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Douglas-fir Tree Mortality Caused by the Douglas-fir Beetle in Thinned and Unthinned Stands in Montana, USA

Nancy Sturdevant[1], Laurel Haavik[1] and José F. Negrón[2,*]

[1]USDA Forest Service, Forest Health Protection, Missoula, MT, USA.
[2]USDA Forest Service, Rocky Mountain Research Station, Fort Collins, CO, USA.
*Corresponding author email: jose.negron@usda.gov

Abstract

Bark beetles are casual agents of tree mortality, often affecting landscapes with diverse topography. The Douglas-fir beetle (*Dendroctonus pseudotsugae* Hopkins) (DFB) uses Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco), as its primary host. Populations often increase following disturbances such as defoliation, fires, or blowdowns and then transition into live healthy trees. Mitigating tree mortality where high mortality levels are incompatible with land manager objectives is of relevance. In this study, we compared mortality levels in eighteen thinned and twelve unthinned pure Douglas-fir stands in the Helena National Forest in Montana. Managed stands were thinned during the summers of 2014 and 2015 and tree mortality evaluated in 2017 and 2018. Douglas-fir beetle populations were at endemic levels in the study area, as represented by low observed tree mortality. Even under endemic populations, 3.6% of Douglas-firs > 12 in diameter at breast height (dbh) were killed in unthinned stands compared to 1.6% in thinned stands. Basal area of trees killed in unthinned stands was 5.4 (± 2.4) ft^2/ac compared with 0.5 (± 0.3) ft^2/ac in thinned stands. Although insect pressure was low, this study indicates that vegetation management could be a tool to mitigate DFB-caused tree mortality. Additional studies conducted under higher insect populations are needed.

Study Implications: Douglas-fir beetle (DFB) can cause extensive mortality of Douglas-fir, particularly in dense stands of large-diameter trees with a high percentage of hosts. Vegetation management through silvicultural thinnings has been proposed as a long-term strategy to mitigate tree mortality from bark beetles. In this study, we compared tree mortality caused by DFB in thinned and unthinned Douglas-fir stands. Douglas-fir beetle populations were at low levels post-thinning and mortality levels were limited. Regardless, we observed increased mortality in denser, unthinned stands compared with thinned stands with lower tree density, suggesting that stand density reductions may mitigate DFB-caused tree mortality.

Keywords: Douglas-fir beetle, *Dendroctonus pseudotsugae*, Douglas-fir, *Pseudotsuga menziesii*, tree mortality, thinning

Forest structure and composition are driven by disturbance processes that include biotic agents such as insects and diseases, abiotic events such as fires and windstorms, and land use practices. Western forests have become increasingly vulnerable to insects and diseases through a series of cascading events and subsequent effects, such as droughts, that result in increased tree stress, elevated winter temperatures that foster increased survival of over-wintering bark beetle populations, and an abundance of susceptible hosts (Breshears et al. 2005, Shaw et al. 2005, Bentz et al. 2010, Fettig et al. 2013, Negrón and Cain 2019). Future climate trends suggest increases in disturbances such as fire, insects and diseases, and stressful growing conditions from drought (Dale et al. 2001, Allen et al. 2010, Sturrock et al. 2011, Seidl et al. 2017, USGCRP 2018, Martin et al. 2020, Higuera et al. 2021). This is especially alarming considering that current forests are likely more adapted to the relatively wet conditions experienced throughout the 20th century (Martin et al. 2020). Forest management practices and historic land use patterns also contribute to current forest stand conditions. In general, fire exclusion throughout much of the 20th century has led to dense forests with intense inter- and intraspecific competition for limited resources. In the absence of frequent low-intensity fire, some shade-tolerant species proliferated. For example, the interior Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco) forest type has expanded, encroaching into grasslands and colonizing habitat that was ponderosa pine forest type maintained through disturbance (Anderson et al. 1987, Heyerdahl et al. 2006). Widespread logging in the late 19th and early 20th century homogenized age and size classes over large areas, resulting in an abundance of overmature Douglas-fir stands.

