https://doi.org/10.5194/egusphere-2025-4622
Preprint. Discussion started: 15 October 2025
© Author(s) 2025. CC BY 4.0 License.

2022 drought consequences on nutrient dynamics in forest soil solutions of a declining spruces plot in the Strengbach catchment (Vosges Mountains, France)

Adrien Saphy[1], Emilie Beaulieu[1], Marie-Noëlle Pons[2], Benjamin Belfort[1], Marie-Claire Pierret[1]

[1] Université de Strasbourg, Institut Terre et Environnement de Strasbourg, Ecole Nationale du Génie de l'Eau et de l'Environnement, UMR 7063, 5 Rue René Descartes, F-67084 Strasbourg, France
[2] Université de Lorraine, CNRS, LRGP, F-54000, Nancy, France

Correspondence to: Marie-Claire Pierret (marie-claire.pierret@unistra.fr)

Abstract

2022 was the hottest and driest year ever recorded in France, including within the Strengbach catchment, a Critical Zone Observatory (http://ohge.unistra.fr) located in a forested watershed of the Vosges Mountains and characterized by declining Norway spruce (*Picea abies*) stands. During and following the summer drought of 2022, an unusual chemical signature was detected in soil solutions, marked by elevated concentrations of K^+, Ca^{2+}, Mg^{2+}, NO_3^-, NH_4^+, Al^{3+}, and Dissolved Organic Carbon (DOC) with significant variations of fluorescence indices (HIX, BIX and FI). Thanks to interdisciplinary monitoring of soil solution chemistry, the impacts of drought on biogeochemical processes—and more broadly, on forest soil fertility—are now better understood. The 2022 drought induced (1) lower mineral dissolution, (2) reduced plant nutrient uptake, (3) increased concentrations in throughfall (4) biological stress on soil microfauna, leading to organic matter accumulation during the dry period and subsequent release upon rewetting, (5) disruption of the nitrogen cycle, with ammonium accumulation during drought followed by intense nitrification after rainfall resumed, and (6) acidification of the soil solution, enhancing the desorption of both nutrient cations and toxic Al^{3+}. Drought affects forest soil reactivity and fertility through physical (water deficit), chemical (nutrient leaching and acidification), and biological (vegetation and microbiota stress) mechanisms. The decline in soil fertility during and after drought is especially concerning for forest ecosystems already subject to nutrient deficiency, such as those in the Strengbach catchment. Understanding these drought-induced biogeochemical disturbances is essential for predicting ecosystem responses to extreme climatic events, whose intensity and frequency are expected to increase in the Vosges Mountains under ongoing climate change.

https://doi.org/10.5194/egusphere-2025-4622
Preprint. Discussion started: 15 October 2025
© Author(s) 2025. CC BY 4.0 License.

1 Introduction

2022 was the hottest year ever recorded in mainland France to date (since 1900), +2.9°C compared with the mean temperature during 1900-1930 period, with a sequence of heatwaves from May onwards (Faranda et al., 2023; Sorel et al., 2023). With a major annual precipitation deficit of 25% in 2022, the months of May and July were the driest on record in France (with deficits of nearly 60% and 85% respectively compared to the normal based on data since 1959) giving rise to a severe meteorological summer drought that spread across Europe (Sorel et al., 2023; Copernicus, 2023). Climate change projections for the end of the century remain very worrying, as simulations predict for France: i) an increase in the number of consecutive days without precipitation of around +5 and +10 days respectively for the scenarios RCP4.5 and RCP.8.5, and ii) an increase in the frequency of heat waves in summer could be +10 to +15 days for the RCP4.5 scenario and approximately double for RCP8.5. (Soubeyroux et al., 2020). Droughts have a major impact on the functioning of forest ecosystems and, whether or not combined with other disturbances, such as fires or insect attacks, they can cause forest dieback (Anderegg et al., 2013; Senf et al., 2020; Gharun et al., 2024; Knutzen et al., 2025).

