Increased Evaporation Following Widespread Tree Mortality Limits Streamflow Response

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Abstract A North American epidemic of mountain pine beetle (MPB) has disturbed over 5 million ha of forest containing headwater catchments crucial to water resources. However, there are limited observations of MPB effects on partitioning of precipitation between vapor loss and streamflow, and to our knowledge these fluxes have not been observed simultaneously following disturbance. We combined eddy covariance vapor loss (V), catchment streamflow (Q), and stable isotope indicators of evaporation (E) to quantify hydrologic partitioning over 3 years in MPB-impacted and control sites. Annual control V was conservative, varying only from 573 to 623 mm, while MPB site V varied more widely from 570 to 700 mm. During wet periods, MPB site V was greater than control V in spite of similar above-canopy potential evapotranspiration (PET). During a wet year, annual MPB V was greater and annual Q was lower as compared to an average year, while in a dry year, essentially all water was partitioned to V. Ratios of 2H and 18O in stream and soil water showed no kinetic evaporation at the control site, while MPB isotope ratios fell below the local meteoric water line, indicating greater E and snowpack sublimation (Ss) counteracted reductions in transpiration (T) and sublimation of canopy-intercepted snow (Ss). Increased E was possibly driven by reduced canopy shading of shortwave radiation, which averaged 21 W m-2 during summer under control forest as compared to 66 W m-2 under MPB forest. These results show that abiotic vapor losses may limit widely expected streamflow increases.

1. Introduction

Forested watersheds are among the most reliable sources of clean water [Brown et al., 2005], but montane forests are undergoing unprecedented die-off due to increased drought, fire, and pathogen infestation [Williams et al., 2010, 2013; Breshears et al., 2009; Adams et al., 2012; Westerling et al., 2006; Huber, 2005; Tokuchi et al., 2004]. Western North America is experiencing an unprecedented epidemic of mountain pine beetle (MPB; Dendroctonus ponderosae) [Raffa et al., 2008; Hicke et al., 2012], which has affected more than 5 million hectares in the western US and British Columbia [Meddens et al., 2012]. MPB introduce blue-stain fungi that inhibit sap flow and usually kill host trees within weeks to months [Hubbard et al., 2013]. Dead trees may retain their needles for 1–3 years, termed a red phase [Wulder et al., 2012]. Dead trees are said to be in a gray phase, which may last years to decades. This progressive canopy loss without immediate soil disturbance is different from harvest or fire, challenging our ability to predict MPB effects on water resources [Clow et al., 2011; Mikkelson et al., 2013a].

Extensive literature provides initial context for hydrologic response to MPB. Forest disturbance studies have established that streamflow (Q) usually increases in proportion to forest removed, with lesser response in dry regions [Stednick, 1996; Brown et al., 2005]. However, few disturbance studies have been conducted within interior conifer forests with annual precipitation of 600–1200 mm [Bosch and Hewlett, 1982], representing much of the North American forest impacted by MPB. Effects of disturbance on Q are the weakest and most variable in such regions ($r^2 = 0.01$) [Stednick, 1996]. Variable Q response reflects variability in vapor loss (V) due to snow sublimation (Ss), evaporation (E), and transpiration (T) [Troendle, 1983; Brown et al., 2013; Hubbard et al., 2007], which remain poorly understood.
Recent work has examined how progressive hydrologic partitioning response to gradual canopy loss may affect water resources and forest succession [Edburg et al., 2012]. Forests regulate partitioning through interception, transpiration, and sheltering the land surface [Troendle and King, 1987; Molatch et al., 2009; Varhola et al., 2010]. Disturbance-driven partitioning changes may affect water resources, including the amount and timing of streamflow [Pugh and Gordon, 2013; Brown et al., 2005; Ellison et al., 2012] and water availability for successional vegetation [Edburg et al., 2012]. Succession is likely to depend on both partitioning between Q and V as well as how V comprises S, E and T [Edburg et al., 2012; Brown et al., 2013; Romme et al., 1986]. The expectations for response to MPB include an initial, large decline in T followed by more gradual increases in E from newly exposed soils and increased T by surviving and new vegetation [Edburg et al., 2012; Romme et al., 1986]. Winter precipitation is a dominant hydrologic input to many infested forests, and the reduction in sublimation of intercepted snow from the canopy (S_c) is expected to increase snowmelt volumes [Pugh and Small, 2012]. The timing and relative magnitudes of these changes are unknown, but the prevailing expectation is for reduced V resulting in greater Q [Pugh and Gordon, 2013].

There is limited and conflicting empirical evidence of Q response to MPB in support of these expectations. Increased Q was reported by Potts [1984] and Bethlahmy [1974], although the increase reported by Bethlahmy [1974] peaked 15 years post-MPB, contrasting with the view that Q increases are immediate and decline over years to decades [Bosch and Hewlett, 1982; Stednick, 1996; Brown et al., 2005]. A recent study of MPB-impacted Colorado catchments found mixed Q responses, attributed in part to variable interactions among topography and canopy loss in controlling V [Brooks et al., 2012; Somor, 2010]. Snowpack observations have shown either that total winter S declined or that increased snowpack sublimation (S_s) compensated for reduced S_c, resulting in no net snowpack change [Boon, 2012; Pugh and Small, 2012; Biederman et al., 2014]. Summer V has been relatively constant during several years following mortality [Brown et al., 2013], although land surface models predict reduced V with declining leaf area index under simulated disturbance [Bewley et al., 2010; Pomeroy et al., 2012; Mikkelsen et al., 2013b]. Similarly, remote-sensing products such as MOD16 (http://www.ntsg.umt.edu/project/mod16) that use plant-mediated algorithms [Mu et al., 2011] predict reduced V [Bright et al., 2013; Maness et al., 2013].

