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Does the spatial arrangement of disturbance within forested watersheds affect loadings of nitrogen to stream waters? A test using Landsat and synoptic stream water data

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ABSTRACT

Remotely sensed maps of forest disturbance provide a powerful tool for predicting spatial and temporal variability in the loading of nitrogen to receiving waters, key data needed for effective watershed management of nutrient pollution. We hypothesize that the spatial arrangement of disturbances within small-forested watersheds can affect N loadings. To test this, we developed schemes for spatially weighting maps of yearly disturbance produced through change analysis of the Landsat Tasseled Cap Disturbance Index (DI), and evaluated the ability of each scheme to predict N concentrations, and subsequently estimated N loads, from forty low-order streams within the Savage River drainage of western Maryland, USA during the 2006–2010 water years, a period encompassing extensive defoliations by gypsy moths (*Lymantria dispar*). We generated a base scheme of unweighted, watershed averaged change in DI (ΔDI), and five other schemes that weighted ΔDI by either a pixel's flow accumulation value, the distance to the watershed outlet, or proximity to the stream. Over the five years, the flow accumulation scheme tended to perform better than other weighting schemes, and even explained slightly more variability than the base scheme during years of moderate N loads ($R^2 = 0.15$ vs. 0.03 in 2007 and $R^2 = 0.30$ vs. 0.18 in 2010). However, this best spatial weighting scheme explained comparable or *less* variability during the two post-defoliation years with larger N loads ($R^2 = 0.43$ vs. 0.44 in 2008 and $R^2 = 0.31$ vs. 0.48 in 2009). Thus, for the purposes of utilizing remote sensing information within watershed management of nutrient pollution, these results suggest that coarse-scale, high temporal frequency data such as MODIS could be well suited for characterizing forest disturbance and predicting the resultant episodic N loads.

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1. Introduction

Nitrogen (N) loading to surface waters has multiple negative environmental effects, such as algal blooms, eutrophication, and the resulting impairment of economically valuable water resources across the globe (Driscoll et al., 2003; Galloway et al., 2003; Kim et al., 2011). This is especially true in the densely populated, yet sixty-percent forested, Chesapeake Bay Watershed of the eastern United States, where forests are simultaneously a buffer against N loading and a nonpoint source of N to the Bay (Shulyer, 1995). The forests of eastern North America are typically very effective N "sinks", retaining a greater amount of atmospherically deposited N than they leak to surface waters (Aber et al., 1998; Lovett et al., 2002), but they also can leach elevated levels of N to surface waters following harvest (Likens et al., 1977), insect defoliations (Eshleman et al., 1998), and storm damage (Houlton et al., 2003).

Since being introduced to eastern North America, the gypsy moth (*Lymantria dispar*) has become the primary defoliator of deciduous forests of the eastern USA (Lovett et al., 2002) and these outbreaks have been documented to increase the N exported to surface waters of the Chesapeake Bay by studies using both aerial surveys (Eshleman et al., 2004) and remotely sensed data of defoliations (e.g., Townsend et al., 2004a). Gypsy moths have a typical feeding preference for oak (*Quercus* spp.) and aspen (*Populus* spp.) species in non-outbreak abundances but become less selective, general defoliators during outbreak periods (Lovett et al., 2006), creating a patchwork of defoliation on the landscape.

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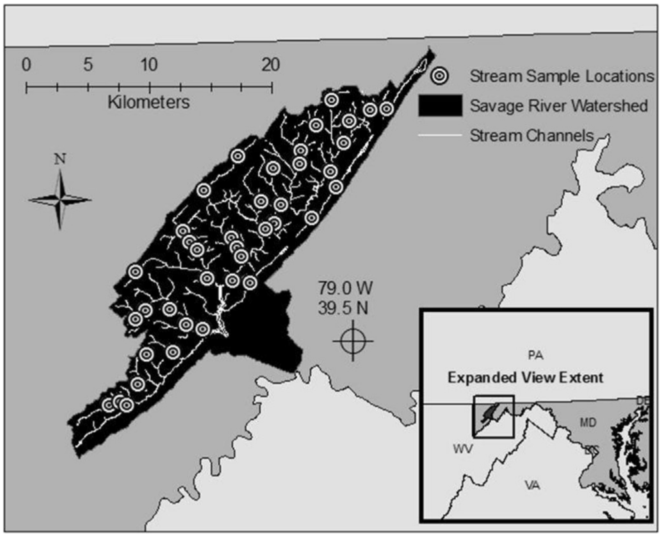

Fig. 1. Map of the Savage River watershed showing the stream reach network and sample locations.

