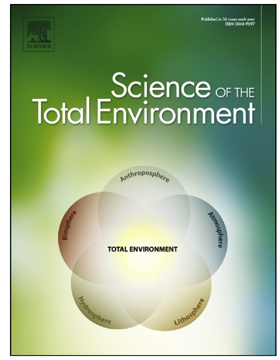
Schmidt, S.I., Hejzlar, J., Kopáček, J., Paule-Mercado, M.C., Porcal, P., Vystavna, Y., Lanta, V. (2022):
Forest damage and subsequent recovery alter the water composition in mountain lake catchments
Sci. Total Environ. **827** , art. 154293

http://dx.doi.org/10.1016/j.scitotenv.2022.154293

Journal Pre-proof



Forest damage and subsequent recovery alter the water composition in mountain lake catchments

Susanne I. Schmidt, Josef Hejzlar, Jiří Kopáček, Ma. Cristina Paule-Mercado, Petr Porcal, Yuliya Vystavna, Vojtěch Lanta

PII: S0048-9697(22)01385-7

DOI: https://doi.org/10.1016/j.scitotenv.2022.154293

Reference: STOTEN 154293

To appear in: *Science of the Total Environment*

Received date: 3 December 2021

Revised date: 20 February 2022

Accepted date: 28 February 2022

Please cite this article as: S.I. Schmidt, J. Hejzlar, J. Kopáček, et al., Forest damage and subsequent recovery alter the water composition in mountain lake catchments, *Science of the Total Environment* (2021), https://doi.org/10.1016/j.scitotenv.2022.154293

Forest damage and subsequent recovery alter the water composition in mountain lake catchments

Susanne I. Schmidt[1,2,*], Josef Hejzlar[1], Jiří Kopáček[1], Ma. Cristina Paule-Mercado[1], Petr Porcal[1], Yuliya Vystavna[1], Vojtěch Lanta[3]

[1] Biology Centre CAS, Institute of Hydrobiology, Na Sádkách 7, 37005 České Budějovice, Czech Republic

[2] present address: Department of Lake Research, Helmholtz Centre for Environmental Research, Magdeburg, Germany

[3] Institute of Botany, Czech Academy of Sciences, Dukelská 135, 37901 Třeboň, Czech Republic

*corresponding author

Abstract

Forest damage by insect infestation directly affects the trees themselves, but also indirectly affects water quality via soil processes. The changes in water composition may undergo different pathways depending on site-specific characteristics and forest components, especially the proportion of coniferous and deciduous trees. Here, we test whether changes in forest components and the intensity of disturbance can predict the chemical properties of water outflow from affected lake catchments. Information about forest regeneration (a phase dominated by deciduous trees) and the proportions of damaged and healthy coniferous trees and treeless areas were obtained from satellite data. The four study catchments of Prášilské, Laka, Plešné, and Čertovo lakes are geographically close and located in the same mountain range (Šumava Mts., Czech Republic) at similar altitude, but they differ in extents of forest disturbances and recoveries. The water quality measured at the lake catchment outflows differed, and better reflected the development of forest components and health than did meteorological (temperature and precipitation) or hydrological (discharge) variables. Several of the outflow properties (concentrations of inorganic aluminium, protons, potassium, calcium, magnesium, alkalinity, dissolved organic carbon (DOC), nitrate, and total phosphorus), responded catchment-specifically and with different delays to forest disturbance. The most pronounced differences occurred in DOC concentrations, which started to increase in the most disturbed Plešné and Laka catchments 7 and 6 years, respectively, after the peak in tree dieback, but did not increase significantly in the Prášilské catchment, which was disturbed several times during the last 3-4 decades. This study demonstrates an importance of extents of forest disturbances, the following changes in forest composition, and catchment-specific characteristics on water composition.

1. Introduction

Surface water quality in forested areas is linked to land use changes, properties of the vegetation type (Andréassian, 2004, Downing 2010, Sebald et al., 2019), and local hydrological and landscape characteristics (Fairchild and Velinsky, 2006, Tranvik et al., 2009, Kopáček et al., 2017). Both anthropogenic influences and natural processes such as sudden forest disturbances can disrupt long-term water quality dynamics (Cuypers et al., 2013, Hrkal et al., 2014, Vystavna et al., 2017, Scarlett et al., 2020). In addition, changes of water properties are closely connected to a range of meteorological and hydrological conditions, and recently are under the effects of globally increasing temperature and precipitation fluctuations (Madsen et al., 2014, Arnell and Gosling, 2016, Shabarova et al., 2021). Considering that the timing and history of disturbances as well as the environmental conditions vary among sites, we need to compare multiple systems in order to capture and better understand the factors driving water quality fluctuations. In most situations, the extent of changes in water quality reflects the severity of disturbances or the type and intensity of management. To tackle issues arising from changes in water quality, there is an urgent need for studies that aim to disentangle the effects of disturbances and environment characteristics by monitoring multiple sites over several years.

Forest disturbances by bark beetle infestations have been under increasing focus in recent years in both North America and Europe (Seidl et al., 2014, 2017). In the mountain systems of Central Europe, bark beetle infestations affect large areas of mature coniferous forest of Norway spruce (*Picea abies*), including those situated at high altitudes (Hais et al. 2009, Pasztor et al., 2014, Seidl et al., 2014, Näsi et al., 2015). Apart from conifers, these forests also contain subdominant deciduous trees, such as European beech (*Fagus sylvatica*), rowan (*Sorbus aucuparia*), birch (*Betula pubescens* and *B. pendula*), and maple (*Acer* *pseudoplatanus*), which are not infested by the spruce bark beetle. Deciduous trees can in such catchments have a temporary advantage in periods when conifers disappear (Sedmáková et al., 2019, Baier et al., 2007, Żywiec et al., 2013, Holeksa et al., 2017, Moravčík, 1994), but later during the forest succession, they are generally displaced by regenerating spruce stands. Growth patterns of deciduous and coniferous trees vary both temporally and spatially, and effects on the chemical properties of soil and consequently on water quality in streams and downstream water bodies can last months, years, and even decades.

Besides their effects on surface and soil temperature, soil wetness, and hydrological characteristics, natural disturbances that destroy large stands of trees can lead to a series of biogeochemical processes in soils and waters, usually lasting several years (Clark et al., 2010, Huber et al., 2004, Kopáček et al., 2017, Mikoláš et al., 2021, Schmidt et al., 2021). For instance, a recent bark beetle outbreak in the unmanaged catchment of Plešné Lake (Czech Republic), and the decayed dead biomass released biodegradable organic carbon and mineral components like ammonium (NH_4^+), phosphate (PO_4^{3-}), and base cations (K^+, Ca^{2+}, and Mg^{2+}) into the soil (Kaňa et al., 2014, 2015), which was followed by a pronounced increase in nutrient leaching into the catchment surface water (Kopáček et al., 2017; Schmidt et al., 2021). The changes in water composition included increasing concentrations of nitrate (NO_3^-), protons (H^+), ionic aluminium (Al_i), K^+, Ca^{2+}, and Mg^{2+} soon after forest disturbances, while increased concentrations of dissolved organic carbon (DOC) was delayed for several years (Kaňa et al., 2013; Kopáček et al., 2017; Schmidt et al., 2021). This highlights the need for studies on disturbances to include the recovery phase, because some catchment and soil characteristics react with pronounced delays (Schmidt et al. 2021).

In this study, we assessed changes in the coniferous and deciduous components of the forest as predictors of both immediate and delayed responses to water quality dynamics. We studied the long-term dynamics of water quality in the outflow of four lakes (Čertovo, Laka, Plešné, and Prášilské) with forested catchments situated in the Šumava Mts. (Czech Republic). Our aim was to disentangle the effects of climate variables and forest stand canopy components on changes in water quality. We predicted that changes in lake catchment outflow water quality could be related to the proportion of healthy, damaged, or regenerating coniferous trees, and regenerating healthy deciduous trees. In addition, we assessed whether a forest disturbance index based on satellite data could be used to predict linear and nonlinear changes in lake catchment water quality.

Our hypotheses were: 1) immediate responses of water chemical conditions are more due to meteorological and hydrological influences than to changes in forest structure, 2) the influence of forest disturbances on water quality dynamics correlates with forest composition (coniferous and deciduous tree components) and forest health, and 3) water quality properties respond with the same delay to forest disturbances in all catchments of the same mountain range.

2. Material and methods

In four lake catchments of the same climatic zone, i.e., temperate forests at an altitude of ca. 1000 to 1400 m a.s.l. in Central Europe, we investigated the short-term effects of meteorological influences and the short and medium-term effects of forest change, estimated from satellite imagery, on catchment outflow water quality. To calculate the proportion of deciduous and coniferous trees and the proportion of coniferous stands that were healthy in contrast to those that showed signs of severe damage, we used the FII index of the Forest Management Institute of the Ministry of Agriculture of the Czech Republic (Ústav pro hospodářskou úpravu lesů, UHUL; http://geoportal.uhul.cz/mapy/mapyzsl.html). We also calculated the damage index cFII (Schmidt et al., 2021) for a catchment-scale assessment of forest health. All the proportions and the index were calculated for each year that the data were available, excluding periods with errors associated with clouds. Together with long-term data of air temperature, precipitation, and catchment outflow, their effects on the chemical properties of water were tested by linear parametric models and nonlinear smoothing models.

