

Provincial Level Projection of the Current Mountain Pine Beetle Outbreak:

An

Overview of the Model (BCMPB) and Results

Appendix 3. Mountain Pine Beetle Projection

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1 Data Preparation Steps

1.1 Get age and percent pine from forest cover database

Spatial layers representing forest age in years and percentage of the volume of timber that is contributed by pine (of any species) were extracted from the provincial digital forest cover map, also known as the Land and Resource Data Warehouse (<http://srmgww.bcgov/bisd/imb/ds/projects/idw/index.html>). Only data available in the LRDW was used to parameterize the beetle model. There is no data in the LRDW for Tree Farm Licenses and some of the large old parks. Forest cover data are available for these areas, and was used when model projections were made, but the quality and currency of this data is not suitable for creating parameter estimates.

Forest age is available directly as a field in the LRDW database. The percentage of pine was determined by identifying which, if any, of the six species in the database were some species of pine and then summing the associated species percent fields for those species. In general, only one pine species was present in a stand although there were a surprising number of exceptions to this rule.

The resulting information was extracted as ARC/INFO polygon coverages and generalized on age and percent pine. The coverages were then converted to grids with a 16 hectare cell size using the ARC POLYGRID command. This command works by intersecting the polygon layer with a 16 hectare grid and determining attribute of the largest resulting polygon for each grid cell. The entire grid cell is then assigned that attribute

1.2 Classify habitat types

We constrain beetles to occur only in areas of suitable climate with some pine component. The pine must also be greater than 60 years old, but stand age is a dynamic layer in our projection model, so we include this factor as a separate constraint, rather

than recalculating the habitat suitability map each year. Thus, we classify each 400-metre cell into one of 6 suitability types according to the following scheme:

If no forest cover data is available (TFL's and Parks), then:

Suitability Type = **No Data**

Otherwise, if data indicates no forest cover (age or percent pine value of -1, indicating lakes, rocks, ice, etc), then:

Suitability Type = **No Forest**

Otherwise, if climate is unsuitable, and percent pine is greater than 0, then:

Suitability Type = Unsuitable Climate, With Pine

Otherwise, if climate is unsuitable, then:

Suitability Type = Unsuitable Climate, No Pine

Otherwise, if there is no pine present, then:

Suitability Type = **Suitable Climate, No Pine**

Otherwise, forest is suitable for beetles:

Suitability Type = **Suitable**

We define climatic suitability broadly by biogeoclimatic zone. Areas within the following biogeoclimatic zones are considered suitable:

- BG, ESSF, ICH, IDF, MS, PP, SBPS, SBS

For reference, zones deemed unsuitable are:

- AT, BWBS, CDF, CWH, MH, SWB

We further classify suitable habitat into discrete age and percent pine classes. We begin with 20-year age classes, running from 80 (61-80 years) through to 240 (>220 years). Percent pine is classified into 25 percent intervals – the 1-25% class includes areas with 1-25 percent pine, and so on. We separate areas labeled as 100% pine into a class of their own, in part because so much of the landscape falls into this one category, and in part because areas of 100% pine appear to be less heavily infested by beetles than areas which are 76-99% pine. This result is counter to our expectation, and we wish to retain a distinct 100% infestation class in order to check later whether the lower infestation rate in these stands remains when other factors are taken into account.

When classifying age and percent pine, there are a number of issues for us to consider. First, and most minimally, the amount of forest in each class must be large enough that we can reasonably assume the probabilities we observe are not just an artifact of small sample sizes. Beyond this, we must keep in mind that categories will be further divided by other factors including infestation history and the number of beetles in neighboring regions. With so many important factors, and so many possible categories of each factor, we run a significant risk of over specifying this model. In general, we should retain the minimum possible number of categories at each stage of model development.

1.3 Assign beetle infested area to suitable habitat

If we accept the unprocessed aerial overview survey at face value, we find that it is not uncommon for beetles to occur in unsuitable areas, including lakes and rivers well as forested area without pine. It is also common for the percentage of trees infested in a stand to be greater than the percentage of trees that are pine in that stand. Both these

situations are impossible, and so indicate errors in either the forest cover data or the beetle mapping. No doubt both data sets contain significant errors, but it is our view that the forest cover database is more reliable than the aerial overview survey data, so we assume that beetles mapped in unsuitable areas indicate an error in the survey data, not in our assessment of habitat suitability.

There are three main types of errors that may occur in the beetle survey data:

- The infestation extent and the number of trees killed within that extent may be correct, but the spatial location may be wrong. We expect this occurs most often when observers are mapping small beetle spots, where it is easy to see that beetles have killed a few trees in a small area, but also easy to get the location of this area slightly wrong. In this case, the beetles mapped do exist, but actually belong in nearby susceptible habitat.
- The infestation extent may be wrong. We expect this occurs when mappers are marking large infestations, and might not bother to omit unsuitable forest areas from the larger polygon. In this case, the beetles mapped are not in the wrong location, but simply do not exist, and should be omitted.
- The percentage of trees killed within an infested area may be wrong. We suspect that the percentage killed is the least reliable aspect of the aerial survey data. In part this is because it is easier to see red trees than green ones, and partly because humans are notoriously poor at assessing the quantitative values by eye. In this case, the infestation is in the right place, but the number of beetles is wrong.

Of course, while we can recognize that three types of errors may occur, we cannot to easily distinguish which type of error has occurred in a particular case, or how to remedy it. That said, we do think that some further processing of the aerial overview survey data will render this data more meaningful and useful.

To begin, we assume that the mapped location of an infestation may be up to 600 metres away from where the actual infestation occurred. In any 144 ha area the number of trees infested by beetles will be approximately right, but the data is uninformative about where exactly the infestation occurred within that area. Thus, we begin by laying a 1200 metre

by 1200 metre grid over the aerial survey polygon data, and summing the amount of beetle kill within each grid cell.

We then lay this 1200 metre beetle coverage over our more finely resolved (400 metre grid) forest cover information. Before continuing, we consider areas where no forest cover data is available (Suitability Type = No Data). Since we have no forest cover data for these areas, we cannot say whether beetles may occur there or not. We begin by erasing the beetles that fall within these No Data areas.

Within each 1200 by 1200 metre area, we assign remaining beetles to suitable habitat if there is any. We assume that no more trees can be infested than there are susceptible pine trees to infest, so the maximum area infested in any forest cell is equal to the percentage of pine. Subject to this constraint, I assign the area infested in each 1200 metre cluster equally among all suitable cells within that cluster. Thus, the infested area assigned to each suitable 400-metre cell is:

$$\text{AreaKilled}_{400} = \text{Min}\left(\frac{\text{AreaKilled}_{1200}}{\text{Number of Suitable Cells}}, \frac{\text{CellArea} * \text{PercentPine}}{100}\right) \quad \text{Eq. 1}$$

where AreaKilled_{1200} is the total area infested in the 1200 metre cluster, CellArea is the area of the 400-metre cell (160,000 m²).

Once we have assigned infested area to the suitable habitat available, we are often left with beetles that we have no place to put. Assuming that locations designated unsuitable for beetles really are (i.e. the forest cover data is right), we determine that these beetles could not really have existed, and omit them from further analysis. For interest sake, we track the proportion of these beetles that fall into each (Figure 1). Overall, the amount of infested area that cannot be assigned to suitable habitat ranges from 13 to 17% over the whole province, depending on the year in question.

1.4 Classify infestation intensity

Having allocated the area infested by beetles among suitable areas, we assign the infestation at each location to one of 5 broad severity classes:

	Lower	"Mid"	Upper
Severe	0.3	0.5	1
Moderate	0.1	0.2	0.299999
Low	0.01	0.05	0.099999
Endemic	0.000001	0.005	0.009999
None	0	0	0

Table 1: Proportion of pine affected by beetles according to the aerial overview survey data.

Note that we are concerned with the proportion of pine area that is affected, rather than the proportion of total area. Thus, a cell where 10% of area is infested by beetles that contains only 10% pine will be considered severely affected. This differs from the severity ratings used in the aerial overview survey, which depend on the overall proportion of all trees that are infested.

1.5 What does “severe” really mean?

We observe that 25% of cells that are severely infested in 1999 to remain severely each year through to 2002. 42% of the cells severely infested in 2000 remain severely infested in 2002. According the classification above, more than 30% of susceptible pine is killed in one year of a “severe” infestation. If we accept a mid-value for severe of 50% kill, we effectively claim that up to 200% of susceptible pine has been killed in many areas over the period from 1999 to 2002. It is logically impossible to kill more than 100% of susceptible pine, so less than 50% must have been killed in at least some “severely” infested areas.

As we have noted before, there are two issues confounding percent kill estimates in the provincial overview data. First, observers tend to overestimate the proportion of red in a stand, and second, last year’s attack can sometimes be mistaken for current attack. So it is

not a surprise that the aerial overview survey tends to overestimate beetle kill, especially when infestations are “severe”.

It is the most severe infestation class that cause the most problems, and that we suspect is most wrong. In the absence of more guiding information, we have decided leave the other infestation classes as they are. We reduce the threshold for a “severe” infestation from 30% to 20% kill, and the mid-value for this category to 30%. Using these numbers, areas can logically remain severe for up to 3 years. We assume after that point that the infestation subsides, and edit the infestation severity maps accordingly. The updated severity classifications are:

	Lower	"Mid"	Upper
Severe	0.2	0.3	1
Moderate	0.1	0.15	0.199999
Low	0.01	0.05	0.099999
Endemic	0.000001	0.005	0.009999
None	0	0	0

Table 2: Proportion of pine affected by beetles according to our reinterpretation of the aerial survey data, in light of the fact that more than 100% of pine cannot be killed over the extent of an infestation.

2 Projection Model Overview

2.1 Basic approach

Our beetle projection model is a discrete probability transition model that runs on an annual time step. Each location in each year will be in one of five beetle states, or infestation severity classes -- NoMPB, Endemic, Low, Moderate, or Severe. The probability that a location will be in a given state depends on the conditions at that location in the previous year. The core of the model is a transition probability table with the following general form:

Conditions at time t			Probability of beetle state, s, at time t + 1				
Index (m)	Factor 1	.. Factor n	NoMPB	Endemic	Low	Moderate	Severe
1	class _{1,1}	.. class _{n, 1}	P _{1,NoMPB}	P _{1,End}	P _{1,Low}	P _{1,Mod}	P _{1,Sev}
...	...	.. class _{n, 1}	...	...	...	...	...
...	class _{1,i}	.. class _{n, 1}	...	...	...	...	...
...	class _{1,1}	.. class _{n,2}	...	...	...	...	...
...	...	.. class _{n,2}	...	...	...	...	...
...	class _{1,i}	.. class _{n,2}	...	...	...	...	...
...	...		...	...	...	...	...
...	...		...	...	...	...	...
M	class _{1,i}	.. class _{n,j}	P _{m,NoMPB}	P _{m,End}	P _{m,Low}	P _{m,Mod}	P _{m,Sev}

Table 3: General form of the transition probability table that underlies the mountain pine beetle projection model.

Factors affecting the probability of a given beetle state at time t include the beetle state in the previous year, the cumulative amount killed by beetles at that location in all previous years, the age, percentage of pine, and climatic conditions of the stand, and the amount of beetle pressure from nearby infestations. We parameterize the transition table by classifying the conditions at each location in each year of our data (1999 – 2002). Each location will be assigned a class value for each of n factors. The combination of class values constitutes a location type or condition, each of which is assigned a unique index value, m. We then count the number of cases in each condition and the number of times that that a given beetle state follows each condition. The probability of future beetle state s given cell condition m is:

$$P_{m,s} = \frac{\text{Number of Locations}_{m,s}}{\text{Number of Locations}_m} \quad \text{Eq. 2}$$

We have found it conceptually useful to group cell conditions into one four main categories. First, we distinguish between infestations that are already in progress, and those locations where there are not yet any beetles. Locations without beetles are further divided into areas within 1 kilometre of a current infestation, areas near enough to a current infestation to be subject to significant long-distance beetle pressure, and areas so far from current infestations that any beetle activity is likely to be due to increases in local

beetle populations, rather than immigration of beetles from other areas. We refer to these latter three categories as “local”, “long-distance”, and “emergent” respectively (Figure 2).

It is worth pausing for a moment here to examine the concept of “beetle pressure” in more detail. It remains a matter of some uncertainty and controversy to how often beetles disperse farther than 1 km, and how much dispersal contributes to infestations in more distant locations. We do not have enough information to settle the question at this time.

What we can say without doubt is that infestations are more likely arise nearer to current infestations than further away from them. This might be either due to beetle dispersal from one location to another, or because locations near to one another tend to be subject to similar weather and climatic conditions that affect the growth of beetle populations. In our conceptual model, we have favoured the dispersal hypothesis over a more environmental approach, largely because we don’t have much information about environmental factors.

It is not our intent to gloss over the uncertainty in this area, nor to claim we understand beetle dispersal and the role it plays in infestation spread. Rather, our aim is to do the best job of predicting the pattern we see given the information we have available. We have done our best to include important factors, and being able to recreate the past gives us some comfort that the model is reasonable. But we may have missed some environmental factors that will be crucial for driving future infestation dynamics. We would welcome any input about what these factors might be, especially if accompanied by data we could use to drive an alternative model. In the meantime, our model predicts what might to happen if beetle dispersal pressure, stand age, percentage of pine and current infestation status are the main drivers of outbreak dynamics. We do not claim that these factors are sufficient, only that they are the best we have come up with so far.