The Douglas-fir beetle (*Dendroctonus pseudotsugae* Hopkins) (DFB) is a native bark beetle that uses Douglas-fir as its primary host. The insect is well distributed across western North America from British Columbia, south along the Pacific Coast, east to the Rocky Mountains, and south to northern Mexico (Wood 1982). DFB is a natural disturbance agent and integral to the ecology of Douglas-fir forests. Populations of DFB are typically at low levels, killing individual trees or small groups of trees scattered across the landscape. Chronic stress from growing conditions (e.g., xeric topography, poor microsites), root disease, repeated defoliation by the western spruce budworm

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(*Choristoneura occidentalis* Freeman) or the Douglas-fir tussock moth (*Orgyia pseudotsugata* McDunnough) render trees more susceptible to DFB (Wright et al. 1984, Mitchell 2000, Negrón et al. 2014, Freeman et al. 2020). Windthrown, fire-damaged, or stressed Douglas-fir trees offer a rich source of susceptible host material that can promote DFB population growth (Furniss 1965, Hood and Bentz 2007). Populations that build in damaged or dying trees often move on to colonize and kill apparently healthy trees (Rasmussen et al. 1996, Cunningham et al. 2005, Hood and Bentz 2007). Drought and increased temperatures have been associated with outbreaks of DFB (Agne et al. 2018).

DFB outbreaks are difficult to predict. Once initiated, outbreaks can last for decades but more commonly are short (2–4 years), spatially aggregated, and usually decline due to intraspecific competition among beetles for limited suitable hosts (Furniss et al. 1979, Dodds et al. 2006, Furniss 2014). Eruptive populations develop in dense older stands (>120 years) with high basal area (>250 ft^2/ac), composed of larger-diameter trees (>14 in. dbh) (Furniss et al. 1981, Weatherby and Thier 1993, Negrón 1998, Shore et al. 1999, Randall et al. 2019). Once an outbreak begins, suitable host availability and their spatial distribution determines the extent of mortality (Negrón et al. 1999, 2001). Mixed species stands are less affected by DFB (McMillin and Allen 2000). Although DFB is a native insect and population fluctuations are part of its ecology, outbreaks can cause extensive host mortality at stand and landscape scales, which can be incompatible with certain resource values.

Direct control strategies to mitigate DFB-caused tree mortality in high-value settings include the use of pheromones. The chemical ecology communication used by DFB during tree colonization is well understood, and a synthetically produced anti-aggregation pheromone (3-methylcyclohex-2-en-1-one) is commercially available and has proven to be very effective at protecting individual high-value trees or limited acreage (Ross 2021). This anti-aggregation pheromone can also be applied aerially over larger or inaccessible areas (Gillette et al. 2009), although this may not be cost-effective. Removal of infested trees through sanitation can curtail growing DFB populations (Lejeune 1961, Furniss et al. 1979, Humphreys 1995). The use of insecticide applications to prevent attacks to live trees in high-value settings is very effective, although not frequently used against DFB. These strategies can provide short-term reductions in tree mortality, but there is an increasing need to develop proactive forest management strategies that mitigate high levels of tree mortality and provide a long-term solution to losses caused by DFB.

