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Large-Scale Thinnings, Ponderosa Pine, and Mountain Pine Beetle in the Black Hills, USA

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Mountain pine beetle (*Dendroctonus ponderosae* Hopkins) (MPB), can cause extensive ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.) mortality in the Black Hills of South Dakota and Wyoming, USA. Lower tree densities have been associated with reduced MPB-caused tree mortality, but few studies have reported on large-scale thinning and most data come from small plots that may not be representative of a large area. We quantified MPB-caused tree mortality in 21 pairs of commercially thinned and unthinned stands across the Black Hills. Both pre- and postoutbreak, unthinned stands had higher ponderosa pine basal area, tree density, and stand density index. Quadratic mean diameter was larger in thinned stands, both pre- and postoutbreak. Percent ponderosa pine basal area and tree density killed by MPB in unthinned stands were 38.2 $\pm$ 7.0 and 34.4 $\pm$ 6.9% compared with 3.9 $\pm$ 3.2 and 3.6 $\pm$ 2.9% in thinned stands, respectively. All stands were thinned within 2 years of exposure to MPB, suggesting a rapid effect from thinning treatments in mitigating tree mortality attributed to MPB. Stand density reductions through silviculture across a large geographical area can abate MPB-caused tree mortality.

Keywords: *Dendroctonus ponderosae*, *Pinus ponderosa*, bark beetles, silviculture

Forest ecosystems are dynamic communities shaped by the expression of multiple agents of change. These agents can be abiotic disturbances, such as fire and wind storms, biotic entities such as disease-causing pathogens, or insects such as defoliators and bark beetles, and human activities through management efforts and land-use activities, among others. The mountain pine beetle (*Dendroctonus ponderosae* Hopkins) (MPB) is a native bark beetle that occurs in conifer forests throughout much of western North America (Wood 1982) and utilizes ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.), as one of its most important hosts. Endemic populations are maintained in stressed hosts, such as trees impacted by lightning or root disease (Eckberg et al. 1994). Eruptive MPB populations occur when conditions become favorable for the insect and unfavorable for its host trees (Thompson and Shrimpton 1984, Mattson and Haack 1987, Boone et al. 2011, Preisler et al. 2012). Populations thrive in overstocked stands composed of an abundance of suitable-sized trees (Safranyik et al. 1974, Sartwell and Stevens 1975, Amman et al. 1977). These stand conditions contribute to tree stress and provide an abundance of suitable host trees for insect populations to successfully colonize and reproduce, eventually causing considerable ponderosa pine mortality over large areas. During the past two decades, outbreaks of MPB have occurred across the western United States and Canada, killing millions of trees (Negrón and Fettig 2014).

Extensive tree mortality can be a challenge to land managers and land owners. For example, tree mortality in fiber production-oriented stands can negate prior investments and management practices. Tree mortality in recreation areas can create safety concerns and removing dead trees can be costly. Wildlife can be affected differentially depending on their habitat requirements (Bonnot et al. 2008, Rota et al. 2014, Saab et al. 2014). Falling trees can increase surface fuels and present hazards for firefighters (Negrón et al. 2008, Klutsch et al. 2013, Jenkins et al. 2014).

The Black Hills National Forest located in South Dakota and Wyoming comprises extensive ponderosa pine forests and is among the most intensively managed in the western United States. These forests have a long history of outbreaks of MPB, with records dating back to the early 1900s (Hopkins 1905). It was in the Black Hills that direct control of MPB was first attempted, and, subsequently, over the past 100 years, direct control was implemented across the West in an attempt to suppress MPB outbreaks by removing infested trees and using insecticides and pheromones, among other treatments (Progar 2005, Fettig et al. 2014, Gillette et al. 2014). Direct control is most effective in small areas and is generally restricted to high-value settings, and it is now recognized as having limited utility in large areas and provides only temporary reductions in populations (see Wood et al. 1985, Wickman 1987, Gillette et al. 2014).

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Stand-level studies in ponderosa pine have indicated reduced tree mortality levels in lower density stands (Sartwell and Stevens 1975, Negrón and Popp 2004, Schmid and Mata 2005, Negrón et al. 2008a). Most of these studies, however, are retrospective in nature and based on quantifying tree mortality postoutbreak. The effectiveness of silvicultural treatments has been studied little because of the difficulty of implementation and costs, yet a few studies have shown reduced bark beetle-caused tree mortality in thinned ponderosa pine stands (Sartwell and Dolph 1976, Schmid and Mata 2005, Egan et al. 2010, Graham et al. 2016). This has led to the approach of minimizing tree mortality through silvicultural strategies aimed to reduce stand density (see Wood et al. 1985 and Fettig et al. 2007 and references therein). Although available data support the use of stand density reduction through thinning in ponderosa pine, most research has been conducted in small plots or small stands, for example, less than 2.5 ac (1 ha), with little replication, or both (McCambridge and Stevens 1982, Schmid and Mata 2005). The efficacy of large-scale implementation remains untested, and data are needed to more effectively assess whether silvicultural treatments are effective for reducing bark beetle-caused tree mortality across large areas.