The variable Q response to MPB and lack of consistency between observations and models demonstrates our limited ability to predict water resources following insect-driven disturbance. There is therefore a need to empirically quantify hydrologic partitioning in insect-disturbed headwater catchments. Snow surveys quantify winter V over a range of spatial scales [Anderton et al., 2004; Musselman et al., 2008; Veatch et al., 2009]. Eddy covariance (EC) quantifies V from a footprint of similar size to a headwater catchment (~10^3 ha) [Wilson et al., 2001; Scott, 2010]. Alternatively, the difference between precipitation (P) and observed Q can be used to estimate catchment-scale vapor loss (V*) assuming negligible storage changes [Jasechko et al., 2013; Clark and Fritz, 1997].

In this study, we quantify hydrologic fluxes during 3 years following MPB infestation at a site with severe MPB-driven forest mortality and at a paired control site to answer the question: How does MPB tree mortality affect partitioning of precipitation between vapor loss and water available for streamflow? To our knowledge, this is the first effort combining onsite precipitation, snow surveys, eddy covariance vapor flux, catchment streamflow, and stable isotope indicators of evaporation to quantify hydrologic response to forest disturbance.

2. Site Description

An MPB-impacted site “MPB” and control site “Unimpacted” were identified in the Central Rocky Mountains, a region severely impacted by MPB [Meddens and Hicke, 2014]. Due to extensive tree mortality, adjacent MPB and control sites having similar characteristics were not found. However, biophysical and meteorological observations at these sites showed them to be well paired (Table 1). The MPB site at Chimney Park, WY is 100 km west of Cheyenne in the Medicine Bow National Forest and the headwaters of the Laramie River (Figure 1). The MPB site experienced severe infestation beginning in 2007, with peak mortality during 2007–2009. The Unimpacted site (Figure 1) is 125 km SSE of the MPB site and 50 km NW of Denver, CO.
within the Niwot Ridge Long-Term Ecological Research (LTER) observatory in the headwaters of Boulder Creek. We did not observe MPB-related tree mortality at the Unimpacted site.

To isolate MPB effects, we selected sites with gentle slopes (5%–8%) and similar elevation of 2750–3000 m (Table 1). The sites have cold winters with continuous snow cover typically lasting from October until May or June and mean annual air temperatures of 1–3°C. The Unimpacted site receives 800 mm mean annual precipitation (MAP), with 400 mm as snow \[\text{[Monson et al., 2002]}\] (Niwot SNOTEL 1981–2012). The MPB site also receives an average of 400 mm snowfall, but drier summers result in lower MAP of 600–650 mm \[\text{[Fahey et al., 1985]}\]. Soils at both sites are sandy loam. Overstory trees at both sites were dominated by lodgepole pine (Pinus contorta) aged 110–140 years since the prior stand replacement with mean tree heights ca. 11 m \[\text{[Knight et al., 1985]}\] (http://ameriflux.lbl.gov). Mean diameters at breast height were 12.1 and 14.0 cm at the Unimpacted and MPB sites, respectively, while stem densities were 3900 and 2500 stems ha\(^{-1}\) \[\text{[Biederman et al., 2014]}\].

### Table 1. Characteristics of the Unimpacted and MPB Study Sites

<table>
<thead>
<tr>
<th>Site</th>
<th>Elev. (m)</th>
<th>Lat. Long.</th>
<th>Mean Annual and Mean Winter Precipitation (mm)</th>
<th>Stand Age (Year)</th>
<th>Stem Density (per ha)</th>
<th>Mean Stem Height (m)</th>
<th>DBH (cm)</th>
<th>Soils</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unimpacted(^b^)</td>
<td>3000</td>
<td>40° 02'</td>
<td>800</td>
<td>100</td>
<td>3900</td>
<td>11.4</td>
<td>12.1</td>
<td>Cryochrepts</td>
</tr>
<tr>
<td>MPB(^c^)</td>
<td>2750</td>
<td>41° 04'</td>
<td>400</td>
<td>90–110</td>
<td>2500</td>
<td>11.1</td>
<td>14.0</td>
<td>Sandy Loam</td>
</tr>
</tbody>
</table>

\(^a^\)The sites had similar elevation, soil texture, stand age, and average tree sizes in lodgepole pine-dominated overstory. Location and elevation are for the eddy covariance (EC) towers. The Unimpacted site had greater stem density in the tower footprint.

\(^b^\)Scott-Denton et al. [2003].

\(^c^\)Knight et al. [1985] and Fahey et al. [1985].

3. Methods

3.1. Experimental Design

The study period comprised hydrologic years 2010–2012 divided into winter and summer by the onset of snowmelt runoff. The Unimpacted site contained an existing above-canopy EC tower forming part of the...
AmeriFlux Core network (http://ameriflux.lbl.gov) and the Niwot SNOTEL station (http://www.wcc.nrcs.usda.gov). The MPB site was instrumented with a new tower and precipitation gauges in 2009 enabling comparable observations of V and meteorology. We instrumented study plots at both sites to observe snow depth, subcanopy solar radiation, soil moisture, and soil water isotopes.