Vegetation management through silvicultural thinnings is considered the best long-term approach to mitigate tree mortality from bark beetles (Fettig et al. 2007). Most knowledge in support of these strategies comes from other forest types such as ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.), lodgepole pine (*Pinus contorta* Dougl. ex. Loud), and, to a lesser extent, Engelmann spruce (*Picea engelmannii* Parry ex Engelm.), (McGregor et al. 1987, Whitehead and Russo 2005, Hansen et al. 2010, Graham et al. 2016, Negrón et al. 2017). For example, increased intertree spacing through thinning reduced lodgepole pine tree mortality caused by mountain pine beetle in British Columbia (Whitehead and Russo 2005). In addition, thinned ponderosa pine stands in the Black Hills of South Dakota and Wyoming experienced 4% mortality compared with 38% in unthinned stands during a mountain pine beetle outbreak (Negrón et al. 2017). Thinning improves the vigor of residual trees, thus improving resistance to bark beetle attack (Waring and Pitman 1985). Thinning also may be effective because the resulting microclimate is no longer conducive to bark beetle pheromone communication, or increased solar radiation warms bark temperatures beyond what is suitable for bark beetle oviposition and development (Bartos and Amman 1989, Amman and Logan 1998, Thistle et al. 2004, Whitehead and Russo 2005).

Vegetation mapping efforts suggest that most (~76%) Douglas-fir forests in Montana are highly or moderately susceptible to DFB (Egan et al. 2018). DFB preference for older, overstocked stands with a high proportion of Douglas-fir and abundant large-diameter trees suggests that tree density reductions may mitigate extensive tree mortality (Lejeune et al. 1961, Williamson and Price 1971, Furniss et al. 1979, Randall et al. 2019). This strategy, to our knowledge, has not been empirically tested. In this study, we compared DFB-caused tree mortality in thinned and unthinned stands in interior Douglas-fir forests in Montana. Our null hypothesis was that DFB-caused tree mortality would not differ between thinned and unthinned stands.

Methods

This study was conducted in the Cabin Creek area of the Townsend Ranger District of the Helena National Forest in west-central Montana. The centroid of the study area was at about latitude 46.3, longitude −111.5 at an elevation of 3,835 ft. which is about 17 miles NE of the city of Townsend, Montana. Thirty-year normals from 1991 to 2020 at these coordinates are minimum and maximum temperatures in January of 13.2°F and 34.1°F, respectively, with a mean of 23.7°F. In July, minimum and maximum temperatures are 51.3°F and 85.1°F, respectively, with a mean of 68.2°F. Annual total precipitation averaged 10.7 in. From 2008 to 2018, which include the study period, minimum and maximum temperatures in January were 12.4°F and 32.8°F, respectively, with a mean of 22.6°F. In July, minimum and maximum temperatures were 51.9°F and 85.1°F, respectively, with a mean of 68.5°F. Annual total precipitation averaged 10.6 in. This indicates that climatic conditions before and during the study period did not differ from the 1991 to 2020 normals (all data from the Prism Climate Group 2021). From 2014 to 2017, acres exhibiting DFB-killed trees on the Townsend Ranger District included a high of 569 in 2015 and a low of 168 in 2016, including some observed mortality in the study area.

We examined a total of thirty stands in the study, eighteen thinned and twelve unthinned stands. Thinned stands were treated during the summers of 2014 and 2015. Thinning prescriptions focused on reducing Douglas-fir basal area to 60–80 ft^2/ac, retaining Douglas-firs > 13 in. dbh, that favored retention of Douglas-firs > 26 in. dbh. Resource objectives included maintaining or enhancing timber productivity, reducing crown-fire potential, retaining trees of higher vigor, mitigating potential tree mortality to DFB by reducing tree density, and creating a late-seral open habitat. We conducted tree mortality assessments in August of 2017 and 2018. Stands ranged in size from 6 to 105 ac (mean = 30.8, SEM ± 6.7). Field crews established a series of variable-radius plots using a 20 BAF (basal area factor) prism in each thinned and unthinned stand. The number of plots per stand varied from six to fifteen and were distributed across a stand to adequately sample the entire stand. For every tree determined to be in the plot, crews recorded species, tree dbh, and tree condition. Tree condition was recorded as live, killed by DFB post-thinning, or dead from unknown causes. We used the presence of boring dust at the base of the tree, signs of resin flow, and presence of DFB galleries under the bark to determine DFB-caused tree mortality. Tree mortality assessment included only trees killed after thinning in treated and untreated stands.