Large operational thinnings on the Black Hills National Forest presented an opportunity to examine the effects of large-scale silvicultural treatments as forest personnel have been implementing thinning treatments over a large area with the intent of reducing the likelihood of MPB infestation and the extent of ponderosa pine mortality, as well as reducing fire risk and severity. In this study, we quantified ponderosa pine mortality caused by MPB in stands treated with commercial thinning to reduce stand density and compare them to unthinned stands across the Black Hills. Our research question was: Can MPB-caused tree mortality be mitigated with large-scale stand density reduction management?

Methods

Study Site

The Black Hills are a forested refuge on the Missouri Plateau of the Great Plains Province, extending about 124 mi (200 km) from north to south and 62 mi (100 km) from east to west and covering about 6,000 mi^2 (about 15,540 km^2), with two-thirds of the area in southwest South Dakota and one-third in northeast Wyoming. Elevation ranges from 4,302 ft (1,311 m) to 7,241 ft (2,207 m). Precipitation varies along elevational and latitudinal gradients with northern and higher elevations generally receiving more precipitation. Average annual precipitation ranges from approximately 16 in. (41 cm) in the southern Black Hills to about 29 in. (74 cm) in the northern Black Hills and occurs predominantly from April to July. The Black Hills are dominated by ponderosa pine with a small component of aspen (*Populus tremuloides* Michx.), white spruce (*Picea glauca* [Moench] Voss), and paper birch (*Betula papyrifera* Marshall). A long history of forest management characterizes the Black Hills (Shepperd and Battaglia 2002).

Sampling

Twenty-one management units (hereafter referred to as stands) that had been commercially thinned were sampled during the summer of 2014 across the Black Hills (Figure 1). Even-aged stands thinned within the past 10 years, at least 25 ac (10 ha) in size and with the same silvicultural prescription, were sampled. Thinning aimed for a postthinning basal area of 40–70 ft^2/ac (9.2–16.1 m^2/ha) while maintaining equal spacing as much as possible and with minimal clumps remaining. All removals consisted of sawtimber-sized trees ≥9 in. dbh (22.9 cm) in addition to those trees that were actively infested by MPB. All stands within the Black Hills that met these criteria were sampled. Each thinned stand was paired with an adjacent unthinned stand within ¼ mi (400 m) (Figure 2). We attempted to delineate unthinned stands to be about the same size as the thinned stands, but this was not always feasible. Thinning took place during an active MPB epidemic that started in the late 1990s, peaked in 2003, and was ongoing at the time sampling was completed. All treated stands had MPB-caused ponderosa pine tree mortality before thinning. The mean ± SEM (hereafter "mean" refers to mean ± SEM) size of thinned stands was 116 ± 16 ac (47 ± 6 ha) and ranged from 29 to 249 ac (from 12 to 101 ha), and the mean size of unthinned stands was 137 ± 19 ac (55 ± 8 ha) and ranged from 35 to 365 ac (from 14 to 148 ha). The mean number of years from thinning to measurement was 4.8 ± 0.5 and ranged from 2 to 9. The mean number of years from MPB exposure to treatment was 1.6 ± 0.1 with all stands thinned within 2 years after exposure to beetles.

We used dbh data from stand inventory records to conduct a power analysis to determine the number of plots to be sampled in each stand. A total of nine variable radius plots were sampled per stand using a 20 basal area factor (BAF) prism (approximates 5 BAF in metric units). For every tree within the plot we recorded species, dbh, and tree condition as live, MPB-killed (including successful current attacks), or dead due to other agents or unknown causes. Plot locations within stands were randomly distributed using geographic information system software and uploaded to a handheld global positioning system device for identifying locations on the ground.

Data Analysis

Using the field-collected data from all plot trees, we calculated basal area and tree density for all species combined, for ponderosa pine only, for MPB-caused tree mortality, and for postoutbreak live trees. We also calculated stand density index (SDI) for ponderosa pine and quadratic mean diameter (QMD) for all species combined and ponderosa pine only. We calculated the percentage of maximum SDI (hereafter referred to as relative SDI) using 450 as maximum SDI (using English units) for ponderosa pine (Long and Shaw 2005). We used the Wilcoxon sign test to identify the significance of differences in the variables examined by subtracting the value for thinned stands from the value for unthinned stands across both treated and untreated stands. The calculated difference was significant if it differed from zero. We used Kruskal-Wallis tests to compare the mean dbh of live and beetle-killed trees across all stands and for the mean number of trees greater than 10 in. dbh and the number of trees greater than 10 in. killed by MPB across all thinned and all unthinned stands.

