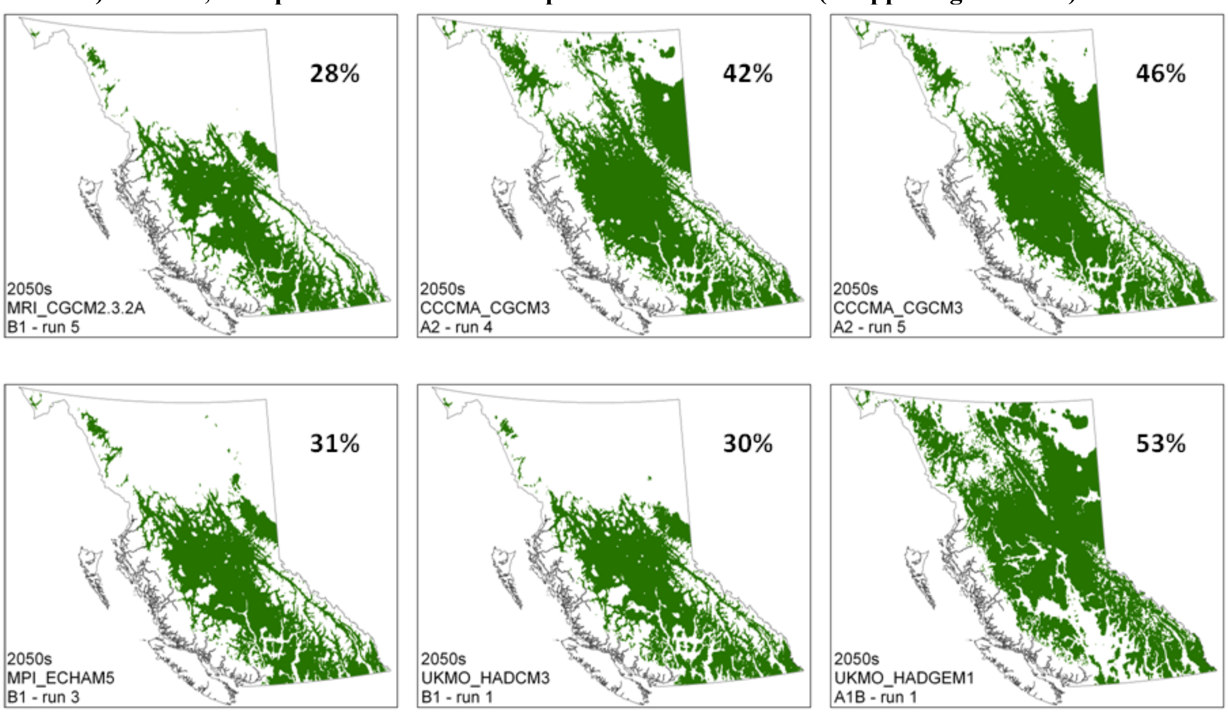


**Figure 23 - Agreement between GCM projections for Douglas fir suitability (defined using a 90% suitability threshold) in 2050s, with percent of the Province predicted to be suitable (in upper right corner).**

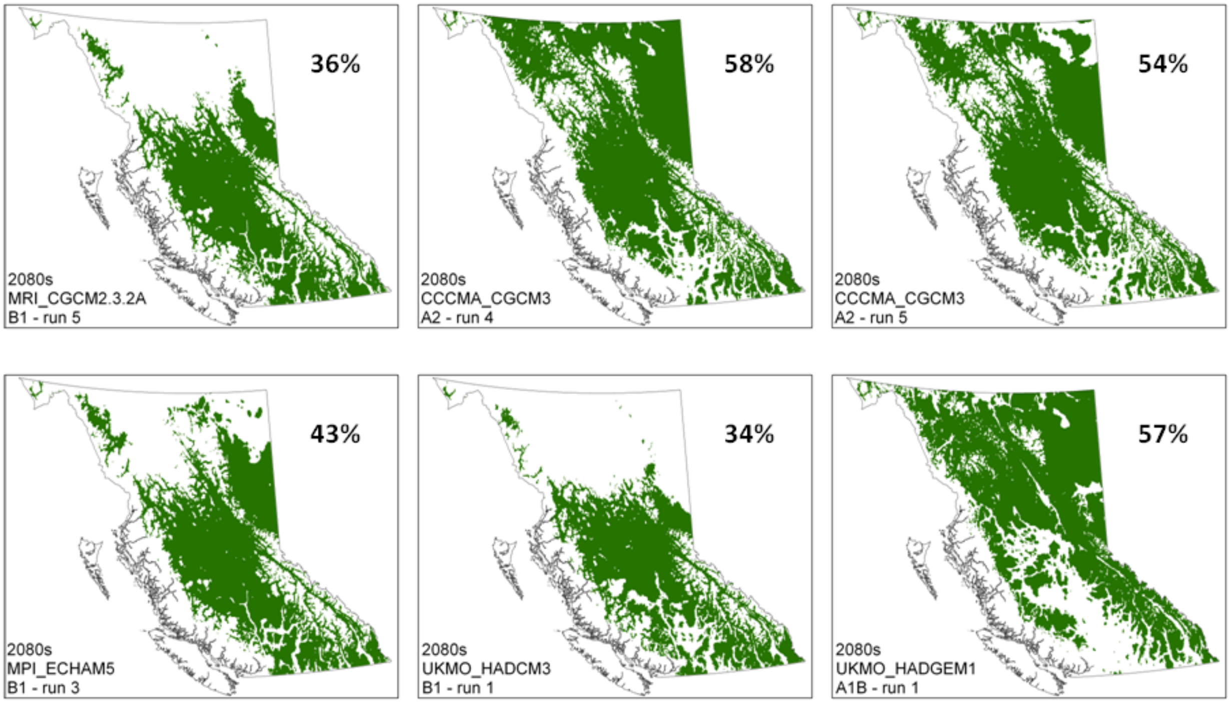


**Figure 24 - Agreement between GCM projections for Douglas fir suitability (defined using a 90% suitability threshold) in 2080s, with percent of the Province predicted to be suitable (in upper right corner).**

