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Responses of soil and water chemistry to mountain pine beetle induced tree mortality in Grand County, Colorado, USA

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ABSTRACT

Pine forest in northern Colorado and southern Wyoming, USA, are experiencing the most severe mountain pine beetle epidemic in recorded history, and possible degradation of drinking-water quality is a major concern. The objective of this study was to investigate possible changes in soil and water chemistry in Grand County, Colorado in response to the epidemic, and to identify major controlling influences on stream-water nutrients and C in areas affected by the mountain pine beetle. Soil moisture and soil N increased in soils beneath trees killed by the mountain pine beetle, reflecting reduced evapotranspiration and litter accumulation and decay. No significant changes in stream-water NO_3^- or dissolved organic C were observed; however, total N and total P increased, possibly due to litter breakdown or increased productivity related to warming air temperatures. Multiple-regression analyses indicated that % of basin affected by mountain pine beetles had minimal influence on stream-water NO_3^- and dissolved organic C; instead, other basin characteristics, such as percent of the basin classified as forest, were much more important.

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1. Introduction

The mountain pine beetle (MPB; *Dendroctonus ponderosae*) is the primary cause of insect-induced mortality in pine forests in western North America (Gibson, 2004). In northern Colorado and southern Wyoming, pine forests are experiencing the most severe MPB epidemic in recorded history, with 70–90% mortality of lodgepole (*Pinus contorta*), limber (*Pinus flexilis*), and Ponderosa (*Pinus ponderosa*) pines on 1.62 million ha (4 million acres) since 1996 (Raffa et al., 2008; http://csfs.colostate.edu/, accessed 2/3/2011).

Contributing factors include an abundance of mature, dense lodgepole forests, drought stress, and warming temperatures, which have allowed the MPB to expand its elevation and latitudinal ranges into areas formerly too cold for the beetle to survive (Carroll et al., 2004). MPB epidemics typically are stopped only by exhaustion of food supply (live trees) or extended periods of cold temperatures (<−30 to −40 °C), which can kill MPB larvae (Carroll et al., 2004). Winter minimum temperatures in western North America have increased substantially since the late 1970s (Easterling et al., 1997), and these increases correlate with range expansion for a variety of insects (Carroll et al., 2004).

The short- and long-term effects of MPB-induced tree mortality on water quality could be profound. Pine needles and twigs, which are relatively rich in nitrogen (N), will decay relatively quickly (Fig. 1; Pearson et al., 1987). Branches and trunks, which have much lower concentrations of N, but substantial carbon (C), will decay more slowly (Fig. 1; Pearson et al., 1987). Much of the N and C released will accumulate in litter and soil, or be taken up by new forest growth (Vitousek and Melillo, 1979). An unknown fraction of N and C will leach into soil solution or groundwater, and may subsequently be transported to surface water.

The quality of drinking-water supplies for communities in the Denver-Fort Collins area could be strongly impacted by the MPB (Ciesla, 2009). The Colorado-Big Thompson project stores water on the western slope of the Continental Divide in the "Three Lakes" system (Grand Lake, Shadow Mountain reservoir and Granby reservoir) and diverts it to the eastern side through a network of tunnels (Fig. 2). A USDA Forest Service report states that the Three Lakes area is "at the epicenter of the current MPB outbreak," and notes the possibility of increasing nutrient and sediment fluxes to the Three Lakes system, where eutrophication is a major concern (Ciesla, 2009). Increasing concentrations of dissolved organic C (DOC) are possible as well, which could lead to increased production of possible carcinogenic disinfection by-products during water treatment (http://www.cdc.gov/safewater/publications_pages/thm.pdf; accessed 1/25/2011).

