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Impacts of climate change on mountain pine beetle habitat connectivity in western Canada

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Mountain Pine Beetle Working Paper 2010-04

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MPBP Project # 7.49

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© 2011 Her Majesty the Queen in Right of Canada
Printed in Canada

Library and Archives Canada Cataloguing in Publication

Riel, W. G. (William G.)
Impacts of climate change on mountain pine beetle habitat connectivity in western Canada [electronic resource] / W.G. Riel, C. Burnett and A. Fall.

(Mountain pine beetle working paper ; 2010-04)
Electronic monograph in PDF format.
Issued also in printed form.
Includes abstract in French.
Includes bibliographical references.
ISBN 978-1-100-18316-9
Cat. no.: Fo143-3/2010-4E-PDF

1. Mountain pine beetle--Geographical distribution--Climatic factors --Alberta--Forecasting. 2. Mountain pine beetle--Habitat--Alberta. 3. Pine --Diseases and pests--Alberta. I. Fall, Andrew, 1966- II. Burnett, C. III. Pacific Forestry Centre IV. Mountain Pine Beetle Initiative (Canada) V. Title.
VI. Series: Mountain Pine Beetle Initiative working paper (Online) ; 2010-04

SB945 M78 R54 2011 634.9'7516768 C2011-980043-8

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Abstract

In 2007, a multi-year connectivity modelling experiment was initiated to better understand the movement potential of mountain pine beetle (MPB) in Alberta and Saskatchewan pine forests. In the first year, spatial models of highly susceptible pine forest connectivity were developed for Alberta and Saskatchewan. The following year, the study focused solely on Alberta pine forests as our investigation turned to examine the effect that different pine species have on the connectivity model. In the third year (2009–10), the influence of climate on the landscape connectivity in Alberta was explored. To investigate the impacts of possible climate changes, minimum planar graphs were developed for the Alberta pine forests based on a modified stand susceptibility index. It was found that the stand susceptibility index most closely reflected observed MPB spread patterns when there were no climatic limitations in the model. A preliminary verification of the connectivity model was also performed. Using the model to determine expected 2009 MPB locations based on observed 2008 MPB source locations, both visual and statistical comparisons were performed to determine how well the model matched observed MPB spread. Generally, MPB were preferentially selecting closely connected habitat, but some of the direction of spread did not follow expected patterns. Some factor other than habitat connectivity (such as wind direction during MPB flight or topography) was influencing MPB spread: this warrants further exploration.

Keywords: mountain pine beetle, *Dendroctonus ponderosae*, jack pine, lodgepole pine, western boreal forest, Alberta, Saskatchewan, risk assessment, climate change

Résumé

En 2007, nous avons entrepris de modéliser la connectivité de l’habitat du dendroctone du pin ponderosa afin de mieux comprendre les directions possibles de dispersion du ravageur dans les forêts de pins de l’Alberta et de la Saskatchewan. La première année, nous avons créé des modèles spatiaux de la connectivité entre les forêts de pins très vulnérables à l’attaque du ravageur. L’année suivante, nous avons étudié l’effet des différentes essences de pins sur le modèle de connectivité, mais uniquement pour les forêts de pins de l’Alberta. La troisième année (2009-2010), nous avons étudié les effets des changements climatiques attendus sur la connectivité du paysage en Alberta; pour ce faire, nous avons établi des graphes MPG (« *minimum planar graphs* ») à partir d’un indice modifié de vulnérabilité des peuplements. La corrélation entre l’indice de vulnérabilité des peuplements et la répartition observée du dendroctone du pin ponderosa était plus étroite lorsque les paramètres climatiques n’étaient pas pris en compte dans le modèle. Nous avons également réalisé une validation préliminaire du modèle de connectivité. Nous avons utilisé le modèle pour prédire la répartition du dendroctone en 2009 à partir de la répartition observée en 2008 et avons déterminé visuellement et statistiquement la concordance entre les prédictions du modèle et la réalité. De façon générale, le dendroctone se déplaçait de préférence vers des milieux favorables proches, mais dans certains cas il ne se dispersait pas dans la direction attendue. Nous en avons conclu que d’autres facteurs que la connectivité du paysage interviennent dans la propagation du dendroctone du pin ponderosa (direction du vent au moment de la dispersion du ravageur, relief, etc.). Ces facteurs doivent faire l’objet d’une étude plus poussée.

Mots clés : dendroctone du pin ponderosa, *Dendroctonus ponderosae*, pin gris, pin tordu, forêt boréale de l’ouest, Alberta, Saskatchewan, évaluation des risques, changement climatique

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1. Introduction

The British Columbia mountain pine beetle (MPB) epidemic reached Alberta's pine forests in 2005, and in subsequent years beetles spread into the Kakwa area north of Willmore Wilderness Park and in the foothills region south of Canmore. In the north, the beetle infested pine stands as far east as Lesser Slave Lake, located 250 km directly north of Edmonton (Figure 1). Because there is less suitable pine habitat in the south, beetle expansion was less extensive (Figure 2).

In 2007 a connectivity modelling experiment was initiated to better understand the movement potential (Taylor et al. 1993) of mountain pine beetle (*Dendroctonus ponderosae* Hopkins) in the Alberta and Saskatchewan pine forests.

Developing models describing the full functional connectivity (With et al. 1997; Tischendorf and Fahrig 2000) of these landscapes was not possible because it requires intensive data and field campaigns (Bélisle et al. 2001; Brooks 2003; Bélisle 2005). It was more feasible to assess the structural connectivity of habitat (i.e., pattern analysis) for the beetle (Urban and Keitt 2001; Fall et al. 2007), and to infer some aspects of functional connectivity by building minimum planar graphs (Fall et al. 2007). We examined connectivity using spatial graphs, which integrate a geometric reference system that ties patches and paths to specific spatial locations and dimensions.

In 2007–08 a Lodgepole pine model of susceptibility was developed to examine Alberta and Saskatchewan forests. In 2008–09 the sensitivity of the models to estimated differences in pine host species was explored in Alberta (Shore et al. 2009). The following year (2009–10), further exploration of the connectivity model was undertaken to investigate the effects of changing climate in Alberta.

For this study, published data from Alberta Sustainable Resource Development (ASRD) and the British Columbia Ministry of Forests (BCMoF) were used. Susceptibility models were prepared by Canadian Forest Service researchers to produce mountain pine beetle susceptibility maps for lodgepole and jack pine stands of Alberta (Shore and Safranyik 1992).

2. Data Exploration to Refine the Connectivity Experiment

In this study, patches were based on a stand susceptibility index (SSI) (Shore and Safranyik 1992) following the methods described in Shore et al. (2009). A stand susceptibility index (SSI) cut-off was set at a value of 30: stands which were rated with an SSI of 30 or greater were considered suitable habitat patches in this model.

In each year of the study, additional MPB survey data provided increasing opportunities to improve the connectivity model.

In 2008–09, exploration of the possible impact that changes in host species could have on landscape connectivity in Alberta was carried out. The pine species in Alberta include lodgepole and jack pine as well as hybrids between the two species. The impact these changes could have on MPB movement through Alberta was explored. To facilitate this experiment, a basic pine hybridization map was generated based on a seed zone map of Alberta.

In 2009–10, additional data allowed different questions to be explored. Following is a description of these experiments.

2.1 Delineating and Quantifying Beetle Source Locations

In the first year of this study (2007–08), we only had ASRD overflight data from 2006 (red dots; Figures 1 and 2). Beetle sources were assumed to have originated from areas around Kakwa in the north and around Banff in the south. Figure 3 shows the connectivity graph produced in 2008–09 addressing hybridization of Alberta. This graph shows cluster size breaks that are based on a main source location northwest of Jasper (Kakwa).

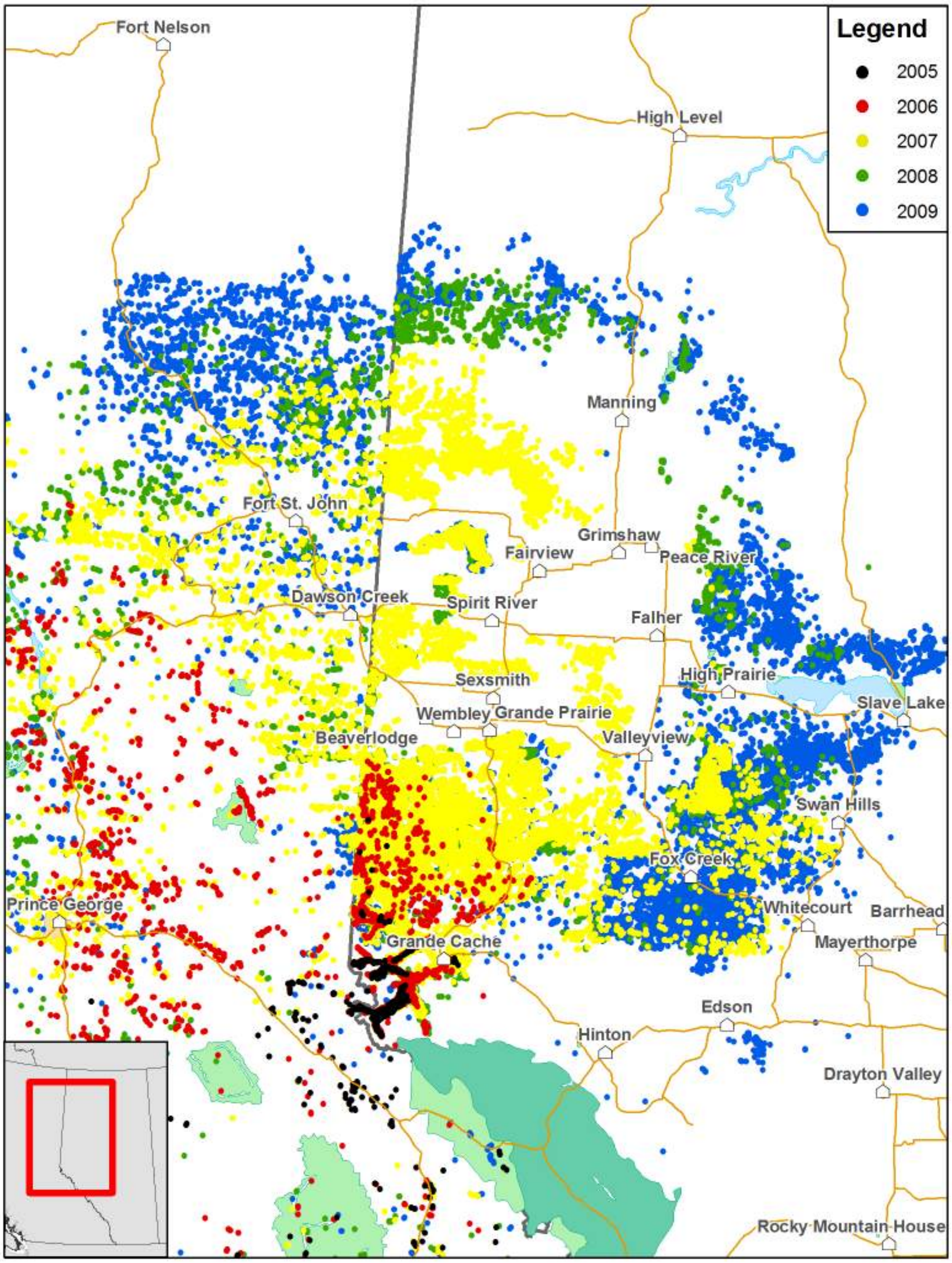

Figure 1. MPB locations (north) from 2005 to 2009 taken from BC Ministry Of Forests and Range (BCMoF) and Alberta Sustainable Resource Development (ASRD) aerial overflight databases.