Results

Across all stands, ponderosa pine was 95.8 ± 1.9% (n = 42) of the basal area, and there was no difference (P = 0.43, df = 1, Wilcoxon sign test) between unthinned stands with 95.3 ± 2.7% (n = 21) and thinned stands with 96.2 ± 3.7% (n = 21). The percentage of ponderosa pine tree density across all stands was 92.9 ± 3.0% (n = 42) and was not different (P = 0.46, df = 1, Wilcoxon sign test) between unthinned stands with 92.5 ± 3.8% (n = 21) and thinned stands with 93.3 ± 4.6% (n = 21). Basal area and tree density for all species combined and for ponderosa pine as well as ponderosa pine SDI and relative SDI were higher in the unthinned stands (Table 1). Thinned stands had larger QMD for all species (not shown) and for ponderosa pine (Table 1). Ponderosa

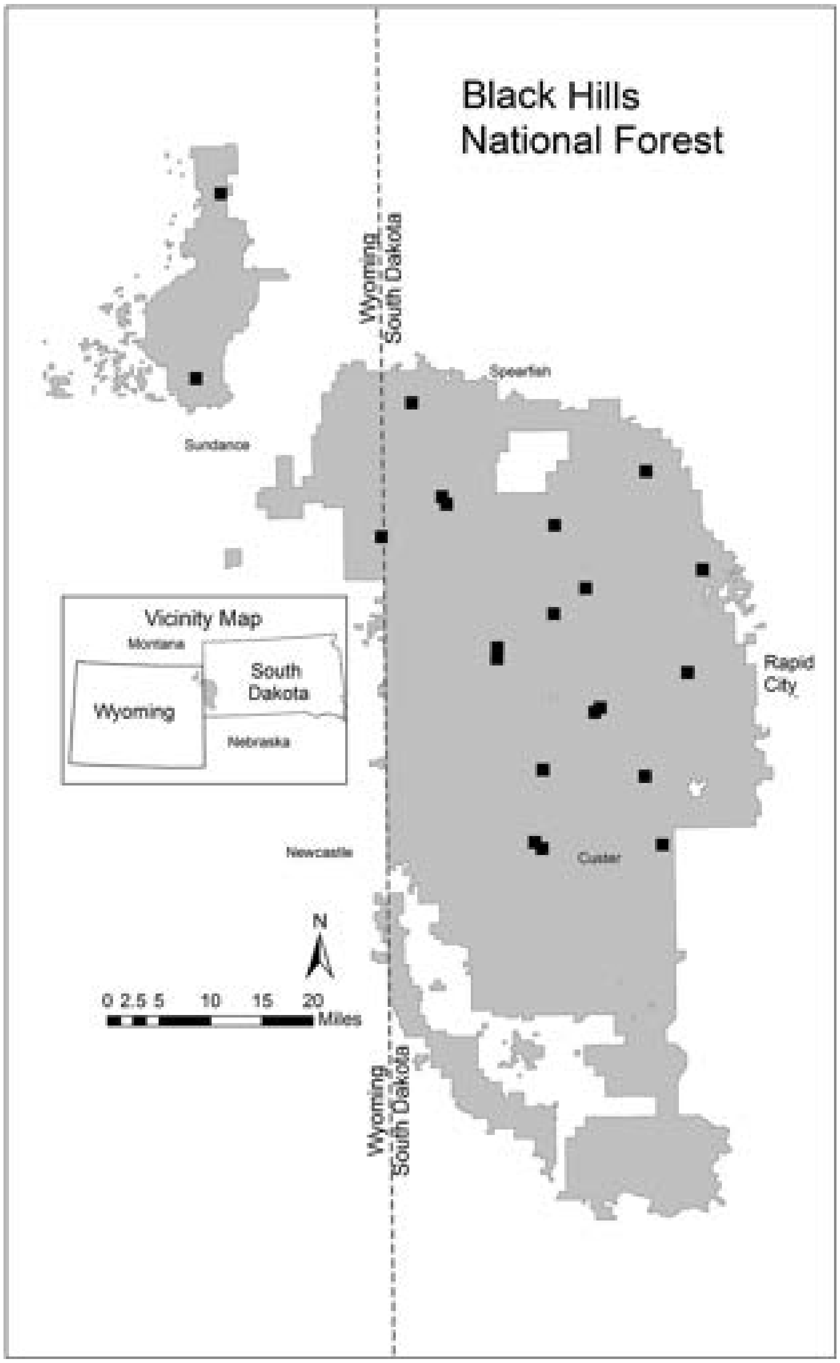

Figure 1. Map of the Black Hills National Forest indicating study locations. Gray represents the forest boundary and the squares represent the location of each stand pair. Black Hills National Forest, South Dakota and Wyoming, 2014.