During 2007–2008, the US Geological Survey (USGS), in cooperation with the USDA Forest Service, conducted a study in Grand County, Colorado, to document possible changes in soil chemistry

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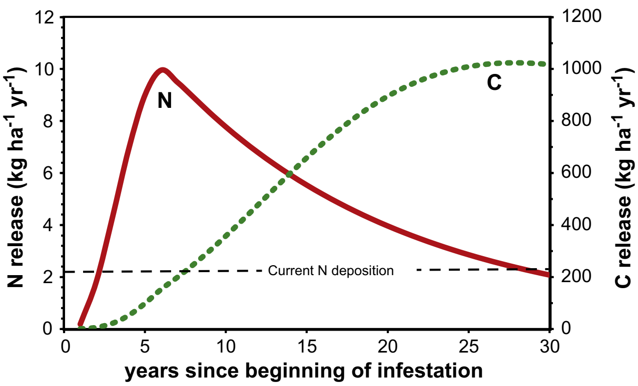

Fig. 1. Hypothetical release of nitrogen (N) and carbon (C) from trees killed by mountain pine beetle.

and water chemistry in response to MPB-induced tree mortality, and to identify major influences on nitrate (NO_3) and DOC concentrations in surface water in the study area. The study approach involved (1) soil chemistry sampling under trees in three stages of MPB attack, including live "green-phase" trees, dead "red-phase" trees, and dead "gray-phase" trees (defined below); (2) synoptic water-quality sampling from streams draining basins with varying intensity and timing of MPB attack, (3) multiple-regression modeling to characterize the relative importance of MPB-induced mortality and basin characteristics in controlling stream-water NO_3 and DOC concentrations, and (4) analysis of trends in stream-water nutrient and C concentrations during 2001–2009 at the largest natural inflows to the Three Lakes system.

2. Methods

Soil samples were collected during October 2008 at 11 sites, under 4–6 trees per site. Each tree was categorized as green-phase (healthy or freshly attacked by MPB), red-phase (1–3 years post-attack, retaining 50–100% needles), or gray-phase ($\geqslant$4 years post-attack; no needles). Three 15 cm deep soil cores of the A horizon were collected per tree, halfway between the bole and the edge of the canopy, in the north, SE and SW compass directions from the bole. Soil samples from under each tree were composited and analyzed for soil moisture, available N, extractable NH_4, and extractable NO_3 as in Rhoades et al. (2008). Soil chemistry under trees in green, red and gray-phases was compared by performing analysis of variance (ANOVA) with a Tukey multiple-range test (Helsel and Hirsch, 1992).

Two to 6 water samples were collected during the 2007 snowmelt period from each of 14 headwater streams, which were selected based on availability of historical streamflow and water-quality data (Fig. 2). Water samples were analyzed for dissolved and total N, DOC, and major dissolved constituents using standard USGS methods (Fishman, 1993). Basin boundaries upstream from each of the water-quality sampling sites were delineated, and the % of basin affected by MPB in individual years during 1996–2007 (%MPB) was quantified for each basin based on digital annual Aerial Detection Survey maps available from the U.S. Forest Service and Colorado State Forest Service (http://www.fs.fed.us/r2/gis/; accessed 1/25/2011). Basin characteristics, including relief, slope, area, elevation, %forest, and annual precipitation were derived for each basin using the USGS StreamStats program (http://water.usgs.gov/osw/streamstats/colorado.html; accessed 1/25/2011).

Stepwise multiple linear regression (MLR) equations were developed for stream-water NO_3 and DOC concentrations; average NO_3 and DOC from the 2007 stream synoptics were used as dependent variables, and %MPB and basin characteristics were used as explanatory variables. The variable that explained the most variance in the chemical variable entered the model first. The variances explained by the remaining explanatory variables were recalculated, and the variable that explained the next greatest amount of variance entered the model next. This iterative process was repeated until no additional variables showed statistically significant correlations to the dependent chemical variable at $p \leqslant 0.1$ (see Clow et al. (2010) for details). DOC was log transformed prior to model development to normalize the input data.

Trends in stream-water chemistry during 2001–2009 were evaluated for three major inlets to the Three Lakes system (East Inlet, North Inlet, and Arapaho Creek) using the Seasonal Kendall Test (SKT), as described in Helsel and Hirsch (1992). The SKT accounts for seasonality by testing for trends in each season and then combining the results. It can be applied to raw and flow-adjusted data, allowing one to account for variations in chemistry attributable to variations in flow. Historical data for the trend analyses were pulled from the USGS National Water Information System (NWIS; http://waterdata.usgs.gov/nwis), and included major dissolved constituents, total N and total P.