2.2 Infestation start model overview

Formally, locations are potential “start” locations if:

- habitat is suitable (percent pine > 0 and bec zone is suitable)
- stand age is greater than 60 years
- there is no current infestation
- cumulative kill by beetles in this location is less than 100%

Given that the preceding necessary conditions are met, the probability of an infestation of given severity arising depends on:

- stand age
- local beetle pressure
- long-distance beetle pressure
- percentage of pine in the stand

See Section 4 for explanation of how beetle pressure is calculated. See Section 5 for discussion of the relationship between cell conditions and infestation start probabilities.

2.3 Infestation progression model overview

An location is “in progress” if:

- habitat is suitable (percent pine > 0 and bec zone is suitable)
- age is greater than 60 years
- there is some current infestation

The progress of infestations that have already started depends on:

- current infestation severity
- cumulative percentage of pine killed by beetles in all preceding years
- percentage of pine in the stand
- local beetle pressure

See Section 6 for more discussion of this aspect of the projection model, and some exploration of the relationship between cell conditions and the progress of infestations.

3 Calculation of beetle pressure

I define “beetle pressure” as a measure of the dispersal pressure sustained in each cell. It is basically an estimate of the number of beetles that will arrive in a cell from other locations, but readers should keep in mind two distinctions between that quantity and the more conceptual “beetle pressure” measure. First, while the number of beetles that arrive in any location will be stochastic, beetle pressure is an entirely deterministic measure of the expected attack level in each cell. Second, while we hope that the relative ranking of beetle pressure values will be meaningful, we have no great faith that our estimated beetle numbers will be accurate.

The “beetle pressure” calculation can be broken into several components:

- Get the number of “source” beetles. This is the expected number of beetles that will be produced at each location given the history of beetles at that location and stand characteristics (age and percent pine).
- Tabulate wind speed and direction information by forest district.
- Devise some method of distributing long-distance dispersers given wind information.
- Devise some method of distributing short-distance dispersers given the relative “attractiveness” of neighbouring cells.

3.1 Get number of “source” beetles

To estimate the number of beetles dispersing from each location, I rely on results from a stand level mountain pine beetle model developed by researchers at the Canadian Forest Service (ref). Predictions from this model across a range of forest stand conditions and beetle attack levels have been tabulated for use in the regional scale MPB/SELES model. This table indicates number of beetles that will be produced and level of damage expected given a range of forest and infestation conditions. In particular, the table contains the following information:

Category	Heading	Description
Predictors – forest attributes	age	age of stand
	si	site index of stand
	sph	density of stand
	pcp	percentage of pine within stand
Predictors – infestation attributes	year	number of years since the infestation began
	numAttackers(t-1)	number of beetles that attacked this stand last year (t-1)
Resultant –	numDispersers(t)	number of emerging beetles that disperse out of the source stand this year (t)
	numLocal(t)	number of emerging beetles that remain in the source stand this year (t)
	percentVolKill	green attack last year (t-1) or red attack this year (t)

Table 4: Structure of the table summarizing output from the stand-level mountain pine beetle model developed by the Canadian Forest Service.

Unfortunately, we cannot use the information in CFS table directly, because do not know the site index or stem density of our stands, nor to we know the exact number of attacking beetles in the stand last year. Basically, we need to predict the number of beetles that will disperse from a location a given the proportion of pine killed in that year, and the age and percentage of pine in the stand.

First, I classify each *percentVolKill* number in the table into one of the five attack severity classes (Table 2). I also calculate the cumulative percentage of volume killed over all previous years of the infestation by summing *percentVolKill* over years 1 to t of the infestation, where t is the current value of *year*. I round this cumulative volume kill to the nearest 20% to get one of 6 *cumVolKill* classes.

I calculate the average number of dispersers and local beetles in each category to get a table with the following columns:

Category	Heading	Description
Predictors – forest attributes	age	age of stand, classified
	pcp	percentage of pine within stand, classified
Predictors – infestation attributes	currSeverity	Percent of pine red-attacked this year (i.e. killed last year), classified
	cumVolKill	Percent of pine killed over all previous years, classified.
Resultant –	numDispersers	number of emerging beetles that disperse out of the source stand this year (t)

Table 5: Structure of the table in BCMPB to provide the number of dispersers emerging from each infested cell.

3.2 Tabulate wind speed and direction

We obtained daily wind speed and wind direction data from weather stations around BC from July 24-Aug15 1970-1995. The “daily” readings are taken for 10 minutes around noon of each day. On the assumption that most of the flight happens in the second week of August, we used data from August 5 to August 15.

I calculated the proportion of times the wind blew in a particular direction and the average speed of wind in each direction over the entire data period (Aug 5 to Aug 15, 1970-1995). Since the location data we have for weather stations is accurate only to within the nearest degree, we group data from weather stations within each forest district.

Wind speed is given in metres per second, and wind direction is rounded to the nearest 45°. Angles are assigned according to geographic convention, where 0 degrees is due north, and angles increase in a clockwise direction through east to south to west and back to north. According to meteorological convention, the “direction” of a wind is the direction from which that wind came. Thus, a north wind will blow beetles to the south from their source location. For reference, direction categories are assigned and referred to as follows:

Direction ID	Description	Angles
N	Wind blows from north to south.	337.5-22.5°, from destination to source cell.
NE	Wind blows from northeast to southwest.	22.5-67.5°, from destination to source cell.
E	Wind blows from east to west.	67.5-112.5°, from destination to source cell.
SE	Wind blows from southeast to northwest.	112.5-157.7°, from destination to source cell.
S	Wind blows from south to north.	157.7-202.5°, from destination to source cell.
SW	Wind blows from southwest to northeast.	202.5-247.5°, from destination to source cell.
W	Wind blows from west to east.	247.5-292.5°, from destination to source cell.
NW	Wind blows from northwest to southeast.	292.5-337.5°, from destination to source cell.

Table 6: Summary of wind direction categories.

I omit from the tabulation days with no wind at all. This is equivalent to saying that beetles will wait until there is wind before rising above the canopy for long distance dispersal. For reference, Appendix 1a contains the broad summary of the frequency of prevailing wind directions across the province that we use. Appendix 1b contains the average wind speed in each direction.

3.3 Long-Distance Dispersal

I get the total number of dispersers given age, percent pine, and infestation severity in each location in each year from the information calculated in Section 3.2. These are the “source” dispersers in each location, *numSource*. I assume that some constant proportion of these dispersers will travel long distance. The actual proportion is not important, because long and short distance beetle pressure will be independent factors in the model, and beetle pressure is a dimensionless quantity.

Wind speed and frequency vary with direction. The probability that dispersers will travel on winds coming from a particular direction is given in Appendix 1a.

I assume that long distance dispersers travel at wind speed until they land. Thus, beetle flight times will be exponentially distributed with a mean of *aveFlightTime*, where:

$$landRate = 1/aveFlightTime \quad \text{Eq. 3}$$

and the probability of any particular flight time, *t*, is:

$$P(t) = landRate * e^{-t*landRate} \quad \text{Eq. 4}$$

In MPB/SELES a constant landing rate of 0.01 per hundred metres is used for long-distance dispersers. Assuming a typical wind speed of 10 metres per second, this translates to a landing rate of 0.001 per second, and an average flight time of approximately 20 minutes, or 0.3 hours.

Once selected, wind speed and direction are assumed to be constant throughout the beetle flight. Thus, the distance traveled by each beetle (*x*) is equal to the flight period of that beetle multiplied by the wind speed, *currWS*:

$$x = t*currWS \quad \text{Eq. 5}$$

The average flight distance of beetles is:

$$E(x) = aveFlightTime*currWS \quad \text{Eq. 6}$$

Given an average wind speed of 10 m/s and an average flight time of 20 minutes, beetles will travel 12 kilometres on average.

Conceptually, the simplest thing to do would be to disperse beetles from each source over a region up to the maximum distance beetles can travel in each direction. However, at a wind speed of 10 m/s, a beetle can travel 108 kilometres in three hours. A circular region with a diameter of 100 km encompasses approximately 200,000 cells in our model. In 2003, there are 195,301 infested cells in British Columbia, each producing some dispersing beetles. On the computers we have available, it takes between 30 seconds and 1 minute to calculate the beetle plume from one source. Multiplying by 195,301 sources, we get a calculation time of between 68 and 136 days for one beetle pressure map for one year.

Clearly, it is not practical to disperse beetles from each source cell independently. Instead, we employ a moving-line type algorithm, where beetles are “smeared” across the landscape in each of 8 wind directions, in much the same way that paint might smear across a canvass on which paint is spattered, and then smeared with a window squeegee. Here the analogy breaks down a bit, because it is impossible to draw the squeegee across the canvas simultaneously in each wind direction, but this is effectively what we do.

More formally, the beetles dispersing from each source are divided into eight groups, each of which will travel in a given wind direction. The proportion of beetles traveling in each direction depends on which forest district the beetles come from (Appendix 1a). We specify a “moving-line” vector, big enough to span the beetle map (slightly longer than the longest diagonal). Beginning with the “North” wind, we start at the top of the beetle map with a line that contains no beetles. Moving from top to bottom (North to South), we pick up dispersing beetles from each source as we pass over. The line carries these beetles southward. At each step, some proportion of beetles being carried by the line are placed back on the landscape. The proportion of beetles deposited depends on the landing rate of beetles (Equation 3) and the average wind speed at that location in that direction (Appendix 1b). While beetles are carried forward by the line, they also diffuse laterally; at each step, 40% of beetles are moved to the adjacent cell in each direction (20% in each direction), and 40% are moved 2 cells away in each direction. 20% of beetles remain in place. When we arrive at the bottom edge of the map, we repeat the spreading process for each of the 7 other wind directions.

Figure 3 shows the results of this smearing process for 2002. First, we see the price that is paid for the greater computational efficiency of our moving line algorithm in the star patterns that form around our beetle sources. This computational artefact could be countered by increasing the number of “swipes” we take with our moving-line, but this takes time. The map shown seems to us an acceptable compromise.

Figure 3 shows at least some amount beetle pressure everywhere in the province. The lowest value represents an expectation that approximately 1/10,000,000,000 of one beetle will at this location per year. Clearly, such a small likelihood of dispersal probably has no

real effect on beetle dynamics in these areas. In the current version of the model, we have chosen to consider long-distance beetle pressures of less than 2.25 as negligible. This is a somewhat arbitrary decision, and we would appreciate any input or insight on the subject. Beetle pressure values above 4.75 are considered uniformly “high”, and we resolve beetle pressure classes to a width of 0.5 units per class. Figure 4 shows the classified beetle pressure map for 2002. Depending on the severity of source infestations, and local wind speed, long-distance beetle pressure can be significant up to 60 or 70 kilometres away from the source.

3.4 Short-distance dispersal

Dispersers that do not travel long-distance distribute themselves among cells within one kilometre of their host cell. In general, the probability of beetles dispersing to a location depends on the quality of habitat at that location, the distance from the source location, the direction of the prevailing wind, and the number of beetles already at that location. As much as possible, I have tried to follow the approach to short-distance dispersal used in SELES/MPB. However, that model takes an iterative approach to short-distance dispersal, where later dispersing beetles make decisions based on the movement of earlier dispersing pioneer beetles. Here, we aspire to a more efficient one-step dispersal model, and so must take a somewhat different approach.

First, in SELES/MPB, the probability that a beetle will move to a particular location is:

$$0.00000001 + distanceFactor * hostFactor * windFactor * hostFactor * pheromoneFactor$$

Eq.7

Where:

$$distanceFactor = 1/d^2$$

Eq. 8

d is the distance from the beetle source in cell widths. I adopt this portion of the model as it is.

The *hostFactor* in SELES/MPB is:

$$hostFactor = (1 - cumKill/100) * SusceptibilityIndex/100 \quad \text{Eq. 9}$$

I cannot adopt this approach directly because we are missing some of the information necessary to calculate the susceptibility index. Using the information we do have, I calculate the *hostFactor* as:

$$hostFactor = (1 - cumKill/100) * (age > 60) * pcp/100 \quad \text{Eq. 10}$$

Again using the information available, I take the *windFactor* directly from Appendix 1a. *windFactor* varies with forest district and the direction to the source location. See Section 3.3 for more details.

The effect of the *pheromoneFactor* is to attract beetles to areas with some other beetles, and repel them from areas that are too crowded. The problem is that I wish to move all beetles simultaneously. Thus, I move beetles on the basis of wind, distance, and host quality alone, and omit the pheromone factor from this model.

4 Infestation start model

4.1 Stand age

Figure 5 shows the effect of stand age on the probability that infestations will start. Overall, infestations are most likely to start in intermediate aged stands (141-160). Although the overall probability of infestations starting declines with age thereafter, the probability that new infestations will be severe continues to increase.

4.2 Beetle pressure

Figure 6 shows the effects of both local and long-distance beetle pressure on infestation start probabilities. As should be, start probability increases with both local and long-distance beetle pressure. The distinctions between local and long-distance beetle pressure, and the method we use to calculate these factors, are explained in detail in Section 3.

4.3 Percentage of pine

Figure 7 shows the effect of percent pine on infestation start probabilities. Overall, infestations are most likely to start in stands that are 75-99 % pine. There is more chance that that an infestation will become severe immediately in stands with less pine. This makes sense when we recall that infestation severity is a measure of the proportion of pine that is killed in a stand. Basically, in a stand with only 30 pine trees, if beetles kill 15 trees the infestation will be severe. If beetles kill 15 trees in a stand with 3000 pine trees, the infestation will be endemic. It is more perplexing to note that start probability is less in stands that are 100 % pine. A closer look shows that 100% pine stands tend to be younger and subject to less beetle pressure than stands classified as 75-99% pine (Figures 8 to 10). Stands subject to more beetle pressure are more likely to be infested.

