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Pest outbreak distribution and forest management impacts in a changing climate in British Columbia

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ABSTRACT

This paper examines the risks associated with forest insect outbreaks in a changing climate from biological and forest management perspectives. Two important Canadian insects were considered: western spruce budworm (WSBW; *Choristoneura occidentalis* Freeman, Lepidoptera: Tortricidae), and spruce bark beetle (SBB; *Dendroctonus rufipennis Kirby*, Coleoptera: Curculionidae). This paper integrates projections of tree species suitability, pest outbreak risk, and bio-economic modelling.

Several methods of estimating pest outbreak risk were investigated. A simple climate envelope method based on empirically derived climate thresholds indicates substantial changes in the distribution of outbreaks in British Columbia for two climate scenarios and both pests. A ''proof of concept'' bio-economic model, to inform forest management decisions in a changing climate, considers major stand-level harvest decision factors, such as preservation of old-growth forest, and even harvest flow rates in the presence of changing tree species suitability and outbreak risk. The model was applied to data for the Okanagan Timber Supply Area and also the entire Province of British Columbia.

At the provincial level, the model determined little net timber production impact, depending on which of two climate scenarios was considered. Several potentially important factors not considered in this first version of the model are discussed, which indicates that impact may be underestimated by this preliminary study. Despite these factors, negative impacts were projected at the Okanagan Timber Supply Area level for both scenarios.

Policy implications are described as well as guidance for future work to determine impacts of climate change on future distribution and abundance of forest resources.

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1. Introduction

Plants and the herbivores that feed on them have co-evolved through the millennia and, where they occur together, their populations may form resilient systems (Holling, 1973). The impact of insect outbreaks on host trees may vary from growth reduction to mortality, while insect populations are influenced by host abundance (Okland and Bjørnstad, 2006). Changes in Earth's climate affect these relationships by changing forest

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distribution and tree species composition, as well as influencing the organisms that live in forests, including pest species. Although native trees and herbivores have co-evolved, the unprecedented fast pace of change and comparatively slow generation time of forest trees may not allow sufficient time for co-evolved herbivore/insect populations adapted to new climates. Projected changes in temperature and precipitation regimes may alter insects' and pathogens' rates of development, ranges, and frequency of outbreaks. By making new ecological niches available, climate controls the introduction of alien pests into new environments as well as the range expansion of native pests. Such invasions into ecosystems where they are absent or rare can have substantial impacts. As a result of these changes in host–pest relationship, climate change is a threat to the sustainability of forests across North America (Logan et al., 2003) and in British Columbia (BC) in particular (BCMFOR, 2006).

Two current forest health issues in BC have been linked to climate change. Increases in incidence of Dothistroma have been associated with increased precipitation (Woods et al., 2005). The size and severity of mountain pine beetle outbreak (*Dendroctonus ponderosae*; Taylor et al., 2006) has been attributed to range expansion associated with two factors. First, climatically favourable habitat increased due particularly to reduced severity of winter temperatures (Carroll et al., 2004; Stahl et al., 2006). Second, the amount of lodgepole pine (its principal host) of susceptible age increased due to decreased stand-replacing disturbances during the past century (Taylor et al., 2006).

Pest outbreaks can have significant impacts on forest health, carbon stocks, and economies of forest-based communities at regional and provincial scales. The present pine beetle outbreak is unprecedented (Kurz et al., 2008). As of 2010, it extended to over 47% of total provincial mature merchantable pine volume and projections indicate that it will hit 65% by 2016 (Walton, 2010). While harvesting has accelerated in affected areas to capture some of the economic value in the dead trees, it will decline in coming years to levels sustainable by the forest that remains. Regional decreases in net domestic product depend on the local intensity of the outbreak and local importance of forestry, and could average 55% in the long term with an accompanying reduction in employment (Patriquin et al., 2007).

The forests of BC contain 18 economically important tree species (Klinka and Chourmouzis, 2005), each with their own suite of potentially destructive insect and/or disease agents (McLean et al., 2005). As insects are poikilothermic, many aspects of their life history are sensitive to changes in temperature. It is prudent to explore potential impacts of climate change on pest/host systems other than the pine beetle/pine system.

This paper examines the risks associated with forest insect outbreaks from both biological and economic perspectives in a changing climate. Two important Canadian insects were used as case studies: western spruce budworm (WSBW; *Choristineura occidentalis* Freeman Lepidoptera: Tortricidae), and spruce bark beetle (SBB; *Dendroctonus rufipennis Kirby* Coleoptera: Curculionidae).

An expert workshop was convened to guide the project (Abbott et al., 2008). Participants from multiple disciplines – climate science, modelling, forestry, ecology, entomology, and economics – were brought together. To maximize contributions, the meeting was small, discussions were plenary, and attendees were assigned papers to read beforehand. A focus on staying relevant to information needs for policy and management was reinforced by BC's Chief Forester opening the workshop.

Recommendations for addressing gaps in knowledge were identified. These guided the work described in the rest of the paper:

1. There are at least 12 native insect species that have the potential for significant detrimental impact on BC forests. These include WSBW and SBB. In addition, Douglas-fir bark beetle (*Dendroctonus brevicomis*) and Western balsam bark beetle (*Dryocoetes confusus*) are also high priority.
2. Current understanding and predictability in individual components of the forest/pest/climate system is a foundation to build upon (Sections 3.1 and 3.2).
3. Statistical methods can be used for exploratory analysis and are more useful if they incorporate biologically meaningful variables based on scientific knowledge and understanding of the pest or host itself (Section 3.3).
4. Economic impact models should consider both monetary and non-monetary values, near-term focus of industry including carbon accounting and market diversification, non-timber forest products, and ecosystem services without direct monetary value (Section 3.4).
5. Models that incorporate biological processes will ultimately be needed, but they are complex, largely untested and under active development (Section 5).

1.1. *Policy implications*

Although the study area is focused on BC, many of the policy implications of this research are relevant throughout North America. In particular, the ability to identify and rank areas for risk provides an opportunity to refine pest management activities. For example, identifying areas with different levels of risk can aid in the allocation of resources for aerial surveys. Defining the climatic conditions that enhance pest outbreaks means that inter-annual variations in weather can be considered when surveying for infestation, e.g., warmer and wetter years may increase risk in some areas and thus indicate areas for increased surveillance.

In addition, identifying areas that may become high risk in the near term (e.g., 2020s) facilitates targeting harvesting to avoid possible loss of timber or reduced value of salvage. Reforestation strategies for sites likely to be at a high risk in the future could be adjusted to increase the percentage of species that would be at a lower risk.

The potential for climates to appear that are not analogous to ones that currently exist in the region (Section 4.3) emphasizes that planning for the future must include consideration of climate change. Thus, these results are further evidence that forest management adaptation strategies are needed (Spittlehouse, 2005).

Finally, although our study used only two climate change projections and simplistic climate envelope techniques, we find that these are useful methods to explore initial assessments of future risk. While it is true that more complex process-based models and larger ensembles of future projections are required to fully quantify risk and uncertainty, climate envelope

methods offer a glimpse into a future considerably different from present. This type of information is useful for integrated climate vulnerability assessments which in turn can prioritize areas for further research (Dawson et al., 2011).

2. History and biology of western spruce budworm and spruce beetle outbreaks

According to the Forest Insect and Disease Survey of the Canadian Forest Service, approximately 60% of the 4.5 million ha of Douglas-fir dominated stands in BC have been affected by WSBW since the early 1900s. Outbreak frequency varied and was highest in the Pemberton area, with at least 4 outbreaks in 80 years (Harris et al., 1985).