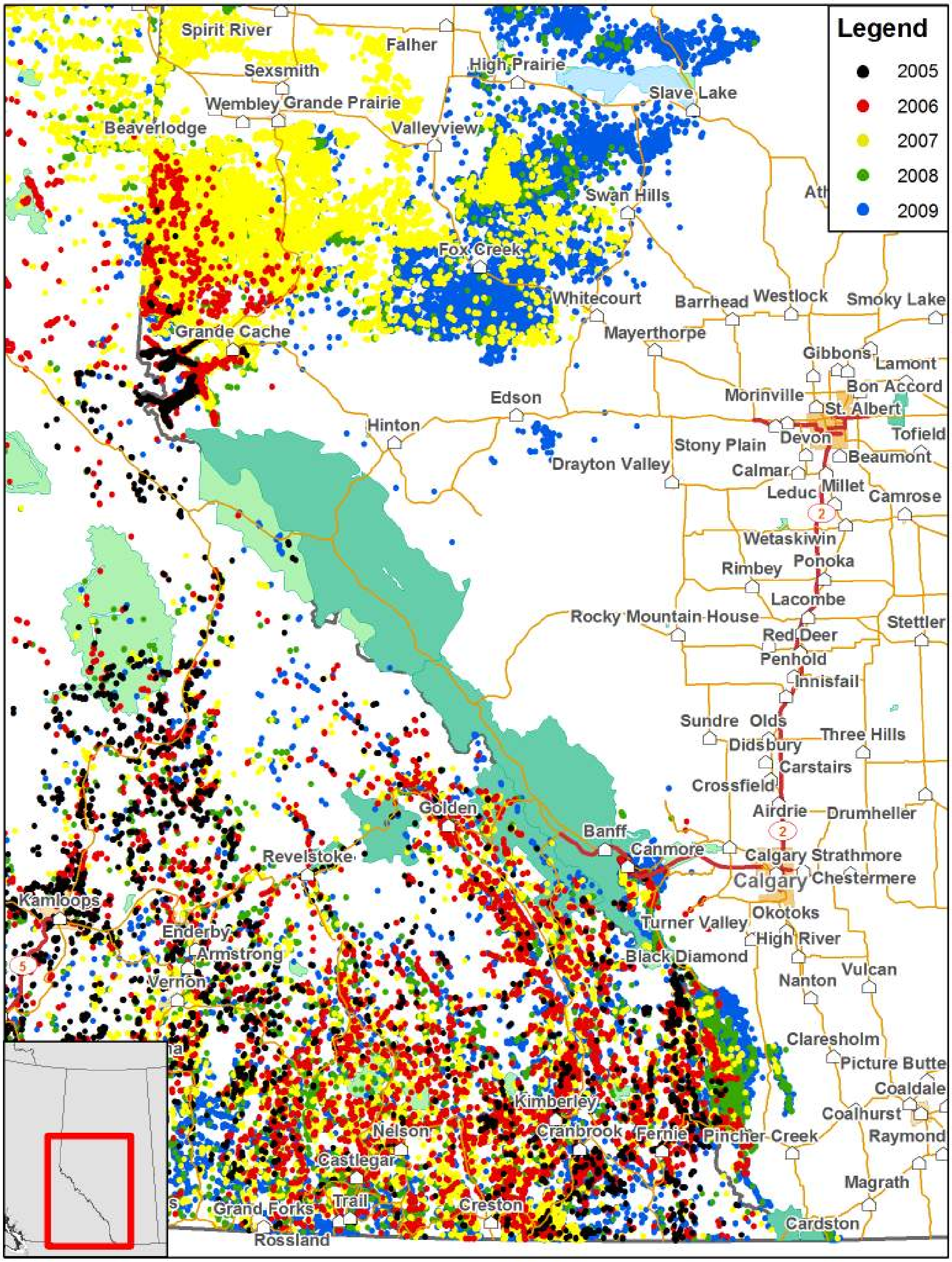

Figure 2. MPB Locations (south) from 2005 to 2009 taken from BCMoF and ASRD aerial overflight databases.

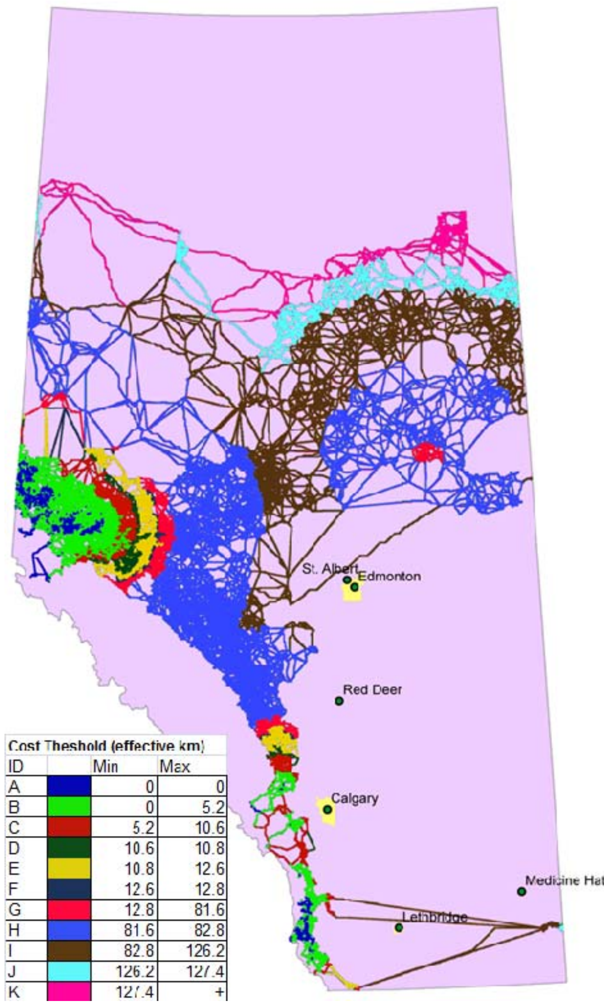

Figure 3. Connectivity graph (Cost) produced in 2008–09 addressing hybridization of Alberta.
(Note: This graph shows cluster size breaks that are based on a main source location northwest of Jasper [Kakwa].)

The following conclusions can be drawn from Figures 1, 2, and 3:

- In 2008+, beetles entered Alberta from sources well north of our original assumed main source location near Kakwa.
- Future assessments of the results from our graph model should use a "distance to beetle" metric based upon a new understanding of the beetle's entry points into Alberta.
- A re-examination of stand susceptibility index cut-off values needs to be explored since lower susceptibility stands (SSI < 30) are clearly affected in Alberta's northern region.

2.2 Exploring the Stand Susceptibility Index Cut-off

In the first year of this study, Beverly Wilson (Resource Analysis Section, Alberta Forest Management Branch) provided 52 GIS files (ESRI shapefile format) containing Alberta Vegetation Inventory (AVI) data as well as a unique stand identification number. These shapefiles cover all pine forests in Alberta. Projection and datum are TTM, NAD83.

Using this AVI data, stand susceptibility index ratings were derived for every stand: the ASRD MPB SSI application (a script run within ESRI ArcGIS) is based on the Shore and Safranyik (1992) model for calculating each stand's susceptibility for MPB. The susceptibility index for a given stand is based on four variables: relative abundance of susceptible pine basal area in the stand; age of dominant and co-dominant live pine; the density of the stand; and the climate suitability of the stand (Shore et al. 2006).

Stand susceptibility index (SSI) was calculated using the following formula:

$$SSI = P \times A \times D \times CF$$

Where: P = percentage of susceptible pine basal area; A = age factor; D = density factor; and CF = climatic factor.

The ASRD MPB SSI application was run against existing Alberta Vegetation Inventory (AVI) data. The AVI was subsequently updated with historical fires and cutovers, and then the SSI and SSI_CF (with climatic factor) values were reset to 0 where the vegetation had been altered. Only polygons where SSI > 0 were kept**.**

The ASRD MPB SSI application produced a dBase (.dbf) file with four fields:

1. POLY_NUM: Keyfield that links back to original AVI data
2. CF: Climatic factor
3. SSI: Stand susceptibility index without climatic limitations (CF = 1.0)
4. SSI_CF: Stand susceptibility index with climatic factor

To generate the connectivity model, a SSI equal to or greater than 30 was used, and the graph analysis was carried out using the Spatially Explicit Landscape Event Simulator (SELES) (Fall and Fall 2001; Fall 2003). The model was built using SSI values which were calculated using climate factor (SSI_CF) and SSI values derived without climatic limitations (SSI), giving some indication of the model's sensitivity to climate.

In addition, the model SSI cut-off was explored: SELES graph analysis was carried out with values of SSI_CF ≥ 20 and SSI_CF ≥ 40, and at the lower extreme, SSI ≥ 15. Figure 4 shows the extent of pine stands for these three values.

Examination of Figures 1 and 4 revealed that:

- the non-climatically restricted SSI (SSI ≥ 30) more closely matches the observed pattern of beetle spread; and
- the climatic factor-modified estimate (SSI_CF) does not reflect the pattern of the actual spread of the MPB. (This may be related to the CF not taking into account or predicting several warm Alberta winters and dry summers.)