pine mortality levels were higher in the unthinned stands as indicated by higher ponderosa pine basal area killed, ponderosa pine tree density killed, percentage of ponderosa pine basal area killed, and percentage of ponderosa pine tree density killed (Table 2). Total basal area and tree density, ponderosa pine basal area and tree density, SDI, and relative SDI remained higher in the unthinned stands postoutbreak as indicated by the live ponderosa pine composition (Table 3). Ponderosa pine QMD remained larger in the thinned stands postoutbreak (Table 3).

Across all stands, the mean dbh of live trees was 11.7 ± 0.1 in. (29.7 ± 0.3 cm) (n = 808), and for MPB-killed trees, the mean dbh was 11.7 ± 0.2 in. (29.7 ± 0.5 cm) (n = 453); the means were not significantly different (χ^2 = 0.2, df = 1, P = 0.89). The mean number of trees >10 in. (25.4 cm) was significantly higher in the unthinned stands (n = 21) with 30.0 ± 1.8 compared to the thinned stands (n = 21) with 10.1 ± 1.5 (χ^2 = 27.4, df = 1, P < 0.0001). The mean number of trees >10 in. (25.4 cm) killed by MPB was significantly higher in the unthinned stands (n = 21) with 13.9 ± 2.4 compared to the thinned stands (n = 21) with 0.5 ± 0.4 (χ^2 =5.2, df = 1, P < 0.02).

Discussion

Our study examined the short-term efficacy of thinning on mitigating tree mortality attributed to MPB across a large scale. Across

Figure 2. Google Earth (www.google.com/earth/) image of a study site with two stand pairs showing the unthinned and thinned stands. Black Hills National Forest, South Dakota and Wyoming, 2014.

Table 1. Total (all species combined) and ponderosa pine (PIPO) basal area, trees per acre, ponderosa pine SDI and relative stand density, and ponderosa pine QMD in unthinned and thinned stands, and mean differences (unthinned − thinned) before a mountain pine beetle outbreak.

Stand measurements	n	Unthinned	Thinned	Mean difference	P
Total basal area (ft^2/ac)	21	115.9 (6.2)	34.0 (4.7)	81.9 (6.8)	<0.0001
PIPO basal area (ft^2/ac)	21	111.1 (7.2)	32.0 (4.5)	79.1 (7.3)	<0.0001
Total tree density (trees/ac)	21	309.5 (45.4)	69.8 (13.4)	239.7 (42.1)	<0.0001
PIPO tree density (trees/ac)	21	290.8 (46.7)	57.9 (10.5)	232.9 (43.4)	<0.0001
PIPO SDI	21	209.2 (16.3)	56.2 (8.3)	153.0 (15.4)	<0.0001
PIPO relative stand density (%)	21	46.5 (3.6)	12.5 (1.8)	34.0 (1.8)	<0.0001
PIPO QMD (in.)	21	11.0 (0.5)	12.5 (0.5)	−1.5 (0.7)	<0.02

Data are means (SEM). Positive differences indicate higher values for unthinned stands and negative differences indicate higher values for thinned stands. Stocking and SDI were higher in unthinned stands. QMD was larger in thinned stands. Black Hills National Forest, South Dakota and Wyoming, 2014.

the network of paired stands in the area examined in this study, thinned stands exhibited less MPB-caused tree mortality than unthinned stands. A large-scale approach for mitigating MPB-caused tree mortality offers a wider perspective and allows us to "scale up" mortality levels supported by stand-level studies. Treating larger stands within a large geographical area where both thinned and unthinned stands occur with silvicultural prescriptions aimed at low basal areas while minimizing clumps can result in a forestwide overall reduction of MPB-caused tree mortality. Removal of MPB-infested trees, as part of the silvicultural prescriptions, may have contributed to reduced MPB-killed trees postthinning by reducing local beetle populations. However, considering that thinnings were

Table 2. Ponderosa pine basal area, trees per acre, percent basal area, and percent trees per acre killed by mountain pine beetle in unthinned and thinned stands and mean differences (unthinned − thinned).