<<Note – I need to do some statistics to test whether the difference between the 75-99% and 100% pine classes is significant given these other factors. My statistics program seems to demand a full binomial array, rather than a summary with sample size and the proportion of successes in each group. I wonder whether SAS might accommodate the data in the form I have it, and whether it might be more efficient to just get Don Sachs to run a test for me, rather than for me get into strange and time-consuming data contortions necessary to make it work here.>>

5 Infestation Progression Model

5.1 Overview

Projecting infestations forward using information from the provincial overview data is problematic because infestation progression in some areas is confounded by changes in survey protocol over time, because we have no management history, and because the time-series only extends for 4 years. For these reasons, I am relying on output from SELES/MPB to guide the projection model. In future, it may be interesting to compare and supplement this information with some analysis of the provincial overview data, but for now I use only the SELES/MPB information.

5.2 Severity last year

Figure 11 shows the effect of infestation severity in the preceding year on infestation severity in the future. As might be expected, severe infestations are more likely to persist than milder ones. However, if we project future severity based this factor alone, infestations could persist to kill much more than 100% of the available host resource. Presumably, there must be some limit on persistence set by the cumulative amount killed.

5.3 Cumulative percent kill

First, in SELES/MPB we know the precise amount of pine that has been killed by beetles. In contrast, we will not know exactly how much pine has been killed, but must rely on estimates of the average percent killed in each severity class. Since the range of actual values in a class (especially the severe class, which ranges from 20-100%) is very large, cumulative percent kill estimates derived by this method tend to be fairly imprecise. It is worth taking a moment to first examine the actual effect of cumulative kill on the progress of infestations, and then investigate the effect of uncertainty in our cumulative kill estimates.

Looking first at the actual kill data, we see that infestations are most likely to persist when cumulative kill is between 10 and 50% (Figure 12). When cumulative kill is very low, the infestation has likely not yet had a chance to escalate. As cumulative kill increases, beetles eventually begin to run out of food. If beetles persist to kill more than 80% of pine, they are likely to continue to kill more than 90%. No beetles persist once 100% of pine has been killed.

Using mid-values in Table 2 to calculate the approximate percent kill, I get the results shown in Figure 13. Here, although the general trends remain apparent, the certainty that infestations that run out of food will subside is obscured by imperfect knowledge of the actual percent kill. To force a solution to this problem, I will terminate infestations artificially when the estimated percent kill reaches 100%. Figure 14 shows the final classification scheme.

5.4 Habitat quality

The persistence of infestations depends on habitat quality. As might be expected, infestations are more likely to persist in less mixed, more purely pine stands (Figure 15). Age, on the other hands, has relatively little effect on the persistence of infestations (Figure 16). The probability that infestations will become or remain severe or moderate is highest in stands of intermediate age (100-140 years old), but this effect is slight compared to the effect of other factors (Figures 10-14).

In general, we run a risk of over-specifying the infestation progression portion of the model, including so many levels of so many factors that there are not enough cases of each type upon which to draw convincing conclusions. Given that the effect of age is so slight, I have chosen to omit it from the infestation progress model at this time. In future, we could generate more SELES/MPB output with which to parameterize this model, which would allow us more freedom to include an age factor without over-specifying the model.

5.5 Local pressure

Finally, whether or not infestations subside, persist, or escalate also depends on external beetle pressure (Figure 17). Infestations tend to get more severe when there are many dispersers arriving from nearby cells. Note this part of the model is thus far premised on the assumption that local beetle pressure as calculated in Section 3 is a good estimate of the actual number of beetle arriving at a location. It might be worth spending some time addressing this assumption in future work.

6 Projection model testing

We parameterized the projection model using data from 1999 to 2002. Our main test of the model was to see how well we could project 2003 using this model. Out of curiosity, we also projected each year from the preceding year (2000 from 1999, etc). We also ran from 1999 through to 2003 to see how errors in the model might compound over years.

We will examine in some detail the nature and spatial distribution of errors in the 2002-2003 projection. Before moving on to these more detailed analyses, Figure 18 compares the cumulative pine volume killed by beetles in the observed data to our various projections. When we project just one year forward (1999 to 2000, 2000 to 2001 and so on), we over-predict in the first two years, and under-predict after that. This means that there are differences between years that are not being captured in our model. The rate of increase from 2002 to 2003 is greater than we expect from knowledge of 2001-2002, and so on back through the years. If this trend continues into the future our model will tend to under predict the progress of the infestation. We will return to this issue later. First, though, we turn our attention to understanding the dynamics of the model in more detail. Note that all numbers reported here are for the timber harvesting land-base only.

To give some context for the more detailed analysis, it is worth taking a look at the observed data from 2002 and 2003 (Figures 19 and 20) It is also worth noting that, according to Joan Westfall and Tim Ebata, the aerial survey data overestimates kill in the Chilcotin area in 2003.

A few discrepancies between the observed data and our prediction are immediately apparent (compare Figures 20 and 21). First, we fail to predict the new outbreak in the Chilcotin, to the south of the current outbreak. Second, our model predicts more endemic infestations will arise across the landscape than the data shows. Finally, we predict that severe infestations will subside to moderate intensity more often than the data shows.

In the model, we have made some distinction between infestations that are already in progress, infestations that start where there is significant local beetle pressure, infestations that start where there is only long-distance beetle pressure, and infestations that start in areas where there is no significant beetle pressure. To understand which components of the model might be performing worse than others, it is worth taking a more detailed at how the model performs in each of these four situations. Figure 22 shows the number of infested cells observed and predicted in each of these categories.

In the infestation in progress sub-model, we predict fewer severe infestations and more low and endemic infestations than the data shows. This accords both our visual observations, and our understanding of what the true situation may be.

First, consider our tendency to predict infestations will subside more often than the data shows. Recall that our infestation projection model is based on output from SELES/MPB, and that we suspect the overview survey tends to overestimate the amount of kill in heavily infested areas. Taking these factors into account, it does not surprise us that our model predicts a different trajectory for infestations in progress than the data shows. Furthermore, we do not trust the survey data enough for this discrepancy to cause us great concern.

Discrepancies between our model and the data in the start model, on the other hand, indicate that there is some difference between our projection year and the preceding years. This difference might be purely stochastic (i.e. particular wind conditions last year carried beetles much farther than we would expect in a particular direction), or they might be more systematic, indicative of some factors affecting beetles that we have not yet taken into account.

Figure 22 shows that in 2003 we significantly under predict emergent starts in all categories, and both local and long-distance low severity starts. I begin with the low infestation starts, which we under-predict mostly because we fail to predict the new Chilcotin outbreak. First, recall that the Chilcotin data probably overestimates the actual kill by beetles in these areas. Second, I note that the pattern looks surprising. I do not know why beetles might have sprung up all across the Chilcotin in 2003, but I am not at all surprised that the model fails to predict this pattern, given behaviour of the outbreak over previous years.

That we under predict emergent starts so consistently is more concerning. Basically, there are two possibilities for why this might be. First, 2003 might have been a better year for beetles than other years. Alternatively, these starts are not really emergent, but depend on the prevailing beetle conditions. The latter possibility would suggest that the threshold at

which we consider beetle pressure to be negligible is too high. It may be worth revisiting this issue in future versions of the model.

Figure 23 compares observed and predicted values for the cumulative percent of susceptible pine volume killed by management unit. Figure 24 shows the spatial distribution of these errors. We tend to under-predict volume killed in more heavily infested management units – most conspicuously, Quesnel, Williams Lake, Lakes and Prince George. We over predict in a few moderately infested units including Morice, Robson Valley, and Merritt. We also do a poor job of predicting kill in a number of TFL's, but these areas are too small to merit serious attention.

7 Projecting forward

Our base run begins in 2004, runs for 20 years to 2023, and includes no management interventions. Figure 25 shows how the proportion of susceptible volume killed increases over that period. In 2003, beetles have killed 8.6% of susceptible pine in the province. It takes until 2010 for beetles to kill 55% of susceptible pine, and by 2023 96% of susceptible pine has been killed by beetles. The remainder of the figures (still missing) show how the spatial pattern of kill changes over time. The infestation in the central region of the province begins to subside by 2005, and has almost entirely subsided by 2009. By then, the Kootenays, Kamloops and more northern regions are fully infested. An outbreak in the far northeast of the province continues to escalate until approximately 2014, after which beetle populations slowly subside across the province. The outbreak in any particular region begins to subside after approximately 5 years, but it takes much longer for the beetles to eat up everything everywhere.

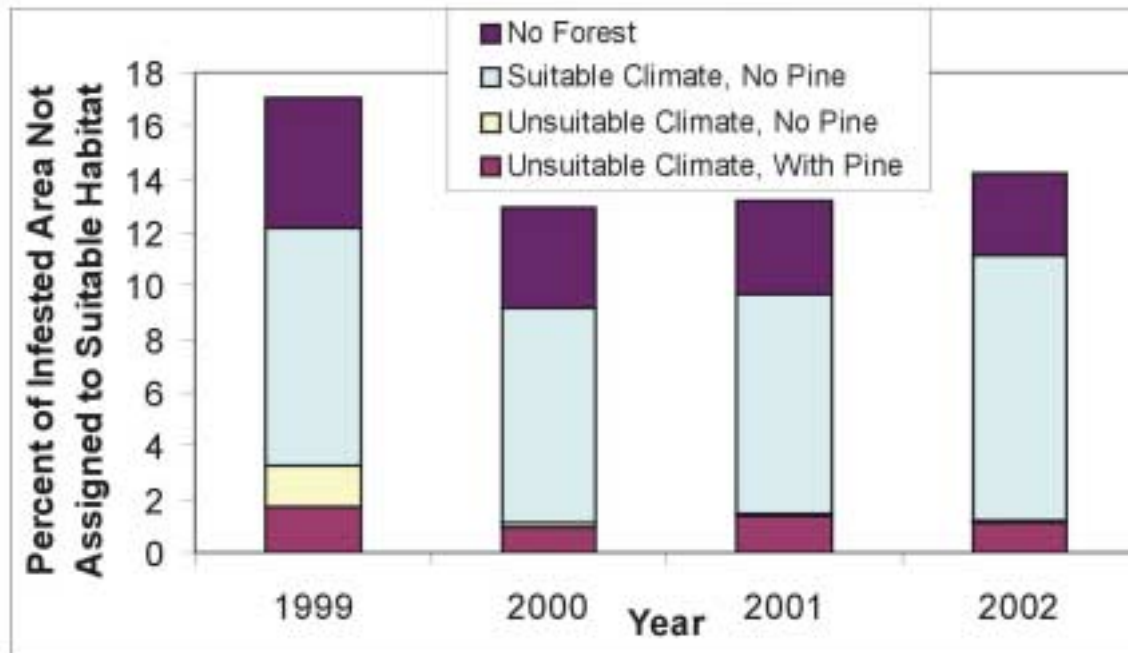


Figure 1: The aerial overview survey data reports more beetles in some areas than there is forest to accommodate those beetles. Where possible, we allocate beetles to adjacent suitable habitat, on the assumption that the spatial location of the infested polygon might not be exact. However, we do not find places to put all of the extra beetles. Here, we show the proportion of beetles lost, and the type of area in which they were lost.

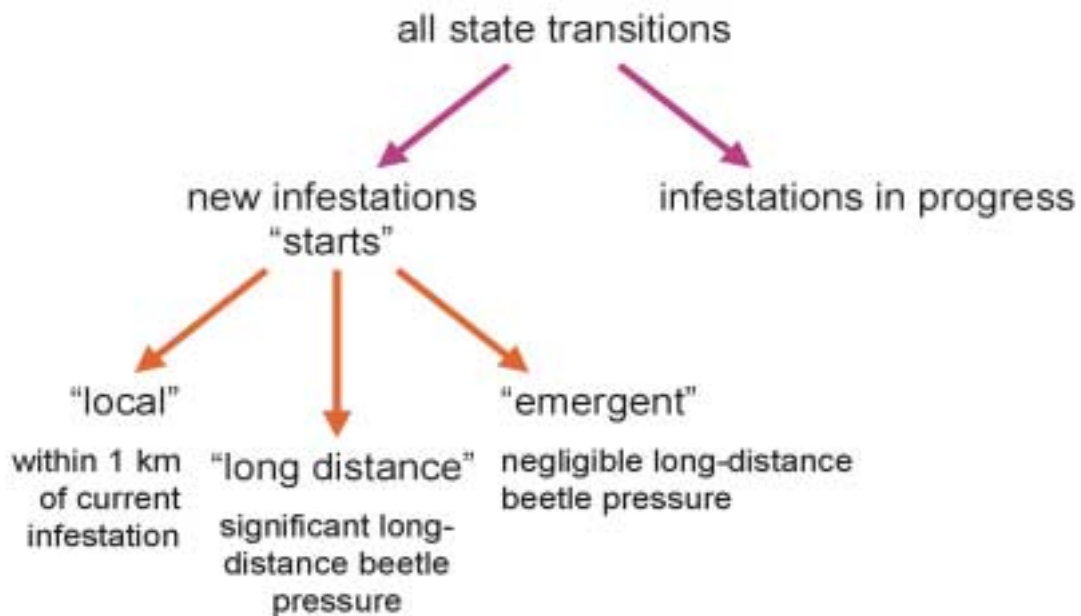


Figure 2: Four sets of conditions in the mountain pine beetle transition model. See Section 2.1 for further discussion.