2.1 Study sites

The four study catchments of Čertovo, Plešné, Prášilské, and Laka lakes (Supplementary Information (SI) Figure A.1, Table A.1) differed in the intensity and duration of disturbances they were subjected to during the last 30 years. All catchments are in unmanaged mountain areas of the Šumava National Park and land use is 100% forest. Hence, anthropogenic impacts in terms of land use are negligible. All four catchments suffered under long-term acidic deposition and have been nitrogen-saturated since the 1960s (Veselý et al., 1998; Majer et al., 2003). These effects were, however, similar in all catchments due to their similar altitudes and close vicinity on the same site of mountain range (Supplementary information, SI, Figure A.1). All four catchments have a cold continental climate, with an average annual air temperature of 4.7 °C (Turek et al., 2014). The annual precipitation averaged ~1,300 mm during the study period (Kopáček et al., 2017).

The catchment bedrock is formed by granite in the Plešné catchment, mica-schist (muscovitic gneiss), quartzite, and small amounts of pegmatite in the Čertovo catchment, mica schist in the Prášilské catchment, and mica schist and granodiorite in the Laka catchment (Veselý, 1994, 1998; Janský and Zbořil, 1999). The granodiorite in the Laka catchment has a higher calcium concentration than mica schist, which has Mg > Ca (Veselý et al., 1998). From a hydrogeological point of view, the dominant rocks have low permeability, with water flow limited to bedrock fissures and surficial aquifers formed in weathered zones (Czech Geological Survey, 2019). Porous cavities between large boulders may be particularly important for subsurface water transport (Vystavna et al., 2020).

The soils in the Plešné catchment are mostly sandy (75%), low in clay content (2%), and include shallow leptosols (38%), podsols (29%) and dystric cambisols (27%), with an average soil depth of 33 cm; the remaining ground surface is bare rock (5%) and wetland (1%) (Kaňa et al., 2014). The soils in the Čertovo catchment are ∼0.5 m deep dystric cambisol (58%), podsol (21%), and shallow (<0.2 m) leptosol (17%); wetlands and bare rocks represent ∼3% and 1%, respectively. Fine soil is sandy (48–81%) with a low (1–4%) content of clay and a catchment weighted mean pool of 225 kg m^{-2} (< 2 mm, dry weight soil fraction). In the Prášilské and Laka catchment, soils are dominated by kryptopodsol (KPm20), podsol (PZm20), and glej (GLh07) (Němeček et al., 2001).

All catchments were predominantly covered by a primeval Norway spruce forest. About 90% of the Plešné catchment was covered with mostly mature Norway spruce until the outbreak of a bark beetle (*Ips typographus* L.) in 2004–2008, when >75% of trees were damaged (Fluksová et al., 2020). Since then, in addition to dominant spruce saplings, the forest has increasingly consisted of birch, rowan, and beech (Kopáček et al., 2017). The Čertovo catchment forest was almost intact in 2000 and consisted mainly of Norway spruce trees with an average age of 140 years, with minor contributions of beech and fir (Kopáček et al., 2016). It was affected by wind-throws in 2007 and 2008, which broke most of the trees along the south–western ridge of the catchment (Kaňa et al., 2014). Other relatively small patches with broken trees and a subsequent bark beetle outbreak occurred in the northern part and throughout the whole Čertovo catchment in 2007–2011. Altogether, the total area of damaged forests (with ~50% dead trees) in the Čertovo catchment increased from ~4% to 18% from 2000 to 2011 (Kopáček et al., 2016). Another windthrow uprooted most trees in a relatively small area along the western ridge of the Čertovo catchment in October 2017 (Kopáček et al. 2020). The vegetation in the Prášilské and Laka catchments has not been characterized in detail. Most of the forest decline occurred in the Laka catchment after the 2007 and 2008 wind-throws and the subsequent bark beetle outbreak. The Prášilské forest was significantly disturbed by wind-throws already between 1984–1995 when the proportion of mature Norway spruce stands in the catchment decreased from ~80 to 30% (Veselý et al., 1980). The coniferous trees had slowly recovered after the forest decline in the late 1980s–early 1990s (Veselý et al., 1998) and reached a new equilibrium in 2005, from which time a more severe bark beetle infestation occurred until 2010. This was probably one reason for the highest proportion of birch, rowan, and European beech in the regenerating Prášilské forest compared to the other catchments. The rest of the mature Prášilské forest was disturbed similarly to the Laka catchment after the 2007–2008 storms.

2.2 Water sampling and analyses

Water samples from the outlets of Plešné and Čertovo lakes (Supplementary information, SI, Figure A.1) have been collected at 3-week intervals starting in 1997 and 1998, respectively. Data prior to this period come from Majer et al. (2003). Data on water composition of the Prášilské and Laka lakes were taken from Veselý et al. (1998) and Kopáček (unpubl. data) and are based on irregular (till 2004), then monthly sampling with additional sampling at high precipitation and snowmelt. During sampling, the water was pre-filtered through a 200 µm sieve to remove coarse particles. Samples were stored in the dark at 4 °C until analysis and were analysed within 2 days. In the laboratory, samples were filtered through either membrane filters (0.45 µm; ions) or through glass-fibre filters (0.4 µm; other analyses).

The water quality characteristics selected for this study are commonly used in freshwater monitoring. These characteristics reflect the key biogeochemical processes in catchment-lake systems and have been shown to change following the bark beetle disturbances (Kopáček et al., 2018; Kaňa et al. 2019). Alkalinity was determined by Gran titration (Gran, 1950). DOC was analysed with TOC 5000A and TOC-L analysers (Shimadzu). Dissolved aluminium (Al) was fractionated according to Driscoll (1984) to non-labile Al and ionic Al species (Al_i) using cation exchange treated samples. Aluminium concentration was determined using the spectrophotometric method of Dougan & Wilson (1974). We assumed that concentrations of organically bound Al (Al_o) were equal to the non-labile Al. The concentration of Al_i was the difference between the concentration of dissolved Al and Al_o concentrations (Kopáček et al. 2001). We determined total phosphorus (TP) according to Kopáček and Hejzlar (1993). Concentrations of NH_4^+-N, NO_3^--N, K^+, Ca^{2+}, Mg^{2+}, Na^+, Cl^-, and SO_4^{2-} were determined by ion chromatography (Dionex IC25 and DIONEX 5000+, USA). The annual mean concentrations in the lake outflows were calculated as arithmetical means.

2.3 Climatic and hydrological data

Annual mean temperatures in the Plešné and Čertovo catchments were derived from measured hourly temperature data series in these catchments in the years 2002 to 2012 using regression modelling from temperature data at the long-running climatic station Churáňov (operated by the Czech Hydrometeorological Institute (CHMI); 49°04′N, 13°37′E; 1118 m a.s.l.) according to Turek et al. (2014). For the Laka and Prášilské catchments, with regard to their location, the average temperatures of the Plešné and Čertovo catchments, respectively were used.

Annual precipitation in the Plešné and Čertovo catchments has been measured since 2000 (Kopáček et al., 2017) and 1998 (Kopáček et al., 2016), respectively. Remaining annual precipitation data in the data series 1990 to 2019 used in this study were calculated from regressions with annual precipitations at nearby CHMI climatic stations, i.e., Churáňov for the Plešné catchment and Špičák (49°10'N, 13°13'E; 973 m a.s.l.) for the Čertovo catchment. Annual precipitation data in the Prášilské and Laka catchments were approximated by data from the closest CHMI climatic station, i.e., Prášily (49°6'25"N, 13°22'43"E; 883 m a.s.l.).

The outflow from the Plešné and Čertovo lakes has been continuously measured at the outlets of the lakes with calibrated gauges since 2001 and 1998, respectively. The other data on annual outflow in the data series 1990 to 2019 of this study were calculated from the values of the average runoff coefficient (i.e., RC = Discharge / Precipitation in the catchment), which were 0.81 for the Plešné and 0.89 for the Čertovo catchment during the measured periods, respectively. The annual outflow values from the Prášilské and Laka catchments were approximated using an average runoff coefficient of 0.85 (calculated from the two other catchments) and the local precipitation. The water residence times in lakes differed from 0.03 yr in Laka to 1.6 yr in Čertovo (Kopáček et al., 2016, 2017, and unpubl. data; Table A.1), causing a between-lake variability in in-lake processes. This effect is discussed in section 4.

2.4 Satellite data analyses (for forest composition and disturbance)

The forest infrared index (FII) of the Forest Management Institute of the Ministry of Agriculture of the Czech Republic was constructed using the reflectance of infrared light of Landsat multispectral satellite scenes (with a spatial resolution of 30 × 30 m), retrieved in August of the respective years (Kukrál, 2015). It was calculated by normalizing the ratio of forest reflectance in the infrared bands of the SWIR (short wave infrared) and NIR (near-infrared) spectra and is available at http://geoportal.uhul.cz/mapy/MapyZsl_Info.html (accessed in November 2021). The reflectance of the forest stand in the near infrared band of NIR radiation contains information about the condition of the cell assimilation apparatus. The reflectance of the forest stand in the middle infrared band of SWIR radiation contains information about the water content in the assimilation apparatus. Note that the FII is most reliable for trees older than 20 years and with a density greater than 70% of the area covered by canopy. In other cases, the raster cell receives a value of 15, and represents any area not covered by forest. The FII data were available for the years 1984, 1986, 1987, 1991 – 2007, 2009 – 2017. Note also that the satellite derived information reflects canopy structure and misses tree components in the undergrowth.