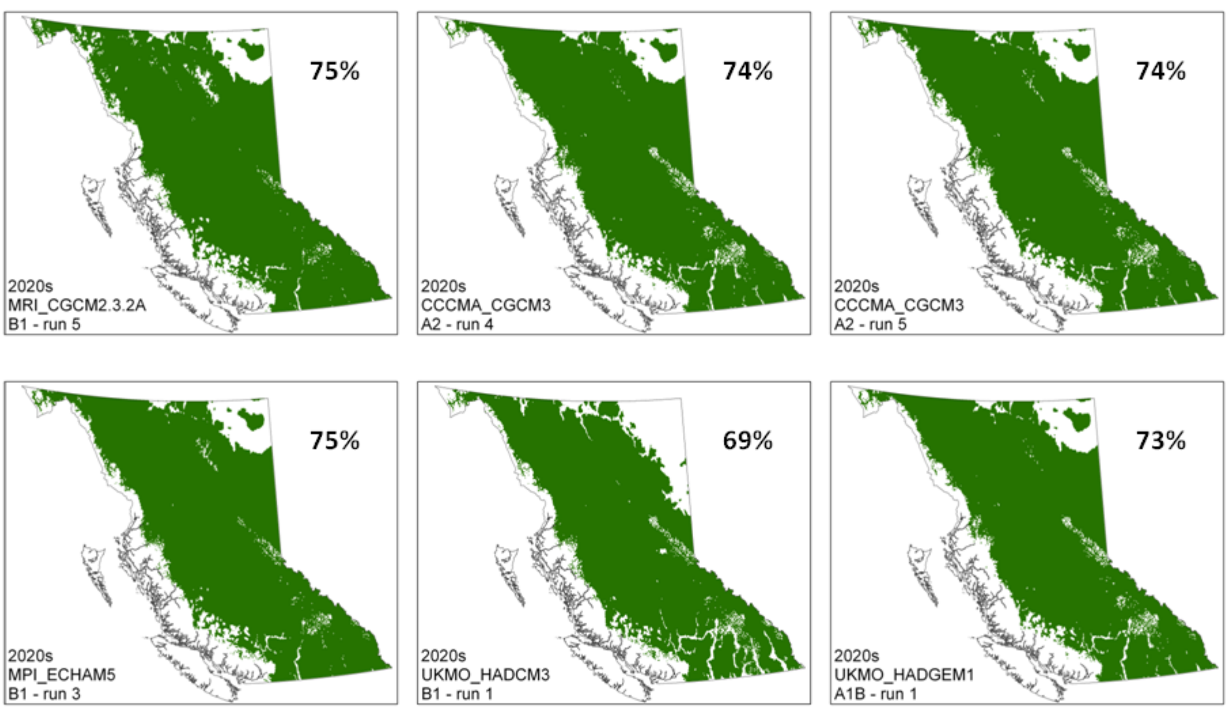


**Figure 25 - Agreement between GCM projections for spruce suitability (defined using a 90% suitability threshold) in 2020s, with percent of the Province predicted to be suitable (in upper right corner).**

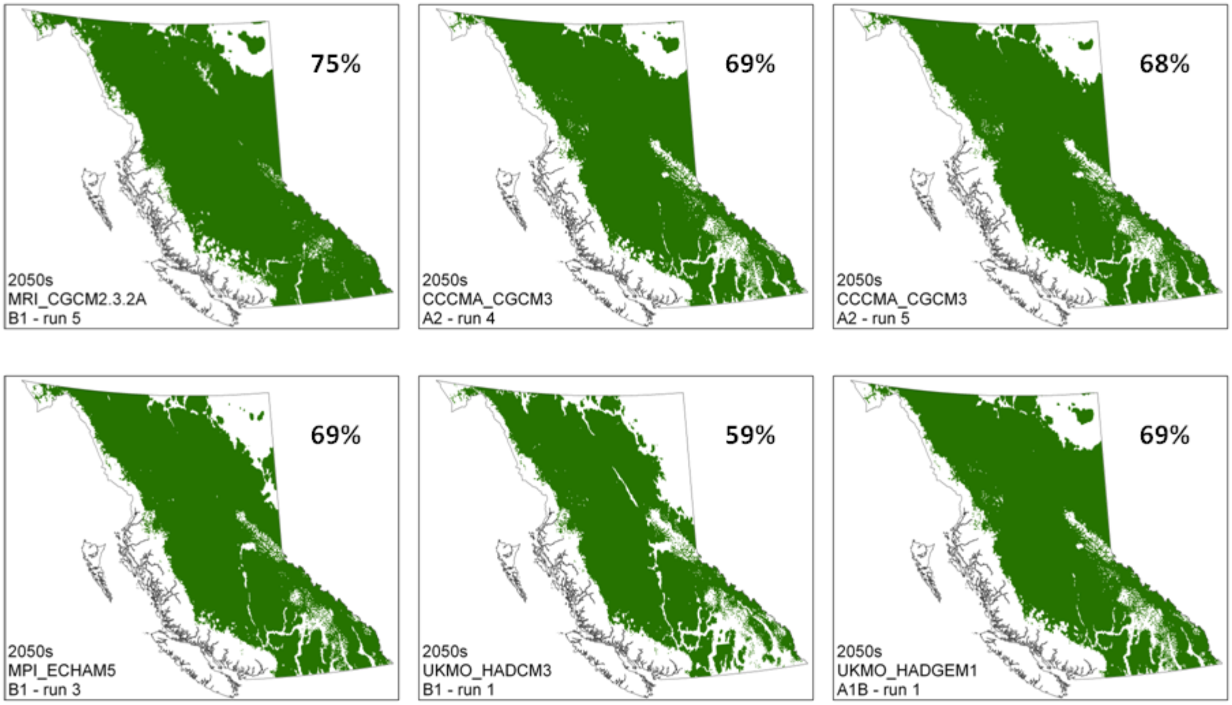


**Figure 26 - Agreement between GCM projections for spruce suitability (defined using a 90% suitability threshold) in 2050s, with percent of the Province predicted to be suitable (in upper right corner).**

