

Characterization of the Jack Pine Forests of Western Canada for Susceptibility to Infestation by the Mountain Pine Beetle

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Abstract

The main goal of this project was to assess provincial scale patterns and connectivity of mountain pine beetle (MPB)-susceptible stands across Alberta and Saskatchewan using graph-based connectivity methods. The approach applies spatial graphs to assess connectivity between high susceptibility stands, as well as proximity across space to known infestations.

In areas with new or no current MPB attack, especially in areas within the expanding range, there is relatively high uncertainty of how the MPB may spread, such as in central-western Alberta. We developed graph-based connectivity methods to assess the spatial pattern of high susceptibility hosts across broad regions, under historic, existing or future climates. This information is aimed to help prioritize and rank stands for treatment in areas at risk of imminent or future infestation, and to identify areas for which treatment has no benefit.

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

Résumé

L'objectif principal du projet était d'évaluer les modèles à l'échelle provinciale et la connectivité des peuplements sensibles aux attaques du dendroctone du pin ponderosa (DPP) à la grandeur de l'Alberta et de la Saskatchewan à l'aide de méthodes de connectivité fondées sur les graphiques. L'approche a recours aux graphiques spatiaux pour évaluer la connectivité entre les peuplements très vulnérables, de même que la proximité aux zones d'infestation connues.

Dans les régions où le DPP n'est pas présent actuellement, surtout dans les régions où le taux d'infestation augmente, comme le centre-ouest de l'Alberta, nous ne savons pas comment le DPP pourrait se répandre. Nous avons élaboré des méthodes de connectivité fondées sur les graphiques pour évaluer la répartition spatiale des hôtes très vulnérables dans les régions élargies, compte tenu du climat passé, actuel et futur. Ces données nous seront utiles pour classer par ordre de priorité les peuplements à traiter dans les régions à risque, dans l'immédiat ou à l'avenir, et déterminer les régions pour lesquelles le traitement ne sera d'aucun avantage.

Mot clés: dendroctone du pin ponderosa, *Dendroctonus ponderosae*, pin gris, pin tordu latifolié, forêt boréale de l'ouest, Alberta, Saskatchewan, évaluation des risques

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1 Introduction

The mountain pine beetle (*Dendroctonus ponderosae*; MPB) is causing devastating losses to the forest resources of British Columbia and is spreading into Alberta. There are concerns regarding the potential of spread across the boreal forest. Management strategies directed at minimizing losses to mature pine stands include reducing beetle populations by direct control methods (harvesting, single tree treatments) or preventative management. Direct control actions are usually reactive management decisions made during beetle epidemics whereas preventative management actions are proactive decisions made to reduce landscape level susceptibility to the mountain pine beetle.

Due to the size of the managed area and the scarcity of resources, tools are required to assist managers in prioritizing areas for treatment and for assessing landscape scale risk of attack. The Canadian Forest Service has developed a number of stand-level tools for this purpose. The Stand Susceptibility and Risk Rating System (Shore and Safranyik 1992, Shore et al. 2000) is used widely to identify the relative potential for, and likelihood of, loss of stand basal area to MPB. Two stand level population dynamics models have been developed: a very detailed, process-based model (Safranyik et al. 1999) and a less detailed, more management-oriented model called MPBSim (Riel et al. 2004).

To provide decision support at the landscape scale, we developed an approach using SELES (Spatially Explicit Landscape Event Simulator; (Fall and Fall 2001)) to extend MPBSim to the landscape level in a spatial modelling environment in which we could disperse beetles to surrounding areas using actual forest inventory and geospatial data. This model, called SELES-MPB, integrates MPB population dynamics with management scenarios that can be used to address a number of questions regarding management strategy and potential impacts. A number of studies have been conducted using SELES-MPB, including the Kamloops Forest District, Lakes Timber Supply Area, the Lignum IFPA, Morice Timber Supply Area, Foothills Model Forest and Dawson Creek Timber Supply Area (Fall et al. 2001, 2002, 2003a, 2003b, 2004, 2006). At very broad scale, however, population methods are not feasible.

Connectivity analysis provides one means of assessing potential spread of MPB across a very broad area of the western boreal forest of Alberta and Saskatchewan. The focus of this project is such an analysis, extending previously developed methods to support analysis of a provincial-scale study area.

This project adapted and applied methods from graph-based connectivity analysis for examining spatial patterns of susceptible hosts and potential spread of MPB across Alberta and Saskatchewan, and in particular to examine likely pathways of spread into jack pine (*Pinus banksiana*) stands that start in central Alberta.

2 Methods

2.1 Study Area and Data

The study area consists of the entire provinces of Alberta and Saskatchewan, excluding a small area at the extreme north. Data on stand scale susceptibility (SSI) was provided in polygon format by Alberta Sustainable Resource Development and Saskatchewan Environment. This information was collated and raster grids were produced at 1 ha/cell (100 m x 100 m) resolution. In order to process such a large area at this relatively fine resolution, we divided the study area into 10 overlapping sub-rectangles (Figure 1), or “boxes”, with five covering each province.

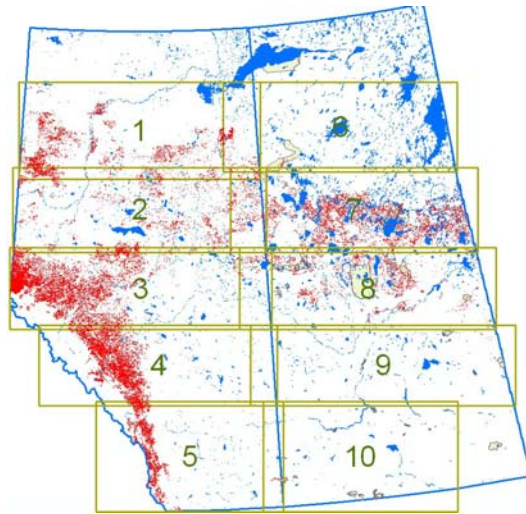


Figure 1. Study area and sub-area rectangles.

The susceptibility data was used to create the two required inputs to the connectivity analysis: definition of base patches, and movement cost surface. The patches are defined as “areas of high susceptibility”. As a base, we used an SSI threshold of 30, with a minimum patch size of 10 ha. Sensitivity analysis varies the SSI threshold by ± 10 . At the default threshold there are approximately 14,700 patches covering an area of about 989,000 ha.

Methods to rigorously quantify cost surfaces for spatial graph connectivity analysis require data unavailable for MPB (O’Brien et al. 2006). One must be clear on the interpretation of the cost surface. In this case, we define cost to refer to the multi-year potential of an area to support spread of MPB infestation. Cost in this context does not refer to ease or speed of movement of an individual, since an individual beetle may actually move across non-forested areas very quickly in long-distance dispersal. Instead, as areas with higher susceptibility have higher productive capacity for MPB populations, we posit the cost varies inversely with susceptibility. We also posit that cost varies directly with distance. As cost is a relative measure in spatial graph connectivity (O’Brien et al. 2006), we set a cost of 1 in the base patches. That is, in higher

susceptibility patches, cost will increase linearly with distance. That is, connectivity is assumed to decrease 1:1 with distance.

We applied the function in Figure 2, in which cost is 1 for stands with susceptibility > 30, and increases linearly from 10 down to 0 as susceptibility decreases down to 0. Non-forested stands have susceptibility of 0, as we have no information on which to distinguish different non-forest cover types or stands with no pine.

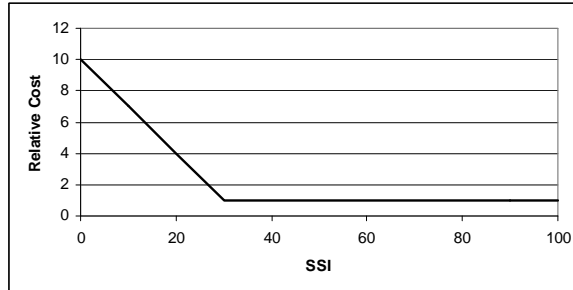


Figure 2. Default cost function used in connectivity analysis

2.2 Connectivity methods to explore broad-scale risk of MPB attack

We adapted connectivity methods using spatial graphs that were developed for assessing woodland caribou habitat in boreal forests (Fall et al. 2007, O'Brien et al. 2006) for examining patterns of MPB hosts. Connectivity is defined as the degree to which pattern impedes or facilitates movement (Taylor et al. 1993). Assessing connectivity of habitat for species of concern at the landscape scale is becoming a key tool for land-use planning and land management (Manseau et al. 2002). In the case of forest pests, the goal is to reduce connectivity, and hence landscape-scale susceptibility with the aim of slowing the rate of spread across a landscape. To do this requires methods to identify areas of high susceptibility that also have high connectivity with other susceptible patches, in particular patches with current MPB attack.

We define “high susceptibility patches” using an estimate of MPB susceptibility for the study landscape and select areas with susceptibility greater than a certain threshold (e.g., 30%) and larger than a minimum size (e.g., 10 ha). The size threshold should reflect the ecological behaviour of MPB and scale of management. To include a simple measure of cost to contrast with straight-line distance and to capture barriers and conduits to spread, we defined cost units as the relative likelihood and rate of spread compared to high susceptibility patches. For a base cost surface, we defined cost to be 1 for high susceptibility sites, and linearly increasing to a maximum cost (e.g., 10) elsewhere. This assumes that lower susceptibility sites will contribute less to the growth (both amount and conductance) of an outbreak proportional to the susceptibility index level. For example, the cost surface applied assumes that MPB will spread twice as effectively (either twice as fast or twice as many offspring) through 70% susceptible habitat than in 35% susceptible habitat.