Ponderosa pine	n	Unthinned	Thinned	Mean difference	P
Basal area killed (ft^2/ac)	21	48.1 (9.0)	1.7 (1.3)	46.4 (9.1)	<0.0001
Trees density killed (trees/ac)	21	87.7 (19.0)	2.9 (2.1)	84.8 (19.1)	<0.0001
Percent basal area killed	21	38.2 (7.0)	3.9 (3.2)	34.3 (7.7)	<0.0001
Percent tree density killed	21	34.4 (6.9)	3.6 (2.9)	30.8 (7.5)	<0.0001

Data are means (SEM). Tree mortality caused by mountain pine beetle was higher in unthinned stands. Black Hills National Forest, South Dakota and Wyoming, 2014.

Table 3. Live total (all species combined) and live ponderosa pine (PIPO) basal area, trees per acre, SDI, relative SDI, and QMD in unthinned and thinned stands and mean differences (unthinned − thinned) after a mountain pine beetle outbreak.

Stand measurements	n	Unthinned	Thinned	Mean difference	P
Total basal area (ft^2/ac)	21	67.8 (9.6)	32.3 (4.7)	35.5 (9.5)	<0.003
PIPO basal area (ft^2/ac)	21	63.0 (9.4)	30.3 (4.5)	32.7 (9.3)	<0.003
Total tree density (trees/ac)	21	203.2 (47.6)	55.0 (9.3)	148.2 (44.9)	<0.0015
PIPO tree density (trees/ac)	21	221.9 (47.6)	66.9 (12.6)	155.0 (44.3)	<0.0002
PIPO SDI	21	121.7 (19.6)	53.1 (8.0)	68.6 (18.8)	0.0003
PIPO relative stand density (%)	21	27.1 (4.3)	11.8 (1.8)	15.3 (4.2)	0.0003
PIPO QMD (in.)	21	10.5 (0.6)	12.4 (0.6)	−1.9 (0.8)	0.01

Data are means (SEM). Positive differences indicate higher values for unthinned stands and negative differences indicate higher values for thinned stands. Stocking and SDI were higher in unthinned stands. QMD was larger in thinned stands. Black Hills National Forest, South Dakota and Wyoming, 2014.

implemented while extensive outbreak populations were active, this was probably not a factor in our results as stands were still exposed to high insect pressure.

Our larger scale examination indicated significantly higher mortality in the population of unthinned stands with an average ponderosa pine basal area of about 110 ft^2/ac (25.3 m^2/ha) compared to about 30 ft^2/ac (6.9 m^2/ha) in a population of thinned stands. This is the case also in smaller-scale studies. For example, Schmid et al. (2007), working at the stand level, monitored thinned 2.5-ac (1-ha) plots in the Black Hills. They reported that 20 years after thinning, ponderosa pine stands thinned to a growing stock level <120 generally had from 0 to 8% of the trees killed by MPB, whereas MPB-caused mortality in uncut stands ranged from 0 to 77%.[1] McCambridge and Stevens (1982) compared three stand pairs thinned to 85, 75, and 45 ft^2/ac (19.5, 17.2, and 10.3 m^2/ha) with three unthinned stands of 201, 182, and 195 ft^2/ac (46.1, 41.8, and 44.8 m^2/ha), respectively, and reported an average of 24.3 trees/ac (60.0 trees/ha) killed by MPB in unthinned stands compared to 9.6 trees/ac (23.7 trees/ha) in the thinned stands. Schmid et al. (2005) suggested that the threshold for highly susceptible stands to MPB in the Black Hills may be around growing stock level 100 (approximate basal area of 100 ft^2/ac), and all of our treated stands had a ponderosa pine basal area <76 ft^2/ac.

In Oregon, Sartwell and Dolph (1976) conducted a stand-level thinning study in ponderosa pine. After an MPB outbreak, two thinning treatments with tree spacing of 18 × 18 ft (5.5 × 5.5 m) and 21 × 21 ft (6.4 × 6.4 m) exhibited no MPB-caused ponderosa pine mortality compared to 7% of ponderosa pine basal area killed in the unthinned stand 5 years posttreatment. Mitchell et al. (1983) evaluated tree vigor and MPB-caused ponderosa pine mortality in stands thinned to various basal area levels and in unthinned stands in eastern Oregon. Tree vigor, quantified as grams of stemwood produced by crown leaf surface area, decreased with increasing stand stocking. During the study, MPB populations were endemic, but most of the observed ponderosa pine mortality was in the low-vigor plots.