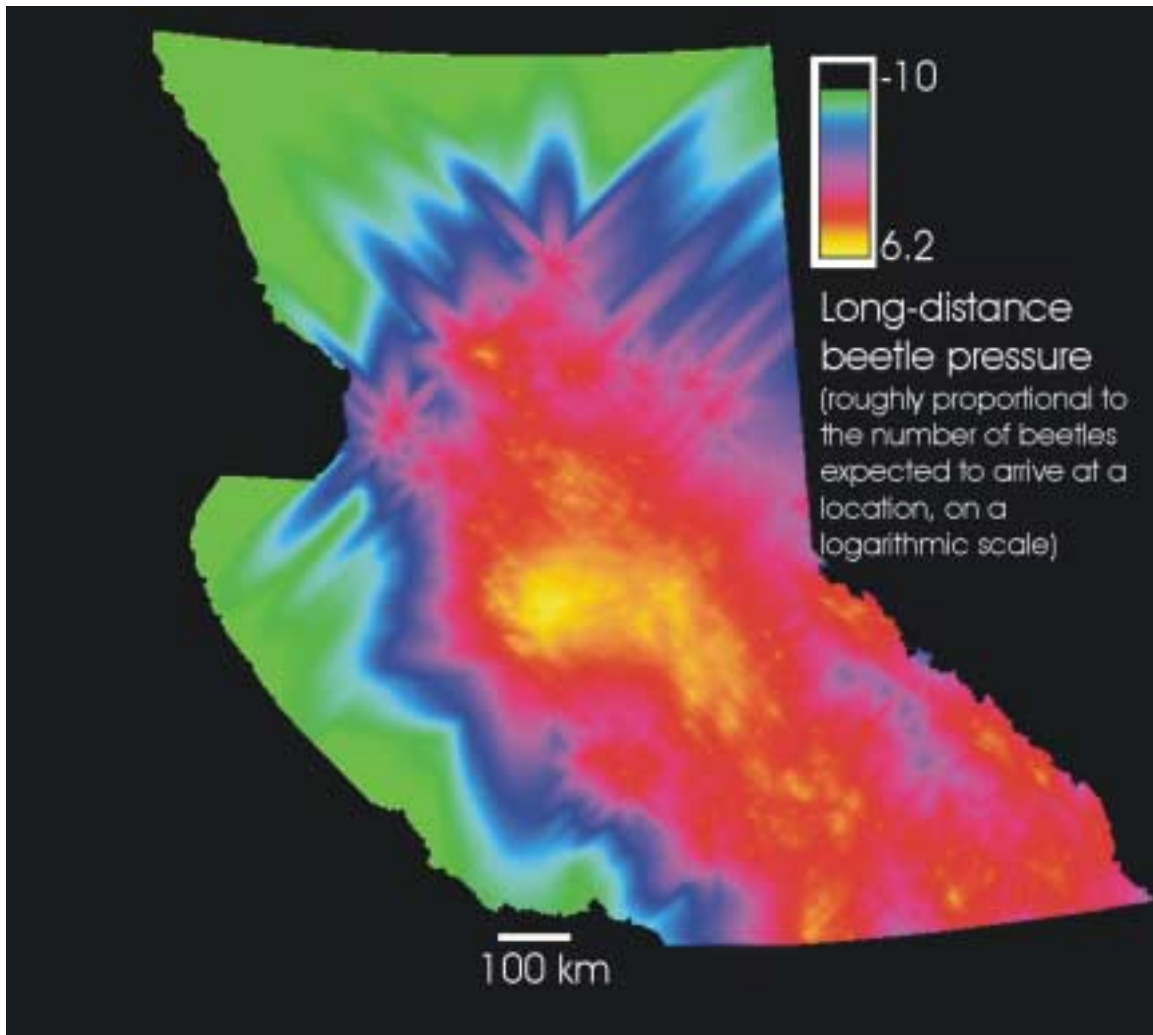


Figure 3: Long-distance beetle pressure in 2002, calculated using a moving-line algorithm. Beetle pressure is shown on a logarithmic scale. Pressure is a measure of the relative number of dispersing beetles expected to arrive at a location, but is a dimensionless quantity. To illustrate, we could reasonably expect that 10 times more beetles might arrive in an area with a beetle pressure of 2 than a beetle pressure of 1. We could not reasonably claim that 200 hundred beetles will arrive at locations with a beetle pressure value of 2.

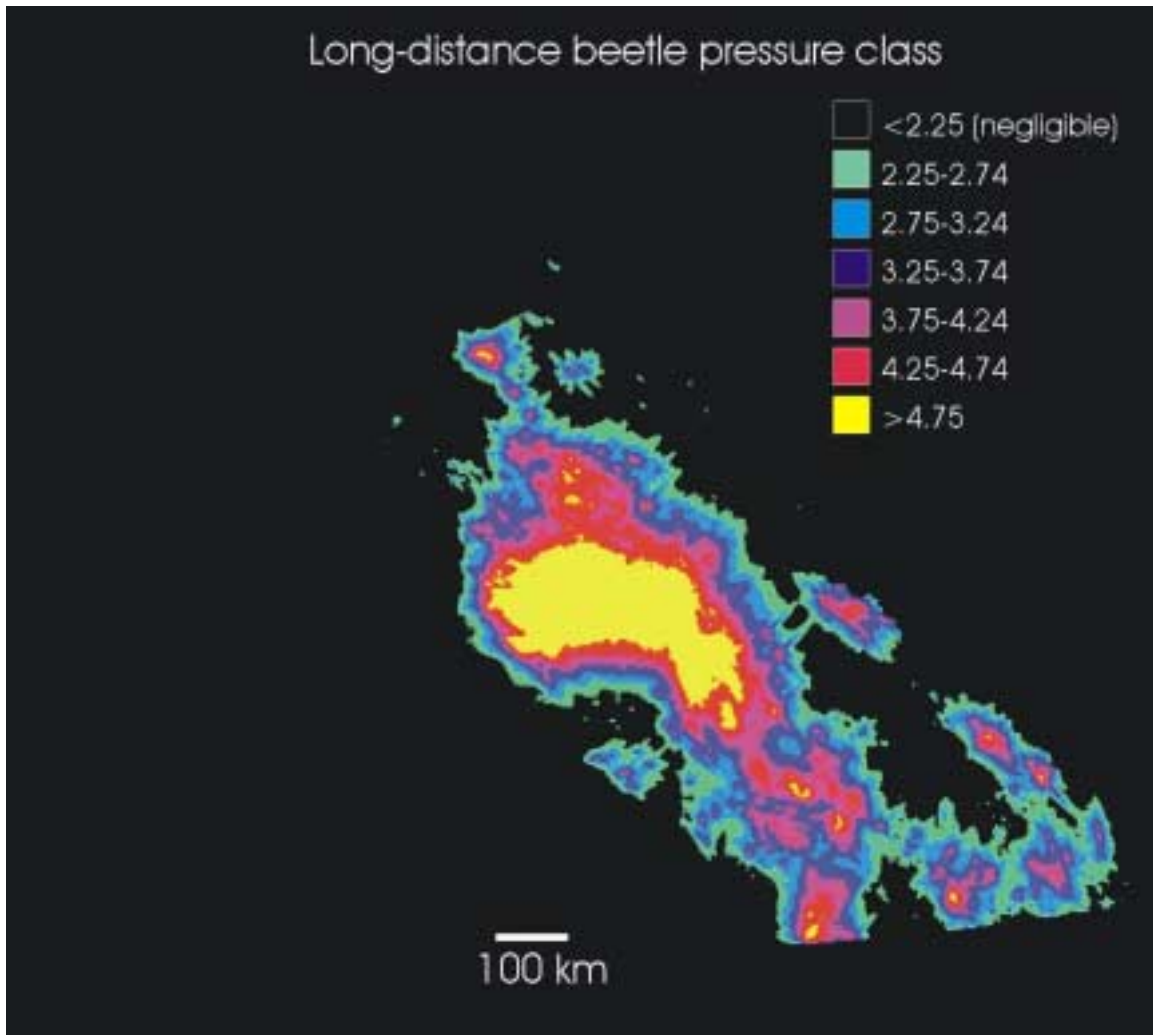


Figure 4: Long-distance beetle pressure classified into classes of 0.5 unit widths. Pressure values of less than 2.25 are considered negligible, having no significant effect on mountain pine beetle dynamics in these areas.

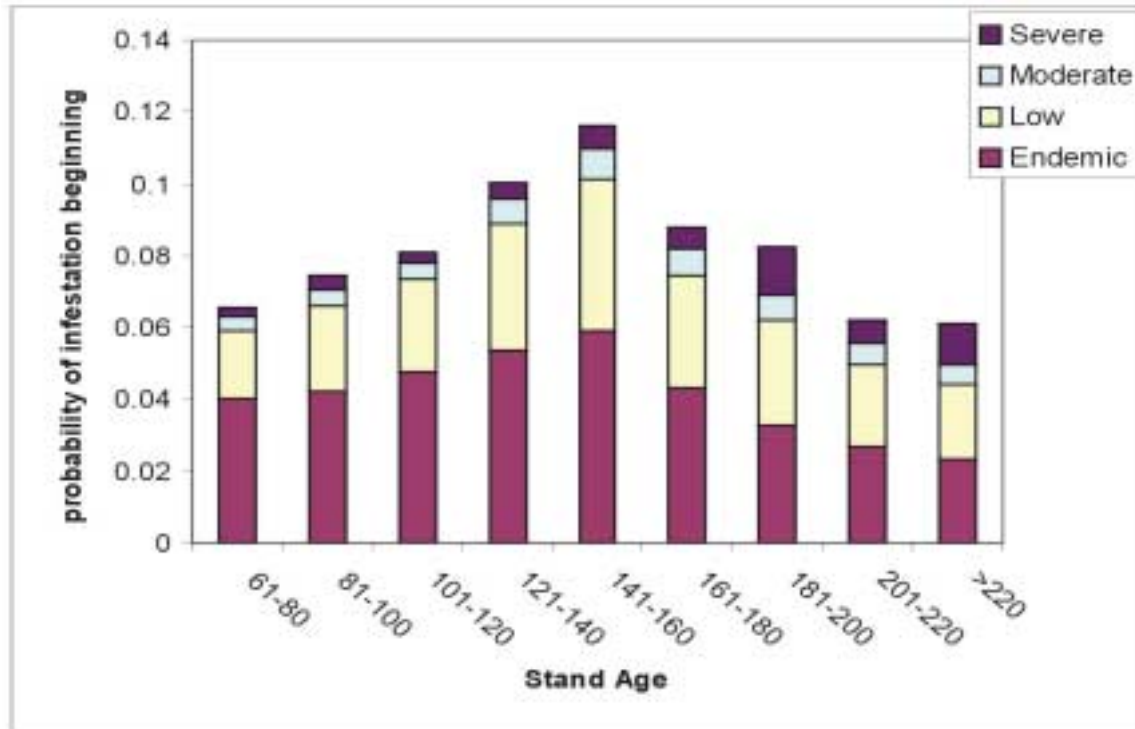


Figure 5: The effect of stand age on the probability an infestation of given severity will start in an area that is not currently infested.

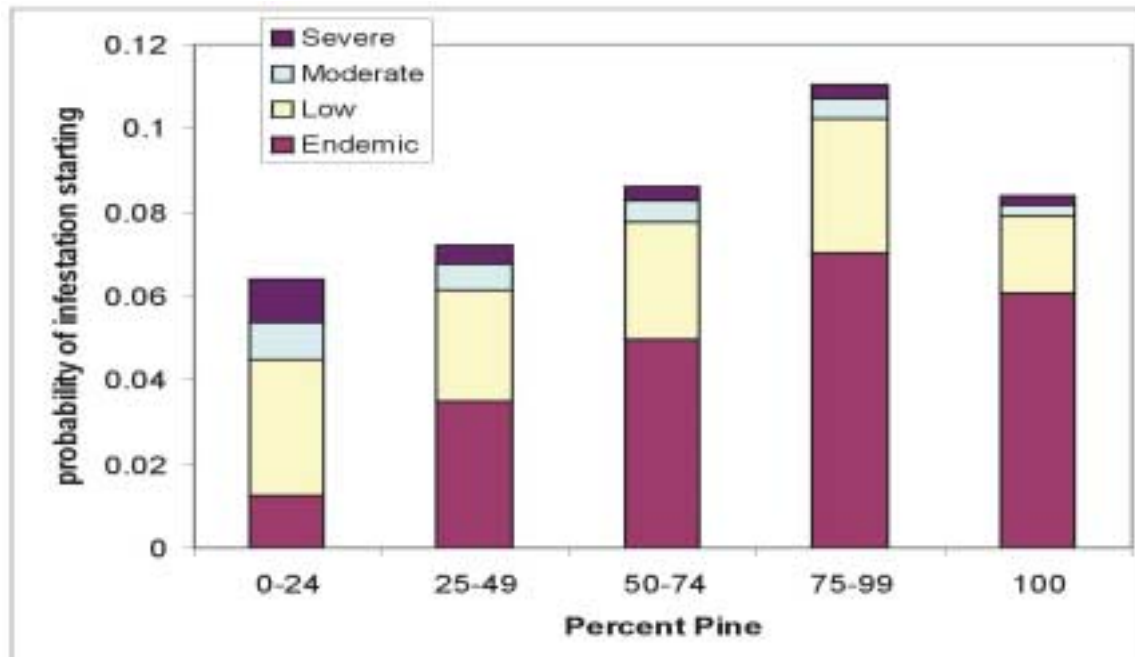


Figure 6: The effect of percent pine on the probability an infestation of given severity will start in an area that is not currently infested.