WSBW feeds on foliage, causing growth loss, top kill, and stem deformities; repeated attack over several years may cause tree mortality (Alfaro et al., 1982). WSBW have a one-year life cycle. Adult moths lay eggs on undersides of needles in August, larvae hatch and spin hibernaculae in which they overwinter and then emerge the following spring. Outbreaks are associated with stands where temperatures permit emergence to be synchronized with bud swelling (Shepherd, 1985). Larvae penetrate swelling buds that have the highest food quality and offer the best protection from predators. Early emergents cannot establish in buds and late emergents are exposed to an extended period of high mortality, although mature larvae will feed on older foliage if buds and new needles are in short supply. Outbreaks may last from one to several years. Collapse may be related to extreme high temperatures during (July) moth flight and oviposition (Thomson et al., 1984). The overwintering stage is cold-tolerant and extreme winter temperatures are not believed to be a limiting factor. Warming may change the timing and synchrony of budflush and bud emergence, which in turn will potentially influence outbreak frequency and severity.

SBB is the most destructive pest of mature Engelmann spruce (*Picea engelmannii*), hybrid spruce (*Picea engelmannii* x *glauca*), and white spruce (Picea glauca) forests in BC (Humphreys and Safranyik, 1993). During 1960–2002, approximately 14% of the 14 million ha of spruce forest in BC were affected by SBB (Forest Insect and Disease Survey data). During endemic conditions, SBB exist in windfall, slash and other downed timber. When populations increase, often following windfall, healthy mature trees can be attacked (Safranyik, 1985). It generally takes two years (semivolitine) for SBB to complete its life cycle in BC, although this can vary from one to three years. Warmer temperatures seem to promote a one year (univoltine) life cycle, allowing populations to expand rapidly (Hansen et al., 2001). A univoltine cycle has been observed in the current outbreak in Yukon (Garbutt et al., 2007) and a long running outbreak on the Kenai Peninsula in Alaska (Berg, 2000).

3. Methods

3.1. Climate and outbreak datasets

High-resolution climate data is required to adequately represent the diverse local climatic conditions across British Columbia's high-relief, mountainous landscape. Historical climate data was obtained from the gridded Parameter-elevation Regression on Independent Slopes Model climate dataset (Daly et al., 2002). Two climate projections were used to represent future climatic conditions. After examining the full set of available global climate model projections for British Columbia, we chose two illustrative projections: one warm, wet (CGCM3 A2 run 5) and one hot, dry (HadGEM1 A1B run 1). It is important to consider these as plausible examples only, not representative of the full range of possible futures. Both historical climate records and future climate projections were downscaled to a consistent 4 km resolution with ClimateBC (version 3.2.1, Wang et al., 2006).

Tree species abundance data were obtained in the form of 1:20,000 scale maps of forest stand composition from the Vegetation Resources Inventory (Province of British Columbia, 2007). These maps are primarily derived from interpretation of aerial photographs, with some ground based validation and data were interpolated to 4 km resolution. More accurate tree species presence records were needed for constructing the models of tree species ranges. These were obtained for BC, western Alberta, northwestern Washington, and the Yukon Territory in the form of survey plot point locations. The presence records do not cover the entire range of the species of interest, but do cover an area representative of the local genetic populations of each species actually present in British Columbia.

Gridded observations of insect outbreaks were obtained from the Canadian Forest Service. Original data consisted of outbreak polygons digitized from aerial sketch maps at approximately 1:125,000 scale (Perkins and Taylor, 2005), which were also interpolated to 4 km. Observations are available for the period 1905–2005 and 1950–2005 for WSBW and SBB, respectively. Due to concerns about lack of completeness with earlier observations, only data from 1950 onward were used. Pest outbreak records cannot be considered continuous time series, due to uncertainty of the interpretation of absence: years with no recorded outbreak may represent years when outbreaks occurred but were not observed due to small size or incomplete spatial coverage of aerial surveys.

3.2. Tree species climate envelopes

Climatic suitability for the tree species of interest was modelled using a correlative principal components analysis (PCA) method based on the techniques described in Robertson et al. (2001). For the tree species themselves, ten climate projections were used to more comprehensively address uncertainty (at least from climate models and greenhouse gas emissions scenarios). For ease of interpretation, percent suitability values relative to the baseline (1961–1990) model were calculated. 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 represented by Vegetation Resources Inventory maps. See Flower et al. (this issue) for additional details of the methodology used for computing tree species climate envelopes.

3.3. Climate envelope of outbreak

The potential influence of climate on pest outbreak risk was modeled using an approach that maps out the future projected locations of the range of present-day climate associated with presence of the species of interest. While climate envelope techniques do not explicitly incorporate known biological responses of pest or host to climate directly, it was agreed at the expert workshop that they are good tools for first-order approximation to prioritize potential climate impacts that will then require further study (Abbott et al., 2008).

We used a percentiles threshold overlap method that associates species ranges with absolute climate thresholds. It is similar to the quantile mapping method of McKenney et al. (2007). Frequency of occurrence of outbreaks and frequency of occurrence of host species were compared throughout the full range of values of each climate variable. If there was an offset between occurrence of pest outbreaks and host trees in areas with a specific range of climatic conditions (e.g., relatively cold areas where many hosts grow but few outbreaks have occurred), that climate variable was inferred to impact the likelihood of pest outbreaks.

All 13 annual and seasonal variables listed in Table 1 on the basis of possible biological relevance (Wang et al., 2006). Thus, we used a correlative approach rather than pre-selecting variables for known influences on SBB/WSBW life cycles. We did not attempt to address issues of collinearity between climate variables, as the technique is not sensitive to correlated variables. The variables selected this way (Table 1) were obtained at 4 km resolution for the 1961–1990 average. Climate envelopes were defined from the spatial minimum, 5th percentile, 95th percentile, and maximum value of each climate variable at all locations where outbreaks occurred between 1961 and 1990. For the purposes of displaying the range on maps, all locations with climatic characteristics within the 5th to 95th percentile for all of the relevant variables were classified as high risk. If one or more variables fell outside this range but all variables were within the minimum and maximum, medium risk was assigned. If any variables were outside of this wider range, the location was considered low risk: i.e., climate was assumed to be outside of the species' requirements. By classifying risk in this way, higher risk areas are those where outbreaks are more likely to occur, not necessarily areas where outbreaks would be expected to be of larger magnitude. Magnitude of outbreak given occurrence is addressed in the bio-economic model (Section 3.4.1).

In cases where projected future climate conditions are outside of the range in which pest outbreaks have ever historically occurred in BC, risk must be considered undefined. This is because these areas have projected climates with no direct historically observed analogue, which this threshold-based technique relies on. As the study did not make use of outbreak data outside of BC, the areas of future undefined risk may be reduced by conducting the analysis with outbreak data from south of BC.

Table 1 – Parameters for pest outbreak climatic envelopes. All variables listed in the left column were tested for influence on the pest range. Only those with an offset between occurrence of pest outbreaks and host trees were included in the percentile threshold overlap method, as shown in the two columns to the right.