A study by Fiddler et al. (1989) showed that thinning reduced MPB-caused ponderosa pine mortality in California, with no mortality in stands of <95 ft^2/ac (21.8 m^2/ha) of basal area 7 years posttreatment. Egan et al. (2010), also working in California, reported ponderosa pine mortality of 6.5 trees/ac (16.1 trees/ha) in unthinned ponderosa pine plantations compared to 0.5 ponderosa pine killed/ac (1.2 trees/ha) in precommercially thinned stands about 20 years postthinning. The effectiveness of thinning for reducing stand susceptibility to several species of bark beetles was evaluated in ponderosa pine and Jeffrey pine forests over a 10-year period in the Tahoe National Forest, California, by Fettig et al. (2012). Thinning from below treatments were implemented to residual basal areas of 80, 120, and 180 ft^2/ac (18.4, 27.5, and 41.3 m^2/ha) and compared with an untreated control. A total of 107 trees died due to bark beetle attack; 21% were ponderosa pines killed by MPB mostly in untreated stands. In the low-density thinning treatments, no pines were killed by bark beetles during the 10-year period.

Various hypotheses are presented in the literature as to how thinning may reduce bark beetle-caused tree mortality. High stand densities can compromise tree vigor and defensive mechanisms (Larsson et al. 1983, Mitchell et al. 1983, Waring and Pitman 1985, Hood et al. 2016). In Arizona, Kolb et al. (1998) examined various insect resistance mechanisms in thinned ponderosa pine stands. Their results indicated that resin production, the primary defense mechanism that the tree has for fighting attacking bark beetles (Vité 1961, Christiansen et al. 1987), declined with increasing stand basal area. Other studies, however, indicate that resin production is variable and can be influenced by other factors such as fire (Gaylord et al. 2007, Hood et al. 2016). Thinning changes the stand microenvironment, making it less favorable for insect populations by possibly augmenting mortality and negatively impacting chemical communication and dispersal. Other studies have suggested that more open stands have higher temperatures, possibly resulting in more insect mortality (Amman et al. 1988, Bartos and Amman 1989, Schmid et al. 1991, Amman and Logan 1998). Increased solar radiation in thinned stands has also been documented (Bartos and Amman 1989, Schmid et al. 1995). This results in more air turbulence, which influences pheromone movement in the stand (Edburg et al. 2010) and possibly has a negative effect on chemical communication processes used by MPB in their infestation dynamics (Thistle et al. 2004, 2005).

Tree spacing after a thinning treatment may also help explain diminished mortality. MPB tends to kill trees in groups, which Geiszler and Gara (1978) proposed is the expression of beetles "switching" to an adjacent new "recipient" tree after an initial "focus" tree is fully colonized. Mitchell and Preisler (1991) investigated spatial relationships during a MPB outbreak in lodgepole pine and inferred that many trees are attacked because of their proximity to the larger diameter trees preferred by MPB. More recently, Whitehead and Russo (2005) observed reduced tree mortality in thinned stands and suggested that what they refer to as "beetle-proofing" can be achieved by managing intertree spacing. The authors attributed the reduced tree mortality to a lower frequency of trees attacked and not to increased resin production.

Although the answer is probably a combination of all of these processes, the microclimate and tree spacing ideas may be the only ones that could explain the immediate effectiveness of the thinning treatments as observed in our study. Cole et al. (1983) also observed abated mortality the year after thinning, whereas McGregor et al. (1987) observed lower mortality by the third year posttreatment. Thinning dense stands reduces competition for resources among trees and fosters increased growth and vigor of residual trees. Although the response of increased growth, basal area increment, and growth efficiency after thinning is well documented (Myers 1958, 1963, Markstrom et al. 1983, Skov et al. 2005, Fajardo et al. 2007), how quickly trees can respond to increased growing space is variable and can take one (Hood et al. 2016) to several years (Oliver 1979, Yang 1998, Kolb et al. 2007). In the case of ponderosa pine, the response may not be evident for at least 10 years postthinning (Oliver and Edminster 1988). Therefore, lower mortality soon after treatment across all stands may be the result of a change in microclimate or tree spacing or both. These factors are modified at the time thinning is implemented, whereas the increase in tree growth and vigor may take longer to occur but have a long-term effect.