3. Results

3.1. Soil chemistry

Soil moisture was greater in soils under red- and gray-phase trees than under green-phase trees, probably due to reduced evapotranspiration (Fig. 3a). Available soil N was lowest in soils under green-phase trees and highest under gray-phase trees (Fig. 3b). These results are consistent with release of N from decaying litter and incorporation of that N into soil organic matter. Extractable ammonium (NH_4) was greatest in soils under red-phase trees (Fig. 3c). Extractable NO_3 was significantly higher in soils under red- and gray-phase trees than under green-phase trees (Fig. 3d). These results are consistent with mineralization of organic N in decaying plant litter to NH_4, followed by nitrification to NO_3 (Griffin et al., 2011). Part of the increase in soil NO_3 and soil moisture was probably due to reduced uptake of nutrients and water associated with MPB-induced mortality, despite increased rates of uptake by young, fast-growing trees nearby whose growth may have been stimulated by increased nutrient, water and light availability.

3.2. Water chemistry

At all of the 2007 synoptic stream sampling sites, NO_3 and DOC concentrations showed a pattern of increasing concentrations on the rising limb of the snowmelt hydrograph and decreasing concentrations during the falling limb, as exemplified by Arapaho Creek, which is the largest natural inflow to the Three Lakes system (Fig. 4). This seasonal pattern is typical of high-elevation, headwater catchments in Colorado and reflects flushing of solutes from the soil by snowmelt, and in the case of NO_3, preferential elution from the snowpack (Campbell et al., 1995).

Nitrate and DOC concentrations showed substantial spatial variation as well (Fig. 5). Percentage forest in the basins was the strongest predictor of spatial variations in stream-water NO_3 and DOC concentrations. Nitrate was negatively related to %forest (adjusted $r^2 = 0.79$) and log DOC was positively related to %forest (adjusted $r^2 = 0.50$). The inverse relationship between NO_3 and %forest may be explained by the uptake of NO_3 by vegetation and soil microbes in forested areas. In contrast, the positive relationship between DOC and %forest probably reflects leaching of organic C from forest soils during snowmelt and storm events (Boyer et al., 1997).

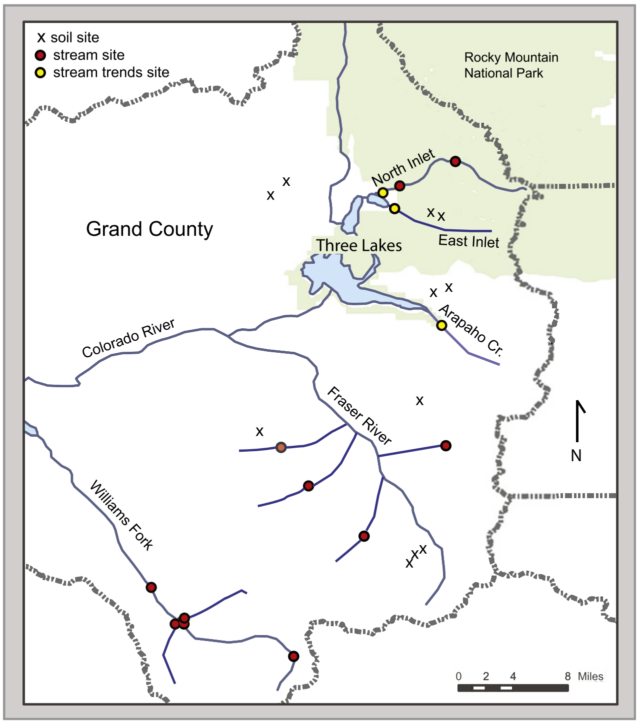

Fig. 2. Map showing sampling sites in Grand County.