Water isotopes were used for two purposes. First, \( \delta^{18}O \) values in soil and stream water were compared to those in rain, snowfall, and evolved snowpack to identify likely water sources. Second, differential fractionation of \( \delta^{18}O \) and \( \delta^2H \) during vaporization into an unsaturated transition layer causes remaining water to plot along evaporation lines of lower slope than the local meteoric water line (LMWL) [Clark and Fritz, 1997; Gonfiantini, 1986]. Evaporation lines are imparted only by S or E, not by T, and we used evaporation lines to identify abiotic V [Gustafson et al., 2010; Biederman et al., 2014; Jasechko et al., 2013]. In a previous paper, we described use of precipitation samples to establish LMWL and snow surveys to quantify winter S at these sites [Biederman et al., 2014].

Streamflow was gauged in a 15 ha MPB catchment overlapping the prevailing MPB tower footprint (Figure 1). Although a stream of comparable size was used for isotope sampling at the Unimpacted site, the Unimpacted site did not include a gauged catchment. To quantify annual changes in water storage, we evaluated soil moisture at both sites and groundwater at the MPB site at the end of each year.

3.2. Stand Characterization and MBP Canopy Mortality

Forest characteristics were obtained for the Unimpacted tower footprint using the AmeriFlux database (http://ameriflux.lbl.gov) and for the MPB site by three methods: (1) Annual ground-based surveys assessed structural metrics and quantified infected trees; (2) A QuickBird image (Satellite Imaging Corp.) acquired in 2011 quantified green, red, and gray canopy using true-color imagery to train and evaluate a maximum likelihood classifier with green band, Normalized Difference Vegetation Index, and Red-Green Index variables [Coops et al., 2006]; and (3) We used the annual Landsat (www.landsat.usgs.gov) mortality classification of Meddens and Hicke [2014] to quantify the percentage of dead canopy (red + gray). Based on observations that infected trees died within months but retained their needles for ca. 2 years, we estimated the percentage of gray trees as a 2 year lag of the Landsat percentage dead, which agreed well with the 2011 QuickBird image.

3.3. Local Climate

Above-canopy climate observations included temperature (T), vapor pressure deficit (VPD), wind speed (WS), and incident shortwave radiation (Rsw). For the Unimpacted site, we obtained AmeriFlux Level 1 data (quality checked, calibrations applied, and gaps filled; http://ameriflux.lbl.gov), while we filled gaps at the MPB site (~5%) using linear regressions against hourly NLDAS forcing data (http://ldas.gsfc.nasa.gov/nldas). Wind speeds were corrected to the same height above canopy at each site using a logarithmic profile [Shuttleworth, 2012]. Above-canopy potential evapotranspiration (PET) was calculated using the open water formulation of Shuttleworth [2012] based on daily mean VPD, T, WS, and net radiation, assuming negligible advection or changes in energy storage over the time scales of interest (days to months). While there are differences between open water and the top of a forest canopy, our objective was reasonable comparison of evaporative demand at each site.

MPB site precipitation was observed using two Alter-shielded weighing gauges (ETI Systems) and a shielded reference weighing gauge (T-200B, Geonor Inc.), with a wind correction for snowfall [Rasmussen et al., 2012]. Precipitation for the Unimpacted site was from an onsite NOAA Climate Reference Network station (www.ncdc.noaa.gov/crn), gap filled (~5%) with SNOTEL data in winter and a tipping bucket in summer.

In 20 subcanopy plots (12 MPB and 8 Unimpacted), we recorded continuous snow depth and shortwave radiation [Biederman et al., 2014]. Peak snow water equivalent (SWE) for 2010 and 2011 was determined by snow surveys and used to estimate winter S (n = 1500 site \(^{-1}\) yr \(^{-1}\)) [Biederman et al., 2014]. In 2012, snowmelt commenced before surveys could be performed, but winter V was quantified by EC observation.

3.4. Soil Moisture and Groundwater

Volumetric soil moisture was observed beginning after snowmelt 2010 in six profiles per site at depths of 10, 30, and 60 cm (EC-5 and 5-TE, Decagon Corp.). Groundwater level was observed from snowmelt 2010 to July 2012 at the MPB site only in a piezometer 114 cm deep located 35 m east of and 3 m elevation above the main channel, ca. 500 m downstream from the MPB catchment outlet (Figure 1).
3.5. Eddy Covariance Vapor Loss
Unimpacted site water vapor loss (V) was provided as a gap-filled Level 1 product (http://ameriflux.lbl.gov) by P. Blanken and S.P. Burns. MPB site V was measured with an open-path infrared gas analyzer (LI-7500, Li-Cor Inc.) and sonic anemometer (CSAT3, Campbell Scientific Inc.). Ten-Hz data were processed to 30 min V following Lee et al. [2004], and periods of insufficient turbulence were removed [Gu et al., 2005]. Seasonal V were computed by three alternate methods: (1) The mean of all 30 min V observations was scaled over the season; (2) Stability-screened subdaily periods were filled using lookup tables of V and weather observations (VPD and net radiation produced similar results) in 15 day periods, with separate tables for morning and afternoon [Falge et al., 2001], which increased V estimates <2%; and (3) Multiday gaps remaining after method 2 were filled by linear interpolation of the adjacent 3 day means, which increased seasonal V estimates <4%. While time series shown use method 2 for visual clarity, reported MPB site seasonal V use method 1, which was most conservative with respect to our conclusion of higher-than-expected V. We tested for the uncertainty introduced by MPB gaps by imposing them on the Unimpacted data set and filling by method 1, which did not affect seasonal V, further suggesting that sampling uncertainty related to gaps was small [Goulden et al., 1996, 2012; Stoy et al., 2006].