Forest dieback is increasing in France, as shown by the latest report from the French National Institute of Geographic and Forest Information (IGN, 2024), with mortality rising from 7.4 Mm^3/year for the period 2005-2013 to 15.2 Mm^3/year for the period 2014-2022 (with statistical uncertainty of around 0.6 Mm^3/year) (IGN, 2024). Drought has direct physiological consequences on trees and can lead to direct mortality by xylem embolism for instance (Bréda et al., 2006; Rodrigez-Calcerrada et al., 2017; Wagner et al., 2023). The 2022 drought had important consequences for French forests, notably mega-fires that burned 58 275 ha of forest in 2022 (San-Miguel-Ayanz et al. 2023). In addition, global warming and frequent droughts have accelerated the spread and intensity of insect attacks, as documented in US forests (Weed et al., 2013; Vose et al., 2016; Frank, 2021). In western Europe, a recent initiative to address our lack of field knowledge regarding the ecological processes underlying biotic forest disturbances has been the creation of the Database of European Forest Insect and Disease Disturbances (DEFID2) (Forzieri et al., 2023). Spruces are boreal trees that are particularly vulnerable to drought, leading to an increase in the tree's vulnerability to parasites, such as the bark beetle (Ips typographus), which devastates Vosges spruce forests (Saintonge, 2022; Gomez et al., 2023; Knutzen et al., 2025). However, all these disturbances affect forests and therefore the carbon sink provided by the soils and tree photosynthetic activity. While forest ecosystems represent the largest terrestrial carbon stock, estimated at 662 gigatonnes worldwide, a decrease of 0.9% has already been estimated between 1990 and 2020 (FAO, 2020). Forest dieback thus threatens

https://doi.org/10.5194/egusphere-2025-4622
Preprint. Discussion started: 15 October 2025
© Author(s) 2025. CC BY 4.0 License.

the mitigation role of forests in climate change, and foreshadows negative feedback (Ciais et al., 2005; Anderegg et al, 2020; Quirion et al., 2021).

Another factor of tree vulnerability to drought is nutrient availability (Gessler et al, 2016; Lévesque et al., 2016; Schmied et al., 2023). How drought affects nutrient dynamics in forest soil is a high concern issue for the prediction of the complex responses of forest ecosystems to drought, in a warming world. Nitrogen is an essential plant nutrient, and the consequences of drought on the nitrogen cycle are documented (Lamersdorf et al., 1998; Muhr et al., 2008; Deng et al., 2021; Krüger et al., 2021; Winter et al., 2023). However, a lack of information persists about the dynamics of all the other nutrients, such as major cations K^+, Ca^{2+} and Mg^{2+}.

To better understand and predict drought-related biogeochemical disturbance, some studies have been carried out on the impact of water shortage on nutrient cycles in forests (Sardans et al., 2008; Touche at al., 2022) and in particular in spruce forests (Dambrine et al., 1993; Nilsen, 1995). These authors observe a decrease in K concentration in biomass, suggesting a reduction of K availability for trees during water deficit. Moreover, exceptional K concentrations in soil solutions at 30cm depth following natural drought events have been documented such as in 2012, in a Canadian boreal forest (Houle et al., 2016). This nutrient export flux was explained by a high K concentration coming from throughfall and the higher mobility of K compared with other major cations through the soil profile. To assess the impact of drought events on forest and soil fertility, the composition of soil solutions can be used as an indicator of nutrient availability. However, studies addressing the impact of natural drought on mineral nutrient dynamics in soil solution remain scarce and require further extension to diverse forest types.

The hydrogeochemical environmental observatory of the Strengbach catchment in Vosges Mountains (France) is a critical zone observatory belonging to the French Network of Critical Zone Observatories (OZCAR). The continuous recording of numerous variables since 1986 makes it a key site for observing the consequences of global changes on environmental parameters (Pierret et al., 2018; Strohmenger et al., 2022). Besides, the drought of 2022 produced highly atypical chemical signals in soil solutions at our study site, a declining spruce (*Picea abies*) plot.

The main objectives of this study were to evaluate the potential impacts of drought 2022 on biogeochemical cycles of major elements, on organic matter and on the fertility of forest soils. Soil solutions were sampled under a spruce plot during the period 2015-2023 and the concentrations of major cations (K^+, Na^+, Ca^{2+}, Mg^{2+}), Al, Si, as well as nitrogen in various forms (NH_4^+, NO_3^-) and Dissolved Organic Matter (DOC) were

https://doi.org/10.5194/egusphere-2025-4622
Preprint. Discussion started: 15 October 2025
© Author(s) 2025. CC BY 4.0 License.

measured. To better understand DOC dynamics, fluorescence of soil solution was monitored between 2020 and 2023. The combined analysis of mineral nutrients and dissolved organic matter, coupled with hydrological modeling, provides a global view of the biogeochemical consequences of drought on the chemistry of soil solutions and, more generally, on soil fertility.