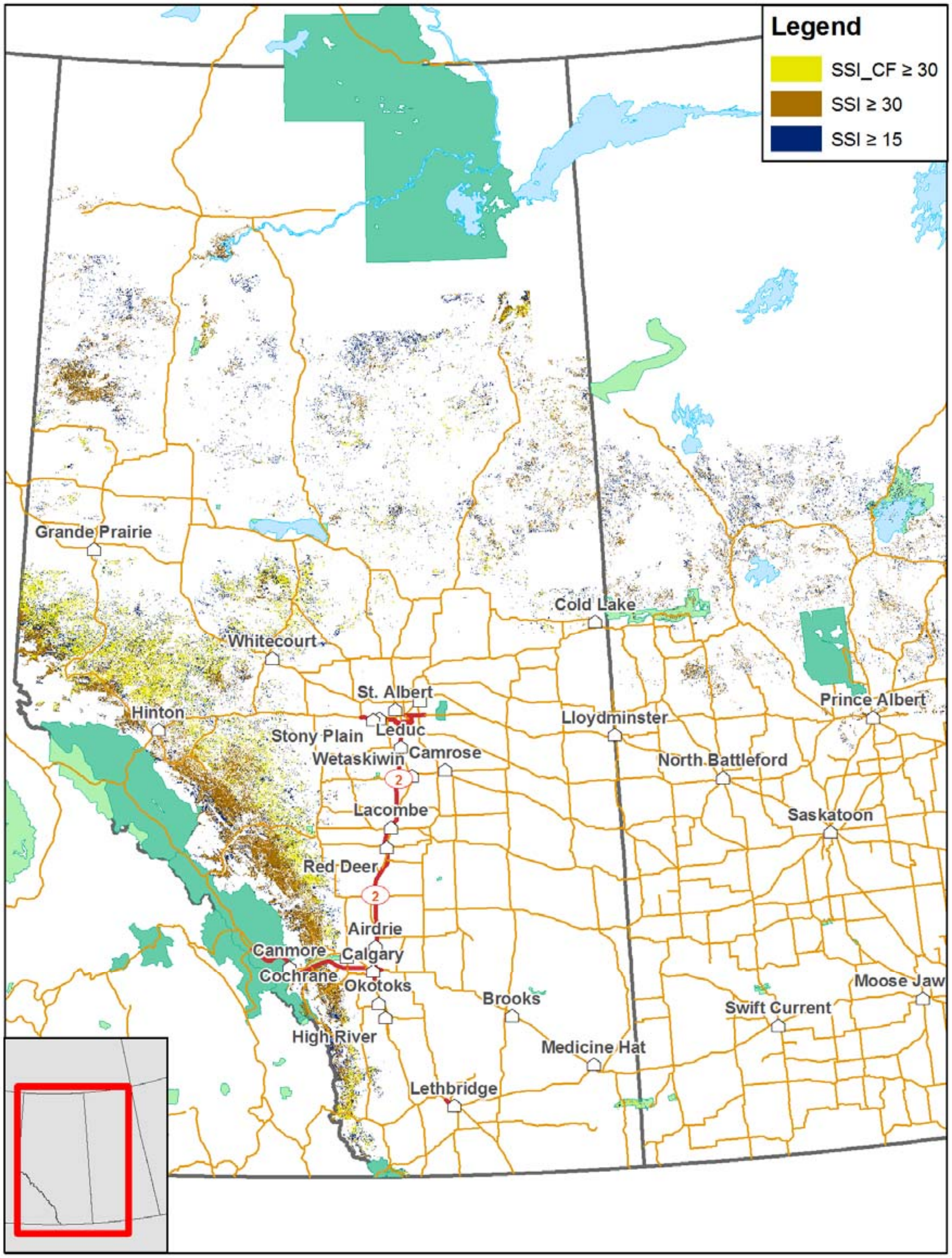

Figure 4. Comparison of pine stand filters.
(Note: The main filter used in 2007–08 was SSI_CF ≥ 30. The filter used in 2009–10 was SSI ≥ 30 [climatic factor removed]. Note the lack of SSI_CF≥ 30 stands in the north regions of the southern Peace District.)

2.3 MPB Sensitivity to Pine Hybridization

The major pine forests in Alberta include lodgepole pine, jack pine, and zones of hybridization. Due to difficulties in identifying species mix and the degree of hybridization which occurs, there are no precise maps showing where each species grows.

Further, natural MPB attack in jack pine has only recently been observed in the field: it is not clear how different (if at all) MPB population dynamics will be in jack pine as compared to lodgepole pine. It is also not clear how applicable models describing MPB dynamics in lodgepole pine are to jack pine and hybrid forests. For example, the SSI values used in this study were developed from data on MPB attacks in lodgepole pine in British Columbia (Shore and Safranyik 1992). It is unclear if the same attributes defining susceptibility to MPB attack in lodgepole pine carry the same degree of importance in jack pine stands.

To gain some preliminary insight into the possible importance of these sources of uncertainty on the Alberta landscape, some data exploration was initiated.

To get a sense of pine species distribution in Alberta, a map based on seed zones (Figure 5) was generated. While this doesn't precisely define species location, it gives some indication of probable locations of lodgepole pine, jack pine, and hybrids, and how they might affect the connectivity of this landscape.

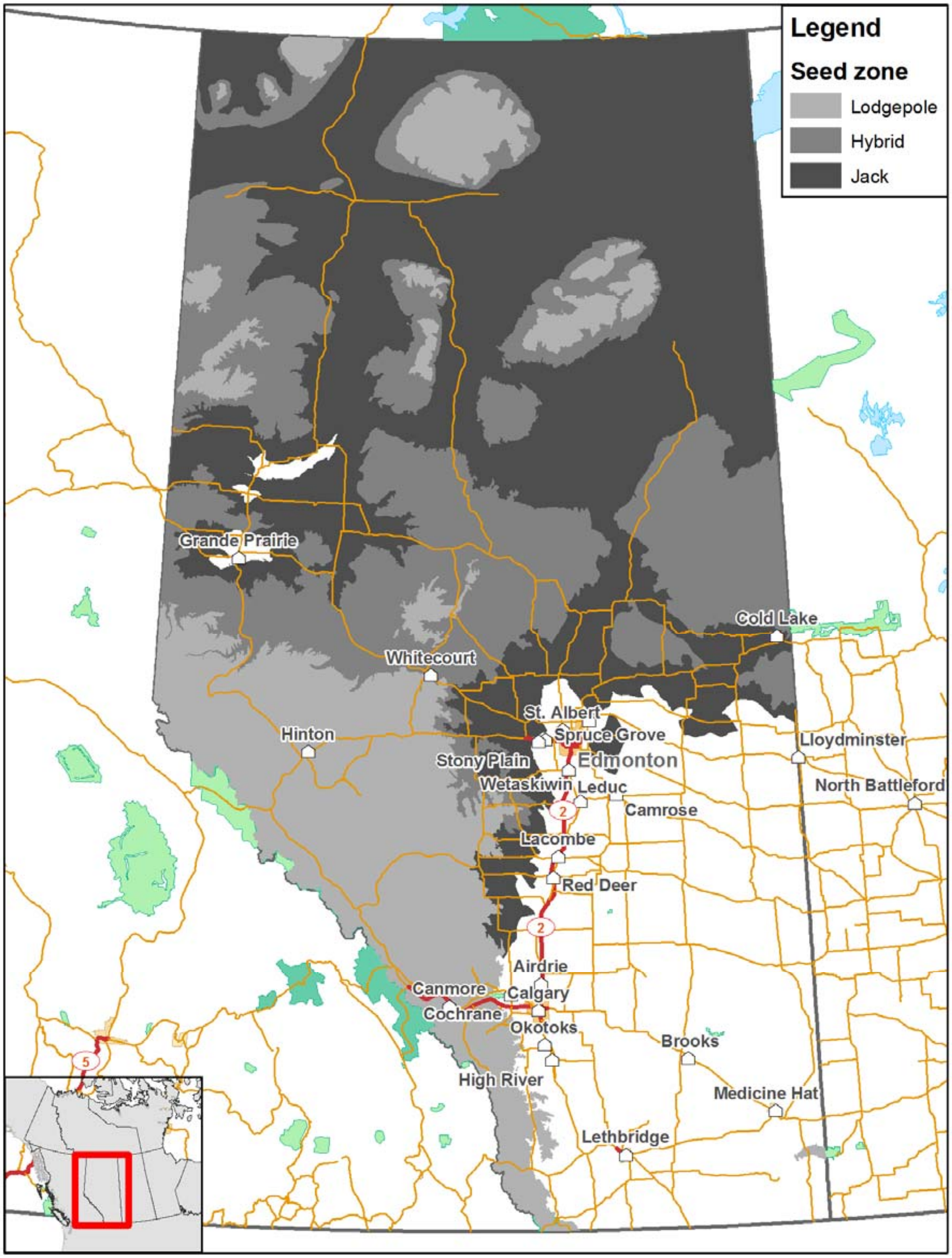

Figure 5. Hybridization zones in Alberta.

Table 1 and Figure 6 show the number of attacked trees stratified by seed zone, and Figure 7 shows the proportion of attacked trees by seed zone. Figures 8, 9, and 10 illustrate yearly MPB spread through seed zones in Alberta.

Table 1. Numbers of attacked trees by seed zone from the ASRD overflight database.

	Year		
Species	2006	2007	2008
Lodgepole	4848	80 497	44 880
Hybrid	202	93 515	47 568
Jack	0	67 557	32 086
Total	**5050**	**241 569**	**124 534**

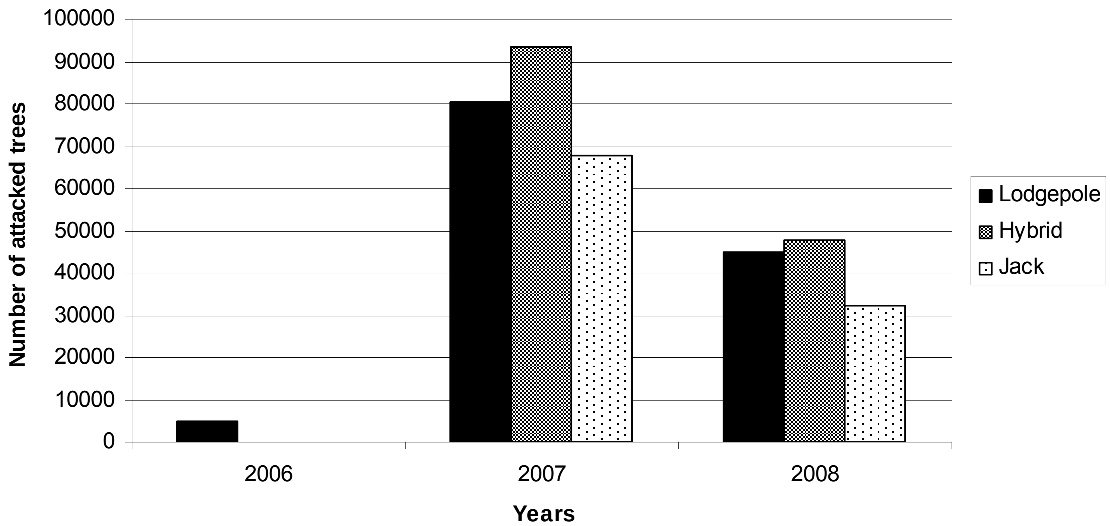

Figure 6. Chart showing number of attacked trees by seed zone from the ASRD overflight database.