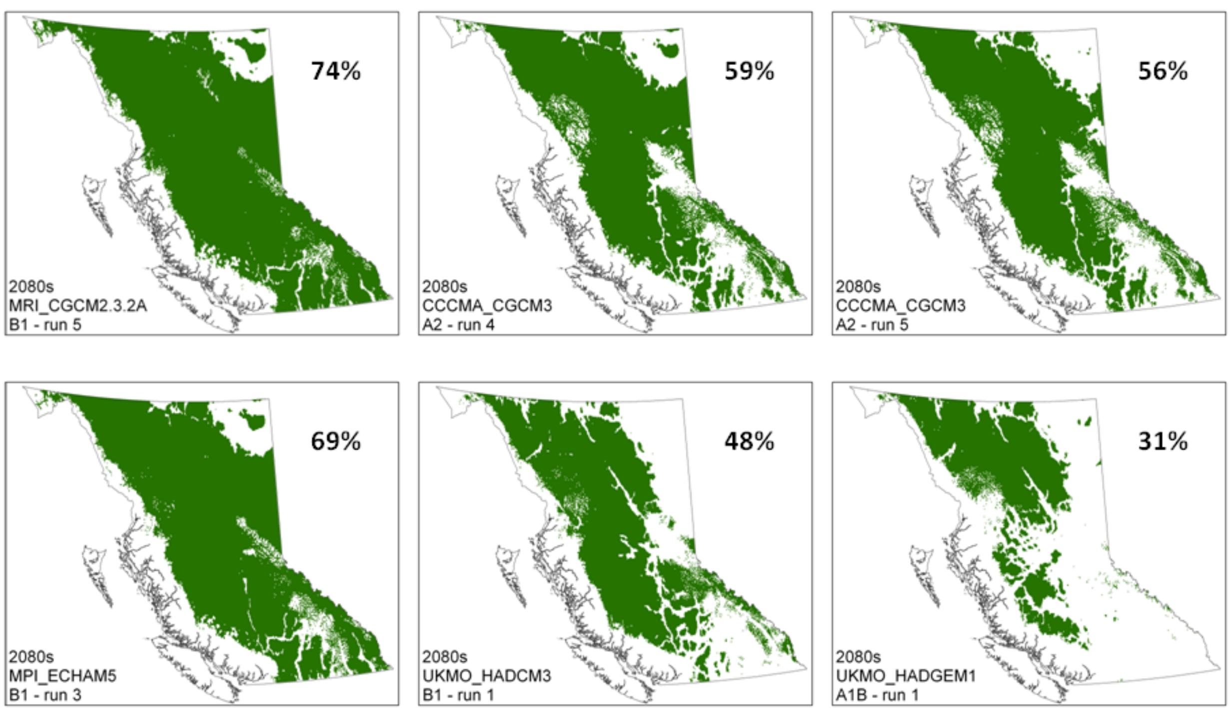


**Figure 27 - Agreement between GCM projections for spruce suitability (defined using a 90% suitability threshold) in 2080s, with percent of the Province predicted to be suitable (in upper right corner).**

