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The impact of treatment on mountain pine beetle infestation rates

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Abstract

The spatial extent of the current mountain pine beetle epidemic in western Canada has highlighted the need to understand the efficacy of treatment strategies. We investigate the effect of five direct-control treatments applied in central British Columbia during a mountain pine beetle epidemic. Using point data from GPS helicopter surveys and kernel density estimators, efficacy was explored through comparisons of infestation intensities at treated locations to randomly selected untreated sites. Small patch and block harvesting treatments showed the clearest signs of reducing infestation intensity; the effects of the fell and burn, monosodium methanearsonate, and pheromone-baited tree treatments were less clear. Through this work, five management guidelines were developed: (1) aggressive treatments can be effective when beetle populations are moderate, although still epidemic; (2) single-tree treatments are only effective when infestation intensities are low or moderate in both the treatment area and surrounding regions; (3) single-tree treatments are the most effective when treatments are intensively applied; (4) overall, the more infested trees removed during treatment, the greater the reduction in infestation intensity; and (5) when it is possible to reduce the infestation levels to 2.5 or fewer infested trees per hectare, treatments can be effectively applied.

KEYWORDS: *epidemic, management, mountain pine beetle, silviculture, treatment.*

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Introduction

Although the mountain pine beetle (*Dendroctonus ponderosae*) is native to British Columbia, present populations have reached epidemic levels, resulting in the largest infestation on record. The current epidemic is attributable to the large numbers of mature lodgepole pine (*Pinus contorta* var. *latifolia*), the preferred host of the mountain pine beetle, and the trend for warmer winter weather (British Columbia Ministry of Forests 2003). The Canadian Forest Service estimates that mature lodgepole pine forests are three times more abundant today than in 1910 due largely to fire suppression programs (Natural Resources Canada 2006). In 2002, an estimated 1 billion m^3 of mature lodgepole pine were at risk to infestation by the mountain pine beetle (Morice and Lakes IFPA 2002).

The depletion of suitable host trees and the effects of cold weather in late fall or early spring caused previous mountain pine beetle outbreaks to collapse (Safranyik *et al.* 1974; Berryman *et al.* 1984; Wood and Unger 1996; Samman and Logan 2000); however, the current outbreak is so vast that a weather-related cessation is unlikely (Eng *et al.* 2004). Eng *et al.*'s model (2004) predicts that this epidemic will continue to increase until approximately 2008 and then gradually decrease over the following 10 years. Based on these projections, an estimated 10.2 million ha of pine will be infested at the peak of the outbreak. In 2020, by the projected end of the outbreak, at least 80% of pine trees are expected to be affected (Eng *et al.* 2004). Although this model does not consider the impact of cold weather or non-harvesting treatments, it does highlight the importance of management and the need for a landscape-level mountain pine beetle strategy now and in the future.

During any mountain pine beetle outbreak, pest management often dominates forest planning, and over the past decade substantial resources have been directed towards controlling the spread of the mountain pine beetle through various treatments. A mountain pine beetle infestation requires susceptible hosts and a beetle population. Treatments that endeavour to reduce or eliminate the beetle population are "direct controls"; those that aim to increase stand vigour, and therefore resistance to infestation, are "indirect controls." Direct controls, which are the focus of this study, are intended to kill the beetles before emergence, breaking the epidemic cycle and returning the population to an endemic state (Shore and Safranyik 2004).

Treatment efficacy was explored through comparisons of infestation intensities at treated locations to randomly selected untreated sites.

The suitability of direct-control treatment, or combination of treatments, depends on the spatial scale of the infestation (Safranyik *et al.* 1974; McMullen *et al.* 1986; Fall *et al.* 2004; Hall 2004; Shore and Safranyik 2004; U.S. Department of Agriculture Forest Service 2005). Direct-control treatments best suited for low- to medium-sized infestations include:

- single-tree removal (Fall *et al.* 2004);
- fell and burn (B.C. Ministry of Forests 1995);
- pheromone-baited trees (Thomson 1991); and
- de-barking, conventional trapping, or application of monosodium methanearsonate (MSMA) (Shore and Safranyik 2004).

We refer to these as "single-tree treatments." Stands with larger infestations are typically treated using block harvesting (Safranyik *et al.* 1974; McMullen *et al.* 1986). When an infestation becomes too large to harvest, management efforts usually turn to salvage operations that aim to recover timber values and return the stand to productivity (Safranyik *et al.* 1974; McMullen *et al.* 1986; Forest Practices Board 2004).

At a stand level, single-tree treatments that destroy the tree are considered highly efficacious at reducing or eliminating beetle populations. Thomson (1991) gives a standard efficacy value of 90% to stands where single-tree treatments are applied to all detected infested trees. By removing most of the infested material before beetle emergence, harvesting is likely more effective than single-tree treatments. However, during harvesting, up to 15% of the brood may survive in the stump of the tree (Thomson 1991). Harvesting is best used in combination with other treatments, especially where infestations are widespread (Fall *et al.* 2004; Hall 2004; U.S. Department of Agriculture Forest Service 2005).

Regardless of the treatment, efficacy will vary spatially due to factors such as adjacent mountain pine beetle populations and management strategies, wind, microclimates, rate of beetle spread, and the accuracy of population detection. For instance, at high spread rates, newly infested stands may be undetected and, therefore, untreated. This allows the mountain pine beetle population to increase and spread further (Thomson 1991).

Even at a fine spatial scale, little empirical research explores the efficacy of widely used direct-control-treatment strategies. Although some researchers feel that (during an epidemic) treatment simply delays the infestation of susceptible stands (Bradley 1989), others indicate that, if used correctly, treatment and suppression can be effective (Berryman 1978; Whitney *et al.* 1978). For example, in a study conducted during a previous mountain pine beetle epidemic, Miller *et al.* (1993) found that treatment reduced beetle-caused forest losses; however, the effects of individual treatment methods were not quantified. Since many direct-control strategies (particularly single-tree treatments) are expensive, labour-intensive, and demand good access to the infested stands, understanding their utility is paramount to effective management.

The goal of our research was to investigate the efficacy of mountain pine beetle treatments on infestation intensities. To meet this goal, we generated surfaces of infestation intensity by applying kernel density estimators (Silverman 1986; Bailey and Gatrell 1995) to point data collected during helicopter monitoring surveys of the mountain pine beetle. Using a combination of buffers and Voronoi diagrams (Okabe *et al.* 2000), we then assigned areas to each treatment site. Next, we investigated the effect of treatment on mountain pine beetle populations by comparing infestation intensities, in the year after treatment, at treated and randomly selected untreated locations. The random selection of untreated locations was conditioned on the initial maximum infestation intensities observed at treated sites.

Study Area and Data

The Morice Timber Supply Area (TSA), which covers approximately 1.5 million ha in British Columbia, is affected by the current mountain pine beetle epidemic (Figure 1). In the Morice TSA, the primary timber species is lodgepole pine (54%); hybrid spruce (*Picea*) is the secondary species. The mountain pine beetle has been monitored in the TSA using point-based, global positioning system (GPS) helicopter surveys, which use indicators of pine mortality (i.e., mainly changes in crown foliage colour) to monitor beetle activity. During helicopter surveys, clusters of infested trees, typically those with yellow and red crowns, are identified and a GPS is used to map cluster centres with a point. For each cluster, the number of infested trees is estimated. The maximum area represented by a GPS point is 0.031 km^2, equivalent to a circle with a radius of 100 m.