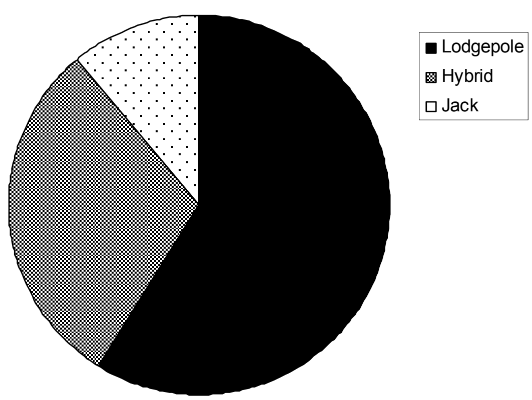

Figure 7. Percentage of pine stands by species stratified by seed zone.

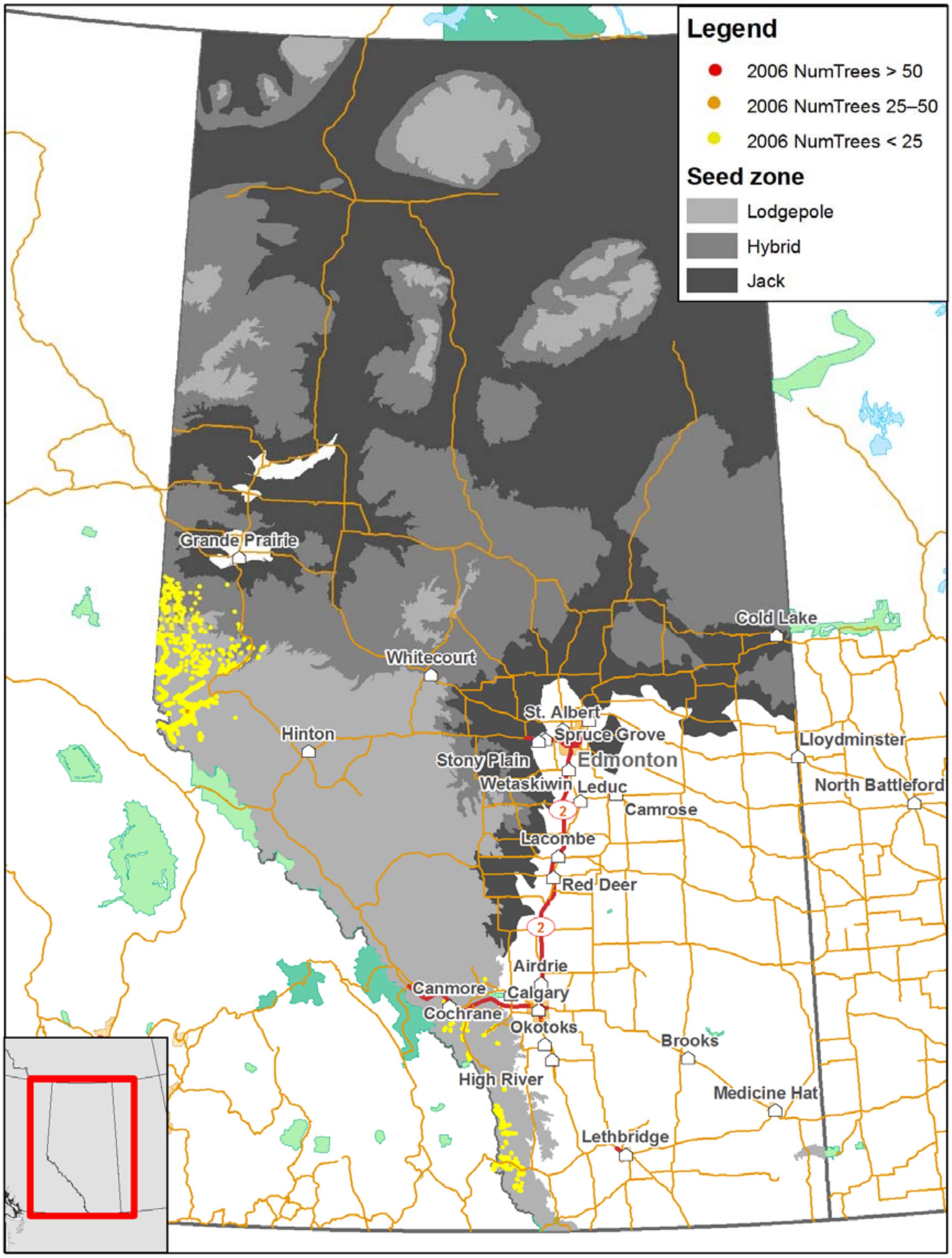

Figure 8. Year 2006 beetle spread overlaid on seed zone map.

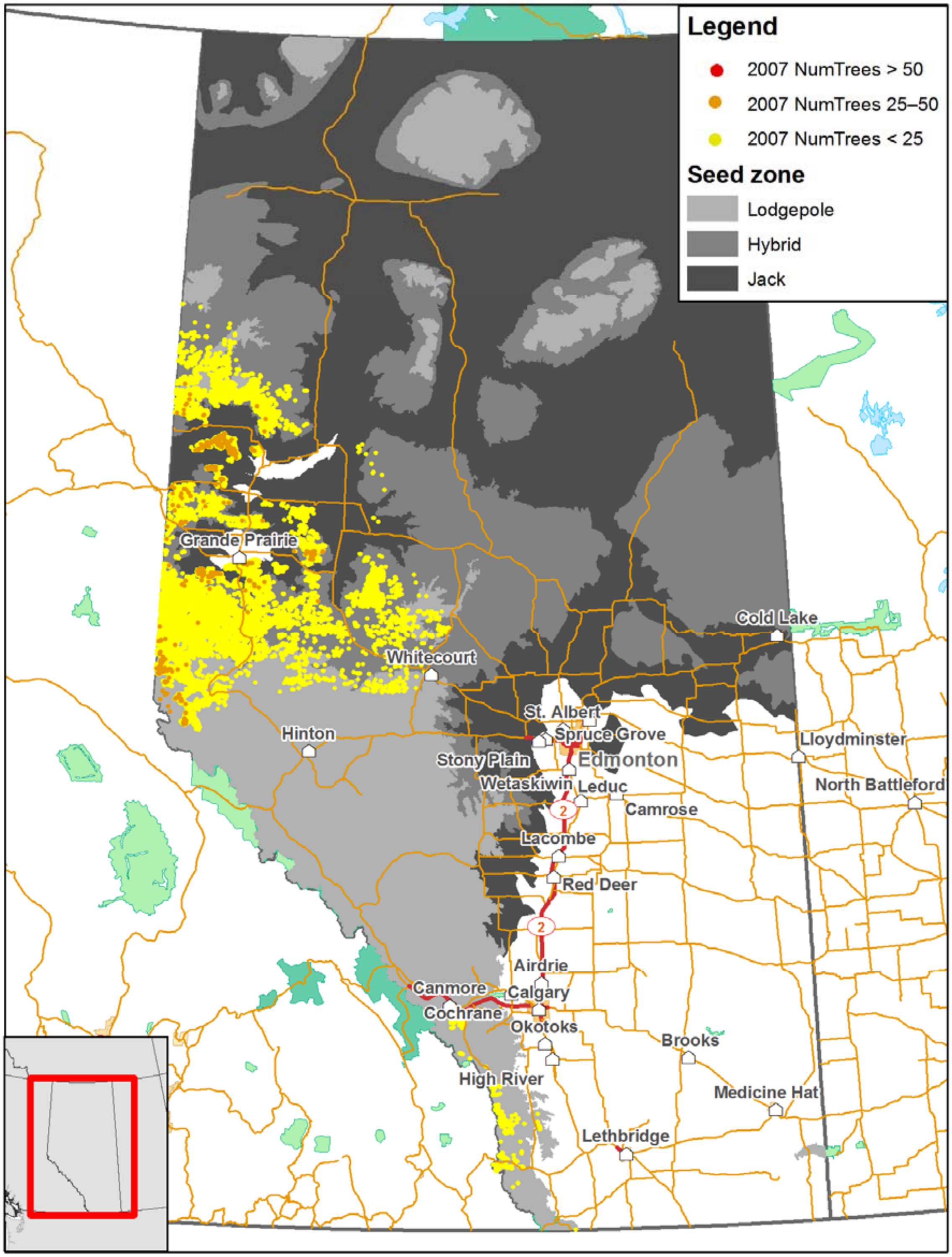

Figure 9. Year 2007 beetle spread overlaid on seed zone map.

