Impacts of the Mountain Pine Beetle on Sawmill Operations, Costs, and Product Values in Montana

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Abstract

Over the past 20 years, the mountain pine beetle (*Dendroctonus ponderosae*) has caused considerable tree mortality across the Rocky Mountain region of the western United States. Although the operational and cost impacts of dead timber are generally well known in the sawmill industry, there remains a need to better understand the impact of large-scale outbreaks on the industry at local and regional scales. Using an expert opinion survey of sawmill managers and procurement staff, this study quantified the relative importance of various cost and operations factors related to harvesting and processing beetle-killed timber in Montana. Respondents reported an average log supply of trees in the red or gray stage of mortality as 24.5 percent of log supply from 2010 to 2014, but this dropped to 5.8 percent by 2015. Cracking and checking were perceived as having the highest negative impact on log value, while waste in milling and breakage of logs in handling were ranked highest for milling operations. For a typical lodgepole pine stand, the volume estimated as sawlogs showed a 15 percent decrease between green and red stages and a 50 percent decrease between red and gray stages, with most of the volume change moving into the pulpwood category. Total average cost increases from green to gray for logging, loading and hauling, and sawmilling were 43, 46, and 46 percent, respectively. Results generally support known relationships between defects, costs, recovery, and value, with some interesting departures with regard to blue stain and equipment maintenance.

Beginning in the late 1990s, the pine forests of Montana began to experience the largest mountain pine beetle (MPB; *Dendroctonus ponderosae*) outbreak in recorded history (Mitton and Ferrenberg 2012). Annual infestation of this native insect peaked in 2009 with approximately 3.7 million acres infested statewide across all tree species and declined to approximately 600,000 acres by 2014 (US Forest Service [USFS] 2015a, 2015b, 2016). Assuming average stocking of 2,000 ft^3 per acre based on intermediate stand density and site index for even-aged lodgepole pine (*Pinus contorta*; McCarter and Long 1986, Long and Shaw 2005), this is equivalent to approximately 7.4 billion ft^3 of timber affected at the peak of the outbreak. The majority of trees killed were lodgepole pine, but MPB also kills ponderosa pine (*Pinus ponderosa*), and both are commercially important tree species in Montana (USFS 2015b).

When trees are attacked by MPB, they typically respond with biochemical and physical defenses to resist attack, including secondary resin accumulation at wound sites (Raffa and Berryman 1983). Even so, damage to the phloem and introduction of fungi (e.g., *Ophiostoma clavigerum* [synonym *Grosmannia clavigera*] and *O. montium*) that spread across the sapwood can disrupt photosynthate and water transport and kill the tree (Waring and Pittman 1985, Six 2003). Trees that do not survive attack move through a series of visually distinct stages from live to dead. During the first year following attack (green stage), evapotranspiration stops, but the needles retain moisture and remain mostly green. Approximately 1 year after attack, the needles desiccate and pigment molecules break down, turning the needles red and brown (red stage; Fig. 1). Over the following 2 or 3 years, the tree is in the red stage, the needles fall to the ground, and once the tree has lost all of its foliage, it enters the gray stage (Fig. 1), where it will remain for many years, depending on several factors, such as the rate of decomposition, weather, and soil conditions. Over the course of the gray stage, the fine branches fall, bark flakes off the stem, and the wood of the stem continues to deteriorate. Finally, individual trees fall to the ground in

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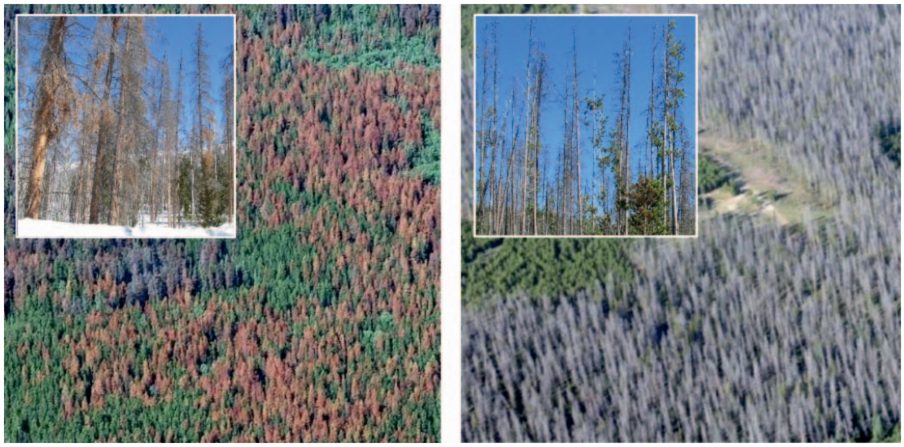

Figure 1.—Forest and trees (inset) in the red stage (left) and gray stage (right) following a mountain pine beetle outbreak. (Photos: Ron Billings, Brian Howell, and Nate Anderson. Color version is available online.)

what is known as the fall stage. Affected trees can be harvested at any stage. However, in the green and red stages and potentially into the early gray stage, the trees retain some portion of their commercial value, depending on species and condition, allowing for financially feasible beetle-kill salvage harvests.

The primary purpose of a salvage harvests is to recover economic value that would otherwise be lost (Helms 1998). There are many different methods to evaluate the financial feasibility of such a harvest, but in general it must generate positive net present value to be considered commercially viable. A positive financial outcome depends primarily on the costs of stumpage (i.e., value of the standing timber), forest operations, and transportation measured against revenue as a function of price tied to log value, which is a function of grade and volume. In this context, log grade is defined as an established quality or use classification, often based on species, diameter, frequency and size of knots, and other attributes, while scale is defined as the weight or volume of a log (Helms 1998).