We calculated the percentage of Douglas-fir trees killed by DFB to compare tree mortality between thinned and unthinned stands. This allowed compensating for differences in the number of trees available for attack. For this analysis, we excluded trees < 12 in. dbh as they are less likely to be attacked by DFB. We used a mixed-effects general linear model with a binomial distribution to compare the percent of trees killed by DFB between thinned and unthinned stands. Using the individual tree data collected from the variable-radius plots, we calculated stand basal area, trees per acre, stand density index, relative stand density index, and quadratic mean diameter for all thinned and unthinned stands pre-DFB infestation, considering all DFB trees killed as live. We used a mixed-effects general linear model with a gamma distribution to compare stand conditions between thinned and unthinned stands pre-infestation. We also compared reductions in basal area and trees per acre because of DFB-caused tree mortality between thinned and unthinned stands using a general linear model with a gamma distribution. For all mixed models, treatment was the fixed effect with stand as a random effect. As stand was a random effect, plot data were averaged across all thinned and unthinned stands. Lastly, we graphed the total number of live and DFB-killed trees by 2-in. dbh classes. Means presented are followed by the standard error. All statistical analysis were conducted using SAS version 9.4 (SAS 2013).

Results

Across all stands, there were 1,039 trees included within the variable plots of which 1,033 (99%) were Douglas-fir. The remaining six trees were three lodgepole pines, two Engelmann spruces, and one subalpine fir (*Abies lasiocarpa* [Hook.] Nutt.). All nonhost species were in unthinned stands. Because all stands were essentially pure Douglas-fir, all nonhosts were removed from analysis. As expected, after thinned stands were treated and prior to DFB infestations, unthinned stands had significantly higher basal area, trees per acre, stand density index, and relative stand density index than thinned stands (Table 1). There was no difference in quadratic mean diameter.

We observed a significantly higher percentage of trees killed by DFB in unthinned stands compared to thinned stands ($F = 7.7$, df = 1, 177, $P < 0.006$) (Figure 1). On a percent basis, twice as many Douglas-fir trees were killed in unthinned stands compared to thinned stands. The DFB-killed trees represented significantly higher basal area per acre in unthinned stands (5.4 ± 2.4) compared to thinned stands (0.5 ± 0.3) ($F = 10.6$, df = 1, 8, $P < 0.01$). There was no difference in trees per acre killed by DFB between unthinned (2.8 ± 1.3) and thinned stands (0.3 ± 0.2) ($F = 4.5$, df = 1, 8, $P < 0.07$). The mean dbh of trees killed by DFB in unthinned stands was 20.6 in. (± 1.1) ($n = 24$) and 18.0 in. (± 2.1) ($n = 3$) in thinned stands. A total of 89% of the trees killed by DFB were ≥ 16 in. in diameter (Figure 2). Diameter distributions of live and DFB-killed trees were not compared statistically as several of the bins had less than five observations.