Eddy covariance systems in mountain terrain are thought to suffer from uncertainty due to larger-scale atmospheric motions such as cold-air drainage [Goulden et al., 2012; Turnipseed et al., 2003]. However, such problems are most severe at night and of greater concern for carbon flux (e.g., respiration) than for V, which is predominantly a daytime flux. Research has shown that for daytime fluxes, mountain EC sites may be comparably accurate to flatter sites [Turnipseed et al., 2002, 2003]. Observations and data processing at both sites were performed according to AmeriFlux guidelines, reducing potential site bias. Energy balance closure at each site averaged about 80%, which is typical for tall-canopy EC systems, including those at more ideal sites [Stoy et al., 2013; Wilson et al., 2002], and energy closure was not forced.

At both EC towers, we differenced annual P and V as an estimate of the residual water available for streamflow Q*, assuming annual changes in catchment water storage ΔS were negligible in comparison to P and V [Wilson et al., 2001; Scott, 2010]. Precipitation and peak SWE were assumed spatially uniform across the tower footprints based on their small dimensions (<15 ha), gentle terrain, and low spatial variability quantified by snow surveys performed in 2010 and 2011 [Biederman et al., 2014, Figures 5 and 6; Table 3].

3.6. Stable Isotope Indicators of Evaporation
Local meteoric water lines (LMWL) on plots of δ2H and δ18O, including both winter and summer P, were previously established for these sites [Biederman et al., 2014]. Soil water was collected from the study plots at the same depths as soil moisture observations in four profiles at the MPB site and three profiles at the Unimpacted site. Water was extracted from porous tension lysimeters (Prenart Mini, Prenart Corp.) during and after snowmelt until the soils became too dry to produce samples under 70 kPa tension. Stream samples were collected daily by auto sampler (ISCO 3700, Teledyne ISCO Corp.) during snowmelt and manually every 1–2 weeks during low flows. Isotopic signatures were not altered during up to 7 days storage inside the auto sampler. Stable isotope ratios (δ2H and δ18O) were determined at the University of Arizona using a liquid water isotope analyzer (DLT-100, Los Gatos Research, Inc.) with standard uncertainties of 0.98 and 0.36 ‰ for δ2H and δ18O, respectively. Stream and soil water samples were placed on plots of δ2H and δ18O, and one-way analysis of covariance was used to test whether samples plotted along evaporation lines with slopes significantly lower than the LMWL (Matlab 2012a, Mathworks Corp.).

3.7. MPB Catchment Streamflow
Streamflow was gaged in a first-order 15 ha MPB catchment overlapping the EC tower footprint (Figure 1). The main channel passed through two culverts, the lower of which was gauged with a water level logger (Hobo U20, Onset Corp.) and verified with manual stage observations several times during runoff. This outlet culvert flowed partially full (tranquil flow throughout), and a rating curve was developed using outlet stage (Type 4 culvert flow) [Chow, 1959]. We assessed sensitivity of annual Q to uncertainty in stage, culvert roughness and slope using a Monte Carlo approach with 10,000 iterations randomly sampling the range of reasonable values determined for each input to the discharge calculation. Standard deviations of resulting annual streamflow varied from 5 to 49 mm, but since most uncertainty varied similarly among years, it affected interannual Q comparisons <10%. Catchment delineation was performed in ARC-GIS 10.1 with the TauDEM toolkit (http://hydrology.uwrl.usu.edu/taudem/)
taudem5.0) using a 1 m airborne laser swath map and verified with field observations. We differenced annual P and Q to estimate catchment-scale vapor loss $V^*$ \cite{Brutsaert, 2005}, again assuming negligible change in storage $\Delta S$ at the annual time scale. As a regional reference, streamflow for the 1100 km² Laramie River above Woods Landing, to which the MPB site drains, was obtained from USGS gauge 6659500 (http://waterdata.usgs.gov).

4. Results

4.1. MPB Infestation

The MPB site infestation began in 2007, and by August 2011, overstory infection reached 77% of trees in the EC tower footprint (Figure 2). Trees reached gray phase approximately 2 years after infection and mortality, and gray-phase estimates for 2010–2012 were 16%, 37%, and 50% of trees in the footprint. Understory appeared to respond rapidly to the release of resources, with cover reaching 28%–37% by summer 2011 in gray-phase stands as compared to 3% in uninfected stands at the MPB site \cite{U. Norton et al., 2014, Nitrous oxide and methane fluxes following beetle infestation in lodgepole pine forests, submitted to Soil Science Society of America Journal}.

4.2. Local Climate

In the 3 years of this study (2010–2012), precipitation at the Unimpacted site was 100%, 128%, and 90% of average (Niwot SNOTEL 1981–2012), while the Cinnabar Park SNOTEL 20 km distant from the MPB site indicated precipitation for 2010–2012 was 121%, 127%, and 74% of the 2004–2012 average. Winter precipitation was similar at the two sites, differing by only 5%–9% (Table 2). The Unimpacted site experienced more summer precipitation, with the largest difference in summer 2012 (125 mm at MPB and 428 mm at Unimpacted).