Defects in salvaged logs can have significant impact on their value. Grade defects include any flaw or character in a log tied to wood quality that reduces the log from one grade to another. Such defects include knots, stains, holes, and bark pockets (Carpenter et al. 1989). Scale defects are those that reduce the scaled mass or volume of a log. They include rot, shake, and severe checks and cracks (Carpenter et al. 1989). Broadly, Snellgrove and Fahey (1977) identified three primary classes of value loss associated with dead timber that are often linked to MPB salvage: (1) volume losses due to breakage during harvest and handling; (2) volume losses due to rot, shake, and checks; and (3) reduction in lumber grade due to ''deterioration-related defects,'' such as staining, secondary insect damage, and bird peck (Carpenter et al. 1989).

Previous research provides significant insights into the specific effects of MPB on forest and sawmill operations under salvage conditions, with impacts felt at nearly every stage of the supply chain. In their thorough synthesis of the issue, Byrne et al. (2006) stated that handling losses due to breakage account for the largest value loss (see also Work 1978). They also highlight a number of operational problems caused by MPB salvage logs, including more risky forest operations, increased log and lumber sorting requirements, difficulties in debarking that require adjustments to reduce fiber damage, higher energy requirements for sawing, jamming of mill and planing equipment due to breakage, and kiln-drying challenges associated with heterogeneous moisture content. Across the chain, checking has especially severe negative impacts on both grade (Mancini 1978) and lumber recovery (Nielson and Wright 1984). Others have effectively synthesized research on this topic, including Snellgrove and Fahey (1977), Fahey et al. (1986), Parry et al. (1996), and Lewis and Hartley (2006), in addition to Safranyik and Wilson (2006).

Objectives and Goals

Despite common understanding of the operational and cost impacts of dead timber generally and MPB timber specifically that has been supported by past research, there remains a need to better understand impacts on industry at the local and regional scales. Referring to MPB volume and grade recovery research, much of which was conducted in the 1970s and 1980s during the previous peak landscape-scale outbreak and at a time with different harvest and milling technology, Byrne et al. (2006) stated that this information ''needs to be developed for post-mountain pine beetle lodgepole pine to predict what would occur in modern spruce-pine-fir lumber sawmills.'' Their broader underlying point is that the impact and response of the industry to MPB can be highly variable, site specific, and localized, depending on weather, climate, soil, industry practices, and technology, and can change over time.

The potential impact of MPB on the forest sector in Montana is high. In 2014, the Montana forest products industry converted 93.1 million board feet (MMBF) of lodgepole pine and 69.4 MMBF of ponderosa pine into lumber, house logs, pulpwood, posts and poles, log furniture, and industrial fuelwood (Hayes and Morgan 2016). However, the Montana forest products industry operated at 62 percent capacity in 2014, partially owing to reported timber supply shortages (McIver et al. 2013, Morgan et al. 2015), which are believed to be related to a variety of factors, including MPB. However, the overall impacts of MPB in the state have not been adequately quantified or evaluated.

To help address this knowledge gap, we conducted a study to quantify the operational, cost, and product value impacts of MPB on the sawmill industry at the state level. We accomplished this by administering an expert opinion survey to the largest sawmills operating in Montana in 2016 and summarizing results to represent the industry as a whole. A questionnaire was designed to capture the perspectives of mill managers and wood procurement staff on the relationships between MPB mortality and procurement variables, such as grade and scale, changes in product mixes, and costs associated with purchasing, harvesting, transporting, and sawing timber. The goals of the study were to evaluate how well perceptions of MPB impact align with those in other parts of North America and to provide new information that can be used to assess and mitigate negative MPB impacts in the future. The study was also developed to inform options for the harvest and use of beetle kill timber in the region for bioenergy and bioproducts, in addition to wood products, and to inform policy makers and industry stakeholders of the potential financial impacts that MPB has on this industry.

Methods

This study was focused on the sawmill industry of the wood product manufacturing sector in the US state of Montana (Fig. 2). Using a survey in 2016, we gathered forest product, cost, and value information from selected sawmills operating in the state. In general, impacts of MPB were quantified by comparing the differing product yields and costs of green-stage, red-stage, and gray-stage timber. During interviews, respondents were also given open-ended opportunities to provide their perspectives and insights into the operational and financial effects of dead timber in their wood supply.

Study area

There are 25.9 million acres of forestland in Montana, with 17.9 million acres under federal ownership (69.1%), 1.1 million acres under state and local government ownership (4.2%), and 6.9 million acres privately owned by individuals, families, Indian tribes, nongovernmental organizations, and corporations (26.6%). Most forestland is located in the western part of the state, as are the majority of sawmills (Fig. 2). Although Montana is home to some of the largest wilderness areas in the contiguous United States, unreserved forestland accounts for 84 percent (21.5 million acres) of Montana's forestland, with 92 percent of unreserved forestland classified as timberland, which is open to harvesting and meets the minimum level of productivity of 20 ft^3 $acre^{-1}$ yr^{-1} (Menlove et al. 2012). Between 44° 21′N and 49°00′N, with elevations ranging from 1,800 to 12,800 feet above sea level, Montana forests are dominated by Douglas-fir (*Pseudotsuga menziesii*; 29%), fir–spruce–mountain hemlock forest type (*Abies* spp., *Picea* spp., and *Tsuga mertensiana*; 20%), lodgepole pine (*P. contorta*; 16%), and ponderosa pine (*P. ponderosa*; 11%), with 24 percent of forest in other, mostly coniferous forest types (USFS 2016).