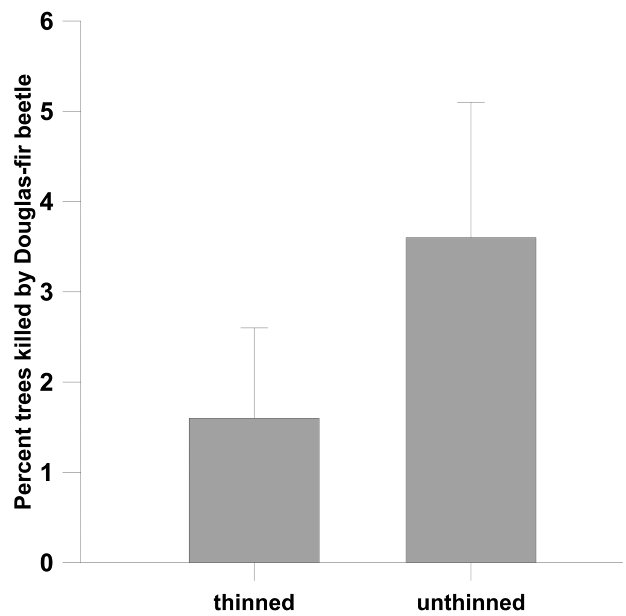

Figure 1. Mean (± SEM) percent of Douglas-fir trees killed by Douglas-fir beetle. Unthinned stands exhibited a significantly higher mean percent of trees killed by DFB than thinned stands ($F = 7.7$, df = 1, 177, $P < 0.006$). Twice as many trees were killed in the unthinned stands. For unthinned stands $n = 89$ and for thinned stands $n = 131$. Townsend Ranger District, Helena National Forest, Montana, 2018.

Table 1. Mean (SEM) Douglas-fir basal area, trees per acre, stand density index, relative stand density index, and quadratic mean diameter in unthinned (12) and thinned (18) stands before a Douglas-fir beetle infestation; $n = 89$ plots for unthinned stands and $n = 131$ plots for thinned stands. Plot data are averaged across all stands as stand was a random effect in the modelling. Townsend Ranger District, Helena National Forest, Montana, 2018.

Stand measurements	Unthinned	Thinned	*P*
Douglas-fir basal area (ft^2/ac)	140.0 (±7.1)	62.0 (±2.5)	<0.0001
Douglas-fir trees per acre	146.3 (±11.7)	51.3 (±3.3)	<0.0001
Douglas-fir stand density index	218.5 (±11.7)	93.8 (±3.9)	<0.0001
Relative stand density index (%)	37.2 (±2.0)	16.0 (±0.1)	<0.0001
Douglas-fir quadratic mean diameter (in)	17.4 (±0.7)	17.5 (±0.4)	=0.4

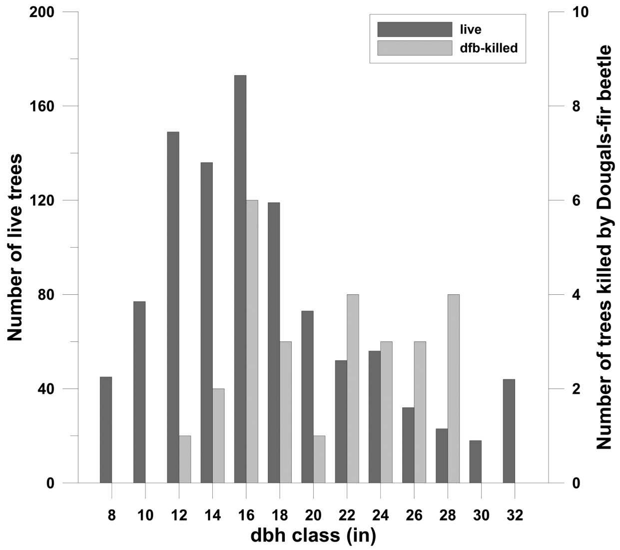

Figure 2. Number of live and trees killed by Douglas-fir beetle by diameter class. Townsend Ranger District, Helena National Forest, Montana, 2018. dbh, diameter at breast height.

Discussion

Higher mortality caused by DFB in unthinned stands is consistent with studies from other forest types and beetle species. Increased mortality levels caused by mountain pine beetle in lodgepole pine are higher in unthinned stands of lodgepole pine (Waring and Pitman 1985, Whitehead and Russo 2005), ponderosa pine (Graham et al. 2016, Negrón et al. 2017), and spruce (Hansen et al. 2010). In this study, thinning treatments significantly reduced basal area, tree density, stand density index, and relative stand density index compared with unthinned stands but did not affect stand quadratic mean diameter. This resulted in a suitable scenario for testing the effectiveness of thinning on mitigating tree mortality caused by DFB, as it presented differences in stocking yet maintained similarly suitable-sized trees for attack in thinned and unthinned stands. Across all stands, most of the trees were > 14 in dbh and most killed trees were in the larger classes, which is the preference exhibited by DFB.