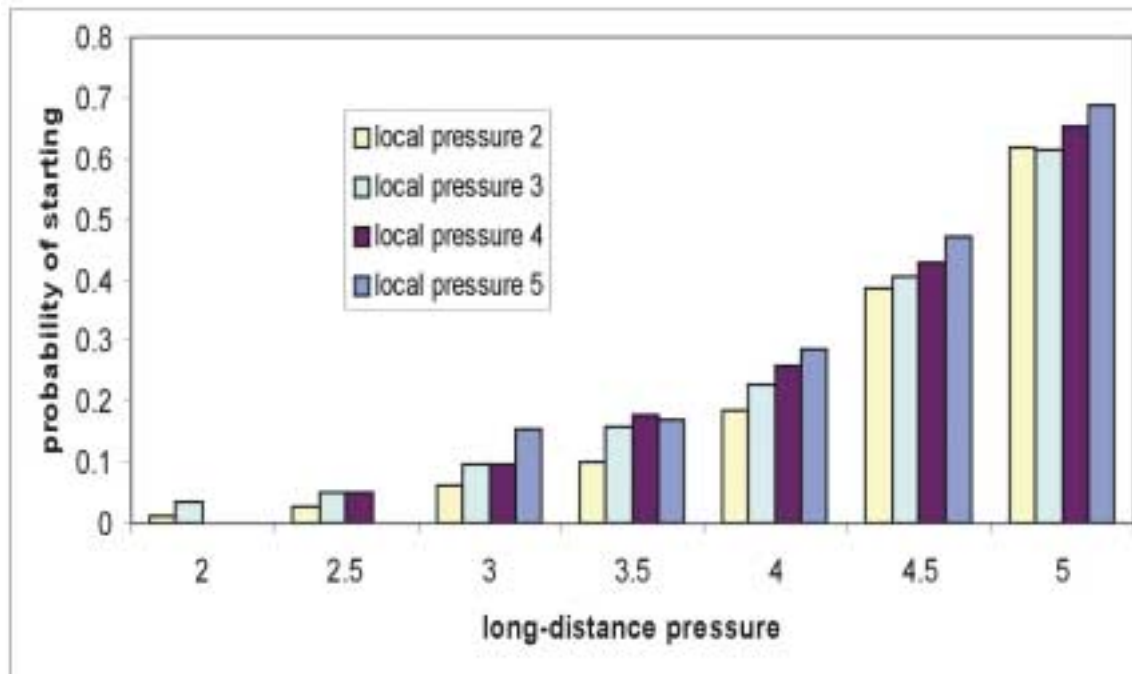


Figure 7: The effect of both long-distance and local beetle pressure on the probability an infestation of any severity will start in an area that is not currently infested.

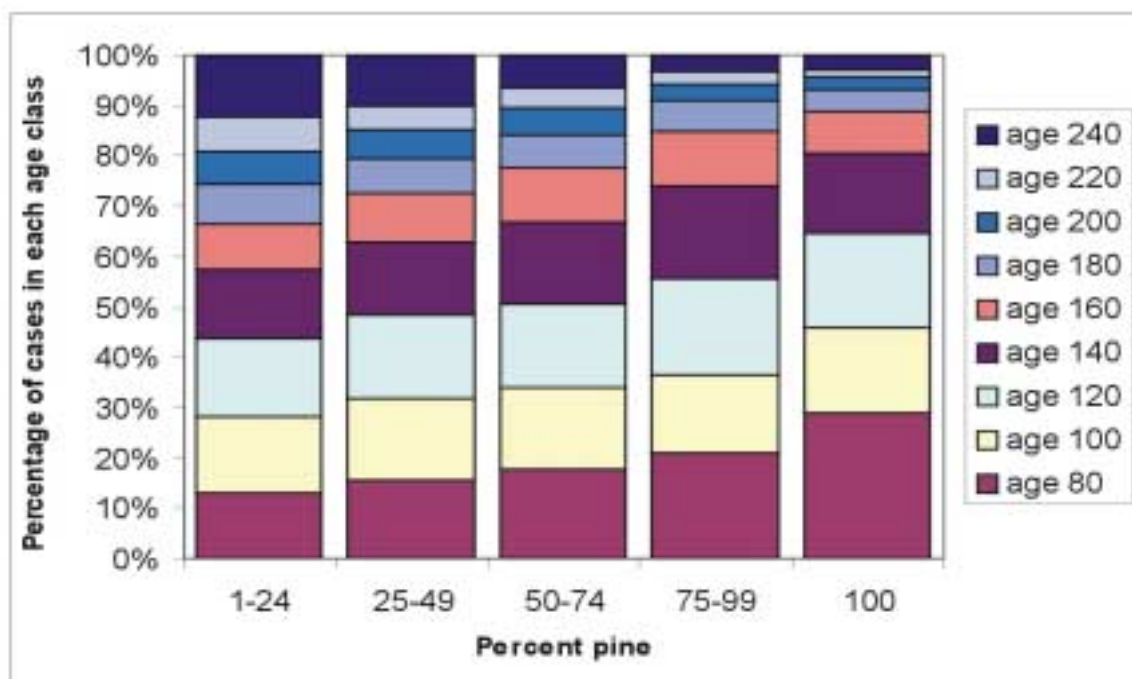


Figure 8: The relationship between age and percent pine. Stands with 100% pine tend to be younger than stands with 75-99% pine.

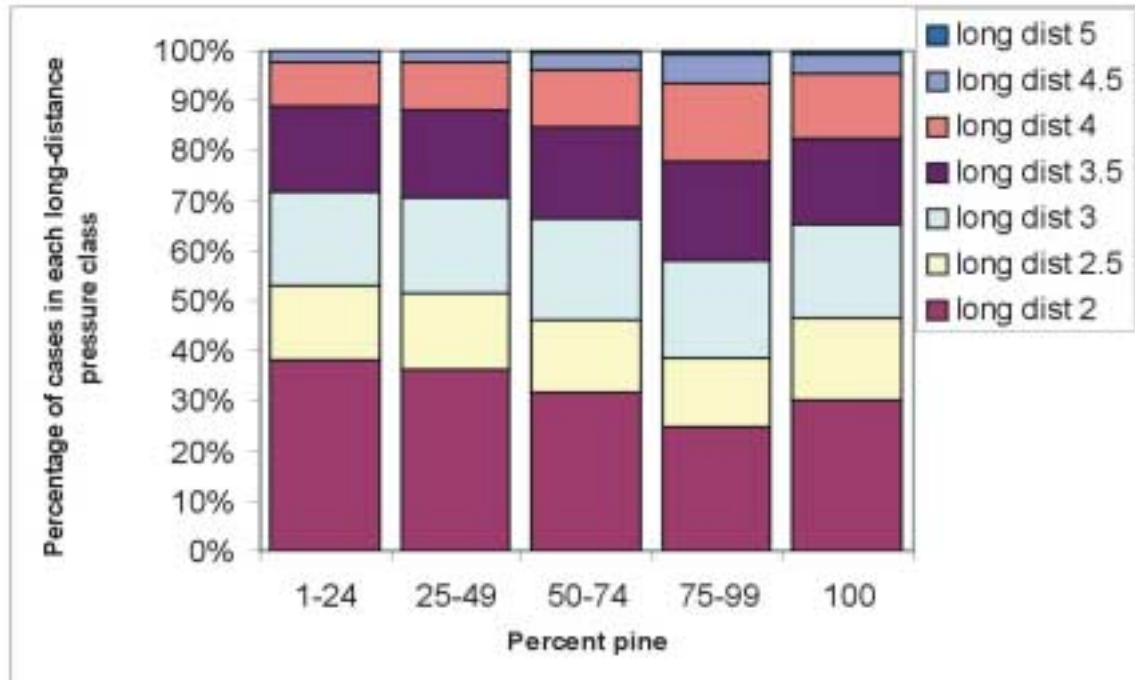


Figure 9: The relationship between long-distance dispersal pressure and percent pine. Stands with 100% pine tend to be subject to less long-distance beetle pressure than stands with 75-99% pine.

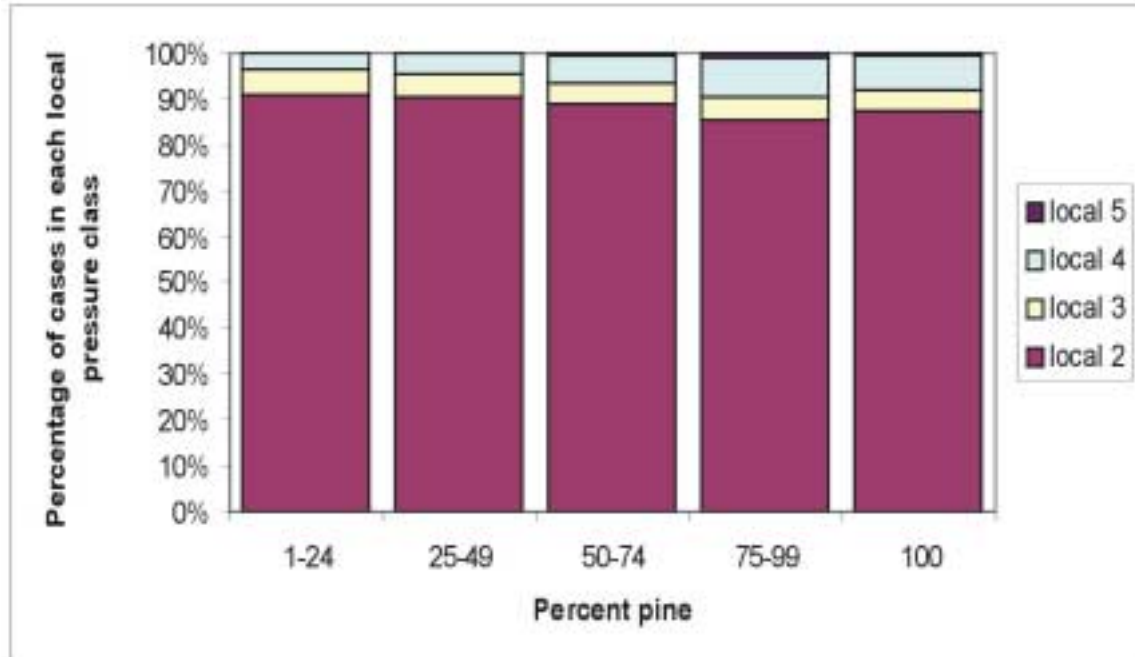


Figure 10: The relationship between local dispersal pressure and percent pine. Stands with 100% pine tend to be subject to less local beetle pressure than stands with 75-99% pine.

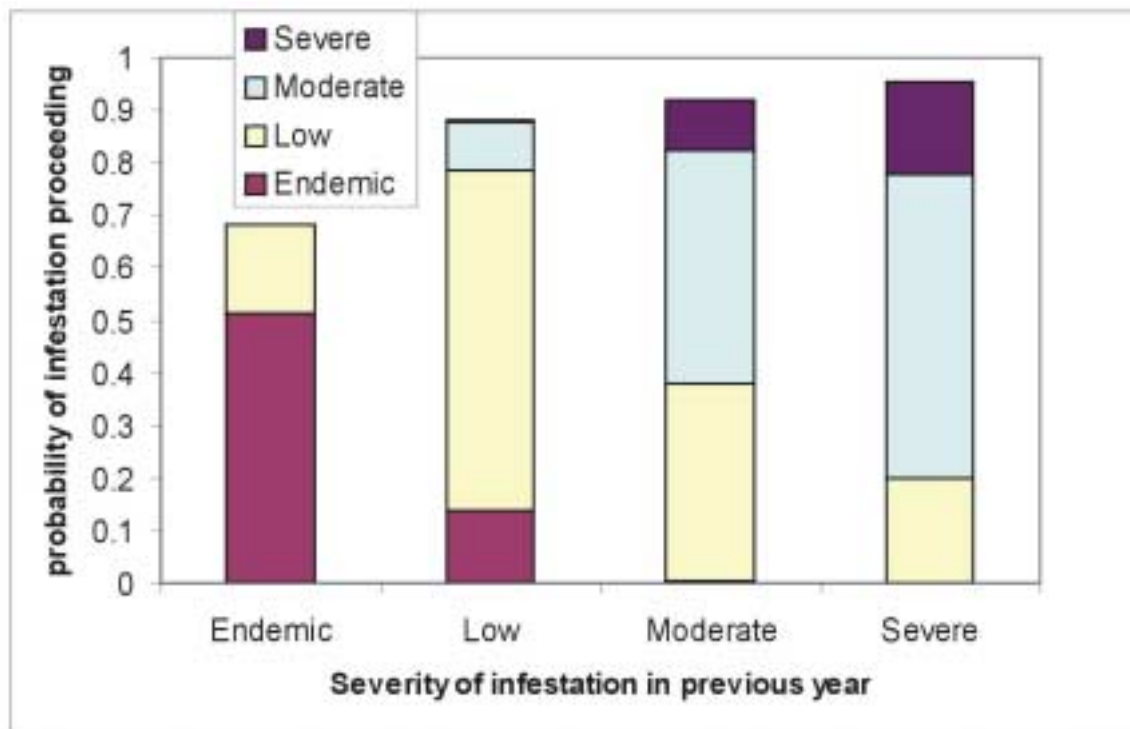


Figure 11: The effect of current infestation severity on future infestation severity.

