Section 4: The mountain pine beetle in novel pine forests: predicting impacts in a warming environment

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4.1 Introduction

Insect herbivory comprises one of the largest sources of disturbance in northern temperate and boreal forests (Dale et al. 2001). Given the sensitivity of herbivorous insects to variations in climate (Bale et al. 2002), combined with evidence of historical increases in herbivory associated with a warming environment (Currano et al. 2008), climate change is expected to have a significant impact on the dynamics of forest insect herbivores and the extent/severity of their impacts in northern forests (Logan et al. 2003). An increase in insect-caused forest disturbance beyond the long-term range of natural variability is also expected to significantly reduce forest carbon reservoirs, increase rates of heterotrophic respiration and cause feedback to future climate change (Kurz et al. 2008).

Recently, Carroll et al. (2004, 2006) showed that the mountain pine beetle (MPB) had significantly expanded its range in western Canada since 1970 as a result of a warming environment. These results, together with the extensive incursions across the Rocky Mountains into north-central Alberta by MPB since 2002, prompted Safranyik et al. (2010) to examine the potential distribution of climatically benign habitats in the boreal and eastern pine forests under climate change. Although they concluded that there was a significant probability of continued eastward expansion by MPB, they also concluded that confidence in their predictions was limited by lack of knowledge of (i) the productivity of MPB in novel pine forests, and (ii) the

potential range of future climatic conditions derived from accepted greenhouse gas emissions scenarios.

Since 2006, Alberta Environment and Sustainable Resources Development (AESRD) has conducted detailed annual assessments of the state of the invading MPB population in central and northern Alberta. In particular, they have measured "*r*-values", the ratio of surviving offspring to parent attacks, for many infested stands throughout the region. Together with stand-level parameters recorded during the sampling and variables derived from a detailed stand-level vegetation resource inventory dataset *r*-values can be used to predict the productivity of MPB infestation within a given stand, and therefore be used as an accurate measure of stand susceptibility. The objective of this study was to combine an empirical model of the role of climate in the beetle's outbreak potential (Safranyik et al. 1975; Carroll et al. 2004) run under a range of future conditions based on a series of greenhouse gas emissions scenarios, with a model of stand susceptibility for MPB that is based upon empirical measures of beetle productivity in novel habitats, to project the distribution and abundance of climatically suitable and susceptible pine stands in the Foothills region of Alberta.

4.2 Methods

4.2.1 Climatic suitability

The MPB model

To quantify the climatic suitability of habitats for MPB, a model of the impact of climatic conditions on the establishment and persistence of MPB populations originally developed by Safranyik et al. (1975) and later modified by Carroll et al. (2004) was employed. The model combines the effects of several critical aspects of climate on the beetle and its host trees, and

has been used successfully in earlier studies to consider the influence of climate on the

potential distribution of MPB in BC and across Canada (Carroll et al. 2004, 2006; Safranyik et al.

2010). Briefly, the model contains four primary variables (P_1, sufficient degree days to achieve

a synchronized, univoltine life cycle; P_2, winter minimum temperatures above -40°C; P_3,

sufficiently warm temperatures during August to facilitate synchronized beetle emergence and

dispersal; P_4, below average precipitation from April to June), and two modifying variables (Y_1,

the variability of growing season precipitation; Y_2, an index of water deficit). Since the criteria

for the primary variables are either true or false, a value for climatic suitability is generated as

the product of (i) the probability of the condition "true" for all primary variables in two or more

consecutive years and (ii) the square root of the product of the modifying variables (see Carroll

et al. 2004; Safranyik et al. 2010 for details).

The MPB climatic suitability model produces values ranging from 0 to 1. Climatic suitability

classes (CSCs) were created by comparing index values with the frequency of mountain pine

beetle infestations across its historic range (Powell 1966). Five distinct CSCs were identified

(very low = 0; low = 0.01-0.05; moderate = 0.06-0.15; high = 0.16-0.35; extreme = 0.36-1.00).

The climatic suitability model was validated by comparing its predictions with the frequency of

MPB infestations and found to be in good concordance with the distribution and abundance of

MPB populations within the beetle's historic range (Safranyik et al. 1975).

Future climate

Three scenarios as defined by the Intergovernmental Panel on Climate Change Special Report

on Emissions Scenarios (Nakićenović and Swart 2000) were chosen to represent the range of

potential future climatic conditions: A2, where the rate of greenhouse gas (GHG) emissions

relative to present day remains unchanged; B1, where the current emissions rate remains steady until mid-century, and then drops to approximately half of that rate by the end of the century; and A1B, where the rate of emissions is intermediate between A2 and B1. Coarse-scale projections of each scenario were extracted from the general circulation model, CGCM3, developed by the Canadian Centre for Climate Modelling and Analysis (McFarlane et al. 2005; Scinocca et al. 2008). Downscaled projections for the Foothills region were produced by Coops et al. (this report) based on ClimateWNA (Wang et al. 2006). To examine the potential for the method of downscaling to influence predictions of climatic suitability, the projections derived from the A2 scenario and CGCM3 general circulation model were also downscaled using the Canadian Regional Climate Model [CRCM (Laprise et al. 2003; Plummer et al. 2006)]. For the ClimateWNA downscaled projections, monthly normals (30-year means and extreme minima and maxima) were produced for the periods 2011-2040, 2041-2070 and 2071-2100. For the CRCM downscaled projections, normals were generated in 10-year intervals from 1981-2011 (i.e. current conditions) to 2071-2100.

4.2.2 Landscape-scale projections of climatic suitability

BioSIM$^©$ software (Régnière et al. 1995; Régnière 1996) was used to generate landscape-wide projections of climatic suitability for MPB from the Safranyik model and the future climate projections. BioSIM spreads the outputs of climate-based models to landscapes using digital representations of the terrain (i.e. a digital elevation model) and suitable weather data. To achieve the highest practical spatial resolution, a 100-meter digital elevation model of the Alberta Foothills region included within BioSIM (obtained from US Geological Survey) was used. Suitable weather data were obtained by generating stochastic daily values from the monthly

climate normals described above for each climate change scenario using a daily weather generator developed by Régnière and Bolstad (1994). This approach minimizes the effect of short-term weather anomalies, enabling focus on longer-term climatic trends. Within BioSIM, spatial interpolation methods were used to obtain air temperature and precipitation information for unsampled points across a landscape using a 'gradient-plus-inverse distance squared' algorithm developed by Nalder and Wein (1998). Universal kriging (e.g. Davis 1986) (with elevation as a drift variable) was used for interpolation between simulation points.

Alberta vegetation inventory (AVI) data were obtained for the Foothills region from Hinton Wood Products. Using ArcGIS® mapping software, climatic suitability projections derived from BioSIM were intersected with AVI data. Maps showing the CSC of stands in which pine species are dominant (i.e. ≥50% of tree species) were generated. One map was created for the most recent climate normals generating period (i.e. 1981-2010) using the CRCM downscaled data. Maps of the future distribution of climatically suitable pine stands for MPB based on each climate change scenario were produced for the periods 2011-2040, 2041-2070 and 2071-2100 based on ClimateWNA downscaling, and then in 10-year intervals (from 1991-2020 to 2071-2100) for the CRCM downscaled projections (scenario A2 only) to facilitate examination of finer temporal trends.

4.2.3 Stand susceptibility

The r-value data

AESRD provided *r*-value data collected throughout the newly invaded pine forests east of the Rockies for the years 2006-2011 (Fig. 1). The parameter, *r*, is determined by removing a standard area of bark from two sides of an infested tree and counting the number of attack

initiations (i.e. number of females) and the number of surviving offspring in the spring prior to beetle emergence. Raw data comprised assessments for individual attacked trees within each infestation. However, to accurately reflect the status of a given infestation (increasing, static or decreasing), *r* must be calculated as the aggregation of the number of attack starts and the number of surviving offspring for all sampled trees (BCMFLNRO 1995). An infestation-level *r*-value was calculated as the ratio of the sum of all surviving offspring to the sum of all attacks determined for each site in each year. Data for 2395 distinct sites were available (Fig. 1); however, the majority of infestations assessed in 2006 resulted in *r* = 0, an expected consequence of limited discriminatory capacity (i.e. attack of unsuitable trees, or over-colonization of suitable trees) by foraging beetles arriving in a new habitat following an energetically costly long-distance dispersal event (e.g. Price 1984). Therefore, data from 2006 were disregarded in subsequent analyses. Furthermore, in the remaining data the vast majority (79.5%) of infestations of ≤3 trees were also associated with *r*-values of 0. This is, too, is not surprising given that once established in a new habitat, epidemic MPB preferentially choose the most vigorous and defensive trees in a stand and therefore require a minimum population size for successful attacks (Safranyik and Carroll 2006; Boone et al. 2011). As a result, data pertaining to infestations of 3 or fewer trees were also dropped from subsequent analyses. Following this screening, a total of 1124 infestations remained available for analysis.

