FINAL REPORT

Title: Do Fuel Reduction Treatments in Alaska Affect Tree Health?

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LIST OF ABBREVIATIONS

NSE	Northern Spruce Engraver
USDA	United States Department of Agriculture
CWD	Coarse Woody Debris
DBH	Diameter at Breast Height
GLMM	Generalized Linnear Mixed Effects Model
CI	95% Confidence Interval
SB	Spruce Beetle

KEYWORDS

Alaska, boreal, fuel reduction treatment, hand-thinned fuel treatment, masticated fuel treatment, spruce beetle, northern spruce engraver, tree health, tree mortality, tree disease, broken top

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Do Fuel Reduction Treatments in Alaska Affect Tree Health?

Abstract

Increasing wildfire risk in Alaska has prompted the adoption of fuel reduction treatments, including hand-thinning and mechanical mastication, to mitigate fire behavior and improve firefighter safety. This intensification of forest management creates disturbances that may negatively, neutrally, or positively influence tree health conditions, including tree mortality, wind damage, disease, and one of the most wide-spread health threats to these forests, bark beetle infestations. This study evaluated the effects of fuel reduction treatments on adverse tree health conditions by surveying 33 sites across two regions experiencing endemic and outbreak levels of spruce beetle infestation in Alaska. We assessed tree mortality, wind damage, disease occurrence, and bark beetle infestation across control, edge, and treatment transects within both hand-thinned and masticated sites. Our results show that in the region with endemic levels of spruce beetle (endemic region), the probability of occurrence of adverse tree health conditions did not differ between trees in control, edge, and treatment transects at hand-thinned sites, or between control and edge transects at masticated sites. This suggests that fuel reduction treatments have no significant impact on forest health in the continental boreal forest of the endemic region. In the more maritime outbreak region, which has recently experienced significant spruce mortality due to the spruce beetle, we found that leave trees in hand-thinned treatments were more likely to be healthy. At hand-thinned sites, trees in treatment transects had 4.1 (95% CI = [1.2, 14.0]) times greater odds of being alive than edge trees, which had 2.1 (CI = [1.2, 3.6]) times greater odds of being alive than control trees, while at masticated sites, control trees had 1.5 (CI = [1.2, 2.1]) times the odds of being alive than edge trees.

In the outbreak region, at hand-thinned sites, white spruce in the control had 11.4 (CI = [2.9, 45.41]) times greater odds of past or current spruce beetle presence than in the edge, and 27.8 (CI = [3.3, 237.0]) times greater odds than in the treatment, but there was no effect of transect on spruce beetle presence in black spruce, or in either white spruce or black spruce at masticated sites. In the outbreak region, the probability of occurrence of wind damage and diseases did not differ between trees in control, edge, and treatment transects at hand-thinned sites, or between control and edge transects at masticated sites.

Our results show that fuel reduction treatments, particularly hand-thinning, effectively reduced the density of dead trees and did not significantly increase tree mortality, wind damage, disease, or bark beetle infestation, with the exception of an increase in northern spruce engraver and disease presence along the edges of masticated sites in the outbreak region. Overall, our findings suggest that fuel treatments reduce hazardous dead trees without sacrificing the health of the remaining trees, providing support for fuel treatments as a low-risk strategy for forest management.

1. Objectives

The Graduate Research Innovation Award was used to supplement a master's thesis on the effect of fuel reduction treatments on tree health in Alaska. The award allowed us to add the component of bark beetle presence into our evaluation of tree health. The objective of this project was to identify the fuel treatment characteristics that drive bark beetle population growth. As we refined our methodology, we focused specifically on bark beetle presence as a stand-in for population growth. We hypothesized that fuel treatments that create high-quality bark beetle substrate, in the form of stressed trees and fresh coarse woody debris, have greater bark beetle presence. We also hypothesized that the effects of fuel treatment on bark beetle presence are greater when initial populations are at endemic levels compared to outbreak levels. We completed our objective by testing for effects of fuel treatment on bark beetle presence, and evaluating how treatment type (hand-thinned vs masticated), region (Interior vs Southcentral Alaska), and amount of suitable coarse woody debris (zero, low, high) influenced the presence of both spruce beetle and northern spruce engraver.

The project addresses the need to understand vegetation dynamics and fuel accumulation following fuel treatments, identified in the task statement. Bark beetles are the most significant tree-killing pests in Alaska, and new or enlarging outbreaks have the potential to rapidly and drastically change fuel characteristics, complicating wildfire management. This research addresses the gap in our knowledge of how trees remaining after fuel treatments are affected by bark beetles.

2. Background

As climate change exacerbates the risk of wildfire in Alaska, strategies for protecting communities are becoming more important (Wolken et al., 2011). This has prompted the inclusion of fuel reduction treatments (hereafter fuel treatments) into community wildfire protection plans across the state (Fairbanks North Star Borough, 2006; Kenai Peninsula Borough, 2022; Matanuska-Susitna Borough, 2021). Fuel treatments mitigate fire threats by either removing fuels or altering their structure (Agee & Skinner, 2005). Major goals of fuel treatments are to improve firefighter safety by reducing the risk of dangerous crown fires (Agee & Skinner, 2005) and to improve access and egress (Jenkins et al., 2012; Kenai Peninsula Borough, 2022; McKinney et al., 2022). As the use of fuel treatments increases in Alaska, it is important to understand their ecological effects. While fuel treatments are recognized as a disturbance with ecological trade-offs (Lehmkuhl et al., 2007; McIver et al., 2013), research on the ecological impact of fuel treatments in Alaskan forests is still sparse (Boyd, 2023; Brown, 2009; Hrobak, 2004; Jandt, 2019; Little et al., 2018; Melvin et al., 2018).

Common fuel treatments in Alaska include hand-thinning and mechanical mastication, both of which reduce tree density and canopy fuel load, reducing the risk of crown fires (Agee & Skinner, 2005; Little et al., 2018). In hand-thinned treatments, crews use chainsaws to remove understory trees that could carry surface fire to the crown, reduce canopy trees to a prescribed density and dispersion, and limb the remaining trees. Large boles may be removed or stacked for firewood collection, then the remaining fuels are piled, piled and burned, scattered, or taken off-site. In masticated treatments, heavy machinery with a masticator attachment (also known as a mulcher, or referred to by their make; e.g. Hydro-Ax, Roller Chopper, Bull Hog) fells trees and breaks apart overstory and understory fuels, resulting in a clear-cut with a compact layer of wood fragments covering the forest floor. Mastication is an efficient way to treat dense stands of small diameter trees, but each type of equipment used has an upper limit to the diameter of trees it can process.

Hand-thinning and mastication create different types of disturbances. Hand-thinning allows for an element of choice regarding which trees to remove (“selective thinning”) (Moreau et al., 2022), while mastication is mostly indiscriminate. For example, less-flammable deciduous broadleaf trees may only be left standing if they can be avoided by the machinery (Jandt, 2019). Hand-thinning partially opens the canopy and is less destructive to the understory, while mastication removes the canopy and the understory (Little et al., 2018). By altering the canopy and understory, fuel treatments alter the microclimate by changing transpiration, wind exposure, and the interception of precipitation and radiation (Battaglia et al., 2009; Chen et al., 1993; Ma et al., 2010). This may be beneficial to the health and growth of the remaining trees (e.g. increased availability of light) (Vincent et al., 2009), or detrimental (e.g. increased wind damage (Harper & Macdonald, 2002). Generally, thinning is considered to decrease mortality of leave trees (those remaining following treatment) (Baah-Acheamfour et al., 2023; Edmonds, 2011), while edge creation (e.g. through clear-cutting) leads to increased mortality of edge trees (those along the edge of the treatment), at least initially (Harper et al., 2005; Jönsson et al., 2007). Fuel treatments may interact with other disturbances, including 1) wind, 2) pathogens, and, of particular concern, 3) bark beetles, leading to variable impacts on tree mortality (Crotteau et al., 2018; Edmonds, 2011; Moreau et al., 2022; Roberts et al., 2020).

Canopy-opening disturbances can increase wind speeds, which are mitigated in denser stands (Hale et al., 2012; Zeng et al., 2006). The risk of wind damage to a tree is influenced by the wind speeds it experiences and the structure of its crown, bole, and roots (Hale et al., 2012). Trees acclimate to wind as they grow, and sudden changes to their exposure to wind can make them more susceptible to damage (Baah-Acheamfour et al., 2023; Zeng et al., 2006). Both leave trees and edge trees may be at higher risk for wind damage, including wind-caused mortality (Harper & Macdonald, 2002; Moreau et al., 2022; Zeng et al., 2006), but thinning strategies can mitigate the risk to leave trees (Baah-Acheamfour et al., 2023).

By altering microclimates, fuel treatments may change the growth factors limiting photosynthate production, the allocation of those photosynthates to defensive compounds, and ultimately the resistance of the tree to pests and pathogens (Fettig et al., 2007; Schultz et al., 2013). Trees actively resist pests and pathogens by producing defensive compounds, and the amount they produce depends on how photosynthates are allocated (Edmonds, 2011; Fettig et al., 2007; Schultz et al., 2013). Generally, pest and pathogen defense mechanisms are a lower priority use for photosynthates than maintenance respiration, reproduction, and growth, so when a tree is limited in photosynthates, its active resistance suffers (Fettig et al., 2007). Additionally, changes in microclimate may either benefit or hinder the growth of pests and pathogens themselves (Mezei (Grosdidier et al., 2020; Mezei et al., 2012).

Tree pathogens are widespread across Alaskan forests and lead to common non-fatal tree diseases (spruce needle cast, spruce needle rust), and less common tree-killing diseases (aspen running canker, trunk rot) (Holsten, 2009). Generally, tree pathogen spread can be mediated by landscape structure (Holdenrieder et al., 2004), and edge effects can be significant in either reducing (Grosdidier et al., 2020), or increasing (Holdenrieder et al., 2004) the risk of disease. Thinning has been shown to reduce the occurrence of some tree pathogens (Moreau et al., 2022; Roberts et al., 2020), but there is, to our knowledge, no published research on the effect of fuel treatment on tree pathogens in Alaska.

Forest disturbance is also an important driver of bark beetle outbreak (Biedermann et al., 2019; Weed et al., 2015). Bark beetles are a significant agent of tree mortality in Alaska (Werner et al., 2006). From 2015 to 2023, an ongoing outbreak of spruce beetle, *Dendroctonus rufipennis* [Kirby], has affected 878,000 hectares of spruce forest, throughout the maritime-influenced boreal forests of Southcentral Alaska, and extending into the Alaska Range, hereafter the "outbreak region" (Figure 1) (USDA Forest Service, Forest Health Protection and its partners, 2024). Spruce beetle is also present at endemic population levels in the boreal forest of Interior Alaska, hereafter the "endemic region" *(*Figure 1) (USDA Forest Service, Forest Health Protection and its partners, 2024). Northern spruce engraver, *Ips perturbatus* [Eichhoff], hereafter "NSE," is present at endemic population levels throughout the outbreak and endemic regions, but causes less tree mortality than spruce beetle (Burnside et al., 2011). In 2023, aerial surveys detected 50 hectares actively affected by NSE, and 36,474 hectares actively affected by spruce beetle (USDA Forest Service, Forest Health Protection and its partners, 2024).

Bark beetles increase in number following disturbances that reduce host resistance (Biedermann et al., 2019; Fettig et al., 2007), so it is important to understand the impact of fuel treatments on the resistance of edge trees and leave trees. Generally, thinning is considered to increase stand resistance to bark beetles (Fettig et al., 2007; Hood et al., 2016; Moreau et al., 2022; Steel et al., 2021). However, it has been suggested that methods of thinning to reduce fuel don't always align with prescriptions for beetle abatement (Fettig & Hilszczański, 2015; Jenkins et al., 2013). For example, while fuel treatments often prescribe thinning from below (small trees removed) (McIver et al., 2013), thinning from above (large trees removed) is a better strategy for increasing stand resistance to bark beetles (Fettig & Hilszczański, 2015). The effect of mastication on stand resistance has seen less research, but a study in a mixed conifer forest in the north-central Sierra Nevada found that mastication did not lead to an increase in bark beetle attacks (Stark et al., 2013), despite concerns about the release of monoterpenes from breaking apart fuels attracting bark beetles (Fettig et al., 2006).

Bark beetles have some ability to discern the strength of a host's defenses, and preferentially attack less-resistant trees when at endemic population levels (Fettig 2007). Fresh dead trees and coarse woody debris have no active resistance to bark beetles, and when of a beetle's preferred species and sufficient diameter, are the main hosts for secondary (non-tree-killing) bark beetles, and are an important resource for primary (tree-killing) bark beetles at endemic levels (Krokene, 2015). Disturbances that create a surfeit of suitable coarse woody debris have been linked to build-up of bark beetles (Christopher J. Fettig et al., 2022; Kacprzyk, 2012). Therefore, there is a need to evaluate the extent to which fuel treatments create suitable coarse woody debris, and if this affects beetle presence in living trees (Fettig et al., 2010).

Excessive tree mortality in stands following treatment could have negative impacts on ecosystem services, such as recreational use of fuel breaks, and create hazardous recreation or firefighting conditions. Tree health and stand structure post-treatment are important to quantify for designing future treatments because they impact the long-term effectiveness of the treatment, the timing and intensity of re-treatment, and the ecosystem services provided by the forest. In addition, positive perceptions of treatment outcomes are important for acceptance of fuel treatments by community members (McCaffrey et al., 2012; Toman et al., 2014). This study aims to understand the impact of fuel treatments on mortality of trees within treatment and along the edges of treatments. Dead trees in and around fuel treatments are hazardous to firefighters and recreational land users, alter fuel structure, and complicate incident management (Jenkins et al., 2012).

To determine the effect of fuel treatments on adverse tree health conditions (i.e. mortality, wind damage, disease, and bark beetle infestation) we surveyed a total of 33 sites between the endemic and outbreak regions that had undergone either a hand-thinned fuel treatment or a masticated fuel treatment. At each site, we collected data along three transects: the “control” transect in the unmanaged forest, the “edge” transect along the edge of the treated area, and the “treatment” transect within the fuel treatment itself. Along each transect, we collected data on tree characteristics including species, diameter, living status, damage, disease, and bark beetle presence, as well as estimating the load of coarse woody debris suitable for hosting bark beetles, and determining transect-level beetle presence. We used these data to model the probability of occurrence of each adverse health condition, given tree and transect characteristics. In this study, we addressed the following questions: 1) Does the probability of adverse tree health conditions differ between control, edge, and treatment transects? 2) What characteristics of trees (i.e. size, species) or fuel treatments (i.e. region, treatment type, level of suitable coarse woody debris) are associated with adverse tree health conditions? We expected to see greater occurrence of adverse tree health conditions in the treatment and edge, compared to the control, and we expected the edge effect to be greater in masticated treatments than hand-thinned treatments. Finally, we expected to find bark beetles with greater frequency on transects with a high level of suitable coarse woody debris.

3. Materials and Methods

3.1 Study Region

Our study area in Interior and Southcentral Alaska is bounded by the Sterling Highway to the south (59°N) and west (152°W), the Richardson Highway (65 °N) to the north, and the Alaska/Canada border to the east (142°W) (Figure *1*). Our domains of inference were defined by the status of the spruce beetle population. The northern portion is the “endemic region” where there is no ongoing spruce beetle outbreak, and the southern portion is the "outbreak region", which has been experiencing an ongoing spruce beetle epidemic from 2015-2024. The endemic and outbreak regions are divided by the northern edge of the Alaska Range, where the furthest north evidence (as of 2023) of the spruce beetle outbreak was recorded in near Healy, AK (63.9°N 148.8°W) (Alaska Forest Health Aerial Detection Survey 2023). The Alaska Range also separates the continental climate of the endemic region from the more maritime climate of the outbreak region (Gallant, 1995). Despite differences in climate, terrain, and soils, the forests of both the endemic and outbreak regions are dominated by the same four tree species: the evergreen needleleafs, black spruce [*Picea mariana* (Mill.) BSP.] and white spruce [*Picea glauca* (Moench) Voss], and the deciduous broadleafs, Alaska paper birch [*Betula neoalaskana* Sarg.], and quaking aspen [*Populus tremuloides* Michx.].

The history of bark beetle epidemics differs between the endemic and outbreak regions. In the endemic region, spruce beetle epidemics are smaller and less common than in the outbreak region, despite a shorter life cycle (Werner et al., 2006; Zwieback et al., 2024). In the outbreak region, two successive spruce beetle outbreaks have drastically altered forest structure. From approximately 1990 – 1999, the first outbreak culled mature white spruce in the Kenai Peninsula-Cook Inlet region, but significant mortality did not extend further north into the Matanuska-Susitna Valley (Werner et al., 2006). By 2015, the remaining white spruce had matured enough to fuel a second outbreak beginning around Cook Inlet (Fettig et al., 2022) and reaching north through the Alaska Range by 2023 (USDA Forest Service, Forest Health Protection and its partners, 2024). NSE is present in both the endemic and outbreak regions, but epidemics are usually small (Fettig et al., 2013; Zabihi et al., 2021).