From 2001 to 2003, 26 215 GPS points were identified through aerial surveys. In 2001 and 2002, field crews surveyed 14 033 sites, during which a treatment strategy was suggested. Not all field locations were treated, but when treatments were applied, the date and treatment type were recorded. The numbers of sites treated in 2001 and 2002 were 1260 and 599, respectively. All treatments that occurred in the Morice TSA in 2001 and 2002 were in areas designated by the British Columbia Ministry of Forests as aggressive emergency management units. These units are characterized as having beetle increase rates that are, on average, five green (newly infested) trees per every red (previously infested) tree.

The onset of the mountain pine beetle infestation was not contemporaneous throughout the TSA. In the north and central regions, the infestation was established by the mid-1990s, whereas the infestation in the southern region became established in 1999 and expanded more rapidly. Management strategies applied to the various regions also differed. In the north, management was more aggressive than in the central region, and fewer treatments were applied in the south as efforts were anticipated to have little effect on the growth of the large beetle population. Anticipating that these regional differences might affect mountain pine beetle behaviour and their response to treatment, the Morice TSA was divided into three sub-areas on the basis of initial date of infestation. Relationships between treatment and infestation rates are presented separately for the North, Middle, and South sub-areas (Figure 1).

Description of Treatment Methods

Five general treatment categories (detailed below) were applied in 2001 and 2002 in the Morice TSA.

1. MSMA
2. pheromone-baited trap trees
3. fell and burn
4. small patch harvest
5. block harvest

Monosodium methanearsonate, or MSMA, is a pesticide that is applied to a frill cut into the bark at the base of infested trees (B.C. Ministry of Forests 1995). The chemical is drawn up through the conductive tissue and kills both the beetles under the bark and the infested tree (Shore and Safranyik 2004). The advantage of this treatment is that all the necessary equipment and

FIGURE 1. Location of the Morice Timber Supply Area in British Columbia.

materials can be transported easily to the site. A disadvantage is that MSMA must be applied within 24 days of initial beetle attack to be completely effective. Detection early in the beetle cycle can be difficult as foliage discoloration is not yet visible (McMullen *et al.* 1986). The widespread field program in the Morice TSA aided in early detection and the use of MSMA.

Tree baits used in the Morice TSA are loaded with a combination of trans-verbenone and exo-brevicomin. No conventional trapping was undertaken during this study. Although tree-baiting does not reduce the beetle population on its own, it increases the efficiency of other treatment strategies by encouraging beetles to aggregate in one area where they can be eliminated (McMullen *et al.* 1986). Typically, tree-baiting is followed by the removal of infested trees (by either fell and burn or small-scale harvesting), or treatment with MSMA. The effectiveness of tree-baiting depends on air temperature, wind speed, and the distance between baited trees and the site of beetle emergence (Barclay *et al.* 1998). Even with a strong wind, only a small proportion of mountain pine beetles respond to pheromone-baited trees located further than 1 km away (Barclay *et al.* 1998).

Fell and burn treatments require the infested tree to be felled, cut into sections, piled on the stump, and burnt on site. Fuel oil may be used to ensure that the burn completely chars the bark. Although this treatment is effective any time before the emergence of the beetles, it is time consuming and may be restricted by fire hazard conditions (McMullen *et al*. 1986). The effectiveness of the treatment may be reduced if the brood is not completely destroyed in both the stump and the stem (Thomson 1991). Fell and burn treatments are most suitable for lightly infested areas, the periphery of larger infestations, and where wood recovery is not practical (Safranyik *et al*. 1974; B.C. Ministry of Forests 1995; Forest Practices Board 2004).

Small patch harvesting involves removing single trees or small patches of infested trees to prevent the spread of beetles into adjacent areas (B.C. Ministry of Forests 1995). For smaller infestations, harvesting the infested patch before beetle emergence can maximize the infested material removed and reduce the mountain pine beetle population in a localized area. This control is best used in combination with other treatments, especially where the infestations are large (U.S. Department of Agriculture Forest Service 2005). The practicality of small patch harvesting may be limited by access, land ownership, environmental sensitivity, and the speed of forest removal (McMullen *et al*. 1986).

Conventional block harvesting is sanitation harvesting on a larger scale (i.e., covering areas > 1 ha), and is considered an efficient short-term method of reducing large populations of beetles (Safranyik *et al*. 1974; McMullen *et al*. 1986; B.C. Ministry of Forests 1995; Shore and Safranyik 2004). Typically, harvesting is directed at the leading edge of the infestation where the highest numbers of currently infested trees exist (Shore and Safranyik 2004). A disadvantage of block harvesting is the potential for spread from stumps, which are estimated to host up to 15% of the brood (Thomson 1991).

Methods

Figure 2 presents an overview of our analysis methods. First, GPS data and kernel density estimators were used to generate infestation intensity surfaces (Nelson *et al.* 2006). Kernel density estimators allow continuous representation of the infestation and enable the data to be presented as infestation intensity rather than counts. A continuous representation also facilitates spatial comparisons of infestation levels through time. The kernel density estimator has advantages over simple overlay methods when converting between discrete and continuous representations in that it calculates values using a window, or zone of influence, and weights the influence of points within it using a distance decay function (Silverman 1986; Bailey and Gatrell 1995). The result is an intensity surface where the expected number of infested trees per unit area varies smoothly from location to location. For the GPS point data, both the locations and areas associated with points are uncertain due to survey error; generating a smoothed representation is one way of reducing data noise (Nelson *et al*. 2006). For details of kernel density estimation, we refer the reader to Bailey and Gatrell (1995) and Silverman (1986).

Conceptually, the intensity $\hat{\lambda}(z)$ at a particular location z in a study area A can be estimated by the naïve kernel estimator:

$$\hat{\lambda}(z) = \frac{\text{the number of events in a disk centred on } z}{\text{area of the disk}} \quad [1]$$

A more precise estimate, $\hat{\lambda}_\tau(z)$, is defined by:

$$\hat{\lambda}_\tau(z) = \frac{1}{p_\tau(z)} \left\{ \sum_{i=1}^{n} \frac{1}{\tau^2} k\left(\frac{(z - z_i)}{\tau}\right) y_i \right\} z \in A \quad [2]$$

where: z and A are defined as above;

τ is the radius of a disk centred on z;

$k(\ )$ is the kernel, or a probability density function, which is symmetric around about the origin;

z_i ($i = 1, \ldots, n$), are locations of n observed events, and

y_i is the attribute value at z_i

The term $p_\tau(z) = \int_A k[(z-u)/\tau]du$ is an edge correction equivalent to the volume under the scaled kernel centred on z, which lies inside of A (Diggle 1985).

