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

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\textbf{A B S T R A C T}

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\textsubscript{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\textsubscript{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; \textit{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 (\textit{Pinus contorta}), limber (\textit{Pinus flexilis}), and Ponderosa (\textit{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 \(-40^\circ\text{C}\)), 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...
and water chemistry in response to MPB-induced tree mortality, and to identify major influences on nitrate (NO₃) 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 NO₃ 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.

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 (NH₄) was greatest in soils under red-phase trees (Fig. 3c). Extractable NO₃ 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 NH₄, followed by nitrification to NO₃ (Griffin et al., 2011). Part of the increase in soil NO₃ 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, NO₃ 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 NO₃, 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 NO₃ 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 NO₃ and %forest may be explained by the uptake of NO₃ 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).
Several MLR models were evaluated for stream-water NO₃, 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 NO₃ concentration (Fig. 6a). Basin relief, a surrogage for mean transit time, was inversely related to NO₃ concentrations, reflecting greater uptake in basins with low relief.

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. 2. Map showing sampling sites in Grand County.

3.3. Multiple-regression modeling

Fig. 3. Means and standard deviations of soil (a) moisture, (b) available N, (c) extractable NH₄, and (d) extractable NO₃ 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 $p \leq 0.1$.

Fig. 4. Seasonal variation in nitrate and DOC in Arapaho Creek.
cating that basin characteristics were the strongest predictors of stream-water NO3 and DOC concentration (see Fig. 6).

3.4. Trends in stream-water chemistry

There were strong downward trends in raw and flow-adjusted NO3 and PO4 concentrations in each of the main inlets to the Three Lakes system during 2001–2009 (Table 1). Some of the decline in NO3 and PO4 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 NH4 and NO3 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...
Table 1

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Note: All values are in milligrams per liter (mg/L).

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**References**