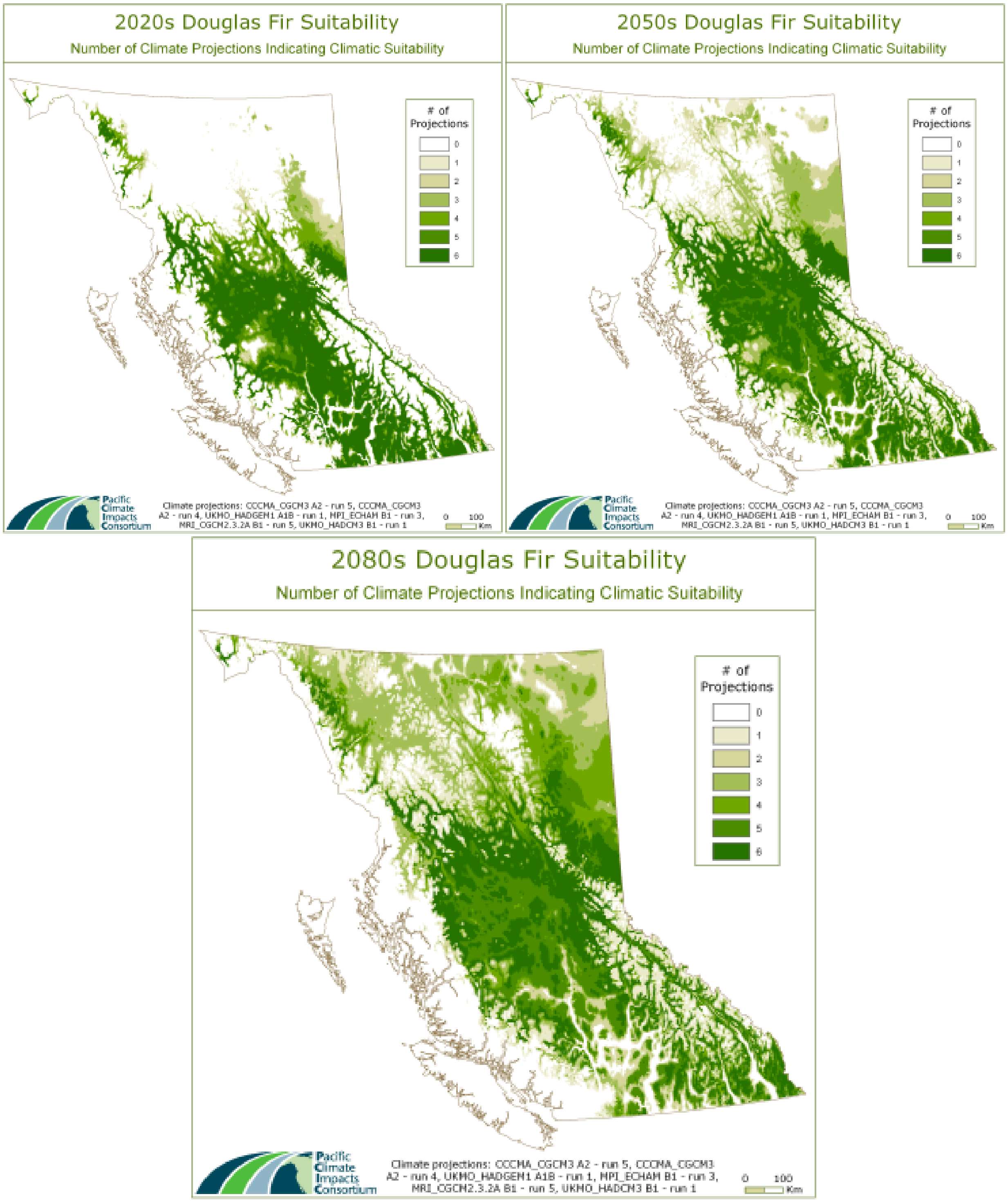


**Figure 28 – Number of climate projections indicating climatic suitability for Douglas fir: 2020s, 2050s, 2080s.**

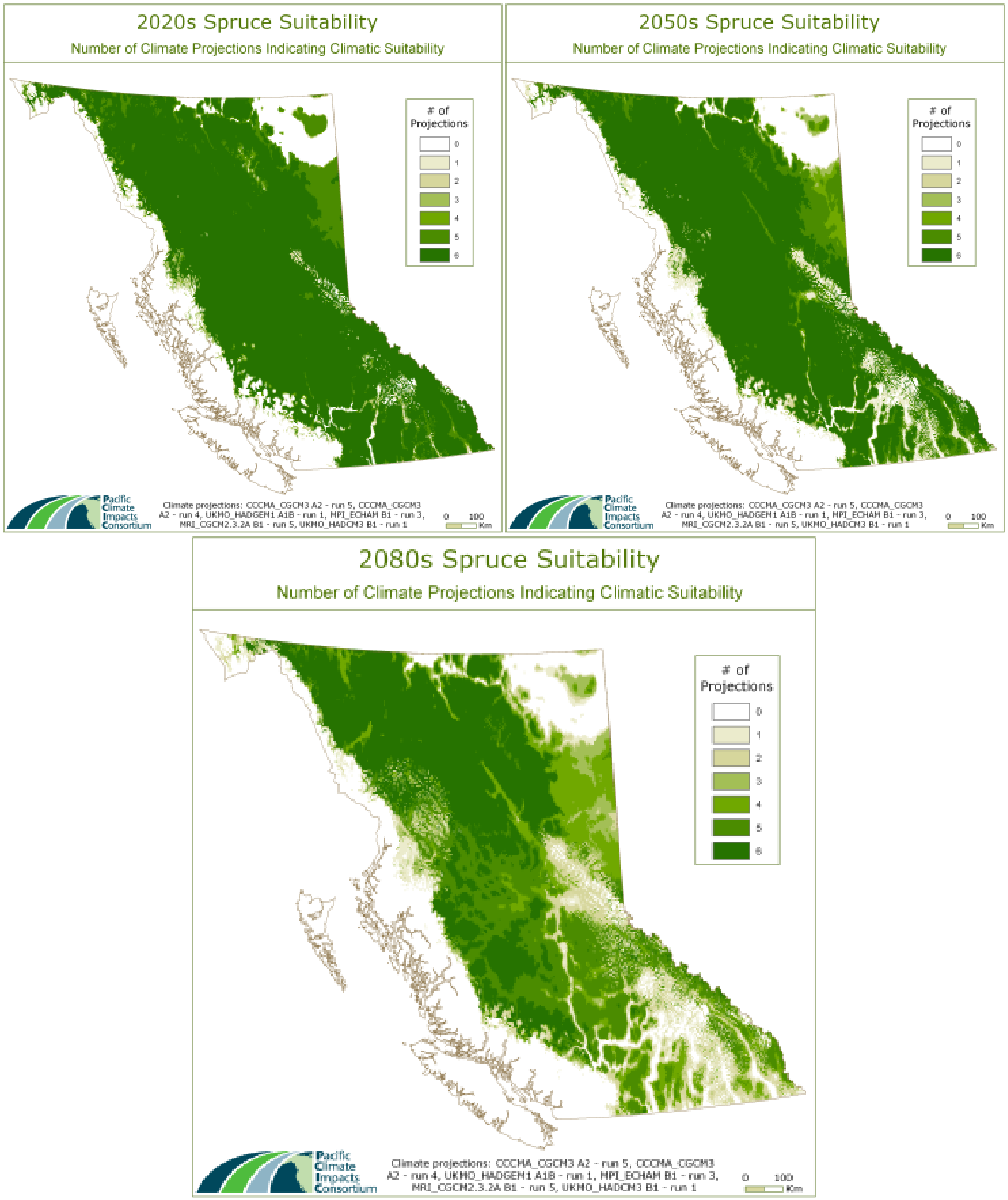


**Figure 29 – Number of climate projections indicating climatic suitability for spruce: 2020s, 2050s, 2080s.**

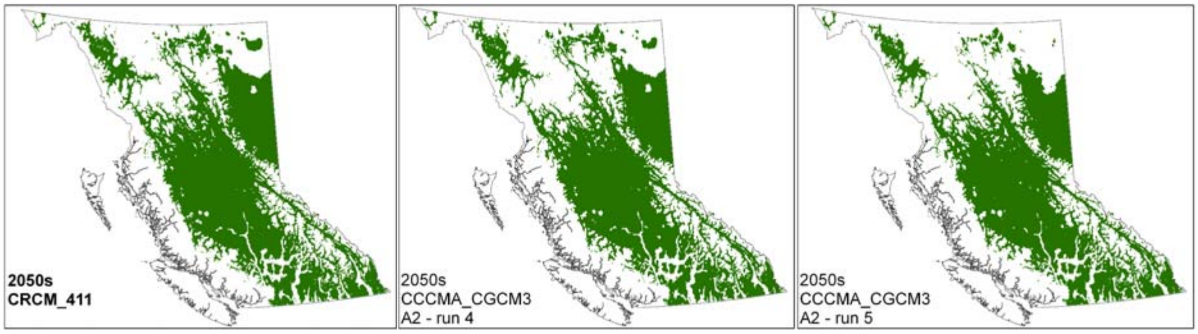


**Figure 30 – Comparison of 2050s Douglas fir suitability from (a) CRCM4.1.1 (b) its driving GCM (CGCM3 A2 run 4) and (c) the same GCM and emissions scenario forced with different initial conditions.**