Variable	SBB	WSBW
Mean annual temperature (MAT)	X	X
Coldest month temperature (CMT)	X	X
Annual temperature range (TD)	X	X
Degree days < 0 °C (DDlt0)	X	X
Degree days < 18 °C (DDlt18)	X	
Mean annual precipitation (MAP)	X	
Annual heat to moisture index (AHM)	X	
Mean summer precipitation (MSP)		X
Summer heat to moisture index (SHM)		X
Warmest month temperature		
Degree days > 18 °C		
Degree days < 5 °C		
Date when degree days > 5 °C = 100		

3.4. Bio-economic modelling

A literature review was conducted in search of a forestry decision aid tool that could use the climate envelope results to investigate the impact of changing pest outbreak distribution on forest management decisions over the 21st century. As no suitable tool was found, a bio-economic model was developed as a proof-of-concept. The main objective of the forest management simulation is to achieve a balance between the harvest volume and the conserved forest area. The optimization method simulates decisions that account for government harvesting guidelines (described below) and to achieve a relatively even flow of harvest for steady employment and revenue in the forest industry. This model incorporates decision making processes that involve competing objectives with constraints at different spatial scales.

The forest management simulation divides the region into square cells that are small enough to capture the diversity of the landscape. We aggregate cells into 20 × 20 square frames, similar to an approach used by Borges et al. (1999). Within each frame, the optimization problem is solved using an approach similar to Mathey et al. (2007). For the Okanagan Timber Supply Area, 600 m cells (36 ha) were used since this size realistically represents the 40 ha cut blocks recommended by the Ministry of Forests. The BC level simulation was made using 4 km cells (1600 ha). Using this larger cell size required adjustments to account for cell-size larger than the area used for harvesting decisions, and an assumption that the entire area of each forested cell is forested. The ratios of the 600 m results to 4 km results for the Okanagan are 0.67 for harvest volume and 0.55 for forest area. These ratios were used to adjust the provincial results and account for the scale differences described above.

The objective of the economic model was to simulate future harvesting and preservation decisions in a simple but realistic manner. Some key features are:

- *Two optimization objectives*: first, to harvest trees in a relatively even flow to sustain forest industry employment; second, to conserve large areas of older trees for forest and climate values. This clustering objective is achieved by

placing more value on conserved cells with neighbours that are also conserved, similar to Mathey et al. (2007).
- *Harvesting constraints consistent with government guidelines*: not harvesting stands that are younger than 80 years, and a 10-year greenup delay. BC government guidelines set out requirements for ensuring that previously harvested cut blocks (cells) are greened-up before adjacent cells are harvested. The purpose of greenup is to provide for hydrological, visual, and wildlife habitat recovery.
- Decisions in each time period about harvesting or conserving a given cell take into account the previous and possible current decisions in the eight adjacent cells (neighbourhoods). This provides the ability to simulate forest management decisions that must consider greenup requirements and the conservation goal of preserving large tracts of forest.
- *Moving frames* to solve the complex interactions between objectives, constraints, and neighbourhoods similar to Borges et al. (1999). The optimization is solved for each frame in the context of results of previous optimizations of other frames. The moving frame method has good convergence properties that are illustrated in supplement.

3.4.1. *Model description*

Numbers listed below in square brackets refer to equation numbers in the supplement.

3.4.1.1. *Constraints*. As non-harvestable forested areas are not included in the timber harvesting land base (THLB), there are three cases. First, a cell can be non-forest: it cannot be harvested or conserved so harvesting and forest variables are fixed to 0 [1]. Second, a cell can be forest but outside the THLB: it cannot be harvested and is conserved [2]. Third, a cell can be forest inside the THLB: a decision must be made whether to harvest or conserve [3]. Even these cells cannot be harvested if they are younger than the minimum harvest age or are old-growth [4]. It is assumed that forested cells can be harvested only once per century, so there is a single-period harvest constraint [5]. Harvesting regulations require greenup of adjacent clear-cuts before another clear-cut in an adjacent stand [6].

3.4.1.2. *Harvest value*. Total value of harvest is based on volume, as in Mathey et al. (2007). A base volume calculation is used that is a function of the age of the cell. This function is based on the Chapman–Richards function as described in van Kooten et al. (1999) [7]. The volume is normalized using the maximum possible harvest volume, which would occur in the final period [8].

3.4.1.3. *Even flow*. An even-flow of harvest volume is required within a timber supply area. This is an external global constraint on the frame optimization achieved by applying a pass-dependent, time-period flow weight in the equation for cell harvest value [9]. Flow weights are updated after every pass to influence the frame optimization towards an overall even flow of harvest [10].

3.4.1.4. *Climate change*. Tree suitability and pest probability enter the model through impacts on volume. Volume is diminished or augmented by climate impacts in direct proportion to the tree suitability measurement [11].

The impact of pests is reflected by an additional volume adjustment. Generally, volume decreases with increased outbreak probability and with a stand-age dependent degree of impact [12]. SBB impact appears to increase with stand age (BCMOF, 1995). Loso (1998) claims a volume reduction of about 40% in mature stands, but finds young stands are resistant. A simple approximation is used where impact is zero up to 60 years then increases linearly to 40% at age 110 [13]. WSBW impact also seems to increase with stand age (Alfaro et al., 2001). A simple linear impact function with age up to a maximum of 25% (Heppner and Turner, 2006) at age 110 is used [14,15].

An additional step is required to convert the percentile threshold (Section 3.3) into impact of outbreak. Additional categories were used to the high (all conditions <5th and >95th percentiles) category used above: <10th/>80th, <15th/>75th, and so on to <30th/>60th. Every location has a climate within one of these bins. The fraction of time during which outbreaks occurred during 1961–1990 within each bin was computed. The bio-economic model uses this fraction as the probability of an outbreak occurring within a cell (thus assuming even distribution of outbreaks in time and throughout the area covered by each bin).

3.4.1.5. *Preservation value*. Forest preservation value occurs when a cell of mature forest (over 110 years) is maintained [16–19]. Conserved forest has more value in large tracts because value results from ability to provide wildlife habitat, non-timber harvest, viewscapes, and non-use value. Thus, forest preservation value increases with size [20]. This spatial goal has been previously included in models for wildlife planning (Bettinger et al., 2002) and forest management (Mathey et al., 2007). No modelling of conserved carbon value was considered.

3.4.1.6. *Objective function*. As in Mathey et al. (2007) the objective function maximized is a weighted average of the normalized harvest volume and normalized conserved forest area. The objective function is therefore a multi-objective function with a weight on the conserved forest area [21].

4. Results

4.1. *Tree species climate envelopes*

The tree species climate envelope model results indicate that environments at higher latitudes and/or elevations than the current range of Douglas-fir may become climatically suitable for this species, while lower elevation interior valleys may become less climatically suitable over the next century. Similarly, upper elevations in northern BC may become more favourable for spruce and southern interior BC less so. Both future climate projections produced similar results, but the hot/dry projection resulted in more rapid changes (see Flower et al., this issue, for full results). It must be remembered that these results apply only to the populations of these species currently present in the province. The projected habitat loss