The next step in the process is to identify the patches and extract a spatial graph. As in Keitt et al. (1997), we represent the configuration of susceptible habitat as a mathematical graph. Nodes in a graph consist of habitat patches, while links represent connections between patches. Links track the Euclidean distance or cumulative cost between the two incident nodes, the starting and ending

raster position of this vector, and the type of link (see below). A *planar* graph is a graph in which, when drawn on a piece of paper, no two links cross. We define the *minimum planar graph* (MPG) for a patch map as the graph consisting of all links e between nodes n_i and n_j with distance or cost d that satisfy the following:

There is at most one link between each pair of nodes.

Links may not cross any other intermediate patches.

There is no other pair of nodes n_k and n_l that are closer than d to each other with a link that crosses e .

There is no node n_k that is closer to the landscape boundary than d with a link that crosses e .

The MPG produces a triangulation of the patches with the exception of some patches near the landscape boundary. This triangulation is a generalization of the Delaunay triangulation (Okabe et al. 2000), but has some unique characteristics. Rather than treating patch nodes as points in Euclidean space, the derivation of the MPG explicitly accounts for patch shape. As a result, the links are not necessarily the shortest Euclidean distance links between nodes, as illustrated in the figure below. The graph on the left-hand side shows a patch configuration. Nodes 3 and 4 are closer than 1 and 2, precluding the link connecting nodes 1 and 2 between points c and d. However, nodes 1 and 2 can have a link between points a and b. The graph on the right-hand side shows the corresponding mathematical graph with nodes as points, which clearly illustrates the triangulation.

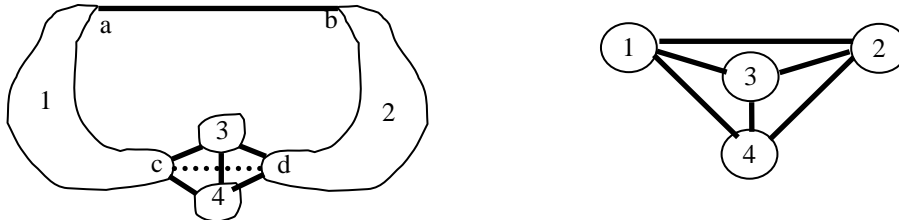


Figure 3. Example minimum planar graph and the underlying Delaunay triangulation.

This effect is more likely to occur when applying a cost surface, as illustrated in Figure 4, which shows how the shortest link in Euclidean space may not be the least-cost link.

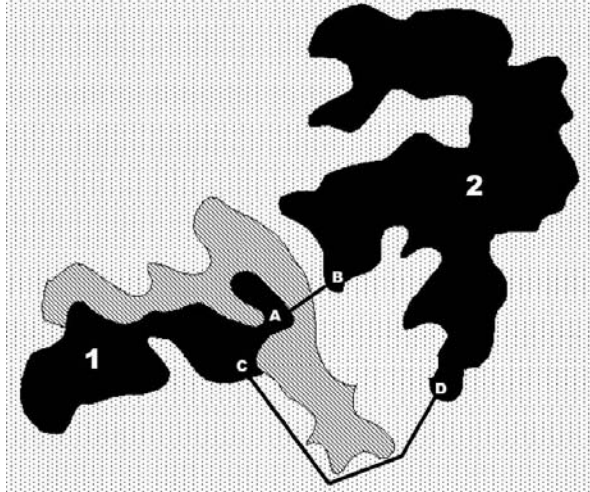


Figure 4. Illustration of the difference between straight-line and least-cost paths linking habitat patches. High quality habitat patches 1 and 2 (black) are connected by a straight-line path (AB) and a least-cost path (CD). The gray area represents relatively high cost.

The minimum planar graph has some useful properties. Both the *nearest neighbour* and *minimum spanning tree* graphs are sub-graphs of the MPG. A nearest neighbour for a node n_i is simply the closest node n_j . The nearest neighbour graph (NNG) contains the set of links between two nodes n_i and n_j , such that n_i is the nearest neighbour of n_j and/or vice versa. The nearest neighbour sub-graph may consist of more than one connected component, but each node has at least one link.

A mathematical *tree* is a graph in which all nodes are connected in a single component and there are no loops. The minimum spanning tree (MST) is the tree for which the sum of all link distances is minimized. The MST consists of all nearest neighbour links plus those links needed to create a single connected component. A link between nodes n_i and n_j with distance d is in the MST if there is no path (sequence of links) from n_i to n_j for which all links have distances less than d . The MPG adds further links to the MST to link all nodes that are closest without violating planarity of the graph.

The next step is to analyze the minimum planar graph using the methods of Keitt et al. (1997). We performed a multi-scale analysis over a range of distance thresholds (e.g., from 0 km to 14 km in 100 m increments). At each threshold k we removed all links from MPG that have distances greater than k . We determined the connected components in the resulting graph G' and computed some component level and graph level metrics. At the component level, we determined the number of patches, and the cluster size. At the graph level, we determined the number of clusters and the *expected cluster size* (ECS), which is defined as the sum of the square of cluster size divided by the total amount of habitat (i.e., the area-weighted mean patch size, or expected size of cluster containing a randomly selected hectare of habitat). The ECS is a more appropriate metric for connectivity analysis than mean cluster size, since it focuses on hectares of habitat as the unit rather than patches (e.g., a small cluster should not have the same contribution to the resulting metric as a large cluster). See Fall et al. (2007) for more details.

We explored connectivity with and without reference to current infestation. To account for connectivity with existing attack, we developed methods for “re-orienting” a spatial graph from the perspective of currently infested patches. After extracting the MPG from the high susceptibility host patches, we *inoculated* patches that contained existing attack by starting an analysis model in such patches and then spreading outward to other patches to identify the

shortest distance or cost through the graph to each node and link. This re-oriented graph can be used for further analysis, such as to identify distance/cost intervals over which connectivity to existing attack is increasing faster or slower.

2.2.1 Previous Application: Mountain Pine Beetle Host Connectivity Analysis in Dawson Creek and Central-Western Alberta

The connectivity approach applied in the Nadina Forest District helped identify aspects of spatial graph analysis that were useful for MPB risk assessment and elements that required further research. In particular, we learned that these methods are more appropriate in areas with newly emerging attack, such as in Dawson Creek and western Alberta, or with risk of future attack. Areas with existing attack are best assessed with more dynamic methods, such as the SELES-MPB landscape-scale population model. We also learned that the base methods for examining overall connectivity of hosts were unable to fully capture risk of spread. To address this deficiency, we developed methods to reorient a spatial graph of MPB host patterns with spatial information on existing attack, as described above.

We applied this approach to a large study area that included the Dawson Creek area in BC, and Jasper National Park, Wilmore Wilderness and a number of forest management units from the BC border to Slave Lake north of Edmonton in Alberta. We found that, using the default parameters, connectivity of susceptible host stands (stands with susceptibility ≥ 65) to current attack increased rapidly up to 65 km effective distance, between about 150 to 250 km effective distance, and between about 350 to 440 km effective distance (Figure 5). Between these ranges, connectivity increased relatively slowly. The plot in Figure 5 helps to identify these threshold ranges, but a key strength of this approach is the ability to map these thresholds spatially to show areas of higher and lower connectivity (Figure 6). Areas with relatively low connectivity represent areas in which MPB may spread more slowly, and management focus may be warranted to treat stands to reduce connectivity further. Areas with relatively high connectivity represent higher risk, and likely lower management utility if MPB become established.

Several presentations have been made on the methods and results of this analysis, with feedback helping to refine the approach and improve utility of results. Discussions with forest managers indicated that this information was useful to help prioritize areas for treatment. For example, a stand with moderate susceptibility but in a well-connected location may be more important to treat than a stand with high susceptibility, but poorly connected to other host stands. A publication on these methods is underway that uses MPB survey information from 2006 for model verification.

