Mountain pine beetle infestation of lodgepole pine in areas of water diversion

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Abstract

The Rocky Mountains have experienced extensive infestations from the mountain pine beetle (Dendroctonus ponderosae Hopkins), affecting numerous pine tree species including lodgepole pine (Pinus contorta Dougl. var. latifolia). Water diversions throughout the Rocky Mountains transport large volumes of water out of the basins of origin, resulting in hydrologic modifications to downstream areas. This study examines the hypothesis that lodgepole pine located below water diversions exhibit an increased incidence of mountain pine beetle infestation and mortality. A ground survey verified diversion structures in a portion of Grand County, Colorado, and sampling plots were established around two types of diversion structures, canals and dams. Field studies assessed mountain pine beetle infestation. Lodgepole pines below diversions show 45.1% higher attack and 38.5% higher mortality than lodgepole pines above diversions. These findings suggest that water diversions are associated with increased infestation and mortality of lodgepole pines in the basins of extraction, with implications for forest and water allocation management.

1. Introduction

The mountain pine beetle (Dendroctonus ponderosae Hopkins) has severely impacted pine species throughout the western USA and Canada in recent years, resulting in large regions with damaged and dead pine trees (Raffa et al., 2008; Logan et al., 2010). Increased mountain pine beetle (MPB) populations are supported by increased temperatures, as well as increased stand density facilitated by fire suppression (Raffa et al., 2008; Negron et al., 2009; Bentz et al., 2010; Logan et al., 2010; Kulakowski et al., 2012). These conditions are compounded by decreased resistance of host trees to bark beetle species due to factors such as drought, increased temperatures, and pollution deposition (Mattson and Haack, 1987; Jones et al., 2004; Raffa et al., 2008; Bentz et al., 2010; Logan et al., 2010; McDowell et al., 2011). Drought can alter the chemical and physical properties of resin, a key defense mechanism, thereby reducing resistance of the host tree to infestation (Mattson and Haack, 1987; Raffa et al., 2008; McDowell et al., 2011). Specifically, drought impairs resin flow and pressure, properties that can impede beetles, as well as the concentration of chemicals that are toxic to beetles (ibid). Climate change is contributing to both increased temperatures and decreased water availability, thereby increasing conditions that favor MPB infestation (Raffa et al., 2008; Bentz et al., 2010; Logan et al., 2010; McDowell et al., 2011).

Water diversion projects extend throughout the Rocky Mountain region, transporting significant volumes of water out of the basins of origin. In Colorado, numerous systems collect and transport water from the western side of the Continental Divide to the eastern side, servicing the Front Range (Colorado’s Decision Support System [CDSS], n.d.). In Grand County, CO, water is diverted from all major basins in the southern and eastern portions of the county using vast systems of dams, canals, and pipelines, based on data from Colorado’s Decision Support System (n.d.), as well as survey data gathered during this study. Dams function to block and collect water from streams, and funnel the water into the diversion canals and pipes. Canals function to transport water, and also collect surface and subsurface flow (Natural Resources Conservation Service [NRCS],...
2010), particularly from a slope (Texas A&M Forest Service, 2008). The area examined in this study contains a portion of the Moffat Tunnel diversion system, which collects from all of the headwaters of the Fraser River (Colorado Division of Wildlife [CDOW], 2010; CDSS, n.d.). This system carried an average of 2.16 cubic meters per second from June 1958 through May 2010, and 2.29 cubic meters per second during the 10-year period prior to this study, based on stream flow data from the east side of the Moffat Tunnel (Colorado Division of Water Resources [CDWR], 2013). This system removes a significant portion of water from the natural river system, based on comparisons of historic stream flow data (Coley/Forrest, Inc, 2007). In a nearby system, researchers have noted that all water is diverted from some streams in some years, resulting in “dry conditions below diversions” (CDOW, 2010).