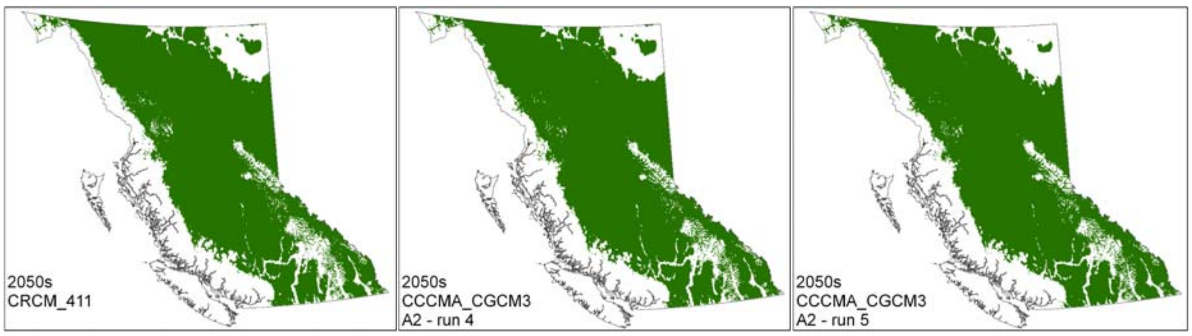


**Figure 31 - Comparison of 2050s Spruce suitability from (a) CRCM4.1.1 (b) its driving GCM (CGCM3 A2 run 4) and (c) the same GCM and emissions scenario forced with different initial conditions.**

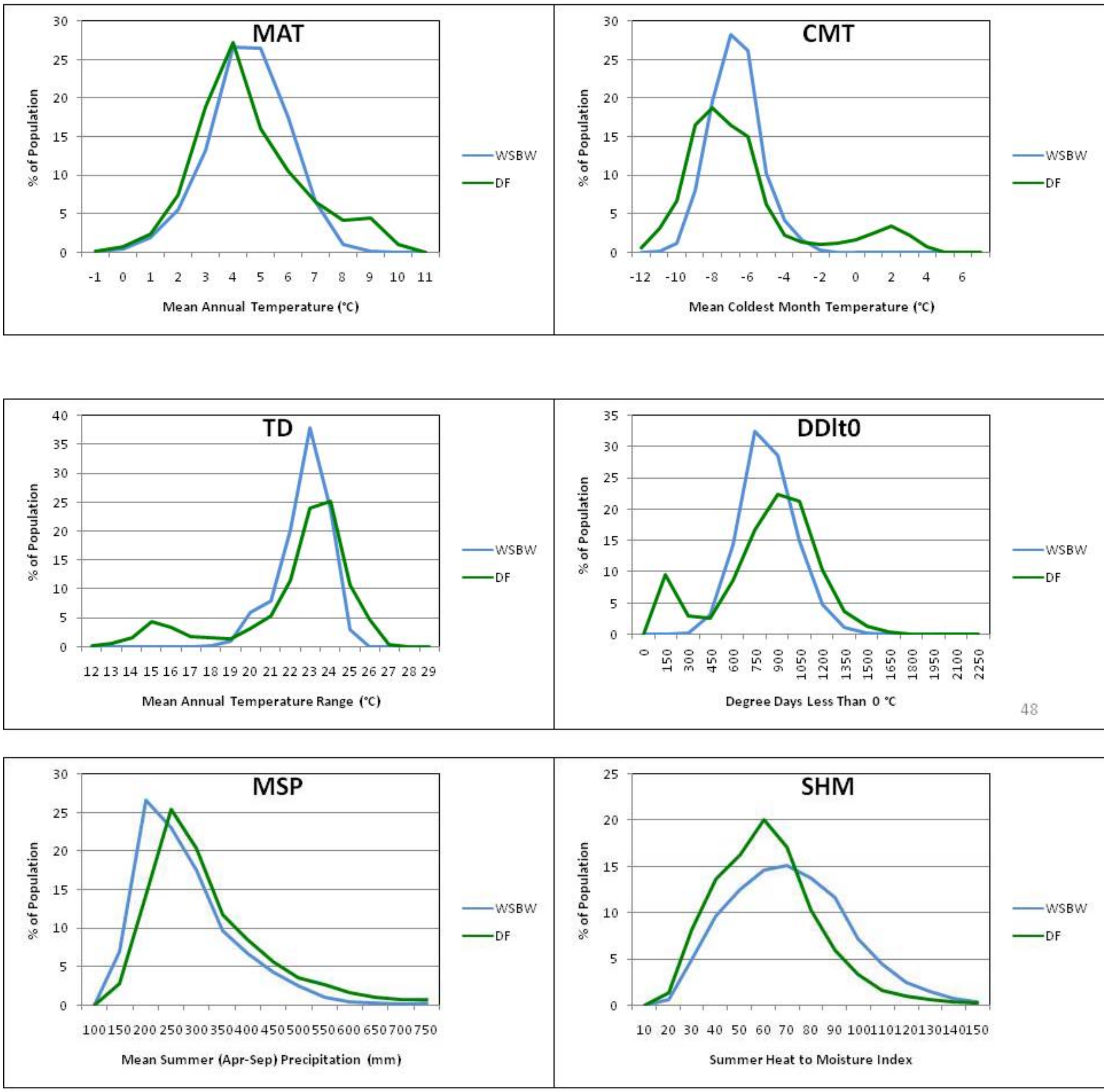


**Figure 32 – Percentage of historical (1961-1990) Western Spruce Budworm (WSBW) outbreaks vs percentage of total host (Douglas fir) population occurring at a specific value of six climate variables: mean annual temperature (MAT), coldest month temperature (CMT), annual temperature range (TD), degree days < 0°C (DDlt0), mean summer precipitation (MSP), and summer heat to moisture index (SHM).**