2 Materials & Methods

2.1 Site presentation

The Strengbach catchment, located in the municipality of Aubure (Haut-Rhin, France) in the Vosges Mountains, has an area of 0.8 km² and an elevation between 850 and 1150 meters. This catchment is mainly covered by acid brown soil and ochreous podzolic soil (Fig. 1) on Ca-poor granitic bedrock (Pierret et al., 2018). The forest covers 90% of the catchment with 80% planted with a monospecific spruce plantation *(Picea abies*) and the rest with beech *(Fagus sylvatica*) (Fichter et al., 1997; Pierret et al., 2018).

Meteorological, hydrological and geochemical variables are monitored since 1986 in the Strengbach catchment by the *Observatoire hydro-geochimique de l'environnement* (OHGE; https://ohge.unistra.fr). The creation of the observatory (with the installation of the first equipment) and the first studies were performed in order to understand the impact of acid rain on forested ecosystems (Probst et al., 1990, 1992, 1995; Pierret et al., 2019). Many studies are still being conducted on environmental issues concerning forest mountainous ecosystems and particularly about forest decline and nutrient deficiency (Fichter et al., 1997; Poszwa et al., 2003; Cenki-Tok et al., 2009; Brioschi et al., 2013; Beaulieu et al., 2020; Oursin et al., 2023).

The climate is oceanic mountainous with an annual mean temperature of 6.17°C, and a mean precipitation of about 101 mm per month during the time period 1987-2024. The annual precipitation (over a calendar year) has varied between 814 mm/year (2023) and 1568 mm/year (2007) with an average of 1214 mm/year. Outlet water flows vary between 464 and 1132 with an average of 732 mm/year. Historically, rainfall was uniformly distributed throughout the year. But we can already observe some climate change consequences at the local scale in the OHGE, so that the OHGE databank is a key tool to understand environmental change consequences (Pierret et al., 2018; Strohmenger et al., 2022).

https://doi.org/10.5194/egusphere-2025-4622
Preprint. Discussion started: 15 October 2025
© Author(s) 2025. CC BY 4.0 License.

2.2 Stand presentation

The plot (VP plot, Fig. 1) is a monospecific spruce *(Picea abies*) plot, planted in the 1900s, which have been declining for several decades due to different reasons: nutrient-poor soils amplified by acid rains until the 1980s (Probst et al., 1990, 1992, 1995), recent several violent storms, successive bark beetle attacks as well as intense drought episodes. The site with still alive trees has been instrumented since 2015 (Fig. 1). Soil solutions are sampled with zero-tension lysimetric plates at four depths (5, 10, 30, 60 cm) every 6 weeks and throughfall water samples are collected with two gutters every two weeks (Pierret et al., 2018).

The studied soil profile (Fig. 1) is a Cambisol (*alocrisol* in the French taxonomy) on granitic bedrock. We can distinguish two litter horizons. The upper litter (OL) which is composed of old needles, herbaceous roots and pieces of wood, is 5 cm thick. The lower humic horizon (OH-OF) is 6 cm thick and is black-colored with a smooth texture. The dark brown/grey horizon A of 5-6 cm is unequally distributed on the profile with wavy transitions. It is followed by a transition layer of 5 cm. At 17cm depth, a brown/red mineral horizon B is found with a lumpy texture. This horizon is homogeneous and very sandy with centimetric gravel.

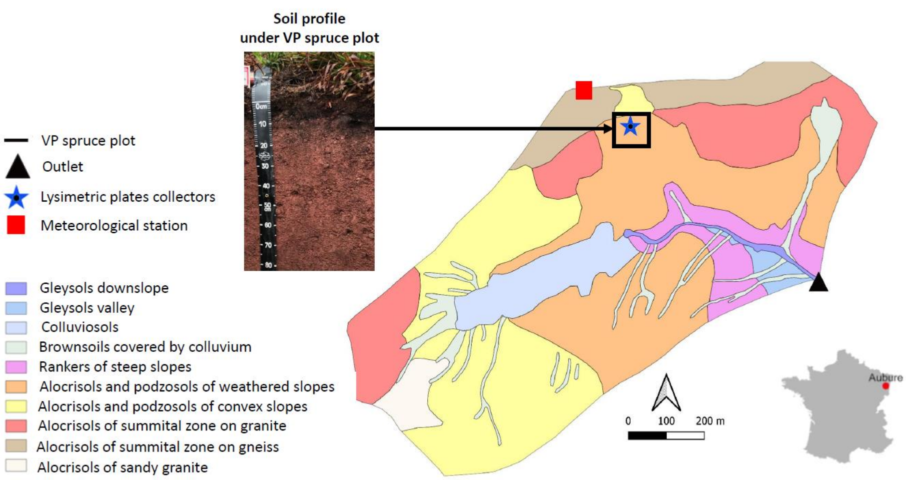


Figure 1: Soil map of the Strengbach watershed with different monitoring equipment and stations, with the location of the studied soil profile of the VP spruce plot.

https://doi.org/10.5194/egusphere-2025-4622
Preprint. Discussion started: 15 October 2025
© Author(s) 2025. CC BY 4.0 License.