3.3. Multiple-regression modeling

Several MLR models were evaluated for stream-water NO_3, and the best model, based on highest adjusted r^2 and lowest root mean square error, included %forest and basin relief as explanatory variables. This model explained 91% of the spatial variation in stream-water NO_3 concentration (Fig. 6a). Basin relief, a surrogage for mean transit time, was inversely related to NO_3 concentrations, reflecting greater uptake in basins with low relief.

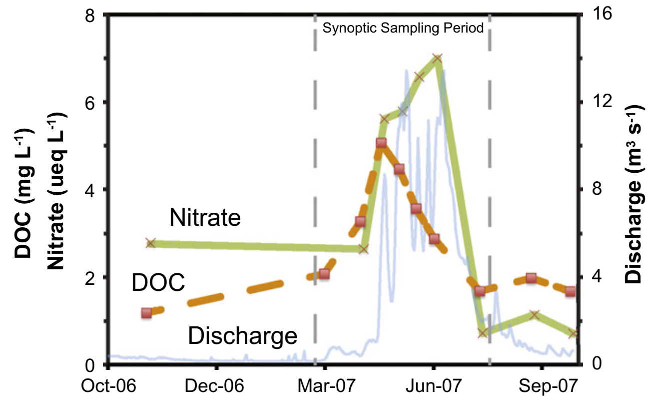

Fig. 4. Seasonal variation in nitrate and DOC in Arapaho Creek.

The best DOC model included %forest, annual precipitation, north-facing slopes greater than 30%, and basin area, and explained 82% of the variance in DOC data (Fig. 6b). Precipitation was positively related to DOC, probably reflecting the relationship between productivity and precipitation in the study area, where forest growth tends to be water limited. Basin area also was positively related to DOC, perhaps because larger basins tend to have more wetlands. The negative relationship between DOC and steep, north-facing slopes may reflect low productivity in this environment due to cold micro-climatic conditions and persistent snowfields.

The input variables selected by the stepwise MLR procedure were not unique in their predictive ability, and some slightly less powerful model variants included %MPB in individual years as significant explanatory variables. However, the amount of variance explained by %MPB was always small relative to other terms, indi-