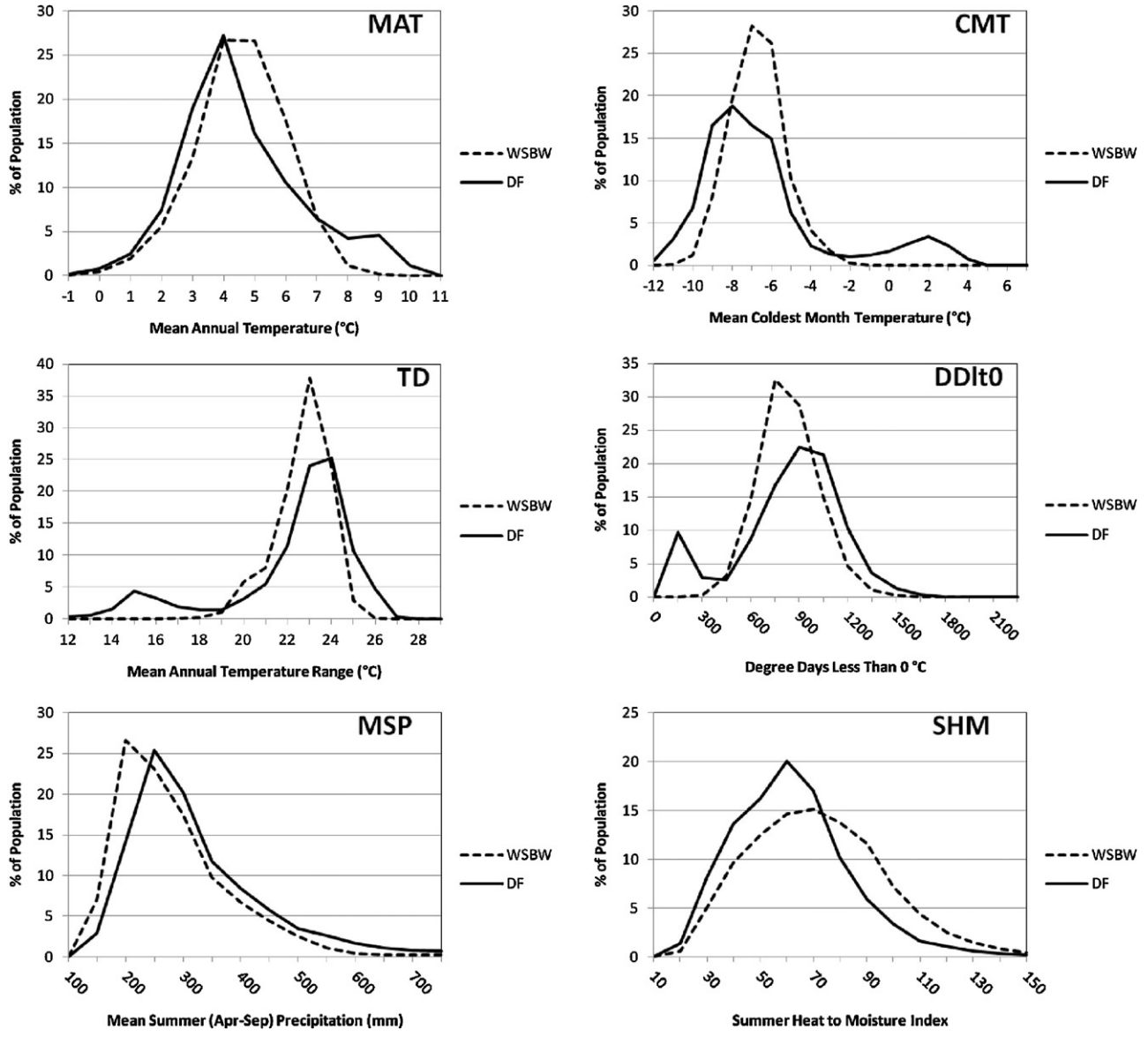

Fig. 1 – Percentage of historical (1961–1990) western spruce budworm (WSBW) outbreaks compared to percentage of total host (Douglas fir) population occurring at a specific value of six climate variables: mean annual temperature (MAT), coldest month temperature (CMT), annual temperature range (TD), degree days < 0 °C (DDlt0), mean summer precipitation (MSP), and summer heat to moisture index (SHM).

may therefore be less drastic if assisted migration is used to introduce trees from different provenances (St Clair and Howe, 2007).

4.2. *Insect outbreak climate envelopes*

The percentile threshold method (Section 3.3) was first used to study changes in the climate envelope of outbreaks that have occurred in the historical period. This was done by comparing the historical (1961–1990) climates occupied by Douglas-fir forests to the climates that experienced WSBW outbreaks as shown in Fig. 1. Outbreaks occurred more frequently in areas that were warmer (higher MAT and lower CMT, TD, and DDlt0) and drier (lower MSP and higher SHM) than the average climate that Douglas-fir grows in. Acronyms for climate variables are listed in Table 1. Assuming the differences in climate are limiting factors, this means there are currently Douglas-fir populations occupying areas too wet and/or too cold for WSBW outbreaks to occur.

The same comparison for spruce and SBB in Fig. 2 shows that SBB outbreaks also occurred in areas that were warmer (higher MAT and lower CMT, TD, DDlt0, and DDlt18) than the average climatology of their hosts. Acronyms for climate variables are listed in Table 1. In contrast to WSBW, SBB outbreaks occurred more often in locations that were drier (higher MAP and lower AHM index). Spruce that is presently at the colder or drier limits of the distribution may be more susceptible to outbreaks where climate is projected to become warmer and wetter in future as its climate becomes no longer too cold or too dry for the pest.