2.5 Damage classification

We identified the degree and type of forest disturbance in each lake catchment by the cFII (Schmidt et al., 2021). This catchment scale index was calculated from the FII by averaging the weighted factors of forest damage in the catchment area and its linear normalization in the range from 0 (no disturbance) to 1 (complete damage); for a more detailed explanation see SI, section B. The FII distinguishes between deciduous and coniferous trees for each forest damage class. The only exception from distinguishing between damage classes for each tree component is that “very strong damage” and “strong damage” are one class for the deciduous trees, while they are two classes in coniferous trees. When clouds, fog or smog are detected, the assessment is not performed (Kukrál, 2015) and this is indicated by grey pixels. No cFII was calculated for those periods.

2.6 Forest components: deciduous versus healthy and disturbed coniferous trees

If the recovery from a disturbance results in the faster growth of deciduous than coniferous trees, and thus deciduous trees dominate the canopy, the catchment scale cFII will show a decrease in disturbance. However, this changed tree component will have other impacts on catchment outflows than just the tree coverage of the soil alone (compare Hrkal et al., 2014). Therefore, in addition to the catchment scale cFII, here, we also related hydrochemical conditions to the ratios of deciduous versus healthy or damaged coniferous trees. The sum of the proportions of deciduous and healthy or damaged coniferous trees plus no forest stands in all raster cells of a catchment is 1, as is the sum of the proportions of the FII classes.

The reclassification of the damage classes from the original FII index is given in Table B.2. The two strongest FII damage classes for coniferous trees were combined into one class “damaged coniferous”, as it was considered that trees in these two classes would not recover. The remaining coniferous classes were combined into the class “healthy coniferous”, comprising healthy and slightly damaged coniferous tree-dominated raster cells (Table B.2). These two classes were contrasted with the proportion of deciduous trees – a subdivision of deciduous trees was not considered useful, as the proportions of deciduous trees were small, and they are not generally affected by the bark beetle, which was the major influence in the catchments. Note that treeless parts of a catchment are usually covered by understorey vegetation (grass, fern, and blueberry) and successfully regenerating trees which are not captured by the FII. The "no trees" category might therefore also be called "poorly regenerating forest".

2.7 Statistical analyses

Forest disturbance and composition

The relative proportion of deciduous, damaged coniferous, and healthy coniferous-dominated raster cells were calculated for each year and Generalized Additive Models (GAMs) were run in dependence on time. Developments of chemical characteristics in the outflow over time were not expected to be linear, because disturbances over time were not linear. Therefore, methods such as the Mann Kendall index are not appropriate in this case. We used nonlinear GAMs instead, to narrow down which disturbance acted during which period in which lake catchment and how it affected catchment outflow water quality characteristics.

Water quality variables in the year of disturbance versus meteorological events or forest characteristics and their changes

We tested the effects of the catchment-scale disturbance index (cFII), the catchment-scale proportions of deciduous tree-dominated and healthy or damaged coniferous tree-dominated raster cells, mean annual temperature, annual precipitation amount and water flow on annual mean concentrations of individual water chemical properties in the four lake outflows. We expected that weather may have linear or nonlinear immediate effects, depending on the catchment and the chemical / physical variable. We therefore used parametric linear models and nonlinear GAMs, analogous to the approach by Xu et al. (2020). The GAMs allowed the inclusion of a non-parametric smoother in parallel to the parametric models. The predictors were fitted as smoothed terms. The *p* values of the linear models were Benjamini-Yekutieli-corrected for multiple testing (Benjamini and Yekutieli, 2001), which is a less severe correction than the one according to Bonferroni (Legendre & Legendre, 2012). Since after this multiple testing correction none of the nonlinear models were significant anymore, we used only linear relationships for testing relationships between forest disturbances after up to 10 years of delay (see next section).

Water quality variables in the years following disturbances, with a time delay of up to 10 years

A previous study had shown that not only the strength but also the direction of relationships of some variables (e.g., DOC or NO_3^-) responding to forest damage can change when tested along a series of annual delays (Schmidt et al., 2021). Instead of using a time delay as a nonlinear predictor, we tested such responses to forest change in the four catchments individually for a suite of delays of up to 10 years in individual linear models. While this increased the number of models, each individual model was thus kept simple and easily interpretable. We extended the previous study (Schmidt et al., 2021) by not only using the damage index cFII as a predictor for water quality, but also by including the catchment-scale proportions of deciduous tree-dominated and healthy or damaged coniferous tree-dominated raster cells. The tested water quality properties were the same as in the linear and nonlinear test of meteorological and hydrological variables versus indicators of forest disturbance. However, since the effects of meteorological and hydrological variables are rather short-lived, we did not include them in the tests on delays. All data analyses, except where indicated, were performed in R v. 4.1.0 (R Core Team, 2021).

3 Results

3.1 The development of forest canopy composition and health

The proportion of raster cells dominated by healthy coniferous trees decreased, while the proportion of deciduous and damaged coniferous trees increased in three out of four catchments (Prášilské, Plešné, Laka) during the study period (Figure 1; Table 1; SI Figures C.1 to C.4). In the Prášilské catchment, raster cells dominated by deciduous trees increased significantly (Table 1) and reached ca. 20% in 2015 (Figure 1; SI, Figure C.4). The catchment-scale cFII index showed a nonlinear trend for the Prášilské catchment, which has been impacted since the 1980s. The coniferous trees in the Plešné catchment were affected by a bark beetle attack from 2004 until 2010, with a peak of disturbance in 2008 and a significant increase in damaged coniferous trees (Table 1). The recovery phase of conifers began after 2008 and lasted until the end of this study (2017), with a gradual increase in the proportion of deciduous trees taking place from 2010 onwards (Figure 1). The Laka catchment was severely disturbed in 2007, since then, the proportion of raster cells dominated by healthy coniferous trees and the number of raster cells classified as damaged coniferous trees increased significantly (Figure 1, Table 1). Forest disturbances in the lake catchments ranged in intensities in the following sequence from not (or negligibly) disturbed to strongly disturbed: Čertovo < Prášilské < Plešné < Laka (SI Table C.1).

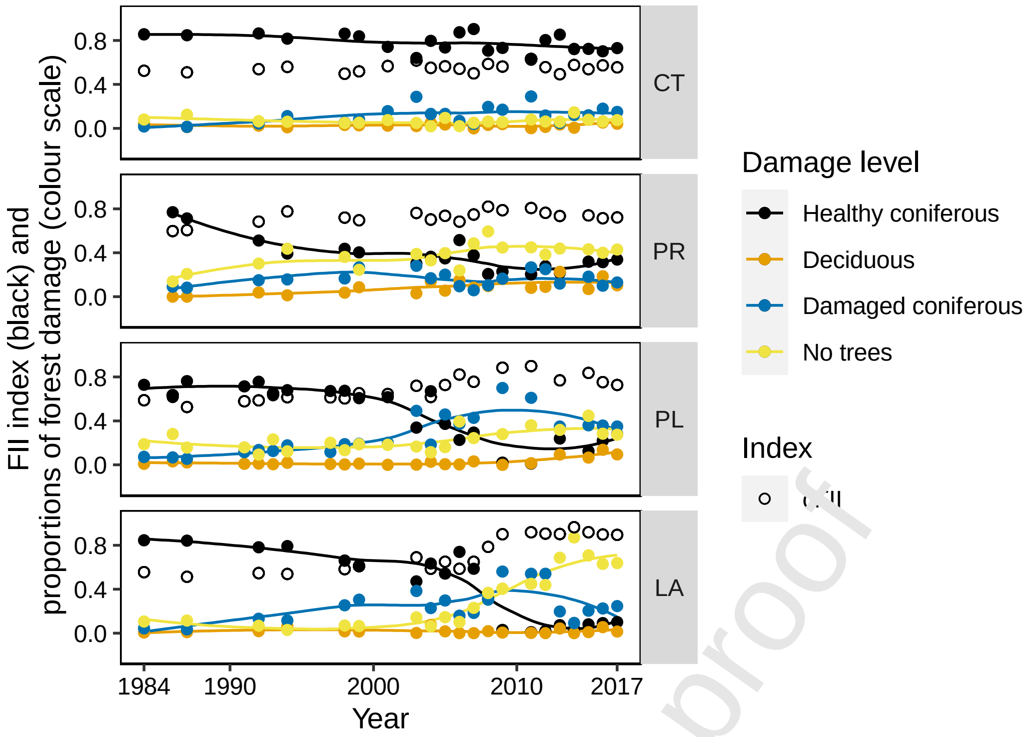


Figure 1: cFII (calculated according to Schmidt et al., 2021; black open dots) and proportions of healthy and damaged coniferous-dominated raster cells (black and blue filled dots, respectively) versus the proportion of deciduous tree-dominated raster cells (dark orange filled dots) over time in the four catchments. Line and coloured areas are the fitted generalized additive model and confidence interval, respectively. CT = Čertovo, PR = Prášilské, PL = Plešné, LA = Laka.

