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Changes in stream chemistry associated with insect defoliation in a Pennsylvania hemlock-hardwoods forest

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Abstract

Disturbances to forested watersheds often lead to elevated concentrations and fluxes of solutes in stream water. We examined the solute chemistry of streams draining mostly old-growth hemlock-hardwoods forest in two adjacent watersheds on the Allegheny High Plateau in northwestern Pennsylvania before, during, and after a single season of defoliation of hardwoods by elm spanworm (*Ennomos subsignarius* Hübner) larvae. Concentrations of potassium, ammonium, and dissolved organic carbon increased during the defoliation or in the following month. During this same time, concentrations of sulfate, nitrate, calcium, and magnesium decreased. However, by the end of the summer, nitrate concentrations exceeded pre-defoliation concentrations (<0.4 mg NO_3-N/L) and then peaked during the following summer (1.4 mg NO_3-N/L). Nitrate concentrations declined to pre-defoliation concentrations by the end of the second summer following defoliation. Calcium and magnesium concentrations, which generally correlated most strongly with sulfate concentrations, increased in conjunction with elevated nitrate concentrations after defoliation. Increases in nitrate, calcium, and magnesium in stream water were consistent with biogeochemical changes following clearcutting and insect defoliation at other locations in eastern North America. Therefore, we hypothesize that elevated nitrification generated nitrate ions which in turn leached calcium and magnesium from soils into the streams. The short-term changes that occurred during and immediately after defoliation in our study suggest that defoliation may influence stream chemistry in other ways, as well (e.g., through the leaching of nutrients and labile carbon from insect frass and greenfall).

Keywords: Base cations; Insect defoliation; Nitrate; Sulfate; Stream chemistry; Watershed

1. Introduction

Severe physical disturbances to forests, such as clearcutting, can alter concentrations and export of solutes in streams (e.g., Likens et al., 1970; Swank, 1988; Jewett et al., 1995). The primary cause of those changes in stream chemistry is disruption of the forest nitrogen (N) cycle (Likens et al., 1970; Bormann and Likens, 1979). Removal of the forest canopy decreases plant N uptake, accelerates N mineralization from organic matter, and increases rates of nitrification (Bormann and Likens, 1979; Holmes and Zak, 1999). Hydrogen ions (H^+) produced by nitrification displace base cations (calcium, magnesium, and potassium) from soil exchange sites into the soil water. The displaced cations then leach into streams with nitrate (NO_3^-) anions (Likens et al., 1970; Bormann and Likens, 1979). Further, with increasing soil acidity, the sulfate (SO_4^{2-}) adsorption capacity of soils may increase, thereby reducing SO_4^{2-} loss to streams (Likens et al., 1970; Nodvin et al., 1988). Thus, increased nitrification following forest disturbance causes multiple changes in stream chemistry and export of dissolved nutrients from forested ecosystems.

Forest disturbances less severe than clearcutting also may influence stream chemistry. Outbreaks of defoliating insects, for example, temporarily thin the forest canopy, permitting more solar radiation to reach the forest floor (Collins, 1961) and reducing transpiration and canopy interception of rain, resulting in warmer, moister conditions (Stephens et al., 1972) which may stimulate microbial activity, including nitrification, in the forest floor (Swank et al., 1981). Also, leaf-chewing insects transfer nutrients via frass and uneaten green leaf fragments (greenfall) from the canopy to the forest

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floor. This transfer prevents the normal withdrawal of nutrients from leaves into stems later in the growing season. As a result, severe defoliation increases the total annual input of nutrients (especially nitrogen, phosphorus, and potassium) in litter (Grace, 1986). Also, nutrient fluxes in throughfall may increase with increasing grazing intensity (Grace, 1978; Seastedt et al., 1983).

Elevated stream solute concentrations have been observed following outbreaks of defoliating caterpillars in the Appalachian Mountains of the United States. In forested watersheds in western North Carolina, average annual volume-weighted stream NO_3-N concentrations increased from 0.002–0.006 to about 0.015–0.025 mg/L during several consecutive years of fall cankerworm (*Alsophila pometaria* Harris) defoliation (Swank et al., 1981). While increased numbers of nitrifying bacteria occurred in soils of defoliated watersheds, concentrations of base cations and other solutes in streams did not change significantly (Swank et al., 1981). However, at the White Oak Run watershed in western Virginia, annual stream NO_3-N concentrations rose from <0.07 mg/L to as high as ~0.8 mg/L during and after three successive years of severe gypsy moth (*Lymantria dispar* L.) defoliation (Webb et al., 1995; Eshleman et al., 1998). Elevated base cation concentrations, elevated acidity, and low SO_4^{2-} concentrations were associated with the elevated NO_3^- concentrations (Webb et al., 1995). Those changes are consistent with the hypothesis that nitrification is the primary mechanism causing changes in stream chemistry after defoliation.