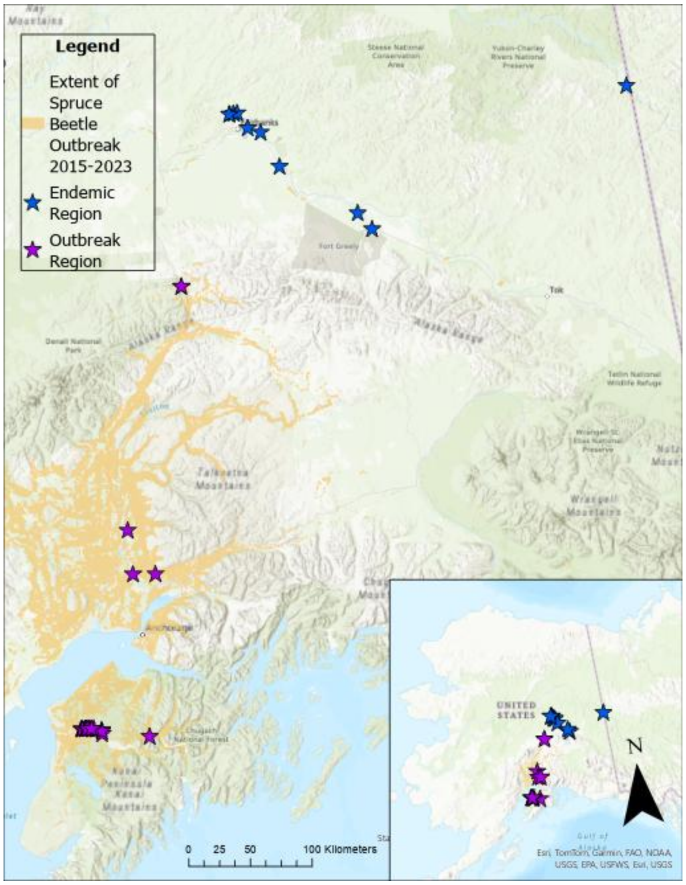

Figure 1. Map of sites in the endemic region (blue) and outbreak region (purple). Orange polygons (enlarged for visibility) represent the extent of the spruce beetle outbreak from 2015-2023, as determined by aerial and ground surveys (USDA Forest Service, Forest Health Protection and its partners, 2024) Latitude and longitude for each site are available in Table 17.

3.2 Site selection

We selected sites in the endemic and outbreak regions from the Alaska Fuel Treatment Dashboard (Schmidt, 2023). We removed sites that were inaccessible by road, or due to land ownership, or that had incomplete information in the database (i.e. missing treatment type, approximate time since treatment, or retreatment history). Using information from community partners and geospatial data, we further filtered sites based on the following criteria: 1) the treatment was next to a control stand with similar topography and land use history, 2) the edge of the treatment was long enough to contain a 190 m transect, 3) sites were installed in the last 10 years and were not retreated, and 4) sites were independent. We considered nearby sites to be independent if they were physically separated by untreated forest, or differed in either type of treatment, year of treatment, or species dominance.

Our preliminary experimental design called for equal numbers of sites in each region and treatment type, but this was adjusted as we visited sites identified through the Dashboard. In the endemic region, we located five masticated sites that met our criteria. In the outbreak region we located ten hand-thinned sites that met our criteria, but sampled only nine due to time constraints. Our final experimental design consisted of 12 sites in the endemic region (7 hand-thinned, 5 masticated), and 21 sites in the outbreak region (9 hand-thinned, 12 masticated) (Table 17). All sampling was conducted in July and August of 2023.

3.3 Transect Establishment

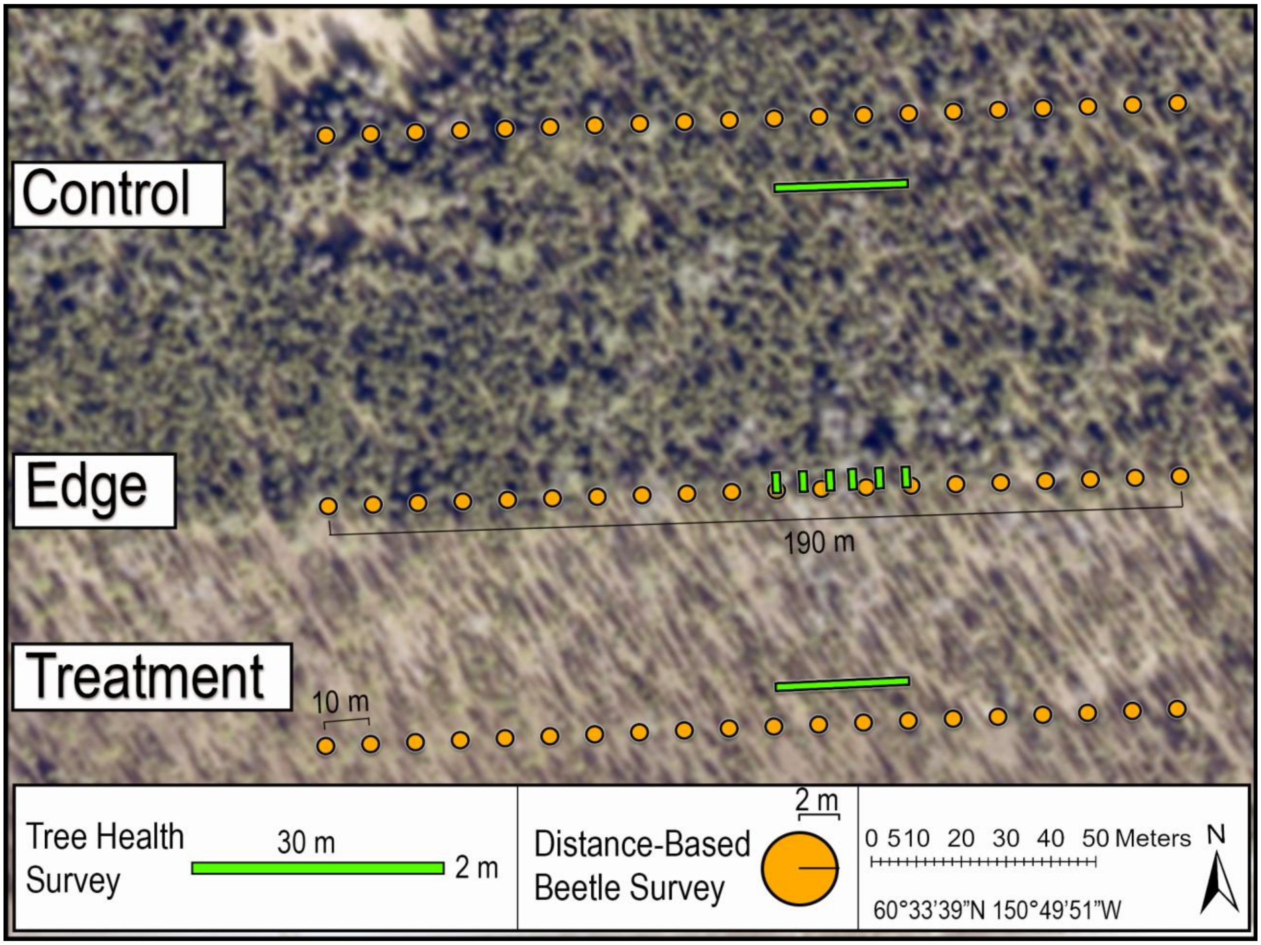

Figure 2. Diagram of transect layout for the Tree Health Survey and the Distance-Based Beetle Survey. Transects are presented to scale over imagery of hand-thinned site "KNA8" in the outbreak region.

At each site, we conducted three surveys: Tree Health Survey, Distance-Based Beetle Survey, and Time-Based Beetle Survey. For the Tree Health and Distance-Based Surveys, we established a set of three transects each. Each survey contained a "control" transect in the unmanaged forest, an "edge" transect along the edge of the treated area, and a "treatment" transect within the fuel treatment itself. To establish the treatment transect of the Tree Health Survey, we selected a location near the center of the fuel treatment and used a random number generator phone app (Peralta, 2021) to produce two numbers of centimeters (1-1,000 cm) by which to off-set the beginning of the transect in two perpendicular directions. Once the 0 m mark was established, we laid a 2 m x 30 m transect in the lengthwise direction of the fuel treatment (Figure 2). To establish the edge transect of the Tree Health Survey, we crossed the fuel treatment widthwise from the beginning of the treatment transect to the forest edge, where we placed the beginning of the edge transect. In masticated treatments, the edge was apparent, based on the ground cover of wood chips. In hand-thinned treatments, we laid a transect tape so that it hugged every other outermost tree. This avoided overfitting the uneven edges and accounted for natural gaps in the canopy. Once the boundary of the edge was established, we laid six 2 m x 5 m sub-transects into the forest, perpendicular to the edge, every 6 m from 0 to 30 m along the edge (Figure 2). The data for the edge transect was collected on these six sub-transects, allowing us to capture edge effects that may extend into the first 5 m of forest (Harper et al., 2015). To establish the control transect of the Tree Health Survey, we traveled ~75 m into the unmanaged forest, perpendicular to the edge. Then, we once again offset the beginning of the transect by 1 – 1000 cm in two directions using randomly generated numbers. This distance from the edge was a compromise between being far enough from treatment to avoid potential beetle spill-over, but still allowing us to capture a comparable stand. We used a compass to lay the 2 m x 30 m control transect parallel to the treatment transect. Transect tape was used to measure the length of the transect and its random offsets, and a meter stick was used to measure the width of the transect.

The treatment, edge, and control transects of the Distance-Based Beetle Survey were 190 m point-transects with a 2 m radius point every 10 m, resulting in a total area of 251 m^2 per transect. To establish the Distance-Based Beetle Survey transects, we walked approximately 95 m away from the 0 m mark of the Tree Health Survey transects, parallel to the Tree Health Survey transects, so that area sampled on either side of the 0 m mark would be roughly equal. We repeated our random number offset in two directions to place the beginning of the Distance-Based Beetle Survey treatment transect, this time with an offset of 5 - 10 m to avoid overlap with the Tree Health Survey transects. In the cases where the fuel break was < 190 m in length, the treatment transect zig-zagged within the treatment. The Distance-Based Beetle Survey edge transect was randomly offset in the direction parallel to the edge by 1 – 10 m, and always offset 2 m into the forest. Overlap with the Tree Health Survey edge transect did occur. The Distance-Based Beetle Survey control transect was randomly offset from the Tree Health Survey control transect by 5 – 25 m in the direction away from the edge. Changes in topography that would significantly alter stand characteristics from those of the forest edge (e.g. wetlands, hills) were avoided, and the control transect was done piecemeal as necessary. A compass and a Garmin eTrex handheld GPS were used to determine a straight path and record tracks, and a meter stick was used to measure the radius of the points on the point-transect.

The Time-Based Beetle Survey was a 10-minute timed search for spruce beetle and NSE presence within 200 m of the 0 m mark of the Tree Health Survey transect, and was performed in the treatment, edge, and control.

3.4 Data Collection

Within each Tree Health Survey transect, we observed every tree taller than 1.4 m. We recorded species, diameter at a height of 1.4 m (DBH), canopy position, and the presence or absence of adverse health conditions including mortality, disease, broken tops, damage from chainsaws or machinery, spruce beetle presence, and NSE presence, as well as whether the tree was standing or downed. We identified diseases with the Pocket Guide for the Identification of Common Forest Diseases and Insects in Alaska (USDA Forest Service, 2021). When we could not identify a specific disease, we categorized it by the part of the tree it affected (i.e. foliar, bud, stem).

Within each Distance-Based Beetle Survey transect, we observed every potential beetle host tree (spruce > 5 cm DBH). We recorded species, mortality, spruce beetle presence, and NSE presence. We recorded DBH class (5cm - 9.9cm, 10cm - 24.9cm, 25cm - 34.9cm, 35cm - 44.9cm, >45cm) using a custom gauge made of cord, with marks for each size class. Typical infestations see spruce beetle breeding in material > 10 cm in diameter (Bleiker et al., 2021), while NSE will breed in material > 5 cm in diameter (Burnside et al., 2011), though these lower limits may be exceeded in cases of extreme population density. To determine the presence of bark beetles, we searched the first 2 m of the bole of each spruce for entrance or exit holes of the appropriate dimensions, as well as pitch tubes. In most cases, entrance and exit holes were sufficient to identify spruce beetle presence, as they are the only insect in the region that creates circular holes in bark ⅛" in diameter. To confirm, we would find at least one unambiguously identifiable live beetle, beetle mummy, or gallery on a transect before recording the presence of a species in any tree on that transect. The holes that NSE leaves behind are more ambiguous, so observations of NSE were confirmed by removing a small section of bark, while taking care to minimize damage to live spruce. In this study, spruce beetle and NSE "presence" refers to both ongoing and past presence (a tree is recorded as having spruce beetle present if has entrance holes, pitch tubes, or galleries belonging to spruce beetle, whether or not there are live spruce beetles present).

In Distance-Based Beetle Survey transects, we also counted the number of pieces of coarse woody debris suitable to host bark beetles, hereafter "suitable debris." We define suitable debris as hard coarse woody debris > 5 cm diameter, with more than half of its bark remaining, and identifiable as spruce. These criteria indicate, liberally, that the debris may have been capable of hosting bark beetles at the time of treatment (within the last 10 years). Because the length of pieces of suitable debris was highly variable (a 50 cm length of bole in a lop-and-scatter treatment is not equivalent to an entire downed tree in terms of hosting bark beetles), we binned the counts into broad categories (zero, low, high) to provide an estimate for the suitable debris load of each transect.

In the Time-based Beetle Survey, we searched the trees and debris most likely to contain spruce beetle and NSE for 10 minutes. We used the same methods as the Distance-Based Beetle Survey to determine beetle presence in a tree. In suitable debris, we investigated every entrance and exit hole by removing bark with a knife. A transect was recorded as having spruce beetle or NSE present if they were present in at least one tree or piece of debris.

3.5 Statistical methods

To determine if adverse tree health conditions differed between treatment transects, edge transects, and control transects, we fit generalized linear mixed effects models (GLMMs) in R, (R Core Team, 2024) using the package 'lme4' (Bates et al., 2015)(Table 1). The response variables were tree living status (living/dead), broken top (broken, unbroken), disease (present/absent), and spruce beetle (present/absent) (Table 1). For the spruce beetle model, we used data from the Distance-Based Beetle Survey. For all other models, we used data from the Tree Health Survey. We used GLMMs with various fixed effects (Table 1), and included site as a random intercept for all models to account for spatial non-independence of trees within sites. We used the binomial distribution with a logit link for all our models. The binomial distribution accommodates binary response variables and the logit link models the log odds of the response (Agresti, 2007).

For each of our GLMMs, the categorical data can be represented in a multiway contingency table, with the cells being counts of cases where the response is true, conditioned on the factors. When many of these cell counts are low or zero, the data can be considered sparse, which can lead to estimates with very large or infinite confidence intervals (Agresti, 2007). Separation arises when the zero cell counts are distributed such that the response can be perfectly (or nearly perfectly) predicted by one or more predictors, leading to similar problems with estimation (Agresti, 2007). With the exception of the tree living status models, we are modeling datasets that are sparse due to outcomes (broken tops, disease, or spruce beetle presence) that are rare across some combinations of factors (e.g. region, treatment type, transect), as well as small sample sizes.

This sparse data places limitations on the structure of viable models, which we discovered during the model selection process. A strategy for modeling sparse data is to either exclude the sparsest groups, or combine them to minimize the number of empty cells (Agresti, 2007). When possible, we modeled each region and treatment type separately (i.e. tree living status models), but the sparse nature of the data led us to include data from both treatments in the region-specific broken top models, and to include data from both regions and treatment types in the disease model (Table 1). Additionally, we could not model tree-level spruce beetle presence in the endemic region, NSE presence in the endemic region, nor NSE presence in hand-thinned treatments in the outbreak region with transect as a fixed effect due to sparse data, and could not model NSE presence in masticated treatments in the outbreak region due to complete separation (all NSE observations were in edge trees while none were in control trees). Finally, for masticated treatments, we always excluded data from the treatment transect for being too sparse (very few trees), which, when both treatment types are included in the same model (i.e. broken top and disease models), results in the treatment transect in hand-thinned treatments also being excluded (we could not include a factor with a variable number of levels). Dead trees were excluded from the disease model as we could not determine past presence of disease. For trees that were excluded from the models, we present relevant results as percentages. For transect-level analyses (not GLMMs) we included all transects with and without trees.

Table 1. Generalized linear mixed effects models, their fixed effects, and the subset of data they include. All models include site as a random effect. Spruce beetle presence models use the Distance-Based Beetle Survey data, and all others use the Tree Health Survey data. Colons between effects indicate interactions. Model summaries are in Table 4.

Subset of Data		Response	Fixed effects	N sites	n trees
Region	Treatment				
Endemic	Hand-thinned	Tree living status	Transect, species, dbh	7	475
	Masticated	Tree living status	Transect, species, dbh	5	246
	Both	Broken top	Transect, treatment, transect:treatment, dbh	12	721
Outbreak	Hand-thinned	Tree living status	Transect, species, dbh	9	404
		Spruce beetle presence	Transect, species, transect:species, size class, debris class	9	653
	Masticated	Tree living status	Transect, species, dbh	12	931
		Spruce beetle presence	Transect, species, transect:species, size class, debris class	12	1213
	Both	Broken top	Transect, treatment, transect:treatment, dbh	21	1335
Both	Both	Disease	Transect, treatment, transect:treatment	33	1421

For each GLMM, we hypothesized fixed effects and their interactions, then tested their significance via likelihood ratio tests between the full model and reduced models lacking each fixed effect or interaction in turn (Bolker et al., 2009). Both significant and insignificant fixed effects were included in the final model, but fixed effects that were hypothesized but non-estimable (e.g. region in the disease model) were not (Table 1, Table 4). We included hypothesized but insignificant interactions (e.g. treatment type in the broken top model) in order to perform the necessary contrasts to answer our research questions. In all cases except the spruce beetle presence models, the sparseness of the data limited the number of factors we could include.

We verified a lack of multicollinearity (Variance Inflation Factors < 5) between all of our factors except those which were part of an interaction, and debris in the spruce beetle hand-thinned model, using the package 'performance' (Lüdecke et al., 2021). We compared the full spruce beetle hand-thinned model to a reduced model without suitable debris (to remove multicollinearity) and found no meaningful change in estimates, so we use the full model to test our research questions. We found no patterns indicating correlation in plots of residuals (simulated using the package 'DHARMa' (Hartig & Hartig, 2017)) versus each factor, as well as against latitude and longitude. We calculated marginal R^2 and conditional R^2 for the GLMMs with the package 'MuMIn' (Barton & Barton, 2015).