Substantial research has provided evidence that water diversions cause measurable changes to stream habitat, including reduced water flow, structural barriers to wildlife movement, altered streambed characteristics, increased water temperatures and altered populations of species dependent on riparian ecosystems (Osmundson et al., 2002; Covington and Hubert, 2003; Uowolo et al., 2005; Hagen and Sabo, 2012). Estuarine habitats downstream from diversion points have been adversely impacted from reduced flow. Stream surveys and sampling were conducted around canals (Sites B and C). A total of 14 plots were established across those sites, surveyed between July and September 2010. At the two sites bisected by a canal, plots were established above and below the canal, with plot centers approximately 18.3 m from the canal edge or adjacent road. At the dam site, plots were established above and below the dam, with plot centers approximately 10.7 m from the stream edge. Circular plots did not overlap and had a radius of 9.75 m (298.65 m$^2$; 0.03 ha), similar to plots used in related studies (e.g., Breece et al., 2008; Morehouse et al., 2008; Negron et al., 2008; Klutsch et al., 2009; Negron et al., 2009). The distance separating above-diversion and below-diversion plots that were situated across from one another, with a canal between them, was approximately 48.8–61.0 m. The distance separating above-diversion and below-diversion plots around the dam was greater than the distance between the canal plots. Plots did not contain evident and current human disturbances other than the active diversion structures. While the long-term history of fire and other disturbance events in this area is unclear, our design with close proximity between plot types at a site presupposes a similar disturbance history.

2. Materials and methods

2.1. Study area

The study area is located in the southeastern portion of Grand County, CO in the Sulphur Ranger District, Arapahoe National Forest, west of the Continental Divide (Fig. 1). The area has mixed land cover, with forests of lodgepole pine (Pinus contorta Douglas ex Loudon var. latifolia Engelmann), Engelmann spruce (Picea engelmannii Parry ex Engelmann), subalpine fir (Abies bifolia A. Murray), and quaking aspen (Populus tremuloides Michaux). Precipitation and temperature data for the area are monitored at a nearby SNOTEL site at 39° 58.146′ N, 105° 14.743′ W and 2950.5 m in elevation (National Elevation and Climate Center [NWCC], 2012). The historical mean annual air temperature is 2.9°C (October 1986–September 2011), and the historical mean annual accumulated precipitation is 35.1 cm (NWCC, 2012). During 2010, the year of our field sampling, the mean annual air temperature was 3.3°C and the mean annual accumulated precipitation was 25.1 cm (January to December 2010) (NWCC, 2012).

In order to determine the types and locations of diversion structures and vegetation, ground surveys covering 33.8 km in total distance were conducted along diversions in three areas in south and southeast Grand County, CO. One area was selected for this study (Fig. 1), because it contained lodgepole pine and a portion of the Moffat Tunnel diversion system. This system uses dams, canals, and pipelines to collect from all headwaters of the Fraser River (CDOW, 2010; CDSS, n.d.). This system first started exporting water across the Continental Divide through the Moffat Tunnel in 1936, and significant additions were made to the system through 1958 (Denver Water, 2013). Diversions were inventoried using a digital camera and a global positioning system (GPS) unit (GPSmap 60CSx, Garmin) with an accuracy of 2.7–3.7 m. Dirt roads provide access along the diversion system.

2.2. Site selection

Three study sites were selected based on the aforementioned ground survey data. One site was established around a dam (Site A), and four additional sites were established around canals (Sites B and C). A total of 14 plots were established across those sites, surveyed between July and September 2010. At the two sites bisected by a canal, plots were established above and below the canal, with plot centers approximately 18.3 m from the canal edge or adjacent road. At the dam site, plots were established above and below the dam, with plot centers approximately 10.7 m from the stream edge. Circular plots did not overlap and had a radius of 9.75 m (298.65 m$^2$; 0.03 ha), similar to plots used in related studies (e.g., Breece et al., 2008; Morehouse et al., 2008; Negron et al., 2008; Klutsch et al., 2009; Negron et al., 2009). The distance separating above-diversion and below-diversion plots that were situated across from one another, with a canal between them, was approximately 48.8–61.0 m. The distance separating above-diversion and below-diversion plots around the dam was greater than the distance between the canal plots. Plots did not contain evident and current human disturbances other than the active diversion structures. While the long-term history of fire and other disturbance events in this area is unclear, our design with close proximity between plot types at a site presupposes a similar disturbance history.