It is important to note that DFB-caused tree mortality levels were low, however, as suggested by the observed mortality. Twenty-four Douglas-firs were killed in the unthinned stands, representing 3.8% of the basal area and 1.9% of the tree density, whereas only three trees were killed in the thinned stands, representing 0.08% of the Douglas-fir basal area and 0.06% of the tree density. Aerial detection surveys indicate that observed DFB-caused tree mortality in Montana from 2012 to 2016 has been variable across the landscape from spatially isolated groups to some outbreak areas. (USDA Forest Service 2014, 2015, 2016, 2017). In 2015, there was elevated mortality east of the study area, yet observed mortality in the study area remained spatially scattered and comprised few trees, a pattern characteristic of endemic populations.

In this study, despite endemic populations, we observed an increase in tree mortality in unthinned stands. Thinned and unthinned stands in the study area were intermingled and comprised an east to west distance of about 4 miles and a north to south distance of about 5 miles (Figure 3). This suggests that, although beetle pressure was low, it was likely about the same for thinned and unthinned stands.

There is scant data on the response of DFB to stand-density reductions through vegetation management. We could only find one other study that observed DFB-caused tree mortality in thinned and unthinned stands, although that was not the objective of the study. Williamson and Price (1971) examined growth response in thinned Douglas-fir stands in Oregon and Washington. They reported decreased growth over 38 years and higher mortality to DFB in unthinned stands than in thinned stands. Some studies indicate that dense stands with large diameter trees, advanced age, and a high composition of Douglas-fir increase susceptibility to DFB (Furniss 1981, Weatherby and Their 1993, Randall and Tensemeyer 1999).

Various factors can influence where and how much mortality may occur during a DFB outbreak both at the landscape and stand level. Negrón et al. (1999) indicated that once a stand is suitable for the development of an infestation, Douglas-fir basal area was the best predictor of potential mortality levels. The spatial distribution of basal area across a stand determines the distribution of tree mortality with denser parts of the stand exhibiting higher mortality (Negrón et al. 2001). Dodds et al. (2004) examined landscape-level DFB infestations using stand susceptibility maps and aerial survey data and indicated that areas more severely infested and with higher levels of mortality were those considered to exhibit a moderate-to-high susceptibility to infestation. Moreover, as DFB populations transitioned from endemic to epidemic levels, infestations became more frequent in stands with a higher susceptibility rating for DFB of infestation.

Another important factor in determining the dynamics of a DFB outbreak is the size of the insect population. Dodds et al. (2006) examined the spatial distribution of landscape-level tree mortality and indicated that under endemic populations, infestations were separated by about 4,600 ft, whereas under an outbreak, infestations were separated by less than 500 ft and groups of infested trees were larger. All stands examined in this study were within an area of about 20 square miles. It is likely that additional infestations within the landscape that included the study area occurred outside of our study sites. The influence of bark beetle population pressure, however, is highly complicated. For example, as the duration of the outbreak increases and local host depletion occurs, dispersal distances of DFB can also increase (Withrow et al. 2013).

We acknowledge that the endemic insect pressure observed in our study sites was lower than expected, cautioning extrapolation of our findings. Nevertheless, we observed reduced mortality in thinned stands. Whether a long-term effect of thinning influences the degree of DFB-caused mortality remains to be determined. Study sites examined in this study will likely be exposed to higher DFB populations in the future. At that time, remeasurement of these plots may shed light on long-term effects of thinning.