In order to estimate the probability of a success for each level of a factor, we use estimated marginal means (EMMs), calculated using the package 'emmeans' (Lenth, 2024). These EMMs represent the mean log odds of a level when the log odds of the other factors are averaged across all their levels. We report EMMs transformed from log odds to probability. We perform pairwise post hoc tests on EMMs (on the log odds scale) for the contrasts of interest, and applied a False Discovery Rate adjustment to the p-values (Benjamini & Hochberg, 1995). These contrasts can be conditioned on other factors, so, for example, we compare the EMMs of each transect by species. The results of these contrasts are transformed into odds ratios (Table 3).

By fitting the GLMMs, we estimate the intercept and the coefficient of each fixed effect. By exponentiating these values, we get the estimated odds that the response is a success (e.g. spruce beetle is present), and estimated odds ratios (ORs) comparing each level of each factor to its reference level, both of which are conditional on the other factors being held at their reference levels (e.g. a small black spruce on a control transect with no debris). An OR of 1 indicates that there is no difference in the odds of a success between two levels of a factor, an OR less than 1 indicates lesser odds, while an OR greater than 1 gives an interpretable effect size (e.g. a big black edge spruce has 20 times greater odds of spruce beetle presence than a small black edge spruce). For this reason, the reference level of each factor may change depending on the model so that significant odds ratios are easier to interpret. We report ORs with their 95% confidence intervals.

We compared transect-level beetle presence with suitable debris load ("zero", "low", "high") using Fisher's exact test, due to some expected cell counts being less than five. We performed Fisher's exact test on the 2x3 contingency table of beetle presence vs suitable debris load, and on each 2x2 subset of that table, and applied a False Discovery Rate adjustment to the p-values.

We also compared transect- and site-level continuous variables (e.g. mean DBH between regions), and proportional variables (e.g. proportion white spruce between treatment types) (Table 2). For continuous variables we calculated a mean of means and pooled standard deviation within each group. To compare the size of spruce and proportion of white spruce between regions and treatment types, we calculated the means of the control transect for each site. We tested the data for normality using Shapo-Wilk tests (Shapiro & Wilk, 1965), and compared averages using independent t-tests for normal data and Wilcoxon Rank Sum tests for non-normal data (Wilcoxon, 1992) (Table 2). We adjusted p-values for multiple comparisons using the False Discovery Rate method.

To determine if our 190m point-transect was a sufficient sampling effort to detect bark beetles when they were present, we calculated the number of trees we would need to sample to have an 80% cumulative probability of detecting spruce beetle and NSE on each transect that had at least one beetle observation. We calculated these theoretical sample sizes using the geometric distribution, where the probability of a success (an infested tree) was the proportion of successes out of the number of trials (trees). When the number of trees needed to detect an infested tree with a cumulative probability of 80% was less than or equal to the number of trees actually sampled, we considered the sampling effort sufficient for that transect.

4. Results

4.1 Stand Structure

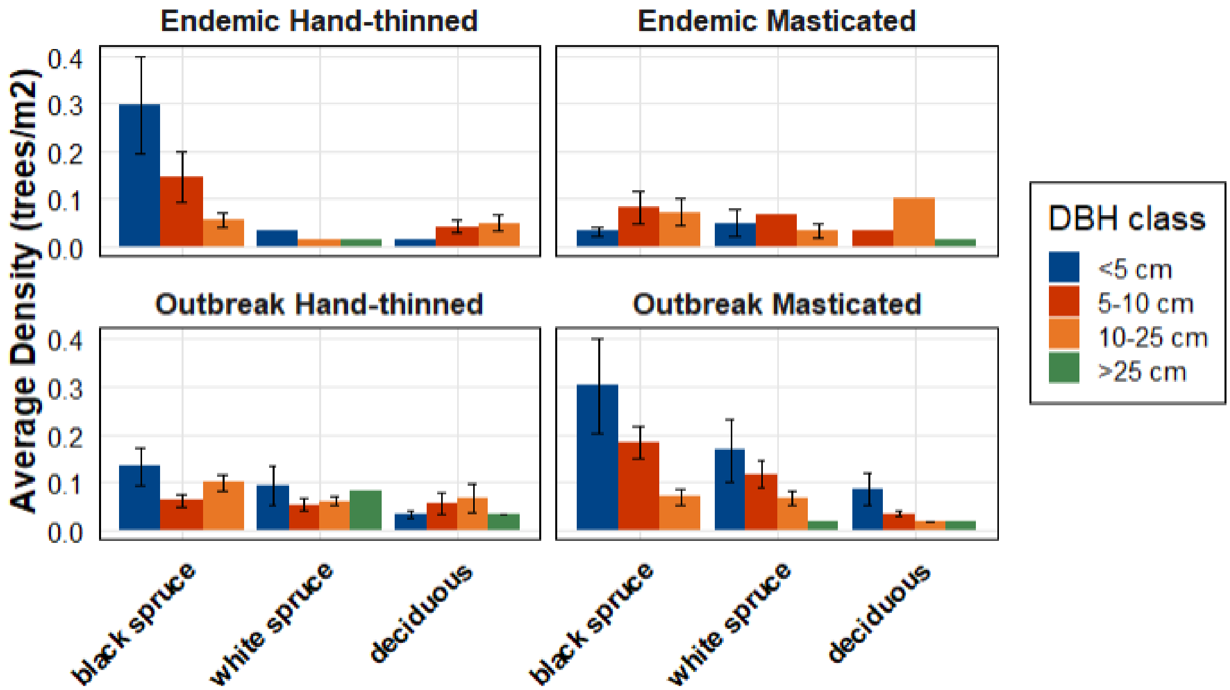

Figure 3. Mean density of trees in unmanaged control stands by species and DBH class for each region and treatment. Means of each species and DBH class exclude stands where no trees in that category were present. White spruce >25 cm DBH are the most preferred host of spruce beetle, followed by white spruce 10-25 cm DBH. White spruce >5 cm and black spruce >10 cm are potential hosts. Data are from the Tree Health Survey. Tabulated data can be found in Tables 10-15.

Small black spruce dominated control stands at hand-thinned sites in the endemic region and masticated sites in the outbreak region. Trees of any species > 25 cm DBH were rare (Figure 3).

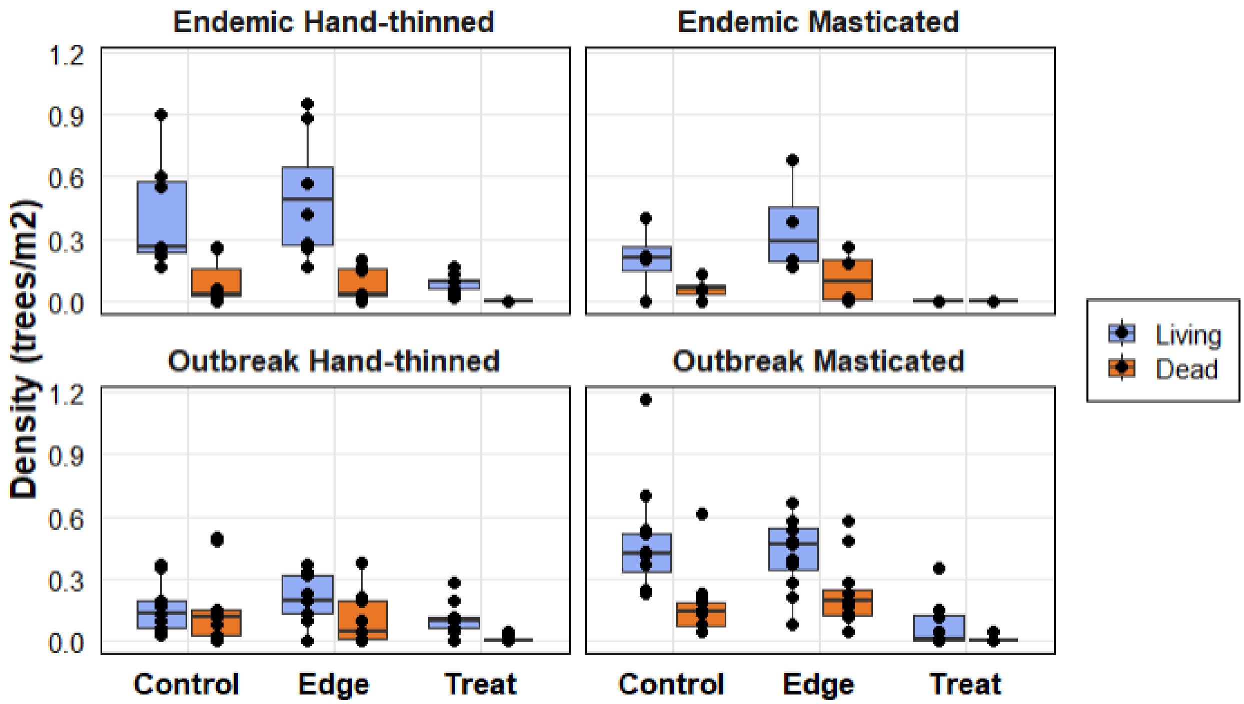

Figure 4. Density of living and dead trees in control, edge, and treatment transects, for each ecoregion and treatment type. Each point represents a transect. Boxes represent medians and quartiles. Data are from the Tree Health Survey.

The density of live trees and the density of dead trees varied within and across regions and treatment types (Figure 4). In treatments transects, dead tree density was reduced to an average of 0.00 trees/m^2 ± 0.00 trees/m^2 in endemic hand-thinned treatments and endemic masticated treatments, 0.01 trees/m^2 ± 0.02 trees/m^2 in outbreak hand-thinned treatments, and 0.00 trees/m^2 ± 0.01 trees/m^2 in outbreak masticated treatments (Figure 4).

Considering only trees that had potential to have been hosts to bark beetles (white spruce and black spruce, ≥ 5 cm DBH, both living and dead), we found both variations and similarities in stand structure between regions and between treatment types. In the endemic region, there was no difference in mean diameter between spruce in the control transects for hand-thinned sites (hand-thinned controls) (10.0 cm ± 3.9 cm) and spruce in the control transects for masticated sites (masticated controls) (9.5 cm ± 3.04 cm) (Table 2). Hand-thinned controls were 3.3% ± 6.0% white spruce, while masticated controls were 12.5% ± 16.9% white spruce (Figure 3). In the outbreak region, mean spruce diameter was higher in hand-thinned controls (13.3 cm ± 4.9 cm) than masticated controls (8.7 cm ± 3.4 cm) (Table 2). White spruce was common in both hand-thinned controls (49.3% ± 34.7%) and masticated controls (25.0% ± 37.4%) (Figure 3).

4.2 Tree Living Status

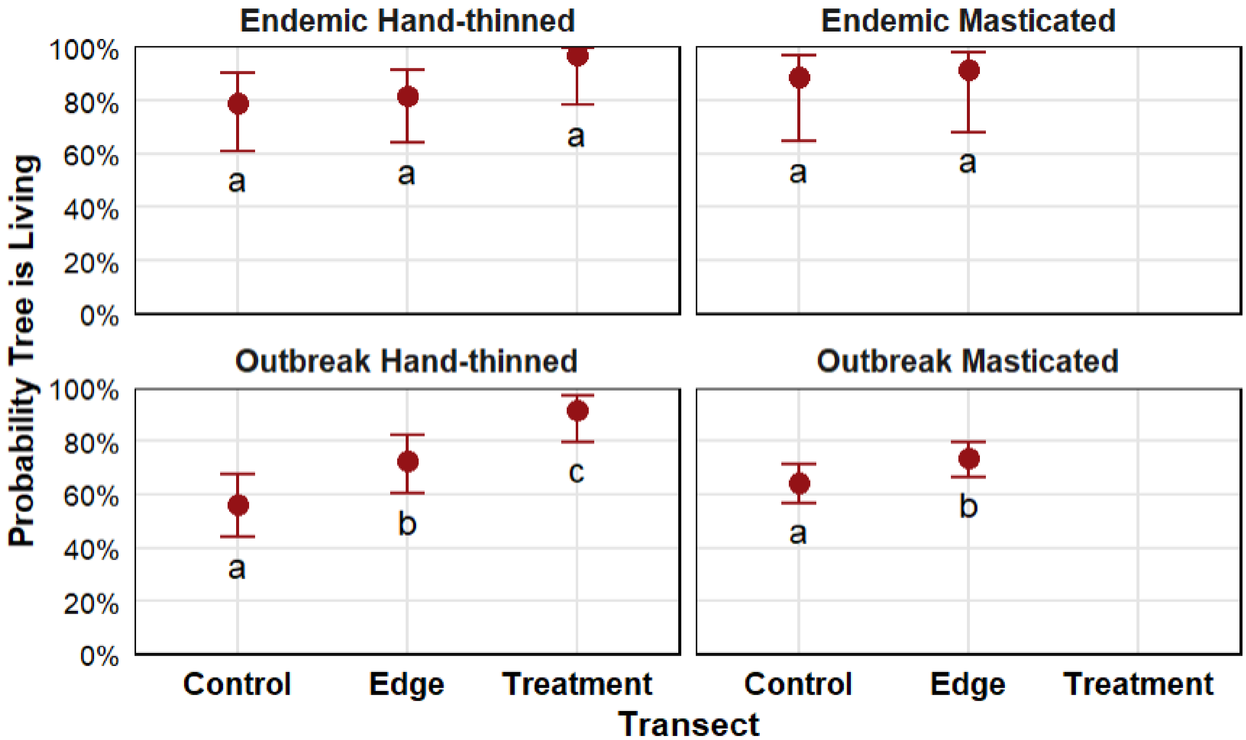

Figure 5. Estimated marginal means of the probability that a tree is living by transect for the tree's region and treatment type. Within each model, EMMs of each transect were compared (Table 3). Significant differences (α = 0.05) between groups are indicated by letters. Error bars represent 95% confidence intervals.

The variables which affected the probability that a tree was living varied between both region and treatment type. In the endemic region, trees had high probabilities of being alive (79%, CI = [61%, 90%] to 97%, CI = [78%, 99%] regardless of transect (Figure 5). In endemic hand-thinned sites, neither species, nor diameter affected these chances (Table 4). In endemic, masticated sites, there was no difference between the control and edge transects, (Figure 5, Table 3), but species and diameter affected the probability that a tree would be living (Table 4). In the outbreak region, leave trees in hand-thinned sites had 3.1 (CI = [1.2, 14.0]) times greater odds of being alive than edge trees (Figure 5, Table 3), which had 2.1 (CI = [1.2, 3.6]) times greater odds of being alive than control trees (Figure 5, Table 3). Living status was also affected by species (Table 4). In masticated outbreak sites, control trees had 1.5 (CI = [1.2, 2.1]) times the odds of being alive than edge trees (Figure 5, Table 3), and species had no effect (Table 4).

4.3 Damage and Disease

Considering both regions and treatment types, we found little evidence of windthrow among leave trees and edge trees. No downed leave trees were observed. Fifteen of 395 (3.8%) hand-thinned edge trees, and 30 of 667 (4.5%) masticated edge trees were downed (but unprocessed) by any force.

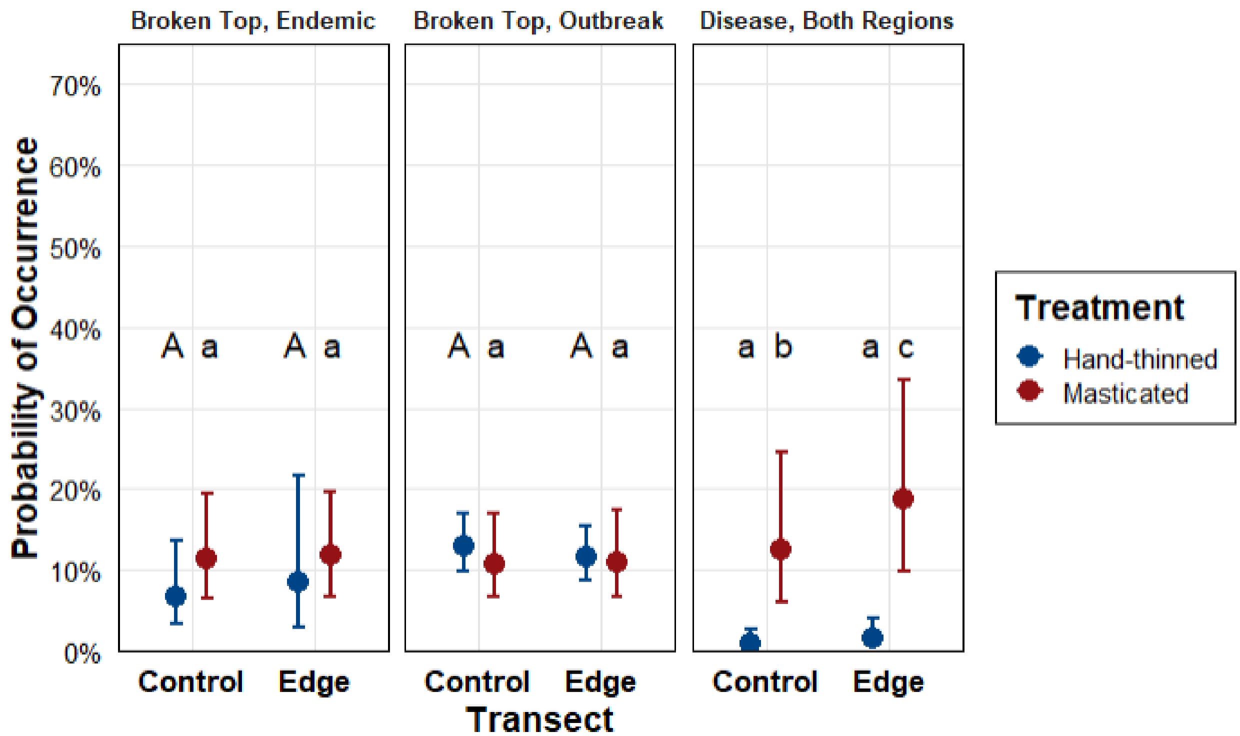

Figure 6. Estimated marginal means of the probability of occurrence of a broken top in the endemic region, a broken top in the outbreak region, or disease in either region, by treatment type and transect. Within each model, EMMs were compared between both treatment type and transect (Table 3). Letters indicate significant difference between groups (α = 0.05). Capital and lowercase letter are for different families of contrasts.