Patterns of snow accumulation and ablation were similar at the two sites (Figure 3). Peak SWE ranged from 212 to 287 mm and differed between the two sites in any year by 3%–24% (Table 2). Spring snowmelt commenced at the same time at each site and ended about 1 week earlier at the MPB site (Figure 3).

Above-canopy T, VPD, WS, and $R_{sw}$ showed similar seasonal means (Table 2) and temporal patterns (Figure 3). Mean T ranged from $-4.0$ to $-5.3^\circ$C in winter and $7.5$–$10.5^\circ$C in summer. Mean VPD averaged 0.13–0.27 kPa in winter and 0.58–0.90 kPa in summer. Mean daily WS ranged from 2.9 to 6.1 m s$^{-1}$ and was greater at the Unimpacted site by 0.3–1.6 m s$^{-1}$. While above-canopy $R_{sw}$ was similar at the two sites, subcanopy $R_{sw}$ under MPB forest was greater by three times or more, averaging 61–70 W m$^{-2}$ in summers 2010 and 2011 as compared to 20–21 W m$^{-2}$ under Unimpacted forest (Table 2).

4.3. Soil Moisture and Groundwater

Mean volumetric soil moisture reached similar maximum values of 36%–39% during snowmelt each year at both sites (Table S1). Trench observations showed saturation, so peak moistures likely indicate porosity. Snowmelt was the dominant input to soil moisture, though a few small increases were observed following summer rainfall. Mean soil moisture usually declined to annually consistent minima at the end of each summer, ca. 25% for MPB and 14% for Unimpacted, indicating no net change in soil moisture storage over time for each site. However, at the end of the dry summer 2012, MPB soil moisture reached a lower mean of 18%, indicating a decline in annual storage.
The onset of snowmelt runoff at the MPB site occurred 9 April, 25 March, and 9 March in the years 2010–2012, respectively (Figure 4). Groundwater responded to snowmelt, with the water table reaching the ground surface (data not shown). Summer groundwater recession did not show observable responses to rain, consistent with minimal response in soil moisture. End-of-year groundwater elevation increased 9 cm in 2011 as compared to 2010. By the time the sensor malfunctioned in July 2012, the elevation had already declined to the ending level from 2011. Given the very dry summer, it is possible that groundwater level declined further by the end of 2012.

4.4. Eddy Covariance Vapor Loss

Vapor loss time series showed similar patterns at each site both seasonally and daily, corresponding to similar PET dynamics (Figure 5). In the wet year 2011, MPB tower V averaged 166% of Unimpacted V during snowmelt, and V remained greater at the MPB site throughout most of the relatively wet summer (Figures 5 and 6). During snowmelt 2012, MPB tower V averaged 204% of Unimpacted V, but a much drier summer at the MPB site appeared to curtail V (Figures 5 and 6). During winter 2012, the sole winter of continuous operation, MPB tower V was similar to Unimpacted V, consistent with snow surveys in 2010 and 2011 showing similar winter S at each site [Biederman et al., 2014]. PET remained similar at the two sites, so higher MPB site V during wet seasons meant that vapor loss rates more closely approached PET (Figure 5 inset).

Annual Unimpacted V was 573, 612, and 623 mm in 2010–2012, an annual variability of only 8%, so the main influence of annual P variability on partitioning was reflected in the estimated residual available for streamflow, Q^*. Annual V was more variable at the MPB site. In 2010, when only an estimated 16% of MPB tower footprint trees had lost their needles and progressed to gray phase (Figure 2), annual V was 570 mm, very similar to the Unimpacted site. In the wet year 2011, when MPB canopy reached 37% gray phase, annual V was 700 mm, or 23% greater than 2010, reducing Q^* by 53%. In the dry year 2012, essentially all available water was partitioned to V, with annual V > P leaving no water for estimated residual streamflow Q^*.

4.5. Stable Isotope Indicators of Evaporation

At both sites, $\delta^{18}O$ ratios in stream and soil water were closer to evolved snowpack than summer P, suggesting snowpack as the primary water source (Table 3), and summer precipitation did not produce a response in stream water isotopes. Beginning with the signature of evolved snowpack, MPB soil water and stream samples plotted along $\delta^{2}H$ versus $\delta^{18}O$ evaporation lines with slopes below the LMWL ($p < 0.05$), signifying kinetic, abiotic evaporation, while the Unimpacted site did not indicate kinetic evaporation (Figure 7). MPB evaporation lines were not different ($p > 0.05$) between soil and stream water, so these were combined into annual lines. Some equilibrium evaporation (saturated transition layer) likely occurred at the Unimpacted site, but the net evaporation rate would be reduced by simultaneous condensation [Clark and Fritz, 1997].
4.6. MPB Catchment Streamflow

We do not have mortality data for the Laramie River (1100 km²), but given the heterogeneity of insect infestation across large catchments, we expect that the relative rate of disturbance was low compared to our MPB site. Consistent with variability in regional precipitation, the Laramie River produced 200, 280, and 50 mm of Q in 2010–2012, corresponding to greater P in 2011 and a very dry 2012 across the region (http://www.wcc.nrcs.usda.gov). In marked contrast, MPB catchment Q declined from 232 mm in 2010 to only 75 mm in 2011, mirroring greater observed V (Table 3). Only 5 mm of MPB catchment Q was measured in the dry year 2012, indicating that nearly all P was partitioned to V.