The type of kernel $k(\ )$ determines how events within the disk will be weighted. Although the kernel type may be theoretically important, it has little impact on kernel output (Silverman 1986:43; Scott 1992:133; Simonoff 1996:103–105). The standard kernel is the Gaussian. For this study, a quartic kernel was used as it is a good approximation of the Gaussian kernel yet is computationally less burdensome (Silverman 1986:76–77; Waller and Gotway 2004:132–133). For large data sets such as the mountain pine beetle data, computational speed is an important factor. Using the quartic kernel equation [2] becomes:

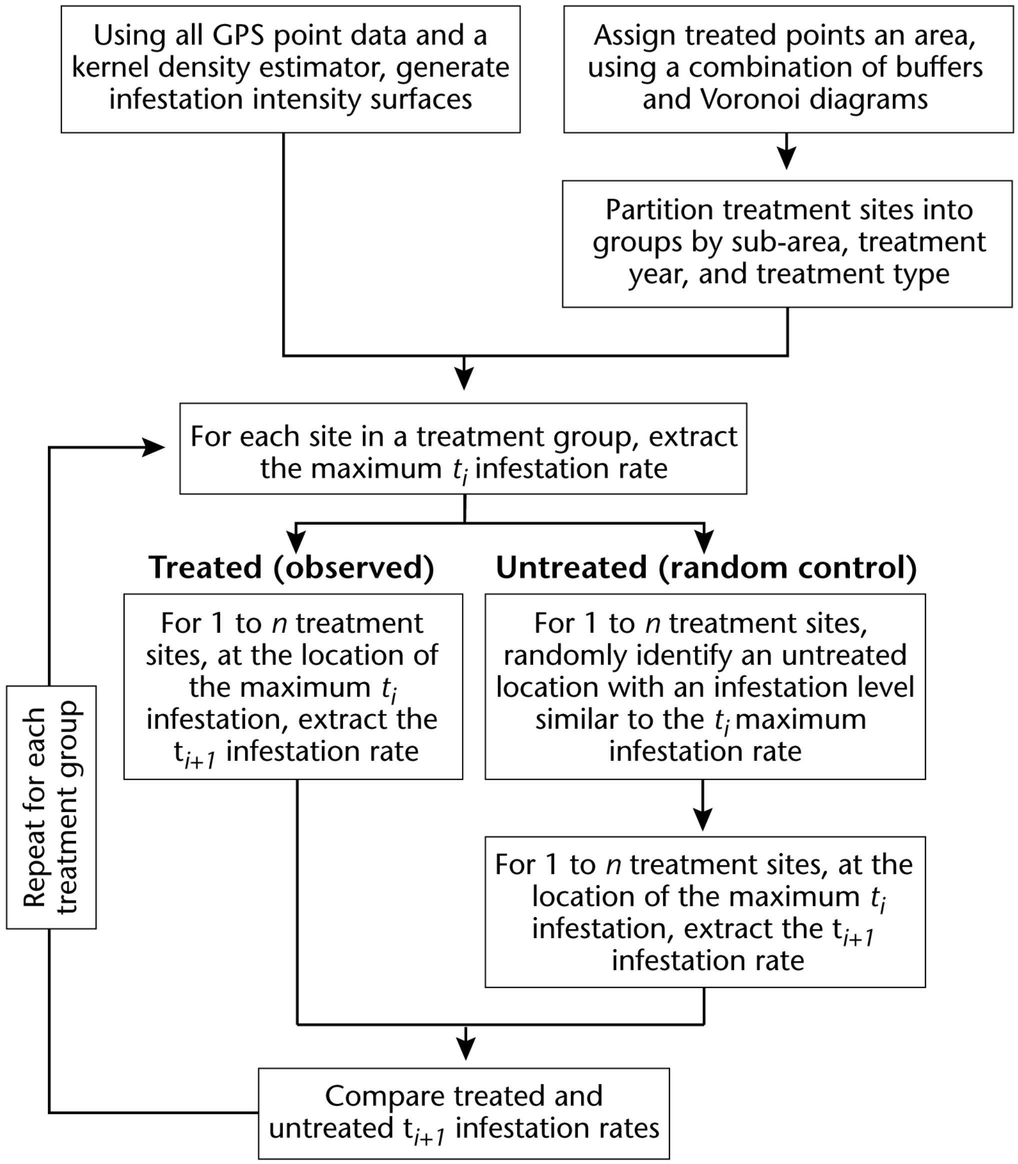

FIGURE 2. Analysis methods used to investigate the efficacy of mountain pine beetle treatments on infestation intensities.

$$\hat{\lambda}_\tau(z) = \frac{1}{p_\tau(z)} \sum_{h_i \le \tau} \frac{3}{\pi\tau^2} \left(1 - \frac{h_i^2}{\tau^2}\right)^2 y_i \, z \in A \qquad [3]$$

where: $h_i = z - z_i$

The amount of smoothing, controlled by τ, has a larger impact on kernel results (Kelsall and Diggle 1995). Small values of τ will reveal small-scale features of the data and larger values will reveal general features. Inevitably, however, some element of subjectivity exists in choosing an appropriate value for τ. For this research, τ was set to 2000 m based on the characteristics of the data (Nelson *et al.* 2006) and mountain pine beetle biology (Safranyik *et al.* 1992; Safranyik and Carroll 2006). The intensity surface was represented as a raster grid with a grid size 200 × 200 m.

The second step in the analysis involved the assignment of areas to points associated with treatments. The spatial locations of treatment sites are marked as points during GPS surveys and have a maximum associated area of 0.031 km^2. The spatial distribution of points provides insight into the variability of area sizes. Points having nearest neighbour distances of less than 200 m are likely to represent treatment areas smaller than 0.031 km^2.

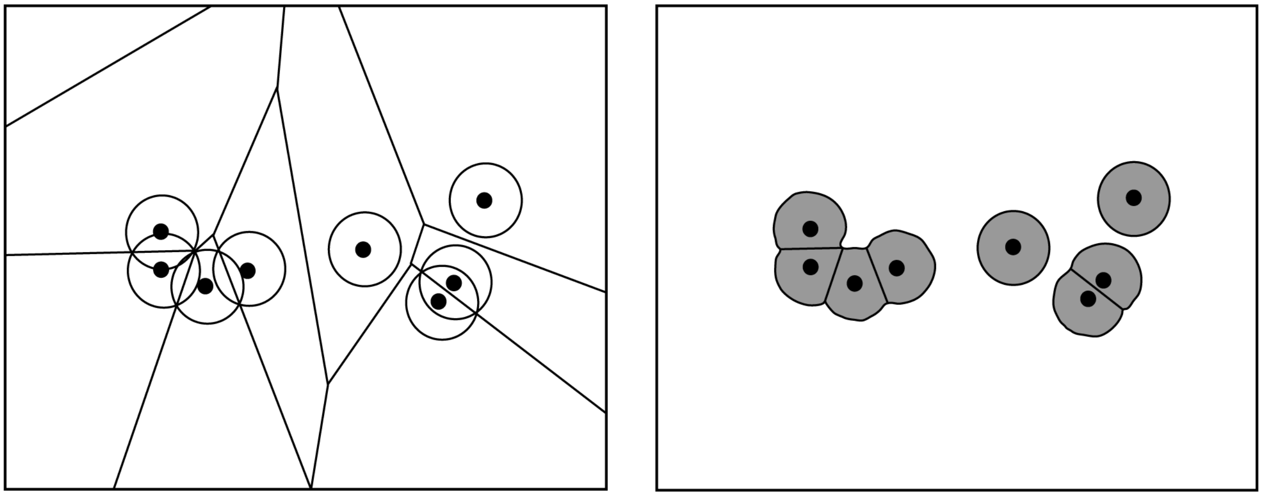

FIGURE 3. Assigning treatment areas to points.