Since calcuation of *r* for a MPB infestation requires an accurate quantification of the number of surviving offspring, assessments should be done as close as possible to the completion of offspring development (i.e. just before beetle emergence and dispersal) to ensure that all mortality associated with overwintering has accrued. However, due to the large number of

sample sites and the vast area to be sampled, *r*-value assessments have traditionally been conducted by AESRD throughout the month of May in each year. As a consequence, mortality from late-season cold events, when MPB is particularly sensitive to subzero temperatures (Safranyik and Carroll 2006), may not be captured and some values of *r* incorrectly inflated as a result. To adjust *r*-values to account for potential late-season cold mortality, the "climatic daily" function in BioSIM (Régnière et al. 1995; Régnière 1996) was used to determine daily minimum temperatures at each sample site in each year based on the 4 closest weather stations. The total number of days from the time that each *r*-value was determined until July 1 with temperatures ≤0 °C [i.e. $(\Sigma d \leq 0)$] was calculated. The variable "*r*-adjusted" was calculated as $r_{adj} = (r/(\Sigma d \leq 0))$.

Predicting r_{adj} from stand/site conditions

To develop a model to predict r_{adj} based upon readily available data, a suite of variables known or suspected to affect MPB populations were assembled from a variety of sources. The diameter of trees at breast height [1.3m above the ground (DBH)] is one of the most basic parameters affecting both host selection and subsequent offspring production by MPB (Safranyik and Carroll 2006). DBH was recorded for each infested tree at each site during *r*-value assessments. The mean DBH of trees in each infestation was calculated and collated with associated values of r_{adj}. Additional stand attributes, such as the percentage of susceptible pine basal area, stand age and density, are also know to affect MPB populations (Shore and Safranyik 1992; Shore et al. 2000). Indeed, these parameters form the basis of a stand susceptibility index developed by Shore and Safranyik (1992) that has been applied to support management decisions throughout western North America. The original susceptibility index

also included a "location factor" to account for variation in MPB dynamics within its historic

range. A modified Shore and Safranyik index (SSI) without the location factor was computed by

AESRD and collated with the r_{adj} data. The expansion of MPB into the pine forests east of the

Rocky Mountains has led to the establishment of infestations not just in pure lodgepole pine,

but also in lodgepole × jack pine hybrids, and recently in pure jack pine (Cullingham et al. 2011).

To examine the potential for lodgepole × jack pine introgression to affect MPB productivity, a

map of hybrid ancestry for Alberta derived from Cullingham et al. (2012) was rasterized and

imported into ArcGIS. A hybrid index score, Q, was extracted for each r-value site. Values of Q

ranging from 0 (pure lodgepole pine) to 1 (pure jack pine) were collated and added to the r_{adj}

data. Lastly, to account for the influence of weather and climate on MPB infestations, the

latitude and elevation of each r-value site was used to calculate an associated "effective

latitude" based upon Hopkins Bioclimatic Law (Hopkins 1920).

Statistical analyses

Quantile regression (Koenker and Bassett 1978) was used to examine the potential

relationships between r_{adj} and the independent and interacting effects of stand/site conditions.

In quantile regression, the response-predictor association is modeled over the entire data

distribution by estimating conditional quantiles (or percentiles) of a response as a function of

the predictors. Quantile regression models do not assume a specific distribution for the error

term and in contrast to least squares regression or generalized linear models, are robust to the

presence of outliers (Cade & Noon 2003). All tests were computed with the R v3.0.0 statistical

programming language (R Development Core 2013). Quantile regressions were conducted

using the quantreg v4.97 package (Koenker 2013).

4.2.4 Future susceptibility

Tree diameter (DBH) was the best predictor of r_{adj} (see Results and Discussion). Unfortunately, DBH is not routinely collected and included in AVI data. To calculate a proxy for tree diameter, the original r-value data with all years and sites included was used in a multiple-regression analysis to assess DBH in relation to stand characteristics. An index of stand susceptibility for novel pine habitats (hereafter, S) was modelled for the pine-dominant stands of the Foothills region as r_{adj} predicted from the DBH proxy and the stand/site characteristics described above. Maps of future pine susceptibility were created using ArcGIS by intersecting the layers of climatic suitability for each climate change scenario and time step described above, considering only those pine-dominant stands with ≥ moderate CSCs, with maps of the susceptibility index, S, grouped as low, moderate and high susceptibility classes (see Results and Discussion).

4.3 Results and Discussion

4.3.1 Climatic suitability

Although much of the Foothills region is currently unavailable to MPB due to poor climatic suitability, in the very near future, even under a conservative projection of future climate, habitats conducive to an outbreak are expected to increase markedly throughout the area. Based upon climatic conditions derived from the recent past (i.e. 1981-2010), only the lower elevations situated in the eastern portion of the region are considered moderately suitable to MPB (Fig. 2). None of the pine-dominant stands showed evidence of being climatically optimal (high and extreme CSCs). Although MPB populations may establish, or perhaps have already established, in the stands with low and very low climatic suitability, epidemic populations are extremely unlikely at present due to high levels of generation mortality expected to be induced

by the direct and indirect effects of adverse weather (Safranyik et al. 1975; Carroll et al. 2004; Safranyik and Carroll 2006).

Under each of the 3 climate change scenarios considered in this study, there appears to be a rapid increase in the amount of climatically suitable, pine dominated forests available to MPB. By the 2011-2040 time step, irrespective of the emissions scenario, virtually all of the Foothills region is expected to be moderately suitable for MPB, with only the highest elevation stands toward the Rockies remaining unsuitable (Fig. 3). Significant resolution becomes apparent among the scenarios midway through this century. By 2041-2070, large portions of the lower elevations of the Foothills becomes highly climatically suitable to MPB in the A2 "business as usual" scenario. As expected, the moderate A1B scenario also precipitates an increase in the amount of habitat optimal to MPB, but at a much slower rate than A2 (Fig. 3). The B1 scenario reflects the expected decrease in emissions by mid-century, with a significant decline in the amount of suitable pine-dominant stands during 2041-2070 relative to the previous time step. By the end of the century, under the A2 scenario approximately half of all pine dominated stands are expected to be climatically optimal for MPB (Fig. 3). For the A1B scenario, there is little change relative to the middle of the century; virtually all pine-dominant stands are anticipated to be moderately suitable to MPB, with minor areas showing high/extreme climatic suitability. Surprisingly, even under the low-emissions B1 scenario, conditions continue to ameliorate for MPB, and by 2070-2100 nearly the entire Foothills region is expected to be moderately suitable to epidemic MPB populations (Fig. 3).

Examination of the expected changes in climatic suitability under the high-emissions A2 scenario at a finer temporal scale (10-year increments) reveals the westward progression toward higher elevations in the occurrence of highly suitable pine stands over time (Fig. 4). Should this scenario prove realistic, the rapid increase in climatic suitability will likely be followed closely by invasion of epidemic MPB into the region. Carroll et al. (2004) clearly showed that MPB populations respond very quickly to a warming environment by rapidly moving into formerly unsuitable habitats at higher elevations and more northerly latitudes. Interestingly, the projections generated using climateWNA (Wang et al. 2006) for downscaling differed substantially from those generated using the CRCM (Caya et al. 1995; Laprise et al. 2003). During the 2011-2040 time step, climateWNA is much more liberal than the CRCM in its projection of climatically suitable habitats. By 2071-2100 the trend reverses with the CRCM-based projections indicating that nearly double the area will be optimal to MPB populations compared to the climateWNA-based predictions (Figs. 3 and 4). Due to their inherent stochasticity, significant variability in the projection of future climatic conditions can arise among global/general circulation models (e.g. Jun et al. 2008) and/or regional downscaling models (e.g. Lucas-Picher et al. 2008; Chen et al. 2013). These results emphasize the importance of the consideration of as many models, scenarios and model runs as is practicable when attempting to plan for the full range of future conditions.