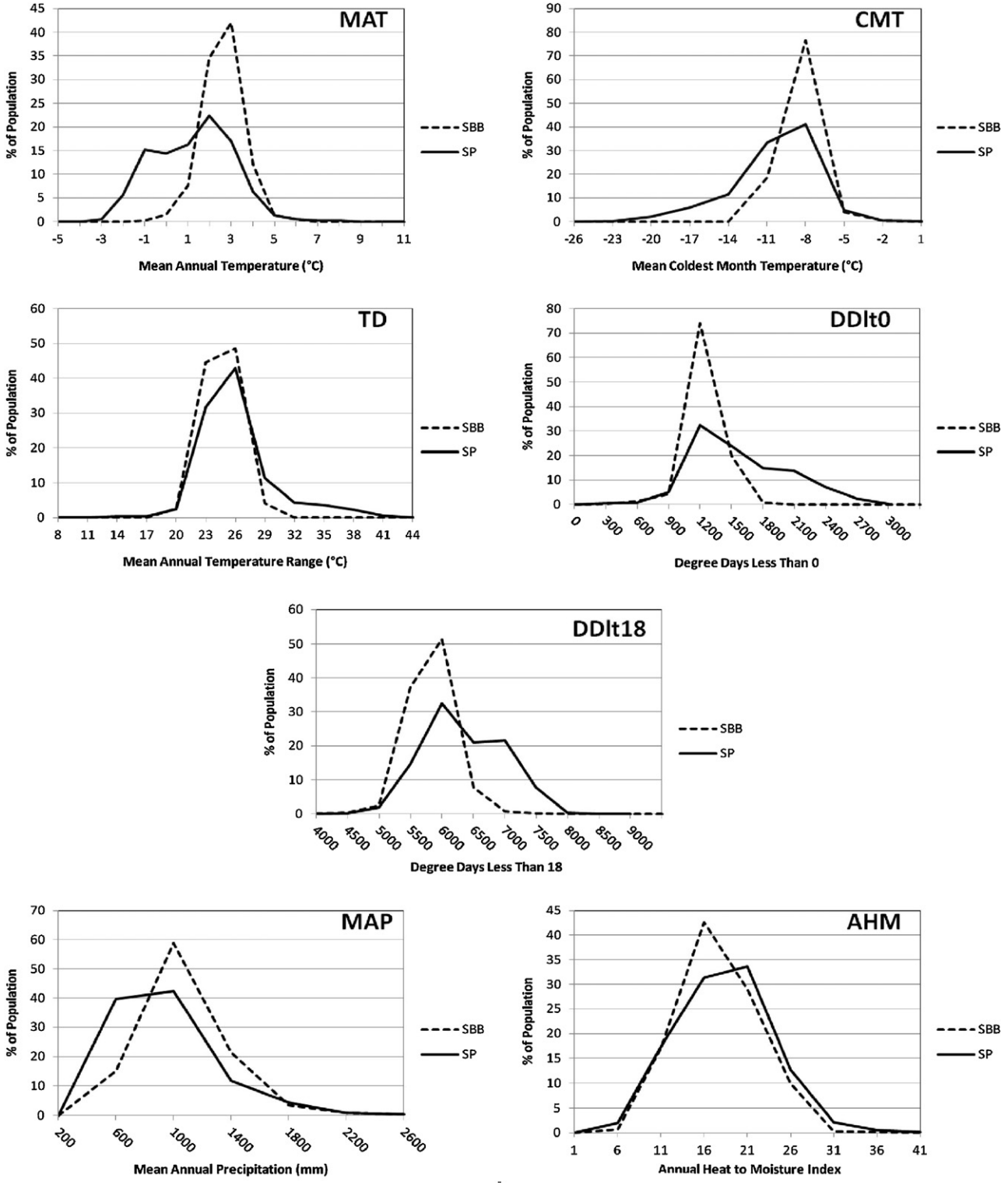

Fig. 2 – Percentage of historical (1961–1990) spruce bark beetle (SBB) outbreaks vs percentage of total host population (spruce) occurring at a specific value of seven climate variables: mean annual temperature (MAT), coldest month temperature (CMT), annual temperature range (TD), degree days < 0 °C (DDlt0), degree days < 18 °C (DDlt18), mean annual precipitation (MAP), and annual heat to moisture index (AHM).

The risk classification described in Section 3.3 is shown for the historical period in Fig. 3. There are many areas with high risk according to our classification, but where outbreaks did not occur. There are several reasons for this, such as availability and vulnerability of host trees, interactions with other pest species, and internal pest population dynamics (Eveleigh et al., 2007). In the case of SBB, significant windthrow may be needed to initiate an outbreak event (Safranyik, 1985).

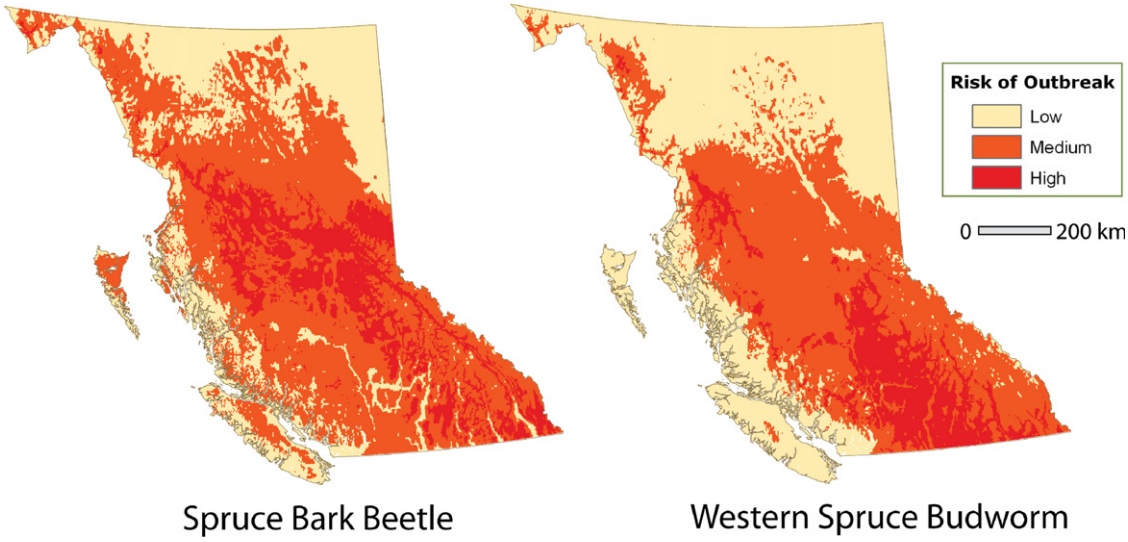

Fig. 3 – Baseline (1961–1990) outbreak risk.

WSBW outbreaks may require synchrony of tree budflush and insect emergence (Thomson and Moncrieff, 1982).

For SBB, 78% of outbreaks occurred in high risk locations, 22% in medium and 0% in low (by definition) during 1961–1990. A check was made to see if historical change in outbreak risk in the 1971–2000 period was consistent with the actual change in outbreak occurrence. Indeed, in the later (warmer) period, 57% of outbreaks occurred in what were previously high risk locations, 42% in medium, and 1% in low. In other words, outbreaks already began to occur more frequently in what were lower risk locations based on 1961–1990 climates. Because climate has been changing during the historical record, it is difficult to compare projected changes in outbreak risk to natural variations (Zhang et al., 1999). This shift in risk according to percentile threshold between these two 30-year periods is insufficient to attribute the observed change in occurrence of outbreaks to climate change. Rather, the result implies only that the change in risk according to the percentile threshold method is in agreement with the change in outbreaks that occurred in the brief historical record.

4.3. *Percentile threshold – future projections*

To adequately quantify uncertainty in projected impacts, an ensemble of many future climate projections must be considered. However, it was considered more important to explore a first small set of plausible future changes in detail. Thus, the two examples shown are illustrative cases only as they do not represent the full range of possible futures. For most of BC, the climate change projected by CGCM3 A2 run 5 is moderately warm and quite wet compared to other projections (Murdock and Spittlehouse, 2011). It is subsequently referred to as warm/wet. Similarly, HadGEM1 A1B run 1 is warmer and drier than other projections in most of BC and thus referred to as hot/dry (Murdock and Spittlehouse, 2011).

The warm/wet scenario shows increasing WSBW outbreak risk in central and northwestern BC and decreases from high to medium risk in many interior southern valleys (Fig. 4 – top panel). Small areas of decreased SBB risk in central BC and increased risk in northwestern BC during 2020s and 2050s (Fig. 5 – top panel) give way to a considerable area of undefined risk by 2080s in central valleys as climatic conditions change sufficiently to have no analogue within the historically observed range of SBB outbreaks in BC.

The hot/dry scenario indicates a smaller area of increasing WSBW risks than the warm/wet scenario. A considerable portion of BC has no historical analogue climate (in BC) by the 2080s (Fig. 4 – bottom panel). Risk of SBB outbreaks shows small increases and a shift to undefined, no historically observed analogue climates at an even quicker pace and bigger scale than WSBW (Fig. 5 – bottom panel).

4.4. *Bio-economic modelling*

The bio-economic model (Section 3.4) was run for three scenarios in Okanagan and BC: a base scenario with no climate change and the warm/wet and hot/dry scenarios described in Section 4.3.