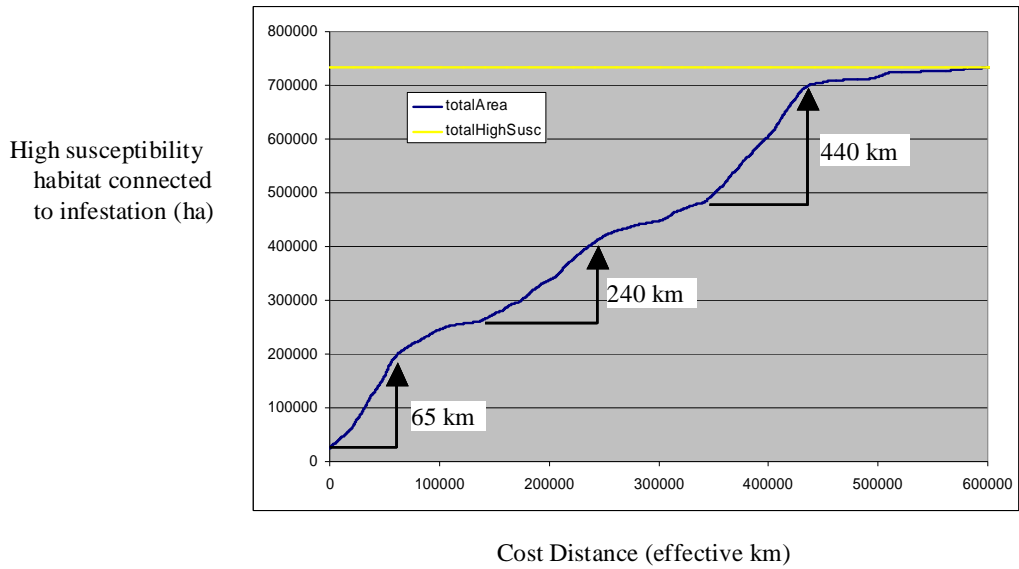


Figure 5. Results of the spatial graph thresholding analysis in the Dawson Creek/west-central Alberta study area. The x-axis is the distance (in cost units, or effective distance in km) to existing attack above which stands are assumed to be disconnected. The y-axis is the area of high susceptible stands connected to existing attack at a given cost threshold. Arrows indicate scales over which there are rapid increases in connectivity to existing attack.

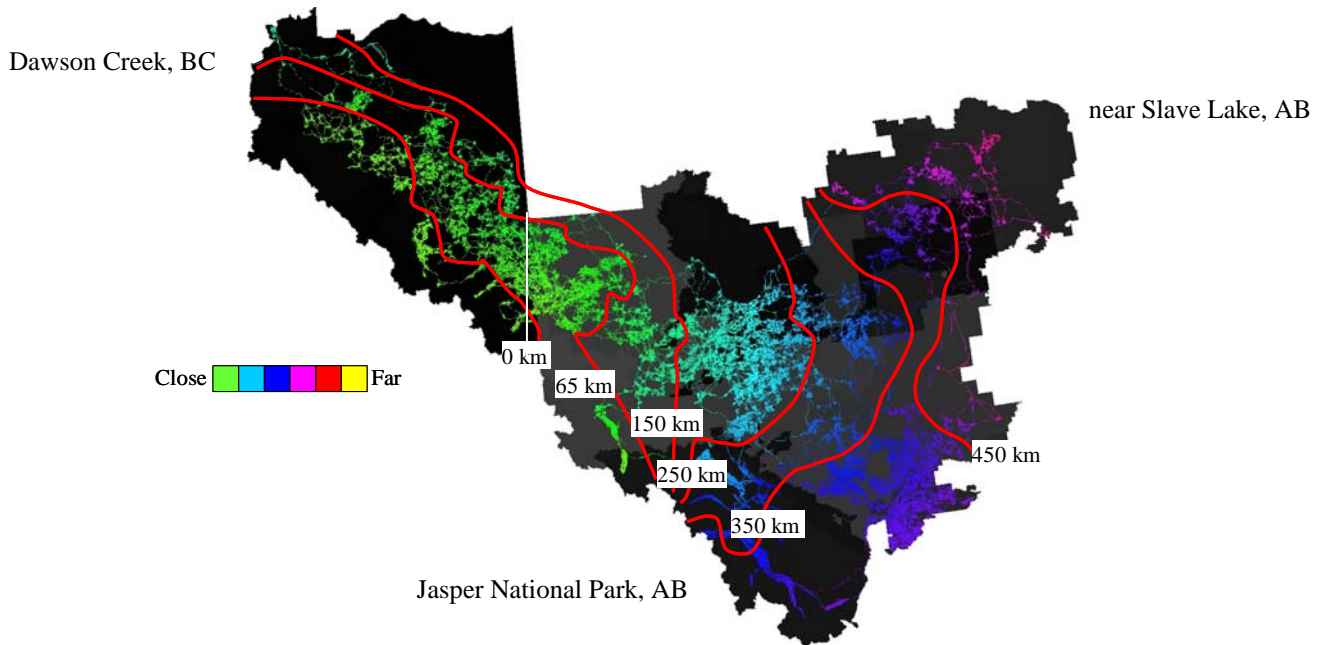


Figure 6. Host connectivity to existing attack in Dawson Creek/west-central Alberta study area. The colours on host stands represent degree of connectivity. The isolines partition host stands based on the thresholding analysis that was used to identify threshold distances with relatively high or low increased in connectivity to existing attack (Figure 5).

2.3 Extending connectivity methods to handle very large data sets

The size of the study area and the goal of processing this at relatively fine resolution (1 ha/cell) creates a computational challenge. It is not possible to load multiple rasters of the entire study area within the memory limits of a 32-bit operating system. Hence we divided the study area into 10 boxes (Figure 1). Extracting and analyzing graphs from individual boxes is possible using “standard” spatial graph methods (e.g., as in Fall et al. 2007). However, to examine connectivity over the entire study area first requires merging these graphs, which required development of new methods for very large data sets. We call the merged graph a “meta-graph” since it retains the essential information in the base spatial graphs and can be used to translate information back to the base graphs, but the meta-graph can be examined non-spatially (more like a standard mathematical graph).

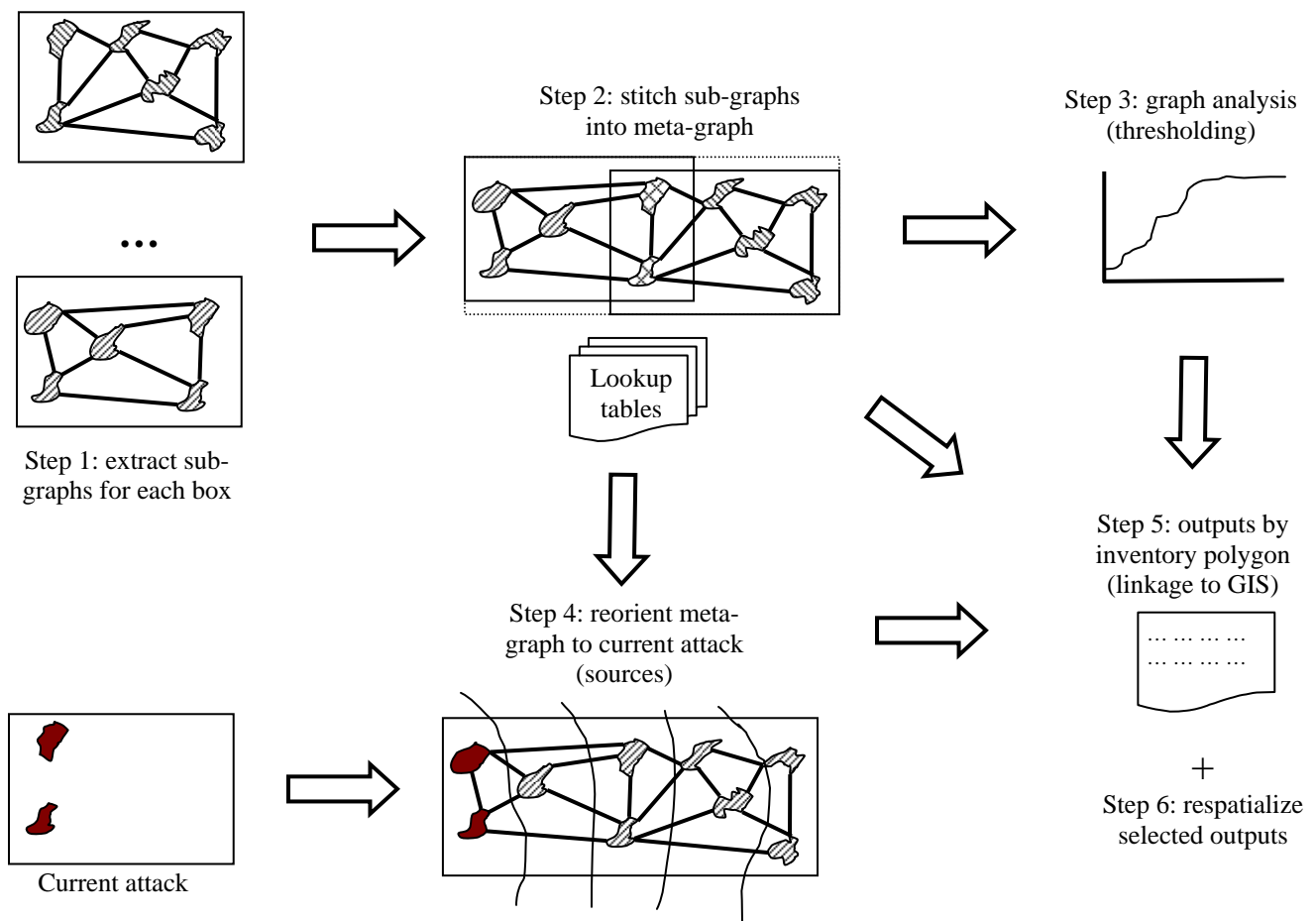


Figure 7. Overall methodology for connectivity analysis of MPB host and attack patterns at a fine resolution and across a very large extent.