4.3.2 Stand susceptibility

The number of MPB offspring per female (r_{adj}), adjusted to account for post-sample mortality associated with lethal low temperatures, was significantly affected by tree diameter (DBH), hybridization (Q) and effective latitude (Table 1), but not the Shore and Safranyik susceptibility

index, SSI (t = 0.0866, P = 0.93). The lack of a significant influence of SSI, an index widely

applied in the native range of MPB (Shore and Safranyik 1992; Shore et al. 2000), is surprising

and serves to underscore the extent to which the pine forests east of the Rocky Mountains vary

as habitat for MPB in relation to those to the west. To date, it has been shown that the

distribution and abundance of pine species differs across Alberta (Safranyik et al. 2010).

Moreover, the genetic structure of pine populations east of the continental divide is distinct

from populations in BC (Cullingham et al. 2011, 2012). These aspects, together with other as of

yet unstudied factors, may alter the expected relationship between stand conditions and MPB

productivity and stand susceptibility.

Although r_{adj} was affected by DBH, Q and effective latitude, the effect of DBH was dependent

upon Q and effective latitude, and the influence of Q was also dependent upon effective

latitude (Table 1). These significant interactions were not unexpected and relatively

straightforward to explain. Given that Q is an index of hybrid ancestry for lodgepole and jack

pines (Cullingham et al. 2012), and that the growth form and habits of the two species are

distinct (e.g. Farrar 1995), it is virtually axiomatic that tree diameter should be dependent on

the degree of hybridization. Similarly, effective latitude is a proxy for climatic conditions in

which sample sites were situated (Hopkins 1920). It is well known that within a tree species

aspects of growth such as radial increment are affected by climate (e.g. Kozlowski 1971), hence

the dependency of DBH on effective latitude. Finally, in Alberta, the west-east separation of

lodgepole and jack pines (see Cullingham et al. 2011) dictates that lodgepole in the west

(toward the Rocky Mountains) will grow on average at higher elevations, and therefore higher

effective latitudes than jack pine. Thus, the influence of Q will be dependent upon effective latitude.

To isolate the relationship between r_{adj} and tree diameter, data were partitioned into 3 levels of effective latitude (<61.5, 61.5-64.5, >64.5) and three levels of hybridization (Q, 0-0.10, 0.10-0.20, >0.20) (see Fig. 5). Significant ($P < 0.05$) simple quantile and linear regressions of r_{adj} (log transformed for normality) on DBH were identified only for the combination of effective latitudes between 61.5 and 64.5, and Q scores between 0 and 0.10. It is not entirely clear why relationships between r_{adj} and DBH did not emerge at other combinations of effective latitude and Q, but it is likely that aspects of host tree phenotype and genotype beyond the scope of this study were the cause. Since the majority of r-value locations, and the entire Foothills region, are situated within the effective latitude-Q combination for which a significant relationship was identified, DBH was used to predict r_{adj} (and hence susceptibility, S) using a simple linear regression as follows: $r_{adj} = S = 10^{0.0462(DBH) - 1.701}$ ($F_{1, 390} = 60.18$, $P < 0.0001$, $r^2 = 0.14$). Given the large amount of unexplained variation in the data (see Fig. 5), values of S were grouped to create susceptibility classes (low, <1.2; moderate, 1.2-2.0; high, >2.0). It is interesting to note that since S and r_{adj} are equivalent, based upon the native range of MPB values of r less than 2.6 for an infestation would be indicative of declining population (BCMFLNRO 1995). The surprisingly rapid spread of MPB through Alberta (Safranyik et al. 2010), despite r-values that are roughly half of that expected in similar circumstances in BC, further emphasizes the novel relationships emerging between the beetle and its newly invaded habitat.

4.3.3 Future susceptibility

Although not all sample sites had the entire suite of associated mensurational characteristics available within the provincial-scale AVI that was included with the *r*-value data, there were sufficient data to indicate that the combination of mean stand height and *Q* could adequately predict mean stand DBH as follows: DBH = 0.677(Height) - 0.879(Height × Q) + 18.497 ($F_{3,1452}$ = 86.47, *P* < 0.0001, R^2 = 0.25). Using this proxy for DBH, *S* was calculated as described above for each pine-dominant stand in the Foothills area based upon the regional AVI data. Although consideration of the potential confounding effects of forest aging and disturbance was beyond the scope of this study, the intersection of S with the pine-dominant stands considered to be climatically suitable (≥ moderate CSCs) at a given time step enables visualization of the pattern of current and future pine susceptibility over the landscape. For example, based upon climatic conditions between 1981 and 2010, 38,827ha of pine was considered to be climatically suitable to MPB, but only 218ha were considered highly susceptible, and another 34,669 moderately susceptible (Fig. 6). This information is extremely relevant in decision making toward indirect management of MPB (*sensu* Whitehead et al. 2006) where modification of the availability of susceptible hosts is the objective. For example, in support of the "healthy pine strategy" currently underway in Alberta (see http://mpb.alberta.ca/AlbertasStrategy/Default.aspx), where mature pine is advanced in the harvest queue to reduce landscape susceptibility, pine-dominant stands that are both climatically suitable and susceptible could be designated the highest priority in the short term.

Examination of the future distribution of climatically suitable and susceptible pine based upon the 3 climate change scenarios considered in this study indicates that unless GHG emissions are

reduced to B1 scenario levels or lower very quickly, virtually the entire region will be highly susceptible to MPB in the near future. Regardless of the SRES scenario (Nakićenović and Swart 2000), by the 2011-2040 time step almost all of the pine-dominant stands in the Foothills area are expected to be both susceptible and suitable with very little change through the remainder of the century (Figs 7, 8 and 9). Except for scenario B1where the area of moderate to highly susceptible pine-dominant stands falls below 300,00ha during the middle of the century as a result of lowered emissions (Fig 9, Table 2), approximately 400,000 to 450,000ha of pine will be at high risk of sustaining a MPB outbreak from 2011-2040 onward (Table 2). Interestingly, when the "business as usual" A2 scenario is examined in finer temporal detail based on the CRCM downscaling, increases in the area of climatically suitable and susceptible pine are modest until 2011-2040, and worsen thereafter (Fig, 10). Indeed, the area of moderate to highly susceptible pine does not approach 400,000ha until the 2031-2060 time step (Table 3). A potential non-linear increase in the amount of optimal habitat for MPB provides added support for the aggressive short-term implementation of indirect tactics intended to reduce the susceptibility of the landscape. These tactics may include pre-emptive harvesting of the highest risk pine-dominant stands as is advocated by the healthy pine strategy. Other tactics may include thinning or spacing stands to increase tree vigour and alter the microclimate reduce the probability of successful attacks by MPB, or selective removal of pine species from mixed stands (Whitehead and Russo 2005; Whitehead et al. 2006). Longer-term tactics to reduce future susceptibility may include conversion to non-pine species and management of pine on shorter rotations to minimize the amount of mature, susceptible pine on the landscape (Whitehead et al. 2006).

4.4 Conclusions

Despite the presence of a considerable amount of pine, the Foothills region has been historically unsuitable for MPB due to the adverse effects of climate (e.g. Carroll et al. 2006; Safranyik et al. 2010). Recent warming has rendered some of the lower elevation pine-dominant stands in the eastern portion of the region climatically suitable, and a large proportion of that pine is susceptible to attack. Even under the most conservative climate change scenario the vast majority of the pine-dominant stands in the area will become suitable and susceptible by the middle of this century. This investigation is the first to construct an index of stand susceptibility for MPB in novel habitats based upon empirical measures of beetle productivity that can account for the apparent altered insect-tree dynamics associated with the pine forests east of the Rocky Mountains. Together with the many and varied tools available to predict and project changes in climatic conditions relevant to MPB, this knowledge can facilitate the identification of high risk stands and landscapes. The anticipated rapid rate of warming in the near term emphasizes the need for prompt, proactive management strategies if the impacts of invasive MPB populations are to be mitigated in Alberta's pine forests.

Table 4.1. Quantile regression model of the independent and interacting effects of tree diameter [measured at breast height (1.3m)], Q, an index of hybrid ancestry where 0 = lodgepole pine and 1 = jack pine (Cullingham et al. 2012), and effective latitude determined from Hopkins Bioclimatic Law (Hopkins 1920) on the number of mountain pine beetle offspring per female (r_{adj}) adjusted to account for post-sample mortality associated with lethal low temperatures (see text for details).

