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The relationship between tree mortality from a pine beetle epidemic and increased dissolved copper levels in the upper Big Thompson River, Colorado

**Andrew H. Fayram · William B. Monahan ·
Frank J. Krist Jr · Frank J. Sapio**

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Abstract Bark beetle outbreaks in the Rocky Mountains caused substantial tree mortality starting in the late 1990s, and continued into the 2000s, with the most severe mortality occurring from 2002 to 2012. Over the same time period, concentrations of dissolved copper in the Big Thompson River (BTR), Colorado, USA, increased significantly and are high enough to negatively affect aquatic life. We examined correlations between dissolved copper and tree mortality in the BTR. Two sites, one consisting of water from the western side of the continental divide and one consisting of water from the eastern side, demonstrated a positive relationship between percentage tree mortality and dissolved copper. The relationships were similar except that the best relationship occurred with a 3-year lag between tree mortality and subsequent dissolved copper levels at the eastern site and with a 5-year lag at the western site. The differential time lag is potentially the result of different levels of carbon in the soil in the watersheds associated with each site because carbon can affect copper mobility. Our results suggest that bark beetle-induced tree mortality may contribute significantly to dissolved copper levels in the BTR.

Keywords Bark beetle · Water quality · Dissolved copper · Tree mortality

Introduction

Millions of acres of trees in the Rocky Mountains have suffered mortality from bark beetle outbreaks (Bentz et al. 2009). These tree mortality events have changed the behavior of ecosystem processes such as fire (Jenkins et al. 2008) and geochemical cycling (Edburg et al. 2012). Although forest recovery may occur without the need for active management (Diskin et al. 2011), indirect effects to water quality may be great enough to require active management while the forests recover. Among other effects, large scale tree die-offs within watersheds have resulted in changes in water quality. Negative effects of tree mortality on water quality include increased total organic carbon levels (Mikkelson et al. 2013; Brouillard et al. 2016), nutrient levels (Huber et al. 2004), and mobility of metals (Mikkelson et al. 2014). Total organic carbon levels are of concern in water bodies that are utilized as drinking water sources because increased carbon levels require additional disinfection by water treatment plants. This additional disinfection increases the amount of "disinfection byproducts" in drinking water and includes carcinogens that must be carefully monitored (Nikolaou and Lekkas 2001). Increased nutrient levels can lead to increases in nuisance plant growth and harmful algal blooms (Hallegraeff 1993). Increased metal mobility associated with large scale tree die offs could increase dissolved

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A. H. Fayram (✉)
Big Thompson Watershed Forum, 800 South Taft Avenue,
Loveland, CO 80537, USA
e-mail: afayram@btwatershed.org

W. B. Monahan · F. J. Krist Jr · F. J. Sapio
USDA Forest Service, Forest Health Assessment and Applied
Sciences Team, 2150 Centre Ave., Bldg. A., Suite 331, Fort
Collins, CO 80526-1891, USA

metals enough to potentially affect drinking water and aquatic life. Although the mobility of metals associated with tree die-offs has been demonstrated in the laboratory and directly under recently killed trees, the magnitude of the effects on waterbodies in affected watersheds and the timing of any effects is unclear (Mikkelson et al. 2014).

One of the metals potentially affected by tree die-offs is dissolved copper. The amount of dissolved copper present in a waterbody is of interest primarily due to its potential effects on aquatic life. While copper is an essential nutrient at low concentrations, it can be toxic at higher levels. Acute effects include mortality, and chronic effects can lead to reduced survival, growth, and reproduction of aquatic organisms (e.g., McKim and Benoit 1971; Winner and Farrell 1976).