In 2014, the year of the last statewide survey of the wood-using industry by the Forest Inventory and Analysis Program (Hayes and Morgan 2016), there were 102 wood products manufacturers in Montana (Fig. 2). From 2009 to 2014, the number of sawmills in Montana decreased 22

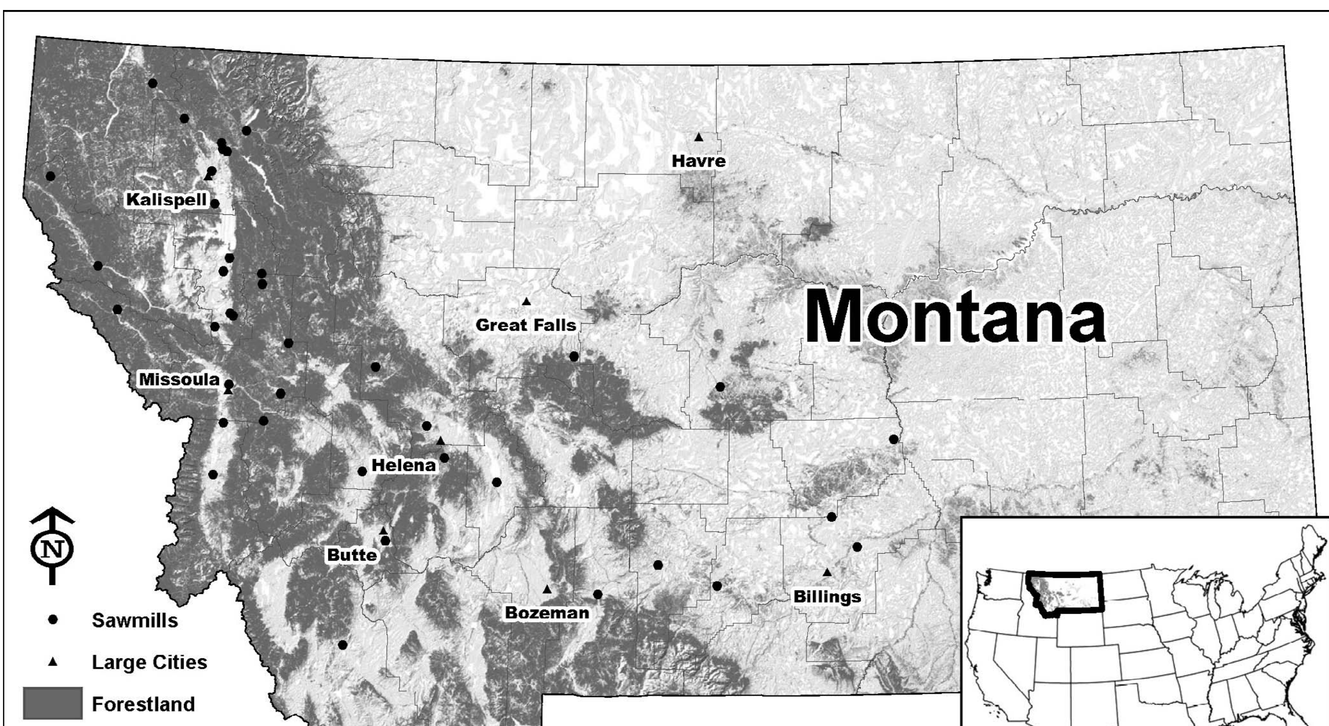

Figure 2.—Map of the state of Montana showing forestland, major cities, and the locations of sawmills operating in 2014. (Credit: Bureau of Business and Economic Research.)

percent, from 41 to 32 sawmills, employing 1,389 people in 2014 (US Bureau of Labor Statistics 2017, Hayes and Morgan 2016). However, statewide, there was a 36 percent increase in sawmill output from 449 MMBF (lumber tally) in 2009 to 611 MMBF (lumber tally) in 2014, some of which was manufactured from timber harvested in other states. Continuing a long-term trend, in 2014 the majority (89%) of the 412 MMBF of timber harvested in Montana was directed to sawmills. Sixty-five percent was obtained from private and tribal lands, 20 percent from national forests, and 15 percent from other public lands (Hayes and Morgan 2016). As described previously, MPB peaked in 2009 in Montana with approximately 3.7 million acres infested and declined to approximately 600,000 acres infested in 2014, representing many billions of cubic feet of dead timber accumulated over the course of the most recent large-scale outbreak.

Survey

In 2016, an expert opinion survey was designed to collect information from Montana sawmill managers and wood procurement staff to characterize the impacts of MPB on the industry. Specifically, we were interested in retrospective perceptions of the impacts of the most recent MPB outbreak, especially over the period from the peak in 2009 through 2015, and its impact on wood supply and supply chain costs. A questionnaire was developed, tested, and revised, and in-person interviews were scheduled and conducted in the spring and summer of 2016 at various sawmills across Montana. Although resource intensive, in-person interviews were conducted based on previous low response rates to mail surveys from this population and to collect the most accurate information possible. The interview format allowed for clarifying questions from respondents as well as more in-depth responses to open-ended questions.