A combination of buffers and Voronoi diagrams was used to assign area size to treatment sites. The Voronoi diagram creates a tessellation of polygons from a set of points. Each polygon consists of the area that is closer to a given point than to any other point (Okabe *et al*. 2000). The result is small Voronoi polygons in areas of high GPS-point density and larger polygons when the points are more dispersed. A circular buffer with a 100 m radius and a Voronoi polygon was generated for each treatment point. Treatment areas were chosen at the intersection of buffers and Voronoi polygons, allowing treatment areas of 0.031 km^2 or smaller depending on point density (Figure 3).

Treatment groups were generated by partitioning sites based on sub-areas, treatment type (MSMA, pheromone-baited trees, fell and burn, small patch harvest, and block harvest), and treatment year. The number of sites in each treatment group is shown in Table 1. Because trends were difficult to identify in groups with fewer sites, 16 treatment groups with 10 or more sites were used in the remainder of the analysis.

The following analysis was undertaken for each treatment group:

- Areas assigned to sites were overlain with the kernel density estimated surfaces, representative of infestation rates (trees per 4 hectares).
- At each treatment site, the maximum infestation intensity in the year of treatment (t_i) was extracted; the maximum value indicated where the infestation is most intense at the site.
- At the location where the maximum infestation intensity was identified, the infestation intensity in the year following treatment (t_{i+1}) was also determined.

TABLE 1. The number of treatment sites in each sub-area and year

	North		**Middle**		**South**		**Morice TSA**	
	t_i **2001**	t_i **2002**	t_i **2001**	t_i **2002**	t_i **2001**	t_i **2002**	t_i **2001**	t_i **2002**
MSMA	523	222	194	200	78	8	**795**	**430**
Pheromone-baited trap	70	1	87	3	36	4	**193**	**8**
Fell and burn	86	2	69	75	6	45	**161**	**122**
Small patch harvest	6	0	87	11	4	0	**97**	**11**
Block harvest	14	1	0	27	0	0	**4**	**28**
Total	**699**	**226**	**437**	**316**	**124**	**57**	**1260**	**599**

To characterize the efficacy of various treatments, the observed t_{i+1} infestation rate for each treatment site was compared to the infestation rate at a randomly selected, untreated location. The random selection of untreated locations was conditioned on the maximum infestation rates observed at treatment sites in t_i. For each site in the treatment group, all untreated locations with similar t_i infestation rates were selected and from these a control location was randomly determined. At the randomly selected untreated site, t_{i+1} infestation intensities were extracted. By forcing the t_i infestation rates to be equivalent in the treated and randomly selected untreated scenarios, we were able to explore how the t_{i+1} infestation rates at treated locations varied relative to rates at untreated sites.

A scatter plot was used for each treatment group to compare treated and untreated t_{i+1} infestation rates. A plot point represents an untreated (y) and treated (x) site with similar t_i infestation intensity. On each plot, a diagonal line was added to aid interpretation. Data points that fall above the line have higher t_{i+1} infestations at the randomly selected untreated site than at the treatment site. Conversely, when a data point occurs below the line, the t_{i+1} infestation intensity is higher for the treated site than at the untreated location. Therefore, the more points occurring above the line, the more often treatment results in smaller infestations relative to randomly selected, untreated locations with the same initial conditions. This exploratory analysis was supported by Mann-Whitney tests, which were used to compare the mean t_{i+1} maximum infestation intensities of treated and randomly selected untreated locations. The null hypothesis that the means of treated and untreated locations are similar was assessed using a significance level of 0.05.

Results

Scatter plots for MSMA treatments are shown in Figure 4. For most treatment groups, scatter plots show approximately equal amounts of data above and below the line. Overall, trends illustrated by these plots indicate that in less than half the cases, sites treated with MSMA have lower t_{i+1} infestation intensities than those found at randomly selected untreated sites (Table 2). An exception is the 2001 MSMA treatment group in the South sub-area, which has more data below the line; although eight untreated locations in this sub-area have t_{i+1} infestation intensities of zero, all rates associated with treatment are greater than zero. For 2001 MSMA treatment groups from the North and Middle sub-area, the t_{i+1} infestation intensities at randomly selected untreated sites range to higher

TABLE 2. Mean of observed and random infestation maximums in t_i and t_{i+1}. Z values are the results of Mann-Whitney test for difference of means between observed treated and randomly selected untreated locations in t_{i+1}. *Italics* is used to indicate treatments where the null hypothesis (i.e, the t_{i+1} mean maximum infestation intensity at treated and untreated locations are not different) is rejected ($\alpha = 0.05$). *Regular italics* indicates those scenarios where the mean maximum t_{i+1} infestation level is lower at treated locations than at untreated infestation. ***Bold italics*** indicates those scenarios where the mean maximum t_{i+1} infestation level at treated locations is higher than at untreated sites.

		North				Middle				South			
	t_i	t_i mean max	t_{i+1} observed mean max	t_{i+1} random mean max	z	t_i mean max	t_{i+1} observed mean max	t_{i+1} random mean max	z	t_i mean max	t_{i+1} observed mean max	t_{i+1} random mean max	z
MSMA	2001	*9.1*	*3.1*	*4.1*	*–2.3*	*8.8*	*5.0*	*5.9*	*–2.0*	***8.0***	***29.1***	***23.0***	***–2.7***
	2002	***3.8***	***13.6***	***8.8***	***–2.9***	***5.5***	***10.5***	***7.8***	***–4.8***	—	—	—	—
Pheromone-baited trap	2001	*14.5*	*1.5*	*5.6*	*–5.4*	***21.8***	***18.6***	***13.4***	***–2.6***	27.3	49.3	40.3	–1.7
	2002	—	—	—	—	—	—	—	—	—	—	—	—
Fell and burn	2001	*6.3*	*0.6*	*2.1*	*–6.2*	***16.5***	***12.1***	***8.1***	***–2.6***	—	—	—	—
	2002	—	—	—	—	2.3	4.5	5.8	–0.1	8.5	5.2	6.6	–0.6
Small patch harvest	2001	—	—	—	—	10.5	4.7	6.3	–1.0	—	—	—	—
	2002	—	—	—	—	13.8	9.7	15.4	–1.5	—	—	—	—
Block harvest	2001	*23.7*	*2.1*	*7.8*	*–2.4*	—	—	—	—	—	—	—	—
	2002	—	—	—	—	*14.9*	*8.8*	*14.1*	*–4.2*	—	—	—	—