In both regions, the probability of having a broken top did not differ between control trees and edge trees for either treatment type (Figure 6, Table 3). Only two trees with broken tops were found among the 117 hand-thinned leave trees.

We found little human-caused mechanical damage by either chainsaw or machinery. At hand-thinned sites, two of 395 (0.5%) edge trees and 18 of 117 (15.3%) leave trees had mechanical damage (beyond limbing). At masticated sites, 10 of 667 (1.4%) edge trees and four of 57 (7.0%) leave trees had mechanical damage. In all cases but three masticated edge trees, damage was recorded as minor.

Without considering region, at hand-thinned sites, the probability of disease in living trees did not vary between edge trees and control trees (Figure 6, Table 3). However, at masticated sites, living edge trees had 1.6 (CI = [1.1, 2.5]) times greater odds of disease than living control trees. Living control trees had 16.3 (CI = [6.91, 38.3] times greater odds of disease in masticated sites than hand-thinned sites (Figure 6, Table 3). Diseased trees were found at 25% of endemic sites and 76% of outbreak sites. Foliar diseases (e.g. needle cast, needle rust) affected 12.9% ± 33.5%

of living trees and stem diseases (e.g. cankers, conks) affected 1.8% ± 13.2% of trees. Disease agents affected 24.6% ± 33.8% of living white spruce, 10.0% ± 17.4% of living black spruce, and 5.5% ± 13.9 of living deciduous trees, but the differences in mean percent diseased were marginally non-significantly between spruce species and deciduous species (Table 2).

4.4 Spruce Beetle

In the endemic region, we observed no spruce with spruce beetles in the distance-based survey, and only a single spruce (a 25 cm DBH living white spruce) with spruce beetles in the time-based survey (Table 16).

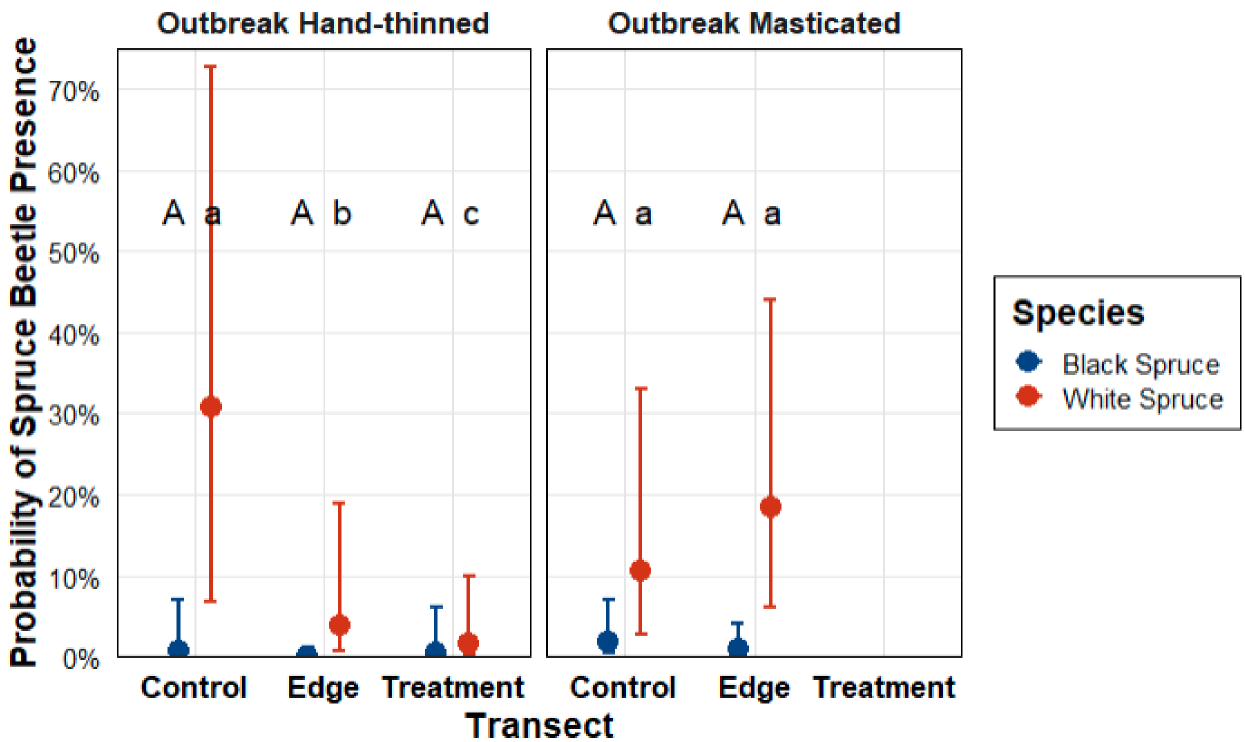

Figure 7. Estimated marginal means of the probability that a spruce in the outbreak region has past or ongoing spruce beetle presence in hand-thinned or masticated treatments, by species and transect. Within each model, EMMs of each species were compared across transects (Table 3). Letters indicate significant difference between groups (α = 0.05). Capital and lowercase letter are for different families of contrasts.

In the outbreak region, across both treatment types, spruce beetle presence was affected by species and size class (Table 4). In the outbreak region, at hand-thinned sites, white spruce in the control transect had significantly higher odds of spruce beetle presence—11.4 times greater than in the edge and 27.7 times greater than in the treatment transects. However, the wide confidence intervals (CI = [2.9, 44.1] and CI = [3.4, 226.5], respectively) suggest these estimates are imprecise. For black spruce, there was no relationship between transect and spruce beetle presence (Figure 7, Table 3). The size class of the tree and the level of suitable spruce debris on a transect also affected the probability of spruce beetle presence in outbreak hand-thinned sites (Table 4). In the outbreak region, at masticated sites, we found no difference in the odds of spruce beetle presence between the control and the edge for either black spruce or white spruce (Figure 7, Table 3), and while size and species predicted spruce beetle presence, the level of suitable debris had no effect (Table 4).

In the outbreak region, spruce beetle presence on a transect, as determined by the time-based survey, occurred at similar frequencies across levels of suitable debris load. There was no difference in the frequency of spruce beetle presence among transects with no suitable debris (67% with spruce beetle), low debris load (38%), or high debris load (85%) (Table 2).

4.5 Northern Spruce Engraver

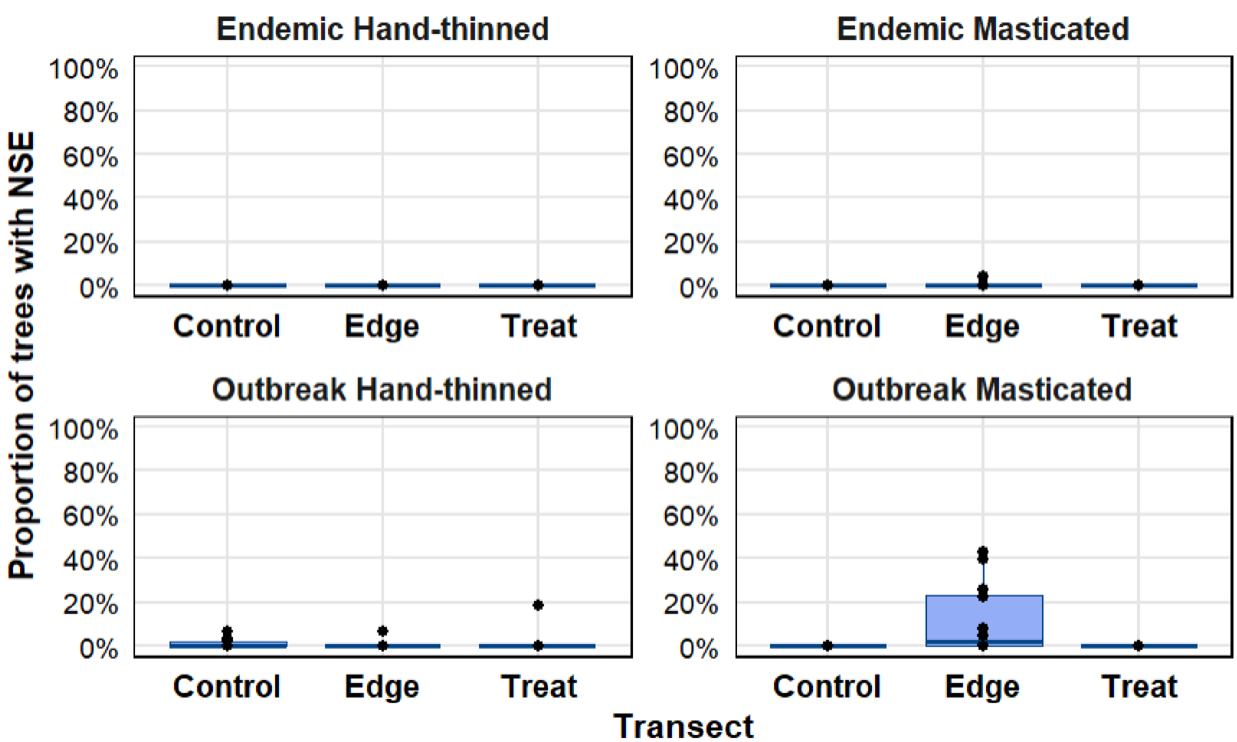

Figure 8. Proportion of trees infested with NSE on each transect, for each region and treatment type. Each point represents a transect. Boxes represent medians and quartiles. Half of edge transects at masticated sites in the outbreak region had spruce with NSE.

In the endemic region, we found a single NSE-infested spruce with the distance-based survey (Figure 8), and only one more with the time-based survey (Table 5, Table 16), both of which were in the edge of masticated treatments which contained NSE-infested debris.

In the outbreak region, of the 70 spruce with NSE presence, 16% (11) were white spruce and 84% (59) were black spruce (Table 6). In hand-thinned outbreak sites, the proportions of spruce with NSE did not differ between the control (1.3% ± 2.4%), edge (0.8% ± 2.4%), and treatment (2.0% ± 6.0%) transects (Table 2). In masticated outbreak sites, fewer spruce with NSE were found in the control (0.0% ± 0.0%) than the edge (11.9% ± 16.3%) (Figure 8, Table 2).

In the outbreak region, with the time-based survey, we found NSE with greater frequency in transects with a high debris load (85% with NSE) than in transects with no debris (20%), and with marginally greater frequency than in transects with low debris (38%) (Table 2). Overall, with the time-based survey, we found living NSE in trees in 12 of 85 transects (14%) and living NSE in trees or debris in 16 of 85 transects (19%).

4.6 Power Analysis

In 29 of 31 transects with at least one spruce beetle-infested tree, our sampling effort was sufficient to detect spruce beetle presence with a cumulative probability of 80%. In transects with at least one NSE-infested tree, 8 of 12 were sufficient for detecting NSE.

5. Discussion

Fuel treatments are a novel disturbance agent in Alaskan forests that may have both positive and negative impacts on forest health. Hand-thinning and mastication remove canopy trees, causing a release of competition and changes microclimate. These disturbances have the potential to benefit the health of the remaining trees by allowing them to produce more photosynthates for growth and pest and pathogen resistance. However, treatments may cause interactions with wind, pathogens, and pests that increase the occurrence of damaged, downed, diseased, or infested trees.

We found that, generally, fuel treatments were not harmful to tree health. Our results show either a decrease or no change in the probability of adverse health conditions (mortality, damage, disease, and infestation) between control trees and edge or treatment trees, with the exception of an increase of NSE and disease along the edges of masticated treatments in the spruce beetle outbreak region. Both hand-thinned and masticated treatments greatly reduced the density of dead trees. In the outbreak region, even edge trees saw a higher probability of being alive than trees in undisturbed forests.

The association of hand-thinned treatments with healthier edge and leave trees (fewer dead and beetle-infested trees) raises the question: are trees in and along the treatments without pre-existing adverse health conditions selected for during treatment, or are they less likely to develop adverse health conditions post-treatment? The first effect, that of selective thinning, is common practice in forest management (Moreau et al., 2022), and can also lead to stands with fewer dead, diseased, or damaged trees post-treatment, through the removal of those trees. Prescriptions for fuel treatments around Alaska have specifically included the removal of dead trees (Jandt, 2019), especially in the outbreak region, where removal of hazardous beetle-killed trees is a priority for fire and land management (KPB CWPP 2022). The second effect, that of an increase in stand resistance to disease or infestation, has been frequently observed in other stands post-thinning

(Moreau et al., 2022). It is likely that both selective thinning and a decrease in mortality post-treatment contributed to our results. In fact, at the majority of our sites with at least one tree remaining in the treatment (13 of 16 hand-thinned and 8 of 9 masticated), we observed no dead trees in the treatment, which is only possible via the removal of all dead trees, and then a complete lack of mortality following treatment.

The edges of hand-thinned and masticated sites in the outbreak region are more ambiguous. Without pre-disturbance data, we cannot separate the effects of selective thinning and changes in mortality and spruce beetle resistance. Because edge trees had a higher probability of being alive, any effect of a change in mortality or spruce beetle resistance was either in the same direction as the effect of selective thinning (increased probability of being alive), or was in the opposite direction (decreased probability of being alive) but smaller in magnitude. In other words, we lack the evidence to determine if edge trees are more or less resistant to mortality and infestation than control trees, but our results are only possible in the absence of a strong decrease in survival or resistance.

We found no evidence for an increase in wind damage following either hand-thinning or mastication. This is in contrast to a recent case study of Alaska fuel breaks that described a major windthrow event in one hand-thinned fuel treatment, and noted minor blowdown in others (Jandt, 2019). Thinning and clearcutting can lead to an increase in wind damage both through increased wind speeds and lack of wind-firmness in the newly exposed trees (Harper et al., 2005; Zeng et al., 2006). We may not have seen an increase in downed trees and broken tops because little time had elapsed since treatment, and thus there were fewer opportunities for a strong wind event.

The majority of the diseases we observed were foliar (spruce needle rust, spruce needle blight), and not considered to cause significant mortality (Edmonds, 2011; Holsten, 2009). We found no evidence that hand-thinned fuel treatments affect the occurrence of disease, but saw a slight increase in the probability of disease at the edges of masticated sites compared to controls. Disease was a rare enough occurrence that our data was too sparse to determine which stand characteristics may have influenced this result, or the greater probability of disease in controls at masticated sites compared to hand-thinned sites. In addition to changes in microclimate and host resistance, potential drivers of disease in these stands could include species composition, host density, or the presence of secondary hosts (Cobb & Metz, 2017).

Although spruce beetle is present in the endemic region, we observed very few at our sites. The 2023 Forest Health Protection Survey showed spruce beetle presence within 3 km of one site with suitable hosts, and within 12 km of another site with no suitable hosts. The distance a spruce beetle will travel to find a host is variable and difficult to estimate (Bleiker et al., 2021), but based on an estimate of < 900 m (Werner & Holsten, 1997) for a typical dispersal, it's not unusual that there was no colonization of the fuel treatment from the nearby population. In fact, the near total lack of spruce beetle in fuel treatments in the endemic region shows that spruce beetles there are either not attracted to fuel treatments from afar, or do not find suitable weak hosts to colonize.

Spruce in the outbreak region in hand-thinned edges and treatments and masticated edges may have seen a decreased probability of spruce beetle presence for a few reasons in addition to the rationales of selective thinning and increased pest resistance. Spruce beetle attack density is highest in full shade, so leave and edge trees may have become less attractive due to solar exposure. The opening of the canopy may also cause aggregation pheromones to disperse more quickly, making coordination of a mass attack more difficult (Bleiker et al., 2021; Fettig et al., 2007).

In the outbreak region, NSE was found at equally low levels (0.8% ± 2.4% to 2.0% ± 6.1%) across the control, edge, and treatment of hand-thinned sites. This is in contrast to a thinned stand in the outbreak region that saw spruce mortality of 47% due to an outbreak of NSE in 1996 (Graves, 2008). In outbreak masticated sites, NSE was found exclusively in the edge. Possible explanations for the colonization of the masticated edge include: 1) edge trees could be less resistant, 2) edge trees could be more attractive, 3) NSE were attracted by volatiles released by the mastication of spruce, 4) NSE overwintered in the masticated mulch, then emerged to attack the most exposed trees, or 5) NSE first colonized un-masticated debris in the edge, then attacked nearby trees. A decrease in the resistance of edge trees is plausible give that we also saw a greater probability of disease in the edge trees of masticated sites in the outbreak region. However, the fact that those trees also had a higher probability of being alive suggests that if edge trees are less resistant to pests and pathogens, it isn't leading to significant mortality.