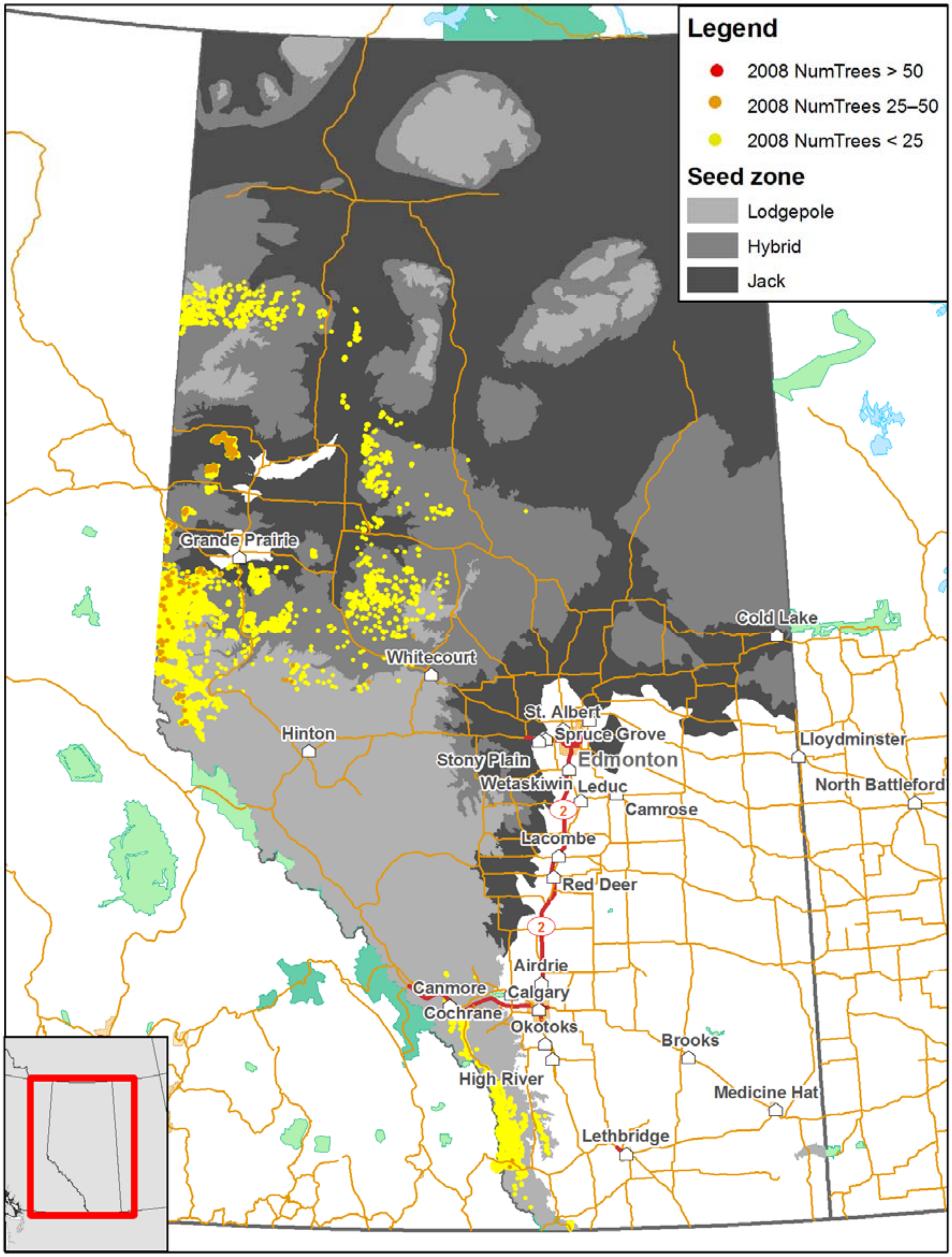

Figure 10. Year 2008 beetle spread overlaid on seed zone map.

The following observations can be made based on Table 1 and Figures 5, 6, 7, 8, 9, and 10:

- MPB are not sensitive to pine hybridization; and
- the beetles have not moved south from the Kakwa area.

This suggests that MPB prefer hybrid or jack pine stands and/or that another factor (possibly prevailing winds or a lack of resources directly west) is moving them north and east rather than south.

2.4 Comparing the 2008–09 Model with Observed MPB Spread

Until this year, inadequate MPB survey data prevented an exploration of how well connectivity graphs compare with observed MPB spread. By 2008-09, enough observations had been recorded to carry out an initial comparison. Both qualitative and quantitative comparisons were undertaken to determine if the model of connectivity can explain MPB movement.

Two approaches were taken. First, patterns were compared visually. Second, a three-way statistical experiment was carried out that included the patch connectedness values from the 2008–09 connectivity graph, the 2007 beetle location patches, and a randomly generated surface of points.

2.4.1 Visual Assessment

Figures 11a–c show the 2006, 2007, and 2008 beetle locations overlaid on the 2008–09 Alberta connectivity graph. From this information it appears that:

- the landscape connectivity graph inadequately connects stands in the north; and
- beetle populations did not travel south (from the Kakwa entry area), a likely path according to 2007–08 and 2008–09 graph experiments.

Further exploration of this phenomenon is required to understand (and better model) why beetle movement south has been inhibited.

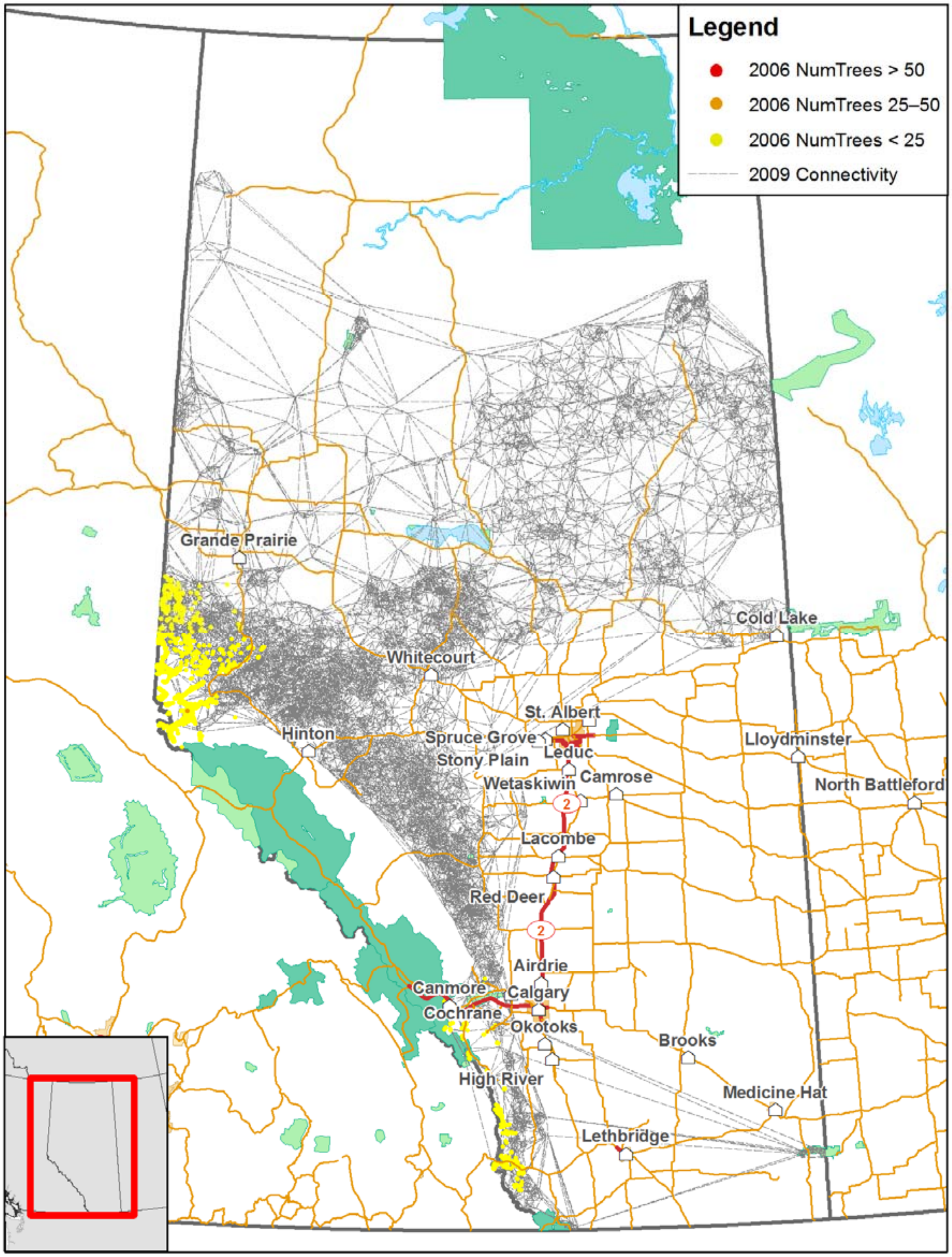

Figure 11a. Year 2006 Alberta aerial overview points overlaid on the 2008–09 stand-connectivity graph.