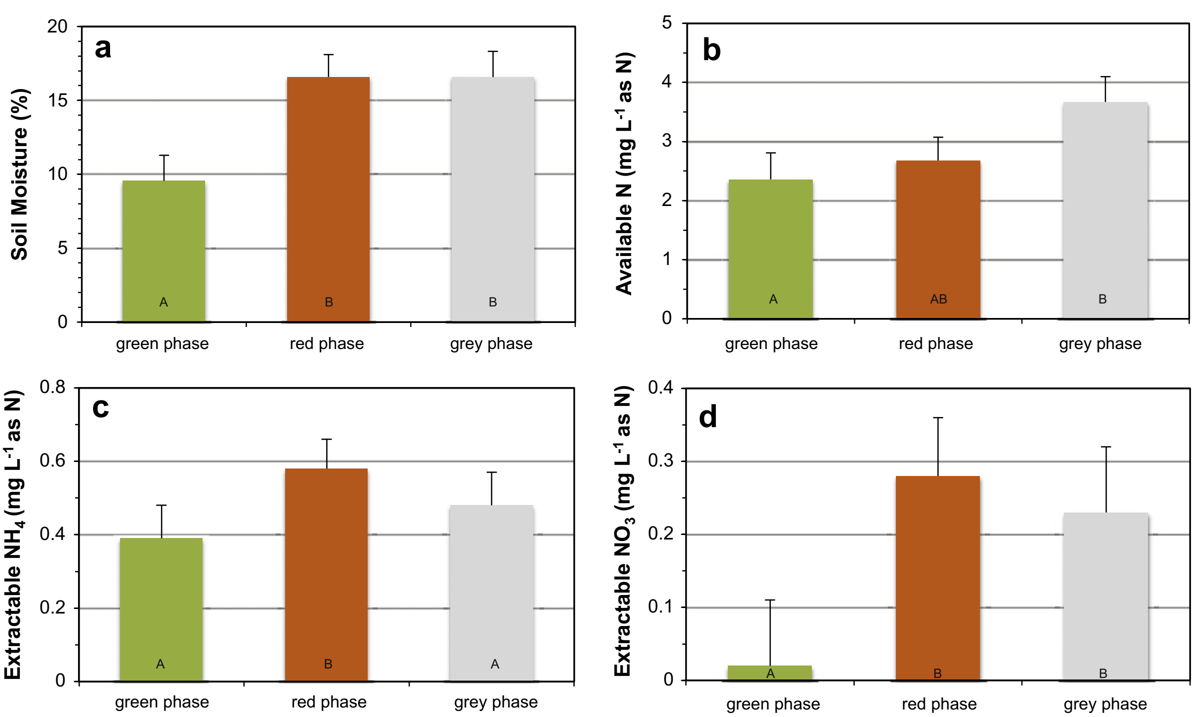

Fig. 3. Means and standard deviations of soil (a) moisture, (b) available N, (c) extractable NH_4, and (d) extractable NO_3 in soils collected under green phase (live), red phase (dead with 50-100% needles), and grey phase (dead without needles) trees. Columns identified by different letters at bottom of each plot indicate that the distributions were significantly different at $p \leqslant 0.1$.

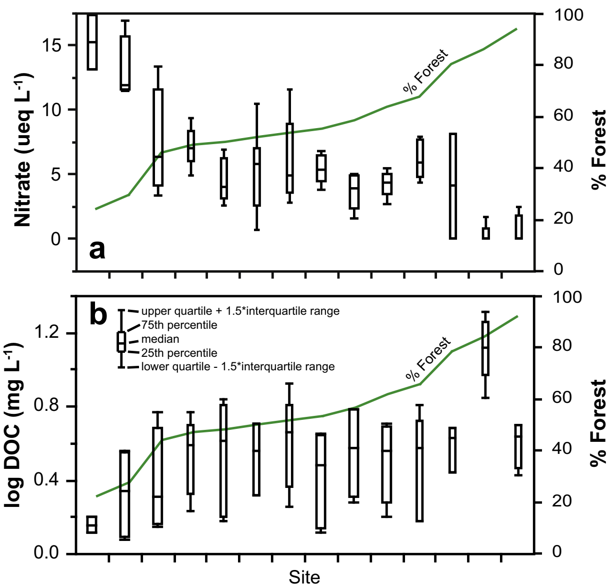

Fig. 5. Box plots showing variations in (a) nitrate and (b) DOC at synoptic stream sampling sites during 2007 snowmelt period.

cating that basin characteristics were the strongest predictors of stream-water NO_3 and DOC concentration (see Fig. 6).

3.4. Trends in stream-water chemistry

There were strong downward trends in raw and flow-adjusted NO_3 and PO_4 concentrations in each of the main inlets to the Three Lakes system during 2001–2009 (Table 1). Some of the decline in NO_3 and PO_4 might reflect recovery from drought conditions that induced high dissolved nutrient concentrations during the early part of the record, although the lack of trends in most major solutes indicates the drought effect was small. In contrast with the trends in dissolved nutrients, total N and total P, which include particulate and dissolved phases, increased in the inlet streams (Table 1). These contrasting trends might reflect increased conversion of dissolved nutrients to particulate form by benthic algae (increased productivity). This is consistent with warming temperatures that have been documented for the 1986–2007 period in northern Colorado (Clow, 2010). Alternatively, the increases in total N and total P could be due to an increase in fluxes of particulate organic matter to surface waters, as might be expected from breakdown of litter derived from trees killed by the MPB.