Bark beetles, primarily the mountain pine beetle (*Dendroctonus ponderosae*), have had a substantial impact on the forests within the watershed of the Big Thompson River (BTR; Colorado, USA). Water quality of the BTR is of central importance to local, regional, and national interests. The headwaters of the BTR begin in Rocky Mountain National Park, which had over 4.5 million visits in 2016. Numerous communities and agricultural interests rely on water from the BTR. The BTR is an integral part of the Colorado-Big Thompson Project that provides drinking water to approximately 900,000 people and irrigation for 650,000 acres of farmland. Demands on available water will continue to increase with populations served by the Colorado-Big Thompson Project expected to increase by over 100% by 2050 (Colorado State Demographers Office 2018).

A number of segments of the BTR are listed as impaired based on dissolved copper levels by the Clean Water Act Section 303(d) since 2008. These impairments are based on water quality standards established by the Clean Water Act and adopted by the Colorado Water Quality Control Commission. The impairments are contained in Colorado's 2016 303(d) List (Regulation 93) (WQCC 2016a, b).

Concentrations of dissolved copper are generally relatively low in the impaired sections of the BTR. However, the concentration of dissolved copper that results in an impairment designation is based on the associated hardness of the water (WQCC 2016a). Relatively low hardness levels cause dissolved copper to become more bioavailable, and therefore more toxic, than in water with higher hardness (e.g., Howarth and Sprague 1978; Long et al. 2004).

Interestingly, half of the segments of the BTR that are considered impaired based on copper are in the upper portion of the river near or inside Rocky Mountain National Park. Clearly, stressors such as grazing, agricultural runoff, mining, and development, which can contribute to reduced water quality, are absent or extremely limited in this portion of the river. Other mechanisms for copper increases such as atmospheric deposition are possible. Significant increases in atmospheric deposition of copper generally occur due to identifiable pollution sources in the vicinity of the study area (Steinnes et al. 1994). However, we are unaware of any new sources of potential copper emissions. In addition, global emissions of copper, which would thereby potentially increase due to atmospheric deposition, have generally shown a downward trend in North America (Pacyna and Pacyna 2001).

Segments of the upper portion of the BTR that are designated as having a copper impairment appear to be experiencing further increases in dissolved copper without an obvious cause (Billica 2017). Coincidentally, increased tree mortality associated with a mountain pine beetle epidemic, which has been exacerbated by climate change (Raffa et al. 2008, Williams et al. 2010), has occurred in the BTR watershed over the past two decades (Mikkelson et al. 2013), and has been linked to other water quality issues (Brouillard et al. 2016). Specifically, Mikkelson et al. (2014) demonstrated that increased copper mobility associated with total dissolved organic carbon levels increased as a result of bark beetle-induced tree mortality. Mikkelson et al. (2014) state "while unclear if manifested in adjacent surface waters, these results demonstrate an increased potential for Zn, Cu, and Al mobility, along with increased deposition of metals and carbon beneath beetle-impacted trees." Thus, increasing copper levels in the upper watershed of the Big Thompson River may be due in part to pine beetle-induced tree mortality.

Our objective in this study is to determine the extent to which tree mortality caused by pine beetles is associated with increases in dissolved copper levels in the upper BTR Watershed, and to identify any time lag between tree mortality and copper inputs into surface water of the BTR. To achieve our objective, we developed a tree mortality index in the upper BTR watershed and related these data to associated dissolved copper data. Our results may be of utility to the water management of the BTR and may generally apply to similar watersheds in the Rocky Mountains.

Methods

Study area

The study location is in the Rocky Mountains of the USA in Colorado, primarily within the boundaries of Rocky Mountain National Park. The BTR mainstem receives water from two primary sources, which include (1) the BTR Watershed and (2) the headwaters of the Colorado River to the west of the continental divide. Water is diverted from headwaters of the Colorado River to the west of the continental divide into the BTR as part of the Colorado-Big Thompson Project. We examined one headwater site that received water only from the BTR headwaters on the eastern side of the continental divide and one canal site that received water only from the headwaters of the Colorado River (Fig. 1).