Given the variable responses of stream chemistry to defoliation in the Appalachians, it is of interest to determine change following defoliations in other regions. We took advantage of an insect outbreak in northwestern Pennsylvania to determine if elevated concentrations of NO_3-N, base cations, and other solutes occurred in streams following defoliation. We present evidence that, consistent with studies in the Appalachians, NO_3-N, calcium, and magnesium concentrations increased for up to 2 years following defoliation. However, we also present evidence of short-term (<2 months) effects of defoliation that would involve mechanisms other than increased nitrification.

2. Methods

2.1. Study area

We examined the stream solute chemistry of two adjacent forested watersheds in the Allegheny National Forest, northwestern Pennsylvania (Fig. 1). The streams from those watersheds (West Fork Run and East Fork Run) drain into the South Branch of Tionesta Creek, a tributary of the Allegheny River. At our sampling locations (Fig. 1), the West Fork Run (WFR) and East Fork Run (EFR) watersheds have areas of 299 and 450 ha, respectively. The watersheds lie between 480 and 600 m a.s.l. on the unglaciated Allegheny High Plateau. The Plateau consists of flat uplands divided by steep-sided valleys (Hough and Forbes, 1943; Bjorkbom and Larson, 1977). Annual average air temperature is 7.8 °C, while

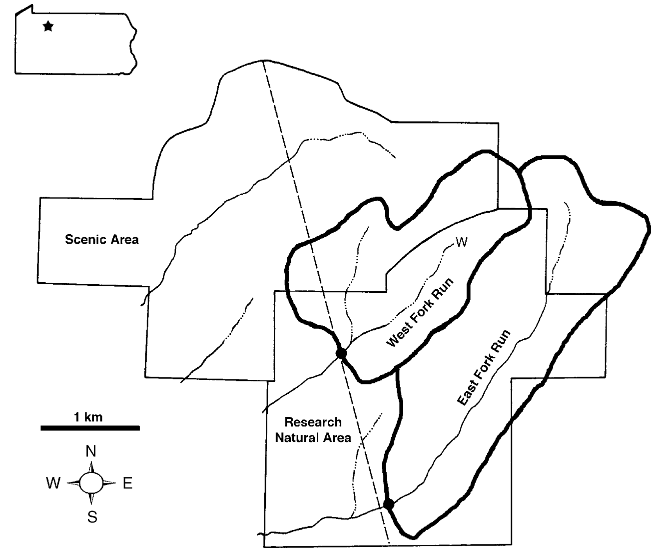

Fig. 1. Location of the West Fork Run and East Fork Run watersheds in relation to the Tionesta Scenic and Research Natural Areas, Allegheny National Forest, Pennsylvania, USA. Watershed boundaries in reference to the sampling site on each stream are depicted with bold lines. Each sampling site is indicated by a filled circle at the base of each watershed. A "W" indicates the presence of a wetland at the source of the main channel of West Fork Run. The natural gas pipeline right-of-way that bisects the Scenic and Research Natural Areas is indicated by a dashed line.

average summer air temperature is 19 °C. The growing season extends from late May through late September (Bjorkbom and Larson, 1977). Annual precipitation (January–December totals) between 1979 and 1998 at the Kane Experimental Forest (<25 km from the study sites) averaged ~124 cm and ranged from 96 to 162 cm (National Atmospheric Deposition Program/National Trends Network, 2006).

Forests dominated by eastern hemlock (*Tsuga canadensis* L.) and American beech (*Fagus grandifolia* Ehrh.) covered most of the Fork Run watersheds. Hemlock was especially abundant near streams in both watersheds. Other common canopy trees included yellow birch (*Betula alleghaniensis* Britton), black cherry (*Prunus serotina* L.), sugar maple (*Acer saccharum* Marsh.), red maple (*Acer rubrum* L.) and white ash (*Fraxinus americana* L.). Within the Tionesta Scenic and Research Natural Areas (Fig. 1), the watersheds were covered mostly by old-growth hemlock-beech forest. Some hardwood stands dominated by black cherry, maples, and beech, which developed following wind storms of 1808 and 1870, also were present in these Natural Areas (Bjorkbom and Larson, 1977). Second-growth hardwood or hemlock-hardwood stands covered the portions of each watershed outside the Scenic and Research Natural Areas (G. Lewis personal observation; N. Karger, Kane Hardwood Company, personal communication). The severe tornado that destroyed much of the old-growth forest in the northern half of the Tionesta Scenic Area in 1985 (Peterson and Pickett, 1991) affected only the northern edges of the Fork Run watersheds (G. Lewis, personal observation).

The bedrock underlying the Fork Run watersheds is primarily of the Pottsville Group, which is composed of interbedded sandstones, siltstones, and shales, with sandstones