The questionnaire was developed to quantify changes in log quality, grade, value, volume, product mix, and costs across the supply chain. Emphasis was placed on comparing green-, red-, and gray-stage timber rather than gathering precise cost and revenue information associated with specific transactions, harvest operations, and products, which we believed would be too sensitive to disclose. In addition to collecting information to characterize each mill's operations, the questionnaire included questions to evaluate the relative importance of various factors affecting log value; changes in timber product yield moving through green-, red-, and gray-stage stand conditions; the relative importance of factors influencing logging and sawmilling costs; cost changes for stumpage, logging, loading and hauling, and milling; and changes in lumber volume and value recovery. Table 1 provides a summary of the questions included and the types of information collected in the questionnaire.

Factors related to grade, scale, logging cost, and milling cost impacts of MPB were identified and included in the questionnaire based on common industry knowledge, the US National Forest Log Scaling Handbook (FSH 2409.11; USFS 2006), and previous research, including Carpenter et al. (1989), Byrne et al. (2006), and others. The relative importance of these factors was evaluated using median and mode values, with factors ranked first by median and then by mode if medians were equal.

To determine the relative distributions of timber products at different stages of mortality, we presented respondents with a sawmill procurement activity in which they estimated the proportion of products in different classes for a typical mature, even-aged lodgepole pine stand moving from green to red to gray condition (Fig. 1). The timber stand presented in the questionnaire was based on reasonable stocking for the region and was described as 100 percent lodgepole pine, 80 years old, 418 trees per acre, average stand diameter at breast height of 8.1 inches, and an average of 12,990 board feet per acre, with 93 percent of volume considered merchantable (Adams 1980, McCarter and Long 1986, Long and Shaw 2005). Respondents were also provided with photographs of trees and stands in the red and gray stages. Product classes included in the activity were those that are marketed in Montana: sawlogs, pulp logs, house logs, post and pole logs, firewood, and biomass (i.e., hog fuel and energy chips), with an option to provide ''other'' with an open-ended description.

Prior to administering the questionnaire, a pretest was conducted with a small group of people who were typical of likely respondents (Salant and Dillman 1994, Krosnick 1999, Dillman et al. 2008), including loggers and industry professionals not included in the sample frame of mills operating in 2014. Questions were revised for clarity as a result of pretesting.

The sample frame included all sawmills operating in Montana in 2015. However, the sample was not a simple random sample. The mills in the sample frame were rank ordered from largest to smallest with regard to reported 2014 annual production, and mills were selected for interviews in order from largest to smallest to capture as much statewide production as possible with limited resources preventing travel to all sawmills across the state. The positive and negative implications of this sample design are discussed in detail in the ''Discussion'' section. The questionnaire was administered in person with at least one mill manager at each facility. Twice during each interview, respondents were given the opportunity to discuss MPB impacts on their sawmill in an open-ended format (Table 1, Questions 2 and 11). Follow-up telephone calls were used to clarify responses when needed. To protect confidentiality, data from the questionnaire and associated qualitative comments by respondents are summarized without identifying information, and the order of entries in the tables is randomized and does not correspond to the rank order of annual production.

Results

Of the 32 Montana sawmills active in 2015, the 6 largest participated in the survey, which is a response rate of 19 percent. Because of the rank order sampling method, these six mills accounted for 69 percent of total statewide lumber production in 2015, which is 371 MMBF of the 535 MMBF statewide total (Bureau of Business and Economic Research 2017). In 2014, the year of the last statewide industry census (Hayes and Morgan 2016), the respondent sawmills produced 428 MMBF with a production capacity of 665 MMBF in aggregate. Two of the six mills produced between 10 and 50 MMBF per year (categorical response), and four produced more than 50 MMBF per year. All respondent sawmills reported processing at least some dead trees in the red or gray stage of MPB mortality. Three reported that 5 percent or less of total log supply was composed of dead trees, one reported 20 percent, and two reported approximately 40 percent. In aggregate, the total amount of MPB

Table 1.—Summary of questions and response options included in the sawmill questionnaire.

Question no.	Focus of question(s)	Response options/information collected
1a, 1b, 1c	Procurement of dead timber	Processing of mountain pine beetle, proportion and total volume of logs from dead trees processed in 2015, 5-yr average proportion of total log volume from dead timber (2000–2015)
2	Challenges associated with dead timber	Open-ended question soliciting information on challenges associated with dead timber
3, 4	Relative importance of factors affecting value of logs from dead trees in red and gray phases	Cracking/checking, heart defects, insect/bird damage, length due to breakage, rot and shake, stain, other (open ended)
5a, 5b, 5c	Proportions of timber products for a lodgepole pine stand moving through green, red, and gray stages	House logs, sawlogs, pulp logs, post and pole wood, firewood, biomass (i.e., hog fuel, energy chips), other (open ended)
6a, 6b	Relative importance of factors affecting changes in logging cost for dead timber in the red and gray stages	Breakage, equipment wear, safety, sorting, yield/waste, lower log weight, other (open ended)
7a, 7b	Relative importance of factors affecting changes in milling cost for dead timber in red and gray stages	Breakage, change in kiln-drying time, dust, equipment maintenance, safety, log sorting, board sorting, yield/waste, other (open ended).
8	Cost comparison of green, red, and gray stands across supply chain (% ± at each stage for each segment)	Stumpage cost, logging cost, loading and transportation cost, milling cost
9a, 9b, 9c	Changes in lumber volume recovery from green to red to gray stage	Cubic recovery percent, lumber recovery factor, overrun
10a, 10b	Changes in lumber value recovery from green to red to gray stage	Gross log value, lumber tally
11	Debrief	Open-ended, semistructured discussion of mountain pine beetle impacts

processed by these mills in 2015 was reported as 21.5 MMBF, which is only 5.8 percent of their total production. However, from 2010 to 2014, the six sawmills had an average log supply of trees in the red or gray stage of 24.5 percent of log supply, with individual responses ranging from 5 to 40 percent.