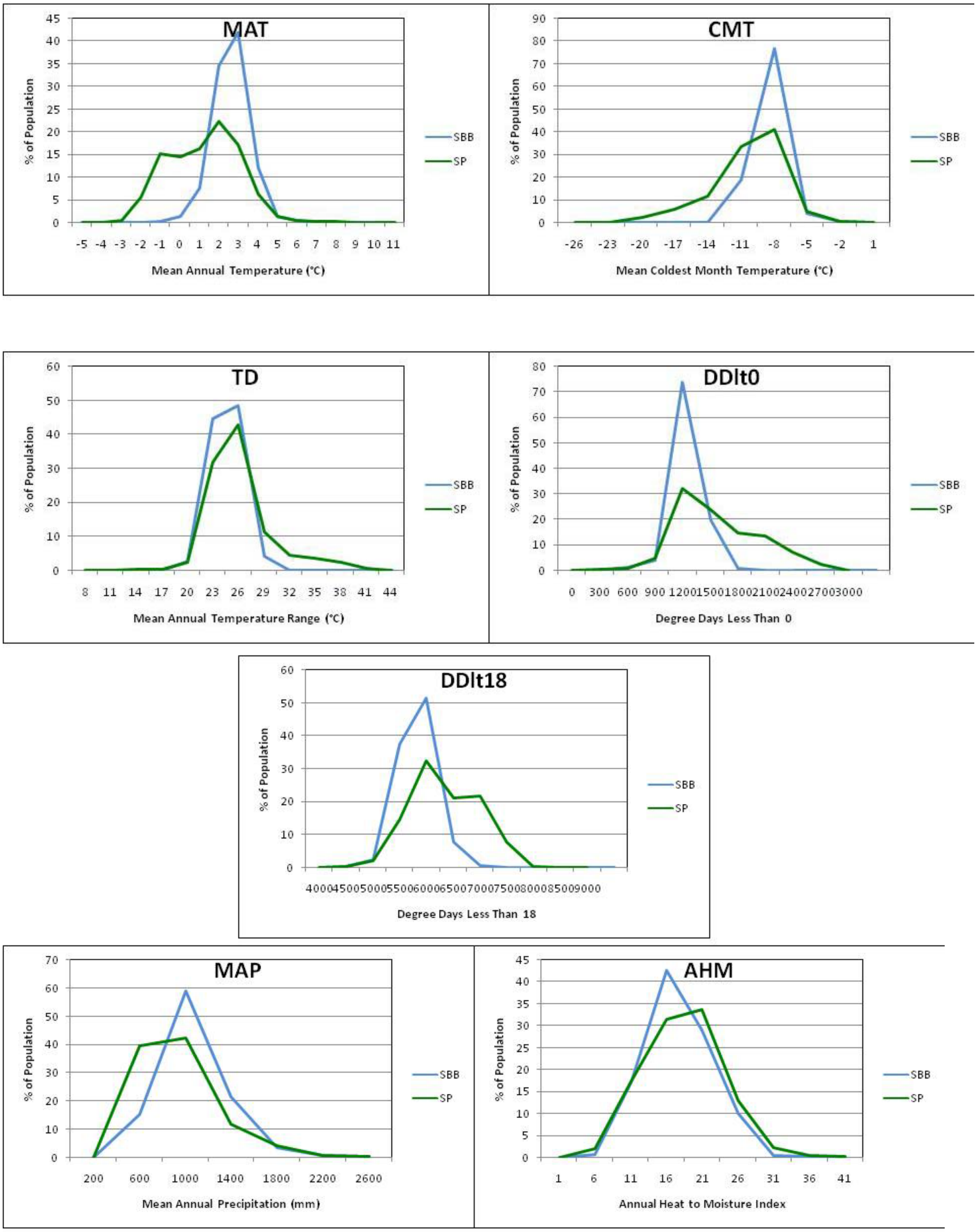


**Figure 33 - Percentage of historical (1961-1990) Spruce Bark Beetle (SBB) outbreaks vs percentage of total host population (spruce) occurring at a specific value of seven climate variables: mean annual temperature (MAT), coldest month temperature (CMT), annual temperature range (TD), degree days < 0°C (DDlt0), degree days < 18°C (DDlt18), mean annual precipitation (MAP), and annual heat to moisture index (AHM).**

