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# Geochemical responses of forested catchments to bark beetle infestation: Evidence from high frequency in-stream electrical conductivity monitoring

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ABSTRACT

Under the present conditions of climate warming, there has been an increased frequency of bark beetle-induced tree mortality in Asia, Europe, and North America. This study analyzed seven years of high frequency monitoring of in-stream electrical conductivity (EC), hydro-climatic conditions, and vegetation dynamics in four experimental catchments located in headwaters of the Sumava Mountains, Central Europe. The aim was to determine the effects of insect-induced forest disturbance on in-stream EC at multiple timescales, including annual and seasonal average conditions, daily variability, and responses to individual rainfall events. Results showed increased annual average in-stream EC values in the bark beetle-infected catchments, with particularly elevated EC values during baseflow conditions. This is likely caused by the cumulative loading of soil water and groundwater that discharge excess amounts of substances such as nitrogen and carbon, which are released via the decomposition of the needles, branches, and trunks of dead trees, into streams. Furthermore, we concluded that infestation-induced changes in event-scale dynamics may be largely responsible for the observed shifts in annual average conditions. For example, systematic EC differences between baseflow conditions and event flow conditions in relatively undisturbed catchments were essentially eliminated in catchments that were highly disturbed by bark beetles. These changes developed relatively rapidly after infestation and have long-lasting (decadal-scale) effects, implying that cumulative impacts of increasingly frequent bark beetle outbreaks may contribute to alterations of the hydrogeochemical conditions in more vulnerable mountain regions.


## 1. Introduction

Forest disturbance resulting from bark beetle infestation is becoming a widespread phenomenon, affecting large forest regions in North America (Bentz et al., 2010), Europe (Seidl et al., 2011), and Asia (Tokuchi et al., 2004). The regions are characterized by large-scale tree mortality, which influences forest ecosystem structures, functions, and services (Anderegg et al., 2015; Edburg et al., 2012). Because bark beetle populations respond to shifts in thermal conditions and water stress (Anderegg et al., 2015; Bentz et al., 2010), future risks of infestation are expected to increase (Berg et al., 2006; Williams et al., 2013) due to projected climate warming and changing precipitation patterns (IPCC, 2014). For instance, forests at higher latitudes and higher elevations, which are currently untouched by bark beetles, will likely become more vulnerable under conditions of climate change (Bentz et al., 2010; Mikkelson et al., 2013b). In areas that are currently vulnerable to bark beetle infestation, the lengthening of warm season can also accelerate the development of a second generation of bark beetles (Seidl et al., 2011), further increasing the vulnerability of these regions.

It is becoming increasingly clear that the hydrological cycling of water and substances can change profoundly in bark beetle-infested regions, as for instance seen in North America (Bearup et al., 2014a; Clow et al., 2011; Edburg et al., 2012; Mikkelson et al., 2013a) and Europe (Beudert et al., 2007; Huber et al., 2004; Kaňa et al., 2013). The changes can be variable in space and time (Rhoades et al., 2013) because insect-induced forest disturbance is a highly dynamic and non-linear process, with varying development rates and different disturbance stages (Wulder et al., 2006; Reed et al., 2014). Effects include not only reductions in interception and evapotranspiration with reduced leaf area and stem density (Bearup et al., 2014a; Beudert et al., 2007; Hubbard

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et al., 2013), but also changes in water geochemistry, with reduced plant carbon uptake, increased decomposition processes, and potential loss of nutrients (Mikkelson et al., 2013b; Rhoades et al., 2013).

Although some impacts of bark beetle infestation and tree mortality show similarities to the impacts of forestry operations such as clear-cuts, recent studies have shown that conclusions regarding impacts are not easily transferrable between the two cases (Adams et al., 2012; Hais et al., 2009). One reason is that forest harvesting, to a large extent, is associated with soil disturbances due to soil compactions caused by forestry machines and the construction of roads (Adams et al., 2012; Mikkelson et al., 2013c). Such conditions result in destructing the bottom layer of vegetation, and changes in microclimatic conditions (Mikkelson et al., 2013c). Notably, whereas clear-cuts have been shown to generally increase average streamflow (Martin et al., 2000; Seibert and McDonnell, 2010), this issue has not been resolved for bark beetle infestation and associated tree mortality because few relevant studies exist, and they reported inconsistent results regarding measurable streamflow impacts across basins (Adams et al., 2012; Buttle and Metcalfe, 2000; Pugh and Gordon, 2013). For example, a recent paired-catchment study in the US (Biederman et al., 2015) compared eight infested catchments to one neighboring control catchment and concluded, in contrast to expectations, that the annual streamflow did not increase.