Coefficients	Value	SE	t	P
Intercept	-2.82377	0.65718	-4.29678	0.00002
DBH	0.13015	0.02529	5.14623	0.00000
Q	-8.19388	3.63373	-2.25495	0.02434
Effective latitude	0.04221	0.01006	4.19492	0.00003
DBH × Q	-0.02555	0.00422	-6.05863	0.00000
DBH × Effective latitude	-0.00195	0.00039	-5.01509	0.00000
Q × Effective latitude	0.14572	0.06159	2.36608	0.01815

Table 4.2. Area and percentage of climatically suitable (i.e. ≥ moderate suitability), pine-dominant (≥50% of all tree species) stands with predicted low, moderate and high susceptibility (S) to attack by the mountain pine beetle (see text for details of susceptibility calculations). Climatic suitability was derived from the Safranyik model (Carroll et al. 2004). SRES scenarios (Nakićenović and Swart 2000) were run with the CGCM3 general circulation model (Scinocca et al. 2008), downscaled using climateWNA (Wang et al. 2006).

| | | SRES Scenario | | | | | |
| | | A2 | | A1B | | B1 | |
	Susceptibility (S)	Area (ha)	%	Area (ha)	%	Area (ha)	%
2011–2040	Low	23,668	5.6	23,668	5.4	23,657	6.0
	Moderate	389,185	93.1	412,869	93.4	365,969	92.7
	High	5,334	1.3	5,333	1.2	5,251	1.3
	Total	418,188		441,872		394,877	
2041–2070	Low	23,668	5.0	23,668	5.1	23,255	7.3
	Moderate	439,837	93.8	436,192	93.8	291,747	91.3
	High	5,390	1.2	5,391	1.2	4,640	1.4
	Total	468,854		465,251		319,642	
2071–2100	Low	23,668	4.9	23,668	5.1	23,669	5.1
	Moderate	450,243	93.9	439,254	93.8	438,842	93.8
	High	5,413	1.1	5,390	1.1	5,371	1.2
	Total	479,325		468,313		467,882	

Table 4.3. Area and percentage of climatically suitable (i.e. ≥ moderate suitability), pine-dominant (≥50% of all tree species) stands with predicted low, moderate and high susceptibility (*S*) to attack by the mountain pine beetle (see text for details of susceptibility calculations). Climatic suitability was derived from the Safranyik model (Carroll et al. 2004) and the A2 climate change scenario (Nakićenović and Swart 2000) run with the CGCM3 general circulation model (Scinocca et al. 2008), downscaled using the Canadian Regional Climate Model (Caya et al. 1995).

	Normals period									
	1991-2020		2001-2030		2011-2040		2021-2050		2031-2060	
S	Area (ha)	%	Area (ha)	%	Area (ha)	%	Area (ha)	%	Area (ha)	%
Low	3,649	10.3	16,075	11.1	18,522	9.1	21,770	7.8	23,596	5.9
Mod.	31,387	89.0	127,097	88.0	182,526	89.9	253,634	90.9	368,677	92.8
High	242	0.7	1,237	0.9	2,107	1.0	3,530	1.3	5,194	1.3
Total	35,278		144,409		203,155		278,934		397,468	