As previously discussed, a variety of scale and grade defects can impact log volume and value. When asked to rank six factors (plus an option to provide ‘‘other’’), in order of importance from 1 to 6, when determining the value of logs in the red and gray stages, sawmills reported *cracking/checking* as having the highest impact on value and *stain* as having the least impact. Table 2 shows the factors and their rank order, from 1 to 6, in which each sawmill ranked the factors, plus the median (Md) and mode (Mo) response for each factor. Median ranks 2, 3, 4, and 5 were *length due to breakage*, *rot and shake*, *heart defects*, and *insect/bird damage*, respectively, with some variability in ranks across respondents. None of the respondents provided an ‘‘other’’ option for ranking.

Respondents ranked, in order of importance from 1 to 6, the factors impacting logging costs in high-mortality stands (Table 3). Sawmills reported *log weight reduction* as having the highest cost impact and *equipment wear* as having the lowest cost impact when logging trees in both the red and the gray stage. It is worth noting here that loggers in this region are often paid by green log weight rather than dry weight or volume (i.e., scale), meaning that logs from standing dead trees that have experienced significant drying are worth less than logs from green trees with high moisture content, all else being equal. This sends a strong price signal to loggers that green logs are preferable to logs from

Table 2.—Factors that impact the overall value of logs in the red and gray stages of mountain pine beetle mortality ranked by median (Md), with mode (Mo) response.

	Respondent sawmills							
Log value factor	1	2	3	4	5	6	Md	Mo
Red phase								
Cracking/checking	1	1	2	1	1	1	1.0	1
Breakage (short logs)	4	2	3	3	2	2	2.5	2
Rot and shake	2	3	5	4	3	3	3.0	3
Heart defects	3	4	4	5	4	4	4.0	4
Insect/bird damage	5	5	6	2	5	5	5.0	5
Stain	6	6	1	6	—[a]	—	6.0	6
Gray phase								
Cracking/checking	—	1	1	1	1	1	1.0	1
Breakage (short logs)	—	2	2	3	2	2	2.0	2
Rot and shake	—	3	4	4	3	3	3.0	3
Heart defects	—	4	5	5	4	4	4.0	4
Insect/bird damage	—	5	6	2	5	5	5.0	5
Stain	—	6	3	6	—	—	6.0	6

[a] — = no data or responses were given.

Table 3.—Factors that impact logging costs for trees in the red and gray stages of mountain pine beetle mortality ranked by median (Md), with mode (Mo) response.

Logging cost factor	Respondent sawmills 1	2	3	4	5	6	Md	Mo
Red phase								
Log weight reduction	4	5	1	1	1	1	1.0	1
Breakage	3	3	3	2	2	2	2.5	3
Yield/waste	2	1	4	3	3	3	3.0	3
Sorting	1	2	2	5	6	6	3.5	2
Safety	5	4	6	4	4	4	4.0	4
Equipment wear	6	6	5	6	5	5	5.5	6
Gray phase								
Log weight reduction	4	5	1	1	1	1	1.0	1
Yield/waste	1	1	2	4	2	2	2.0	2
Breakage	3	4	3	3	3	3	3.0	3
Safety	5	2	6	2	4	4	4.0	2
Sorting	2	3	4	5	6	6	4.5	6
Equipment wear	6	6	5	6	5	5	5.5	6

standing dead trees. Behind *log weight reduction*, *breakage* and *yield/waste* were in the 2 and 3 ranks in both stages, with *safety* and *sorting* in the 4 and 5 ranks. None of the respondents provided an ''other'' option for ranking. *Breakage* captures unintentional breakage of the main stem during felling, skidding, and handling, while *yield/waste* refers to intentional trim to meet log specifications, typically at the stump or on the landing.

Similarly, Table 4 shows the relative importance of factors affecting milling costs in the red and gray stages. *Trim/waste* in milling (also called ''downfall''), which refers to intentional size reductions and sorting, and *breakage* of logs at the mill are ranked 1 and 2 in the red phase and ranked 2 and 1 in the gray phase, respectively. Among the least impactful factors, *equipment maintenance* and *kiln-drying time* are ranked 7 and 8, respectively, in both phases. *Dust* is ranked 3 in both phases, and board sorting, log sorting, and safety are in the middle of the rankings. None of the respondents provided an ''other'' option for ranking.

Recall that respondents were presented with a description of a typical mature, even-aged lodgepole pine stand as the basis to provide information on product distributions as stands move from green to red to gray. Table 5 displays the results of that exercise, including average proportion in each product category in each mortality stage as well as the percent change in the proportion of individual products between the mortality stages. Moving from green to red to gray, the proportion of the volume of the stand in the sawlog category falls from 85 to 73 to 36 percent, and the volume of pulpwood increases from 4 to 18 to 46 percent. The volume of firewood increases from 0.0 to 2 to 13 percent. The

Table 4.—Factors that impact sawmilling costs for trees in the red and gray stages of mountain pine beetle mortality ranked by median (Md), with mode (Mo) response.

