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Changes in surface water chemistry caused by natural forest dieback in an unmanaged mountain catchment

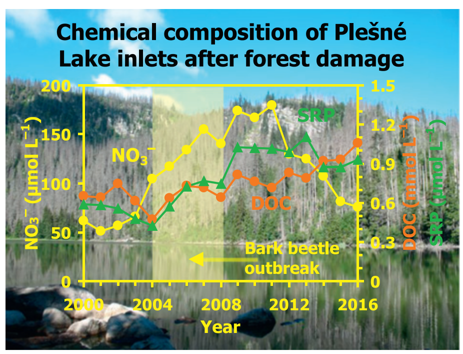
J. Kopáček [a,b,*], H. Fluksová [b], J. Hejzlar [a], J. Kaňa [a], P. Porcal [a], J. Turek [a]

[a] Biology Centre CAS, Institute of Hydrobiology, Na Sádkách 7, 37005 České Budějovice, Czech Republic
[b] Faculty of Science, University of South Bohemia, Branišovská 31, 37005 České Budějovice, Czech Republic

HIGHLIGHTS

- Forest dieback changed chemistry of all water fluxes in unmanaged mountain forest.
- Deposition of NO_3, Ca, Mg, K, Al, DOC and P decreased but their leaching increased.
- Magnitude, timing and duration of changes differed for elements and fluxes.
- Terrestrial losses of elements were less distinct but longer than after clear-cuts.
- In-lake processes mitigated changes in the water composition after forest dieback.

GRAPHICAL ABSTRACT



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ABSTRACT

Ionic and nutrient compositions of throughfall, tributaries and lake outlet were analysed in the Plešné catchment-lake system (an unmanaged mountain forest in Central Europe) from 1997 to 2016. The aim was to evaluate changes in surface water chemistry after natural forest dieback. In the 2004–2008, 93% of the Norway spruce trees were killed by bark beetle outbreak, and all dead biomass remained in the catchment. Forest dieback changed the chemistry of all water fluxes, and the magnitude, timing, and duration of these changes differed for individual water constituents. The most pronounced decreases in throughfall concentrations occurred for K^+, dissolved organic carbon (DOC), Ca^{2+} and Mg^{2+}, i.e. elements mostly originating from canopy leaching, while concentrations of NH_4^+ and soluble reactive phosphorus (SRP) remained almost unaffected. In tributaries, the most rapid changes were increases in NO_3^-, K^+, H^+ and ionic aluminium (Al_i) concentrations, while terrestrial export of DOC and P forms started more slowly. Immediately after the forest dieback, increase in NO_3^- concentrations was delayed by elevated DOC availability in soils. NO_3^- became the dominant anion, with maximum concentrations up to 346 μeq L^{-1} within 5–7 years after the bark beetle outbreak, and then started to decrease. Terrestrial exports of Al_i, K^+, H^+, Mg^{2+}, and Ca^{2+} accompanied NO_3^- leaching, but their trends differed due to their different sources. Elevated losses of SRP, DOC, and dissolved organic nitrogen continued until the end of the study. In the lake, microbial processes significantly decreased concentrations of NO_3^-, organic acid anions, H^+ and Al_i, and confounded the chemical trends observed in tributaries. Our results suggest that terrestrial losses of elements and the deterioration of waters after forest dieback are less pronounced in unmanaged than managed (clear-cut) catchments.

* Corresponding author at: Biology Centre CAS, Institute of Hydrobiology, Na Sádkách 7, 37005 České Budějovice, Czech Republic.
E-mail address: jkopacek@hbu.cas.cz (J. Kopáček).

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1. Introduction

Forest disturbances (diebacks, windthrows, clear-cuts or other harvesting methods) result in alterations of the microclimate, hydrology, and biogeochemical cycles of many elements in affected areas (e.g., Swank et al., 2001; Finér et al., 2003; Huber, 2005). Forest disturbances abruptly increase the amount of bioavailable fresh organic matter (litter, dead roots and aboveground tree parts) on the forest floor and in upper soil horizons, while nutrient uptake by trees decreases. Reduced canopy shading and lower transpiration result in elevated soil temperature and moisture (Hais and Kučera, 2008; Mikkelson et al., 2013). These conditions promote soil microbial activity and mineralization rates in soils (Zhang and Zak, 1995; Burns and Murdoch, 2005). In addition, reductions in the supplies of energy-rich plant assimilates from dead trees to mycorrhizal fungal symbionts reduces the biomass of mycorrhizal fungi, causes changes in soil microbial communities, and alters soil C and N cycling (Högberg et al., 2007). The elevated availability of inorganic N in soils is manifested by increased NH_4^+ and NO_3^- concentrations in soil solutions and increased leaching of NO_3^-, base cations (Ca^{2+}, Mg^{2+}, K^+ and Na^+), H^+, and ionic aluminium (Al_i) (e.g., Huber et al., 2004a, b; Tahovská et al., 2010; McHale et al., 2007). The intensities of individual responses depend on the disturbance type, with differences between clear-cuts and natural forest dieback (Huber et al., 2004a, b; Huber, 2005), and the extent of nitrogen-saturation of the forest ecosystem (Piirainen et al., 2002).

Natural disturbances have received less empirical attention than clear-cuts, because they are stochastic and highly variable. An understanding of their effects on ecosystem functioning is, however, very important for models assessing nutrient losses from unmanaged vs. managed forest ecosystems (e.g., Aber and Driscoll, 1997; Houlton et al., 2003). The need for data on ecosystem responses to natural forest dieback has recently increased due to climate developments. Increasing air temperature and frequency of droughts and windthrows have elevated the susceptibility of mature forests to insect attacks and large-scale tree mortalities in numerous regions in Europe, North America, and Asia (e.g., Huber et al., 2004a; Tokuchi et al., 2004; Mikkelson et al., 2013).