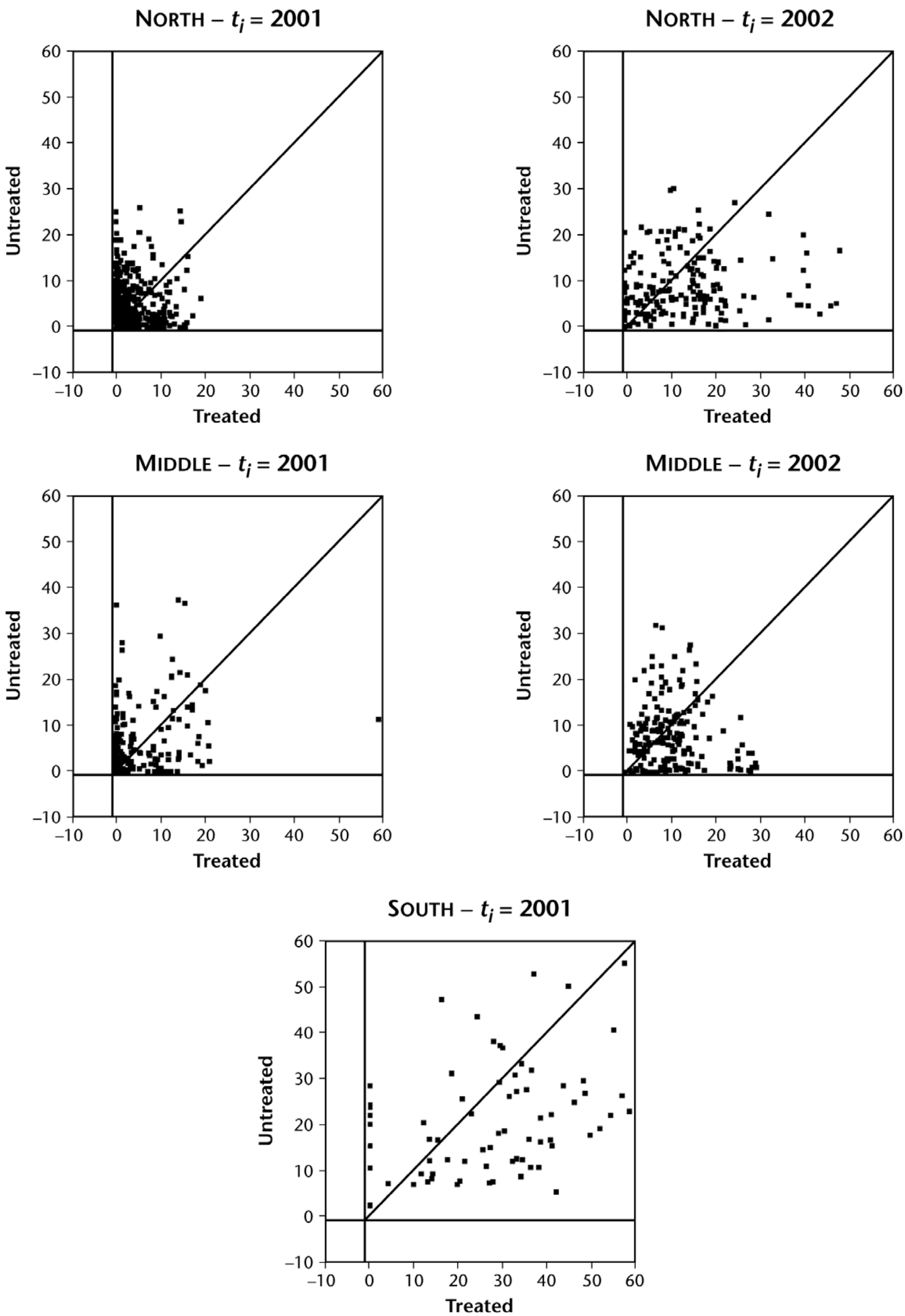

FIGURE 4. Comparison of t_{i+1} infestation intensities for MSMA treatment areas and untreated sites.

values than observed at treated locations; for other treatment groups, however, the ranges are similar or higher values are found at the MSMA-treated sites. For all years and sub-areas, the hypothesis that the mean maximum infestation intensities a year after treatment are similar for treated and untreated sites can be rejected; however, for three out of five treatment groups (North 2001, Middle 2002, and South 2001) the random locations have lower mean t_{i+1} maximum infestation rates than the treated locations (Table 2).

Scatter plots associated with pheromone-baited tree treatments are shown in Figure 5. Some scatter plots show reduced t_{i+1} infestation rates when pheromone baiting is used, but others do not. A reduced t_{i+1} infestation rate (relative to randomly selected untreated locations) is observed for North sub-area sites treated with pheromone baiting in 2001. Most points are found above the line, indicating that untreated locations have higher t_{i+1} infestation intensities. Also, in t_{i+1}, pheromone-baited treatment sites have infestation intensities ranging

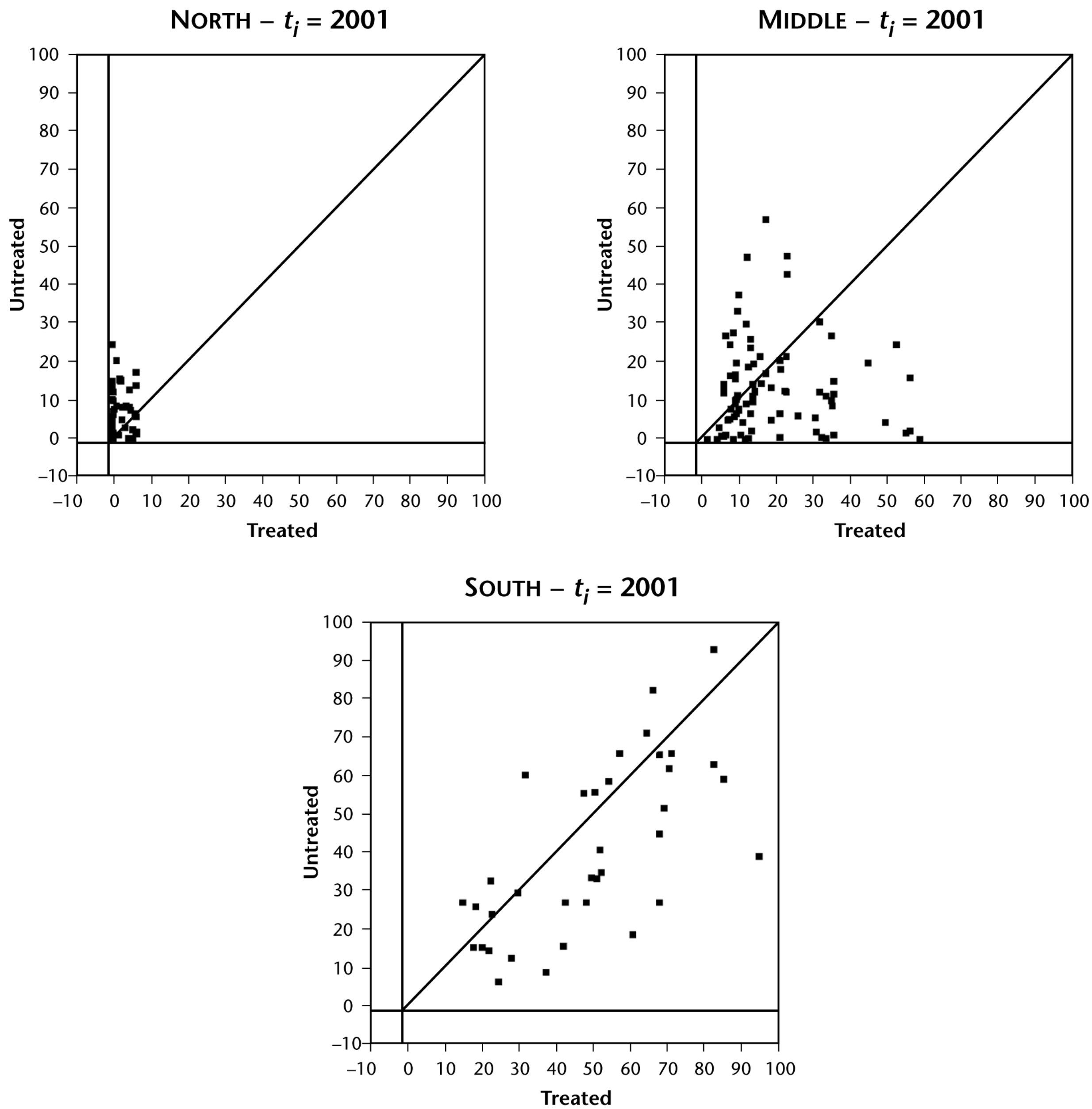

FIGURE 5. Comparison of t_{i+1} infestation intensities for pheromone-baited trap treatment areas and untreated sites.