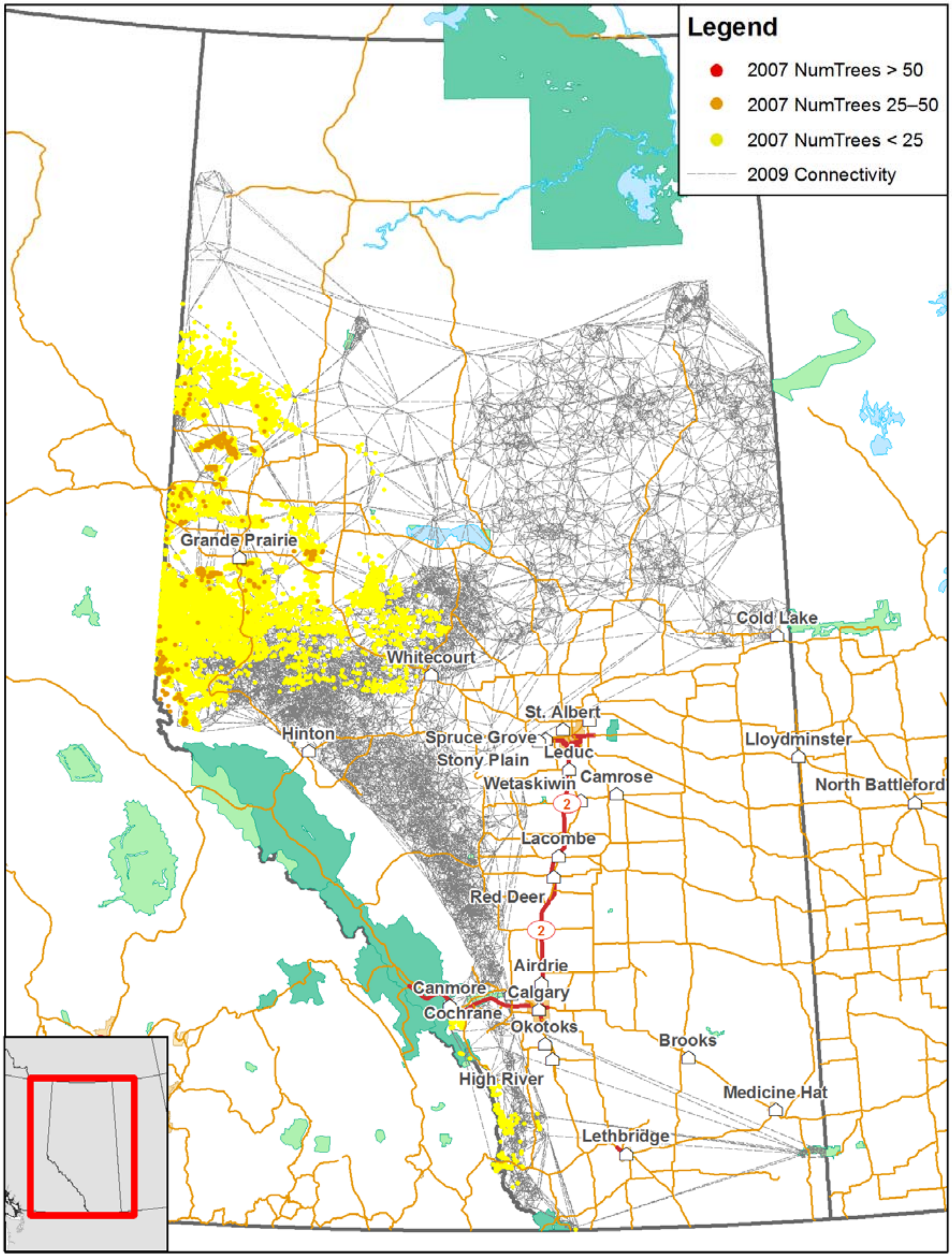

Figure 11b. Year 2007 Alberta aerial overview points overlaid on the 2008–09 stand-connectivity graph.

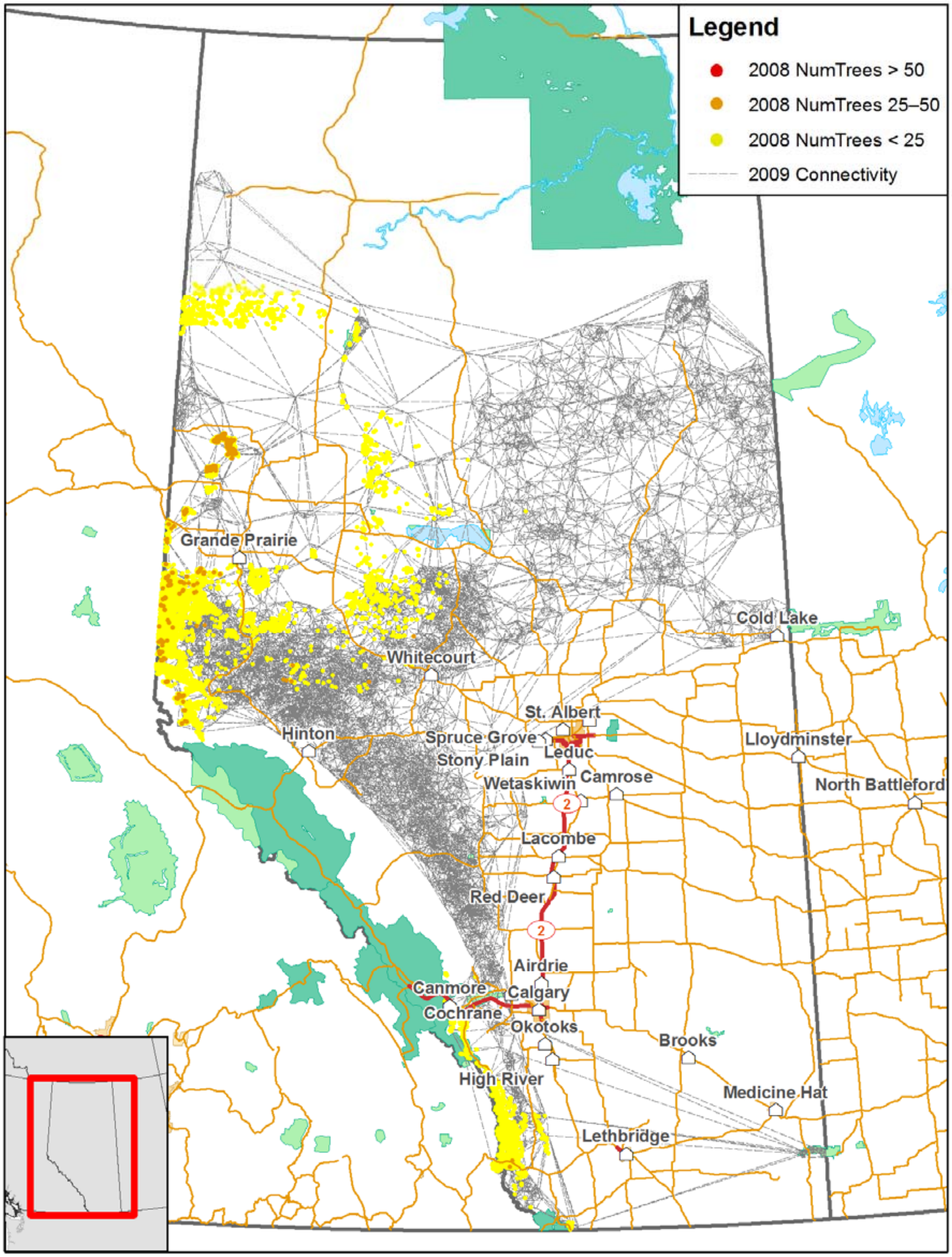

Figure 11c. Year 2008 Alberta aerial overview points overlaid on the 2008–09 stand-connectivity graph.

2.4.2 Statistical Assessment

For this assessment, the 2007 beetle locations were used to statistically assess the 2008–09 model. Observed 2007 attack locations were compared with randomly generated locations to determine if the connectivity model could explain some of the MPB spread. In an effort to reduce the influence of distance to MPB source, the random patch selection pattern was constrained to mimic the observed pattern as closely as possible. The landscape was divided into zones or bins of 40 km distances from the original 2006 beetle locations, and the number of observed attacks in each zone was used to guide the number of random beetle patches chosen. Using 40 km bins resulted in six zones. Table 2 and Figure 11 show how many beetle patches were recorded in the 2007 aerial overflight data.

Table 2. Number of infested patches binned by distance from source (2006 points).

Bin Number	Metres from Source	2007 Patches
1	1–40000	2971
2	40001–80000	212
3	80001–120000	56
4	120001–160000	313
5	160001–200000	59
6	200001 +	5

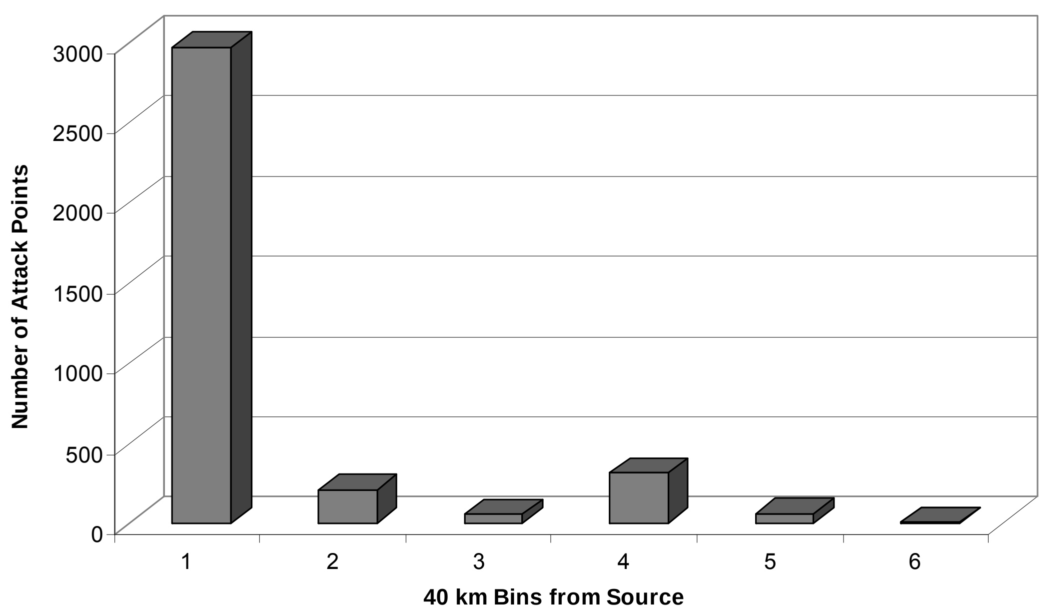

Figure 12. Distance from the original beetle attack in 2006 to the 2007 beetle attack, stratified into 40 km bins.

The random patch selection was bound in two additional ways: 1) points were placed in areas that held pine patches with SSI_CF ≥ 30; and 2) the number of random patches per 40 km bin were consistent with the bin statistics described in Table 2 and Figure 11. The random patch spatial locations are show in Figure 13.