Questions also remain regarding the impacts of bark beetle-induced tree mortality on soil and water geochemistry, which have been shown to be diverse, and include changes in carbon (Kaňa et al., 2013; Reed et al., 2014; Xiong et al., 2011), nutrient (Beudert et al., 2007; Mikkelson et al., 2013b; Huber et al., 2004), and trace metal balances (Bearup et al., 2014b). Such changes can be complex, as exemplified by studies addressing pine forest responses to insect infestation (Clow et al., 2011; Edburg et al., 2012; Mikkelson et al., 2013b). Their results for pine forest showed that nitrogen (N) rich needles initially decayed more quickly than branches with low N and high carbon (C) concentrations. After tree dieback, the N and C released from the tree trunks then accumulated in the soil, which acted as a sink. The nutrients were then available for transport via subsurface flow or uptake by the subsequent regenerating forest. Although previous studies provided valuable insight regarding relevant processes, they did not investigate the relationships between potential characteristic variations during short-term events and long-term changes in average conditions, which may reflect the fundamental mechanisms behind the overall impacts of bark beetle infestations on hydrogeochemical conditions at various temporal scales.

It is acknowledged that there are considerable methodological and practical difficulties related to measuring the governing hydrogeochemical parameters at sufficient spatial and temporal resolutions. In particular, detection of long-term changes in average conditions typically requires multi-year measurement data. Notably, conditions may change considerably and rapidly during short hydrological events, to the extent that most substance mobilization may occur during events involving heavy rainfall or snowmelt (Clason et al., 2015; Pietroń et al., 2015). Therefore, requirements for sampling frequency and duration may exceed what is feasible for the geochemical parameters, whose determination is based on laboratory assessment, such as humic acid, N, $NO_3^-$, $NH_4^+$, phosphorus (P), trace metals, and organic carbon.

A feasible alternative to multi-sampling of hydrogeochemical parameters is provided by monitoring of in-stream electrical conductivity (EC). For instance, the use of automated sensor networks allows for high frequency on-site monitoring, which can be integrated with continuous water stage monitoring to provide high-resolution data sets over long-term spans (Hem, 2012; Maidment, 1992). EC, a normalized measure of the ability of water to conduct an electric current, is directly related to the concentration of salts dissolved in water (Hem, 2012). EC can reflect the degree of mixing of waters with different salinities, such as event water (i.e., precipitation) and different pre-event waters (i.e., water stored in the soil and/or groundwater systems of a catchment) (Ahearn et al., 2004; Laudon and Slaymaker, 1997; Martínez-Santos et al., 2014; Pinder and Jones, 1969).

Our study, which is based on seven-year, high frequency in-stream EC and streamflow monitoring in four small experimental catchments (approximately 3.5 $km^2$), focuses on the following research objectives:

1) Testing the hypothesis that insect-induced forest disturbance can change hydrogeochemical characteristics at the catchment scale, to the extent that it influences in-stream EC monitoring;
2) Determining the effects of insect-induced forest disturbance on in-stream EC responses at multiple timescales across catchments with relatively healthy forests and different disturbance stages of mortality, decay, and regeneration;
3) Testing whether the EC responses during individual hydrological events differ in catchments impacted and not impacted by bark beetles.

## 2. Materials and methods

### 2.1. Study area

The study area in the upper Vydra basin, with its four experimental catchments, is located in the headwaters of the Sumava Mountains, the Czech Republic, Central Europe (Fig. 1), and features an elevated montane plain with moderate hillslopes (Langhammer et al., 2015). Geologically, the basin is developed in the Moldanubicum (crystalline core of the Bohemian Massif), and the bedrock is mainly composed of metamorphic gneiss and schists with intrusions of granite (more than 20 m below the surface). Entic Podzols, Histosols, and Gleysols are common soil types (Němeček, 2002). The pH value of streams in this region is around 6.0, see e.g. Ferda et al. (1971) and Ruzicková and Kotrbová (2000). This region features a typical mid-latitude montane climate, with an average annual precipitation of 1370 mm and a mean air temperature of 3.6 °C (Langhammer et al., 2015).

Norway spruce (*Picea abies*), beech (*Fagus sylvatica*), and European silver fir (*Abies alba*) are the dominant tree species (Vacek and Podrazsky, 2003). Since the 1990 s, the Norway spruce in the southwestern upper Vydra basin has been subjected to bark beetle (*Ips typographus* [L.]) infestation after severe windstorms in the Bavarian Forest (Hais et al., 2009; Langhammer et al., 2015). In the study region, the infestation accelerated after the most recent windstorms in 2007 and 2008. As a result, large-scale bark beetle-induced tree mortality was present in the basin, and it affected more than 50% of the basin area by 2010. As a part of Sumava National Park, the basin had strictly limited socioeconomic activities, and the entire disturbed area was left to natural processes, without substantial human intervention or countermeasures against the bark beetle attacks. However, some affected areas have regenerated rapidly.

### 2.2. Experimental sites

Four experimental catchments in the upper Vydra basin, namely, Hajenka (HAJ), Breznicky (BRE), Rokytka (ROK), and Ptaci (PTA) (Fig. 1), were selected as study sites (Table 1). They were selected because long-term monitoring series with ten-minute EC data from 2009 to 2015 (referring to hydrological year 2009 to hydrological year 2015) were available, and because they represent