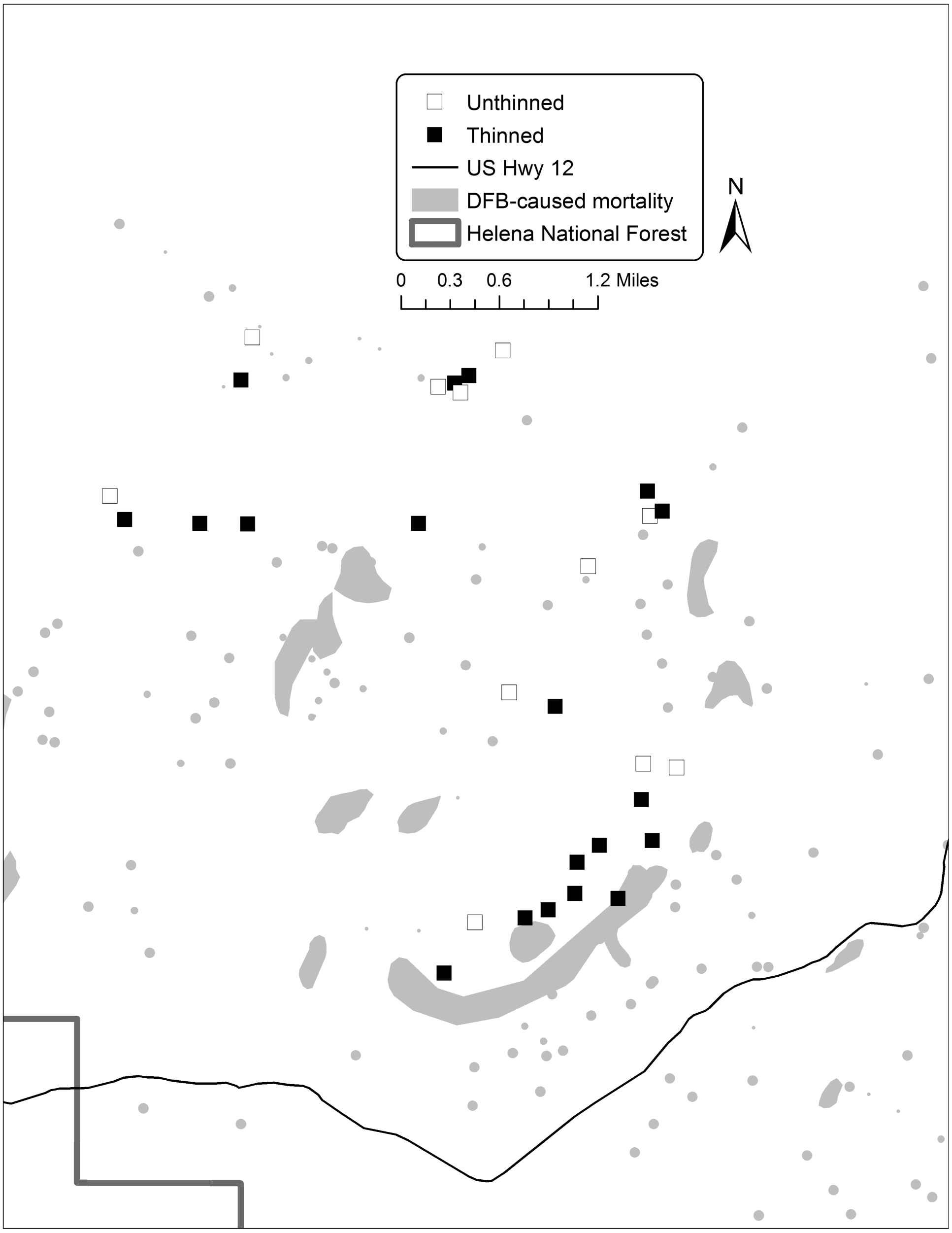

Figure 3. Douglas-fir beetle–caused mortality in the vicinity of study sites in the Cabin Creek area. Gray areas indicate cumulative Douglas-fir beetle–caused mortality 2014–2019. Black squares indicate thinned stands and open squares indicate unthinned stands. Data from the USDA Forest Service, Region 1, Forest Health Protection, Aerial Detection Survey. Townsend Ranger District, Helena National Forest, Montana, 2018.

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