2.3. Plot measurements

Elevation, aspect, and location were measured at the central point of each plot with the GPS. Slope was estimated using a slope meter. For all standing trees with DBH $\geq 2.54$ cm breast height (DBH), measured at 1.37 m above the ground, DBH and species were recorded. Also, all lodgepole pines with DBH $\geq 2.54$ cm were visually assessed for MPB infestation using the following indicator ratings: living trees without indicators (1 = alive, not attacked), trees with indicators and a majority of green needles (2 = attacked but alive), trees with indicators and majority or entirety of brown or missing needles (3 = beetle-killed), trees dead from indeterminate or non-MPB cause (4 = dead). Indicators of MPB infestation were characterized by bore or exit holes, boring debris at the base of the tree, or pitch tubes. Since trees with small DBH are generally considered less likely to be attacked (Amman, 1977), researchers have often applied a cutoff DBH value in order to exclude small DBH trees from analysis (Breece et al., 2008; Waring and Sic, 2005). In this study, only MPB infestation indicator data for lodgepole pines with DBH $\geq 2.54$ cm utilized in studies assessing MPB in ponderosa pine (Negron et al,
and various bark beetle species in pines (Waring and Six, 2005; Morehouse et al., 2008; Negron et al., 2009). Measured trees were marked with chalk to prevent duplicate measurements. We measured soil moisture using a FieldScout TDR 100 Soil Moisture Meter (Spectrum Technologies). The rocky substrate limited measurements to a 7.6 cm probe incapable of reaching below the uppermost soil. Due to this limitation, these data are not reported here.

2.4. Statistical analysis

Statistical tests and distribution plots were performed using Minitab 16 (Minitab Inc., 2010). Data for all sites were pooled by their position in relation to the diversion structure (above or below). Due to non-normal data distribution, non-parametric tests were applied, similar to Klutsch et al. (2009). Statistical tests included the Mann–Whitney, cross-tabulation with chi-square and Fisher’s exact test, $\alpha = 0.05$.

3. Results

3.1. Plot characteristics

Elevations for below-diversion and above-diversion plots differed less than 50 m, ranging from 2843.5 to 2893.5 m and 2871.2 to 2919.4 m above sea level, respectively. Aspect was also similar between plots within each site, ranging from west to north. Estimated slopes ranged from 5 to 20° (median 10°) for plots below diversions, and 15 to 30° (median 15°) for plots above diversions. A total of 1126 trees of all species with DBH $\geq$ 2.54 cm were measured across all plots, 708 above diversions and 418 below diversions. Of these, plots above diversions contained 87.0% lodgepole pine, while plots below diversions contained 71.3% lodgepole pine. Median DBH of lodgepole pines was 11.4 cm above diversions and 17.0 cm below diversions (one-way Mann–Whitney, $p < 0.001$).

3.2. Diversions, MPB infestation, and tree mortality

A total of 663 lodgepole pines with DBH $\geq$ 7.62 cm were assessed for MPB infestation indicators, 437 above diversions and 226 below diversions. The proportion of lodgepole pines alive and not attacked was 86.3% above diversions, and 42.0% below diversions, a 44.3% higher proportion of non-infested lodgepole pines above diversions. The proportion of beetle-killed lodgepole pines was 4.8% above diversions and 41.2% below diversions, a 36.4% higher proportion of beetle-killed lodgepole pines below diversions. The MPB infestation indicator ratings differed significantly between above- and below-diversion plots (Pearson chi-square = 164.191, DF = 3, $p < 0.001$). Lodgepole pines with an indeterminate or non-MPB-related cause of death were excluded from further analysis, constituting 12 trees below diversions and 16 trees above diversions.

To analyze differences in the incidence of MPB attack, lodgepole pines were reclassified as non-MPB-attacked or MPB-attacked.
Lodgepole pines with MPB infestation ratings of 2 or 3 were classified as MPB-attacked (Fig. 2a). The proportion of lodgepole pines attacked by MPB was 10.5% above diversions and 55.6% below diversions, a 45.1% higher proportion of MPB-attacked lodgepole pines below diversions (Fisher's exact test, p < 0.001).

To analyze differences in the incidence of mortality due to MPB infestation, lodgepole pines were reclassified as non-MPB-killed or MPB-killed. Lodgepole pines with MPB infestation ratings of 1 or 2 were classified as non-MPB-killed (Fig. 2b). The proportion of lodgepole pines killed by MPB was 5.0% above diversions and 43.5% below diversions, a 38.5% higher proportion of MPB-killed below diversions (Fisher's exact test, p < 0.001).