In addition to higher stocking levels, unthinned stands may also be more attractive to MPB because of a higher abundance of large trees (>10 in. [25.4 cm] dbh). MPB preferentially attacks the larger diameter trees first in lodgepole pine forests (Safranyik et al. 1974, Amman et al. 1977, Mitchell and Preisler 1991). In ponderosa pine, however, the preference for attacking the largest trees first has not been confirmed, but over the duration of an outbreak more large trees are attacked (McCambridge et al. 1982, Negrón and Popp 2004, Negrón et al. 2008a, Schmid and Mata 2005). All of our study stands had a ponderosa pine QMD >8.0 in. (20.3 cm), suitable for MPB attack (Sartwell and Stevens 1975). Although there were no differences in mean dbh between beetle-killed trees and live trees across all stands, unthinned stands had significantly more trees >10 in. (25.4 cm) than the thinned stands. In addition, unthinned stands had significantly more trees >10 in. (25.4 cm) killed by MPB than thinned stands. Negrón et al. (2008a) indicated that similar-sized trees are more likely to be attacked in denser stands and that stands with a higher proportion of basal area in trees ≥10 in. (25.4 cm) are more likely to be attacked.

Thinned stands are also subject to less competition for resources among trees. Across all of our study stands, treated stands had a lower SDI and a relative SDI of 13 ± 2% compared with 47 ± 3% for the unthinned stands (Figure 3A and B). This suggests that unthinned stands were approaching the lower level of self-thinning, which is considered to start at about a relative SDI of 55% (Long and Shaw 2005). On the other hand, thinned stands were well below the onset of competition, which is considered to begin at a relative SDI of about 25%. When relative SDI approaches 35%, maximum stand growth and full site occupancy are achieved. At 13%, the treated stands are maximizing tree growth and will presumably be more vigorous, which according to previous studies, translates to higher tree resistance (Larsson et al. 1983, Waring and Pitman 1985). This suggests that treated stands are positioned to benefit over the long-term from thinning by maintaining lower susceptibility to bark beetle attacks until increased tree growth carries them to a susceptible state again (Schmid et al. 2007). Consistent with these findings Oliver (1995) examined even-aged ponderosa pine stands in California and reported substantial mortality when the relative SDI was >54% (based on a maximum SDI of 450 as used in this study).

In this study, neither the spatial configuration of stands in the landscape nor that of the insect populations was addressed. Quantifying landscape-level bark beetle populations is difficult and requires the use of tree mortality as a surrogate. Spatial distribution of vegetation, such as the distribution of susceptible stands in the landscape, and landscape attributes influence insect dynamics and dispersal (Chubaty et al. 2009, Fettig et al. 2014, Lundquist and Reich 2014). Long-range dispersal can be influenced by winds (Jackson et al. 2008) and can vary with population levels (Withrow et al. 2013), whereas short-range dispersal can be influenced by intertree distance, the distribution of low-vigor trees, and within-stand density gradients (Geiszler and Gara 1978, Mitchell and Preisler 1991, Olsen et al. 1996, Negrón et al. 2001). Distance between patches of habitat, i.e., susceptible stands, will influence insect population movement. Discerning the timing and location of where MPB populations will probably occur could inform land managers in developing appropriate management strategies (Lundquist and Reich 2014). These are topics that could contribute to enhancing management strategies to mitigate bark beetle-caused tree mortality over a large geographical area.

The thinning treatments examined in this study were implemented amid an extensive MPB epidemic and therefore were implemented under a worst-case scenario. Because bark beetles exhibit periodic eruptive outbreaks, the current thinking is that silvicultural management should be conducted between outbreaks when populations are at low levels and not implemented when insect populations are active (Fettig et al. 2007). However, thinning studies have been conducted during active outbreaks and have demonstrated reduced tree mortality in lower density conditions (McCambridge and Stevens 1982, Cole et al. 1983, McGregor et al. 1987). Therefore, an important aspect of using stand density reduction treatments is the timing of implementation. This is a question that warrants further examination as it could have important implications in how managers plan and respond to outbreak MPB populations.

It is important to indicate that thinning for mitigation of MPB-caused mortality will not always be effective. Given enough insect pressure, mortality in thinned stands can occur and can be extensive. Four thinned stands in our study exhibited ponderosa pine mortality, with a 130-ac stand having considerable mortality of 67 ± 14% ponderosa pine basal area killed and 61 ± 16% trees/ac killed compared with 38 ± 11 and 28 ± 10% in the corresponding paired unthinned 150-ac stand, respectively. Schmid and Mata (2005) indicated that thinning areas <10 ac (4 ha) that are surrounded by