Our multi-step methodology is illustrated in Figure 7 and described in the following sub-sections. There are five broad steps (some of which involve several smaller tasks). In general, a very large study area is divided into smaller pieces for which spatial analysis is manageable (in this case 10 boxes). Spatial graphs are extracted on each sub-area (step 1), and then merged, or stitched, into a whole meta-graph (that is now non-spatial; step 2). The meta-graph can be analyzed using standard landscape graph techniques. The stitching is done in such a way that it is straightforward to link back to the underlying base sub-graphs. Threshold analysis (step 3) is used to identify “critical thresholds” or distances/costs at which there are large increases in connectivity in host patches, which in turn indicates key distances/costs at which the landscape pattern coalesces. These critical thresholds can be compared with scales based on management and MPB ecology. Given spatial information on current attack, a spatial graph can be *reoriented* relative to patches with attack (source patches) to identify distances/costs at which patches connect with existing attack (step 4). To assist with planning, results are then mapped (via the spatial lookup tables) to inventory polygon identifiers, which can then be reloaded into a GIS system (step 5). In addition, some results can be re-spatialized for reporting and visualization (step 6).

2.3.1 Extract spatial graphs from each box

The first step is to extract the minimum planar graph for each of the 10 boxes. Each resulting spatial graph is defined by two rasters (patch id and link id) and two tables (patch information and link information, indexed by id). Base graphs must be extracted for each variation of assumptions (e.g., changes cost surface or high-susceptibility patch definition).

2.3.2 Prepare base graphs for non-spatial analysis

The standard spatial graph output must be revised to allow it to be used in a meta-graph. In particular, spatial location information (e.g., location of end nodes of links) has no meaning in a meta-graph. To traverse a meta-graph requires computing the distances between the end nodes to two links incident on a patch. To handle this in a standard spatial graph is straight-forward, simply using a distance function between the locations of the two end nodes. To compute this in a meta-graph, we add to each link end node that row and column offset to the centroid of the patch. Given this, the distance between two end nodes can be computed using Pythagoras’ formula. That is, the number of rows and columns between the end nodes, dy and dx , can be obtained by subtracting the row and column offsets. Then distance is computed as $(dx^2 + dy^2)^{0.5}$.

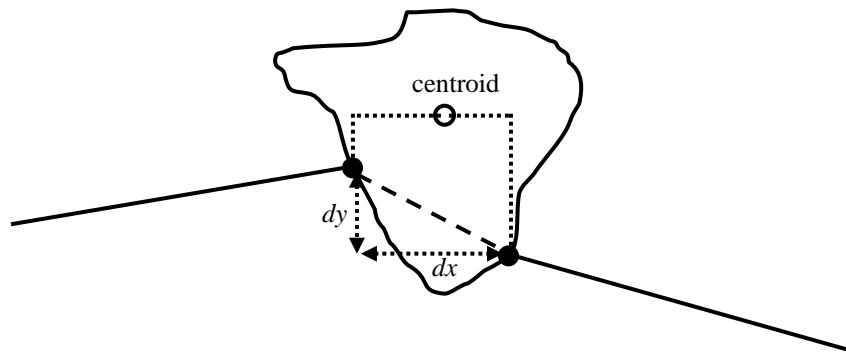


Figure 8. Computing distance between two link end-nodes using Pythagoras' formula and offsets from each end node to the patch centroid.

2.3.3 Spatially merge overlapping pairs of boxes (*graph stitching*)

The boxes were created explicitly with enough overlap to ensure that adjacent pairs can be matched through shared patches. Additionally, care was taken with the georeferencing to be sure that the patch pattern within the overlap areas matched (although some patches may be cut off in one or both boxes). Graphs can be merged, or stitched, to create a graph equivalent to one that would have been produced for the combined area, if the overlap area contains a common set of links across the overlap region. Technically, this means for each subgraph, the overlap area contains a path from a patch at one side of the overlap region to a patch at the other side.

A model was designed and implemented to spatially merge two graphs that overlap (Figure 9). First, the smallest encompassing rectangle is identified, and the patch and link id layers from both graphs are aligned within. Then a correspondence between patches within the overlap area is made. A new spatial graph is created with the union of the two patch sets and the two link sets. Output consists of (a) the merged spatial graph and (b) lookup tables to allow transformation to and from patch id's in the base graphs, and the merged patch id's.

Again, due to the size of the study area, it is not possible to simply merge graphs from all boxes into a single whole. Instead, spatial merging is done on each pair of overlapping graphs to produce the "transformation look-up tables". For the 10 boxes there are 21 overlapping pairs north-to-south, west-to-east, west-to-northeast and west-to-southeast.

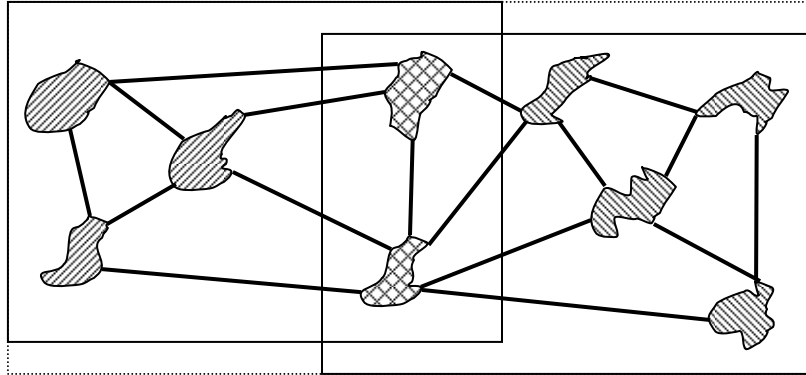


Figure 9. Spatial merging of two overlapping spatial graphs.

2.3.4 Non-spatially merge graphs into a single meta-graph (*meta-graph stitching*)

The spatial graph patch and link tables for each box can be cross-referenced via the transformation lookup tables produced via spatial stitching. Memory is not an issue for the entire study area, as long as no grids are required. Hence, a non-spatial merging model was designed and implemented to load just the non-spatial aspects of two overlapping graphs, as well as the corresponding transformation lookup tables, to merge the results into a single graph, and to output the results.

Using this model, overlapping pairs of graphs can be incrementally merged to produce a single graph for the entire study area. Starting with the graph for box 1, we incrementally merge the graph for box 2, then the graph for box 3, etc. The resulting graph is perhaps best considered as a “semi-spatial” graph, since some of the spatial information is not retained. However, it retains sufficient information for analysis, and transformation lookup tables are created to allow simple cross-referencing with the base spatial graphs.

2.3.5 Identify “source” (current attack) patches

Patches in the spatial base graphs as well as the meta-graph can be associated with current attack using infestation mapping. This step simply produces a table indexed by patch id to indicate which patches have attack within.

2.3.6 Analyze connectivity of meta-graph

The spatial graph connectivity analysis models were adapted for semi-spatial graphs. These were adapted to produce multi-scale connectivity metrics for a meta-graph, since the spatial patch id and link id information is not required for these assessments. Spatial outputs from the “standard” spatial graph analysis models were removed. The overall non-spatial results are the same as for a fully spatial graph. This step can be used to identify “critical thresholds” (Fall et al. 2007, Urban and Keitt 2001), distances or costs with large increases in inter-patch connectivity. This step is

the final step for non-spatial assessment of a spatial graph. Graphs can be assessed independent of source attack, or within the context of existing attack.

2.3.7 Reorient meta-graph in terms of source patches

Current infestation data (e.g., from overview flights) can be used to identify patches that contain current attack. Starting from these “source patches”, a spatial graph can be reoriented from the perspective of this attack. That is, the distance or cost through a graph from attack to each patch can be computed via diffusion (spread) from the source patches along links, counting up the link lengths/costs as well as distances through patches between link end points (Figure 8). For a meta-graph, the diffusion models needed to be modified to operate in a non-spatial context. The information compute a priori for the spatial sub-graphs can be used to allow diffusion through a graph without the need to explicitly represent space. A reoriented graph can be used to produce distance or cost isolines from existing attack (e.g., Figure 6).

2.3.8 Scale results back to base boxes for spatial outputs

To produce spatial outputs (e.g., maps and visualizations), the transformation tables can be used to scale results back to the 10 base boxes. Now each box will have information from the overall graph, which can be used to produce the spatial outputs that the spatial graph analysis methods can produce for single graphs in smaller study areas. This can be used either to export to a GIS for cartographic mapping, or to produce images and visualizations within SELES.

2.4 Polygon linkage: producing non-spatial outputs for each polygon

The first task in this step is to identify a correspondence from polygons to patches. This is not as trivial as it might seem. First, inventory stand polygons are identified using two numbers: base inventory and polygon number within base inventory. Second, given that polygons are delineated using a variety of factors, a single “high susceptibility patch” may consist of multiple polygons. For example, two adjacent stands may be different ages (and so have different polygon identifiers), but may both be relatively old, and so both be classified as high susceptibility.

As part of the analysis step, a table is loaded that allows a lookup from underlying inventory map / polygon information to patch id. This is used to produce an output table that contains patch-scale connectivity information that can be linked with inventory GIS databases for planning.