The canal site is located in Rocky Mountain National Park close to the outlet of the Alva B. Adams Tunnel. This tunnel transfers water underneath the Continental Divide in the Rocky Mountains from Grand Lake and Lake Granby in the headwaters of the Colorado River to the BTR as part of the Colorado-Big Thompson Project. Since the water at the canal site and at the headwater site come from two entirely different watersheds, both with extensive pine beetle related tree mortality, we considered the relationship between copper and tree mortality at each site to be ostensibly independent from each other.

We evaluated the tree mortality and dissolved copper relationship separately for each site. The watershed area associated with the canal site comprised all surveyed sub-watersheds (12-digit, or 6th level, hydrologic unit code [HUC], referred to hereafter as HUC12 sub-

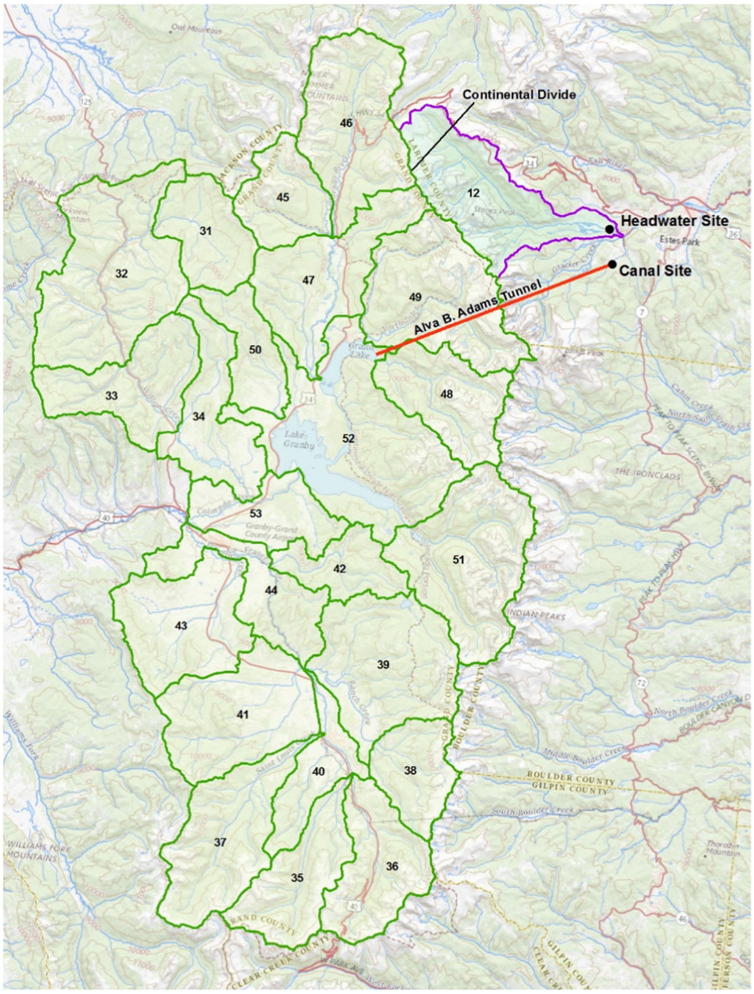


Fig. 1 Subwatersheds in the Big Thompson River watershed and headwaters of the Colorado River that contribute to the Colorado-Big Thompson Project and sampling locations. Subwatershed 12 is associated with the headwaters site and subwatersheds 31-53 are associated with the canal site. Base Map Source: USGS Topo map service that combines the most current data (Boundaries, Geographic Names, Transportation, Elevation, Hydrography, Land Cover, and other themes)

watershed) west of the continental divide and above 2386 m in elevation (Fig. 1). The elevation of Windy Gap Reservoir is 2386 m and is the lowest point at which water is collected and fed into the Adams Tunnel for distribution through the Colorado-Big Thompson Project. The watershed area associated with the headwater site comprised of the surveyed HUC12 sub-watershed east of the continental divide and upstream of the headwater site (Fig. 1).