to 7 trees per 4 hectares, whereas untreated locations have infestation intensities that range to approximately 25 trees per 4 hectares. For 2001 pheromone-baited treatment sites in the Middle sub-area, the range of infestation intensities in t_{i+1} is similar to untreated locations, but a larger number of comparisons show higher infestation intensities in the treated case. The same trend is found (only more strongly) in the South sub-area when sites are treated with pheromone-baiting in 2001. The inconsistencies in these exploratory results are supported by tests of the null hypothesis that mean t_{i+1} maximum infestation intensities are similar for untreated and pheromone-baited treatment locations. The null hypothesis is rejected for the North 2001 and Middle 2001 treatment groups (Table 2). The Middle 2001 treatment group, however, has a higher mean t_{i+1} maximum infestation intensity when pheromone-baiting treatments have occurred. An increase in the mean t_{i+1} infestation rate, although not statistically significant, is also observed for the South 2001 treatment group.

Scatter-plot trends associated with fell and burn treatments are variable (Figure 6). For 2001 fell and burn treatments applied in the North sub-area, most sites have lower t_{i+1} infestation intensities than at untreated locations. As well, the t_{i+1} infestation intensities associated with fell and burn treatments range from zero to approximately 5 trees per 4 hectares; for untreated cases, values range from zero to approximately 9 trees per 4 hectares.

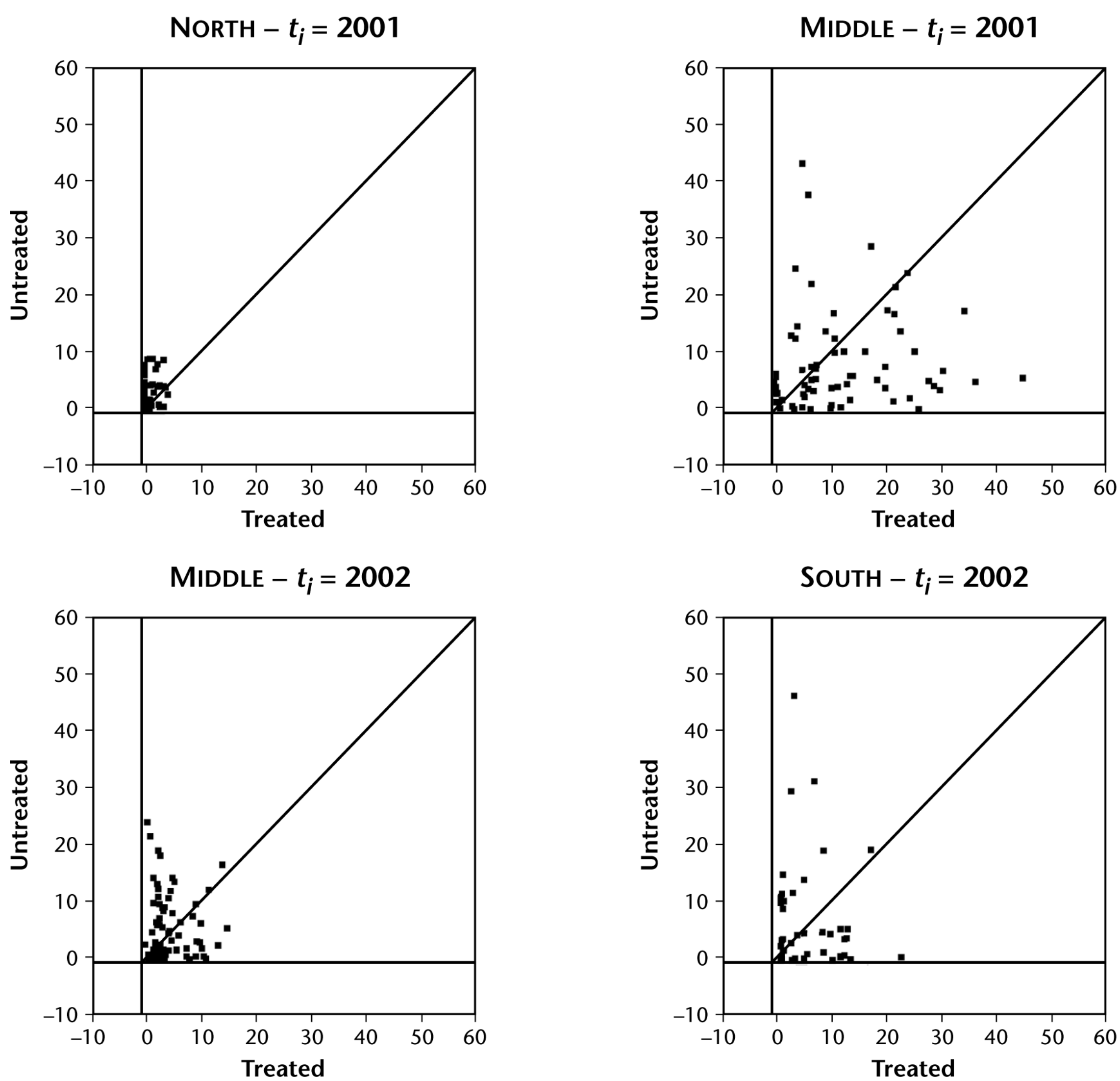

FIGURE 6. Comparison of t_{i+1} infestation intensities for fell and burn treatment areas and untreated sites.

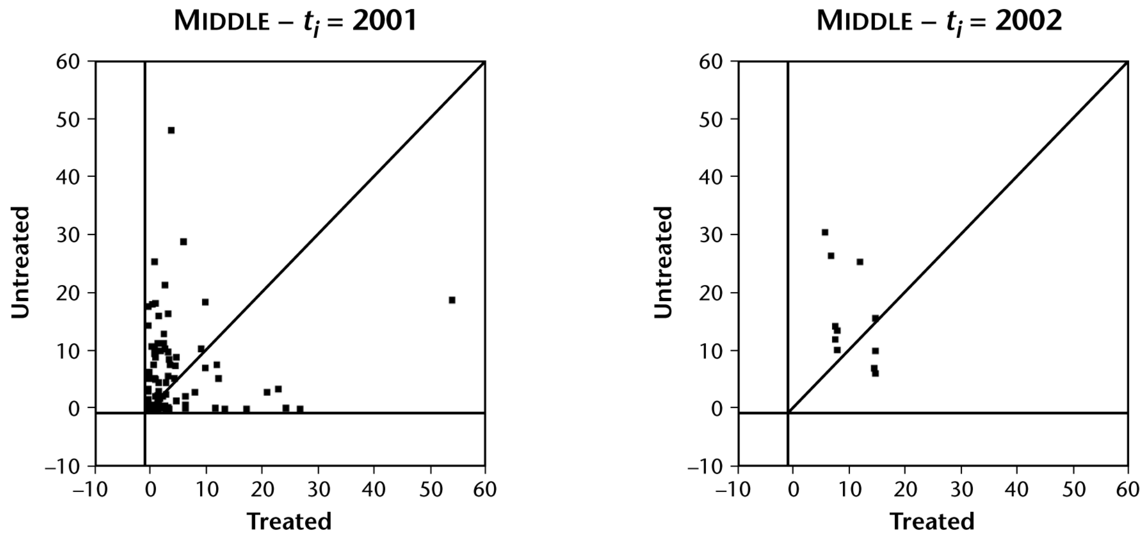

FIGURE 7. Comparison of t_{i+1} infestation intensities for small patch harvest treatment areas and untreated sites.