The table produced in this step has the following attributes:

MgmtUnit: Inventory identifier (usual tied to underlying management unit)

PolygonNum: polygon number within management unit inventory

PatchId: patch identifier assigned in connectivity analysis

Dist2ClosestMPBkm: distance through spatial graph to closest mapped attack

Cost2ClosestMPB: cost (effective distance) to closest mapped attack

aCluster1: size (hectares) of cluster to which polygon is joined at a 400 m distance threshold

aCluster1_cost: size (hectares) of cluster to which polygon is joined at a 400 cost units threshold

aCluster2: size (hectares) of cluster to which polygon is joined at a 1000 m distance threshold

aCluster2_cost: size (hectares) of cluster to which polygon is joined at a 1000 cost units threshold

aCluster3: size (hectares) of cluster to which polygon is joined at a 2000 m distance threshold

aCluster3_cost: size (hectares) of cluster to which polygon is joined at a 2000 cost units threshold

pECS_Cluster1: ratio of aCluster1 to expected cluster size at a 400 m distance threshold

pECS_Cluster1_cost: ratio of aCluster1_cost to expected cluster size at a 400 cost units threshold

pECS_Cluster2: ratio of aCluster2 to expected cluster size at a 1000 m distance threshold

pECS_Cluster2_cost: ratio of aCluster2_cost to expected cluster size at a 1000 cost units threshold

pECS_Cluster3: ratio of aCluster3 to expected cluster size at a 2000 m distance threshold

pECS_Cluster3_cost: ratio of aCluster3_cost to expected cluster size at a 2000 cost units threshold

The distance and cost of the polygon to the nearest attack indicates proximity to existing known infestation. The cluster size metrics (e.g., aCluster1) indicates the degree to which this polygon is connected to other high-susceptibility hosts at various scales.

The ECS ratios (e.g., pECS_Cluster1) indicate the relative size of the connected cluster to which this polygon is joined at different thresholds. A value greater than 1 means that this connected cluster is larger than the expected size of cluster for a randomly selected hectare (i.e., well-connected), while a value less than 1 indicates a relatively poorly connected cluster.

3 Results

3.1 Base Analysis

The base analysis defined “high susceptibility patches” as areas with a susceptibility rating of at least 30. This level was chosen to identify areas that have a potential to support and grow beetle populations. We used a size threshold of 10 ha. We include in the base analysis a graph based on a Euclidean distance, as well as a graph based on the default cost function (i.e., a cost of 1 for areas with susceptibility of 30 or more, increasing linearly to a cost of 10 for areas with susceptibility of 0).

3.1.1 Extract spatial graphs from each box

The graphs for each of the 10 boxes and each scenario (Euclidean or cost surface) were extracted as stand-alone spatial graphs.

Figure 10 shows a portion of the graph from box 3 to illustrate the pattern in an area with a moderate to high degree of connectivity.

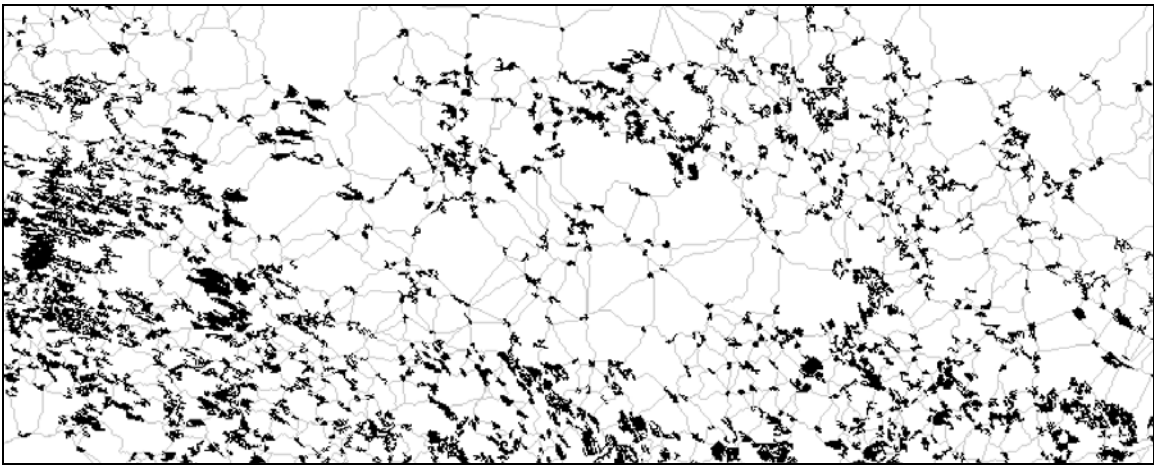


Figure 10. Portion of minimum planar graph from box 3, using base cost surface.

3.1.2 Spatially merge overlapping pairs of boxes (*graph stitching*)

For each overlapping pair of boxes (21 pairs for the 10 boxes of the study area), the spatial stitching creates complete spatial graphs (e.g., Figure 11). Each pair also created the cross-referencing lookup tables.

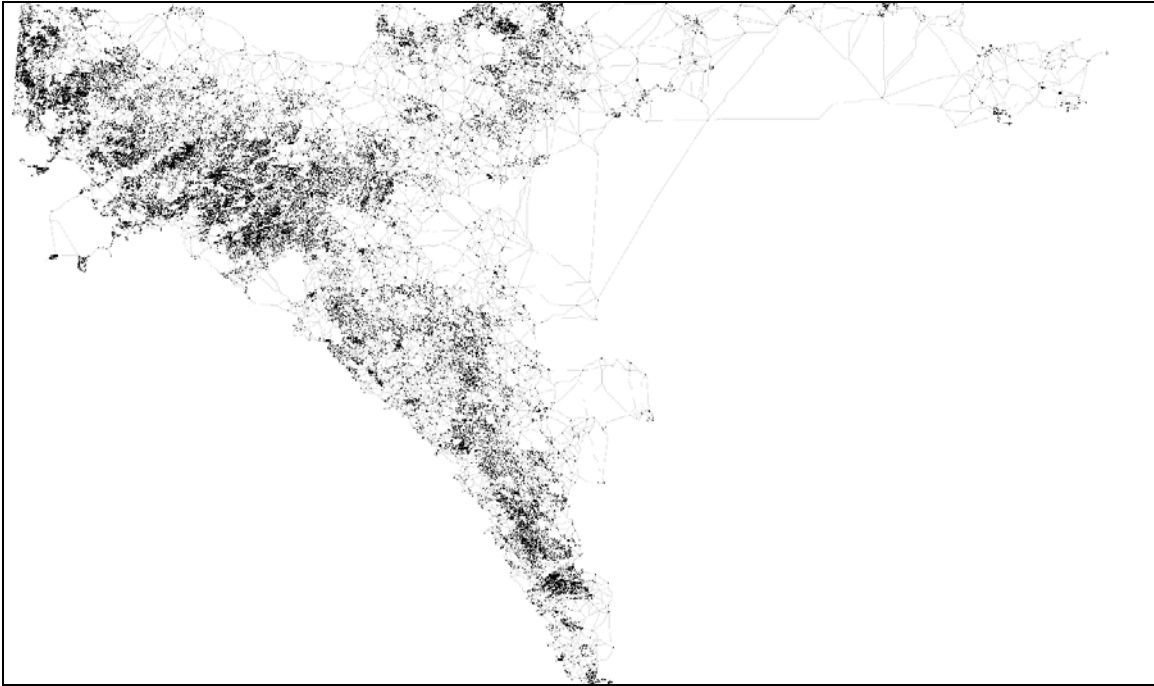


Figure 11. Stitched minimum planar graph from boxes 3 and 4, using base cost surface.

3.1.3 Non-spatially merge graphs into a single meta-graph (*meta-graph stitching*)

The resulting meta-graph using Euclidean distance and the base cost surface had 14,651 patches, consisting of an area of approximately 989,000 ha, as well as almost 50,000 links.

3.1.4 Analyze connectivity of meta-graph

We analyzed the Euclidean graph using 200 m threshold increments from 0 m to 200 km (Figure 12). Since expected cluster size is much closer to the maximum cluster size at each threshold than the mean cluster size, this suggests that habitat is skewed to having most habitat clustered in one area, and the rest more dispersed. Most dramatic increases occur within the first 13 km, with large steps up at ranges less than 2km, at 2.8 km, 10.8 km and 12.6 km (Figure 13).

When using the cost surface, habitat connects at higher thresholds (i.e., is interpreted as being less connected due to higher cost matrix areas), surpassing an expected cluster size of 600,000 ha at 12.8 effective km, compared with 2.8 km using Euclidean distance (Figure 14). Key thresholds are at 5.2 effective km, 10.8 effective km, 13 effective km (Figure 15), and 82.4 effective km (Figure 14).