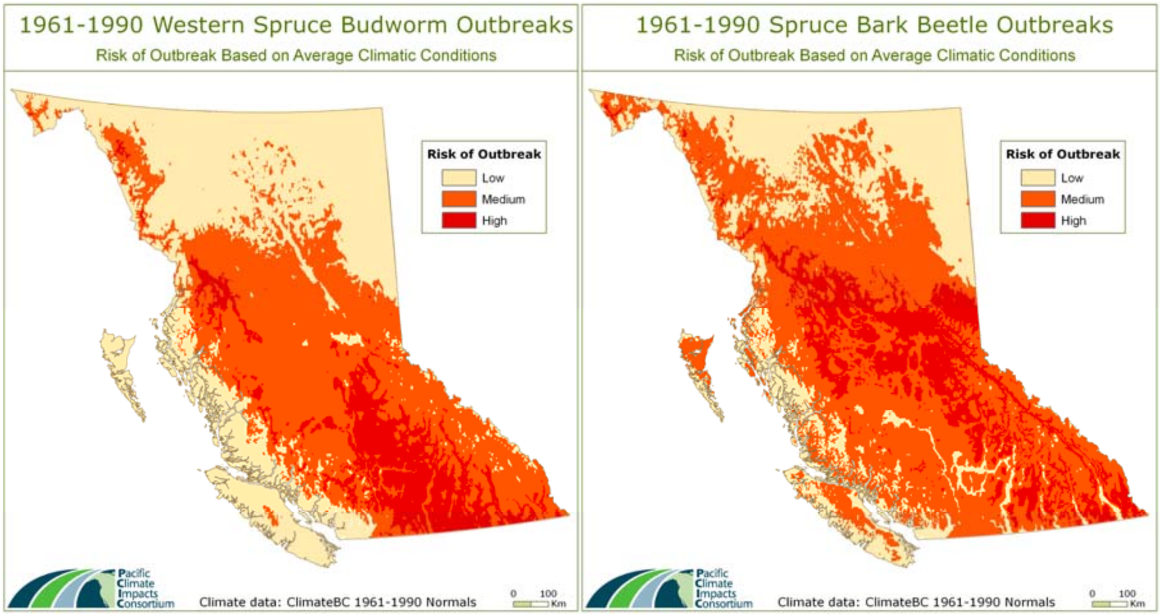


**Figure 34 – Baseline (1961-1990) Western Spruce Budworm and Spruce Bark Beetle outbreak risk.**

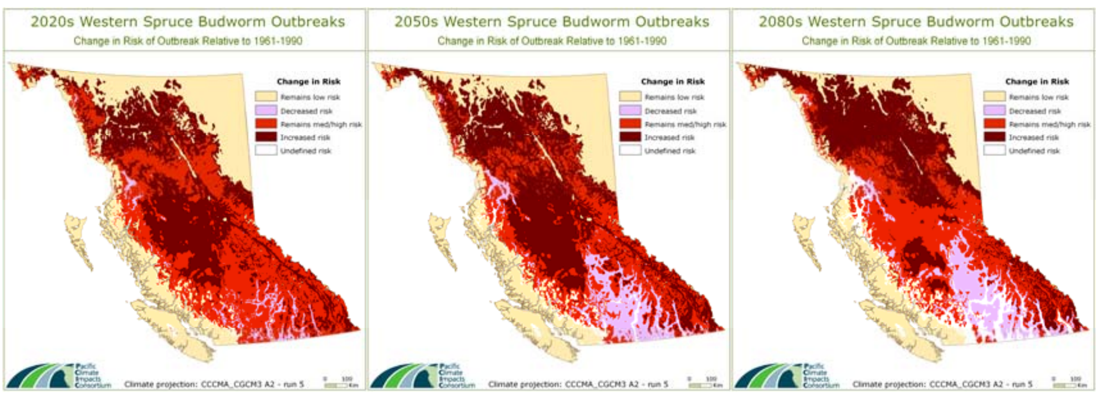


**Figure 35 - Projected Western Spruce Budworm outbreak risk: Warm/Wet projection (CGCM3 A2 run 5).**

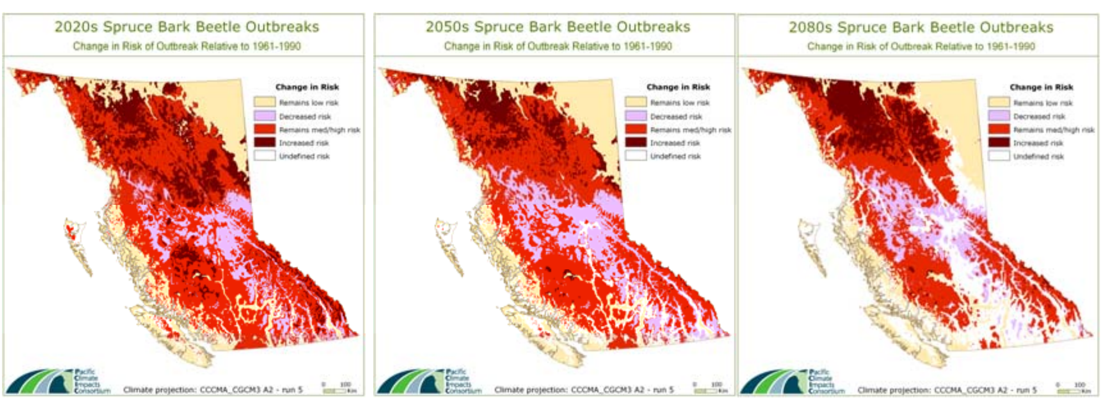


**Figure 36 - Projected Spruce Bark Beetle outbreak risk: Warm/Wet projection (CGCM3 A2 run 5).**

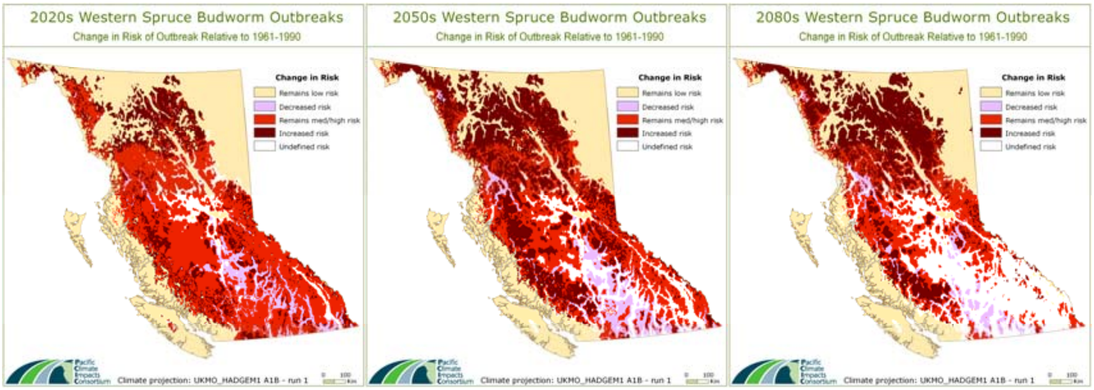

**Figure 37 - Projected Western Spruce Budworm outbreak risk: Hot/Dry projection (HadGEM A1B run 1).**

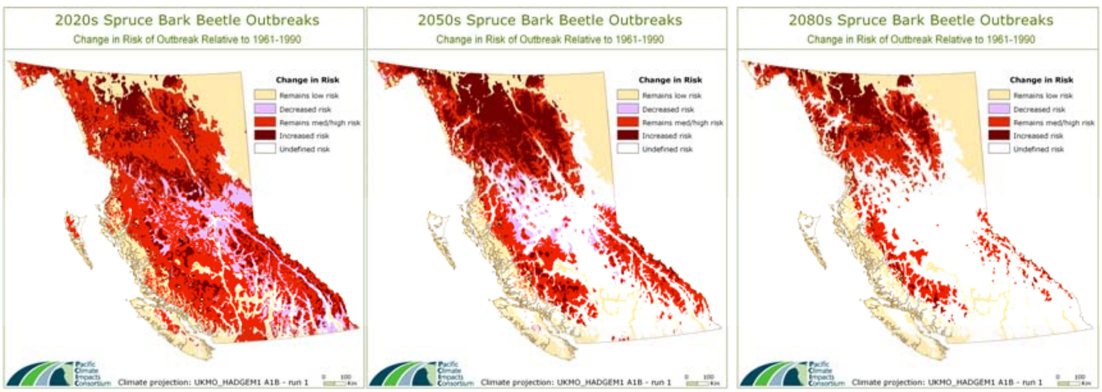

**Figure 38 - Projected Spruce Bark Beetle outbreak risk: Hot/Dry projection (HadGEM A1B run 1).**

## Appendix A – Following a point through tree species suitability

A single point was randomly selected from southern British Columbia within the current range of Douglas fir.

| | |
|---|---|
| Latitude | 52.377917° |
| Longitude | -122.477917° |
| Elevation | 914 m asl |

**Step 1:** Eight climate variables are extracted from ClimateBC for the point. Each variable was standardized by subtracting the mean of that variable as calculated for all the Douglas fir vegetation plots, then dividing by the standard deviation as calculated for those same plots.

| | Original Variable | Standardization Equation | Standardized Variable |
|---|---|---|---|
| MAT (°C) | 3.6 | (3.6 -4.608)/2.42555) | -.415576 |
| MWMT (°C) | 14.9 | (14.9 -15.45)/2.081961 | -.264174 |
| MCMT (°C) | -8.4 | (-8.4 - (-6.477))/3.747043 | -.531321 |
| TD (°C) | 23.3 | (23.3 -21.93)/3.073722 | .445714 |
| MAP (mm) | 532 | (532 -891.8)/693.967046 | -.518468 |
| MSP (mm) | 292 | (292 -280.1)/113.612230 | .104742 |
| AHM | 25.6 | (25.6 - 22.57)/10.874293 | .278639 |
| SHM | 51 | (51 - 64.94)/31.221376 | -.446489 |

**Step 2:** A score is calculated for each principal component by multiplying each standardized climate variable by its loading on that component. The scores are then divided by the eigenvalue of that component.

**SCORE1:** ((((-.415576)*(0.123)) + ((-.531321)*(-0.263))+(( .445714)*(0.404))+(( -.518468)*(-0.485))+(( .104742)*(-0.436))+(( .278639)*(0.448))+(( -.446489)*(0.343)))/3.751827) = **0.118919141**

**SCORE2:** ((((-.415576)*(-0.536)) + ((-.264174)*( -0.488)) + ((-.531321)*(-0.467))+(( .445714)*(0.239))+(( -.518468) *(-0.115)) + ((.104742)*(0.163))+(( .278639)*(-0.151))+(( -.446489)*(-0.370)))/3.271719) = **0.276961869**

**Step 3:** The scores are squared and summed, giving the squared Euclidian distance from the centre of the climatic envelope: (0.118919141*0.118919141) + (0.276961869*0.276961869) = **0.090849639**

**Step 4:** The