DBH values were sorted into classes by plots above and below diversions, based on percentages of lodgepole pine within each plot type, either above or below (Fig. 3). Across all DBH classes, plots below diversions exhibited higher percentages of both MPB-attacked and MPB-killed lodgepole pine. These proportions were statistically significant (Fisher's exact test, p < 0.001) for DBH classes 10–20 cm and 20–30 cm. Other classes contained fewer data, affecting the reliability of the statistical test.

4. Discussion

In this study, plots below diversions contained significantly higher percentages of lodgepole pine attacked and killed by MPB. These findings lend support to the hypothesis that water diversions are associated with higher incidence of MPB infestation and mortality. Diversions have been shown to reduce water availability to areas below diversions. Reduced water availability is caused by the physical nature of diversion structures, including canals, which intercept surface and subsurface water (Texas A M Forest Service, 2008; NRCS, 2010). Diversions have also been observed to reduce stream flow (Carriquiry and Sanchez, 1999; Rodriguez et al., 2001; Osmundson et al., 2002; Uowolo et al., 2005), as well as lower water tables and change soil chemistry (Chimner and Cooper, 2003).

This study examined plots above and below an active and extensive diversion system that exports substantial amounts of water (CDSS, n.d.). Based on the extent and activity of this system, it is likely that water is reduced in areas below diversion structures. The diversion system in this study was active in the sites for at least 52 years prior to the study (Denver Water, 2013), creating the potential for long-term impacts. Since above-diversion and below-diversion plots were in close proximity, plot types are expected to share similar fire and climate histories.

Drought stress affects multiple tree characteristics, including ones that can act as cues for insects to attack (Mattson and Haack, 1987). Furthermore, once attacked, drought-stressed trees are less able to respond successfully to the attack (Mattson and Haack, 1987; Raffa et al., 2008). This study found both increased incidence of attack and mortality in lodgepole pines below diversions, which may indicate that lodgepole pines below diversions are more drought-stressed and less healthy compared to those above diversions.

Structural characteristics are affected by factors such as drought and fire (Raffa et al., 2008; Negron et al., 2009; Logan et al., 2010), and structural characteristics can affect MPB infestation (Negron et al., 2008; Klutsch et al., 2009; Kulakowski et al., 2012) through such factors as tree size, in that smaller trees are less likely to be attacked (Amman, 1977). Furthermore, MPB infestation can also alter stand structure (Amman, 1977; Dordel et al., 2008; Klutsch et al., 2009). The relationships between environmental conditions, MPB infestation, and stand structure are complex. In this study, regardless of differences in stand structure, increased proportions of attack and mortality below diversions were found within each DBH class. This type of comparison points to a consistent pattern of increased MPB attack and MPB-induced lodgepole pine mortality below diversions, regardless of tree size.

Some of the diversion structures observed in this study, such as dams, have control features that prevent or allow flow release from the diversion. During this study, many structures, including the dam at Site A, were consistently observed to have control features that were closed to prevent flow releases into areas below the diversion. These observations, combined with similar observations at nearby systems (CDOW, 2010) and stream flow data for this system (CDWR, 2013), indicate substantial and consistent extractions of water by this diversion system.

5. Conclusions

The results of this study indicate that water diversions are associated with increased MPB attack and mortality in the Rocky Mountains of Colorado. Further research is needed to define the mechanism, magnitude, and scope of this relationship. In particular, future research should attempt to document changes in soil moisture in diversion areas, the effect of distance from diversions, and larger sample sizes over a larger geographic area. Such studies could contribute to improved understanding of ecosystem water requirements. Recent efforts acknowledge the importance of environmental requirements in water allocation strategies (Hillman et al., 2012; Larson et al., 2013; Perona et al., 2013). To achieve proper strategies, policymakers and managers should understand water diversion impacts. The ongoing trend of decreasing supply (IPCC, 2007) and increasing demand (Camp Dresser and McKee and Harvey Economics, 2010) will intensify pressure on diverted basins and will require well-informed water management strategies.
Fig. 3. DBH distributions as a percentage of the lodgepole pines within each plot type, either above or below diversions: (a) above diversions as MPB-attacked and non-MPB-attacked, (b) above diversions as MPB-killed and non-MPB-killed, (c) below diversions as MPB-attacked and non-MPB-attacked, (d) below diversions as MPB-killed and non-MPB-killed, Grand County, CO, 2010. Data are shown as stacked values.

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References