5. Discussion

Following severe insect-driven forest disturbance in the central Rocky Mountains, tower vapor loss (V) was higher and streamflow (Q) was lower than expected. Kinetic fractionation of stream and soil water isotopes suggested that higher evaporation (E) and snowpack sublimation (Ss) counteracted likely reduction in transpiration (T) and canopy sublimation (Sc). Results from these multiple lines of observation contrast with prior studies based only on streamflow [Potts, 1984; Bethlahmy, 1974], model simulations [Bewley et al., 2010; Mikkelson et al., 2013b; Pomeroy et al., 2012], or remote sensing [Bright et al., 2013; Maness et al., 2013], which suggest reduced V and increased Q. Given that the observed response contradicts expectations, we first discuss each line of evidence and associated uncertainties. Next, we draw inferences regarding mechanisms and drivers of V. Finally, we discuss how observed V exceeding expectations impacts our understanding of hydrologic response to disturbance. While absolute accuracy of V could affect water budget...
comparisons, the inferences of this study are based on how the temporal progression at the MPB site differs from the expected behavior observed at the Unimpacted site. Errors in $V$ are known to depend on the magnitudes of $V$ and radiative forcing, with secondary dependence on vegetation type and wind speed [Richardson et al., 2006]. These factors are alike among site-years (Figure 2), likely increasing error similarity and improving our confidence in site-year comparisons. Since energy closure was similar (ca. 80%) for all site-years, not forcing closure would not impact such comparisons.

Sources of uncertainty in MPB catchment $Q$ include stage measurement and the stage-discharge relationship. Monte Carlo simulation showed comparison among years was robust to these uncertainties. Most importantly, the amount that $Q$ was lower in 2011 than 2010 was relatively insensitive, varying between 62 and 74%.

While the study conclusions rely primarily on direct observations of $V$ and $Q$, the comparison of catchment and tower water budgets provides somewhat rare and useful cross validation [Wilson et al., 2001; Goulden et al., 2012; Scott, 2010]. Though negligible annual $\Delta S$ is commonly assumed for water budget analyses [e.g., Wilson et al., 2001; Hubbart et al., 2007; Scott, 2010], this study offers relevant observations. First, MPB streamflow reached similar low summer values ($<0.2\text{ mm d}^{-1}$) each year (Figure 4), and isotopes reflected only the signature of snowmelt progressively enriched by kinetic fractionation, providing no evidence of a shift in sources (Figure 7). Second, soil moisture reached similar low values at the end of most years (Table S1), indicating no $\Delta S$ in soil. The exception was the MPB site in the dry year 2012, when an end-of-year reduction of 7% would suggest $\Delta S$ ca. 70 mm in the top meter of soil, consistent with observations of Yaseef et al. [2010] during the driest years at an arid site. Third, the

**Figure 5.** (a) Vapor loss ($V$) and (b) potential evapotranspiration (PET), and otherwise as in Figure 3. Inset plots show the summer 15 day mean ratio $V$/PET. In the wet year 2011, when 36% of MPB trees had lost their needles, $V$ was greater at the MPB site throughout snowmelt and the rest of summer. In 2012, when 50% of trees had lost their needles, MPB site $V$ was greater during snowmelt but less during the rest of summer, which was much drier at the MPB site. The 2012 winter vapor losses were similar for the two sites, consistent with snow surveys showing equal amounts of winter $V$ in 2010 and 2011.

Above-canopy PET was similar at the two sites, and periods of higher $V$ at the MPB site corresponded to $V$/PET closer to one than at the Unimpacted site.

**Figure 6.** Cumulative annual precipitation ($P$) and vapor loss ($V$), and otherwise as in Figure 3. When precipitation was similar at each site in 2010, annual $V$ was similar. In the wettest year, 2011, MPB tower $V$ (slope of cumulative $V$) which was larger than Unimpacted $V$ during snowmelt and throughout the summer, led to 18% greater annual $V$. In 2012, larger $V$ at the MPB site during snowmelt was counteracted by lower $V$ during late summer, which was much drier for the MPB site, resulting in a similar annual $V$ to 2010. For visual clarity, gaps in the $V$ record were filled with the mean flux of the given season described as method 1 in the Methods text.
Table 3. Water Budget Fluxes at the Two Eddy Covariance Towers and the MPB Catchment

<table>
<thead>
<tr>
<th>Year</th>
<th>P Year</th>
<th>W</th>
<th>S</th>
<th>Year</th>
<th>Residual Streamflow Q*</th>
<th>Streamflow Q</th>
<th>Residual Vapor Loss V*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unimpacted</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2010</td>
<td>801</td>
<td>190</td>
<td>383</td>
<td>573</td>
<td>228</td>
<td>No catchment observations</td>
<td></td>
</tr>
<tr>
<td>2011</td>
<td>1025</td>
<td>189</td>
<td>423</td>
<td>612</td>
<td>413</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2012</td>
<td>722</td>
<td>194</td>
<td>429</td>
<td>623</td>
<td>99</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MPB</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2010</td>
<td>751</td>
<td>154</td>
<td>416</td>
<td>570</td>
<td>182</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2011</td>
<td>786</td>
<td>160</td>
<td>540</td>
<td>700</td>
<td>86</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2012</td>
<td>488</td>
<td>207</td>
<td>384</td>
<td>591</td>
<td>0*</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Annual eddy covariance vapor loss V varied by only 8% at the Unimpacted tower as compared to 23% at the MPB tower. MPB vapor loss was 130 mm greater in 2011 than 2010, while MPB catchment streamflow (Q) was 157 mm less despite more precipitation (P). In the dry year 2012, both tower and catchment water balances showed essentially all available water was partitioned to V. MPB tower and catchment water balances showed good agreement in temporal patterns, although V−V* varied from +51 to −148 mm.