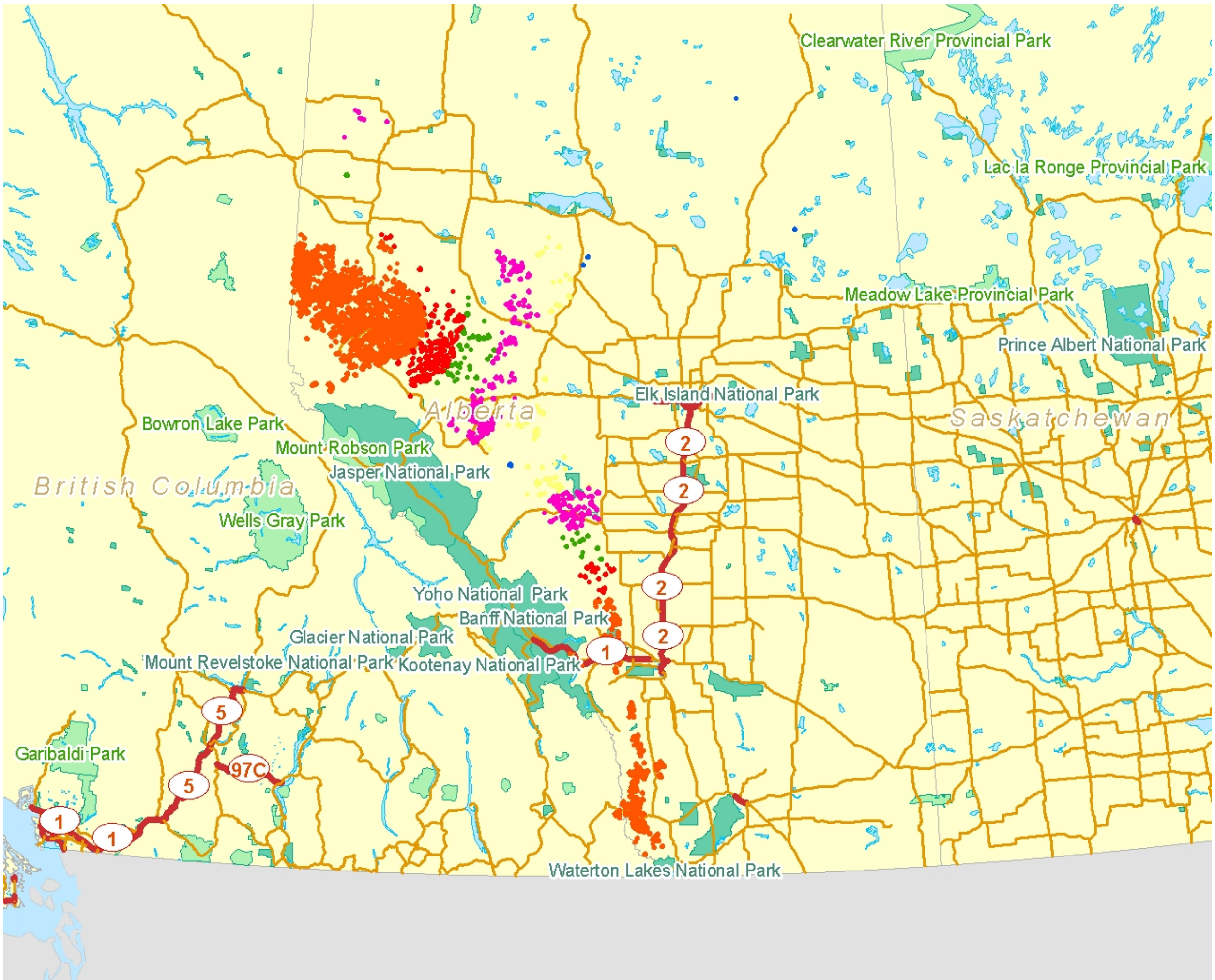

Figure 13. Spatial location of randomly selected patches.
(Note: Orange = Bin 1; Red = Bin 2; Green = Bin 3; Purple = Bin 4; Yellow = Bin 5; Blue = Bin 6.)

Patch characteristics were collected for the 2008–09 model and the random patches by generating a pivot table in a spreadsheet. The following patch connectivity characteristics were examined: distance to 2006 source beetle in both the Euclidean (Dist2ClosestMPB) and Cost (Cost2ClosestMPB) (Shore et al. 2009), the expected cluster size at 500 m (aCluster1), the expected cluster size at 1000 m (aCluster2), and the expected cluster size at 1500 m (aCluster3).

Results

The results of this assessment are given in Table 3. The following is noteworthy:

- The distances to source beetle (Cost and Euclidean) were shorter through the 2008–09 model patches than through the random patches in Bin 1, but equivalent or longer in Bins 2 through 5.
- The expected cluster size metrics were lower for the 2008–09 model than for the random patches. This suggests that the 2008–09 model is choosing patches that are not very connected.

Table 3. Exploration results: 2008–09 connectivity model (SSI_CF ≥ 30 modified with hybridization coefficients) versus randomly (constrained by distance bin) placed beetle locations.

a) 2008–09 Model

40 km Bin	Count in Bin	Average Dist2ClosestMPB (km)	Average Cost2ClosestMPB (km)	Average aCluster1 (ha)	Average aCluster2 (ha)	Average aCluster3 (ha)
1 (0–40km)	2971	4.21	4.65	33 600	351 063	667 789
2 (41–80km)	216	48.40	54.10	38 687	107 798	178 794
3 (81–120km)	56	93.41	99.00	61 906	117 338	191 027
4 (121–160km)	313	136.28	147.25	7 906	16 157	66 618
5 (161–200km)	59	188.16	195.78	593	8 137	27 530
6 (201–240km)	5	216.96	232.62	53	80	108
Weighted Average	3620	22.94	24.82	31 535	297 901	567 899

b) Random Placed

40 km Bin	Count in Bin	Average Dist2ClosestMPB (km)	Average Cost2ClosestMPB (km)	Average aCluster1 (ha)	Average aCluster2 (ha)	Average aCluster3 (ha)
1 (0–40km)	2971	6.34	6.90	94 378	353 262	639 402
2 (41–80km)	216	51.22	53.70	168 004	359 646	676 829
3 (81–120km)	55	85.52	88.65	127 216	331 706	671 004
4 (121–160km)	313	133.61	139.81	22 669	124 411	516 450
5 (161–200km)	59	175.03	183.43	20 492	116 466	526 196
6 (201–240km)	5	281.48	295.20	1 754	15 968	175 621
Weighted Average	3619	24.36	25.71	91 737	329 196	628 996

Discussion

Conclusions about Euclidean and Cost distances to attack are outlined below:

- The model points have lower values than the random points within a 40 km buffer. This implies that the susceptible habitat is configured closer to attack than random.
- The observed MPB attack points are even closer than the model points, so MPB are preferentially selecting habitat that is close to attack, as one would expect. Since the 40 km buffer bins are straight-line distance and the distance/cost to attack values are "through the minimum planar graph" (Fall et al. 2007), this result provides some evidence that connectivity analysis can provide some insight into landscape scale risk.
- The average size cluster of attack points compared to sample points is surprising. The three metrics are the average size of a connected cluster of habitat for a point (attack or sample) in a graph at a given threshold (500 m, 1000 m, or 1500 m). Our expectation for this preliminary exploration was that MPB would preferentially be in more connected habitat, which would be reflected in a larger than expected average cluster size. However, average cluster size of sample points was substantially larger than for attack points. Although counter to our expectations, the degree of difference warrants further exploration to clarify. This is likely related to the lack of beetle movement in a southern direction.

These observations lead us to propose the following hypotheses:

Hypothesis 1 Some geographic feature or wind pattern has prevented MPB movement south, thus pushing the beetle into less connected patches.

Hypothesis 2 The bins and thresholds used for the statistics weren't adequate to discern effects.

Hypothesis 3 The geometry of the habitat may be limiting the degrees of freedom for selection of habitat by MPB. If spread is primarily via local dispersal, then there will be strong correlation with distance irrespective of connectivity.

Hypothesis 4 MPB may preferentially be selecting smaller clusters (e.g., perhaps the smaller clusters represent more mixed stands with more competition-stressed pine trees that might be prone to incipient outbreaks).

Further Data Exploration

The previous hypotheses may be explored with further analysis, including the following:

- Exploration of geographic features and predominant wind direction during the flight period could be initiated.
- The sample points were randomly chosen from susceptible stands within the 40 km buffers. Over the duration of an outbreak, one would expect that large clusters would have more attack, at least proportional to their size. However, if attack points originate from long-distance dispersal (e.g., from west of the Rockies), a more scattered, random pattern may be expected, since MPB are relatively poor fliers and they likely descend initially from above-canopy based on down drafts and other factors not linked to stand susceptibility. An alternate sampling method would be to pick random points within each 40 km buffer, and then identify the nearest susceptible patch (possibly excluding points that may fall very far from a susceptible patch, say > 10 km).

- The 40 km buffer width might be overly large, especially for the first 40 km. Perhaps a geometric scaling would be better to reflect larger areas covered by expanding radius—something like 0–10km, 10–30 km, 30–70 km, etc.).
- The thresholds of 500 m, 1000 m, and 1500 m used for assessing cluster sizes could be refined to consider additional distances and get a more complete picture of what the method is capable of showing.

3. Analysis of 2009–10: New Graph Extraction

Based on the data and past model exploration conducted in Section 2, we refined our model specifications to generate a minimum planar graph (Fall et al. 2007) for the Alberta and Saskatchewan landscape, generating paths between every pair of patches. We only used the Euclidean method with the following specifications: SSI ≥ 30, no coefficient for hybridization.

A minimum planar graph is a spatial generalization of Delaunay triangulations, which provide a reasonable approximation of complete mathematical graphs (Fall et al. 2007), and facilitates visualization and comprehension of the network of connections across landscapes. If, as some authors have suggested, the minimum spanning tree identifies the connectivity "backbone" of a landscape, then the minimum planar graph identifies the connectivity "network" (Fall et al. 2007).

The graph extraction was done using the SELES (Fall and Fall 2001). Minimum planar graphs were extracted for each of the 10 sub-set boxes that cover Alberta and Saskatchewan (Figure 14) and then stitched together into a meta-graph. This process is documented in Shore et al. (2009).

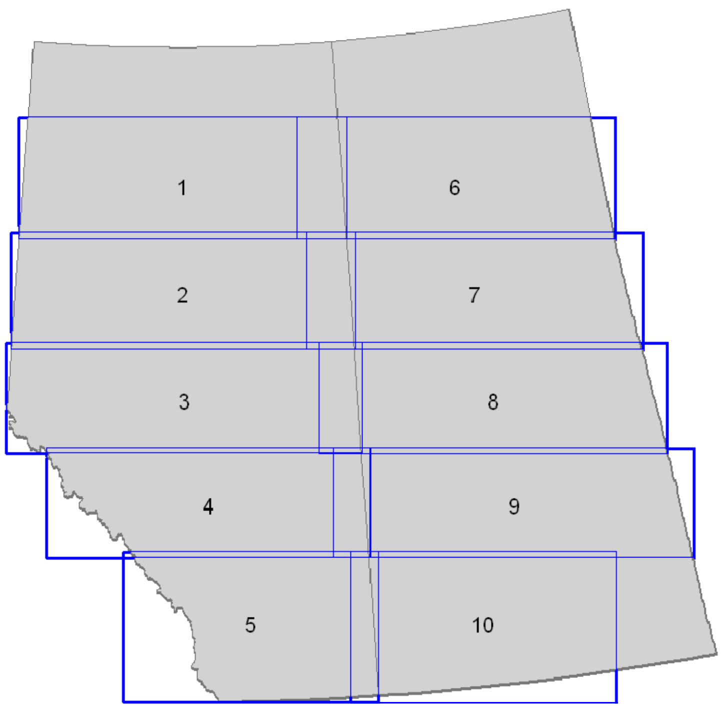

Figure 14. Alberta and Saskatchewan analysis boxes covering all pine habitats.