Water quality data

Data were collected from two sites in the BTR by United States Geological Survey (USGS) staff between 2001 and 2016 at the canal site and between 2008 and 2016 at the headwater site. Dissolved copper concentrations were quantified by USGS using methodology outlined by Faires (1993), EPA (1994) or Garbarino et al. (2006), depending on the year. Samples with dissolved copper levels below the detection limit for the analysis method were treated as half of the reported detection limit. Detection limits ranged from 0.4 to 2.0 μg/L and generally decreased over time as methodology improved.

Tree mortality data

Data on tree mortality were obtained from the National Insect and Disease Survey (IDS, Forest Health Protection 2017). Within the study area, IDS provides complete survey coverage of all treed areas from 1997 to the present. IDS data were collected by means of aerial sketch mapping—a technique in which trained aerial observers manually delineate and attribute the causes of mortality (occurring over the past year) on high resolution imagery at 1:100,000 to 250,000 scale (McConnell et al. 2000). IDS data are commonly used in similar studies quantifying tree mortality and ecological impacts at landscape scales (e.g., Hicke et al. 2016).

For each year and HUC12 sub-watershed, we calculated the total acres with tree mortality. We calculated the annual percentage of tree mortality by summing the acres with newly dead trees in each sub-watershed by year, divided by the sum of treed area (Ellenwood et al. 2015). The headwaters site received runoff from only one sub-watershed (HUC ID 12, Fig. 1). The tree mortality data associated with the canal site sub-watersheds included all of those to the west of the continental divide and above Windy Gap Reservoir (elevation 2386 m) (HUC IDs 31-53, Fig. 1).

Statistical analysis

If dissolved copper levels in the BTR are associated with tree mortality, it is possible that there is a time lag between the time of tree death and the presence of dissolved copper in the river since copper released from the tree must travel through the soil prior to entering the water. Mobility of metals through soil depends on numerous factors such as pH and the amount of dissolved organic matter (Zhou and Wong 2001). We used a cross correlation function (ccf) (R Core Team 2016) for dissolved copper and percentage tree mortality for the canal site to determine what lags should be included in our generalized linear model (GLM). The cross-correlation function of tree mortality estimates and dissolved copper levels at the canal site suggested that a lag of up to 5 years between tree mortality estimates and subsequent dissolved copper estimates may occur ($r = 0.664$). We used the cross-correlation function from the canal site for variable selection because a longer time series of data was available for this site (2001–2016) compared to the headwater site (2008–2016). As such, we included lags of 0 to 5 years as possible predictive variables for regression models for both sites.

The use of both backward and forward variable selection methods in regression model construction has been questioned (Rencher and Pun 1980; Graham 2003). We used the function “bestglm” in the R programming environment (R Core Team 2016) for variable selection. “Bestglm” tests all combinations of selected predictor variables and identifies the best model based on the chosen information criterion, Bayesian Information Criterion (BIC) in our case. Briefly, BIC is a model selection criterion used to select the “best” model from a defined set of models and is related to the Akaike Information Criterion (AIC). Both BIC and AIC seek to balance variable inclusion with parsimony by incorporating a penalty term for the number of parameters in the model. The BIC is the more conservative of the two criteria (i.e., less likely to include additional parameters). The model with the lowest BIC is considered to be the best model.

To further ensure the simplest and most conservative model, variables that improved the BIC but were not significant ($\alpha = 0.05$) were excluded from the final models. In addition, in the event that selected predictor variables were correlated ($p < 0.05$), the variable with the lowest p value in the glm model was retained. If significant models were available for both sites, we determined similarity of slopes and intercepts with an analysis of covariance approach. An $\alpha = 0.05$ was used to determine significance in all statistical tests.