4. Discussion

The significant increases in available N and extractable NH_4 and NO_3 observed in soil beneath trees killed by the MPB indicate a substantial shift in soil nutrient chemistry in response to the MPB epidemic. However, the increases in soil N were not reflected in stream-water chemistry. The apparent lack of response in stream-water chemistry is intriguing, and could be due to a variety

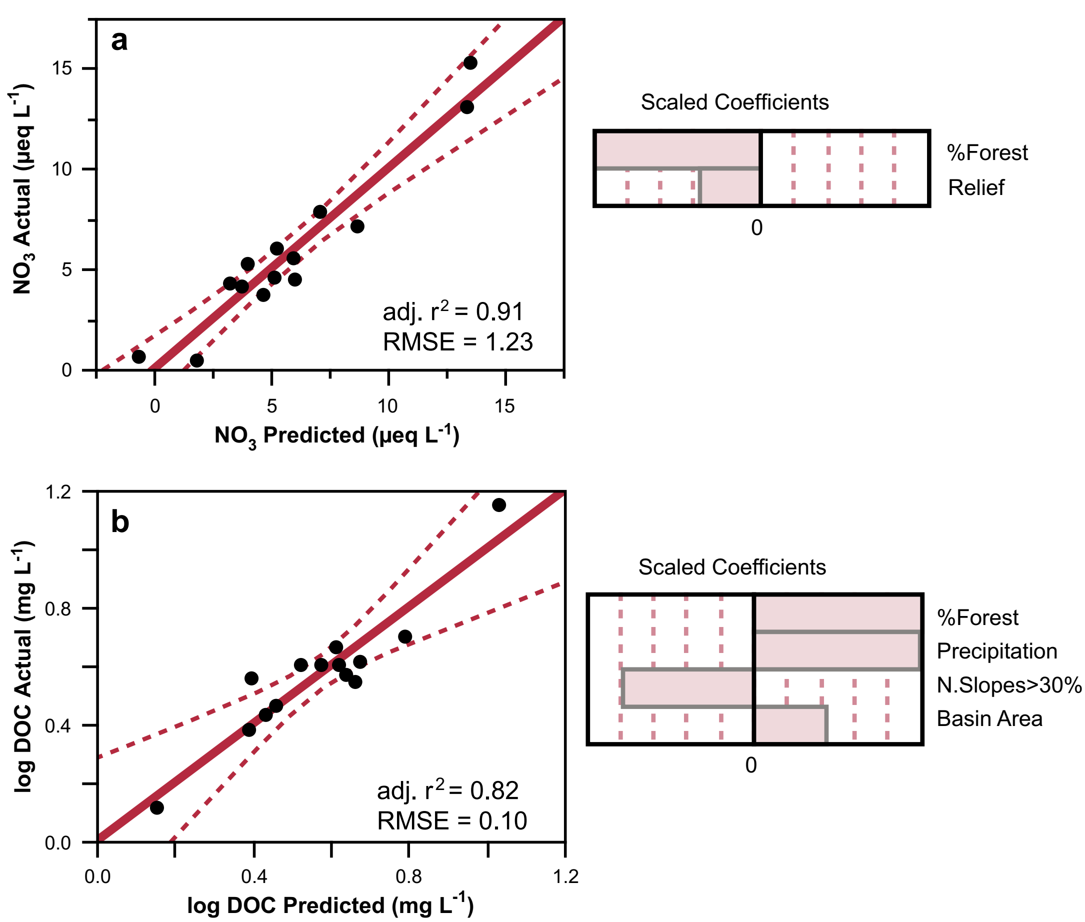

Fig. 6. Stream-water NO_3 and DOC models. Solid red line represents the regression equation. Dashed lines represent 95% confidence intervals for the regression equations. Scaled coefficients are beta coefficients centered by mean, scaled by range/2, and show the relative influence of factors in the regression equation. RMSE is root mean square error; adj. r^2 is adjusted r^2. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1
Trends, flow-adjusted trends, and associated *p*-values for constituent in major inlets to Three Lakes system, 2001–2009.[a] Italicized values indicate statistically significant trends ($p < 0\ 05$).