|	Normals period							
	1941-2070		2051-2080		2061-2090		2071-2100	
S	Area (ha)	%	Area (ha)	%	Area (ha)	%	Area (ha)	%
Low	23,595	5.2	23,596	5.0	23,596	5.0	23,596	4.9
Mod.	425,861	93.6	438,626	93.8	446,268	93.9	449,249	93.9
High	5,430	1.2	5,431	1.2	5,431	1.1	5,431	1.2
Total	454,888		467,653		475,303		478,284	
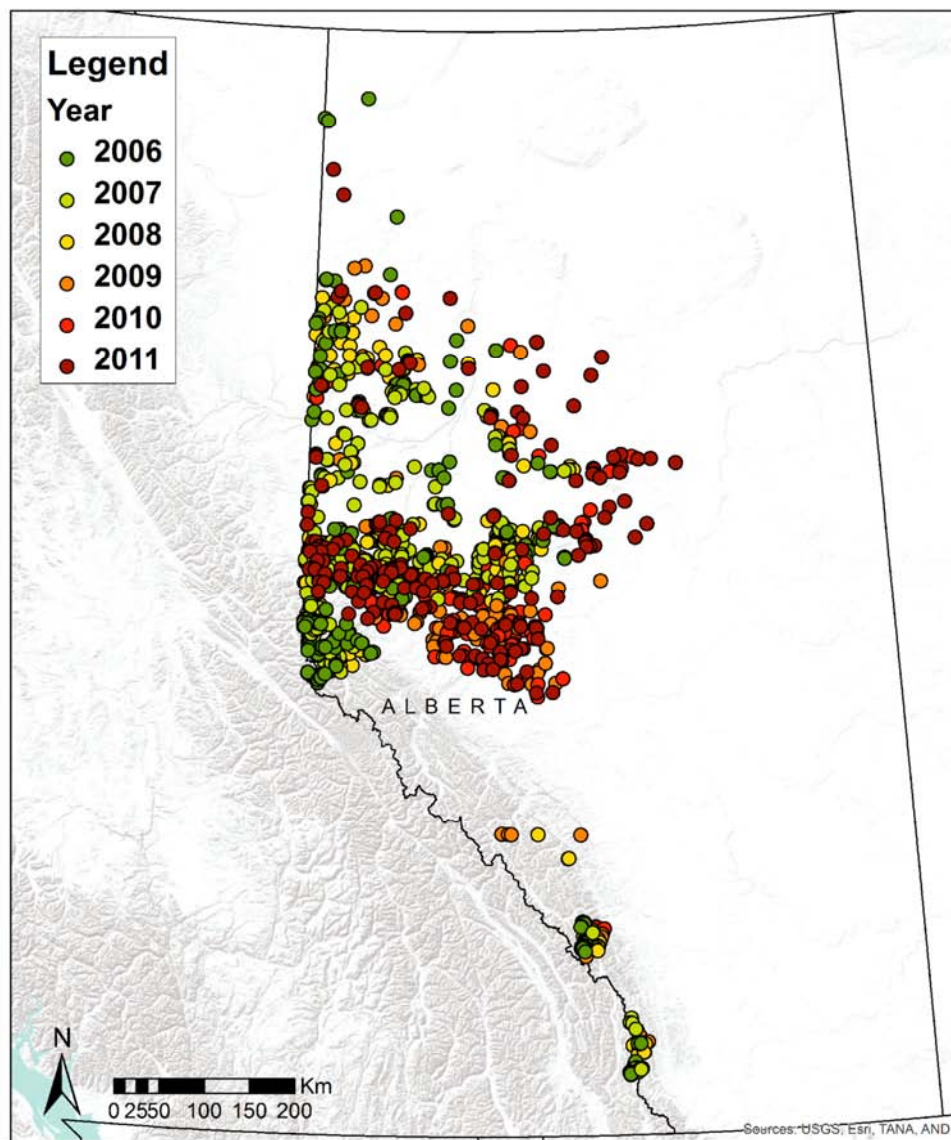
Figure 4.1 Location of r-value sample sites in Alberta from 2006 to 2011. Sampling was conducted by Alberta Environment and Sustainable Resources Development.
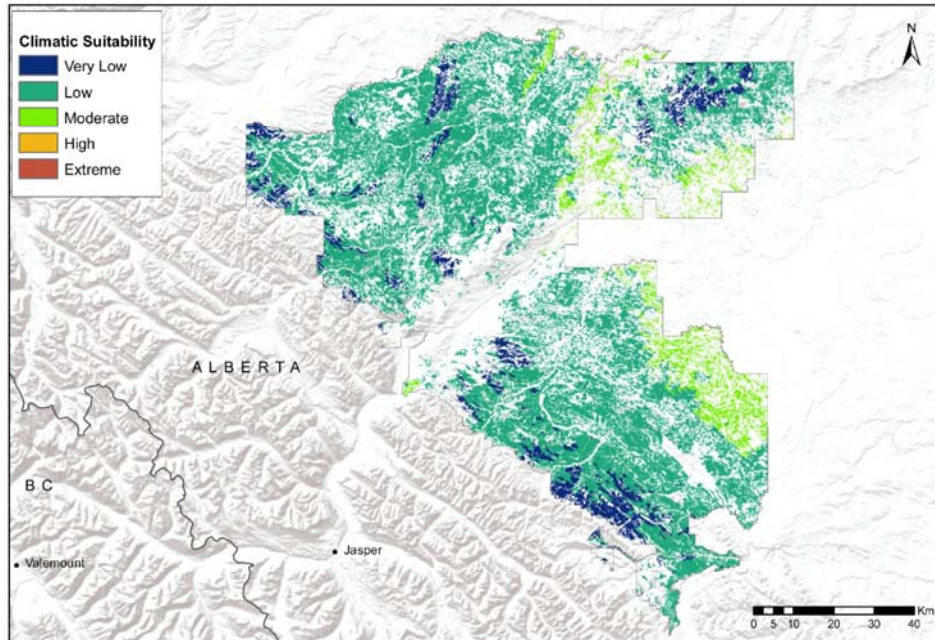
Figure 4.2 Distributions of pine-dominant (≥ 50% of tree species) stands indicating their climatic suitability during recent decades for the mountain pine beetle. Climatic suitability classes were derived from the Safranyik model of climatic suitability (Carroll et al. 2004) and mean conditions for 1981-2010.
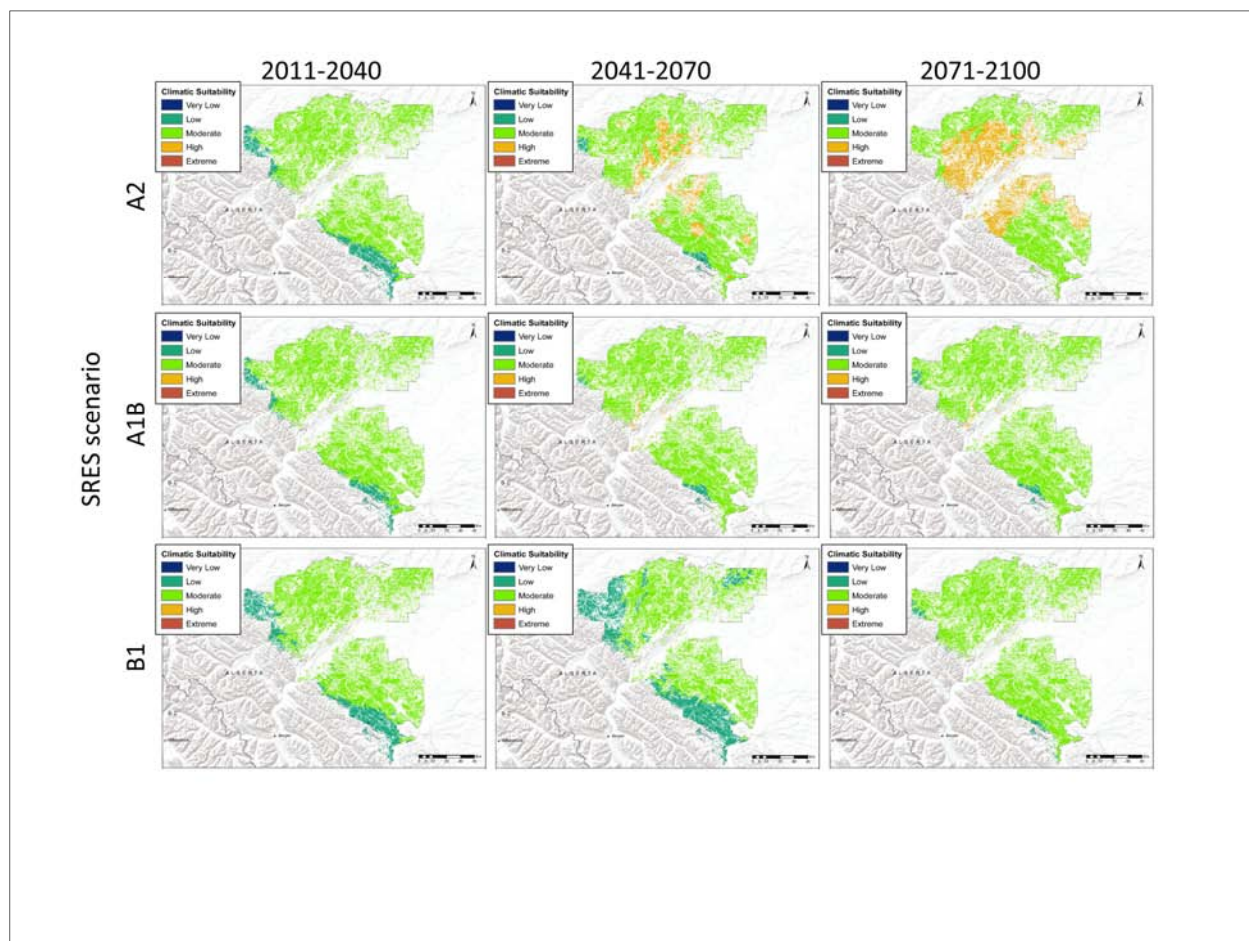
Figure 4.3 Distributions of pine-dominant (≥ 50% of tree species) stands indicating their future climatic suitability for the mountain pine beetle derived from the Safranyik model of climatic suitability (Carroll et al. 2004) and 3 climate change scenarios [Special Report on Emissions Scenarios (SRES)] run with the CGCM3 general circulation model (Scinocca et al. 2008) and downscaled using climateWNA (Wang et al. 2006). Scenario (A2) = no change in the rate of greenhouse gas emissions; Scenario B1= emissions declining by 2040 to half of the current rate by 2100; scenario A1B = intermediate emissions between A2 and B1 (Nakićenović and Swart 2000).