Simulated Okanagan harvest volume for the base scenario is 2.3 million m^3, near the typical Annual Allowable Cut of 2.6 million m^3 (Snetsinger, 2006). Harvest volume decreases for both warm/wet and hot/dry scenarios with a slight increase in conserved forest area for hot/dry (Table 2). The BC level simulation has a base Annual Allowable Cut of 32 million m^3, less than half the current provincial value of 70–75 million m^3 (Pedersen, 2003). The simulation is optimized only for the constraints and assumptions used. Most of the differences between the simulated and actual values are due to the constraint of conserving mature (defined as >110 years) and old growth stands. Additional runs could be done to investigate optimal Annual Allowable Cut under climate change with different harvest/preservation objectives. In particular, since SBB outbreak risk increases with tree age or size, forest management regimes that increase net forest age may result in increased SBB losses. Harvest volume

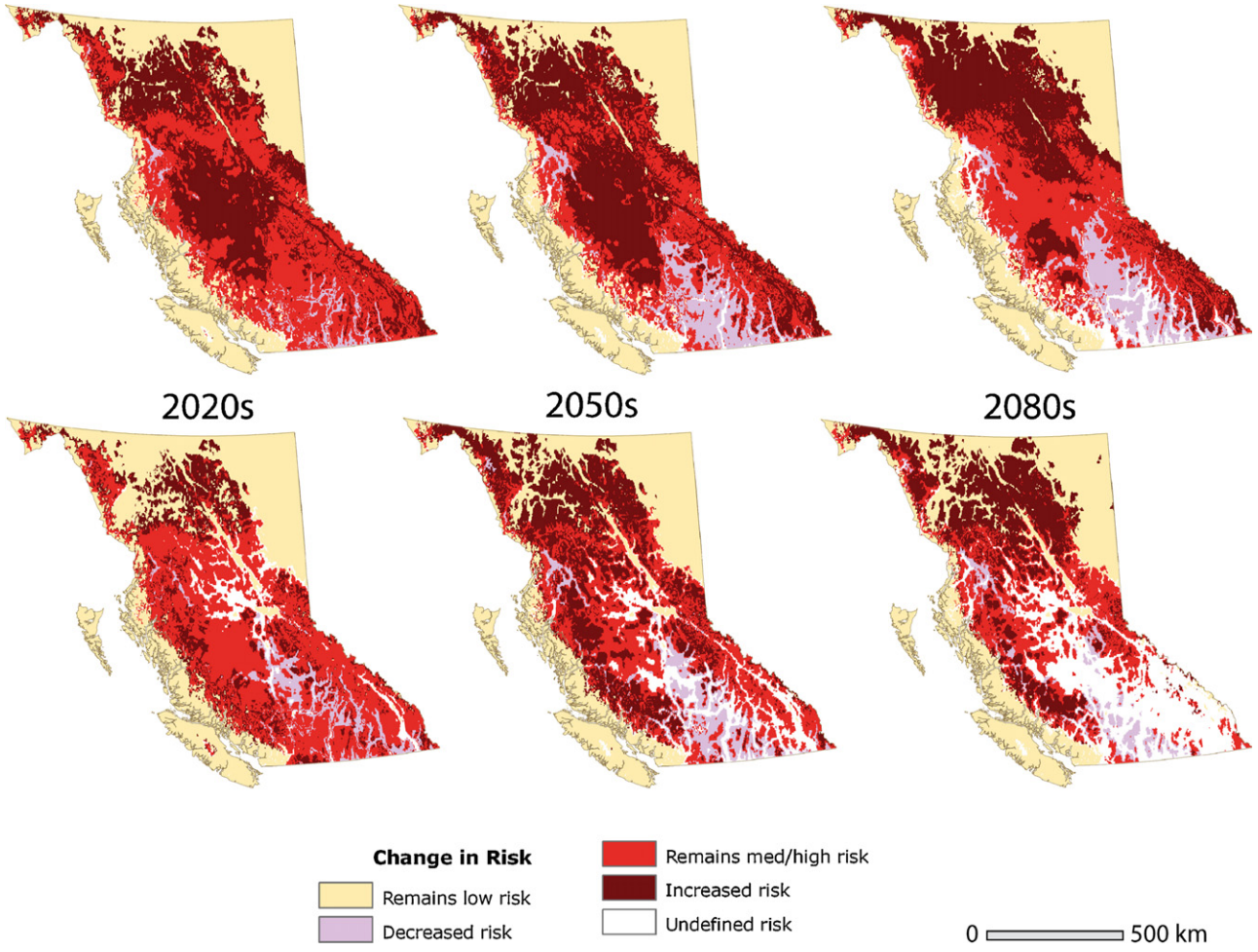

Fig. 4 – Projected western spruce budworm outbreak risk: top row: Warm/Wet projection (CGCM3 A2 run 5), bottom row: hot/dry projection (HadGEM A1B run 1) for 2020s (left), 2050s (middle), and 2080s (right).

increases slightly for warm/wet and stays about the same for hot/dry; conserved forest area is unchanged in both cases.

5. Discussion

The purpose of this assessment was to understand the potential for changing SBB and WSBW outbreaks in BC due to climate change. Robust projections for planning and policy will require considerable additional work to eliminate many assumptions described below. This prevents us making quantitative statements about likelihood of the projected impacts and uncertainty. Eventually, biological/phenological process-based outbreak models making use of high (temporal and spatial) resolution downscaled climate projections will be required. The intention here was to use simple techniques to get a first indication of impacts and to guide further analysis.

5.1. *Climate and pest modelling*

To ensure ability to conduct further analysis and relevance to other geographic areas, an effort was made to assess and investigate alternate methods. The results of the "blind alleys" are beyond the scope of this paper, but three detours in particular helped inform the authors' assessment of strengths, weaknesses, and assumptions in the results that are presented.

First, an attempt was made to identify triggers between climate anomalies and outbreaks using monthly precipitation and temperature anomalies, guided by a conceptual model that climate might provide conditions to initiate an outbreak but as insect population increases other factors dominate (Safranyik and Carroll, 2006). Several different combinations of lagged climate anomaly – outbreak response were investigated, but no relationship sufficient for subsequent bio-economic modelling was found.

Second, the principal component analysis technique that was used for suitability of host tree species was also applied to one of the pests (SBB outbreak). Locations with medium-high risk in the hot/dry scenario by the 2080s according to each method are shown in Fig. 6. Both agree on the large area of risk in northwestern BC, as well as a vast area of undefined risk. They also generally agree on the two other main areas with risk: high elevations in the Columbia Basin and the Coast Mountains, but differ in the area at risk in each of these regions. Percentiles threshold was preferred because its inclusion of absolute climatic thresholds was considered to