	Discharge ($m^3\ s^{-1}$)	SC (μS cm^{-1})	DO (mg L^{-1})	TKN (mg L^{-1} as N)	NO_3 (μeq L^{-1})	TP (mg L^{-1})	PO_4 (μeq L^{-1})	Ca (μeq L^{-1})	Mg (μeq L^{-1})	Na (μeq L^{-1})	K (μeq L^{-1})	CL (μeq L^{-1})	SO_4 (μeq L^{-1})	Alkalinity (μeq L^{-1})	DOC (mg L^{-1})	SiO_2 (μmol L^{-1})
East inlet																
Trend	0.03	0.000	0.000	0.008	−0.362	0.0005	−0.0300	0.050	0.127	0.368	0.071	0.141	−0.582	0.517	0.050	0.249
p-Value	.089	.414	.589	*.029*	*.003*	*.000*	*.000*	.861	.436	.219	.095	*.012*	*.002*	.160	.077	.588
Flow-adjusted trend		0.245	0.003	0.006	−0.325	0.0004	−0.0253	0.908	0.369	0.900	0.107	0.175	−0.267	3.321	0.009	0.970
Flow-adjusted *p*-value		*.012*	.824	*.033*	*.010*	*.003*	*.000*	.098	*.037*	*.002*	*.019*	*.009*	.384	*.002*	.862	.116
Count	59	58	57	24	57	57	57	58	58	58	58	58	58	53	58	53
North inlet																
Trend	0.06	0.000	0.060	0.014	−0.339	0.0005	−0.0242	0.333	0.115	0.145	0.032	0.141	−0.594	0.000	0.033	0.216
p-Value	.094	.365	.209	*.015*	*.006*	*.000*	*.000*	.692	.351	.565	.302	*.035*	*.000*	.604	.068	.844
Flow-adjusted trend		0.262	0.081	0 014	−0.292	0.0004	−0.0243	04:7	0.29?	0.956	0.043	0161	−0.224	2347	0042	1 279
Flow-adjusted *p*-value		*.047*	.156	*.002*	*.042*	*.013*	*.000*	.305	.201	.146	.454	086	*.038*	.071	.355	.280
Count	58	57	58	23	56	56	55	57	57	57	57	57	57	48	57	53
Arapaho Cr																
Trend	0.02	0.000	0.000	0.004	−0.259	0.0003	−0.0242	−1.188	0.000	0.174	0.116	0.000	−0.998	−1.000	0.045	−0.373
p-Value	.502	.565	.896	.296	*.008*	.072	*.000*	.607	1.000	.666	.243	.896	*.018*	.607	.180	.565
Flow-adjusted trend		0.084	0.004	0.010	−0.282	0.0003	−0.0218	0.251	0.473	0.515	0.111	0.077	−0.373	3.102	0.019	−0.354
Flow-adjusted *p*-value		.663	.830	*.037*	*.005*	.086	*.000*	.864	.303	*.048*	.198	.391	.492	.128	.597	.632
Count	60	58	59	22	59	58	59	59	59	59	59	59	59	49	58	55

[a] SC, specific conductance; DO, dissolved oxygen; TKN, Total Kjeldahl Nitrogen; NO_3, nitrate; TP, total phosphorus; PO_4, orthophosphate; Ca, calcium; Mg, magnesium; Na, sodium; K, potassium; Cl, chloride; SO_4, sulfate; DOC, dissolved organic carbon; SiO_2, silica.

of mechanisms. William Lewis and James McCutchan (University of Colorado, Boulder; pers. comm., 2011) have suggested several possible explanations: (1) spatial and temporal heterogeneity in MPB-induced tree mortality causes a damped response over time; (2) most MPB-induced tree mortality occurs on xeric hill slopes, where leaching of nutrients from soil to groundwater tends to be delayed; and (3) uptake of NO_3 by remaining young trees, shrubs, and grasses reduces potential increases in stream-water NO_3.

Although stream-water NO_3 concentrations have not increased in response to the MPB, total N and total P concentrations have increased, which may have important implications for drinking-water quality in the Three Lakes system. The MPB epidemic reached its peak in the Three Lakes basin during 2006–2008, and much of the associated litter is just beginning to accumulate and decay. Additional inputs of nutrients from litter decay to soils are likely, but it will take time for nutrients to be transported through soils and groundwater to aquatic ecosystems. Increases in surface water NO_3 and DOC might still occur in response to MPB-induced tree mortality, although the changes are likely to be subtle and gradual in nature.

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