V−P in 2012, consistent with very low catchment Q and an annual decline in soil moisture.

small changes in end-of-year groundwater level indicated minimal ∆S. Taking the difference of the maximum and minimum spatially averaged soil moistures during the study as an estimate of drainable porosity, the 9 cm water table increase in 2011 corresponds to ∆S of only 15 mm. Finally, the residual between MPB catchment Q and tower-estimated Q* ranged from 5 to 50 mm (1%–7% of P), comparable to Wilson et al. [2001]. We interpret these collective observations to support the assumption of negligible ∆S in all site-years except MPB in the dry year 2012, when observations suggest ca. 70 mm release from soil water storage.

MPB V exceeded P by 143 mm in the dry year 2012 (Table 3), as reported during dry years at other arid and semiarid sites [e.g., Dore et al., 2010; Yaseef et al., 2010]. V−P is consistent with estimated ∆S of −70 mm but could additionally indicate water advection into the footprint or observational uncertainty. Release from soil water storage could contribute to V by T of deeply rooted surviving trees and understory and by E and T of water reaching the surface in convergent areas of the tower footprint (i.e., near the stream). Since subsurface flow paths do not necessarily conform to terrain-based catchment delineation, we cannot exclude subsurface flow into the tower footprint [Mackay et al., 2002; Thompson et al., 2011], although we observed no corresponding increase in streamflow. While there is uncertainty in eddy covariance V as described above, errors such as lack of energy closure and failure to capture fluxes from large-scale atmospheric motions would tend to result in underestimates [Stoy et al., 2006, 2013]. Although snow surveys indicated relatively uniform SWE over large scales in 2010 and 2011 [Biederman et al., 2014], effective P could have been underestimated in 2012, when a snow survey was not performed, impacting the water budget [Flerchinger and Cooley, 2000]. Uncertainties in observations and assumptions highlight the value of concurrent streamflow and eddy covariance observations, but they do not alter the surprising result that whatever water was available in 2012, nearly all of it was vaporized.

Stand-scale evaluations of forest disturbance often focus on reduced canopy sublimation (S_c) of intercepted snow [Troendle, 1983; Pugh and Small, 2012]. However, process-based research has shown that intermediate forest density can minimize total winter S and enhance soil moisture through an optimal balance of interception and shading [Veatch et al., 2009; Gustafson et al., 2010; Gray et al., 2002]. Accordingly, severe canopy loss can drive increases in snowpack sublimation (S_s), canceling or outweighing reduced S_c [Biederman et al., 2014; Harpold et al., 2014]. In a study at the MPB site, although S_c diminished to zero in gray-phase stands, snow surveys showed total S was 36%–38% of winter snowfall, illustrating counteracting changes in S_c and S_s [Biederman et al., 2014, Figures 3 and 6]. Kinetic fractionation of MPB snowpack confirmed at least 50%–66% of the total S was S_s [Biederman et al., 2014, Figure 4]. In the present study, greater MPB site V as compared to Unimpacted during snowmelt 2011 and 2012 (Figure 5) suggests that E or S_s was large, as demonstrated by Schelker et al. [2013].

Vapor loss was not partitioned into T and E in this study, but available evidence suggests T declined and E increased, maintaining or possibly increasing total V (Table 3). While understory growth and increased T rates in surviving vegetation may be stimulated by increased availability of water, light and nutrients [Kozlowski, 2002; McMillin, 2003; Van Pelt, 1999; Hubbard et al., 2013; Romme et al., 1986], it is very likely that in
this study, stand-scale T declined. Observations following severe MPB mortality of lodgepole pine in Alberta, Canada showed increased T of 21%–40% per unit of surviving leaf area, but stand-scale T fell by 47% [Piňa, 2013]. With 77% mortality in the present study, even a 50% T rate increase by surviving vegetation would result in 66% reduction of stand-scale T. Accordingly, stable isotope fractionation of soil water, which does not occur during T, indicated greater kinetic E at the MPB site (Figure 7).

In light of the existing expectations for more streamflow, our observations of higher V (Figure 5), due in part to greater E (Figure 7), are initially surprising. After 2010, MPB site V was a greater fraction of PET during wet periods, specifically snowmelt 2011 and 2012 and summer 2011. Since above-canopy PET was quite similar between sites (Figure 5), increased Ss and E from the wet surface were likely enhanced by canopy opening. Despite similar above-canopy $R_{sw}$ at the two sites, the MPB site received more than 300% greater subcanopy $R_{sw}$ (Table 2). Increases in remotely sensed winter albedo following MPB infestation suggest reduced shortwave shading may drive increased Ss and E from the surface for years to a decade or more postdisturbance [Bright et al., 2013; Vanderhoof et al., 2013; O’Halloran et al., 2012]. While trees are efficient

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**Figure 7.** Stable water isotopes in soil water and streams and the local meteoric water line (LMWL) for the (a) Unimpacted and (b) MPB sites. Stream and soil water were not distinguishable from the LMWL at the Unimpacted site ($p > 0.05$). At the MPB site, evaporation line slopes less than the LMWL ($p < 0.05$) demonstrated kinetic fractionation as a result of abiotic evaporation.