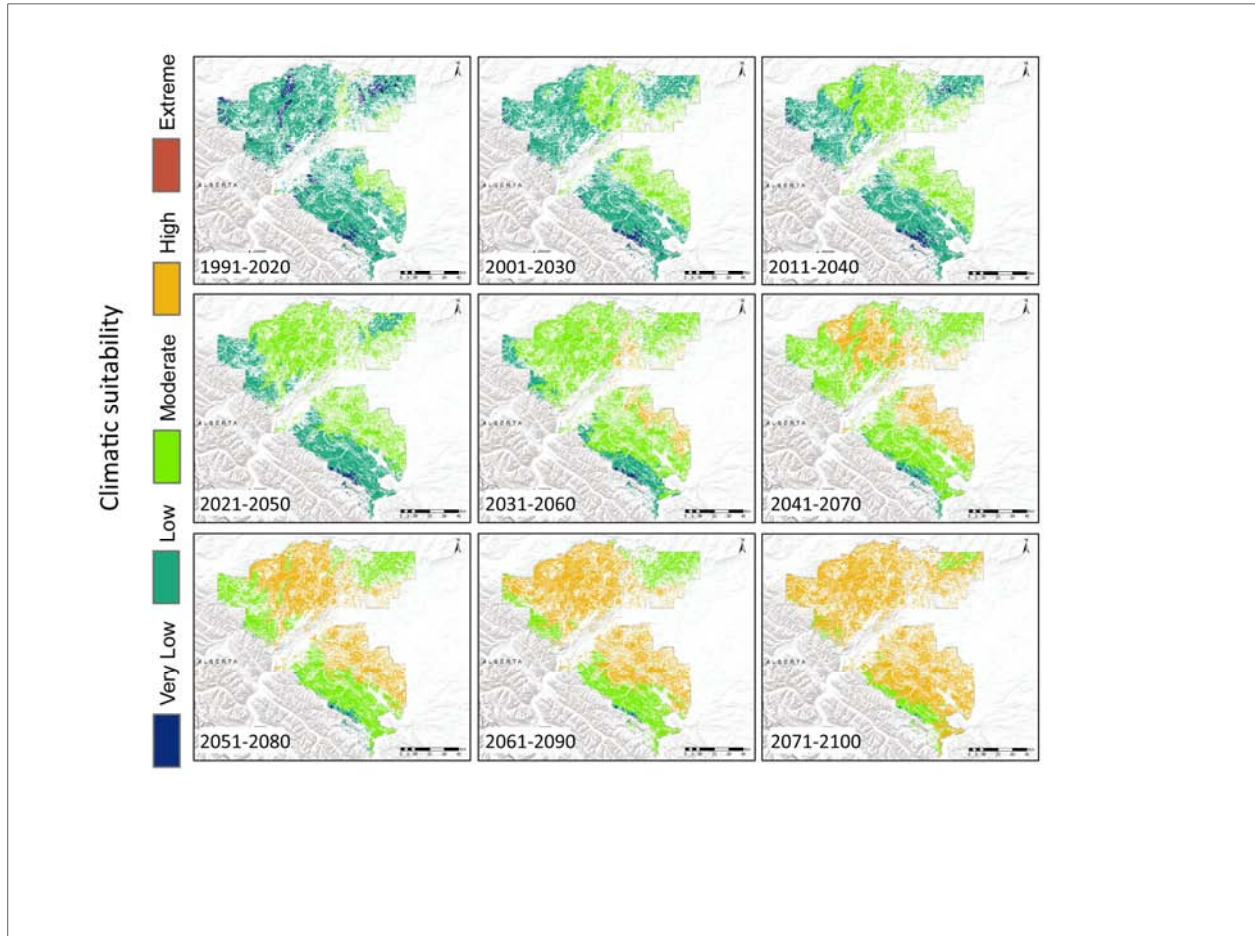
Figure 4.4 Distributions of pine-dominant (≥ 50% of tree species) stands indicating their future climatic suitability for the mountain pine beetle derived from the Safranyik model of climatic suitability (Carroll et al. 2004) and the A2 climate change scenario (Nakićenović and Swart 2000) run with the CGCM3 general circulation model (Scinocca et al. 2008) and downscaled using the Canadian Regional Climate Model (Caya et al. 1995).
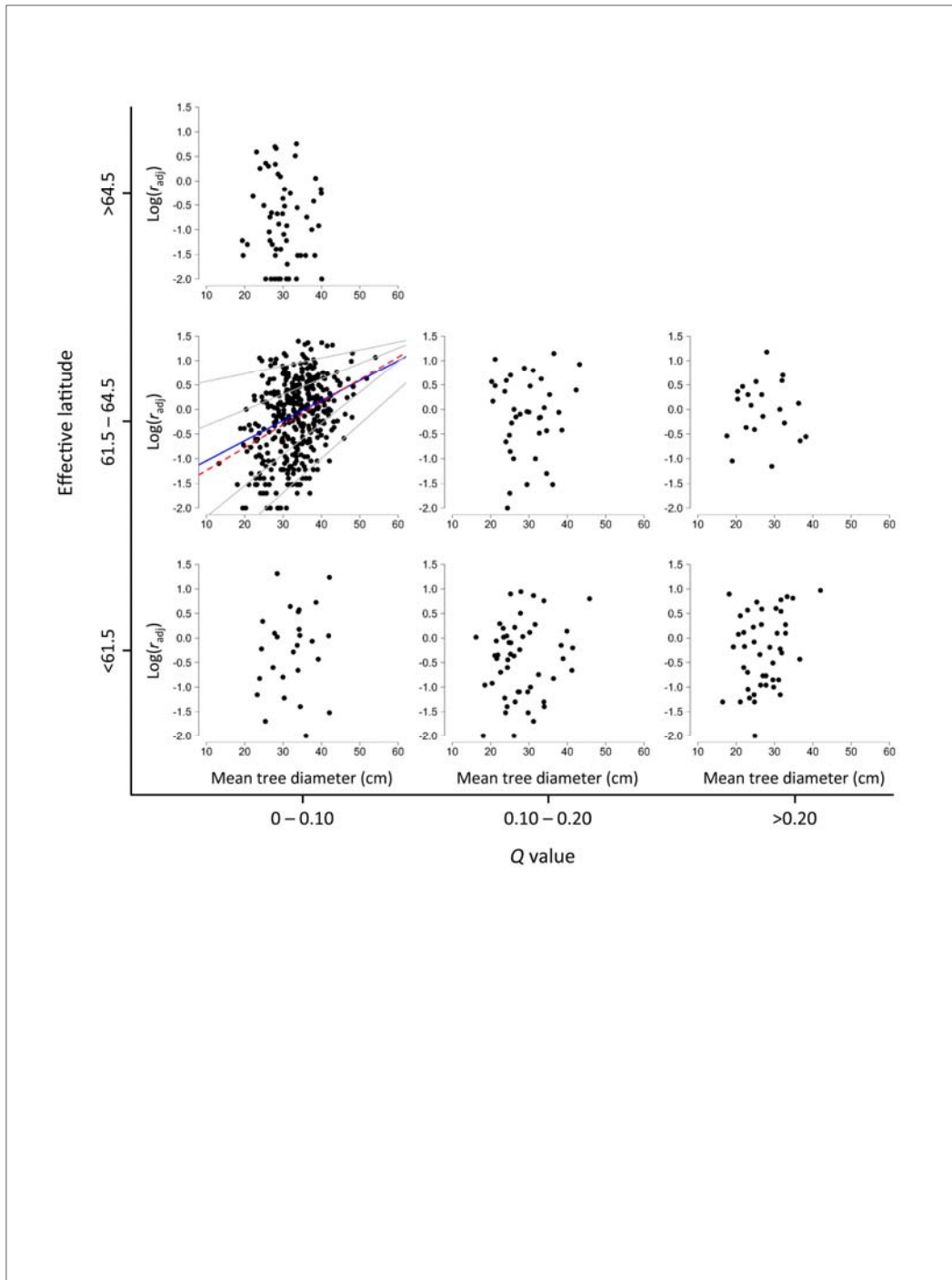
Figure 4.5 Scatterplots and quantile regression fits examining the relationship between tree diameter [measured at breast height (1.3m)] and the number of mountain pine beetle offspring per female (r), adjusted to account for post-sample mortality associated with lethal low temperatures (see text for details). Where significant, quantile regression lines (i.e. 10th, 25th, 75th, and 90th percentiles) are superimposed on the plot in gray, the median fit in solid blue, and the least squares estimate of the conditional mean function as the dashed red line. Scatterplots are presented along axes denoting the significant interaction between Q, an index of hybrid ancestry where 0 = lodgepole pine and 1 = jack pine (Cullingham et al. 2012), and effective latitude determined from Hopkins Bioclimatic Law (Hopkins 1920). Sampling locations representing combinations of effective latitudes >64.5 and Q values from 0.10 – 0.20 and >0.20 did not exist, and therefore scatterplots are not shown. See text for details.