Logging cost factor	Respondent sawmills 1	2	3	4	5	6	Md	Mo
Red phase								
Trim/waste/downfall	1	3	2	1	2	2	2.0	2
Breakage	2	3	6	2	1	1	2.0	2
Dust	3	5	3	3	3	3	3.0	3
Board sorting	6	4	1	4	—[a]	—	4.0	4
Log sorting	7	1	4	6	—	—	5.0	—
Safety	8	6	7	5	4	4	5.5	4
Equipment maintenance	4	7	5	7	—	—	6.0	7
Kiln-drying time	5	2	8	8	—	—	6.5	8
Gray phase								
Breakage	—	1	3	1	1	1	1.0	1
Trim/waste/downfall	—	2	1	2	2	2	2.0	2
Dust	—	5	4	3	3	3	3.0	3
Board sorting	—	4	2	4	—	—	4.0	4
Safety	—	6	5	5	4	4	5.0	5
Log sorting	—	1	7	6	—	—	6.0	—
Equipment maintenance	—	7	6	7	—	—	7.0	7
Kiln-drying time	—	3	8	8	—	—	8.0	8

[a] — = no data or responses were given.

Table 5.—Timber product distribution in the three stages of mountain pine beetle mortality and percent change in product classes between stages.

Product	Stand mortality stage (% vol)			Change between stages (%)		
	Green	Red	Gray	Green to red	Red to gray	Green to gray
House log	0	4	4	—[a]	0	—
Sawlog	85	73	36	−15	−51	−58
Pulp log	4	18	46	+320	+160	+992
Post and pole	11	5	2	−54	−60	−82
Firewood	0	2	13	—	+670	—
Total	100	100	100	—	—	—

[a] — = no data or responses were given.

volume of post and pole wood decreases from 11 to 5 to 2 percent, and the volume of house logs increases slightly from green to red to gray, from 0 to 4 to 4 percent, but on average these products were reported as relatively smaller components of the product mix. These trends are visualized in Figure 3. By far, the transition of a sawlog-dominant harvest to a pulpwood-dominant harvest is the most striking trend, with a 10-fold increase in the volume of pulpwood when the stand moves from green to gray, increasing from 4 percent pulpwood to 46 percent pulpwood on average. Also, the proportion of volume categorized as sawlogs shows only a 15 percent decrease between the green and red stages but a 49 percent decrease when moving from red to gray.

Regarding the costs of harvesting and milling timber from such a stand, respondents reported a decrease in stumpage costs but increasing logging, loading, and transportation costs and increasing sawmilling costs (Table 6). On average, stumpage costs fell by 35 percent from green to red and another 46 percent from red to gray, for a total drop in stumpage cost of 81 percent. On average, logging, loading and hauling, and sawmilling all see relatively the same cost increases at each stage, increasing 15, 18, and 15 percent, respectively, from green to red and then an additional 28, 28, and 31, respectively, from red to gray. Total average cost increases from green to gray for logging, loading and hauling, and sawmilling are 43, 46, and 46 percent, respectively. These values are unweighted means. Weighted by each sawmill's total 2015 production of MPB logs, from the green to red stage, average stumpage, logging, loading and hauling, and sawmilling costs decreased 34 percent and increased 19, 20, and 21 percent, respectively. From the red to gray stage, weighted average costs for stumpage, logging, loading and hauling, and sawmilling decreased 56 percent and increased 41, 41, and 36 percent, respectively. Total weighted average costs for stumpage, logging, loading and hauling, and sawmilling decreased 90 percent and increased 60, 61, and 57 percent, respectively, from the green to gray stage.

Unlike Questions 1 through 8 (Table 1), most respondents left questions about lumber volume recovery (9a and 9b) and lumber value recovery (10a, 10b, and 10c) blank. Multiple respondents explained that MPB effects on these recovery factors, as presented, were less well known to them and also that this information is generally considered sensitive and proprietary. For these questions, only 14 of 48 potential responses were provided; therefore, results are not reported here. However, four of the six respondents were willing to provide estimates of changes in overrun at different stand stages. Overrun is the difference between the greater volume of product actually sawn compared with the lesser volume of logs scaled (Helms 1998), which is most often expressed as a percentage. Average overrun of red-stage timber was reduced by 10 percent, and average overrun was reduced by 26 percent for gray-stage timber compared with green timber. In practice, this reduction in

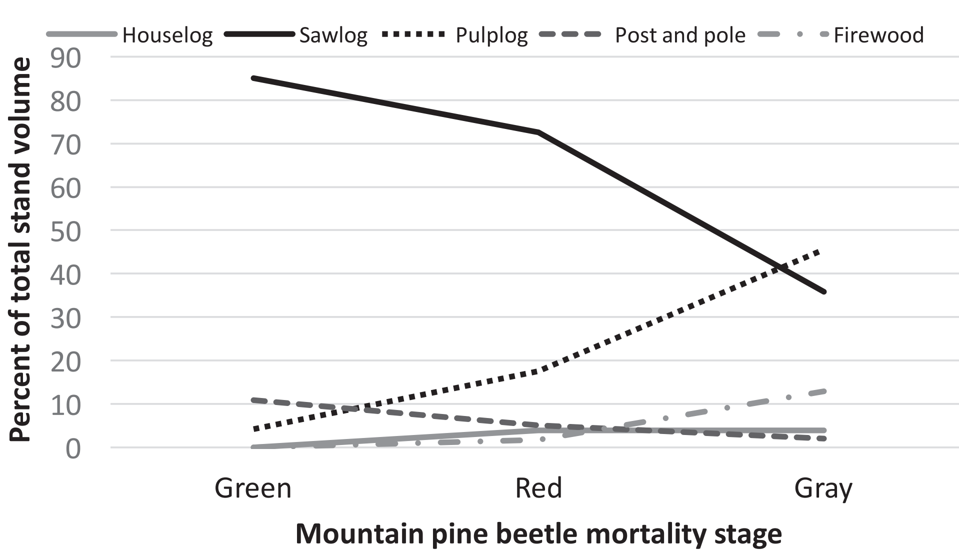

Figure 3.—Average distribution of products for harvested stands in the three stages of mountain pine beetle mortality.