*Table 1: Significant generalized additive model (GAM) parameters for the nonlinear trends shown in Figure 1. CT = Čertovo, PL = Plešné, LA = Laka, PR = Prášilské catchments. Healthy conif. = proportion of healthy coniferous-dominated raster cells, damaged conif. = proportion of damaged coniferous-dominated raster cells, deciduous = proportion of deciduous-dominated raster cells. S value: smoothing term; F = ANOVA test statistic; p = probability level. The stars indicate the statistical significance levels: *, p = 0.05; **, p = 0.01; and ***, p = 0.001.*

Site	Component	S value	F	p	
PR	Deciduous	106.38	5.16	0.013	*
PL	Damaged conif.	41.80	19.26	0.000	***
LA	Healthy conif.	-26.04	7.59	0.003	**
LA	Damaged conif.	28.51	3.77	0.034	*

3.2 Temporal trends in water quality and climatic variables

Air temperature gradually increased in all four catchments (Figure 2). The composition of lake outflows from the four catchments differed in absolute values, ranges, and temporal trends for most variables (Figure 2). Concentrations of SO_4^{2-} decreased in all catchments, while H^+ decreased in all catchments but Laka. All three disturbed catchments showed peaks in concentrations of K^+, Mg^{2+}, and NO_3^- around 2010. TP was low in the Čertovo and the Laka and Prášilské catchments. In these catchments, no models involving concentrations of TP were significant (see also below, and SI, Table D.1). The TP concentrations were highest in the Plešné catchment, and increased after the bark beetle infestation (Figure 2).

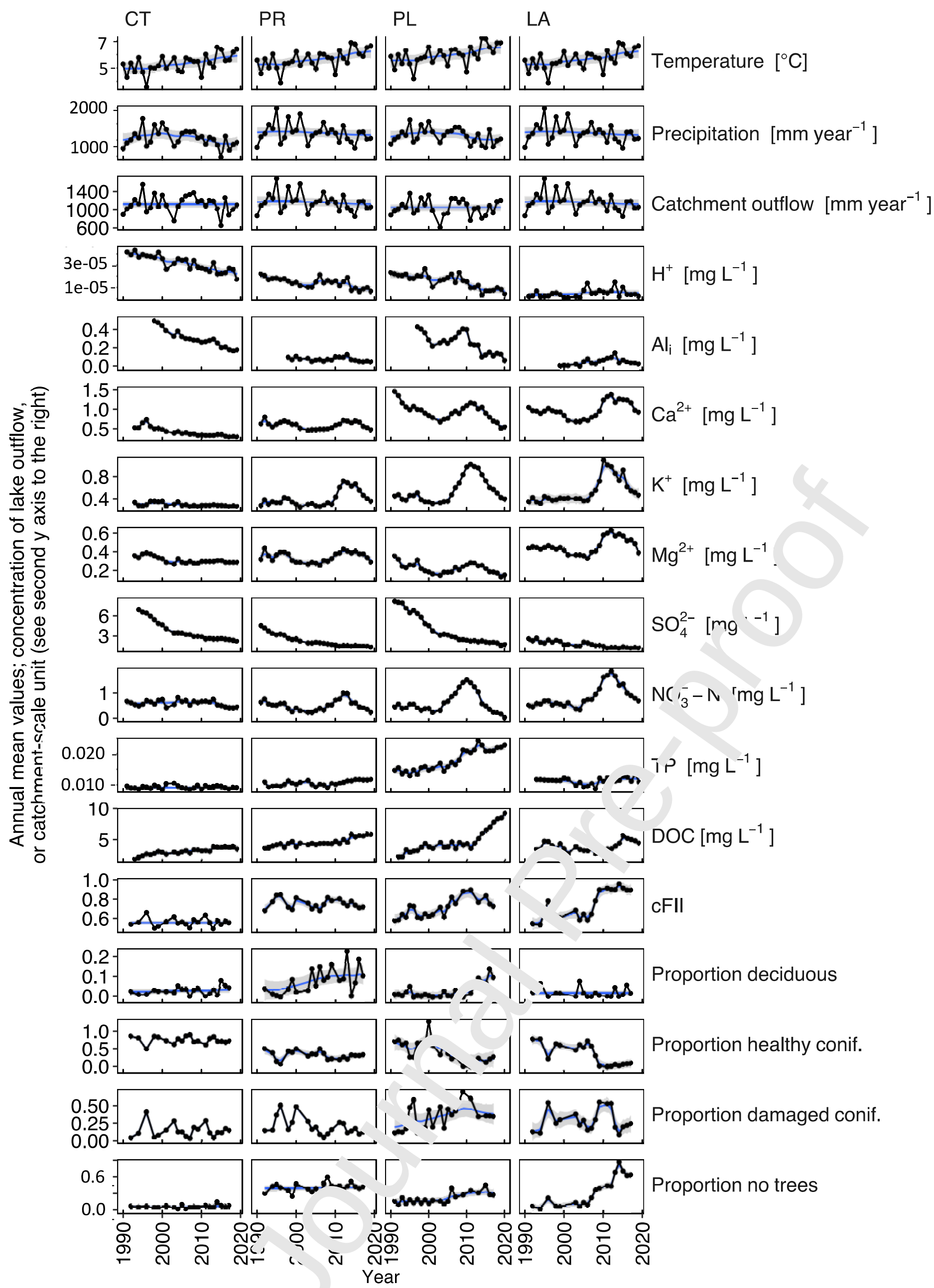


Figure 2: Changes in water chemical characteristics, climatic and hydrological characteristics, cFII index and proportions of forest types over time (black dots). GAM smoothening was used to fit the trends, depicted as blue lines with grey confidence intervals. "Proportion deciduous" = proportion of deciduous-tree-dominated raster cells; "Proportion healthy conif." = proportion of healthy-coniferous-tree-dominated raster cells; "Proportion damaged conif." = proportion of damaged-tree-dominated raster cells; "Proportion no trees" = proportion of raster cells without trees older than 20 years. TP = total phosphorus;

lake catchments: CT = Čertovo, PR = Prášilské, PL = Plešné, LA = Laka. The complete version including non-significant observations see in the SI, Figure D.1.

3.3 Relationship between water quality versus hydrological, meteorological, and forest characteristics

There was only one significant model using meteorological (precipitation and temperature) or hydrological data (an increasing temperature correlating with increasing alkalinity in the outflow from Plešné; SI, Table D.1). Models with forest characteristics as the independent variable were only significant for the Plešné and Laka catchment (Table 2; SI, Table D.1).

Table 2. Partial results of generalized additive models (GAMs) of the effects of the disturbance index (cFII), the proportion of treeless raster cells (nt), the proportion of raster cells with deciduous forest (e), and the proportion of raster cells with healthy coniferous trees (hc) on water quality characteristics. Only GAMs scoring significant are presented. The full table is given in SI, Table D.1.

		NO_3^-	TP	K	Ca^{2+}	Mg^{2+}	SO_4^{2-}
PL	cFII	*↗	*↗	*↗			*↘
	nt		*↗	*↗			
	e						
LA	cFII	*↗		*↗	*↗	*↗	*↘
	nt	*↗		*↗	*↗	*↗	*↘
	hc	*↘		*↘	*↘	*↘	*↗

With the cFII variable, concentrations of NO_3^- and K^+ increased, while SO_4^{2-} decreased in the Plešné and Laka catchments, Mg^{2+} and Ca^{2+} increased in Laka, and TP increased in Plešné (Table 2; SI, Table D.1). There was a positive correlation between the proportion of treeless raster cells with outflow properties (TP and K^+ in the Plešné catchment and NO_3^-, K^+, Mg^{2+} and Ca^{2+} in the Laka catchment). In the Plešné catchment, an increasing proportion of deciduous tree-dominated raster cells correlated positively with alkalinity and DOC (SI, Table D.1). In the Laka catchment, the proportion of raster cells dominated by healthy coniferous trees was negatively correlated with NO_3^-, K^+, Mg^{2+}, and Ca^{2+}, but positively with SO_4^{2-} (Table 2; SI, Table D.1).

3.4 Delayed responses of water quality after forest disturbances

Water chemical properties correlated with cFII and the proportions of raster cells dominated by tree components after time delays of up to 10 years in Plešné, Laka and Prášilské catchments (Table D.2). In the Laka catchment, SO_4^{2-} correlated negatively with cFII within two years. In the Plešné catchment, DOC increased with increasing cFII with a 7- to 10-year delay, while the delay was only 6 years in the Laka catchment. In the Plešné catchment, TP increased with increasing cFII with a delay of 2 to 7 years, with an increasing proportion of treeless raster cells with a 2- or 3-year delay, with the proportion of deciduous trees after a 5- to 10-year delay, and with the proportion of healthy coniferous trees with a 3- to 10-year delay.

In the Prášilské catchment, SO_4^{2-} concentrations responded negatively to increasing cFII and to the proportion of treeless raster cells after 7 and 8 years, and DOC increased with the proportion of deciduous tree-dominated raster cells after 8 and 10 years. Models of cFII and water quality were significant 38 times and models based on the proportion of deciduous trees were significant in only 12 cases. For more details see SI, Part D, Table D.2

4 Discussion

Changes in the proportions of forest components and health had immediate as well as delayed effects on water composition in affected catchments. This was true not only for the Plešné catchment, as shown previously (Kaňa et al., 2013; Kopáček et al., 2017; Schmidt et al., 2021), but also for the two other disturbed Prášilské and Laka catchments. This finding is in concordance with results found in other catchments worldwide, e.g., in Canada (Hicke et al., 2012), Japan (Tokuchi et al., 2004), Central Europe (Beudert et al., 2014), and the USA (Aber et al., 1997, De Rose et al., 2007; Griffin et al., 2011; Mikkelson et al., 2013).