Previous studies of defoliation-induced N export to the contributing surface waters of the Chesapeake Bay have successfully used air photos or remotely sensed maps of forest disturbance to predict spatial patterns in the loading of N to surface waters in the water year following a major outbreak (e.g., Eshleman et al., 2009). However, none of these studies has explored either the spatial or temporal characteristics of these relationships. Since research from agricultural systems has shown that the spatial arrangement of N sources (agricultural fields) and N sinks (riparian vegetation) can be very important for predicting N loading (Peterjohn and Correll, 1984; King et al., 2005; Baker et al., 2006; Weller et al., 2011), we ask: do quantitative measures of the spatial arrangement of disturbance within a watershed improve predictions of N loading to forested streams? Relative to the binary of agricultural field (N source) or riparian vegetation (N sink), answering this question in a forested system is more complicated because a pixel in a forested watershed could be an N sink or an N source depending on its disturbance status. Also, does the relationship of disturbance to N export remain static through time? To answer this question we explore the statistical relationships in years prior to and following the peak defoliation event used exclusively in previous studies of this type.

We employ a Landsat based method (Deel et al., 2012) to measure the continuous variation in forest disturbance occurring within low-order watersheds in the Savage River (SR) watershed in the western panhandle of Maryland (Fig. 1) for the five years (2005–2009) surrounding an extensive gypsy moth defoliation outbreak that peaked in 2007. Water quality is evaluated for 2006–2010, since nutrient responses in watersheds are typically lagged one year. We use linear regression analyses to determine whether different spatial-weighting schemes provide additional explanatory power in predicting spatial variation in stream water total dissolved N (TDN) concentration from five years of synoptic ($n = 40$ watersheds) stream survey data.

The serendipitous availability of five years of new synoptic stream survey data bracketing the major defoliation event in 2007 provides the unique opportunity to evaluate the importance of spatial patterns throughout a full cycle of pre- to post-disturbance. These data provide an opportunity to test these relationships outside the availability of the more costly high spatial and temporal resolution monitoring of low order streams to evaluate the influences forest disturbances have on stream N dynamics.

2. Methods

2.1. Study area

We use data from 40 randomly selected watersheds within the Savage River drainage basin, a fifth order tributary of the Potomac River situated in Garrett County, in the western panhandle of Maryland, USA (Fig. 1). While nearby to the Fifteen Mile Creek basin that has been used for similar investigations (e.g., Townsend et al., 2004b), Savage River is physiographically distinct and has a novel dataset of stream N concentrations not previously described in relationship to forest disturbances. The Savage River basin is located in the Allegheny Plateau region of the Appalachian Highlands on the windward side of the Allegheny Front. Elevations range from 374 to 940 m with an average elevation 745 m. The watershed is composed of fluvially dissected topography with soils derived from the shale and sandstone bedrock. Forests cover an average of 82% of the land within our sampled watersheds and common species present include oaks (*Quercus* spp.), black cherry (*Prunus serotina*), maples (*Acer* spp.), and eastern hemlock (*Tsuga canadensis*), as well as plantations of spruce (*Picea* spp.), pine (*Pinus* spp.), and larch (*Larix* spp.) (Foster and Townsend, 2004). Despite the presence of non-forest lands (typically hay fields) within our study area, correlation analyses of our land cover and stream water data indicate that these non-forest lands have minimal correlation ($r < 0.5$) with the variability in N concentrations within the study area. This is likely due to the small percentage of non-forested land cover, which is typically located on the gently sloping plateaus that divide the watersheds, and the minimal use of fertilizer across all watersheds. Our study watersheds are largely within the Savage River State Forest, which manages the forests on a 100-year rotation for timber harvesting and conservation (Schaefer and Brown, 1991). The SR has experienced extensive gypsy moth defoliation events during our study period with the peak defoliation event occurring in the 2007 growing season and with smaller scale defoliations in 2006 and 2008.

2.2. Stream sampling

We measured changes in stream TDN concentration following the random stream reach sampling technique outlined by Townsend et al. (2004a) and employed as part of earlier work to define the N export from the SR watershed (Hypio, 2000). The design ensures that the probability for stream selection for sampling is directly proportional to the length of the stream reach with respect to the overall length of all streams in the watershed, thus yielding an unbiased selection of stream reaches for the entire watershed. We collected 1.0 L "grab" samples of spring baseflow at least one week after a major precipitation event, from the selected stream reaches at the farthest downstream portion of the reach before its confluence with the next stream reach. The samples were kept on ice while being transported to the lab, and were then filtered and preserved (frozen) within 24 h. The TDN was measured colorimetrically on a Lachat flow injection analyzer following either an in-line or off-line heated persulfate digestion.

2.3. Stream loading estimation

Though this study does not have the high temporal frequency N sampling or watershed specific discharge measurements necessary for exact measurements of N loads, we extrapolated the spring baseflow concentrations to annual N loads based on the expected

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