Studies on ecosystem changes associated with natural forest dieback usually begin after the onset of a disturbance, and the preceding background data are often lacking. Here, we present results of long-term research on Plešné Lake (a Central European mountain forest lake) that began well before a dieback of unmanaged forest in its catchment (Majer et al., 2003). This situation enabled evaluating of changes in the chemical composition of all major water fluxes within the whole catchment-lake system. The aims of this study were to (i) quantify changes in concentrations of major ions and nutrients in throughfall, stream, and lake water after the forest dieback, (ii) compare them with similar ecosystem responses following clear-cut or biomass removal from disturbed managed forests, and (iii) evaluate the dominant factors, controlling differences in magnitude, timing, and duration of these changes for individual water constituents.

2. Materials and methods

2.1. Description of the study site

Plešné Lake (PL) is situated in the Bohemian Forest (Šumava Mountains) at the Czech-Austrian border (47.777°N, 13.867°E; ~150 km south of Prague) at an elevation of 1089 m (Supporting information, SI, Part SI-1). The lake has two surface (PL-I and PL-II) and two known subsurface (PL-III and PL-IV) tributaries (Fig. SI-1). PL is a dimictic, mesotrophic lake of glacial origin, with surface area of 7.5 ha, maximum depth of 17 m, and water residence time of approximately one year. The lake was already atmospherically acidified in the early 1960s (pH < 5.4), and acidification progressed until the middle 1980s, when pH ranged between 4.4 and 4.7 (Majer et al., 2003). At present, the lake is in the process of chemical recovery from acidification, with a re-establishment of the carbonate buffering system and pH approaching ~5.5. PL is fishless at present, with recovering plankton and littoral communities and macrophytes (Čtvrtlíková et al., 2016; Vrba et al., 2016). Anoxia occurs regularly in the PL hypolimnion during both the winter and summer stratification periods (Kopáček et al., 2004).

The PL catchment (67 ha including the lake) is steep, with a maximum local relief of 288 m. The bedrock is made up of granite. The catchment is covered with acidic and shallow soils (leptosol, podsol, and dystric cambisol); wetlands and bare rocks represent ~5% and 1%, respectively. Forest vegetation occupies 90% of the PL catchment and is dominated by Norway spruce (*Picea abies*) with a minor contribution of birch (*Betula pubescens* and *B. pendula*), rowan (*Sorbus aucuparia*), and European beech (*Fagus sylvatica*). Understory vegetation is dominated by blueberry (*Vaccinium myrtillus*), fern (*Athyrium distentifolium*), and grass (*Calamagrostis villosa*). The PL catchment was N-saturated and lake water had elevated nitrate concentrations already in the early 1960s (Majer et al., 2003).

In 2000, the unmanaged mature spruce forest was healthy, with an average density of ~300 adult trees ha^{-1} and only an ~7% proportion of dead trees (Fig. 1a). Then, however, most of the PL forest was attacked by a bark beetle (*Ips typographus*) between 2004 and 2008, and 93% of the PL forest area lost >80% of its original mature spruce trees (Figs. SI-1, 2). Dead trees lost most of their needles during the first several months after infestation, and subsequently they have been continuously losing twigs, bark, and branches and have also been broken by winds (Kopáček et al., 2015). All dead biomass has been left in the PL catchment, because the area is part of the Šumava National Park (declared in 1991). The only forest management practice used to deal with the damaged stands was the manual removal of bark from some (<5%) dead trees. Natural forest regeneration started within 1–3 years after the dieback of adult trees, when the availability of sunlight on the forest floor increased due to the thinning of dead canopies. This process was rapid, and the number of young trees (seedlings, diameter of canopy < 0.8 m) increased by an order of magnitude between 2005 and 2015, with average densities of 47 and 670 trees ha^{-1}, respectively. Similarly, the biomass of understory vegetation, especially blueberry, increased after the forest dieback (Matějka, 2015).

Soils were sampled repeatedly from 9 to 21 pits distributed over the whole catchment in 1997–2001, 2010 and 2015 (Table SI-1), and continuously in 6-week intervals at one research plot (TF-L; Fig. SI-1) during 2008–2016 (Kaňa et al., 2013, 2015). Soil samples were analysed for pH and exchangeable base cations, Al_i, and H^+ (Table SI-1). The elevated litter fall, accompanying forest dieback, caused changes in the chemistry of the uppermost (O and A) soil horizons. Median values of base saturation (percent proportion of base cations in the effective cation exchange capacity) increased after the bark beetle infestation from 39 to 65% in O-horizon and from 21 to 38% in A-horizon between 1997 and 2001 and 2015, while concentrations of exchangeable Al_i decreased in both horizons (Table SI-1). For more details see SI (Part SI-1).

2.2. Water sampling and analyses

Atmospheric deposition was collected in a treeless area (elevation of 1087 m, 2 collectors) and at two throughfall plots differing in elevation (low, 1122 m, TF-L; and high, 1334 m, TF-H; 9 collectors each) in biweekly to monthly intervals (details in SI, Part SI-2). The average air temperature was 5.6 and 4.2 °C at 2 m above ground at the TF-L and TF-H plots, respectively, during 2002–2012. The TF-H and TF-L plots were affected by a bark beetle outbreak in the summers of 2004 and 2006, respectively, and all adult trees above the collectors died within 2–3 years of infestation and were broken by winds by the end of this study (Fig. 1b,c).

Samples from lake tributaries and its outlet were taken in three-week intervals and biweekly (weekly during the snowmelt period), respectively. Discharges of surface tributaries were estimated using a stopwatch and