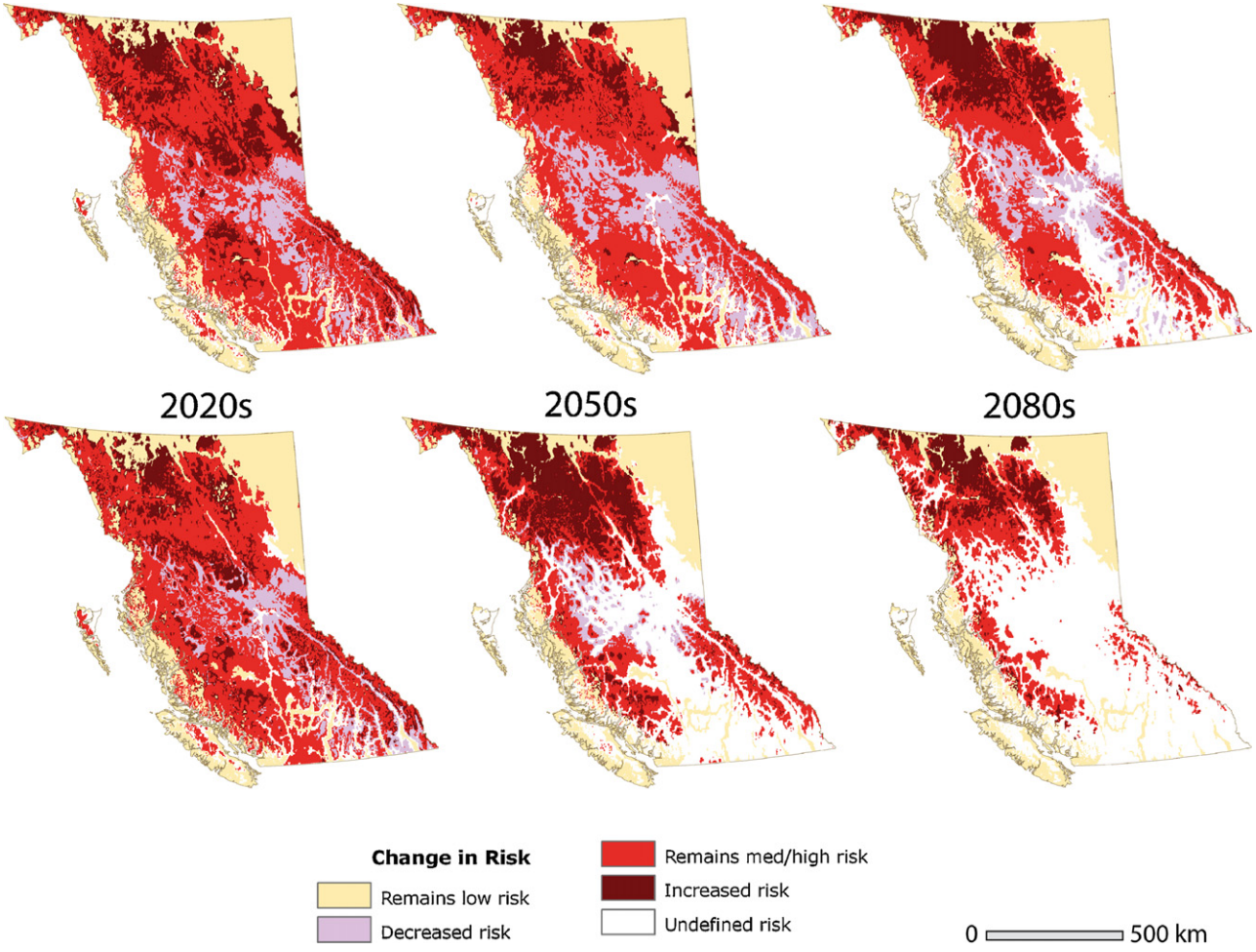

Fig. 5 – Projected spruce bark beetle outbreak risk: top row: warm/wet projection (CGCM3 A2 run 5), bottom row: hot/dry projection (HadGEM A1B run 1) for 2020s (left), 2050s (middle), and 2080s (right).

be a more biologically realistic representation for outbreak risk. These results suggest that a comprehensive intercomparison of climate envelope methods may be warranted.

Third, a model of WSBW and Douglas-fir budflush (Thomson and Moncrieff, 1982) was implemented in the BioSIM software environment (Régnière et al., 1995). Preliminary results were tested at three stations within BC: Hope, Pemberton, and Saanichton (Ford and Taylor, 2007). This step allowed for testing of hypotheses around the relationships between WSBW and climate in the historical record.

Undertaking these three investigations resulted in co-location of previously disparate datasets, improved the ability of the inter-disciplinary team to communicate with each other, and contributed towards development of common tools. The main benefit, however, was to assist in illuminating the cascading sets of assumptions upon which results are built. The remainder of the discussion focuses on these assumptions.

There are several shortcomings with projected changes in host tree suitability as described fully in Flower et al. (this issue). Specifically, the method assumes a linear response to climate variables only and that changes in correlation between variables will be small. Our decision to model three spruce species as a single ecological unit due to their uniform

Table 2 – Harvest volume and forest area impact for Okanagan Timber Supply Area (TSA) and province.

		Harvest volume (million m^3)	% change	Forest area (kilohectares)	% change
Okanagan (400 m)	Base	2.2527	n/a	765	n/a
	WarmWet	2.1953	−2.5%	765	0.0%
	HotDry	2.1506	−4.5%	775	+1.4%
Province (4 km)	Base	31.7416	n/a	47,287	n/a
	WarmWet	31.8948	+0.5%	47,290	0.0%
	HotDry	31.7448	+0.0%	47,296	0.0%

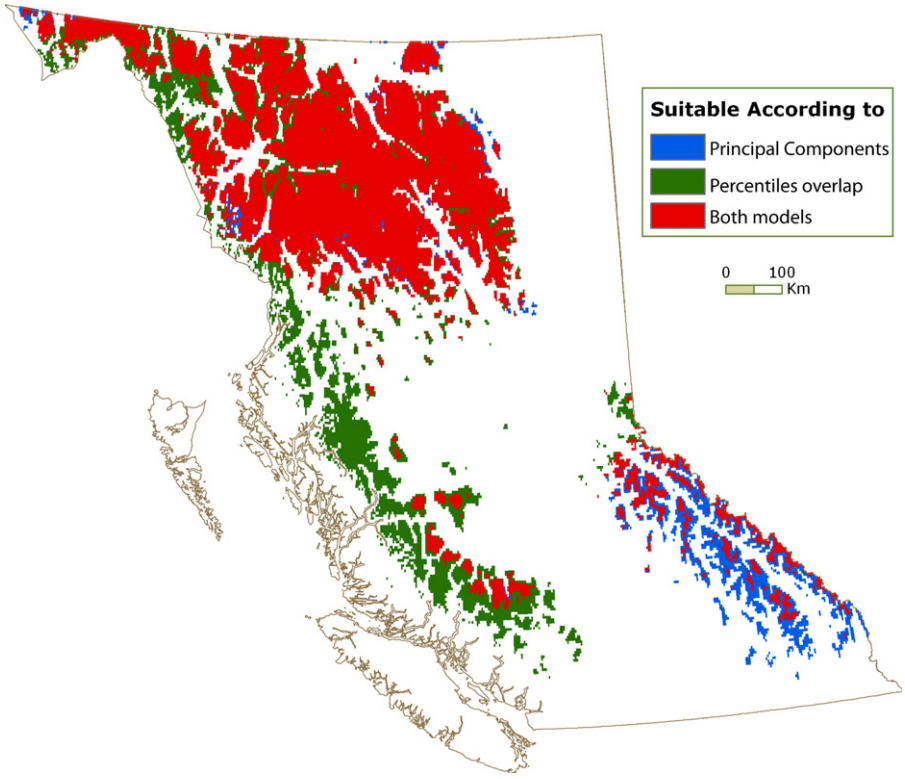

Fig. 6 – Projected spruce bark beetle outbreak risk (medium and high risk; 2080s): comparison of principal components method to percentile threshold method.

susceptibility to spruce bark beetle outbreaks may have added uncertainty to our results, as it is possible that the tree species could respond to climate change in an individualistic manner. However, our success in modelling the range of these three species as a single unit indicates that their collective range reflects climatic limiting factors shared by all three species. In addition, the method is based on presence-only records. The net effect is likely overestimation of future suitability as most factors not considered (soils, mycorrhizal fungi, sensitivity of tree establishment to extremes, competition, interactions of species in novel ecosystems, etc.) would lead to lower tree health and suitability, and dispersal rates were not incorporated in the bioclimatic envelopes models.