Results

The ranges of dissolved copper concentrations and percentage tree mortality were fairly similar in the sub-watersheds associated with each site. The ranges of annual mean dissolved copper concentrations were 1.21–2.83 μg/L for the headwater site and 0.73–2.28 μg/L for the canal site. However, the overall mean dissolved copper level was slightly lower in the canal site (mean = 1.44 μg/L) than in the headwater site (mean = 1.92 μg/L). In addition, the chronic copper standard based on hardness was generally higher at the canal site than at the headwater site primarily because the average hardness at the canal site (18.9 mg/L $CaCO_3$) was approximately twice as high as at the headwater site (8.9 mg/L $CaCO_3$) (Figs. 2 and 3). Lower hardness results in increased copper toxicity to aquatic organisms (e.g., Howarth and Sprague 1978, Long et al. 2004). The ranges of percentage tree mortality, for which there were associated dissolved copper measurements at the identified lag (below), were 3.6–35.9% for the headwater site and 2.4–29.70% for the canal site.

An initial analysis of dissolved copper over lags ranging up to 5 years resulted in the inclusion of a lag of 0 years and a lag of 3 years for the headwater site (BIC = − 13.00) and lags of 1, 4, and 5 years for the canal site (BIC = − 27.31). However, when we constructed a GLM for the headwater site, the lag of 0 was not significant ($t = -1.331$, $p = 0.23$) while the lag of 3 was ($t = 2.484$, $p = 0.048$). Therefore, the lag of zero was removed from the model. The model including only the lag of 3 years demonstrated a significant relationship between percentage of tree mortality and dissolved copper (Dissolved copper = 1.1727 + 4.1749 × Lag of 3 years percent tree mortality, $t = 2.412$, $p = 0.047$, $R^2 = 0.45$) (Fig. 4). All variables in the GLM for the canal site (lags of 1, 4, and 5 years) were significant; however there was also significant correlation between a lag of 5 years and a lag of 4 years ($r = 0.76$, $p = 0.006$). The lag of 5 years had a much lower p value in the model ($p = 0.001$) than the lag of 4 years ($p = 0.01$) so the 4-year lag was removed from the model. When we ran the GLM again with lags of 1 and 5 years, the lag of 1 year was not significant ($t = 1.027$, $p = 0.335$) and was removed from the model. The resulting model including only a lag of 5 years demonstrated a significant relationship between percentage tree mortality and dissolved copper (Dissolved copper = 0.8606 + 3.6555 × Lag of 5 years percent tree mortality, $t = 2.938$, $p = 0.017$, $R^2 = 0.4896$) (Fig. 5).

The relationships between dissolved copper and percentage tree mortality at each of the two sites were similar to each other, except for a difference in the number of years between tree mortality and the resulting dissolved copper levels in the river system (Figs. 4 and 5). The analysis of covariance indicated that the interaction between the site location and percentage mortality was not significant, indicating that the slopes in the relationships were the same (interaction $t = -0.25$, $p = 0.806$). Similarly, when the interaction term was removed, the site variable was not significant, indicating that the intercepts in the two relationships were the

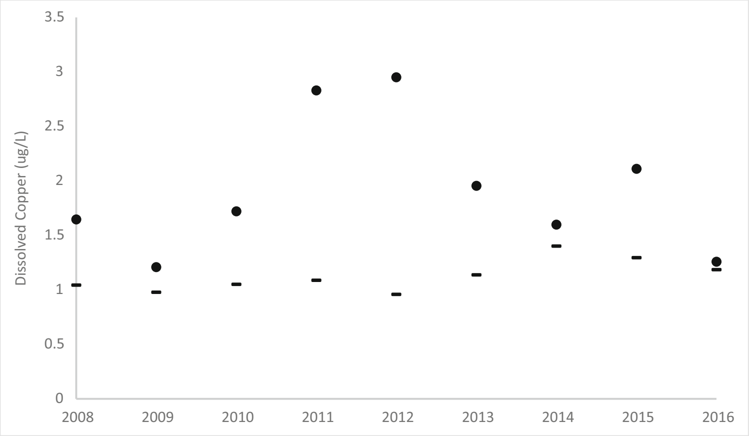


Fig. 2 Average annual dissolved copper concentrations (black circles) and chronic standard based on average hardness levels (black dashes) at the headwater site in the Big Thompson River