A unique characteristic of the results from the North 2001 treatment group is that t_{i+1} values had little variance. In the Middle sub-area in 2001, the impact of fell and burn treatments appears to be negligible. More points are observed below the line (i.e., larger infestations when treatments were applied) and the ranges of t_{i+1} infestation intensities are approximately the same. In the Middle sub-area, the impact of fell and burn treatments applied in 2002 is unclear. Although the t_{i+1} infestation intensities associated with untreated locations range to higher values (25 versus 15 trees per 4 hectares), the majority of scatter-plot points are below the line, which indicates that treated sites tend to have larger infestations. A similar pattern is seen in the South sub-area for sites treated with fell and burn in 2002. Again, the range of t_{i+1} maximum infestation intensities is greater for untreated locations; however, an approximately equal number of scatter-plot points fall above and below the line. The variability in results is supported by the statistical tests reported in Table 2. In three of the four treatment groups, the mean of t_{i+1} maximum infestation intensities of treated locations is less than at random untreated locations; only in North t_i 2001 is the null hypothesis rejected.

The Middle sub-area is the only region where small patch harvests were used (Figure 7). Overall, small patch harvesting appears to generate some reduction in t_{i+1} infestation intensities. For locations treated in 2001, the range of t_{i+1} infestation intensities is similar between treated and untreated cases; however, more cases fall above the line, which indicates that infestations associated with untreated areas tend to be larger than those associated with treatments. Fewer sites received small patch harvest treatments in 2002, but the impact of treatment is stronger. In all but three cases, the t_{i+1} infestation intensities are higher for untreated cases. As well, the maximum t_{i+1} infestation intensity is 2.5 times greater for untreated cases. The statistical test indicates that, although the mean maximum t_{i+1} infestation intensities are lower for untreated sites than for treated sites, the null hypothesis of equal means cannot be rejected (Table 2).

Infestation trends associated with block harvesting demonstrate that treatment leads to a reduction in t_{i+1} infestation intensity (Figure 8). For the North 2001 treatment group, t_{i+1} infestation intensities were typically smaller for sites treated by block harvesting than for untreated sites. As well, the maximum t_{i+1} infestation intensity was nearly five times greater for the untreated scenarios than for block harvest treatment scenarios. In the Middle sub-area, for sites treated by block harvesting in 2002, the infestation intensities in t_{i+1} were almost always greater for untreated scenarios and maximum infestation rates found at untreated sites were more than two times the size of those found after block harvesting. These results seem to indicate that block harvesting leads to a reduction in infestation intensity and are supported by lower mean maximum infestation intensities in t_{i+1} when harvesting occurs and rejection of the null hypothesis of mean equality (Table 2). This may reflect that, in contrast to single-tree treatments, harvesting removes the remaining susceptible trees.

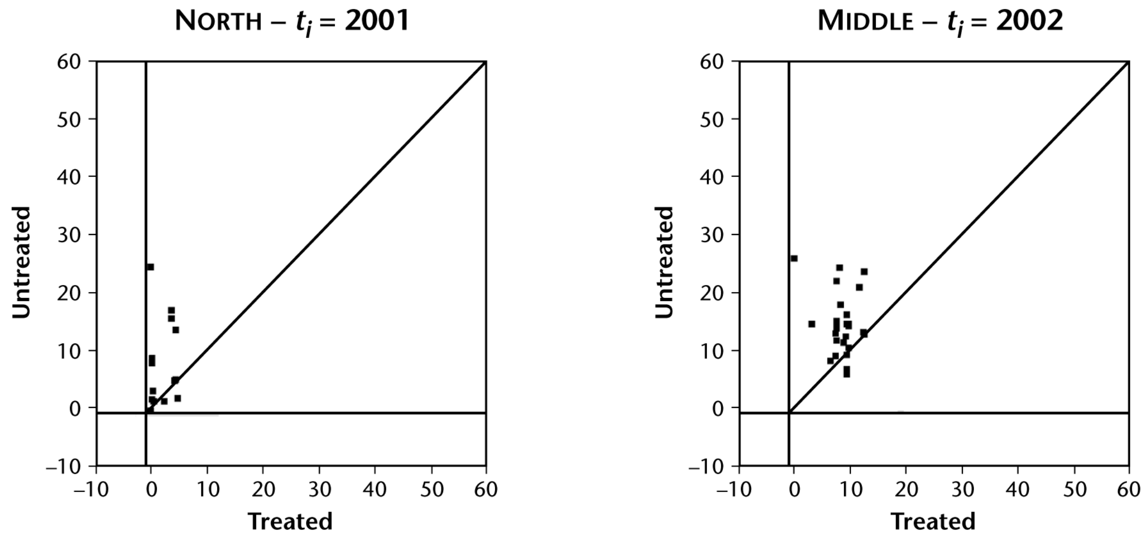

FIGURE 8. Comparison of t_{i+1} infestation intensities for block harvest treatment areas and untreated sites.

Discussion

The comprehensive data set collected for the Morice TSA provides a unique opportunity to explore the effects of treatment on mountain pine beetle infestation rates. Using a kernel density estimator, point data from 2001 to 2003 were used to generate annual surfaces of infestation intensity. This provides a spatially continuous representation of the infestation and enables spatial-temporal investigation of treatment efficacy.

The random selection of untreated locations was conditioned on the maximum infestation intensity at treated locations in t_i. By holding the t_i infestation intensities constant, we produced a control group that allowed us to explore the impact of treatments relative to untreated locations with similar initial conditions. This method, however, does not provide a control for any differences in the initial conditions in the immediate vicinity of the treated and untreated locations. Although the treated and untreated locations had similar infestation intensity, no constraint required that their neighbourhoods be similar. The use of a kernel density estimated surface minimizes the effect of the neighbourhood. Kernel surfaces change in a smooth continuous fashion which minimizes differences in the neighbourhoods of locations with similar maximum infestations, providing the neighbourhoods are not large.

Substantial variability was evident in the impact of MSMA treatments. Overall, MSMA does not appear to lead to a reduction in t_{i+1} infestation rates. This may indicate that MSMA has little efficacy during a mountain pine beetle epidemic. Given that stabilization of mountain pine beetle population size requires 97.5% mortality, even small errors in timing or application of MSMA will lead to population growth. The lack of detectable impact may be linked to the susceptible trees that remain after an MSMA treatment. Even if the treatment successfully killed more than 97.5% of the brood, the remaining trees in an area may be infested by mountain pine beetles that emigrate from other sites; however, in British Columbia, single-tree treatments are typically applied in aggressive emergency management units with the efficacy target of 80%. The intent is to treat at least 80% of the infested trees the first year and at least 80% of infested trees again in the following year. If the beetle spread ratio is about 5:1 during the first year, suppression is possible only if 80% or more of infested trees are effectively treated (see Carroll *et al.* 2006:164).