Similarly, the percentile threshold outbreak risk method is prone to underestimating impacts as it assumes that where no historical analogue conditions exist, there is no risk of outbreak and this would not usually be the case, particularly in locations where tree species are also projected to no longer be suitable. Furthermore, the percentile threshold method represents potential changes in the spatial distribution of outbreak locations only (range), not in the frequency or severity of outbreaks.

5.2. *Bio-economic modelling*

Most of the bio-economic modelling assumptions also likely underestimate impacts:

- Most (>75%) of the trees harvested in BC are neither Douglas-fir nor spruce. Simulations assume all other tree species are not impacted by climate change and no pests other than SBB and WSBW are affected by climate change. Losses would probably increase if all host and pest species were included (despite new possibilities of competition between species).
- The possibility of greater spatial continuity of areas susceptible to outbreak is not considered, although this may be an important aspect of catastrophic outbreaks as was the case in the recent Mountain Pine Beetle outbreak.
- Climate envelope approaches used here are based on a short period of historical record and assume that climate determines hosts distribution in a way that will hold in future. Tree species suitability is furthermore assumed to be indicative of forest health. This will result in an underestimation of negative future impacts if future forest health is reduced following the pine beetle outbreak, which has no past analogue.
- There is no change in status of forest or non-forest cells into the future and no change in the timer harvesting land base (THLB). It is possible that currently forested locations could become unable to support a forest-based ecosystem, even though projected climate is suitable for an individual tree species. It is also possible that changes to locations in the THLB as climate changes could have large effects.
- The impacts of forest age dependent insects such as SBB on harvest rates depend on the age composition of the THLB. The conservation value given to older forests in this model (effectively removing it from the simulation) may result in lower harvest impacts than would result otherwise.

- There is no change in either harvest or conservation values. If climate change results in ecosystem degradation, or if carbon markets such as the Pacific Carbon Trust become an incentive for conservation then the non-harvest value per unit area may be expected to rise relative to harvest. Feedback between forest change and climate change could be considerable (Kurz, 2010). If susceptibility to disturbance by fire increases, both harvest and conservation values could be reduced. A potential increase in productivity from carbon fertilization could counteract some of the preceding factors expected to reduce value, but this effect appears to be smaller than previously thought (Gedalof and Berg, 2010). Finally, there is no monetization of values throughout the simulation and no representation of projected future changes in global forestry markets.

6. Conclusions

As a result of this project, we find that long term forest management plans cannot assume that pest outbreak risk will remain the same in the coming century as it was in the last. Second, because there is a wide range of other uncertainty (e.g., greenhouse gas emissions, climate models) simple climate envelope techniques are useful tools to conduct initial assessments and are suitable for use to inform decision-making while more comprehensive models are in development. Finally, considerable additional research is required into regional economic modelling, but investing in these methods is needed to assist in prioritizing how to adapt to climate change while minimizing negative economic impacts.

6.1. *Integration of multi-disciplinary domains*

This research is part of a larger, interdisciplinary project in which bioclimatic envelope modelling of both tree and forest pest species was carried out in conjunction with forest simulation techniques to assess the potential economic and ecological impacts of climate change on British Columbia's forests. The research team included forest scientists, climate scientists, and resource managers. The development and implementation of this research was guided by communication with stakeholders in the forest management community (Abbott et al., 2008).

We used several strategies to integrate the disciplines represented in this project in their co-production of knowledge. In addition to the workshop described in the introduction, frequent meetings of researchers working on separate components ensured that the work in different components of the research would be compatible. For example, data requirements of the bioeconomic model influenced the choice of climate envelope technique for modelling future pest risk (the model needed information on percent affected per cell on average over a thirty year period rather than tracking individual outbreaks). Decision makers were engaged both early on through guidance from the Chief Forester for BC in the interdisciplinary workshop as well as upon project completion through presentations, seminars, and a webinar attended by (stand level) decision-makers. The next step is to determine how these results can be incorporated into an integrated risk-management framework (Dawson et al., 2011) for pest management.

6.2. *Pest risk modelling*

Projecting future outbreak risk ultimately needs to be informed by process-level modelling of pest life cycles. Insect life cycles can be represented by multiple life stages, each of which may respond differently and sometimes non-linearly to climate (Logan and Powell, 2001). Thus biological models are available for only a few forest insects in Canada. Although climatically driven spruce beetle voltinism modelling has been explored (Hansen et al., 2001), voltinism is only one important process affecting outbreak distribution. Correlative modelling approaches used here were able to make use of available bias-corrected/elevation-corrected climate projections (Section 3.1).

The climate envelope models used in this study provide a quantitative estimate of projected change and help determine whether the subject warrants further assessment. Results indicate that for vast areas of BC, there is now increased reason to be concerned about both SBB and WSBW outbreak risk due to climate change. It is significant that the envelope modelling indicates that the future climate in substantial areas of the present SBB and WSBW range has no historical analogue. An application of the SBB voltinism model by Bentz et al. (2010) demonstrates potential expansion of SBB outbreaks based on one critical aspect of SBB development. Our finding of increased SBB risk in northern and higher elevation areas is consistent with their finding of increasing proportion of univoltine habitat. Lower elevations in the central and southern interior that they project to be univoltine habitat have no historical analogue, however, suggesting that the tolerance of SBB to warm/dry conditions should be investigated.

Due to several assumptions described in the discussion (Section 5), the projected outbreak risk (Section 4.3) and forest management impacts (Section 4.4) are likely best-case scenarios. WSBW outbreak suitability is projected to increase considerably in central and northwestern BC and SBB to decrease in central BC and increase in the northwest. These projections must be considered in the context of where the affected tree species are now, and are projected to be in future (Flower et al., this issue) based on climate data only. Without this context, for example, an ''increase'' in WSBW outbreak in northwestern BC, where neither host nor outbreak occur is nonsensical.

6.3. *Bio-economic modelling*

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. It is likely the first spatial harvest model to be implemented at a provincial scale. This required a compromise in spatial resolution so that it was computationally feasible. The results of this preliminary modelling are quite sensitive to harvest constraint assumptions. Positive or neutral impacts on Douglas-fir and spruce are indicated by the model, depending on climate scenario. However, in the one case where a single timber supply area was considered

(Okanagan), a net negative economic impact is expected under all circumstances.

The geographic distribution of economic impact is important, but requires analysis at a regional level. In British Columbia, forest level modelling is carried out independently in roughly 70 areas of approximately 1000–100,000 km^2 in size to guide harvest level setting. However, bio-economic models are needed to examine the potential effects of changing environmental conditions, policies, and mitigation/adaptation strategies at larger spatial scales (regional, provincial, national).

6.4. *Further work*

Further work that could significantly improve and expand upon these results includes:

- extend the study to other tree and pest species, at 600 m resolution for all timber supply areas,
- account for some assumptions and neglected factors listed in the discussion, such as the fact that most (>75%) tree species harvested in BC are other than the two simulated here,
- explicitly link relative climate suitability and outbreak risk to forest productivity/forest health,
- compare results to methods that can use presence/absence data where available, and that can make use of indices of extremes in addition to changes in decadal and 30-year averages,
- extend the outbreak data further south to reduce no-analogue situations (Rehfeldt et al., 2012),
- compare results of climate envelope methods to process-based models driven by statistical and/or dynamical downscaling at selected locations where historical verification can be performed.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.envsci.2012.07.026.

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