4. Results and Discussion

MPB habitat in Alberta doesn’t connect smoothly, but rather in semi-discrete jumps due to the pattern of pine forests in the province. Figure 15 shows how the habitat connects and indicates distance thresholds where MPB habitat becomes well connected. Figure 16 shows spatially where these thresholds occur.

We can make the following observations from Figures 15 and 16:

- The spatial graph reaches a maximum connectivity faster using SSI ≥ 30 (~ 19 km) than with SSI_CF ≥ 30 with hybridization coefficients (~ 39 km). This is what we would expect as the SSI ≥ 30 introduces many more available patches for the graph network to connect through.
- The SSI ≥ 30 graph connects earlier, reaching an expected cluster size of 250 000 within a kilometre, whereas SSI_CF ≥ 30 reaches this milestone at approximately 2 km.

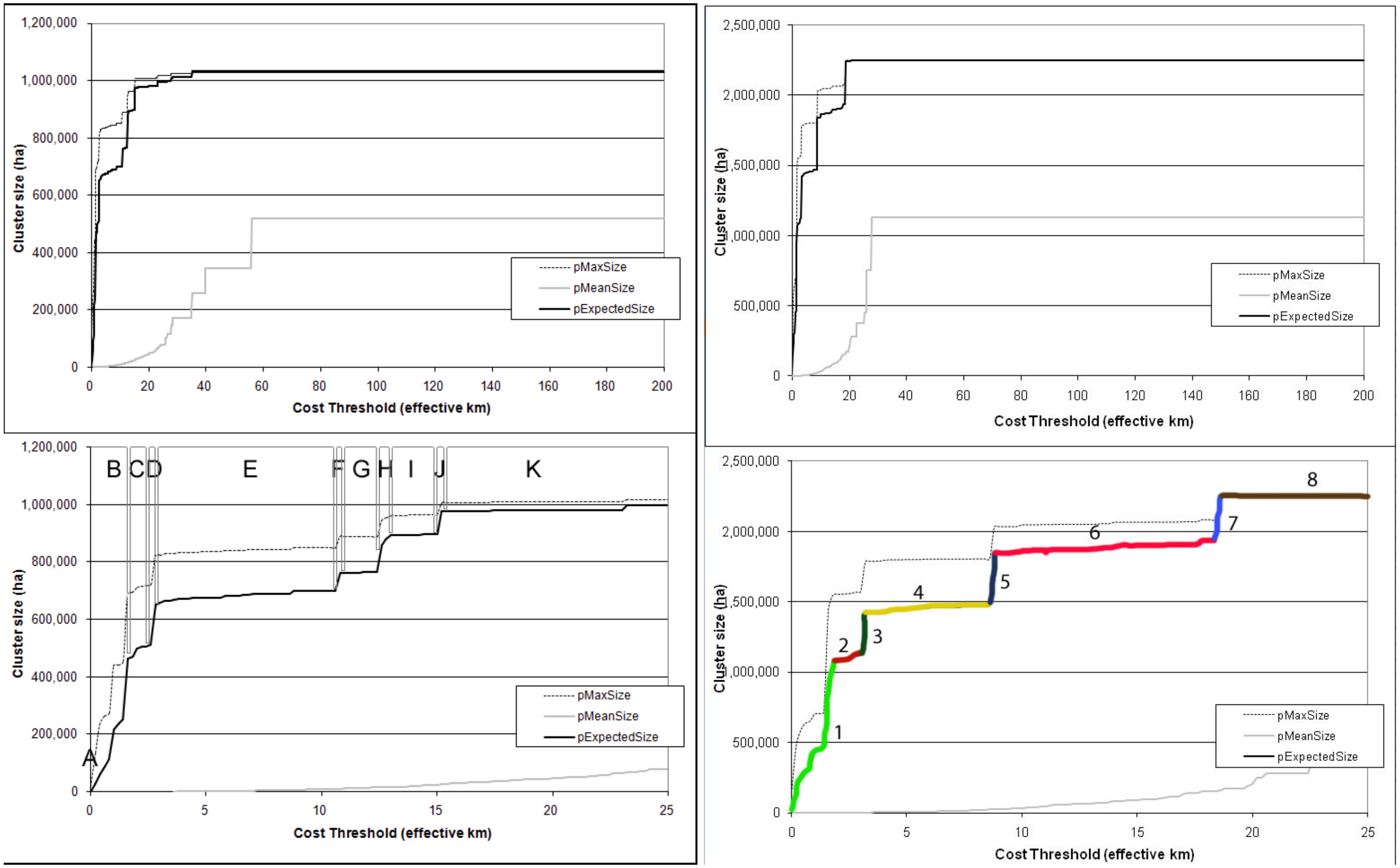

Figure 15. Contrasting connectivity "breaks" in the landscape (Euclidean) in SSI_CF ≥ 30 with hybridization coefficients for the 2008–09 experiment (left) and SSI ≥ 30 with no hybridization coefficients for the 2009–10 experiment (right).
(Note: Upper portions of the charts show the whole graph. Lower images show detail on scales 0–25 km.)

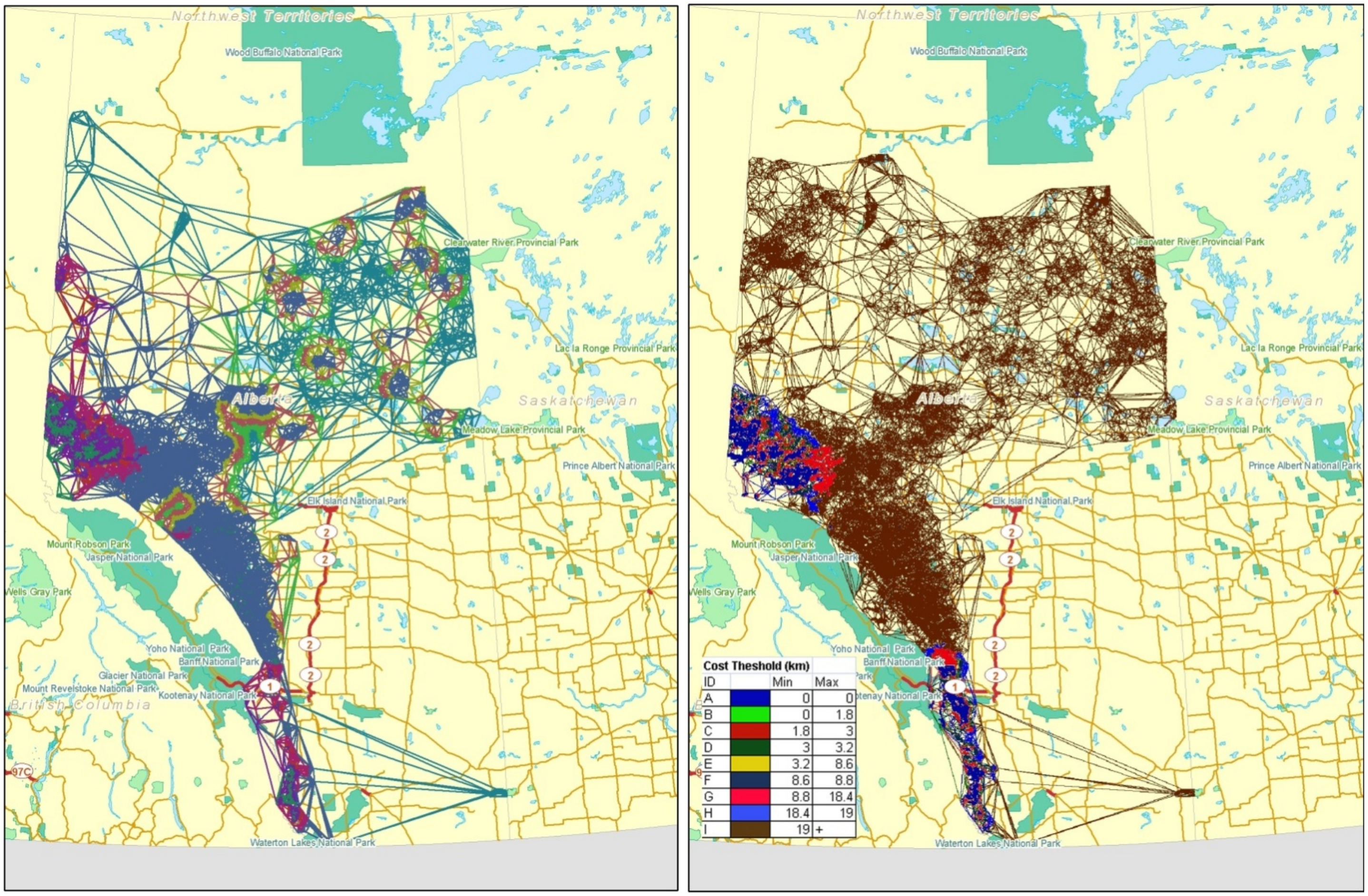

Figure 16. Connectivity models for 2008–09 (left) and 2009–10 (right).

5. Conclusions

A minimum planar graph for the whole of the Alberta pine forest landscape was generated, based on the currently accepted susceptibility index formula (Shore and Safranyik 1992). The 2009–10 model was run using new parameters based on a detailed data exploration (Section 2). The following conclusions follow from this work:

- We are moving in the correct direction for climate change modelling. Removing climatic limitations from susceptibility ratings reflects observed beetle activity far more accurately than using susceptibility ratings which incorporate current climate estimates.
- It appears that tree species differences are significant and will incorporate biological field data as it becomes available to support further model parameterization and spatial bounding.

There are several ways to improve connectivity analysis and risk assessment using this model. Future work will include:

- using new MPB survey data to further refine the connectivity model;
- incorporating appropriate observations on MPB attack dynamics in jack pine and hybrids to refine stand susceptibility index estimates;
- exploring the impacts of prevailing wind during MPB dispersal events to refine the connectivity model; and
- looking at the whole graph using updated forest and beetle inventory, and bring the Saskatchewan landscape back into our model.

6. Acknowledgements

This project was partially funded by the Government of Canada through the department of Natural Resources Canada, Canadian Forest Service. Publication does not necessarily signify that the contents of this report reflect the views or policies of Natural Resources Canada, Canadian Forest Service.

We thank Alberta Sustainable Forest Development for collaboration and data, in particular Bev Wilson, Dan Lux, Aaron McGill, and Karl Peck. We also thank Saskatchewan Environment, in particular Rory McIntosh.

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