Table 6.—Changes in stumpage and operations costs between the three stages of mountain pine beetle mortality.

Cost category	Change in cost by stage (% change)[a]		
	Green to red	Red to gray	Green to gray
Stumpage	−35	−46	−81
Logging	15	28	43
Loading and hauling	18	28	46
Sawmilling	15	31	46

[a] Change in cost using green as the baseline cost.

overrun translates to a loss (i.e., per unit production cost increase) and is a negative attribute of MPB timber.

Answers to the open-ended, semistructured question (Table 1, Question 2) and the debrief question (Table 1, Question 11) provide additional insights into how respondents viewed the impacts of MPB. Comments are summarized here, with quoted excerpts from written responses and transcripts of debrief conversations. Many comments reinforced the relationships between defects, higher costs, lower recovery, and lower value. One respondent summed up the challenges of MPB timber this way: ''realization drops by 20 to 30 percent due to splits and checking . . . production costs rise due to breakage and jam ups . . . and lumber prices are reduced.'' Difficulties in marketing MPB lumber were raised by several respondents. Stands affected by MPB were considered viable in the early stages (i.e., ''green with some red stage timber''), but heavily impacted stands in later stages, especially gray, were viewed as viable timber salvage sales only if paired with more valuable green timber that could be mixed in ''to get the most value,'' especially if the red and gray component is classified as ''nonsaw optional,'' which means that it can be classified as less than sawlog quality for the purposes of reporting product yields from the stand. Proximity to the mill and associated transportation costs were also important, with one respondent stating that ''20 to 40 miles [from the mill] may be economical,'' with more distant salvage harvests considered unviable.

Several other concerns and observations are of note. Because of the low moisture and low sap content in standing deadwood, saws and chippers do not perform well compared with green timber. Obviously, MPB logs result in lower-grade lumber, but the by-product wood chips from milling are also less desirable for pulp production, mostly because of the blue stain. Dust control was cited as a problem in the comments and ranked third in the milling cost factor comparison. With regard to biomass, one respondent reported that much of the bark flakes off the logs before they arrive at the mill, leaving low bark yield and a lower hog fuel component, and because MPB logging residues are very dry, trucks hauling hog fuel hit volume before weight, making transportation of hog fuel from MPB mill and logging residues economically inefficient. One respondent specifically criticized the timing of the survey: ''this survey is too late, and covers the wrong time period,'' referring to the survey being conducted after the most severe impacts on Montana forests and the industry rather than during or even before the outbreak. This comment is illustrated by the result showing a drop in the proportion of total log supply in the red and gray stages from 24.5 percent for the period from 2010 to 2014 to 5.8 percent for 2015.

Discussion

Despite some potential positive short-term impacts on wood supply, such as an increase in planned, sold and cut timber (Byrne et al. 2006) and feedstock for bioenergy uses (Stennes and McBeath 2006), MPB is widely acknowledged as having generally negative impacts on wood supply by reducing log quality and recoverable volume as well as negatively impacting operability in the forest and at the sawmill. There is no doubt that harvesting, transporting, and sawing the large volumes of dead timber created by the most recent MPB outbreak have presented serious challenges to land managers and the industry in the Rocky Mountain region, including Montana. Given that the impact and response to MPB can be variable and localized, this study was designed to provide more detailed information about how MPB affects forest and sawmill operations and production costs along the sawn product supply chain in Montana.

Before discussing the results, several limitations associated with the survey design must be addressed. Participating mills accounted for 69 percent of the total 2015 sawlog supply in the state of Montana. However, the survey was not a simple random sample but rather focused on the largest mills in order to capture information about as much production as possible under our time and resource constraints. As a result, it did not collect information about the perceptions and experiences of managers of smaller production mills. We assumed that smaller mills would face the same challenges associated with MPB as the larger mills but have no information to evaluate this assumption. It is possible that such mills may have procurement practices or operational characteristics that are affected differently by MPB. Some might benefit from factors such as increased wood supply, while others may not have the capacity to adapt to milling dead timber efficiently. Also, some segments of the broader forest industry that are closely tied to sawmills, such as firewood operations and wood pellet mills, may benefit from the increased supply of roundwood from MPB salvage, even if sawmills are negatively impacted. Those benefits are not captured here. Results should be viewed with these caveats in mind. Even so, the results do provide new information for evaluating the impacts of large-scale mortality on the sawmill sector in this region.

Many responses and individual comments reinforced known relationships between defects, higher costs, lower recovery, and lower value, but there were some interesting departures from expectations. Log staining is visually dramatic and serves as a clear reminder of grade defects that can reduce the value of MPB timber and products but does not, by itself, compromise the physical integrity of the wood for most uses. Staining has also been the focus of efforts to brand blue-stained MPB lumber and products as aesthetically desirable and of ''artisan quality'' (e.g., Sustainable Lumber Company 2017). However, volume defects, especially checking and cracking, were considered much more important by our respondents in determining the overall value of MPB logs (Table 2). In fact, staining ranked last in the list. This is not to say that good marketing is not valuable, but it is more difficult to see how marketing efforts might compensate directly for losses related to volume defects associated with MPB, even if they successfully close the price gap between stained and unstained lumber.