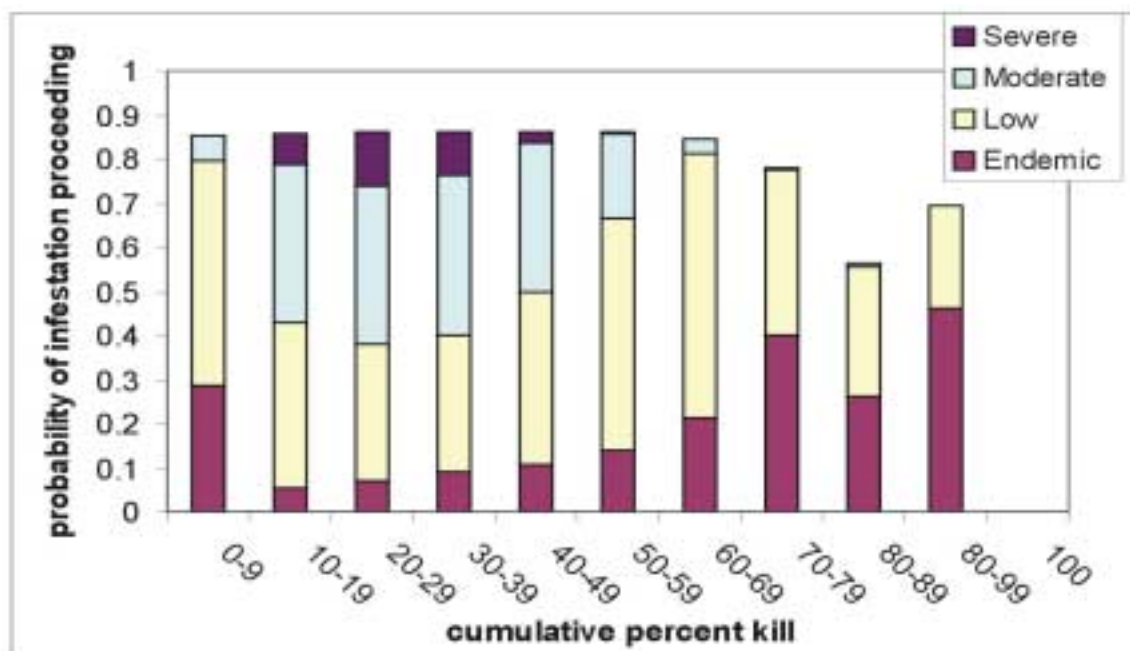


Figure 12: The effect of actual cumulative kill on future infestation severity. Cumulative kill values are exact, based on perfect knowledge of SELES/MPB, rather than estimated from mid-point values for each severity class.

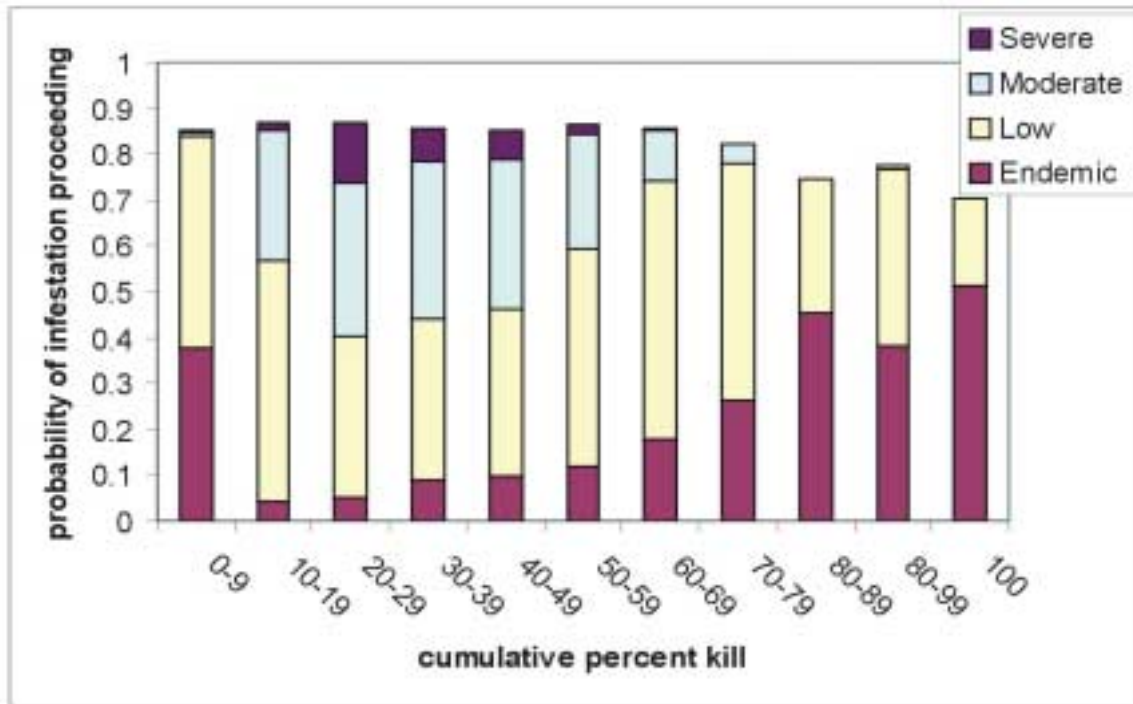


Figure 13: The effect of estimated cumulative kill on future infestation severity. Cumulative kill values are approximate, estimated from mid-point values for each severity class, rather than exact knowledge.

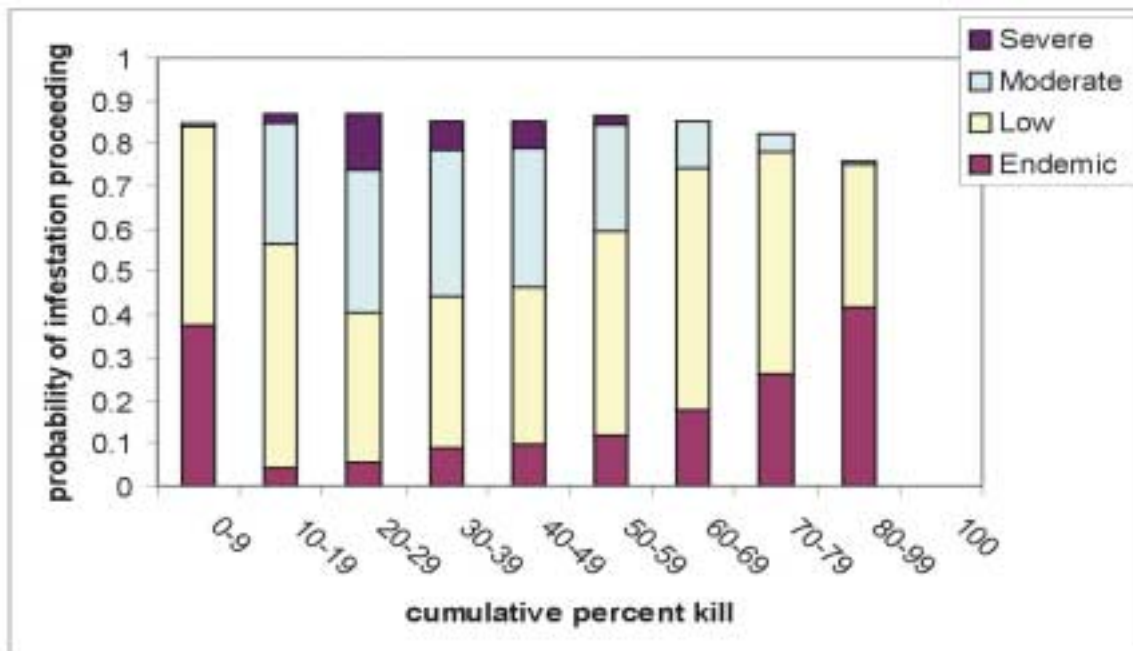


Figure 14: The effect of estimated cumulative kill on future infestation severity, modified to stop infestations from continuing after cumulative kill reaches 100%. Cumulative kill values are approximate, estimated from mid-point values for each severity class, rather than exact knowledge.

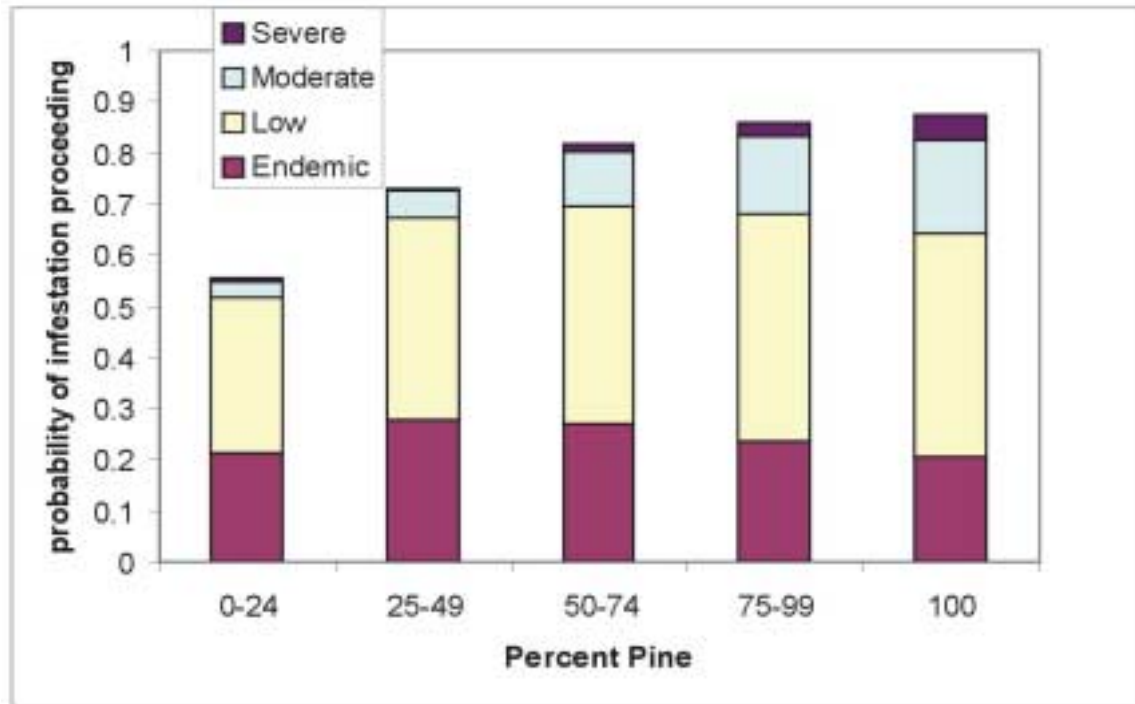


Figure 15: Effect of percent pine on the progress of infestations.

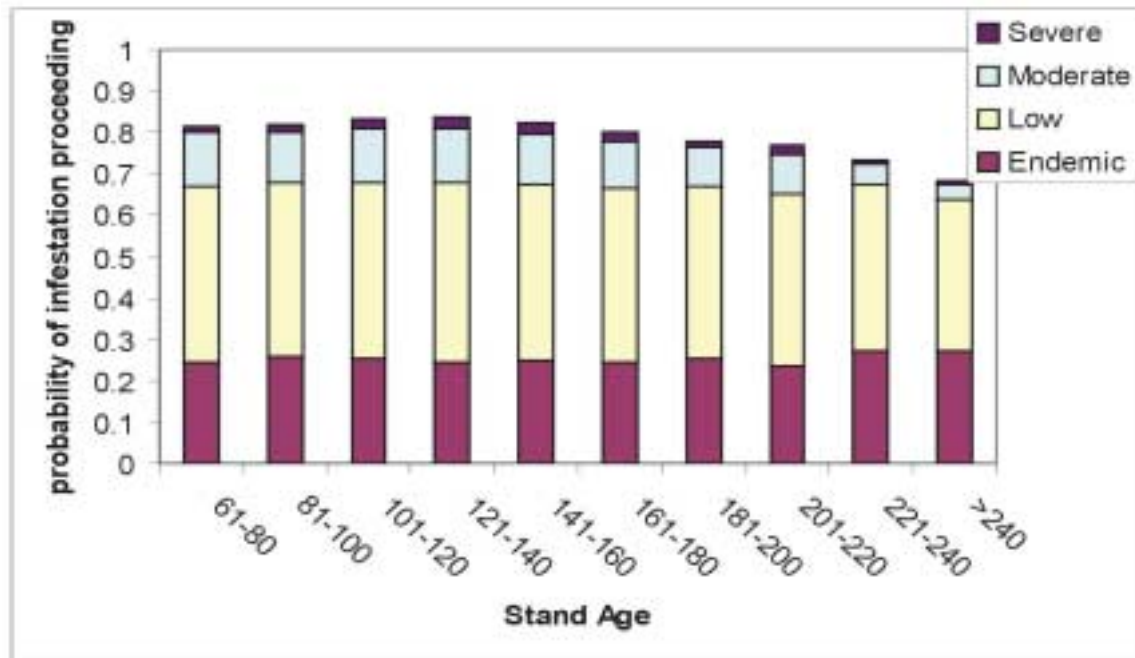


Figure 16: Effect of stand age on the progress of infestations.

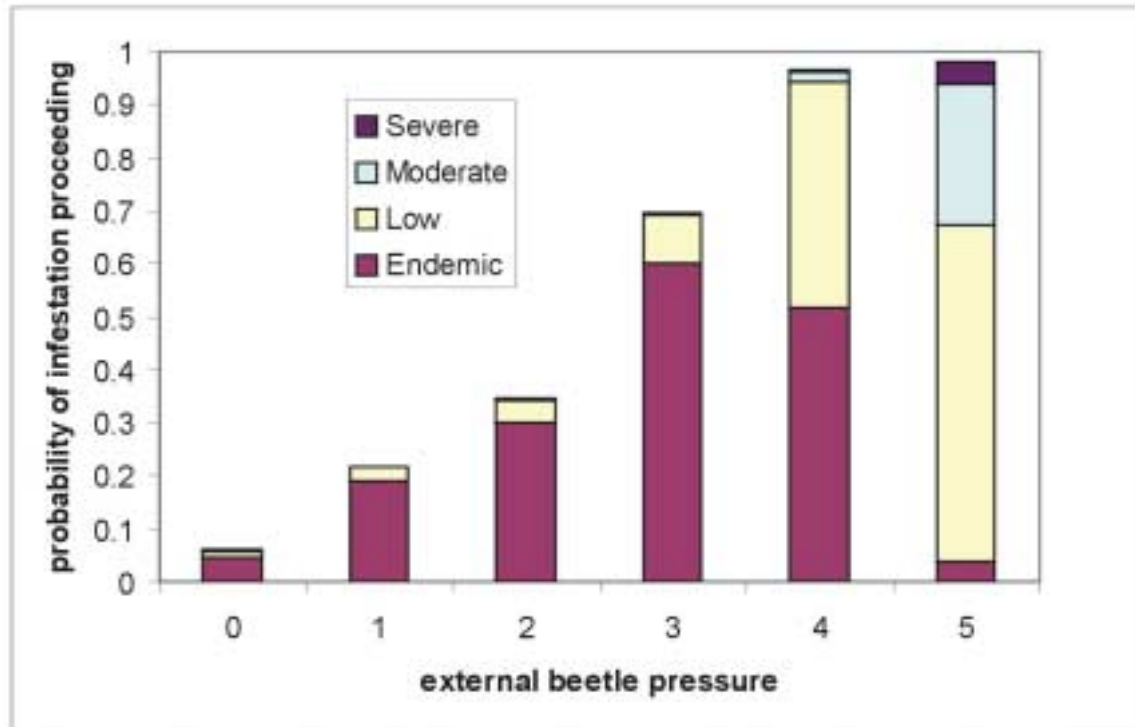


Figure 17: The effect of local beetle pressure on the progress of infestations.