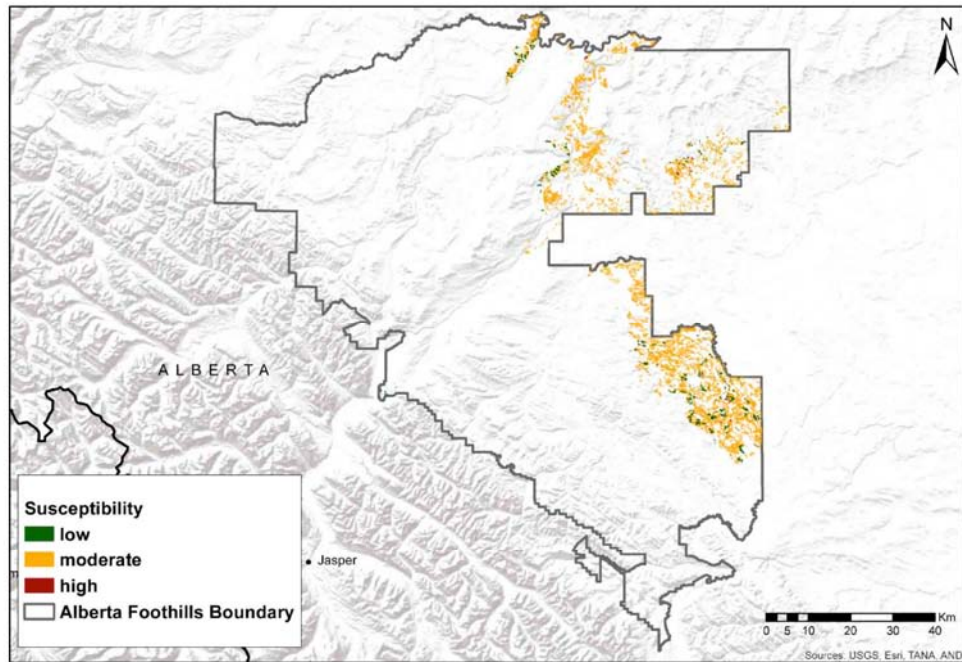
Figure 4.6 Current distribution of climatically suitable (i.e. ≥ moderate suitability), pine-dominant (≥ 50% of tree species) stands indicating their susceptibility to attack by the mountain pine beetle (see text for details of susceptibility calculations). Climatic suitability was derived from the Safranyik model (Carroll et al. 2004) and mean conditions for 1981-2010.
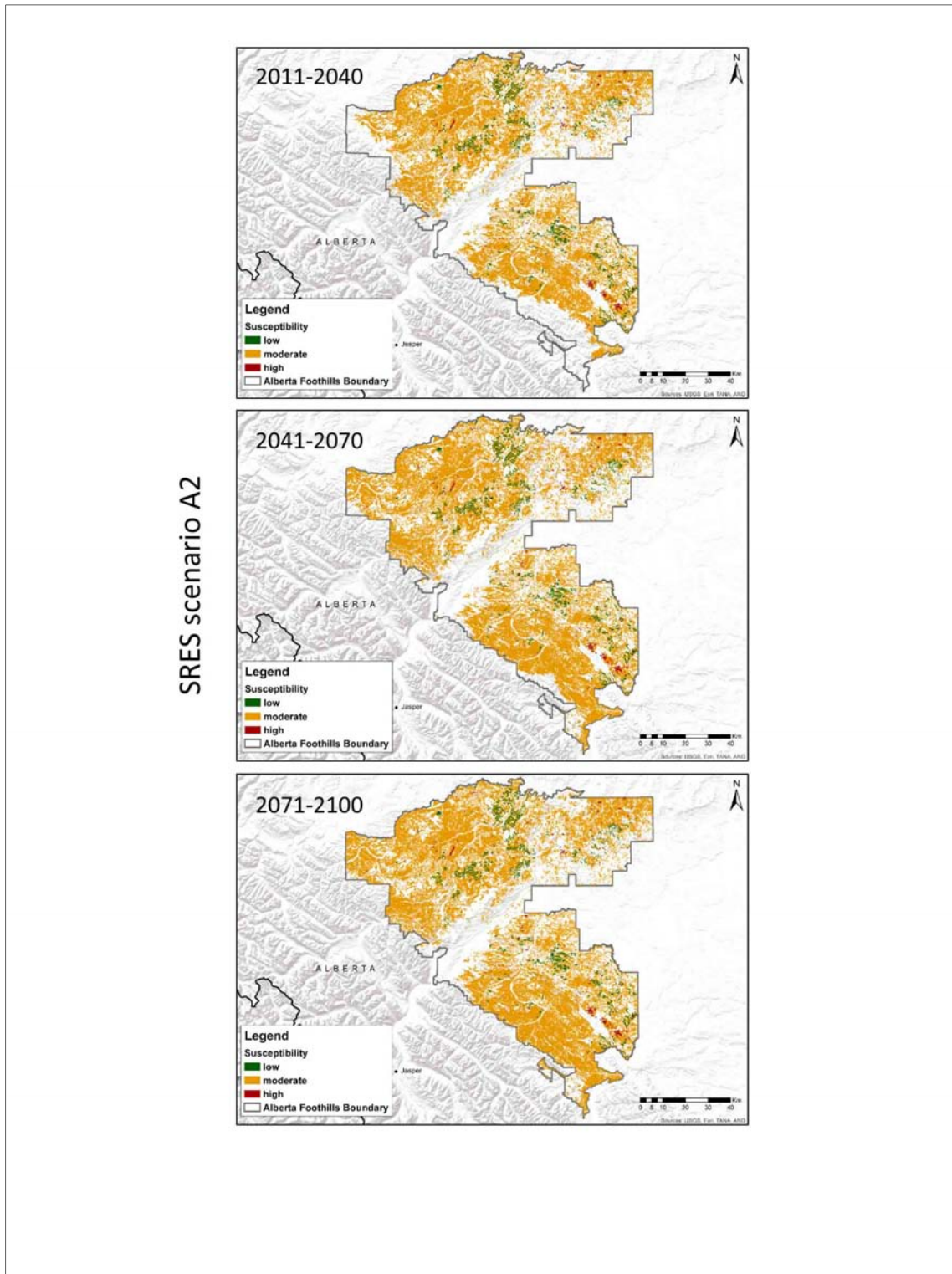
Figure 4.7 Future distributions of climatically suitable (i.e. ≥ moderate suitability), pine-dominant (≥ 50% of tree species) stands indicating their predicted susceptibility to attack by the mountain pine beetle (see text for details of susceptibility calculations). Climatic suitability was derived from the Safranyik model (Carroll et al. 2004) and the A2 climate change scenario (Nakićenović and Swart 2000) run with the CGCM3 general circulation model (Scinocca et al. 2008), downscaled using climateWNA (Wang et al. 2006).
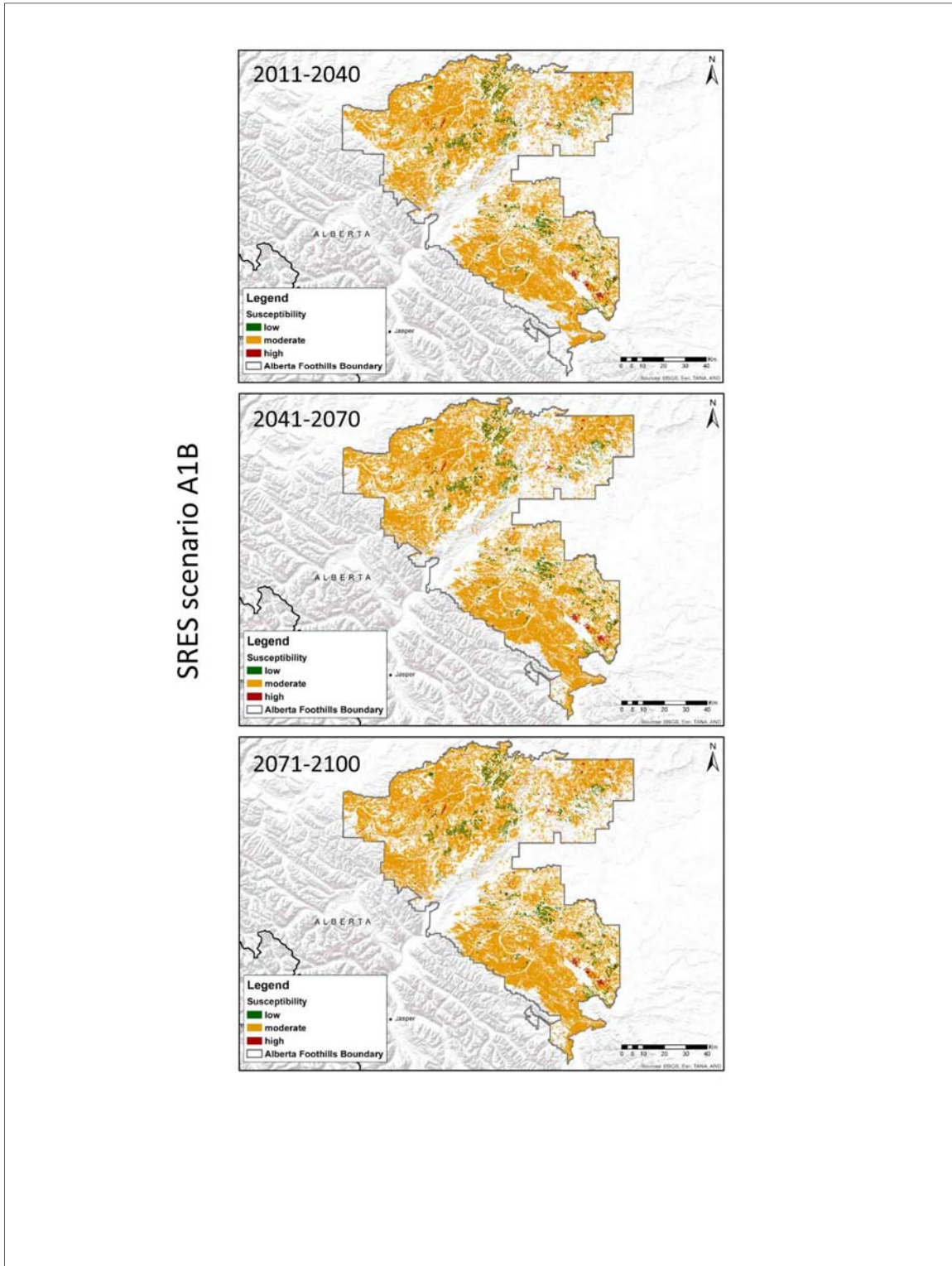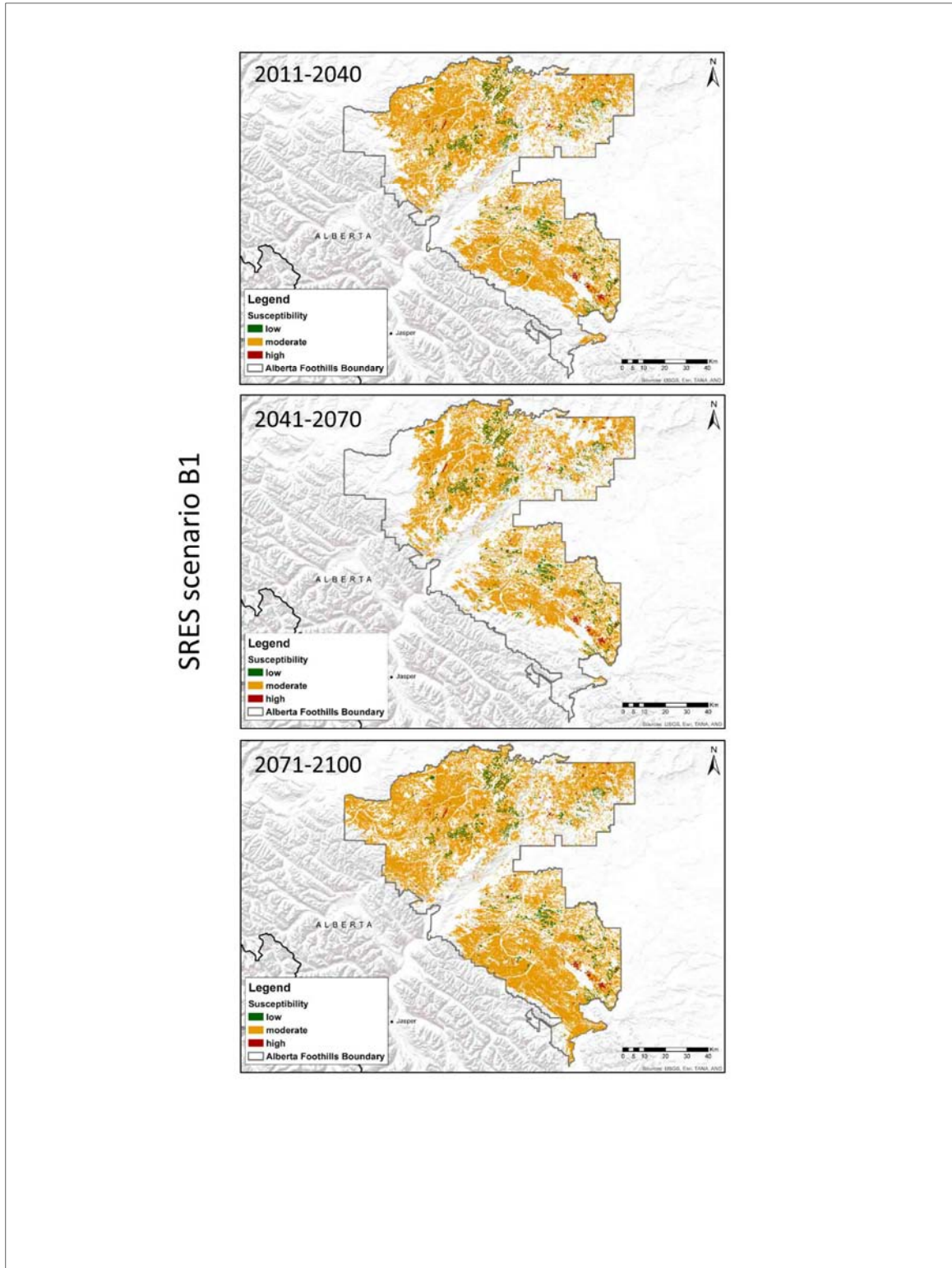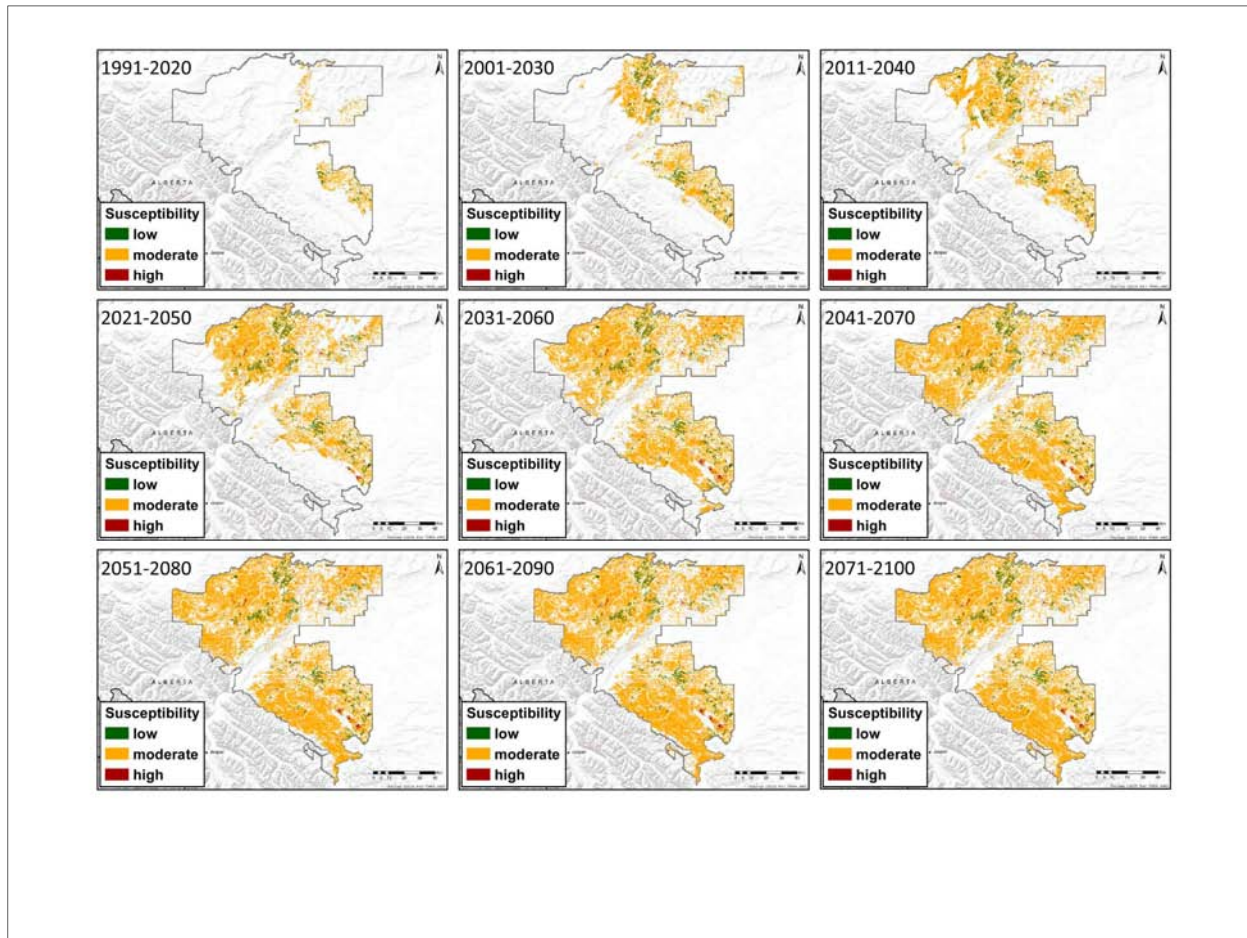