In this study, we used chemical composition of lake outflows instead of inlets that would otherwise more straightforwardly reflect changes in vegetation cover. The different water residence times of lakes thus differently affected in-lake removal of some water constituents, especially NO_3^-, H^+, TP, DOC, and Al_i (e.g., Kopáček et al., 2019). Their concentration changes were thus less pronounced in outflows than inlets, but their trends remained identical (Kopáček et al., 2016; 2017). Moreover, the study lakes have 3–7 inlets and their sub-catchments are in some cases too small for using remote sensing data based on the Landsat sensor (30 m resolution) with a reasonable accuracy. The composition of lake outlets reflects and integrates changes in whole catchments, thus providing the simplest way of long-term monitoring of temporal changes in small catchment-lake systems.

The forest disturbance index cFII and other satellite data-derived variables for forest composition and health explained more variation in the catchment outflow composition in the same year than hydrological and meteorological characteristics. Therefore, our hypothesis that meteorological and hydrological properties would better predict the chemical properties of the same year was rejected. This contrasts with several previous results where hydrological and meteorological patterns were in good agreement with water chemical characteristics (e.g., Freeman et al., 2001; Temnerud & Weyhenmeyer, 2008). In our study area, the influence from forest disturbances was more severe during the period studied than the meteorological and hydrological influences.

Forest composition and forest health as predictors in general

The proportions and health of forest components played important roles in the mid- to long-term development of chemical properties in the three disturbed catchments. This confirms the second hypothesis predicting influences of forest disturbances on water quality dynamics being related to forest composition (coniferous and deciduous tree components) and forest health. In contrast, none of the forest characteristics changed much over time in the undisturbed Čertovo catchment, serving thus as an unaffected control for studies on ongoing lake and catchment changes.

The fact that the responses varied considerably among the disturbed Laka, Plešné, and Prášilské catchments underlines that forest disturbances create complex patterns comprising different growth structures and recovery stages, which cannot be simply used as a proxy for changes in landscape patterns. Instead, environmental constraints that interact with forest disturbances must be considered (Gundersen et al., 1998; Huber et al., 2004; Kallenbach et al., 2018; Rosenvald and Rosenvald, 2017). In addition, catchment-specific responses to forest disturbances limit a simple extrapolation of results from one site to another. One reason is that changes in water composition following forest disturbances depend on site-specific, small-scale hydrogeological patterns, mediated by soil. Unlike meteorological influences that tend to vary at the hectare scale or above, and can therefore be extrapolated easier than soil processes, small-scale soil processes are not transferrable across areas (Hrkal et al., 2014), varying even at centimetre and lower scales (Franklin and Mills, 2009; Pagel et al., 2014; Schmidt et al., 2017).

The catchment outflow responses to forest disturbances varied for individual chemical variables, for disturbance types, and with different delays. This indicates that catchment-specific conditions in the three disturbed lake catchments shaped the response more than the strength of the disturbance, and we thus reject our hypothesis that the dynamics of water quality properties would respond with the same delay to forest disturbances in all catchments from the same mountain range.

Comparison the Laka and Plešné catchments

In many ways, the Plešné and Laka catchments were quite similar in the development of the chemical properties of their outflow, as they suffered from the bark beetle infestation and vast tree dieback in a similar way. The dieback started later in Laka though, and when looking more closely, these two catchments differed in their detailed responses of physical and chemical properties to tree dieback and recovery. Deciduous trees became established to a different degree before they were outcompeted by recovering coniferous trees in the two catchments. In the Plešné catchment, only the increase in damaged coniferous trees was significant, while in the Laka catchment, also the decrease in healthy coniferous trees was significant. The catchments differed in chemical characteristics of outflows due to different responses to atmospheric acidification. The entire Šumava region received similarly high levels of acidic deposition, increasing until the late 1980s, and then sharply decreasing (Kopáček et al., 2017). Local conditions, such as soil depth and composition and also catchment steepness, however, predetermined how much SO_4^{2-} and H^+ from the acidic deposition was retained in soils and for how long. In this context, concentrations of SO_4^{2-} and H^+ decreased in the Plešné catchment since the early 1990s, consistent with the general trend of recovering waters in Europe (Stoddard et al., 1999). In contrast, SO_4^{2-} and H^+ concentrations were lowest in the Laka outflow already in the early 1990s (Veselý et al., 1998), and the following changes during the recovery from atmospheric acidification were less pronounced than in the other disturbed catchments (Figure 2; Figure D.1). One possible explanation for this difference in SO_4^{2-} and H^+ concentrations between the Laka and Plešné catchments is the flatter topography of Laka catchment, and consequently, the deeper soils that retained more deposited SO_4^{2-} and have been releasing it more slowly than the steeper and soil-poorer Plešné catchment. The Laka catchment might also have been better buffered against atmospheric acidic deposition due to subtle differences in the geological bedrock quality, since granodiorite with a high calcium concentration underlies parts of this catchment (Veselý et al., 1998). The lower extent of soil acidification in the Laka catchment also most likely resulted in lower gibbsite [$Al(OH)_3$] dissolution. Consequently, the concentrations of exchangeable Al_i ions on the soil exchangeable complex were probably lower, while those of base cations were higher in the Laka than Plešné soils during the peak of acidic deposition (Figure 2). This resulted in a lower proportion of base cations liberated from decomposing dead biomass after tree dieback being retained in the Laka soils and releasing less Al_i to the receiving waters. In contrast, in the Plešné catchment with low soil base saturation, the K^+, Ca^{2+}, Mg^{2+}, and NH_4^+ liberated from the decaying biomass replaced more H^+ and Al_i from the soil sorption complex and increased their in-lake concentrations (Kaňa et al., 2015, 2019), and were themselves released to receiving waters only with a delay. The more pronounced, and slightly slower, cation exchange processes in the Plešné soils thus temporarily delayed the ongoing recovery from atmospheric deposition more in the Plešné than the Laka catchment.

The DOC concentrations started to increase significantly with increasing cFII in the Plešné outflow 7 years after tree dieback and this increase was significant also after 8 to 10 years (Kopáček et al., 2018), while in the Laka catchment, the significant increase occurred only after 6 years. The delay of DOC leaching from soils in the Laka catchment was thus not as long as in the Plešné catchment. pH was higher in the Laka than Plešné outflow (Figure 2), and possibly Laka soil water had higher pH than soil water in the Plešné catchment. This might have led to lower DOC immobilization in the Laka soils during the period of atmospheric acidification. While there was a peak in DOC concentrations 6 years after the tree dieback in the Laka catchment, these DOC values were not much higher than in other years, and declined steadily after the peak. In contrast, the rise in DOC concentrations continues in the Plešné catchment. The Laka catchment was the only one that had decreasing DOC concentrations in the outflow after 2015. We assume that the proportion of treeless areas, which was considerably higher in the Laka than in Plešné catchment, could have contributed to this difference because undergrowth of herbs and shrubs took place in treeless areas (Matějka, 2015). Such a change usually results in wetter and warmer soils (Kaňa et al., 2019, Kopáček et al., 2020, Moreno-Fernández et al., 2021). Increased surface temperatures might have led to higher mineralization of biomass to CO_2, and therefore less carbon was probably released in the form of DOC from the Laka catchment.

Forest disturbances – few general patterns

In this study, the herbaceous biomass can be assumed to have been highest where the satellite data characterized raster cells as treeless. However, the proportion of treeless raster cells was the independent variable in only 12 significant models with water quality as the dependent variable, versus 38 models based on cFII. The reason for this may be that herbaceous plants influence soil chemical properties only marginally (Stefanowicz et al., 2021). Where areas become treeless because of clear-cutting, the effect on outflow characteristics is higher, as shown by Prescott et al. (2000). These authors observed that litter on the soil dries out due to the suddenly missing canopy and lack of undergrowth, and degradation of organic matter slows down. But slow tree death in an unmanaged area leads to the undergrowth changing accordingly, and effects on catchment outflows take a longer time.

One general observation for the catchment outflow characteristics of the three disturbed catchments was an overall rise in DOC. However, this rise took different shapes in the four catchments. Other than that, there were hardly any features common to all four catchments investigated here. The proportion of damaged coniferous trees was the predicting variable in only 16 significant linear models, which (with one exception for a Prášilské model) involved only the Plešné catchment. One reason for the different behaviour might lie in the different geological structure and soil composition. Many of the significant models in Plešné involved TP. The Plešné granite contains more phosphorus than other granites (Frýda & Breiter, 1995), and this phosphorus is released through exchange with water more than from the phosphorus-poor mica schist and gneiss in the other catchments (Kaňa & Kopáček, 2006).

Protecting catchments for drinking water production

We can estimate effects for downstream stake holders and make recommendations to forest managers in the support of sustainable water budget management. This management needs to take soil and catchment outflow pH and alkalinity into account when planning and managing restoration. Drinking water treatment plants can expect a peak in DOC with a 6 to 10 year delay, depending on the soil water pH in the catchments. This delay may not only be quantitative, however, because the DOC properties change in warmer and nitrogen-richer soils (van den Enden et al., 2021). This may have further effects for downstream drinking water treatment technologies, which increasingly must deal with the brownification of raw water (Monteith et al., 2007). Where soils remain moist, which is usually the case when any type of undergrowth occurs, be it herbaceous or temporary deciduous tree cover, organic matter may be degraded microbially *in situ*, before being flushed out. Soil wetness is thus a crucial factor for DOC loads from catchments. Further investigations are needed to ascertain best practices under different soil and climate conditions.

5 Conclusion

We demonstrate that satellite-derived data may be used to indirectly predict changes in water chemical exports from mountain forest catchments. Importantly, the index and proportions of forest component but also tree health status provide better predictions than air temperature, precipitation amount, and lake outflow. The advantage of similar data based on remote sensing is their applicability even without detail information on tree components and health gathered directly in the field.