**Figure 8.** Annual observations of hydrologic partitioning to vapor loss V and streamflow Q expressed as a percentage of precipitation P (i.e., $V/P = \text{vapor loss coefficient} \quad \text{and} \quad Q/P = \text{runoff coefficient}$). Partitioning was less variable at the Unimpacted site and followed the pattern of interannual climate, with lower vapor loss coefficient in wetter years (Table 3). The MPB site showed greater partitioning to V and less to Q in 2011 as compared to 2010 in spite of larger P. In 2012, which was very dry at the MPB site, tower V exceeded P, in part due to a release of stored water, and very little Q was observed.
evaporators and are known to transpire during snowmelt [Moore et al., 2008], cold soil temperatures may suppress T [Simonova et al., 2000; Mellander et al., 2004], possibly contributing to lower V:PET at the Unimpacted site during snowmelt (Figure 5 inset). We hypothesize that during warm dry periods, soil E would be limited by transport of water to the soil surface at the MPB site, while Unimpacted site T would more effectively vaporize deeper water sources. Unfortunately, large site differences in P during summer 2012 obscured evaluation of this hypothesis, and further research is required to clarify controls on the seasonal dynamics of E and T following disturbance.

At the Unimpacted site, partitioning followed annual climate (Figure 8), with V:P greatest in the driest, warmest year (2012) and lowest in the coolest, wettest year (2011). Such expected response to annual climate was not observed at the MPB site, where V:P was greater and Q:P was lower in the wet year 2011 as compared to 2010 (Figure 8). These results contrast with prevailing expectations and modeled hydrologic responses to MPB [Pugh and Gordon, 2013; Bewley et al., 2010; Bright et al., 2013; Maness et al., 2013], but prior observations have shown Q response may indeed be small following forest disturbance in semiarid mountains [Bosch and Hewlett, 1982; Brooks et al., 2012; Somor, 2010], including even zero Q response with 100% forest removal [Stednick, 1996].

This study clarifies that following severe forest disturbance (1) vapor loss may be conserved or possibly increase, particularly during periods when water is abundant at the land surface, and (2) increased abiotic E counteracts some portion of reduced vapor loss by S, and T. These results agree with the hydrologic response suggested by Edburg et al. [2012] but demonstrate that increases in vapor loss terms (S, E, and T by survivors) may collectively be as large as or larger than reductions in S, and overstory T due to canopy loss, constraining expected streamflow response.

Our results highlight several priorities for future research. First, it is necessary to determine the applicability of results across the range of latitude and climate within the MPB epidemic from Canada [e.g., Brown et al., 2013] to Arizona [e.g., Morehouse et al., 2008] and to other disturbance types [Frank et al., 2014; Hicke et al., 2012]. MPB site V appeared to depend on availability of water at the surface, so V could be less following tree removal at sites with less snow cover or more well-drained soils. Second, complex topography has been shown to influence hydrologic partitioning [Scott, 2010; Flerchinger and Cooley, 2000; Flerchinger et al., 2010], yet it is unclear how forest disturbance impacts vary with topography. We hypothesize that forest hillslopes with greater exposure to incident solar radiation may produce greater abiotic V following disturbance, as suggested by Rinehart et al. [2008]. Third, our observations of counteracting V increases contrast with land surface models [Bewley et al., 2010; Mikkelson et al., 2013b; Pomeroy et al., 2012] and remote-sensing products [Bright et al., 2013; Maness et al., 2013], demonstrating a need to improve representation of V. Fourth, resource managers remain uncertain about how interactions among climate change, forest disturbance, and forest management will affect water for forests [Grant et al., 2013] and downstream water resources [Clow, 2010; Harpold et al., 2012]. Our observations of increased subcanopy solar radiation and greater V during periods of wet land surface suggest forest disturbance may increase the sensitivity of hydrologic partitioning to climate, but further work is needed to quantify the controls on S, E, and T, their contributions to total V, and how seasonal timing of these fluxes may change [Bearup et al., 2014]. Finally, it is possible that increased abiotic evaporation may limit water availability in disturbed forests, with feedbacks to progression of mortality and forest succession [Kaiser et al., 2012; Grant et al., 2013].

6. Conclusions

Numerous forest disturbance studies [see Brown et al., 2005] suggest that streamflow increase will be large initially and return to baseline with regrowth over 10–15 years. Surprisingly, we are unaware of any observations demonstrating increased streamflow during the present MPB epidemic (post-1994). While ongoing mortality may continue to alter hydrologic partitioning, conterminous eddy covariance and streamflow observations provided evidence that total vapor loss could be conserved or even increase, constraining expected streamflow increases, while stable isotope fractionation confirmed increased abiotic evaporation. The present results help clarify the lack of streamflow response observed at the larger scales relevant to water resources.
Acknowledgments

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References

Clark, I., and P. Fritz (1997), Environmental isotopes in Hydrogeology, Lewis Publ, Boca Raton, Fla.
Gonfiantini, R. (1986), Environmental isotopes in lake studies, in Handbook of Environmental Isotope Geochemistry: The terrestrial Environ-