Figure 4.8 Future distributions of climatically suitable (i.e. ≥ moderate suitability), pine-dominant (≥ 50% of tree species) stands indicating their predicted susceptibility to attack by the mountain pine beetle (see text for details of susceptibility calculations). Climatic suitability was derived from the Safranyik model (Carroll et al. 2004) and the A1B climate change scenario (Nakićenović and Swart 2000) run with the CGCM3 general circulation model (Scinocca et al. 2008), downscaled using climateWNA (Wang et al. 2006).

Figure 4.9 Future distributions of climatically suitable (i.e. ≥ moderate suitability), pine-dominant (≥ 50% of tree species) stands indicating their predicted susceptibility to attack by the mountain pine beetle (see text for details of susceptibility calculations). Climatic suitability was derived from the Safranyik model (Carroll et al. 2004) and the B1 climate change scenario (Nakićenović and Swart 2000) run with the CGCM3 general circulation model (Scinocca et al. 2008), downscaled using climateWNA (Wang et al. 2006).

Figure 4.10 Future distributions of climatically suitable (i.e. ≥ moderate suitability), pine-dominant (≥ 50% of tree species) stands indicating their predicted susceptibility to attack by the mountain pine beetle (see text for details of susceptibility calculations). Climatic suitability was derived from the Safranyik model (Carroll et al. 2004) and the A2 climate change scenario (Nakićenović and Swart 2000) run with the CGCM3 general circulation model (Scinocca et al. 2008), downscaled using the Canadian Regional Climate Model (Caya et al. 1995).