The attractiveness of edge trees has been suggested as a mechanism for why the related *Ips typographus* attacks spruce on the edge of stands more often than spruce in the interior of stands (Schroeder & Lindelöw, 2002). Specifically, that the higher amount of solar radiation received by the edge trees made them more attractive, and this has been supported, even to the extent that the shading provided by a tree's own branches are enough to make a difference in the amount of *I. typographus* attacks (Mezei et al., 2012). Though preferences for solar exposure vary among *Ips* species, NSE is known to preferentially attack the tops of logs, and logs more exposed to sunlight, and to breed more successfully when infesting the tops of logs (Fettig et al., 2013). In the outbreak region, all of our masticated edges were south-facing (9) or west facing (3), and though we did not measure it, many edge trees had exposed boles, having self-pruned their lower branches due to the dense canopy. It is possible that trees on the edge of masticated treatments were more attractive to NSE because their boles were more exposed to the sun.

The attraction of bark beetles to volatiles released during fuel treatment has been a suggested mechanism for the increase in bark beetle attacks (including related *Ips* species) on Ponderosa pine following chipping of fuels (Fettig et al., 2006), but is dependent on the mastication being done soon before or during NSE flight, as the volatiles diffuse over time (Fettig et al., 2006). The suitability of masticated debris as overwintering habitat is possible explanation (Moan, 2023), given that NSE usually overwinters in the duff near the base of its host tree (Burnside et al., 2011), but as of yet we are not aware of any published attempts to observe NSE overwintering in masticated fuel treatments. Finally, the success of NSE in debris in the masticated edge is supported by the correlation between suitable debris load and NSE presence on a transect. Overall, the preference of NSE for masticated edge trees in the outbreak region is interesting, but is likely not increasing the amount of hazard trees because masticated edge trees still had a higher probability of being alive than control trees.

The correlation between suitable debris load and NSE presence on a transect shows the importance of dead host material to NSE. It is somewhat surprising that the relationship between spruce beetle presence at the transect level and suitable debris load was marginally non-significant ($p = 0.0621$), even though suitable debris load was a marginally significant ($p = 0.0476$) predictor of spruce beetle presence at the tree level at hand-thinned sites (Table 2, Table 4). The type of suitable host debris in which we found beetles provides some insights into the fuel break characteristics that could allow for bark beetle build-up. Two hand-thinned treatments had burn piles with slash too small for beetles, but hosted beetles in the larger-diameter debris that had been stacked for firewood collection. At one hand-thinned treatment where piles had been burned, beetles were found in debris that hadn't been thoroughly gathered into a pile. Five masticated edges had beetles living in debris that had been knocked over into the edge and left incompletely masticated. The treatment with the most beetles was dense with large-diameter white spruce that had been knocked down, but left mostly intact, by a Roller Chopper unsuited for the size of the trees. These cases show that treatment of residuals differs within the broader treatment types of hand-thinned and masticated, and that the level of thoroughness that is sufficient for fuel reduction is not always enough for beetle abatement.

Several limitations prevent us from drawing further conclusions. Firstly, without pretreatment data, we could not prove if the fuel treatment came before or after the bark beetle outbreak for each site. Secondly, NSE detection was likely low, as NSE often attacks the tops of trees, rather the first 2 m of the bole where our observations took place (Burnside 2011). Thirdly, our control transects were close enough to the edge of treatments that spillover of spruce beetle could have occurred, due to its wide dispersal range. Finally, the study is limited in scope, both temporally and spatially. Different relationships between fuel treatments and adverse tree health conditions may emerge as time since disturbance passes (Harper 2005), or in another region in a different state of the spruce beetle rotation, such as the Copper River Basin.

6. Conclusions and Implications

6.1 Conclusions

This study found no evidence that fuel treatments negatively impact the health of leave trees or edge trees, with the exception of the edge of masticated treatments in the outbreak region. Here, NSE and disease were found in a small proportion of trees, but masticated edge trees still had a higher probability of being alive than trees in the controls. Both hand-thinning and mastication effectively reduced the density of dead trees within treatments, without prompting further mortality. If the density of dead trees remains low, there will be less risk to the safety of recreational users of fuel treatments and firefighters.

Fuel treatments differ from similar disturbances like the construction of utility and seismic lines, in that the primary goal (fuel reduction) is complementary to bark beetle risk management. When fuels are burned, chipped, or masticated, they will neither carry crown fire, impeded firefighters, nor host bark beetles. Similarly, removal of actively infested trees for sanitization or removal of beetle-killed trees for hazard reduction also decreases fuel load (Kenai Peninsula Borough, 2022). Thinning may increase stand resistance to bark beetles, especially when care is taken to properly treat residuals by following existing management best practices (DeGomez et al., 2008; Fettig & Hilszczański, 2015; McIver et al., 2013). By considering wildfire risk management and bark beetle risk management together, opportunities could arise for management actions that work towards both goals simultaneously.

6.2 Implications for management

These results provide a green light for implementing future fuel treatments in Interior Alaska (given that bark beetle populations remain at endemic levels), and for hand-thinned treatments in wake of the ongoing spruce beetle outbreak. The culling of mature white spruce by the spruce beetle outbreak provides an opportunity to treat stands through the next decade with very little risk for sparking another outbreak. Mastication also appears to be a safe treatment method that does not increase the amount of hazard trees, but edges should be monitored for build-up of NSE and disease. If build-up may lead to significant tree mortality, managers should consider sanitization by removing the affected trees.

Many fuel treatment prescriptions in Alaska already follow best practices for bark beetle management. For example, masticating in winter avoids releasing attractive volatiles during beetle flight in the late spring, and thorough clean-up of fuels and complete mastication or burning prevents beetles from building-up in coarse woody debris. However, we found enough sites with residual debris that the level of suitable debris was correlated with NSE presence. An overlooked location of debris was the edges of masticated treatments where trees had been felled into the edge by machine, but escaped mastication. We suggest removing or debarking this debris to prevent bark beetle build-up.

6.3 Implications for future research

Further investigation is needed in regions where the risk of new bark beetle outbreak is high (e.g. Copper River Basin) due to high densities of mature white spruce. In Interior Alaska, spruce beetle outbreaks are historically small, while in the Cook Inlet Region, the current spruce beetle outbreak has already killed a large portion of the preferred hosts. Our conclusions do not extend to regions primed for outbreak.

Given that hand-thinning is a safe method of fuel treatment in regards to tree health, questions can be asked about how to use thinning to maximize co-benefits. For example, should stands be thinned before, during, or after bark beetle outbreak? Thinning before an outbreak may increase stand resistance to bark beetle, thinning during an outbreak could combat it on a local scale through sanitization, and thinning (or masticating) after may prevent the scenario in which expense is put into a hand-thinned treatment only for the leave trees to later be killed by beetles. To answer this question, more research is needed on thinning prescriptions in Alaskan forests to identify the density and dispersion of trees that confers the maximum resistance to spruce beetle.

There is also the intriguing possibility of using fuel treatment residuals as "trap trees" (Bleiker et al., 2021) to help manage bark beetle populations (felled hosts are left intentionally to be colonized by beetles and are then destroyed before the beetles re-emerge). However, this method is not without risks (beetles may spill-over into live trees if there are too few trap trees; late processing of trap trees could allow the colonizing adults or their offspring to escape, and instead harm their natural predators). To effectively utilize trap trees in fuel breaks, we would need an understanding of the best density and timing specific to regional stand structure, climate, and bark beetle populations.

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Appendix B. List of Science Delivery Products

1. Publications

   Thesis for Master's student Jonas Noomah. Accepted and submitted to Northern Arizona University, December 2024.

   In preparation: *Do Fuel Reduction Treatments in Alaska Affect Tree Health?* to be submitted for publication in peer-reviewed journal (Ecosphere). Expected submission January 2025.

2. Knowledge Transfer

   Alaska Interagency Fuels Management Workshop, Feb 2024. *Preliminary Results: Bark Beetles in Fuel Treatments?*

   Denali National Park and Preserve, presentation to staff. July 2024. *New Research on Bark Beetles in Fuel Breaks.*

   Public presentation at Nikiski Community Center. Aug 2024. *New Research on Bark Beetles in Fuel Breaks.*

   Northern Arizona University, Center for Ecosystem Science and Society seminar. Nov 2024. *Do Fuel Treatments in Alaska Affect Tree Health?*

   Planned: Direct outreach to land managers once manuscript is published. Plan to share paper brief, link to paper, management brochure, and site risk-assessments.

3. Outreach Materials

   Management brochure. *Are There Bark Beetles in Your Fuel Break?*

Appendix C. Metadata

The data includes site, transect, and tree characteristics. Site variables are region, treatment type, and geographic coordinates (Appendix D, Table 17). Transect variables are stand structure characteristics (Appendix D, Tables 12-15), bark beetle presence, and level of coarse woody debris. Tree variables are species, DBH, living status, damage, disease, and bark beetle presence.

The metadata consists of a description of the study, experimental design, field methods, and data. It includes information on the personnel who collected the data, including a contact person. It describes the structure of the data files, each variable in the data, and each site. Also included in the metadata is the code used to perform the quality assurance and analysis.

The data and metadata are in the process of being submitted to the Bonanza Creek Long Term Ecological Research Program (BNZ LTER) data catalog and archived with the Environmental Data Initiative. We will provide the Joint Fire Science Program with a DOI when one is available. They will remain archived at BNZ LTER, and also piped to the Arctic Data Center. Data will be made publicly available. In the original data management plan, we expected to archive voucher specimens of trapped bark beetles. However, we forwent beetle trapping in favor of tree-level observations of beetle presence to describe beetle presence, so no voucher specimens were collected.

Appendix D. Supplementary Data

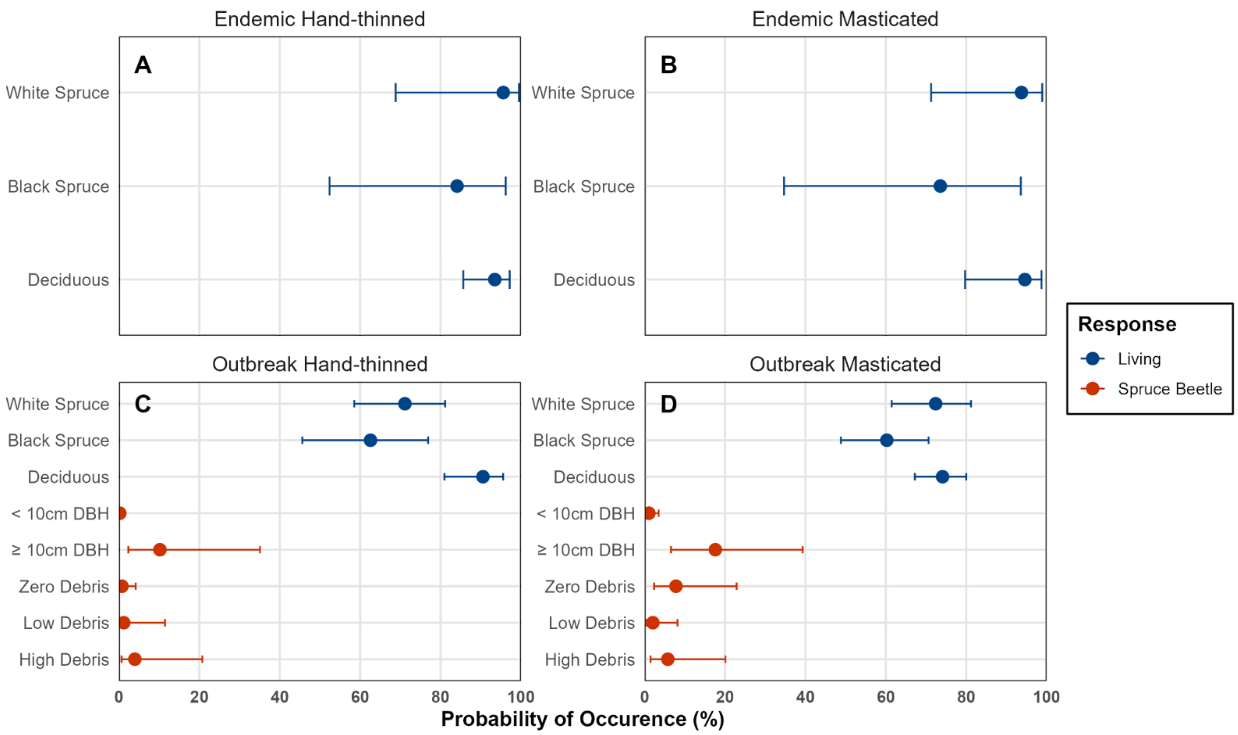

Figure 9. Estimated marginal means of each level of each factor from the Tree Living Status and Spruce Beetle models, excepting those presented in Figure 5 and Figure 7.

Table 2Contrasts and their p-values for continuous, proportional, and frequency data. Contrast indicates which levels are being compared, and group specifies the level of another variable on which the contrast is conditioned (results of the contrast are only applicable within the group). When there are multiple contrasts within a family, p-values are adjusted by the False Discovery Rate method. Significance is indicated by stars (* p < 0.05; ** p < 0.01; *** p < 0.001).

Response	Contrast	Group	Test	n1	n2	pval	Adjusted pval	significance
mean dbh	Endemic Hand-thinned / Endemic Masticated	spruce > 5cm dbh	t-test	7	4	0.7336	0.7336	-
	Outbreak Hand-thinned / Outbreak Masticated	spruce > 5cm dbh	t-test	9	12	0.0204	0.0408	*
white spruce proportion	Hand-thinned / Masticated	Endemic	Wilcoxon	7	4	0.3028	0.3028	-
black spruce proportion	Hand-thinned / Masticated	Endemic	Wilcoxon	7	4	0.2547	0.3028	-
white spruce proportion	Hand-thinned / Masticated	Outbreak	Wilcoxon	9	12	0.0781	0.1562	-
black spruce proportion	Hand-thinned / Masticated	Outbreak	Wilcoxon	9	12	0.0346	0.1384	-
living tree density	Control / Edge	Endemic Hand-thinned	Wilcoxon	8	8	0.5233	0.6280	-
	Control / Treatment	Endemic Hand-thinned	Wilcoxon	4	4	0.7715	0.8416	-
	Edge / Treatment	Endemic Hand-thinned	Wilcoxon	9	9	0.5063	0.6280	-
	Control / Edge	Endemic Masticated	Wilcoxon	12	12	0.8622	0.8622	-
	Control / Treatment	Endemic Masticated	Wilcoxon	8	8	0.0017	0.0051	**
	Edge / Treatment	Endemic Masticated	Wilcoxon	4	4	0.0689	0.1190	-
	Control / Edge	Outbreak Hand-thinned	Wilcoxon	9	9	0.4510	0.6280	-
	Control / Treatment	Outbreak Hand-thinned	Wilcoxon	12	12	0.0001	0.0009	***
	Edge / Treatment	Outbreak Hand-thinned	Wilcoxon	8	8	0.0011	0.0043	**
	Control / Edge	Outbreak Masticated	Wilcoxon	4	4	0.0211	0.0506	-
	Control / Treatment	Outbreak Masticated	Wilcoxon	9	9	0.0694	0.1190	-
	Edge / Treatment	Outbreak Masticated	Wilcoxon	12	12	0.0001	0.0009	***
dead tree density	Control / Edge	Endemic Hand-thinned	Wilcoxon	8	7	0.8594	0.8594	-

Response	Contrast	Group	Test	n1	n2	pval	Adjusted pval	significance
	Control / Treatment	Endemic Hand-thinned	Wilcoxon	4	4	0.7715	0.8416	-
	Edge / Treatment	Endemic Hand-thinned	Wilcoxon	9	9	0.5652	0.6782	-
	Control / Edge	Endemic Masticated	Wilcoxon	12	12	0.1824	0.2432	-
	Control / Treatment	Endemic Masticated	Wilcoxon	8	7	0.0037	0.0088	**
	Edge / Treatment	Endemic Masticated	Wilcoxon	4	4	0.0689	0.1034	-
	Control / Edge	Outbreak Hand-thinned	Wilcoxon	9	9	0.0035	0.0088	**
	Control / Treatment	Outbreak Hand-thinned	Wilcoxon	12	12	0.0000	0.0001	***
	Edge / Treatment	Outbreak Hand-thinned	Wilcoxon	8	7	0.0025	0.0088	**
	Control / Edge	Outbreak Masticated	Wilcoxon	4	4	0.0689	0.1034	-
dead tree density	Control / Treatment	Outbreak Masticated	Wilcoxon	9	9	0.0063	0.0125	*
	Edge / Treatment	Outbreak Masticated	Wilcoxon	12	12	0.0000	0.0001	***
	Hand-thinned / Masticated	Endemic	Wilcoxon	7	4	0.1849	0.1849	-
	Hand-thinned / Masticated	Outbreak	Wilcoxon	9	12	0.0009	0.0037	**
	Endemic / Outbreak	Hand-thinned	Wilcoxon	7	9	0.0228	0.0327	*
	Endemic / Outbreak	Masticated	Wilcoxon	4	12	0.0245	0.0327	*
	Hand-thinned / Masticated	Endemic	Wilcoxon	7	4	1.0000	1.0000	-
	Hand-thinned / Masticated	Outbreak	Wilcoxon	9	12	0.4753	0.6337	-
	Endemic / Outbreak	Hand-thinned	Wilcoxon	7	9	0.3644	0.6337	-
	Endemic / Outbreak	Masticated	Wilcoxon	4	12	0.0983	0.3933	-
percent diseased	Living White Spruce / Living Black Spruce	-	Wilcoxon	22	27	0.6001	0.6001	-
	Living White Spruce / Living Deciduous	-	Wilcoxon	22	25	0.0534	0.0865	-
	Living Black Spruce / Living Deciduous	-	Wilcoxon	27	25	0.0577	0.0865	-
percent NSE infestation	Outbreak Hand-thinned Control / Edge	Outbreak Hand-thinned	Wilcoxon	9	8	0.4007	0.6010	-
	Outbreak Hand-thinned Control / Treatment	Outbreak Hand-thinned	Wilcoxon	9	9	0.3961	0.6010	-