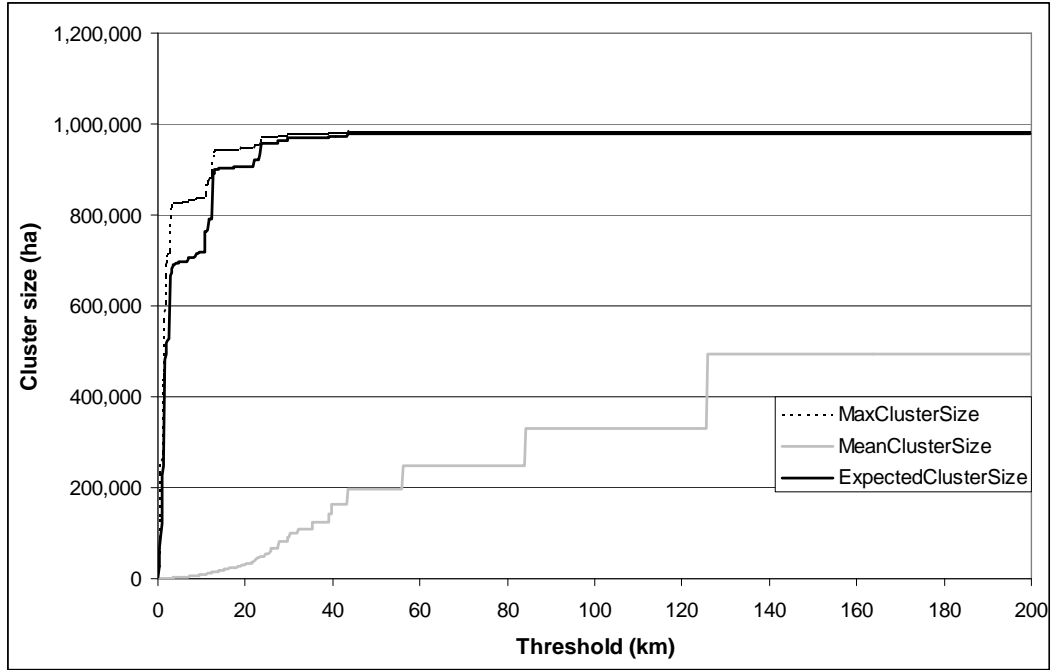


Figure 12. Overall results of meta-graph analysis using Euclidean distance.

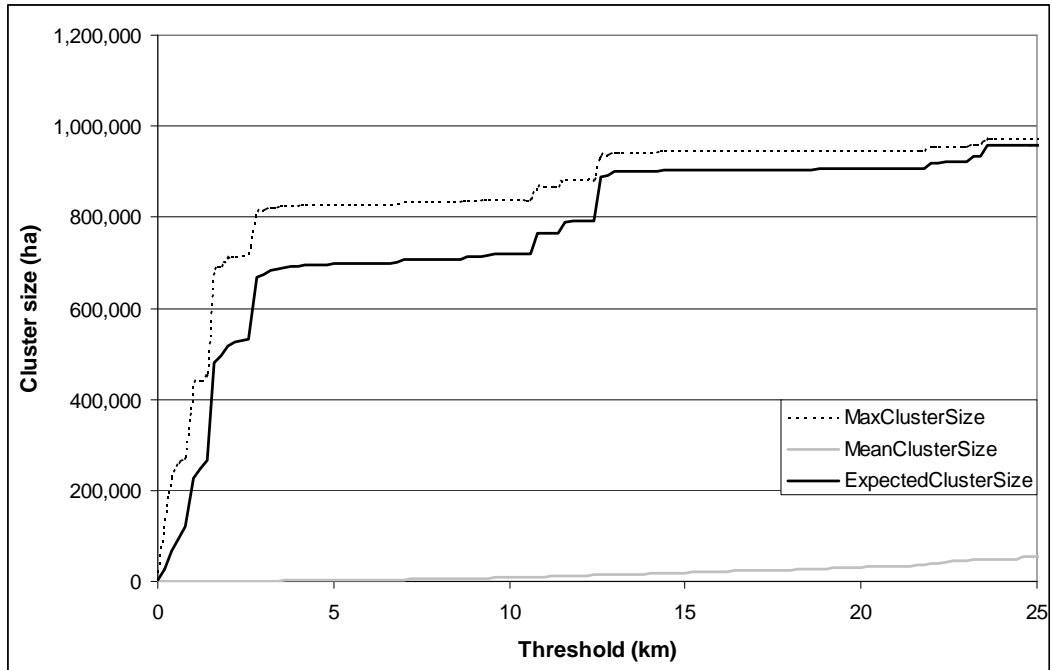


Figure 13. Results of meta-graph analysis using Euclidean distance over first 25 km of thresholds.

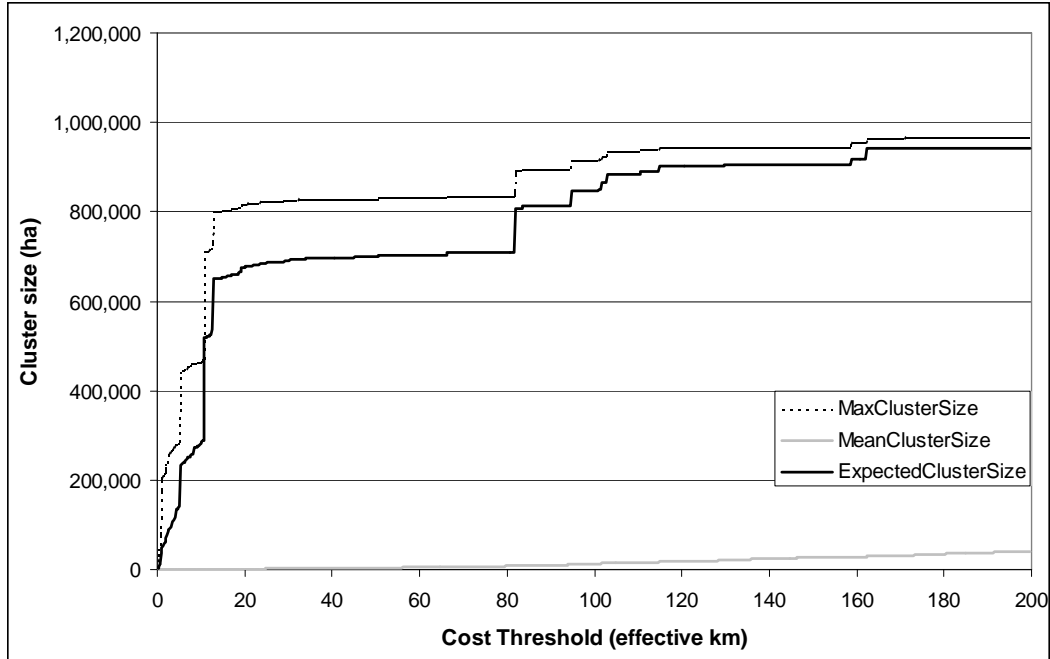


Figure 14. Overall results of meta-graph analysis using Cost distance.

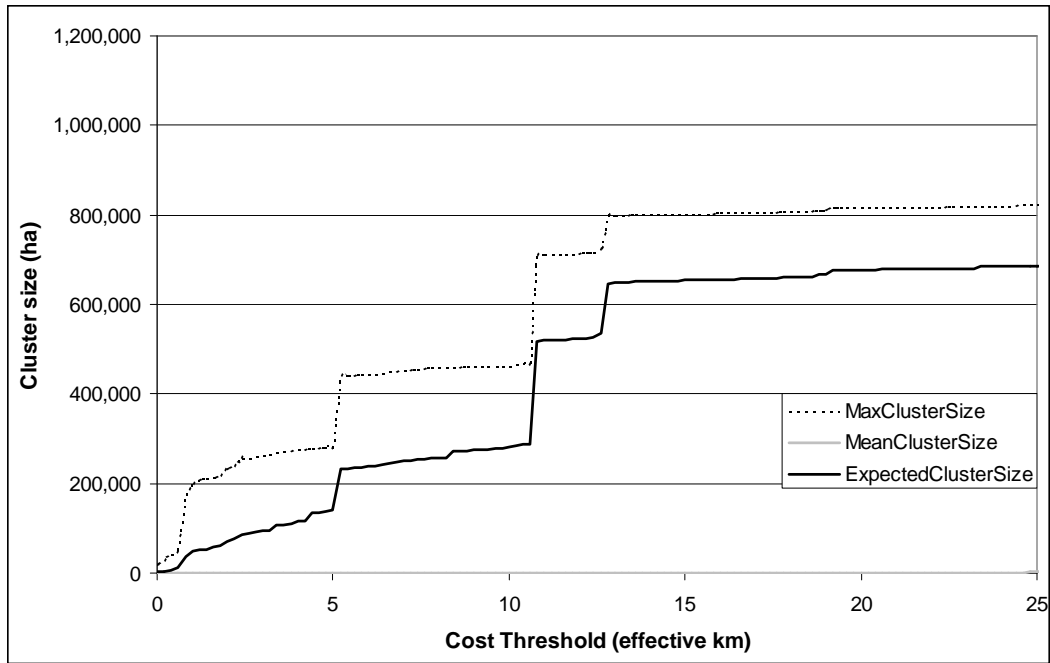


Figure 15. Results of meta-graph analysis using Cost distance over first 25 km of thresholds.

The above critical thresholds indicate scales at which relatively large increases in connectivity of susceptible hosts occur. The ability to map back to the base graphs is key to helping to understanding the spatial patterns and location of these increases. To produce a complete map

requires re-spatializing meta-graph results back to the base maps (boxes 1 to 10). Images and cartographic maps can then be made for individual boxes, or rasters can be imported into a GIS (e.g., ArcGIS) for producing a complete digital cartographic product.

The following figures show the meta-graph derived using the cost surface at three of the key thresholds for cost distances of 6 effective km, 11 effective km and 83 effective km. These figures illustrate the pattern of stands with a susceptible rating of at least 30 across this broad region. The first (Figure 16) shows how the central-western area becomes connected at a relatively low threshold. The second (Figure 17) indicates that many of the remaining habitat clusters join at a moderate threshold. The third (Figure 18) indicates the scale at which most of the habitat is connected in a single cluster.