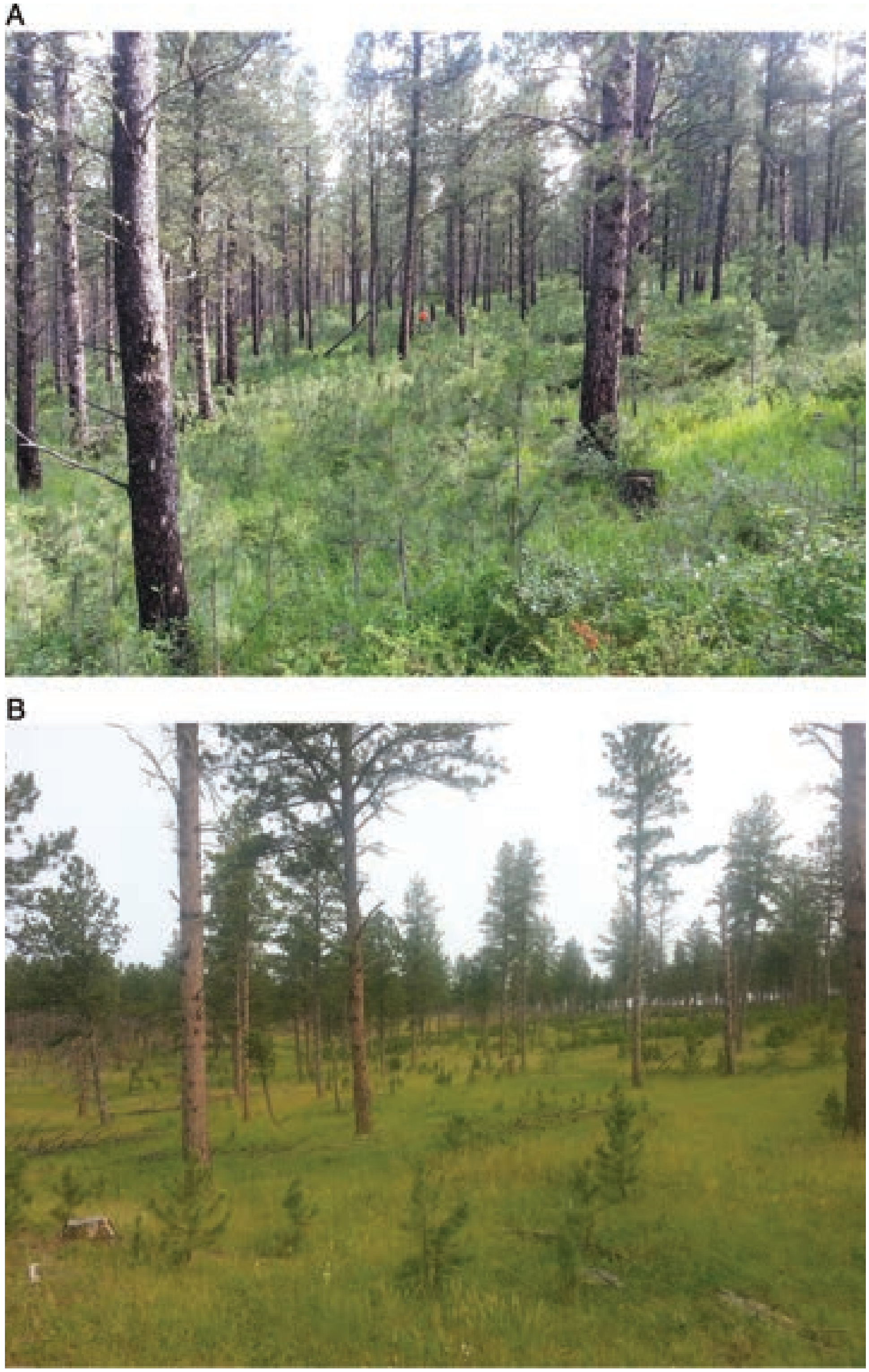

Figure 3. Images portraying typical study sites: an unthinned stand (A) and a thinned stand (B). Black Hills National Forest, South Dakota and Wyoming, 2014.

unmanaged susceptible stands may be ineffective as MPB populations can move to the thinned stands from the surrounding areas. Whitehead and Russo (2005) indicate that high beetle populations during an outbreak can still cause extensive mortality in thinned stands.

In dealing with a native disturbance agent like MPB operating in its natural environment of ponderosa pine forests, the intent is not to stop an epidemic or preclude future outbreaks as these are not achievable goals. Rather, the goal is to mitigate extensive tree mortality and facilitate meeting the management direction for a given area. Acknowledging that some level of scientific rigor is compromised by not being able to conduct a priori planning, the thinning projects in the Black Hills National Forest offered a suitable scenario to examine tree mortality across large managed areas. Realizing that there is a suite of objectives that a land manager needs to consider while implementing management strategies, silvicultural thinning can be a useful tool to mitigate tree mortality caused by MPB across a large area.

Endnote

1. Growing stock level is a function of basal area and mean stand dbh and equals basal area when the postthinning mean dbh is ≥10 in. This measurement is seldom used anymore. The reader is referred to Myers (1967) for additional information.

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