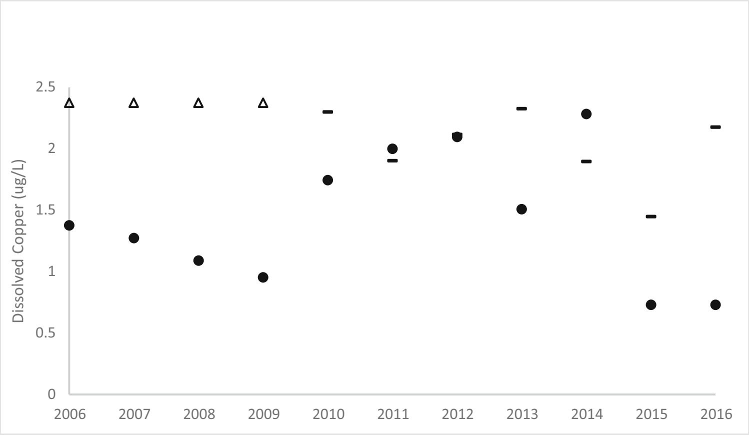


Fig. 3 Average annual dissolved copper concentrations (black circles) and chronic standard based on average hardness levels (black dashes) at the canal site containing water from the headwaters of the Colorado River. No hardness values were available from 2006 to 2008. Therefore, the mean hardness value from 2009 is used in dissolved copper chronic standard calculations for these years and is represented by triangles

same ($t = -1.982$, $p = 0.064$), but the percent mortality remained significant ($t = 3.877$, $p = 0.001$).

Discussion

Our results suggest that there is a significant correlation between dissolved copper and bark beetle-induced tree mortality in the BTR and that recent increases in copper in the upper portion of the watershed are likely due in part to recent tree mortality events. Mikkelson et al. (2014) demonstrated the potential for metals such as copper to infiltrate surface waters adjacent to areas with increased tree mortality, and our results suggest that this mechanism has indeed increased copper concentration in the BTR. Organic carbon levels increase following bark beetle-induced tree mortality events (Huber et al. 2004), in part through the increased deposition of needles (Yavitt and Fahey 1986). Elevated organic carbon levels in turn can increase metal transport through soil (Davis 1984). Similarly, leaching from evergreen needles may contribute directly to increases in dissolved copper availability as the needles can bioaccumulate heavy metals through atmospheric uptake (Samecka-Cymerman et al. 2006).

Bark beetle-induced mortality in the area surrounding the BTR watershed was most severe between 2002 and 2012, and although elevated mortality continues, it appears to be less severe in recent years (Hicke et al. 2016). Correspondingly, dissolved copper levels in both of our sample sites have decreased somewhat in recent years with mean dissolved copper values declining from 2.95 to 1.26 μg/L at the headwater site and from 2.10 to 0.73 μg/L at the canal site between 2012 and 2016 (Figs. 2 and 3).

The lag time between changes in non-point source management and resulting water quality can range from months to decades, with generally longer lags associated

Fig. 4 Percent tree mortality, associated dissolved copper concentrations 3 years after tree mortality estimate, and estimated regression relationship at the headwater site in the Big Thompson River