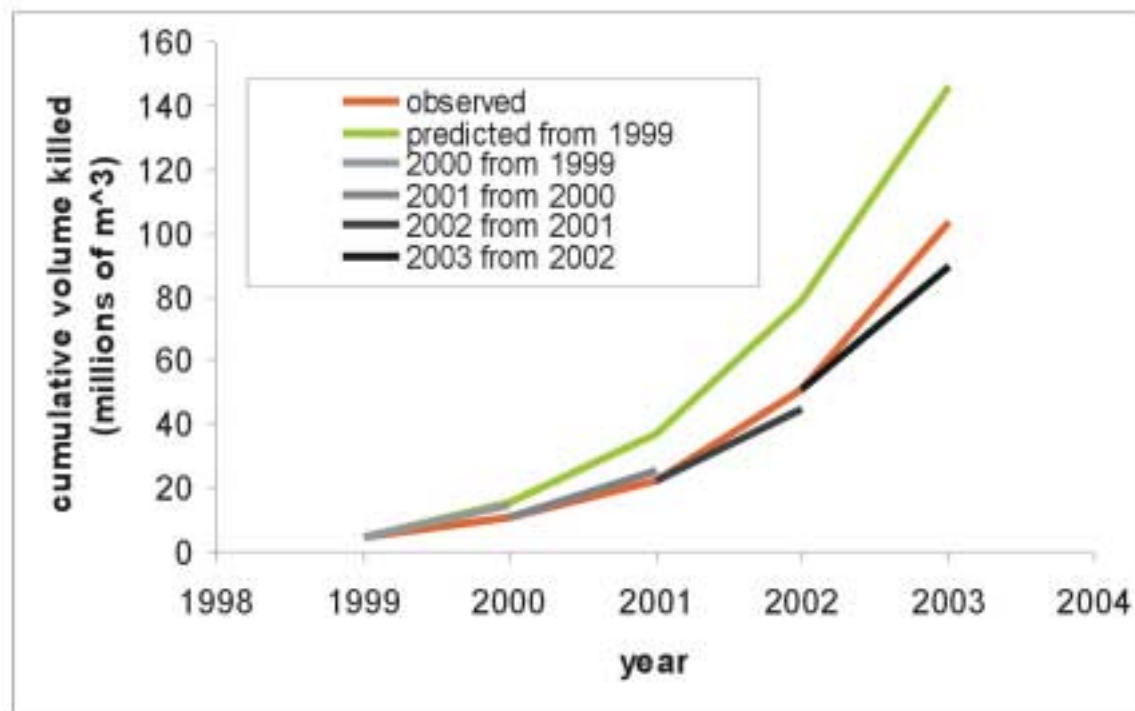


Figure 18: Cumulative pine volume killed by beetles across the timber harvesting land-base between 1999 and 2003. Predictions are from a projection model parameterized with 1999 to 2002 data, so 2003 is a “blind” test of the model.

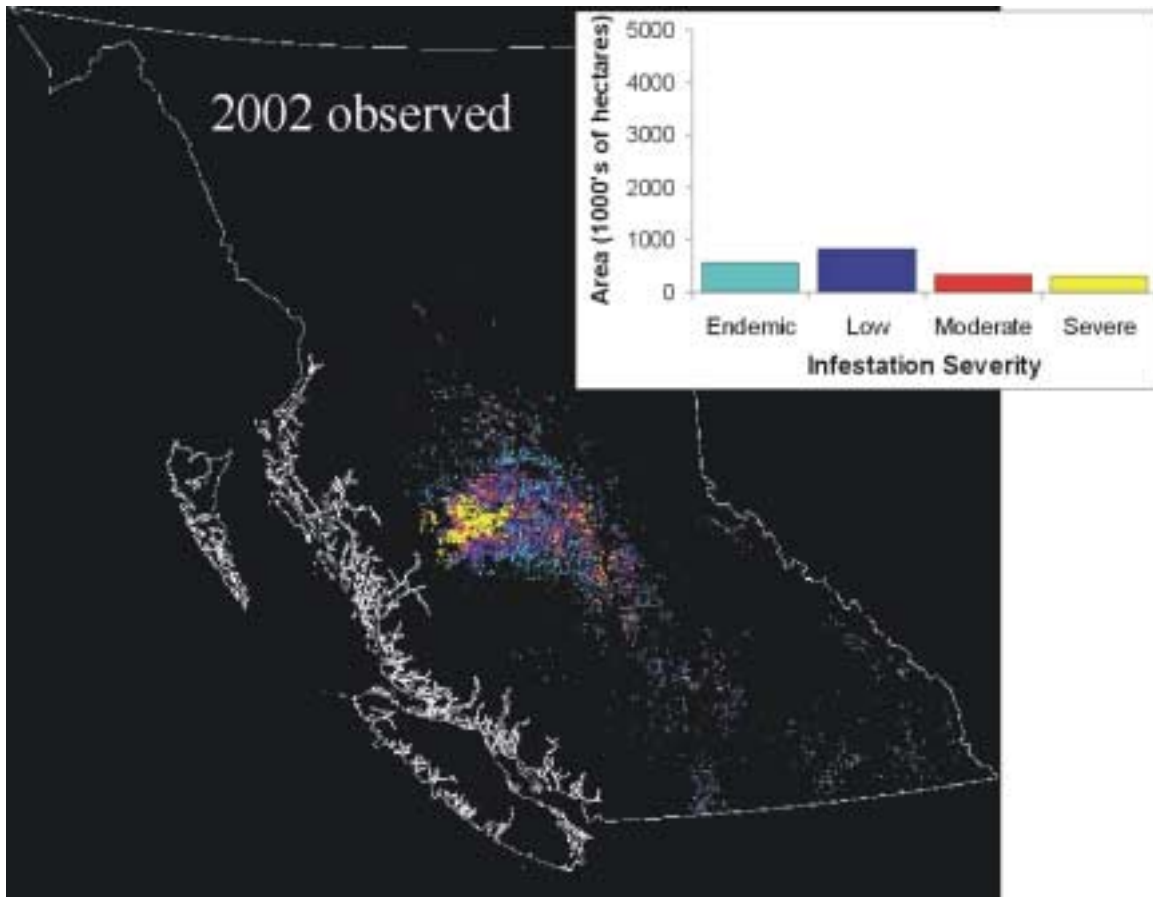


Figure 19: Mountain pine beetle infestation severity across British Columbia in 2002, according to aerial overview survey data processed as described in Section 1 of this document.

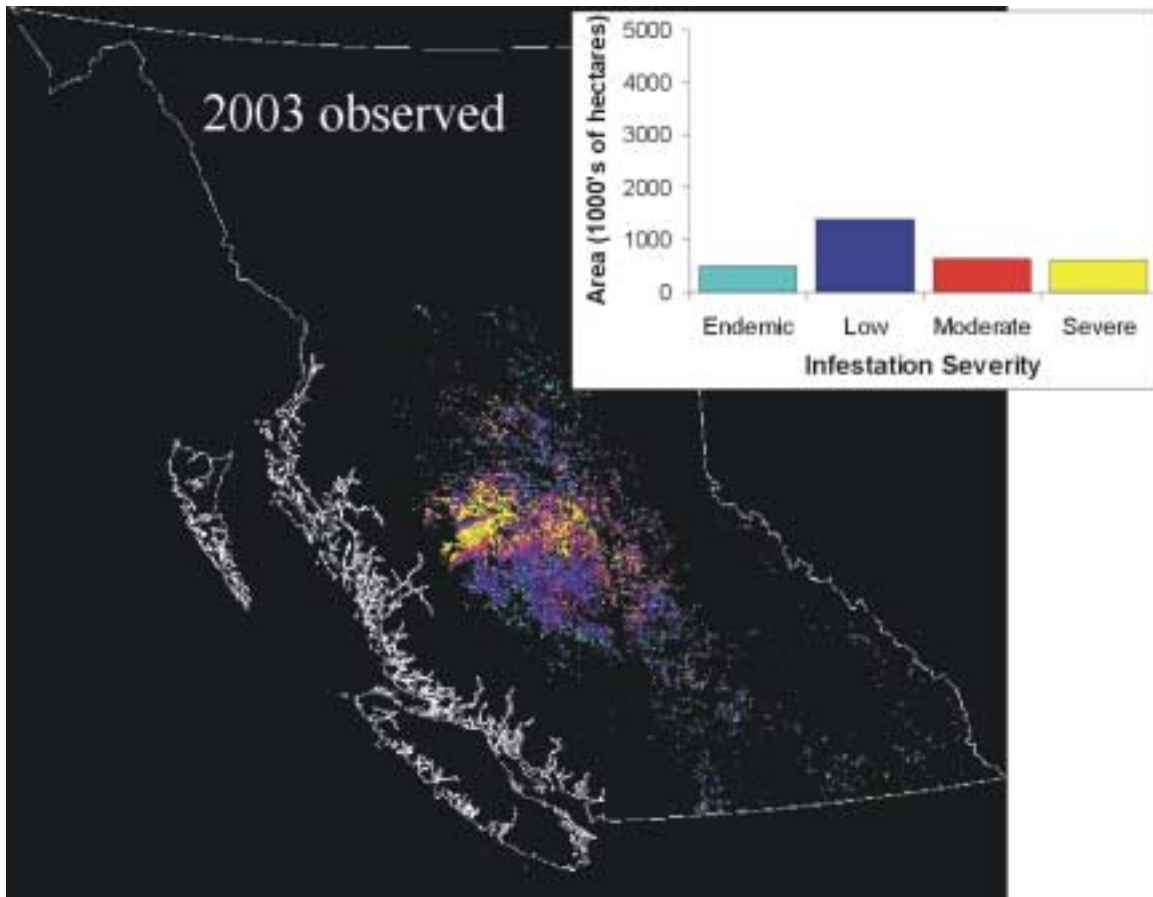


Figure 20: Mountain pine beetle infestation severity across British Columbia in 2003, according to aerial overview survey data processed as described in Section 1 of this document.

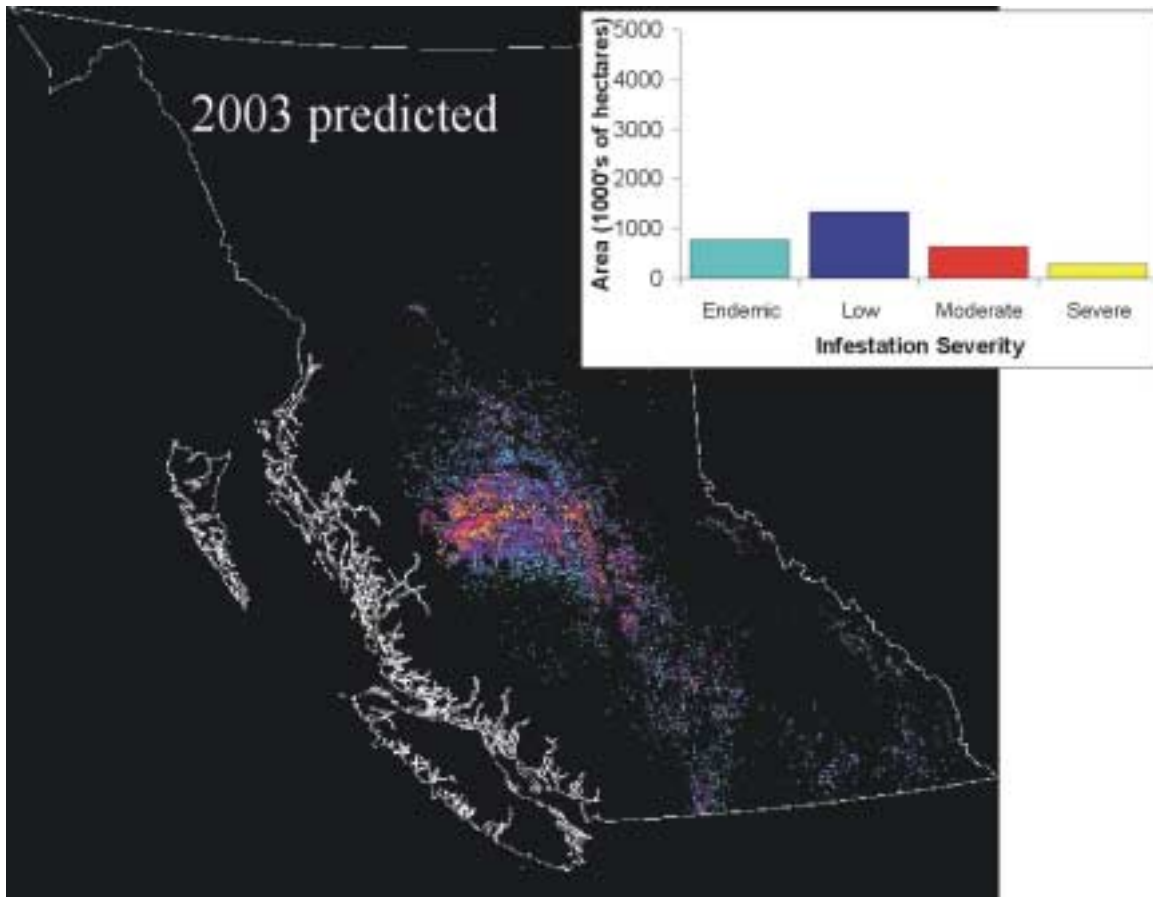


Figure 21: Mountain pine beetle severity across British Columbia in 2003, predicted by our projection model from observed mountain pine beetle severity in the preceding year (2002).