Results from pheromone-bait treatments are the most difficult to interpret because baiting is used in combination with other single-tree treatments. An increase in t_{i+1} infestation intensity could be the result of effective treatment, as mountain pine beetles are concentrated in a specific location, with nearby sites hosting fewer beetles. It is interesting that the variability in t_{i+1} infestation rates is greatest in the South sub-area where infestation magnitude is generally largest, and lowest in the North where infestations are more moderate and heavily treated. This may indicate that while the efficacy of pheromone-bait treatments is difficult to characterize, the heavy treatment of the North sub-area had an overall impact in reducing the infestation. As well, these results highlight an inherent spatial variability in treatment efficacy that probably reflects heterogeneity in landscape conditions.

The impact of fell and burn treatments is variable. When compared with the MSMA and pheromone-bait treatments, however, trends in t_{i+1} infestation intensity reductions are more clear. Differences in these trends are of interest because all single-tree treatment results are subject to similar interpretation issues. For instance, single-tree treatment methods leave susceptible trees on-site that could be infested by immigrating mountain pine beetles, regardless of local treatment efficacy.

Although the detectable reduction in t_{i+1} infestation rates is greater for fell and burn treatments than for the MSMA and pheromone-baiting treatments, further investigation is required to determine which is more effective when management resources are finite. The MSMA treatment is faster and less expensive to apply and, therefore, can be used to treat more infestation centres than the fell and burn treatment. If more data were available, it would be interesting to determine how the efficacy of these treatments plays out over several years. Also, as with pheromone-baited trees, the North sub-area had the lowest and least variable t_{i+1} infestation rates, which may be further evidence of the effectiveness of the more aggressive strategy in this region. An interesting difference in these methods is that fell and burn treatments actually remove infested trees. As detection is associated with change in crown foliage colour, fell and burn sites are less likely than MSMA or pheromone-baited tree sites to have treated trees re-counted as infested in the following year.

Small patch and block harvesting both reduce t_{i+1} infestation intensity; however, the reduction is more pronounced with the block harvesting treatment. Infested trees may remain after small patch harvesting because many blocks are approximately 1 ha in size, whereas the spatial grain for analysis is 4 ha. Therefore, trees neighbouring harvest sites may be infested in future years and are spatially indexed as the same location. As with all spatial analysis, the spatial grain applied in this treatment study affects the interpretation of treatment efficacy. A spatial grain of 4 ha may be too general to identify local effects, but it does help us to understand the implications of management over broader regions.

Interpreting the efficacy of harvesting is complicated by the opposite issue of single-tree treatments. The efficacy of single-tree treatments is affected by the remaining susceptible trees at a site, which may become hosts for neighbouring beetle populations. Although no susceptible trees are left within a harvested small patch or block, mountain pine beetles that remain in stumps may emigrate and infest other locations. Still, within 4 ha areas, small patch and block harvesting more consistently reduce t_{i+1} infestation intensities than do single-tree treatments. Overall, the more infested trees removed during treatment, the greater the reduction in t_{i+1} infestation intensity.

The trend found between efficacy and general treatment levels within each of the sub-areas is an interesting one. In the North sub-area, treatment was aggressive when the infestation rates were relatively moderate. In this sub-area, declining rates in infestation levels, relative to the randomly selected untreated locations, were observed for four of the five treatments. The North sub-area approximates British Columbia's northern limit for the mountain pine beetle. This sub-area, therefore, experienced less pressure from beetles outside the border of the study area than did the Middle and South sub-areas. In the Middle sub-area, fewer treatments took place; in the South sub-area, infestation was very high and treatment rates the lowest. In general, treatment in these two regions produced less marked reductions in infestation than in the North. These results may indicate that when mountain pine beetle populations are at moderate, although still epidemic, levels in and around the treatment site, aggressive treatment is effective.

No trend was evident between initial (t_i) infestation rates and treatment efficacy; however, a trend was evident with t_{i+1} infestation levels. In all cases, the random and observed values in t_{i+1} move in the same direction relative to the infestation levels in t_i. This seems to indicate that the global infestation levels are affecting the local treatment efficacy. In addition, in all cases when mean t_{i+1} maximum infestation rates are less than 10 trees per 4 hectares (200 × 200 m), treatment leads to a reduction in t_{i+1} infestation intensity relative to random untreated locations (although not always statistically significant). Infestation levels in t_{i+1} result from the combined effects of climate, the number of susceptible hosts (which will change as an infestation progresses), and treatment. When conditions enable a reduction in the infestation levels to 2.5 or fewer infested trees per hectare, treatment can be effectively applied. Although it is difficult to know in t_i whether such conditions will prevail, in locations where the infestation rates are very high, harvesting seems to be the only treatment option that will likely reduce infestation rates at a specific site. When infestations occur in isolated pockets, however, various treatment options will likely reduce infestation rates, particularly when applied intensively.

Conclusions

Forest managers have long assumed that single-tree treatments work best when infestation levels are low. Our analysis confirms this theory and the appropriateness of historical management strategies. It is difficult for managers to know when to switch from single-tree treatments to larger-area treatments. Our results indicate that single-tree treatments are most effective in the absence of intense beetle populations in nearby regions. During 2001 and 2002, the South sub-area was under intense pressure from beetle populations in the southeast. In the North and Middle sub-areas, beetle populations in bordering regions were low in 2001 and intense in 2002. Although general infestation levels in 2001 were much greater in the North and Middle sub-areas than in the South, the absence of beetles outside these regions allowed for effective MSMA treatments. In 2002, beetle populations were intense in areas adjacent to the entire eastern border of Morice TSA. As a result, MSMA treatments were ineffective in all sub-areas.

Five important management implications are evident from this research.

1. When mountain pine beetle populations are moderate, although still epidemic, aggressive treatments can be effective.
2. Single-tree treatments will only be effective when infestation intensities are low or moderate in both the treatment area and surrounding regions.
3. Single-tree treatments will be most effective when treatments are applied intensively throughout a region.
4. Overall, the more infested trees removed during treatment, the greater the reduction in infestation intensity in the following year.
5. When conditions enable a reduction in the infestation levels to 2.5 or fewer infested trees per hectare, treatment can be effectively applied.

As an exploratory investigation of treatment effects, our research represents an important first step in providing information about treatment efficacy to managers and modellers. Further investigation should explore the impact of treatment density and the spatial configuration of treatments on efficacy. As well, a multiyear study of the response of infestation rates to treatment would be useful.

Our results indicate that single-tree treatments are most effective in the absence of intense beetle populations in nearby regions.

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Test Your Knowledge . . .

The impact of treatment on mountain pine beetle infestation rates

How well can you recall some of the main messages in the preceding research report? Test your knowledge by answering the following questions. Answers are at the bottom of the page.

1. The efficacy of treatment is the most clear for which treatment type?
   A) Small patch and block harvesting
   B) MSMA
   C) Fell and burn
   D) Block harvesting

2. Under what conditions are mountain pine beetle treatments likely to be ineffective?
   A) Where infestation levels are increasing
   B) Where infestation levels in surrounding areas are high
   C) Where infestation levels are low

3. When mountain pine beetle populations reach epidemic levels there is no point in attempting treatment.
   A) True
   B) False

ANSWERS

1. A 2. B 3. B