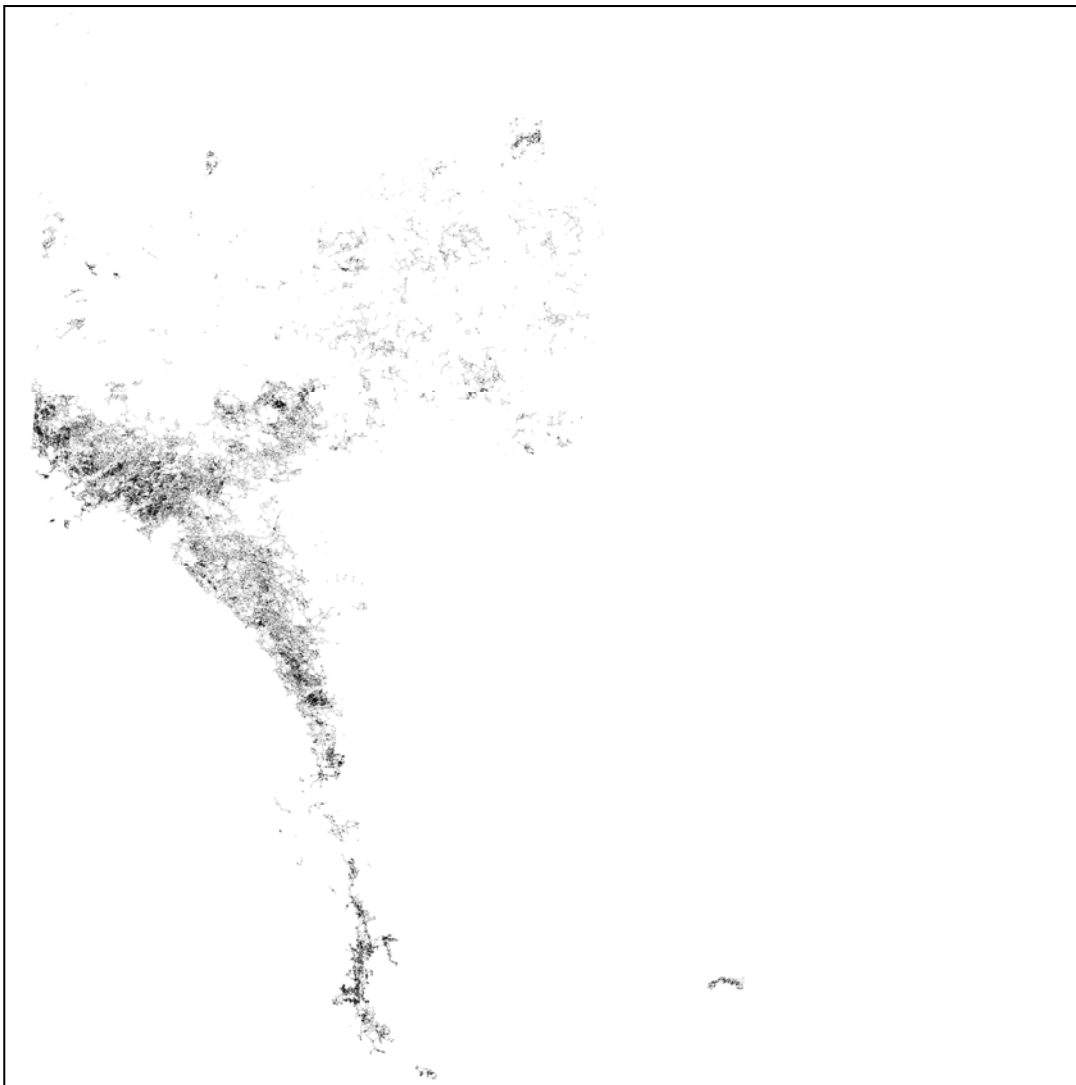


Figure 16. Patches with susceptibility of at least 30 and links with an effective distance of 6 km or less (cost distance).

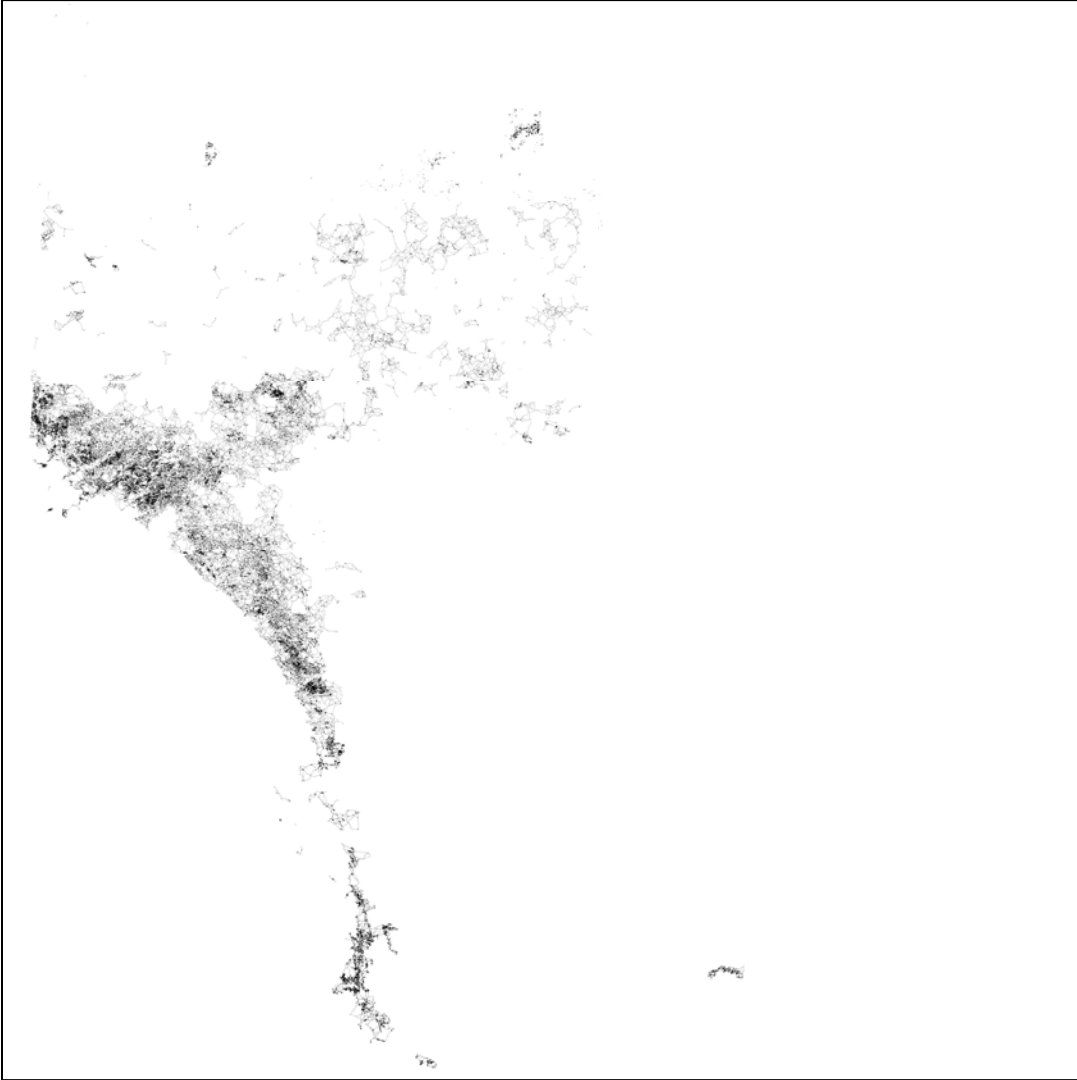


Figure 17. Patches with susceptibility of at least 30 and links with an effective distance of 11 km or less (cost distance).