While hydrogeological conditions are similar in many areas of the Šumava Mountains located at similar elevation, we show that some catchments may differ in water quality dynamics due to the different geological background, terrain steepness and soil properties. This study shows that disturbances such as forest dieback due to insect infestation do not necessarily lead to identical effects on water composition in different lake catchments. Hence, it is not possible to simply extrapolate our experience from one affected catchment to another. The exact reasons for the differences, such as soil and microbial processes, should be subject to further investigations.

Acknowledgements

We are indebted to Martin Hais, University of South Bohemia, for detailed discussions on remote sensing imagery. The analysis of water composition was supported by the Czech Science Foundation [project No. P503-22-05421S] and the analysis of the FII, by the TAČR KAPPA project No. 2020TO01000202 funded by the Norway Grants. SIS acknowledges funding through MEMOBIC [EU Operational Programme Research, Development and Education No. CZ.02.2.69/0.0/ 0.0/16_027/0008357], and by the Ministry of Education, Youth and Sports of the Czech Republic [grant number CZ.02.1.01/0.0/0.0/16 025/0007417]. VL was supported by the projects RVO 67985939 (The Czech Academy of Sciences) and 21-26883S (The Czech Science Foundation). We thank D. W. Hardekopf for linguistic proofreading and two anonymous reviewers for their constructive comments.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon request.

References

Aber, J.D., Driscoll, C.T. (1997). Effects of land use, climate variation, and N deposition on N cycling and C storage in northern hardwood forests. Global Biogeochem. Cycles 11, 639–648. https://doi.org/10.1029/97GB01366

Andréassian, V. (2004). Waters and forests: From historical controversy to scientific debate. Journal of Hydrology, 291(1), 1–27. doi: 10.1016/j.jhydrol.2003.12.015

Arnell, N.W., Gosling, S.N. (2016). The impacts of climate change on river flood risk at the global scale. Climatic Change 134, 387–401. https://doi.org/10.1007/s10584-014-1084-5

Baier, R., Meyer, J., Göttlein, A. (2007). Regeneration niches of Norway spruce (Picea abies [L.] Karst.) saplings in small canopy gaps in mixed mountain forests of the Bavarian Limestone Alps. Eur. J. For. Res. 126, 11–22. doi: 10.1007/s10342-005-0091-5

Benjamini, Y., Yekutieli, D. (2001). The control of the false discovery rate in multiple testing under dependency. Ann. Stat. 29, 1165–1188. doi: 10.1214/aos/1013699998

Clark, J.M., Bottrell, S.H., Evans, C.D., Monteith, D.T., Bartlett, R., Rose, R., Newton, R.J., Chapman, P.J. (2010). The importance of the relationship between scale and process in understanding long-term DOC dynamics. Science of The Total Environment 408, 2768–2775. https://doi.org/10.1016/j.scitotenv.2010.02.046

Cuypers, D., Lust, A., Geerken, T., Gorissen, L., Peters, G., Karstensen, J., Prieler, S., Fisher, G., Hizsnyik, E., Van Velthuizen, H., European Commission, Directorate-General for the Environment, Vito, Centre for International Cooperation in Advanced Education and Research (Bonn), & International Institute for Applied Systems Analysis (Laxenburg). (2013). The impact of EU consumption on deforestation: Comprehensive analysis of the impact of EU consumption on deforestation: final report. Publications Office. http://dx.publications.europa.eu/10.2779/82226

Czech Geological Survey (2019). Maps 1:25000 of the Czech Republic [available online at the official website - http://mapy.geology.cz/geocr_25/]. Accessed 13th of September 2021.

De Rose, R.J., Long, J.N. (2007). Disturbance, structure, and composition: Spruce beetle and Engelmann spruce forests on the Markagunt Plateau, Utah. Forest Ecology and Management 244, 16–23. doi: 10.1016/j.foreco.2007.03.065

Dougan, W. K.; Wilson, A. L. (1974). The absorptiometric determination of aluminium in water. A comparison of some chromogenic reagents and the development of an improved method, Analyst, 99, 413–430.

Downing, J. A. Emerging global role of small lakes and ponds: little things mean a lot. Limnetica 29, 9–24 (2010).

Driscoll, C. T. (1984). A procedure for the fractionation of aqueous aluminum in dilute acidic waters. Int. J. Environ. Anal. Chem., 16, 267−284.

Fairchild, G.W., Velinsky, D.J. (2006). Effects of small ponds on stream water chemistry. Lake and Reservoir Management 22, 321–330. https://doi.org/10.1080/07438140609354366

Fluksová, H., Grill, S., Bače, R., Hais, M. (2020). Dynamics of stand replacing-disturbance and biomass estimation in the Plešné Lake basin. Silva Gabreta, 26, 99–116.

Franklin, R.B., Mills, A.L. (2009). Importance of spatially structured environmental heterogeneity in controlling microbial community composition at small spatial scales in an agricultural field. Soil Biol. Biochem. 41, 1833–1840. doi: 10.1016/j.soilbio.2009.06.003

Freeman, C., Evans, C.D., Monteith, D.T., Reynolds, B., Fenner, N. (2001). Export of organic carbon from peat soils. Nature 412, 785–785. https://doi.org/10.1038/35090628

Frýda, J., Breiter, K. (1995). Alkali feldspars as a main phosphorus reservoirs in rare-metal granites: three examples from the Bohemian Massif (Czech Republic). Terra Nova 7, 315–320. doi: 10.1111/j.1365-3121.1995.tb00800.x

Gran, G. (1950). Determination of the equivalence point in potentiometric titration. Acta Chem. Scand. 4, 559–577. DOI: 10.3891/acta.chem.scand.04-0559.

Griffin, J. M., Turner, M. G., Simard, M. (2011). Nitrogen cycling following mountain pine beetle disturbance in lodgepole pine forests of Greater Yellowstone. Forest Ecology and Management, 261(6), 1077–1089. doi: 10.1016/j.foreco.2010.12.031

Gundersen, P., Callesen, I., de Vries, W. (1998). Nitrate leaching in forest ecosystems is related to forest floor C/N ratios. Environmental Pollution, 102, 403–407.

Hais, M., Jonášová, M., Langhammer, J., Kučera, T. (2009). Comparison of two types of forest disturbance using multitemporal Landsat TM/ETM+ imagery and field vegetation data. Remote Sensing of Environment, 113(4), 835–845. doi: 10.1016/j.rse.2008.12.012

Hicke, J.A., Allen, C.D., Desai, A.R., Dietze, M.C., Hall, R.J., (Ted) Hogg, E.H., Kashian, D.M., Moore, D., Raffa, K.F., Sturrock, R.N., Vogelmann, J. (2012). Effects of biotic disturbances on forest carbon cycling in the United States and Canada. Global Change Biology 18, 7–34. https://doi.org/10.1111/j.1365-2486.2011.02543.x

Holeksa, J., Jaloviar, P., Kucbel, S., Saniga, M., Svoboda, M., Szewczyk, J., Szwagrzyk, J., Zielonka, T., Żywiec, M. (2017). Models of disturbance driven dynamics in the West Carpathian spruce forests. For. Ecol. Manag., Ecology of Mountain Forest Ecosystems in Europe 388, 79–89. doi: 10.1016/j.foreco.2016.08.026

Hrkal, Z., Burda, J., Fottová, D., Hrkalová, M., Nováková, H., Novotná, E. (2014). Groundwater quality development in area suffering from long term impact of acid atmospheric deposition – The role of forest cover in Czech Republic case study. doi: 10.5772/32900

Huber, C., Baumgarten, M., Göttlein, A., Rotter, V. (2004). Nitrogen turnover and nitrate leaching after bark beetle attack in mountainous spruce stands of the Bavarian Forest National Park. Water, Air and Soil Pollution: Focus, 4(2), 391–414. doi: 10.1023/B:WAFO.0000028367.69158.8d

Kallenbach, E.M.F., Sand-Jensen, K., Morsing, J., Martinsen, K.T., Kragh, T., Raulund-Rasmussen, K., Baastrup-Spohr, L. (2018). Early ecosystem responses to watershed restoration along a headwater stream. Ecological Engineering 116, 154–162. https://doi.org/10.1016/j.ecoleng.2018.03.005

Janský, B., Zbořil, A. (1999). The Prášilské lake. Acta Univ. Carol. Geogr. 2, 53–67.