Response	Contrast	Group	Test	n1	n2	pval	Adjusted pval	significance
	Outbreak Hand-thinned Edge / Treatment	Outbreak Hand-thinned	Wilcoxon	8	9	1.0000	1.0000	-
	Outbreak Masticated Control / Edge	Outbreak Masticated	Wilcoxon	12	12	0.0071	0.0071	**
NSE infestation proportion	Zero Debris / Low Debris	Outbreak	Fisher	30	13	0.2327	0.2327	-
	Zero Debris / High Debris	Outbreak	Fisher	30	13	0.0004	0.0013	**
	Low Debris / High Debris	Outbreak	Fisher	13	13	0.0414	0.0621	-
SB infestation proportion	Zero Debris / Low Debris	Outbreak	Fisher	13	25	0.0279	0.0621	-
	Zero Debris / High Debris	Outbreak	Fisher	13	25	1.0000	1.0000	-
	Low Debris / High Debris	Outbreak	Fisher	13	13	0.0414	0.0621	-

Table 3. Comparisons of estimated marginal means. Contrast indicates which levels are being compared, and group specifies the level of another variable on which the contrast is conditioned (results of the contrast are only applicable within the group). When there are multiple contrasts within a family, p-values are adjusted by the False Discovery Rate method. Significance is indicated by stars (* p < 0.05; ** p < 0.01; *** p < 0.001). Odds ratios indicate the change in odds from the first level indicated in the contrast to the second. LCL and UCL indicate the lower and upper 95% confidence limits, respectively.

model	contrast	group	odds.ratio	LCL	UCL	adjusted pval	significance
Tree living status, Endemic, Hand-thinned	Edge / Control	-	1.15	0.57	2.31	0.6265	-
	Treatment / Control	-	7.90	0.63	98.69	0.1021	-
	Treatment / Edge	-	6.86	0.55	85.91	0.1021	-
Tree living status, Endemic, Masticated	Edge / Control	-	1.36	0.49	3.76	0.5497	-
Tree living status, Outbreak, Hand-thinned	Edge / Control	-	2.07	1.14	3.78	0.0056	**
	Treatment / Control	-	8.60	2.49	29.78	0.0001	***
	Treatment / Edge	-	4.15	1.17	14.75	0.0072	**
Tree living status, Outbreak, Masticated	Edge / Control	-	1.55	1.15	2.10	0.0042	**
Tree living status, Endemic, Hand-thinned	Black Spruce / White Spruce	Control	3.19	0.54	19.07	0.3589	-
	Deciduous / white spruce	Control	1.43	0.14	14.45	0.7129	-
	Deciduous / black spruce	Control	0.45	0.07	2.78	0.4368	-
	Black Spruce / White Spruce	Edge	3.19	0.54	19.07	0.3589	-

model	contrast	group	odds.ratio	LCL	UCL	adjusted pval	significance
	Deciduous / white spruce	Edge	1.43	0.14	14.45	0.7129	-
	Deciduous / black spruce	Edge	0.45	0.07	2.78	0.4368	-
	Black Spruce / White Spruce	Treatment	3.19	0.54	19.07	0.3589	-
	Deciduous / white spruce	Treatment	1.43	0.14	14.45	0.7129	-
	Deciduous / black spruce	Treatment	0.45	0.07	2.78	0.4368	-
Tree living status, Endemic, Masticated	Black Spruce / White Spruce	Control	6.30	1.47	26.99	0.0074	**
	Deciduous / white spruce	Control	5.39	0.72	40.57	0.0685	-
	Deciduous / black spruce	Control	0.86	0.15	4.89	0.8304	-
	Black Spruce / White Spruce	Edge	6.30	1.47	26.99	0.0074	**
	Deciduous / white spruce	Edge	5.39	0.72	40.57	0.0685	-
	Deciduous / black spruce	Edge	0.86	0.15	4.89	0.8304	-
Tree living status, Outbreak, Hand-thinned	Black Spruce / White Spruce	Control	6.31	2.24	17.76	0.0001	***
Tree living status, Outbreak, Hand-thinned	Deciduous / white spruce	Control	1.71	0.81	3.62	0.0846	-
	Deciduous / black spruce	Control	0.27	0.11	0.69	0.0013	**
	Black Spruce / White Spruce	Edge	6.31	2.24	17.76	0.0001	***
	Deciduous / white spruce	Edge	1.71	0.81	3.62	0.0846	-
	Deciduous / black spruce	Edge	0.27	0.11	0.69	0.0013	**
	Black Spruce / White Spruce	Treatment	6.31	2.24	17.76	0.0001	***
	Deciduous / white spruce	Treatment	1.71	0.81	3.62	0.0846	-
	Deciduous / black spruce	Treatment	0.27	0.11	0.69	0.0013	**
Tree living status, Outbreak, Masticated	Black Spruce / White Spruce	Control	1.89	0.99	3.59	0.0528	-
	Deciduous / white spruce	Control	1.73	0.81	3.69	0.1237	-

model	contrast	group	odds.ratio	LCL	UCL	adjusted pval	significance
	Deciduous / black spruce	Control	0.92	0.49	1.71	0.7360	-
	Black Spruce / White Spruce	Edge	1.89	0.99	3.59	0.0528	-
	Deciduous / white spruce	Edge	1.73	0.81	3.69	0.1237	-
	Deciduous / black spruce	Edge	0.92	0.49	1.71	0.7360	-
Broken top, Endemic	Edge / Control	Hand-thinned	1.27	0.51	3.18	0.6078	-
	Edge / Control	Masticated	1.03	0.57	1.86	0.9257	-
Broken top, Outbreak	Edge / Control	Hand-thinned	0.89	0.60	1.32	0.5533	-
	Edge / Control	Masticated	1.02	0.52	2.00	0.9512	-
Broken top, Endemic	Masticated / (Hand-thinned)	Control	1.77	0.72	4.34	0.2116	-
	Masticated / (Hand-thinned)	Edge	1.43	0.42	4.90	0.5661	-
Broken top, Outbreak	Masticated / (Hand-thinned)	Control	0.81	0.44	1.50	0.5064	-
	Masticated / (Hand-thinned)	Edge	0.93	0.50	1.73	0.8280	-
Disease	Edge / Control	Hand-thinned	1.61	0.70	3.68	0.2627	-
	Edge / Control	Masticated	1.62	1.07	2.47	0.0241	*
	Masticated / (Hand-thinned)	Control	13.98	5.35	36.55	0.0000	***
Disease	Masticated / (Hand-thinned)	Edge	14.12	6.37	31.29	0.0000	***
Spruce beetle, Outbreak, Hand-thinned	Edge / Control	Black Spruce	0.18	0.02	1.85	0.2329	-
	Treatment / Control	Black Spruce	0.64	0.02	22.36	0.7614	-
	Treatment / Edge	Black Spruce	3.60	0.10	123.42	0.5786	-
	Edge / Control	White Spruce	0.09	0.02	0.35	0.0001	***
	Treatment / Control	White Spruce	0.04	0.00	0.31	0.0003	***
	Treatment / Edge	White Spruce	0.41	0.05	3.05	0.2874	-
	Control / Edge	Black Spruce	5.65	0.54	59.25	0.2329	-
	Control / Treatment	Black Spruce	1.57	0.04	55.15	0.7614	-

model	contrast	group	odds.ratio	LCL	UCL	adjusted pval	significance
	Edge / Treatment	Black Spruce	0.28	0.01	9.53	0.5786	-
	Control / Edge	White Spruce	11.36	2.84	45.41	0.0001	***
	Control / Treatment	White Spruce	27.75	3.25	236.91	0.0003	***
	Edge / Treatment	White Spruce	2.44	0.33	18.19	0.2874	-
	White Spruce / Black Spruce	Control	57.30	14.12	232.52	0.0000	***
	White Spruce / Black Spruce	Edge	28.50	7.71	105.36	0.0000	***
	White Spruce / Black Spruce	Treatment	3.24	0.40	26.02	0.2682	-
	≥10cm dbh / <10cm dbh	-	53.26	23.15	122.53	0.0000	***
Spruce beetle, Outbreak, Masticated	Control / Edge	Black Spruce	1.85	0.41	8.30	0.4199	-
	Control / Edge	White Spruce	0.52	0.18	1.50	0.2262	-
	Edge / Control	Black Spruce	0.54	0.12	2.42	0.4199	-
	Edge / Control	White Spruce	1.91	0.67	5.48	0.2262	-
	White Spruce / Black Spruce	Edge	22.25	6.73	73.62	0.0000	***
	White Spruce / Black Spruce	Control	6.27	2.47	15.93	0.0001	***
Spruce beetle, Outbreak, Masticated	≥10cm dbh / <10cm dbh	-	19.99	10.97	36.44	0.0000	***

Table 4. Significance of effects of generalized linear mixed models, tested with likelihood ratio chi-squared tests. Significance is indicated by stars (* $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$). Marginal R^2 indicates the percentage of variance explained by the fixed effects, while conditional R^2 indicates the percentage of variance explained by the fixed effects and the random effect.

Model	variable	p value	significance	Marginal R^2 / Conditional R^2
Tree living status, Endemic, Hand-Thinned	Transect	0.0403	*	0.13/0.1
	Species	0.2453	-	
	DBH	0.0892	-	
	Site	0.0057	**	
Tree living status, Endemic, Masticated	Transect	0.5533	-	0.10/0.47
	Species	0.0085	**	
	DBH	0.0054	**	
	Site	0.0001	***	
Tree living status, Outbreak, Hand-Thinned	Transect	0.0000	***	0.29/0.34
	Species	0.0000	***	
	DBH	0.3646	-	
	Site	0.0170	*	
Tree living status, Outbreak, Masticated	Transect	0.0041	**	0.036/0.08
	Species	0.0793	-	
	DBH	0.5420	-	
	Site	0.0002	***	
Broken Top, Endemic	Transect	0.8772	-	0.02/0.12
	Treatment	0.4197	-	
	DBH	0.3969	-	
	Transect:Treatment	0.7065	-	
	Site	0.0158	*	
Broken Top, Outbreak	Transect	0.8379	-	0.00/0.02
	Treatment	0.7969	-	
	DBH	0.8057	-	
	Transect:Treatment	0.7247	-	
	Site	0.1343	-	
Disease	Transect	0.0396	*	0.22/0.59
	Treatment	0.0000	***	
	Transect:Treatment	0.9837	-	
	Site	0.0000	***	
Spruce beetle, Outbreak, Hand-Thinned	Transect	0.0000	***	<0.01/0.03
	Species	0.0000	***	
	Size Factor	0.0000	***	
	Debris	0.0476	*	

Model	variable	p value	significance	Marginal R^2 / Conditional R^2
	Transect:Species	0.1018	-	
	Site	0.0000	***	
Spruce beetle, Outbreak, Masticated	Transect	0.0861	-	0.24/0.55
	Species	0.0000	***	
	Size Factor	0.0000	***	
	Debris	0.1430	-	
	Transect:Species	0.0415	*	
	Site	0.0000	***	

Table 5. Counts of trees in the endemic region infested/uninfested with spruce beetle, by size class, spruce species, site, and transect. Small spruce are < 10 cm DBH, large spruce are ≥ 10 cm DBH.

	Control				Edge				Treatment			
Site	Large, White	Large, Black	Small, White	Small, Black	Large, White	Large, Black	Small, White	Small, Black	Large, White	Large, Black	Small, White	Small, Black
Hand-thinned												
BAD1	-/1	-/18	-/-	-/29	-/-	-/10	-/-	-/20	-/-	-/1	-/-	-/2
GS1	-/-	-/12	-/-	-/23	-/-	-/14	-/-	-/38	-/-	-/1	-/1	-/14
GS2	-/-	-/2	-/-	-/14	-/-	-/2	-/-	-/46	-/-	-/-	-/-	-/12
VG1	-/-	-/9	-/1	-/7	-/4	-/5	-/1	-/2	-/1	-/-	-/-	-/-
VG2	-/-	-/10	-/-	-/31	-/-	-/7	-/-	-/47	-/-	-/4	-/-	-/3
Masticated												
DEXP1	-/1	-/6	-/1	-/20	-/-	-/9	-/-	-/11	-/-	-/-	-/-	-/-
DEXP2	-/-	-/-	-/-	-/-	-/3	-/13	-/-	-/8	-/-	-/-	-/-	-/-
FTW1	-/7	-/2	-/17	-/12	-/1	-/3	-/2	-/19	-/-	-/-	-/-	-/-
SAL1	-/1	-/1	-/-	-/53	-/-	-/-	-/-	-/-	-/-	-/6	-/-	-/11
WS1	-/-	-/22	-/-	-/24	-/14	-/-	-/5	-/-	-/-	-/-	-/-	-/-

Table 6. Counts of trees in the outbreak region infested/uninfested with spruce beetle, by size class, spruce species, site, and transect. Small spruce are < 10 cm DBH, large spruce are ≥ 10 cm DBH.

	Control				Edge				Treatment			
Site	Large, White	Large, Black	Small, White	Small, Black	Large, White	Large, Black	Small, White	Small, Black	Large, White	Large, Black	Small, White	Small, Black
Hand-thinned												
CCS1	7/4	-/-	1/-	-/-	1/12	-/-	-/11	-/-	-/1	-/-	-/4	-/-
DNP1	1/17	-/-	-/26	-/-	-/16	-/-	-/24	-/-	-/11	-/-	-/3	-/-
DNP2	-/16	-/-	-/32	-/-	-/16	-/-	-/10	-/-	-/13	-/-	-/5	-/-
HH1	5/-	-/-	-/5	-/-	9/1	-/-	-/15	-/-	-/4	-/-	-/2	-/-
JACW1	8/2	-/1	2/13	-/1	7/10	1/1	1/20	-/1	1/-	-/-	-/-	-/-
KNA5	7/2	1/1	2/39	-/-	-/-	-/-	-/-	-/-	-/-	-/-	-/1	-/-
KNA8	12/-	1/8	4/10	-/9	31/3	2/12	2/12	-/12	4/4	2/5	-/5	-/2
LL1	-/1	-/17	-/-	-/7	1/-	1/16	-/-	-/10	-/-	-/15	-/-	-/3
SUN1	19/1	2/2	2/5	-/1	3/2	-/4	-/2	-/3	2/-	-/-	-/-	-/-
Masticated												
AMPL1	4/1	1/10	-/1	1/28	3/4	-/17	-/1	-/44	-/-	-/-	-/-	-/-
ANTN1	-/-	-/31	-/-	-/54	-/3	-/12	-/-	-/38	-/-	-/-	-/-	-/-
JON1	-/-	-/5	-/-	-/42	-/-	-/1	-/-	-/30	-/-	-/-	-/-	-/-
KNA1	-/2	5/23	-/1	-/18	2/1	2/19	-/6	-/8	-/-	-/-	-/-	-/-
KNA2	1/-	2/13	-/3	-/46	-/1	-/8	-/4	-/15	-/-	-/-	-/-	-/-
KNA3	13/2	-/-	2/14	-/-	14/1	-/-	3/5	-/-	-/-	-/-	-/-	-/-
KNA6	6/3	1/-	7/26	-/1	17/3	-/-	7/29	-/-	-/-	-/-	-/-	-/-
KNA7	15/5	-/-	2/16	1/-	1-/1	-/-	5/18	1/-	-/-	-/-	-/-	-/-
KNA9	-/6	2/2	-/1	-/1	2/3	-/-	-/2	-/1	-/1	-/-	-/-	-/-
KNAU4	8/-	1/9	2/8	-/27	-/1	2/11	1/5	-/35	-/-	-/-	-/-	-/-
MRE1	-/-	-/18	-/-	-/43	-/-	-/24	-/-	-/51	-/-	-/-	-/-	-/-
MRW1	-/-	-/19	-/-	-/78	-/-	-/21	-/-	-/90	-/-	-/-	-/-	-/-

Table 7. Counts of trees in the endemic region infested/uninfested with northern spruce engraver, by size class, spruce species, site, and transect. Small spruce are < 10 cm DBH, large spruce are ≥ 10 cm DBH.

	Control				Edge				Treatment			
Site	Large, White	Large, Black	Small, White	Small, Black	Large, White	Large, Black	Small, White	Small, Black	Large, White	Large, Black	Small, White	Small, Black
Hand-thinned												
BAD1	-/1	-/18	-/-	-/29	-/-	-/10	-/-	-/20	-/-	-/1	-/-	-/2
GS1	-/-	-/12	-/-	-/23	-/-	-/14	-/-	-/38	-/-	-/1	-/1	-/14
GS2	-/-	-/2	-/-	-/14	-/-	-/2	-/-	-/46	-/-	-/-	-/-	-/12
VG1	-/-	-/9	-/1	-/7	-/4	-/5	-/1	-/2	-/1	-/-	-/-	-/-
VG2	-/-	-/10	-/-	-/31	-/-	-/7	-/-	-/47	-/-	-/4	-/-	-/3
Masticated												
DEXP1	-/1	-/6	-/1	-/20	-/-	-/9	-/-	-/11	-/-	-/-	-/-	-/-
DEXP2	-/-	-/-	-/-	-/-	-/3	1/12	-/-	-/8	-/-	-/-	-/-	-/-
FTW1	-/7	-/2	-/17	-/12	-/1	-/3	-/2	-/19	-/-	-/-	-/-	-/-
SAL1	-/1	-/1	-/-	-/53	-/-	-/-	-/-	-/-	-/-	-/6	-/-	-/11
WS1	-/-	-/22	-/-	-/24	-/14	-/-	-/5	-/-	-/-	-/-	-/-	-/-

Table 8. Counts of trees in the outbreak region infested/uninfested with northern spruce engraver, by size class, spruce species, site, and transect. Small spruce are < 10 cm DBH, large spruce are ≥ 10 cm DBH.