Log weight reduction was generally considered the most impactful variable for logging cost because it is directly connected to the delivered value of the logs when they are purchased on a green weight basis rather than based on scale. This effect is rapid, with logs losing moisture relatively quickly after death in dry climates, depending on weather and site conditions. Although this factor was included on the questionnaire after pretesting based on the recommendation of the testers, this ''cost'' variable is somewhat misleading because it is really directly related not to operational costs but rather to log value associated with the green weight payment structure. Product loss and low yields due to *breakage* and *yield/waste* stood out as the most impactful direct operational cost in logging and also as the factors that most affect milling costs. Anyone who has observed the harvest and handling of MPB logs in the gray stage has seen significant breakage in the stand, at the log landing, and in the log yard of the sawmill as well as downfall along the production line, depending on time since mortality and associated degradation. For the firms involved in the supply chain, this translates directly into higher per-unit production costs by reducing merchantable output, even if MPB products are salable.

Although previous research has highlighted mechanical difficulties, such as fiber loss and jamming in debarking, jamming and higher energy requirements in sawing, and jamming of milling and planing equipment due to breakage, equipment wear is among the least important variables for both logging costs and milling costs for the respondents of this survey. Only kiln-drying time is ranked lower in terms of impact on milling costs. It is unclear why this would be so, especially for mills with more than 40 percent of their wood supply classified as dead timber, but it is possible that modern equipment is less prone to jamming and other mechanical problems that were highlighted in previous articles dating back to the 1980s and earlier. For example, many modern mills in western North America have been designed to handle small-diameter logs with high-throughput mechanized systems, which may be more robust to the types of logs generated by MPB salvage.

As with previous outbreaks, millions of acres of forest affected by MPB will regenerate without harvesting or silvicultural treatment of any kind, including forests that are not accessible to harvesting by administrative designation or lack of road access as well as stands that are technically designated as timberland but have been deemed uneconomical to harvest. Increased costs and lower recovery of valuable grades of lumber are the hammer and anvil that combine to make economically efficient beetle kill salvage more difficult the longer a high-mortality stand remains unharvested. If a stand is determined to be suitable for salvage harvesting, Figure 3 illustrates the economic risk in delaying harvesting decisions and activity. For a typical lodgepole pine stand, the distribution of volume categorized as sawlogs declines over time as the stand moves from green to red to gray, with the product mix moving rapidly from higher-grade products to lower-grade products. In practical terms, what is initially designated as a salvage harvest may eventually become a prescription to reduce fire risk (i.e., fuel treatment) with attendant higher costs and lower value. For example, Kim et al. (2017) documented harvesting costs in such a scenario on a lodgepole pine stand in Helena National Forest that was attacked by MPB in 2008 but harvested in 2015. They concluded in part that delayed harvesting led to higher costs and lower-value recovery and quantified the effect using forest operations data.

Although obviously a problem for sawmills, the increase in the proportion of low-grade materials, combined with breakage and waste, would appear to present a clear wood supply opportunity for pulp mills and enterprises requiring low-cost biomass feedstock. Although blue-stained wood is not preferable for pulp, beetle kill has been targeted for bioenergy uses ranging from electricity to liquid fuels to bioproducts, such as the charcoal soil amendment known as biochar. However, optimism for biomass flows from MPB runs headlong into the same cost constraints that apply to harvesting timber for higher-value products. Concentrations may be high and stumpage cost quite low for these materials, possibly even zero or negative (i.e., subsidized), but logistics costs escalate as deteriorated wood becomes more prone to breakage. Furthermore, few biomass-only operations can bear the full cost of harvesting and transportation independent of a fully integrated supply chain that includes higher-value products such as sawlogs. This makes timely, well-planned harvesting in MPB stands important in terms of both harvesting costs and value recovery regardless of the product mix.

More broadly, our results highlight the potential disconnection between forest management needs and forest product supply chains, especially if stands that are candidates for salvage remain unharvested for many years. Several mills involved in this survey, as well as loggers and truckers in Montana and other parts of the Rocky Mountain region, specifically avoid MPB timber. Payment structures in many areas send strong price signals that green wood is highly preferable to standing dead and downed timber. This makes it difficult for forest managers to employ silviculture not only to recover timber value but also to achieve other objectives, such as reducing fire risk and protecting infrastructure and recreational opportunities. This effect can be intensified if beetle kill stands that would otherwise be harvested are not even considered for harvest because administrative procedures (e.g., compliance with the National Environmental Policy Act) would delay harvest enough to degrade products to the point that revenues do not cover costs.

Conclusions

MPB is widely acknowledged as having significant negative impacts on wood supply despite potential short-term increases in timber availability and wood flows associated with salvage harvests. In general, this study supports known relationships between defects, higher costs, lower recovery, and lower value. Results illustrate both the escalating costs and the declining values associated with timber as MPB stands over time. In the state of Montana, MPB timber currently makes up a much smaller component of the log supply than at the height of the outbreak in 2009. In preparing for the next outbreak, planning and timely harvest will be critical in meeting forest management needs and enhancing values that are facilitated by harvest and downstream wood products manufacturing.

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