Kaňa, J., Kopáček, J. (2006). Impact of soil sorption characteristics and bedrock composition on phosphorus concentrations in two Bohemian Forest lakes. Water Air Soil Pollut., 173, 243–259. doi: 10.1007/s11270-005-9065-y

Kaňa, J., Kopáček, J., Tahovská, K., Šantrůčková, H. (2019). Tree dieback and related changes in nitrogen dynamics modify the concentrations and proportions of cations on soil sorption complex. Ecological Indicators, 97, 319–328. doi: 10.1016/j.ecolind.2018.10.032

Kaňa, J., Šantrůčková, H., Kopáček, J., Peroutková, M., Matějíčková, I. (2014). Chemical and biochemical characteristics of soils in the catchments of Čertovo and Plešné lakes (Bohemian Forest) in 2010. Silva Gabreta, 20(3), 97–123

Kaňa, J., Tahovská, K., Kopáček, J. (2013). Response of soil chemistry to forest dieback after bark beetle infestation. Biogeochemistry, 113(1–3), 369–383. doi: 10.1007/s10533-012-9765-5

Kaňa, J., Tahovská, K., Kopáček, J., Šantrůčková, H. (2015). Excess of organic carbon in mountain spruce forest soils after bark beetle outbreak altered microbial N transformations and mitigated N-saturation. PLoS ONE, 10(7), e0134165–e0134165. doi: 10.1371/journal.pone.0134165

Kopáček, J., Bače, R., Hejzlar, J., Kaňa, J., Kučera, T., Matějka, K., Porcal, P., Turek, J. (2020). Changes in microclimate and hydrology in an unmanaged mountain forest catchment after insect-induced tree dieback. Science of The Total Environment, 720, 137518. doi: 10.1016/j.scitotenv.2020.137518

Kopáček, J.; Borovec, J.; Hejzlar, J.; Porcal, P. (2001). Parallel spectrophotometric determinations of iron, aluminum, and phosphorus in soil and sediment extracts, Commun. Soil Sci. Plan., 32, 1431–1443.

Kopáček, J., Evans, C. D., Hejzlar, J., Kaňa, J., Porcal, P., Šantrůčková, H. (2018). Factors affecting leaching of dissolved organic carbon after tree dieback in an unmanaged European mountain forest. Environ. Sci. Technol., 52: 6291−6299. doi: 10.1021/acs.est.8b00478

Kopáček, J., Fluksová, H., Hejzlar, J., Kaňa, J., Porcal, P., Turek, J. (2017). Changes in surface water chemistry caused by natural forest dieback in an unmanaged mountain catchment. Science of the Total Environment, 584–585, 971–981. doi: 10.1016/j.scitotenv.2017.01.148

Kopáček, J., Hejzlar, J., Kaňa, J., Porcal, P., Turek, J. (2016). The sensitivity of water chemistry to climate in a forested, nitrogen-saturated catchment recovering from acidification. Ecological Indicators 63, 196–208. https://doi.org/10.1016/j.ecolind.2015.12.014

Kopáček, J., Kaňa, J., Porcal, P., Vrba, J., Norton, S.A. (2019). Effects of tree dieback on lake water acidity in the unmanaged catchment of Plešné Lake, Czech Republic. Limnology and Oceanography 64, 1614–1626. https://doi.org/10.1002/lno.11139

Kukrál, J. (2015). Adaptace lesů na klimatické změny a extrémní meteorologické jevy. Centrum aplikovaného výzkumu a dalšího vzdělávání, o.p.s., Písek a nakladatelství JIH, České Budějovice České Budějovice. http://www.vyzkumnecentrum.eu/wp-content/uploads/2015/09/Adaptace_les%C5%AF_na_klimatick%C3%A9_zm%C4%9Bny_a_extr%C3%A9mn%C3%AD_meteorlogogick%C3%A9_jevy-1.pdf

Legendre, P., Legendre, L. (2012). Numerical ecology. Elsevier.

Madsen, H., Lawrence, D., Lang, M., Martinkova, M. Kjeldsen, T. R. (2014). Review of trend analysis and climate change projections of extreme precipitation and floods in Europe. J. Hydrol. 519, 3634–3650. https://doi.org/10.1016/j.jhydrol.2014.11.003

Majer, V., Cosby, B.J., Kopáček, J., Veselý, J. (2003). Modelling reversibility of Central European mountain lakes from acidification: Part I - The Bohemian Forest. Hydrol. Earth System Sci., 7(4): 494-509

Matějka, K. (2015). Disturbance-induced changes in the plant biomass in forests near Plešné and Čertovo Lakes. J. For. Sci. 61 (4):156–168. http://dx.doi.org/10.17221/109/2014-JFS.

Mikkelson, K. M., Bearup, L. A., Maxwell, R. M., Stednick, J. D., McCray, J. E., Sharp, J. O. (2013). Bark beetle infestation impacts on nutrient cycling, water quality and interdependent hydrological effects. Biogeochemistry, 115(1), 1–21. doi: 10.1007/s10533-013-9875-8

Mikoláš, M., Svitok, M., Bače, R., Meigs, G.W., Keeton, W.S., Keith, H., Buechling, A., Trotsiuk, V., Kozák, D., Bollmann, K., Begovič, K., Čada, V., Chaskovskyy, O., Ralhan, D., Dušátko, M., Ferenčík, M., Frankovič, M., Gloor, R., Hofmeister, J., Janda, P., Kameniar, O., Lábusová, J., Majdanová, L., Nagel, T.A., Pavlin, J., Pettit, J.L., Rodrigo, R., Roibu, C.-C., Rydval, M., Sabatini, F.M., Schurman, J., Synek, M., Vostarek, O., Zemlerová, V., Svoboda, M. (2021). Natural disturbance impacts on trade-offs and co-benefits of forest biodiversity and carbon. Proceedings of the Royal Society B: Biological Sciences 288, 20211631. https://doi.org/10.1098/rspb.2021.1631

Monteith, D.T., Stoddard, J.L., Evans, C.D., Wit, H.A.D., Forsius, M., Jeffries, D.S., Vuorenmaa, J., Keller, B., Wilander, A., Skjelkva, B.L. (2007). Dissolved organic carbon trends resulting from changes in atmospheric deposition chemistry. Nature 450, 537–541. doi: 10.1038/nature06316

Moravčík, P. (1994). Development of new forest stands after a large scale forest decline in the Krušné hory Mountains. Ecol. Eng., Special Issue: Forest Ecosystem Development 3, 57–69. doi: 10.1016/0925-8574(94)90012-4

Moreno-Fernández, D., Viana-Soto, A., Camarero, J.J., Zavala, M.A., Tijerín, J., García, M. (2021). Using spectral indices as early warning signals of forest dieback: The case of drought-prone Pinus pinaster forests. Science of The Total Environment 793, 148578. https://doi.org/10.1016/j.scitotenv.2021.148578

Murphy, J., Riley, J. P. (1962). A modified single solution method for the determination of phosphate in natural waters. Analytica Chimica Acta, 27, 31–36.

Näsi, R., Honkavaara, E., Lyytikäinen-Saarenmaa, P., Blomqvist, M., Litkey, P., Hakala, T., Viljanen, N., Kantola, T., Tanhuanpää, T., Holopainen, M. (2015). Using UAV-based photogrammetry and hyperspectral imaging for mapping bark beetle damage at tree-level. Remote Sens., 7, 15467-15493. https://doi.org/10.3390/rs71115467

Němeček, J., Macků, J., Vokoun, J., Vavříček, D., Novák, P., 2001. Taxonomický klasifikační systém půd České republiky. ČZU Praha – VÚMOP, Praha.

Pagel, H., Ingwersen, J., Poll, C., Kandeler, E., Streck, T. (2014). Micro-scale modeling of pesticide degradation coupled to carbon turnover in the detritusphere: model description and sensitivity analysis. Biogeochemistry 117, 185–204. doi: 10.1007/s10533-013-9851-3

Pasztor F., C. Matulla, W. Rammer, M. J. Lexer (2014). Drivers of the bark beetle disturbance regime in Alpine forests in Austria. Forest Ecology and Management 318:349-358. https://doi.org/10.1016/j.foreco.2014.01.044.

Prescott, C.E., Blevins, L.L., Staley, C.L. (2000). Effects of clear-cutting on decomposition rates of litter and forest floor in forests of British Columbia. Can. J. For. Res. 30, 1751–1757. doi: 10.1139/x00-102

R Core Team. (2021). R: A Language and Environment for Statistical Computing. The R Foundation for Statistical Computing. https://www.R-project.org/

Rosenvald, R., Rosenvald, K. (2017). The influence of forest management and timber use options on carbon sequestration and the consequences on biodiversity. Forestry Studies 67, 37–49. https://doi.org/10.1515/fsmu-2017-0011

Scarlett, K. R., Kim, S., Lovin, L. M., Chatterjee, S., Scott, J. T., Brooks, B. W. (2020). Global scanning of cylindrospermopsin: Critical review and analysis of aquatic occurrence, bioaccumulation, toxicity and health hazards. Science of The Total Environment, 738, 139807. doi: 10.1016/j.scitotenv.2020.139807

Schmidt, S.I., Cuthbert, M.O., Schwientek, M. (2017). Towards an integrated understanding of how micro scale processes shape groundwater ecosystem functions. Science of the Total Environment 592, 215–227. https://doi.org/10.1016/j.scitotenv.2017.03.047

Schmidt, S. I., Hejzlar, J., Kopáček, J., Paule-Mercado, M. C., Porcal, P. Vystavna, Y. (2021). Relationships between a catchment-scale forest disturbance index, time delays, and chemical properties of surface water. Ecological Indicators, 125, 107558. doi: 10.1016/j.ecolind.2021.107558.