	Control				Edge				Treatment			
Site	Large, White	Large, Black	Small, White	Small, Black	Large, White	Large, Black	Small, White	Small, Black	Large, White	Large, Black	Small, White	Small, Black
Hand-thinned												
CCS1	-/11	-/-	-/1	-/-	-/13	-/-	-/11	-/-	-/1	-/-	-/4	-/-
DNP1	-/18	-/-	-/26	-/-	-/16	-/-	-/24	-/-	-/11	-/-	-/3	-/-
DNP2	-/16	-/-	-/32	-/-	-/16	-/-	-/10	-/-	-/13	-/-	-/5	-/-
HH1	-/5	-/-	-/5	-/-	-/10	-/-	-/15	-/-	-/4	-/-	-/2	-/-
JACW1	-/10	-/1	-/15	-/1	-/17	-/2	-/21	-/1	-/1	-/-	-/-	-/-
KNA5	-/9	1/1	-/41	-/-	-/-	-/-	-/-	-/-	-/-	-/-	-/1	-/-
KNA8	-/12	1/8	2/12	-/9	2/32	3/11	-/14	-/12	3/5	1/6	-/5	-/2
LL1	-/1	-/17	-/-	-/7	-/1	-/17	-/-	-/10	-/-	-/15	-/-	-/3
SUN1	1/19	-/4	-/7	-/1	-/5	-/4	-/2	-/3	-/2	-/-	-/-	-/-
Masticated												
AMPL1	-/5	-/11	-/1	-/29	-/7	-/17	-/1	-/44	-/-	-/-	-/-	-/-
ANTN1	-/-	-/31	-/-	-/54	-/3	-/12	-/-	-/38	-/-	-/-	-/-	-/-
JON1	-/-	-/5	-/-	-/42	-/-	-/1	-/-	7/23	-/-	-/-	-/-	-/-

Site	Control				Edge				Treatment			
	Large, White	Large, Black	Small, White	Small, Black	Large, White	Large, Black	Small, White	Small, Black	Large, White	Large, Black	Small, White	Small, Black
KNA1	-/2	-/28	-/1	-/18	-/3	15/6	-/6	-/8	-/-	-/-	-/-	-/-
KNA2	-/1	-/15	-/3	-/46	1/-	6/2	1/3	4/11	-/-	-/-	-/-	-/-
KNA3	-/15	-/-	-/16	-/-	-/15	-/-	1/7	-/-	-/-	-/-	-/-	-/-
KNA6	-/9	-/1	-/33	-/1	-/20	-/-	-/36	-/-	-/-	-/-	-/-	-/-
KNA7	-/20	-/-	-/18	-/1	-/11	-/-	-/23	-/1	-/-	-/-	-/-	-/-
KNA9	-/6	-/4	-/1	-/1	-/5	-/-	-/2	-/1	-/1	-/-	-/-	-/-
KNAU4	-/8	-/10	-/10	-/27	-/1	4/9	-/6	1-/25	-/-	-/-	-/-	-/-
MRE1	-/-	-/18	-/-	-/43	-/-	1/23	-/-	5/46	-/-	-/-	-/-	-/-
MRW1	-/-	-/19	-/-	-/78	-/-	-/21	-/-	-/90	-/-	-/-	-/-	-/-

Table 9. Summary of proportion of trees with disease and broken tops by region, treatment, and transect.

	Disease			Broken Top		
transect	N Sites	Mean	SD	N Sites	Mean	SD
Endemic, Hand-thinned						
Control	7	2.2%	3.1%	7	8.4%	8.2%
Edge	7	3.6%	5.6%	7	10.9%	9.0%
Treat	7	0.0%	0.0%	7	1.4%	3.8%
Endemic, Masticated						
Control	4	0.0%	0.0%	4	16.8%	5.5%
Edge	5	13.6%	22.1%	5	9.7%	9.6%
Treat	1	0.0%	-	1	7.1%	-
Outbreak, Hand-thinned						
Control	9	6.1%	11.0%	9	9.9%	8.4%
Edge	8	4.4%	4.8%	8	12.2%	8.4%
Treat	8	6.2%	17.7%	8	1.0%	2.9%
Outbreak, Masticated						
Control	12	23.5%	20.9%	12	13.3%	7.9%
Edge	12	28.0%	21.8%	12	13.1%	7.2%
Treat	8	1.8%	5.1%	8	1.0%	2.9%

Table 10. Summary of control stand characteristics for each region and treatment type. Includes live and dead trees. Standard deviation (SD) could not be calculated when the number of sites (N) is equal to 1. SDp is pooled standard deviation. Data are from the Tree Health Survey.

		DBH (cm)			Basal Area (cm2 m-1)			Density (trees ha-1)			Percent Living		
Treatment	Species	Mean	Pooled SD	N Sites	Mean	SD	N Sites	Mean	SD	N Sites	Mean	SD	N Sites
Endemic Region													
Hand-thinned	black spruce	6.6	3.1	7	16	8	7	4,595	3,772	7	91	12	7
	deciduous	13.1	6.6	2	15	12	2	1,000	943	2	80	28	2
	other	4.7	1.4	3	1	2	3	444	347	3	33	58	3
	white spruce	16.1	5.8	2	12	17	2	333	0	2	100	0	2
Masticated	black spruce	8.0	3.4	3	13	8	3	1,889	948	3	89	13	3
	deciduous	17.5	-	1	41	-	1	1,500	-	1	67	-	1
	other	8.8	-	1	8	-	1	1,167	-	1	14	-	1
	white spruce	9.4	-	3	6	7	3	778	1,058	3	97	5	3
Outbreak Region													
Hand-thinned	black spruce	7.2	4.6	5	13	11	5	2,233	2,097	5	44	38	5
	deciduous	14.6	6.7	8	16	16	8	750	1,073	8	79	38	8
	white spruce	12.3	5.7	8	23	31	8	1,604	1,244	8	47	39	8
Masticated	black spruce	6.5	2.8	11	14	9	11	4,470	4,061	11	75	27	11
	deciduous	7.3	5.4	8	5	5	8	1,000	1,247	8	70	36	8
	white spruce	6.8	4.8	7	14	15	7	2,762	3,576	7	73	24	7

Table 11. Summary of control stand characteristics for each region and treatment type. Includes only living trees. Standard deviation (SD) could not be calculated when the number of sites (N) is equal to 1. SD_p is pooled standard deviation. Data are from the Tree Health Survey.

		DBH (cm)			Basal Area (cm2 m-1)			Density (trees ha-1)			Percent Living		
Treatment	Species	Mean	Pooled SD	N Sites	Mean	SD	N Sites	Mean	SD	N Sites	Mean	SD	N Sites
Endemic Region													
Hand-thinned	black spruce	6.7	3.1	7	14	8	7	3,905	2,926	7	91	12	7
	deciduous	14.8	6.5	2	14	10	2	667	471	2	80	28	2
	other	4.2	-	1	0	-	1	167	-	1	33	58	3
	white spruce	16.1	5.8	2	12	17	2	333	0	2	100	0	2
Masticated	black spruce	8.0	3.5	3	11	6	3	1,611	674	3	89	13	3
	deciduous	21.3	-	1	36	-	1	1,000	-	1	67	-	1
	other	14.2	-	1	3	-	1	167	-	1	14	-	1
	white spruce	9.5	-	3	6	7	3	722	962	3	97	5	3
Outbreak Region													
Hand-thinned	black spruce	7.6	4.3	4	7	6	4	1,000	758	4	44	38	5
	deciduous	15.0	6.2	7	16	17	7	714	1,022	7	79	38	8
	white spruce	8.9	3.8	6	7	5	6	944	455	6	47	39	8
Masticated	black spruce	6.0	2.8	10	13	8	10	3,950	3,374	10	75	27	11
	deciduous	8.2	5.1	7	5	5	7	905	1,166	7	70	36	8
	white spruce	6.7	3.4	7	7	6	7	1,524	1,626	7	73	24	7

Table 12. Stand summary characteristics of each transect at each hand-thinned site in the endemic region. Includes both living and dead trees.

Transect	Species	Total Trees	Density (live trees ha-1)	Basal Area (cm2 m-1)	Mean DBH (cm)	SD DBH (cm)	Percent Living (%)	Percent Broken Top (%)	Percent Diseased (%)
EVI1									
Control	black spruce	13	2,167	8	5.1	5.0	100.0	0.0	0.0
Control	other	2	333	0	2.6	0.1	0.0	0.0	0.0

Transect	Species	Total Trees	Density (live trees ha-1)	Basal Area (cm2 m-1)	Mean DBH (cm)	SD DBH (cm)	Percent Living (%)	Percent Broken Top (%)	Percent Diseased (%)
Control	white spruce	2	333	0	1.8	0.1	100.0	0.0	50.0
Edge	black spruce	27	4,500	24	7.4	3.6	74.1	3.7	3.7
Edge	deciduous	3	500	0	1.2	0.9	100.0	0.0	0.0
Edge	white spruce	17	2,833	25	8.2	6.7	82.4	5.9	29.4
Treat	black spruce	3	500	8	14.3	1.7	100.0	0.0	0.0
Treat	white spruce	3	500	19	19.8	11.1	100.0	0.0	0.0
BAD1									
Control	black spruce	50	8,333	18	4.4	2.8	70.0	10.0	2.0
Control	other	1	167	0	4.2	-	100.0	0.0	0.0
Edge	black spruce	40	6,667	13	4.5	2.4	80.0	5.0	0.0
Edge	other	3	500	1	3.8	1.1	66.7	33.3	0.0
Treat	black spruce	1	167	2	11.7	-	100.0	0.0	0.0
GS2									
Control	black spruce	10	1,667	4	4.6	3.3	100.0	0.0	0.0
Edge	black spruce	36	6,000	14	5.1	1.8	94.4	8.3	5.6
Treat	black spruce	8	1,333	4	6.0	1.4	100.0	0.0	0.0
SAL1									
Control	black spruce	65	10,833	19	4.1	2.4	83.1	21.5	0.0
Control	other	5	833	4	7.2	1.6	0.0	40.0	0.0
Edge	black spruce	116	19,333	26	3.5	2.2	94.8	9.5	40.5
Edge	other	8	1,333	3	4.9	2.3	0.0	50.0	0.0
Treat	black spruce	12	2,000	4	4.7	1.6	100.0	8.3	0.0
GS1									
Control	black spruce	14	2,333	19	9.3	4.4	85.7	7.1	0.0
Control	deciduous	2	333	6	14.1	9.5	100.0	50.0	50.0

Transect	Species	Total Trees	Density (live trees ha-1)	Basal Area (cm2 m-1)	Mean DBH (cm)	SD DBH (cm)	Percent Living (%)	Percent Broken Top (%)	Percent Diseased (%)
Control	white spruce	2	333	25	30.2	8.1	100.0	0.0	0.0
Edge	black spruce	11	1,833	12	8.5	3.9	90.9	27.3	0.0
Treat	black spruce	6	1,000	11	11.8	2.0	100.0	0.0	0.0
VG2									
Control	black spruce	34	5,667	28	7.3	3.0	97.1	2.9	0.0
Edge	black spruce	24	4,000	31	9.4	3.6	100.0	4.2	4.2
Edge	deciduous	1	167	0	5.2	-	100.0	100.0	0.0
Treat	black spruce	4	667	9	12.9	2.9	100.0	0.0	0.0
Treat	deciduous	2	333	2	8.8	1.0	100.0	0.0	0.0
VG1									
Control	black spruce	7	1,167	12	11.0	3.7	100.0	0.0	0.0
Control	deciduous	10	1,667	24	12.2	6.2	60.0	20.0	0.0
Edge	black spruce	9	1,500	34	14.7	9.3	77.8	0.0	0.0
Edge	deciduous	3	500	10	14.9	6.5	100.0	0.0	0.0
Edge	white spruce	5	833	9	11.4	1.6	100.0	0.0	0.0
Treat	deciduous	4	667	13	14.6	6.5	100.0	0.0	0.0

Table 13. Stand summary characteristics of each transect of each masticated site in the endemic region. Includes both living and dead trees.

Transect	Species	Total Trees	Density (live trees ha-1)	Basal Area (cm2 m-1)	Mean DBH (cm)	SD DBH (cm)	Percent Living (%)	Percent Broken Top (%)	Percent Diseased (%)
WS1									
Control	black spruce	16	2,667	18	9.0	2.7	75.0	12.5	0.0
Control	white spruce	1	167	4	16.6	-	100.0	0.0	0.0
Edge	black spruce	8	1,333	20	13.3	4.2	100.0	0.0	0.0

Transect	Species	Total Trees	Density (live trees ha-1)	Basal Area (cm2 m-1)	Mean DBH (cm)	SD DBH (cm)	Percent Living (%)	Percent Broken Top (%)	Percent Diseased (%)
Edge	white spruce	2	333	6	14.6	0.0	100.0	0.0	0.0
SAL1									
Control	black spruce	65	10,833	19	4.1	2.4	83.1	21.5	0.0
Control	other	5	833	4	7.2	1.6	0.0	40.0	0.0
Edge	black spruce	116	19,333	26	3.5	2.2	94.8	9.5	40.5
Edge	other	8	1,333	3	4.9	2.3	0.0	50.0	0.0
Treat	black spruce	12	2,000	4	4.7	1.6	100.0	8.3	0.0
FTW1									
Control	black spruce	13	2,167	15	8.9	3.5	92.3	0.0	0.0
Control	other	7	1,167	8	8.8	3.6	14.3	57.1	0.0
Control	white spruce	12	2,000	14	7.5	6.2	91.7	0.0	0.0
Edge	black spruce	41	6,833	27	6.3	3.3	85.4	24.4	0.0
Edge	deciduous	5	833	5	8.2	3.8	80.0	40.0	0.0
Edge	other	2	333	1	5.3	2.6	0.0	0.0	0.0
Edge	white spruce	4	667	3	7.4	2.9	50.0	25.0	0.0
DEXP2									
Edge	black spruce	9	1,500	5	5.5	3.3	100.0	22.2	0.0
Edge	deciduous	2	333	19	25.4	13.5	50.0	0.0	0.0
Edge	white spruce	2	333	2	6.4	8.4	100.0	0.0	0.0
DEXP1									
Control	black spruce	5	833	4	6.0	4.9	100.0	0.0	0.0
Control	deciduous	9	1,500	41	17.5	6.6	66.7	33.3	0.0
Control	white spruce	1	167	0	4.0	-	100.0	0.0	0.0
Edge	black spruce	31	5,167	24	7.0	3.1	67.7	0.0	3.2
Edge	deciduous	7	1,167	7	7.9	3.9	28.6	42.9	0.0
Edge	other	1	167	0	3.2	-	0.0	0.0	0.0

Table 14. Stand summary characteristics of each hand-thinned site in the outbreak region. Includes both living and dead trees.

Transect	Species	Total Trees	Density (live trees ha-1)	Basal Area (cm2 m-1)	Mean DBH (cm)	SD DBH (cm)	Percent Living (%)	Percent Broken Top (%)	Percent Diseased (%)
SUN1									
Control	deciduous	4	667	30	21.9	11.6	100.0	0.0	0.0
Control	white spruce	2	333	7	15.8	6.2	0.0	50.0	50.0
Edge	deciduous	3	500	48	34.3	8.9	66.7	33.3	33.3
Edge	white spruce	4	667	0	2.7	0.7	100.0	0.0	0.0
LL1									
Control	black spruce	11	1,833	17	9.8	5.0	54.5	18.2	0.0
Control	deciduous	2	333	20	27.5	1.6	100.0	50.0	50.0
Edge	black spruce	11	1,833	18	9.9	5.7	54.5	27.3	9.1
Edge	deciduous	3	500	9	14.0	7.4	66.7	33.3	0.0
Treat	black spruce	3	500	16	19.9	1.5	100.0	0.0	0.0
Treat	deciduous	4	667	18	18.3	2.2	100.0	0.0	0.0
CCS1									
Control	white spruce	10	1,667	98	24.6	12.6	30.0	0.0	0.0
Edge	deciduous	2	333	25	30.9	1.0	100.0	50.0	50.0
Edge	white spruce	15	2,500	17	7.7	5.5	80.0	0.0	0.0
Treat	other	1	167	41	56.2	-	100.0	0.0	0.0
Treat	white spruce	2	333	2	8.6	1.4	100.0	0.0	0.0
KNA8									
Control	black spruce	27	4,500	28	7.5	5.0	18.5	18.5	0.0
Control	deciduous	5	833	7	7.1	8.6	40.0	0.0	0.0
Control	white spruce	9	1,500	20	11.8	5.9	55.6	0.0	44.4
Edge	black spruce	15	2,500	18	7.5	6.2	40.0	20.0	0.0
Edge	deciduous	3	500	32	28.2	6.0	66.7	33.3	0.0
Edge	white spruce	6	1,000	7	8.2	4.6	66.7	0.0	16.7