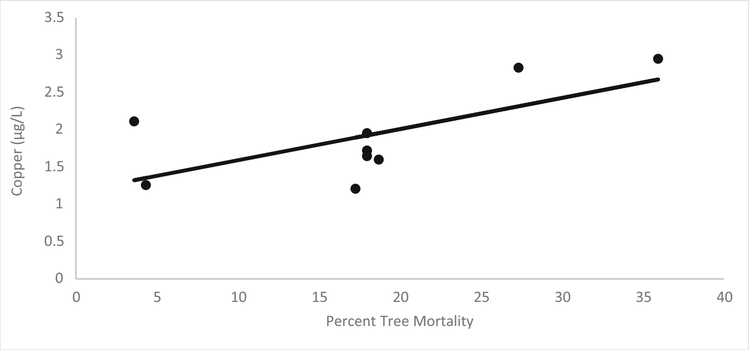
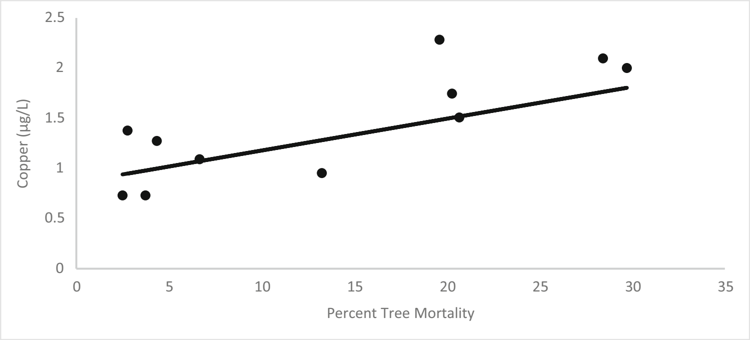


Fig. 5 Percent tree mortality, associated dissolved copper concentrations 5 years after tree mortality estimate, and estimated regression relationship at the canal site containing water from the headwaters of the Colorado River



with contaminants that move through the ground water, compared to those that move primarily through surface waters (Meals et al. 2010). The length of time between release of a pollutant and its subsequent presence in the water body will depend in part on the bulk density, organic carbon, and porosity of the associated soil (Meals et al. 2010). The mobility of copper through the soil depends in part on the amount of dissolved organic carbon, with increased copper mobility being associated with higher levels of organic carbon under certain conditions (Zhou and Wong 2001; Han and Thompson 2003). Huber et al. (2004) demonstrated increases in dissolved organic carbon in the humus efflux (0 cm) of a spruce forest in the mountains of Bavaria from the year of a bark beetle-induced dieback up to 5 years after the dieback. In and around the BTR, soil composition differs between the eastern and western side of the continental divide, with the eastern side containing a higher amount of total carbon in the soil (Rueth and Baron 2002). The elevated amount of total carbon present in the soil on the eastern side of the continental divide, which includes the watershed associated with our headwater site, may facilitate the mobility of dissolved copper through the soil and result in a shorter lag time between tree death and subsequent increases in dissolved copper in the BTR when compared to water from the western side of the continental divide.

Bark beetle-induced tree mortality has been substantial throughout the western United States (Hicke et al. 2016) and therefore our results may be generally applicable to other watersheds. Clearly, the exact nature of the lag times and coefficients we developed for the dissolved cooper-tree mortality relationship in the BTR will not be directly applicable to other watersheds in the same geographic region due to differences in characteristics such as geomorphology, soil types, and forest composition. However, the positive relationship between tree mortality and subsequent dissolved copper level in associated waterbodies may generally be valid for watersheds similar to the BTR. For example, the Cache La Poudre River (CLPR) is a major tributary to the South Platte River approximately 30 km to the north of the BTR and like the BTR has its headwaters in Rocky Mountain National Park. Dissolved copper levels in the CLPR are relatively low but a relatively high level of dissolved copper (~ 6.4 μg/L) was recorded in May of 2009 (Oropeza and Heath 2013). Subsequent water samples showed dissolved copper levels declining to ~ 0.5 μg/L by 2012 (Oropeza and Heath 2013), which is a similar pattern to the BTR dissolved copper values (Figs. 2 and 3).

Our results suggest that broad scale tree mortality events, such as those caused by bark beetles, can result in conditions that indirectly and negatively affect aquatic ecosystems such as the BTR. As forests recover from these events, dissolved copper levels are likely to decrease as well. However, given ongoing climactic changes, these events are likely to become more common. Increases in dissolved copper levels and negative impacts to aquatic ecosystems can be expected when large scale tree mortality events occur.

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