Sebald, J., Senf, C., Heiser, M., Scheidl, C., Pflugmacher, D., Seidl, R. (2019). The effects of forest cover and disturbance on torrential hazards: Large-scale evidence from the Eastern Alps. Environmental Research Letters, 14(11), 114032. doi: 10.1088/1748-9326/ab4937

Sedmáková, D., Sedmák, R., Bosela, M., Ježík, M., Blaženec, M., Hlásny, T., Marušák, R. (2019). Growth-climate responses indicate shifts in the competitive ability of European beech and Norway spruce under recent climate warming in East-Central Europe. Dendrochronologia 54, 37–48. doi: 10.1016/j.dendro.2019.02.001

Seidl, R., Schelhaas, M.-J., Rammer, W., Verkerk, P.J. (2014). Increasing forest disturbances in Europe and their impact on carbon storage. Nature Clim Change 4, 806–810. https://doi.org/10.1038/nclimate2318

Seidl, R., Thom, D., Kautz, M., Martin-Benito, D., Peltoniemi, M., Vacchiano, G., Wild, J., Ascoli, D., Petr, M., Honkaniemi, J., Lexer, M.J., Trotsiuk, V., Mairota, P., Svoboda, M., Fabrika, M., Nagel, T.A., Reyer, C.P.O. (2017). Forest disturbances under climate change. Nature Clim Change 7, 395–402. https://doi.org/10.1038/nclimate3303

Shabarova, T., Salcher, M.M., Porcal, P., Znachor, P., Nedoma, J., Grossart, H.-P., Seďa, J., Hejzlar, J., Šimek, K. (2021). Recovery of freshwater microbial communities after extreme rain events is mediated by cyclic succession. Nature Microbiology 1–10. https://doi.org/10.1038/s41564-020-00852-1

Stefanowicz, A.M., Kapusta, P., Stanek, M., Rola, K., Zubek, S. (2021). Herbaceous plant species support soil microbial performance in deciduous temperate forests. Science of The Total Environment 151313. https://doi.org/10.1016/j.scitotenv.2021.151313

Stoddard, J.L., Jeffries, D.S., Lükewille, A., Clair, T.A., Dillon, P.J., Driscoll, C.T., Forsius, M., Johannessen, M., Kahl, J.S., Kellogg, J.H., Kemp, A., Mannio, J., Monteith, D.T., Murdoch, P.S., Patrick, S., Rebsdorf, A., Skjelkvåle, B.L., Stainton, M.P., Traaen, T., van Dam, H., Webster, K.E., Wieting, J., Wilander, A. (1999). Regional trends in aquatic recovery from acidification in North America and Europe. Nature 401, 575–578. doi: 10.1038/44114

Temnerud, J., Weyhenmeyer, G.A. (2008). Abrupt changes in air temperature and precipitation: Do they matter for water chemistry? Global Biogeochemical Cycles 22, 2, GB2008. https://doi.org/10.1029/2007GB003023.

Tokuchi, N., Ohte, N., Hobara, S., Kim, S.-J., Masanori, K. (2004). Changes in biogeochemical cycling following forest defoliation by pine wilt disease in Kiryu experimental catchment in Japan. Hydrological Processes 18, 2727–2736. doi: 10.1002/hyp.5578

Tranvik, L.J., Downing, J.A., Cotner, J.B., Loiselle, S.A., Striegl, R.G., Ballatore, T.J., Dillon, P., Finlay, K., Fortino, K., Knoll, L.B., Kortelainen, P.L., Kutser, T., Larsen, Soren., Laurion, I., Leech, D.M., McCallister, S.L., McKnight, D.M., Melack, J.M., Overholt, E., Porter, J.A., Prairie, Y., Renwick, W.H., Roland, F., Sherman, B.S., Schindler, D.W., Sobek, S., Tremblay, A., Vanni, M.J., Verschoor, A.M., von Wachenfeldt, E., Weyhenmeyer, G.A. (2009). Lakes and reservoirs as regulators of carbon cycling and climate. Limnology and Oceanography 54, 2298–2314. https://doi.org/10.4319/lo.2009.54.6_part_2.2298

Turek, J., Fluksová, H., Hejzlar, J., Kopáček, J., Porcal, P. (2014). Modelling air temperature in catchments of Čertovo and Plešné lakes in the Bohemian Forest back to 1781. Silva Gabreta, 20(1), 1–24.

vandenEnden, L., Anthony, M.A., Frey, S.D., Simpson, M.J. (2021). Biogeochemical evolution of soil organic matter composition after a decade of warming and nitrogen addition. Biogeochemistry 156, 161–175. doi: 10.1007/s10533-021-00837-0

Veselý, J. (1994). Investigation of the nature of the Šumava lakes: A review. Časopis Národního Muzea, Praha, Řada Přírodovědná, 163, 103–120.

Veselý, J., Hruška, J., Norton, S.A., Johnson, C.E. (1998). Trends in water chemistry of acidified Bohemian lakes from 1984 to 1995: I. Major solutes. Water Air Soil Pollut., 108, 107-127.

Vogelmann, J. E. (1990). Comparison between two vegetation indices for measuring different types of forest damage in the north-eastern United States. International Journal of Remote Sensing, 11(12), 2281–2297. doi: 10.1080/01431169008955175

Vystavna, Y., Hejzlar, J., Kopáček, J. (2017). Long-term trends of phosphorus concentrations in an artificial lake: socio-economic and climate drivers. PLoS ONE 12, e0186917. https://doi.org/10.1371/journal.pone.0186917

Vystavna, Y., Holko, L., Hejzlar, J., Persiou, A., Graham, N.D., Juras, R., Huneau, F., Gibson, J. (2018). Isotopic response of runoff to forest disturbance in small mountain catchments. Hydrological Processes 32, 3650–3661. https://doi.org/10.1002/hyp.13280

Vystavna, Y., Paule-Mercado, M., Juras, R., Schmidt, S. I., Kopáček, J., Hejzlar, J., Huneau, F. (2021). Effect of snowmelt on the dynamics, isotopic and chemical composition of runoff in mature and regenerated forested catchments. Journal of Hydrology, 598, 126437. doi: 10.1016/j.jhydrol.2021.126437.

Vystavna, Y., Schmidt, S. I., Kopáček, J., Hejzlar, J., Holko, L., Matiatos, I., Wassenaar, L. I., Persoiu, A., Badaluta, C. A., Huneau, F. (2020). Small-scale chemical and isotopic variability of hydrological pathways in a mountain lake catchment. Journal of Hydrology, 585, 124834. doi: 10.1016/j.jhydrol.2020.124834

Xu, X., Zhang, Y., Chen, Q., Li, N., Shi, K., Zhang, Y. (2020). Regime shifts in shallow lakes observed by remote sensing and the implications for management. Ecological Indicators, 113, 106285. doi: 10.1016/j.ecolind.2020.106285.

Yavitt, J. B., Fahey, T. J. (1986). Litter decay and leaching from the forest floor in Pinus contorta (Lodgepole pine) ecosystems. Journal of Ecology, 74(2), 525–545. doi: 10.2307/2260272

Żywiec, M., Holeksa, J., Wesołowska, M., Szewczyk, J., Zwijacz-Kozica, T., Kapusta, P. (2013). Sorbus aucuparia regeneration in a coarse-grained spruce forest – a landscape scale. J. Veg. Sci. 24, 735–743. doi: 10.1111/j.1654-1103.2012.01493.x

Author statement file - relevant CRediT roles

SIS	*Susanne I. Schmidt*
JH	*Josef Hejzlar*
JK	*Jiří Kopáček*
CM	*Ma. Cristina Paule-Mercado*
PP	*Petr Porcal*
YV	*Yuliya Vystavna*
VL	*Vojtěch Lanta*

Conceptualization: SIS, VL, JH, JK

Data curation: JK, JH, PP

Formal analysis: SIS, VL, CM, YV

Funding acquisition: JK, JH, PP, VL

Field investigation: JK

Methodology: all authors

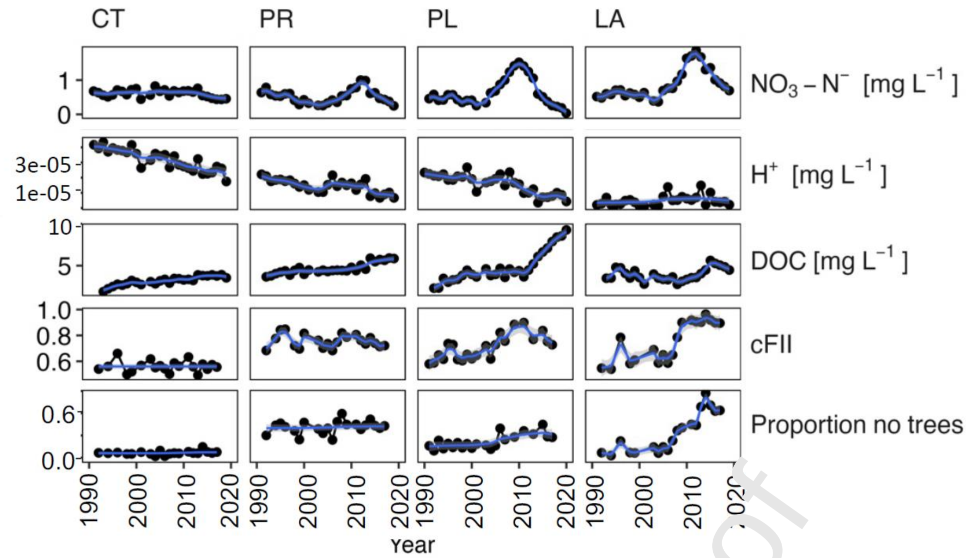
Project administration: JK, PP

Writing – original draft: all authors

Writing – review & editing: all authors and David Hardekopf (see acknowledgements)

COMPETING INTERESTS STATEMENT

The authors have no competing interests to declare.



Graphical abstract

Highlights

- Forest damage by insects affects lake water quality via soil processes indirectly.
- Water chemical response to damage reflected forest succession.
- Water chemical response to damage depended on site-specific characteristics.
- The delay of damage response was site- and variable-specific.