square root of the squared and summed score can be taken, giving us the Euclidian distance from the centre of the climatic envelope. In this case, distance = **0.301412739**

**Step 5:** The Euclidian distance can then be converted to percent suitability to make interpretation easier. This is calculated as 1 – (distance / maximum historical distance); in this case percent suitability is equal to 1 - (0.301412739 / 6.67331) = **0.954833098**, giving a suitability value of 96%.

## Appendix B – Following a point through pest outbreak risk assessment

A single point was randomly selected from southern British Columbia within the historical (1961-1990) range of Western Spruce Budworm outbreaks.

| | |
|---|---|
| Latitude | 52.377917° |
| Longitude | -122.477917° |
| Elevation | 914 m asl |

**Step 1:** Six climate variables are extracted from ClimateBC for the 4-km grid cell that the point falls within.

| Variable | Value |
|---|---|
| Mean annual temperature (°C) | 3.2 |
| Coldest month temperature (°C) | -8.5 |
| Annual temperature range (°C) | 23 |
| Mean summer precipitation (mm) | 311 |
| Summer heat to moisture index | 46.6 |
| Degree days < 0°C | 952 |

**Step 2:** The values of these six climate variables are compared to the range of values classified as high or medium risk, based on analysis of historical outbreak records. If the values of all the climate variables fall within the High Risk class, the point is classified as High Risk. If the values of all the climate variables fall outside of the High Risk range of values, but within the wider range of values labeled as Medium Risk, the point is classified as Medium Risk. If the values of any of the climate variables are outside the range of values labeled as Medium Risk, the point is classified as Low Risk.

| Variable | High Risk (5th to 95th percentiles) | Medium Risk (minimum to maximum) |
|---|---|---|
| Mean annual temperature (°C) | 1.6, 6.6 | -3, 9 |
| Coldest month temperature (°C) | -9.3, -4.0 | -12.8, -1.2 |
| Annual temperature range (°C) | 19.7, 24.3 | 16.6, 25.8 |
| Mean summer precipitation (mm) | 145, 457 | 96, 896 |
| Summer heat to moisture index | 29.3, 1121.1 | 14.5, 198.9 |
| Degree days < 0°C | 484, 1079 | 191, 1861 |

In this case, all of the six relevant climate variables at our point fall within the High Risk class, and our point is therefore labeled as High Risk.

## Appendix C – Bio-economic model

Additional technical details are provided in the attached report by post-doctoral consultant, Dr. Alan Mehlenbacher: Economic Impact of Climate Change on Douglas Fir and Spruce Forests in British Columbia, pages Appendix C – 1 to 31.