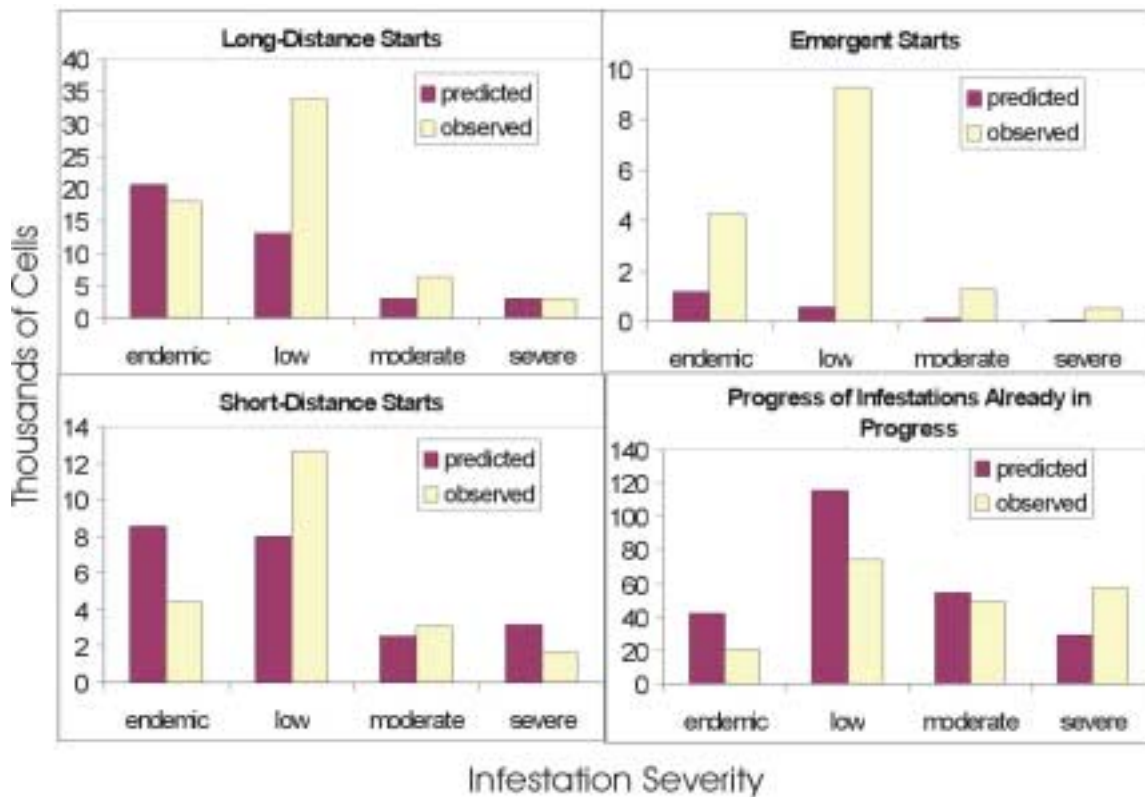


Figure 22: Performance of the projection model in each of four model sub-sections. The model under-predicts low infestation starts, emergent infestation starts of all severity, and the severity of infestation already in progress.

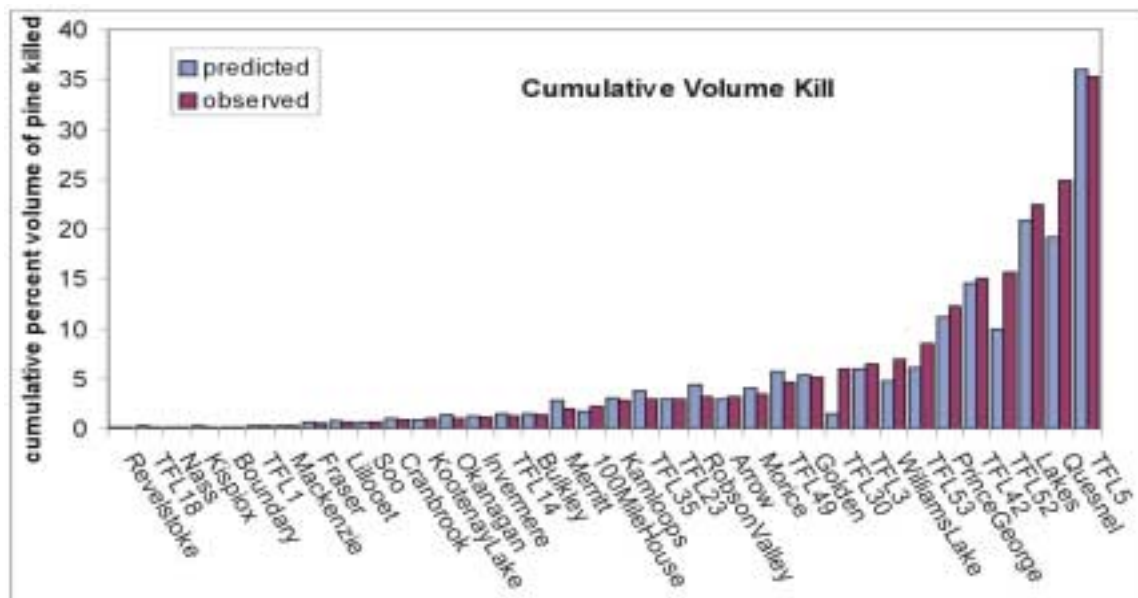


Figure 23: Variation in the performance of the projection model between mountain pine beetle management units. The model tends to under-predict volume killed in heavily infested areas, and over-predict kill in some moderately infested districts.

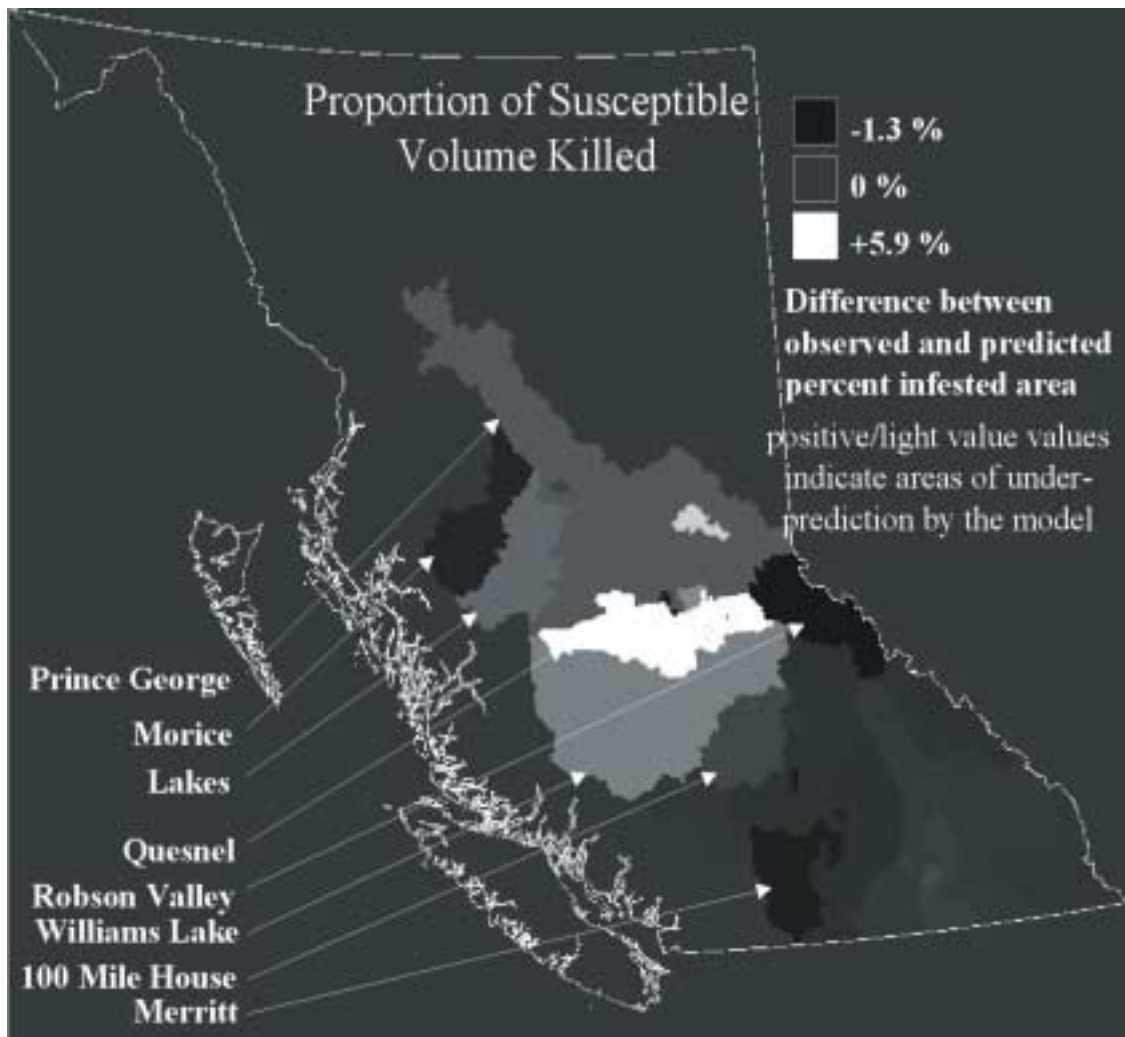


Figure 24: Spatial distribution of model errors. The model tends to under-predict near the centre of the infestation. Areas of over-prediction are scattered across the rest of the province, with no obvious spatial factor uniting them.

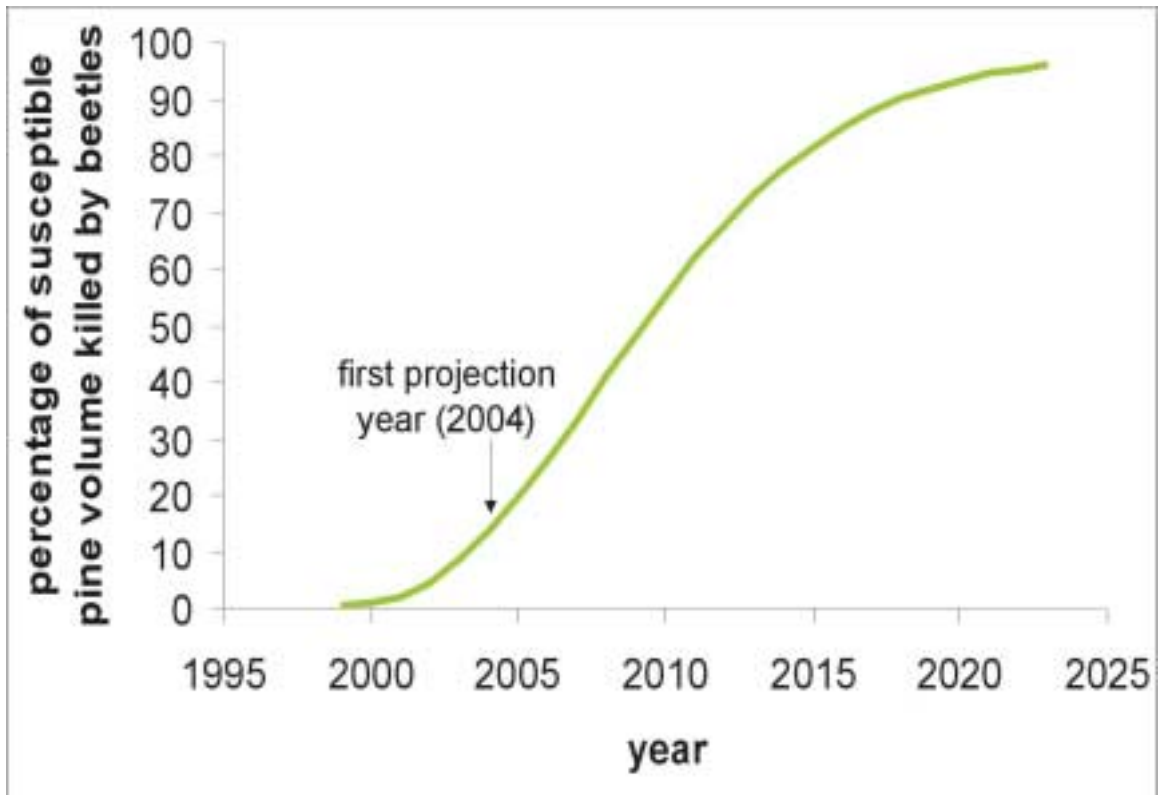


Figure 25: Long-term behaviour of the mountain pine beetle model in the absence of any management intervention. Values before 2004 are from observed data, while values after are the result of one 20-year run of the projection model starting in 2002.