Transect	Species	Total Trees	Density (live trees ha-1)	Basal Area (cm2 m-1)	Mean DBH (cm)	SD DBH (cm)	Percent Living (%)	Percent Broken Top (%)	Percent Diseased (%)
Treat	black spruce	6	1,000	15	13.8	1.4	50.0	0.0	33.3
Treat	deciduous	1	167	0	0.4	-	100.0	0.0	0.0
Treat	white spruce	2	333	2	6.8	5.3	100.0	0.0	100.0
KNA5									
Control	deciduous	20	3,333	45	12.0	5.5	90.0	10.0	0.0
Control	white spruce	4	667	1	5.0	1.6	100.0	0.0	25.0
Edge	deciduous	19	3,167	41	11.8	5.3	73.7	21.1	0.0
Edge	other	1	167	29	47.4	-	100.0	0.0	0.0
Edge	white spruce	25	4,167	10	4.9	2.7	28.0	0.0	8.0
Treat	deciduous	19	3,167	70	15.5	6.7	89.5	0.0	0.0
HH1									
Control	black spruce	2	333	3	10.8	0.4	0.0	0.0	50.0
Control	deciduous	2	333	19	27.0	2.0	100.0	0.0	0.0
Control	white spruce	7	1,167	21	14.4	4.6	0.0	0.0	14.3
Edge	black spruce	1	167	4	17.8	-	100.0	0.0	0.0
Edge	deciduous	5	833	17	13.9	8.8	80.0	20.0	20.0
Edge	other	2	333	1	4.8	1.9	100.0	0.0	0.0
Edge	white spruce	1	167	1	9.0	-	100.0	0.0	0.0
Treat	deciduous	10	1,667	42	16.6	7.1	100.0	10.0	0.0
Treat	white spruce	2	333	1	7.3	0.8	100.0	0.0	0.0
DNP2									
Control	black spruce	1	167	0	2.6	-	100.0	0.0	0.0
Control	deciduous	1	167	2	11.6	-	100.0	0.0	0.0
Control	white spruce	4	667	13	15.5	3.8	100.0	0.0	0.0
Treat	deciduous	1	167	1	7.9	-	100.0	0.0	0.0
Treat	white spruce	3	500	6	12.2	3.0	100.0	0.0	0.0
DNP1									
Control	deciduous	1	167	1	6.5	-	0.0	100.0	100.0

Transect	Species	Total Trees	Density (live trees ha-1)	Basal Area (cm2 m-1)	Mean DBH (cm)	SD DBH (cm)	Percent Living (%)	Percent Broken Top (%)	Percent Diseased (%)
Control	white spruce	17	2,833	13	6.9	3.4	58.8	11.8	0.0
Edge	deciduous	1	167	4	17.5	-	100.0	0.0	0.0
Edge	white spruce	21	3,500	27	9.1	4.3	85.7	0.0	9.5
Treat	white spruce	7	1,167	26	16.4	3.6	100.0	0.0	0.0
JACW1									
Control	black spruce	26	4,333	15	5.1	4.2	46.2	7.7	7.7
Control	deciduous	1	167	0	3.1	-	100.0	100.0	0.0
Control	white spruce	24	4,000	7	4.0	2.5	33.3	12.5	0.0
Edge	black spruce	4	667	6	9.6	4.5	50.0	0.0	0.0
Edge	deciduous	1	167	0	1.2	-	100.0	100.0	0.0
Edge	other	8	1,333	8	4.4	7.7	0.0	0.0	0.0
Edge	white spruce	20	3,333	7	4.5	2.3	85.0	15.0	0.0
Treat	deciduous	4	667	48	27.6	14.7	100.0	0.0	0.0

Table 15. Stand summary characteristics of each masticated site in the outbreak region. Includes both living and dead trees.

Transect	Species	Total Trees	Density (live trees ha-1)	Basal Area (cm2 m-1)	Mean DBH (cm)	SD DBH (cm)	Percent Living (%)	Percent Broken Top (%)	Percent Diseased (%)
MRE1									
Control	black spruce	40	6,667	23	5.6	3.6	80.0	15.0	35.0
Edge	black spruce	46	7,667	38	7.0	3.6	63.0	19.6	32.6
KNAU4									
Control	black spruce	81	13,500	17	3.4	2.2	86.4	8.6	1.2
Edge	black spruce	47	7,833	22	5.5	2.5	74.5	12.8	4.3
MRW1									

Transect	Species	Total Trees	Density (live trees ha-1)	Basal Area (cm2 m-1)	Mean DBH (cm)	SD DBH (cm)	Percent Living (%)	Percent Broken Top (%)	Percent Diseased (%)
Control	black spruce	56	9,333	22	4.9	2.4	75.0	23.2	0.0
Edge	black spruce	34	5,667	23	6.4	3.1	70.6	14.7	0.0
KNA7									
Control	black spruce	1	167	0	3.5	-	100.0	0.0	0.0
Control	deciduous	1	167	2	12.2	-	100.0	0.0	0.0
Control	white spruce	33	5,500	31	6.4	5.6	72.7	6.1	27.3
Edge	deciduous	1	167	4	16.4	-	100.0	0.0	0.0
Edge	white spruce	74	12,333	26	4.2	3.0	52.7	4.1	33.8
Treat	deciduous	1	167	6	22.3	-	100.0	0.0	0.0
KNA6									
Control	deciduous	4	667	6	7.8	9.1	100.0	0.0	0.0
Control	white spruce	58	9,667	36	5.6	4.1	36.2	8.6	13.8
Edge	deciduous	1	167	0	3.7	-	100.0	0.0	0.0
Edge	other	1	167	17	36.4	-	100.0	0.0	0.0
Edge	white spruce	27	4,500	21	6.7	4.0	55.6	7.4	33.3
Treat	deciduous	1	167	4	18.3	-	100.0	0.0	0.0
JON1									
Control	black spruce	30	5,000	12	5.2	1.9	86.7	10.0	60.0
Control	deciduous	1	167	0	5.9	-	0.0	0.0	0.0
Edge	black spruce	16	2,667	6	4.7	2.3	56.2	18.8	43.8
Edge	deciduous	9	1,500	3	5.0	1.7	44.4	22.2	0.0
Treat	deciduous	9	1,500	0	0.9	0.6	100.0	0.0	0.0
KNA9									
Control	black spruce	9	1,500	1	3.0	1.9	100.0	0.0	55.6
Control	deciduous	24	4,000	8	3.6	3.8	87.5	37.5	4.2
Control	white spruce	1	167	0	1.3	-	100.0	0.0	100.0
Edge	black spruce	2	333	8	15.9	8.9	50.0	0.0	0.0
Edge	deciduous	31	5,167	66	7.3	10.6	83.9	9.7	3.2

Transect	Species	Total Trees	Density (live trees ha-1)	Basal Area (cm2 m-1)	Mean DBH (cm)	SD DBH (cm)	Percent Living (%)	Percent Broken Top (%)	Percent Diseased (%)
Edge	other	1	167	0	1.2	-	0.0	100.0	0.0
Edge	white spruce	5	833	1	3.4	2.3	100.0	0.0	100.0
Treat	deciduous	12	2,000	2	2.9	2.8	75.0	8.3	0.0
KNA3									
Control	black spruce	1	167	2	12.7	-	0.0	0.0	0.0
Control	deciduous	5	833	15	11.9	10.9	100.0	0.0	0.0
Control	white spruce	12	2,000	13	7.6	4.9	83.3	0.0	66.7
Edge	deciduous	5	833	6	6.7	6.9	40.0	40.0	0.0
Edge	white spruce	7	1,167	22	12.7	9.3	42.9	14.3	14.3
Treat	deciduous	4	667	18	17.2	8.0	100.0	0.0	0.0
Treat	white spruce	3	500	3	7.2	4.8	100.0	0.0	33.3
KNA2									
Control	black spruce	13	2,167	22	10.9	3.5	84.6	15.4	30.8
Control	deciduous	3	500	4	8.7	4.7	66.7	0.0	33.3
Control	white spruce	1	167	2	12.5	-	100.0	0.0	100.0
Edge	black spruce	38	6,333	34	7.8	2.8	31.6	13.2	13.2
Edge	deciduous	13	2,167	18	8.7	5.5	76.9	23.1	7.7
KNA1									
Control	black spruce	17	2,833	23	9.6	3.5	76.5	23.5	5.9
Control	white spruce	2	333	1	5.0	0.8	50.0	0.0	0.0
Edge	black spruce	25	4,167	34	9.3	4.3	80.0	4.0	32.0
Edge	deciduous	2	333	0	2.0	0.4	100.0	0.0	0.0
Edge	white spruce	16	2,667	13	6.6	4.4	81.2	0.0	43.8
Treat	deciduous	1	167	19	38.5	-	100.0	0.0	0.0
AMPL1									
Control	black spruce	22	3,667	9	5.1	2.4	59.1	22.7	0.0
Control	deciduous	4	667	0	2.5	0.6	75.0	25.0	0.0

Transect	Species	Total Trees	Density (live trees ha-1)	Basal Area (cm2 m-1)	Mean DBH (cm)	SD DBH (cm)	Percent Living (%)	Percent Broken Top (%)	Percent Diseased (%)
Control	white spruce	9	1,500	14	8.9	6.4	66.7	11.1	0.0
Edge	black spruce	27	4,500	10	4.8	2.5	88.9	3.7	3.7
Edge	deciduous	4	667	15	9.2	16.5	100.0	25.0	0.0
Treat	deciduous	3	500	7	7.8	12.7	100.0	0.0	0.0
ANTN1									
Control	black spruce	25	4,167	23	7.3	4.1	80.0	8.0	16.0
Control	deciduous	6	1,000	3	5.5	3.5	33.3	16.7	0.0
Edge	black spruce	26	4,333	28	7.7	4.8	80.8	7.7	11.5
Edge	deciduous	16	2,667	7	5.5	1.8	43.8	37.5	31.2
Treat	deciduous	21	3,500	0	0.8	0.3	100.0	0.0	0.0

Table 16. Presence of live beetles or empty beetle galleries at each transect, as determined by the Time-Based Beetle Survey and the Distance-Based Beetle Survey. SB = spruce beetle. Live SB or NSE in Trees indicates if beetles were found in living trees in addition to or instead of debris.

Site	Transect	Spruce Debris	SB, Timed	SB, Distance	NSE, Timed	NSE, Distance	Live SB or NSE in Trees
Endemic, Hand-thinned							
EVI1	Control	Zero	-	-	-	-	-
EVI1	Edge	Zero	-	-	Live, Galleries	-	-
EVI1	Treat	Zero	-	-	Live, Galleries	-	-
GS1	Control	Zero	-	-	-	-	-
GS1	Edge	Zero	-	-	-	-	-
GS1	Treat	Zero	-	-	-	-	-
GS2	Control	Zero	-	-	-	-	-
GS2	Edge	Zero	-	-	-	-	-
GS2	Treat	Zero	-	-	-	-	-
SAL1	Control	Zero	-	-	-	-	-
SAL1	Treat	Low	-	-	-	-	-

Site	Transect	Spruce Debris	SB, Timed	SB, Distance	NSE, Timed	NSE, Distance	Live SB or NSE in Trees
VG1	Control	Zero	-	-	-	-	-
VG1	Edge	Zero	-	-	-	-	-
VG1	Treat	Zero	Live, Galleries	-	-	-	Yes
VG2	Control	Zero	-	-	-	-	-
VG2	Edge	Zero	-	-	-	-	-
VG2	Treat	Low	-	-	-	-	-
Endemic, Masticated							
BAD1	Control	Zero	Galleries	-	-	-	-
BAD1	Edge	Zero	-	-	-	-	-
BAD1	Treat	Zero	-	-	-	-	-
DEXP1	Control	Zero	-	-	-	-	-
DEXP1	Edge	Low	-	-	-	-	-
DEXP1	Treat	Zero	-	-	-	-	-
DEXP2	Edge	Low	-	-	Live, Galleries	Galleries	-
DEXP2	Treat	Zero	-	-	Galleries	-	-
FTW1	Control	Zero	-	-	-	-	-
FTW1	Edge	Zero	-	-	-	-	-
FTW1	Treat	Zero	-	-	-	-	-
SAL1	Treat	Low	-	-	-	-	-
WS1	Control	Zero	-	-	-	-	-
WS1	Edge	Low	-	-	Live, Galleries	-	Yes
WS1	Treat	Zero	-	-	Live, Galleries	-	-
Outbreak, Hand-thinned							
CCS1	Control	Zero	Galleries	Galleries	-	-	-
CCS1	Edge	Zero	Galleries	Galleries	-	-	-
CCS1	Treat	Zero	Live, Galleries	-	Live, Galleries	-	-
DNP1	Control	Zero	Live, Galleries	Live, Galleries	-	-	Yes
DNP1	Edge	Zero	Live, Galleries	-	-	-	-
DNP1	Treat	Zero	-	-	-	-	-
DNP2	Control	Zero	Galleries	-	-	-	-
DNP2	Edge	Zero	-	-	-	-	-
DNP2	Treat	Zero	Live, Galleries	-	Live, Galleries	-	-
HH1	Control	Zero	Galleries	Galleries	-	-	-

Site	Transect	Spruce Debris	SB, Timed	SB, Distance	NSE, Timed	NSE, Distance	Live SB or NSE in Trees
HH1	Edge	Zero	Galleries	Galleries	-	-	-
HH1	Treat	Zero	-	-	-	-	-
JACW1	Control	Zero	Live, Galleries	Galleries	-	-	Yes
JACW1	Edge	Zero	Live, Galleries	Galleries	Live, Galleries	-	Yes
JACW1	Treat	High	Live, Galleries	Galleries	Live, Galleries	-	-
KNA5	Control	Zero	Galleries	Galleries	Galleries	Galleries	-
KNA5	Treat	High	Live, Galleries	-	Live, Galleries	-	-
KNA8	Control	Zero	Galleries	Galleries	Galleries	Galleries	-
KNA8	Edge	Zero	Galleries	Galleries	Galleries	Galleries	-
KNA8	Treat	Zero	Galleries	Galleries	Live, Galleries	Galleries	Yes
LL1	Control	Zero	Galleries	-	-	-	-
LL1	Edge	Low	Galleries	Galleries	-	-	-
LL1	Treat	Low	-	-	-	-	-
SUN1	Control	Zero	Galleries	Galleries	Live, Galleries	Galleries	-
SUN1	Edge	Zero	Galleries	Galleries	-	-	-
SUN1	Treat	Zero	Live, Galleries	Galleries	Live, Galleries	-	-
Outbreak, Masticated							
AMPL1	Control	Zero	Galleries	Galleries	-	-	-
AMPL1	Edge	Zero	Galleries	Galleries	-	-	-
AMPL1	Treat	Zero	-	-	-	-	-
ANTN1	Control	Zero	-	-	-	-	-
ANTN1	Edge	Zero	-	-	Galleries	-	-
ANTN1	Treat	Zero	-	-	-	-	-
JON1	Control	Zero	-	-	-	-	-
JON1	Edge	Zero	-	-	Galleries	Galleries	-
JON1	Treat	Zero	-	-	-	-	-
KNA1	Control	Zero	Live, Galleries	Galleries	-	-	Yes
KNA1	Edge	Zero	Galleries	Galleries	Live, Galleries	Galleries	Yes
KNA1	Treat	Zero	Galleries	-	-	-	-
KNA2	Control	Zero	Galleries	Galleries	-	-	-
KNA2	Edge	Zero	-	-	Live, Galleries	Galleries	Yes
KNA2	Treat	Zero	-	-	-	-	-

Site	Transect	Spruce Debris	SB, Timed	SB, Distance	NSE, Timed	NSE, Distance	Live SB or NSE in Trees
KNA3	Control	Zero	Galleries	Galleries	-	-	-
KNA3	Edge	Zero	Galleries	Galleries	Galleries	Galleries	-
KNA3	Treat	Zero	Galleries	-	Live, Galleries	-	-
KNA6	Control	Zero	Galleries	Galleries	-	-	-
KNA6	Edge	Zero	Galleries	Galleries	Galleries	-	-
KNA6	Treat	Zero	Galleries	-	Galleries	-	-
KNA7	Control	Zero	Galleries	Galleries	-	-	-
KNA7	Edge	Zero	Galleries	Galleries	-	-	-
KNA7	Treat	Zero	-	-	-	-	-
KNA9	Control	Zero	Galleries	Galleries	Galleries	-	-
KNA9	Edge	Zero	Galleries	Galleries	Galleries	-	-
KNA9	Treat	Low	-	-	Live, Galleries	-	Yes
KNAU4	Control	Zero	Galleries	Galleries	-	-	-
KNAU4	Edge	Zero	-	Galleries	Live, Galleries	Galleries	Yes
KNAU4	Treat	Zero	Galleries	-	Live, Galleries	-	-
MRE1	Control	Zero	-	-	-	-	-
MRE1	Edge	Zero	-	-	Live, Galleries	Galleries	Yes
MRE1	Treat	Zero	-	-	-	-	-
MRW1	Control	Low	-	-	-	-	-
MRW1	Edge	Low	-	-	-	-	-
MRW1	Treat	Zero	-	-	-	-	-

Table 17. Latitude and longitude of sites, represented by the 0 m mark of the treatment transect.

Site	Latitude	Longitude
Endemic, Hand-thinned		
BAD1	64.79995	-147.3439
EVI1	64.74702	-141.0529
GS1	64.95770	-147.7794
GS2	64.95748	-147.7115
SAL1	64.54001	-147.0927
VG1	64.95384	-147.8515
VG2	64.95383	-147.8591
Endemic, Masticated		
DEXP1	64.01119	-145.6697

Site	Latitude	Longitude
DEXP2	64.00900	-145.6660
FTW1	64.84058	-147.5659
SAL1	64.53903	-147.0937
WS1	64.13840	-145.8698
Outbreak, Hand-thinned		
CCS1	60.48135	-149.8832
DNP1	63.73253	-148.9066
DNP2	63.73363	-148.8983
HH1	61.98904	-150.0272
JACW1	60.56057	-150.8406
KNA5	60.56004	-150.8881
KNA8	60.56040	-150.8337
LL1	61.66679	-149.9884
SUN1	61.65740	-149.6404
Outbreak, Masticated		
AMPL1	60.54993	-150.5875
ANTN1	60.51968	-150.5878
JON1	60.53842	-150.5888
KNA1	60.56009	-150.7675
KNA2	60.56063	-150.7789
KNA3	60.56059	-150.8959
KNA6	60.56061	-150.8779
KNA7	60.56039	-150.8700
KNA9	60.56041	-150.8105
KNAU4	60.56080	-150.8031
MRE1	60.56054	-150.7066
MRW1	60.56074	-150.7444