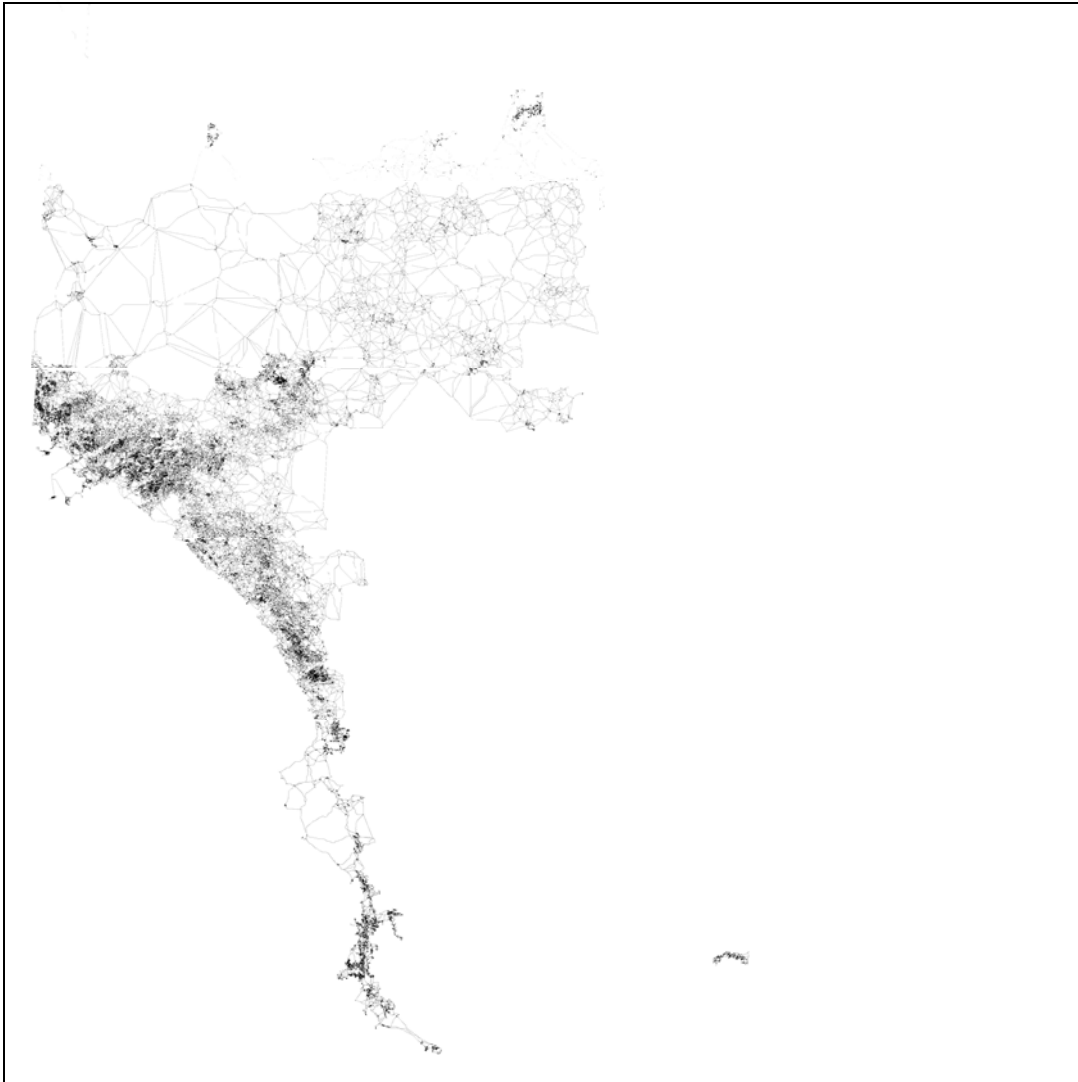


Figure 18. Patches with susceptibility of at least 30 and links with an effective distance of 83 km or less (cost distance).

3.1.5 Reorient meta-graph in terms of source patches

Reorienting the meta-graph from the perspective of the known attack shows a rapid increase in area close to known attack, decreasing with distance (Figure 19). This declining area with distance indicates that the attack is closest to the area with the most susceptible stands (or, that the area of susceptible stands decreases steadily as one moves away from the attack towards the east). This suggests that the areas in the west have a challenge to deal with attack in proximity to relatively high proportions of susceptible stands, but conversely, that areas further east than about 200 km from known attack have a combination of relatively low connection to attack and relatively low density of susceptible stands. The same general pattern holds when looking at cost (effective distance) from attacked stands (Figure 20).

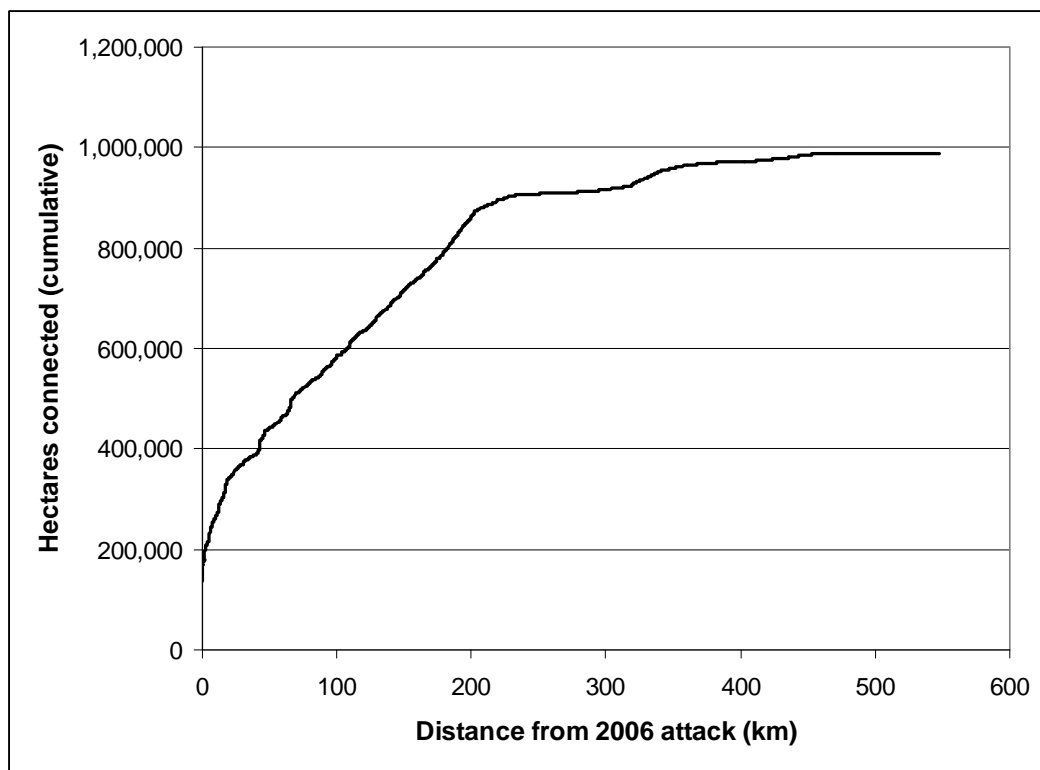


Figure 19. Cumulative area of high susceptible stands with distance from known attack (Euclidean distance).

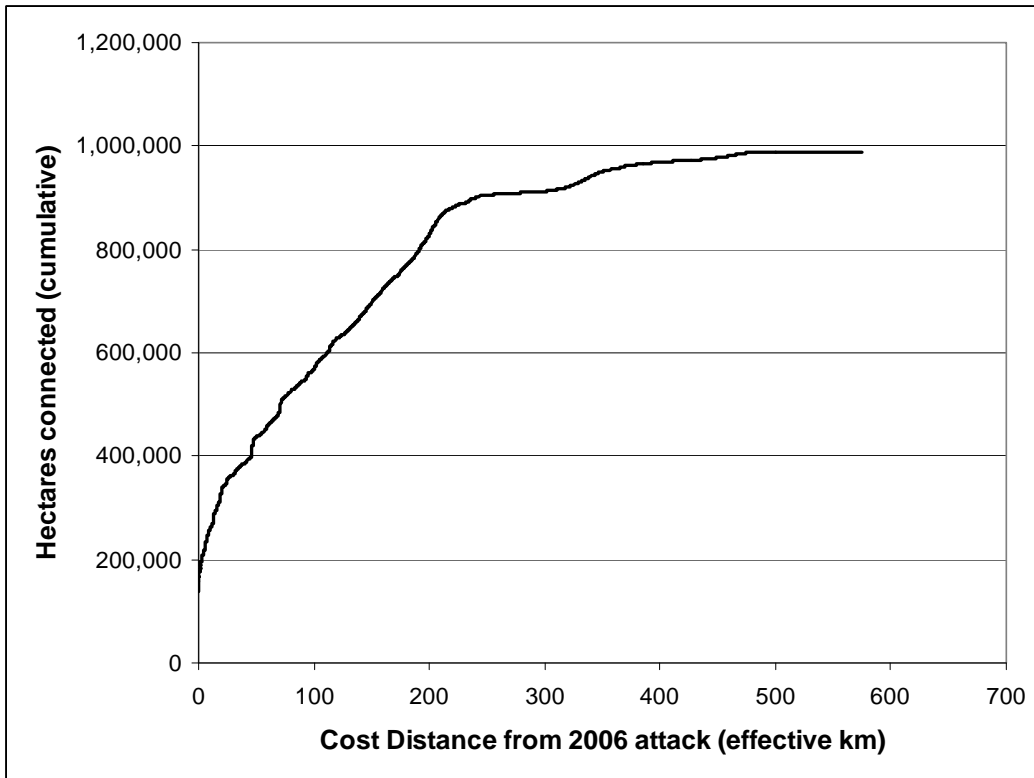


Figure 20. Cumulative area of high susceptible stands with distance from known attack (Cost distance).

3.1.6 Polygon linkage

Linkage of base results back to the ASRD polygons produced a file with the attributes described in section 2.4. This has been provided to ASRD for use in their forestry planning process.

4 Conclusion

This project aimed to assess the connectivity of pine stands with high MPB susceptibility to MPB across the broad geographic extent of Alberta and Saskatchewan, and at a relatively fine resolution of 1 ha / cell, using spatial graphs. This posed a number of technical and theoretical challenges, for which solutions were found via a multi-step spatial analysis process. A second goal was to provide information at the stand level on connectivity metrics relevant in forestry planning. This was done by linking information to GIS polygon identifiers and generating a table of connectivity metrics at the forest inventory polygon level.

Our analysis suggests that western Alberta, especially in the Foothills and Smoky areas (north and east of Jasper and Willmore Wilderness) are fairly well connected, and post a high landscape-scale risk of MPB. Abundance and connectivity of hosts decreases as one moves east across the boreal forest of Alberta and into Saskatchewan.

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