2.3 Chemical analysis of soil solution

Soil solutions were collected in clean polyethylene (HDPE) containers sampled from the field and filtered with cellulose acetate filters 0.45µm pore diameter membrane *Merck-Millipore* on PTFE filtration unit. Conductivity and pH were measured with *HQ440d Hach* multimeter. The dissolved organic carbon (DOC) was determined using a carbon analyser (*Shimadzu TOC-VCPH*) with an uncertainty of 2 to 3.5 %. The accuracy of the analysis was assessed by regular measurement of PERADE-17 river water CRM (*Environment and Climate Change Canada* matrix reference materials). K^+, Na^+, Ca^{2+}, Mg^{2+}, NH_4^+ and NO_3^- concentrations were determined by ion chromatography on a *Thermo Scientific Dionex ICS-5000+*. Al and Si concentrations were measured by ICP-AES on a *Thermo Scientific iCAP 6000 SERIES*. PERADE-17 and SLRS-6 water CRMs (certified by *Environment and Climate Change Canada*) were used as standards and the analytical uncertainty for ions concentrations is ± 2%.

Fluorescence spectra were obtained on a Hitachi F-2500 spectrofluorometer equipped with a Xenon lamp, using FL Solution 2.0 software and a 1 cm x 1 cm (3.5 mL) quartz cuvette. Emission spectra were collected for three excitation wavelengths (λ_{ex} = 254 nm, 310 nm and 370 nm) with a step of 1 nm and slits of 2.5 nm. The humification index HIX was calculated on emission spectra for λ_{ex} = 254 nm as the ratio of the sum of the fluorescence intensities (F) between 435 and 480nm over the sum of the fluorescence intensities between 300 and 345nm (Zsolnay et al., 1999), (eq.1). The index BIX was calculated as the ratio of fluorescence intensity emitted at 380nm over 430nm for λ_{ex} = 310 nm (Huguet et al., 2009) (Eq 2). The index FI was calculated as the ratio of fluorescence intensities at 450 and 500nm for λ_{ex} = 370 nm (eq. 3) (McKnight et al., 2001).

$$\mathrm{HIX} = \frac{\sum \mathrm{F(435\text{-}480nm)}}{\sum \mathrm{F(300\text{-}345nm)}}, \lambda_{ex} = 254\mathrm{nm} \qquad \text{(eq. 1)}$$

$$\mathrm{BIX} = \frac{\mathrm{F(380nm)}}{\mathrm{F(430nm)}}, \ \lambda_{ex} = 310\mathrm{nm} \qquad \text{(eq. 2)}$$

$$\mathrm{FI} = \frac{\mathrm{F(450nm)}}{\mathrm{F(500nm)}}, \lambda_{ex} = 370\mathrm{nm} \qquad \text{(eq. 3)}$$

https://doi.org/10.5194/egusphere-2025-4622
Preprint. Discussion started: 15 October 2025
© Author(s) 2025. CC BY 4.0 License.

2.4 Hydrological soil modelling

The drought events can create variations in soil water content. To evaluate the changes in water availability in the soil profile induced by rainfall decrease, an in-house daily water balance calculation code is applied to a soil profile under spruces. BILHYDAY, whose structure was inspired by the model developed by Granier et al. (1999), takes meteorological data as inputs with stand parameters (leaf area index, soil porosity and residual water content). Based on a conceptual reservoir approach to describe hydrological processes of the soil-tree-atmosphere continuum, the model simulates water content variation over time at different depths, as well as evapotranspiration (evaporation from the soil and transpiration from trees). The relative extractable soil water is calculated similarly to Granier et al. (1999) and can be used to assess water stress. When it falls below 0.4, it triggers the physiological effects of water stress on the trees, i.e., stomatal closure (Bréda et al., 2006).

2.5 Statistical analysis

To highlight outlier concentrations, a Grubbs statistical test is performed on the entire 2015-2023 period for each parameter, using the 'outliers' package on R (Komsta, 2022). Multivariate statistical analysis helps to highlight atypical observations in long-term monitoring and can reveal the impact of extreme events on soil when many parameters are measured (Knight et al., 2024). A non-metric multidimensional scaling (NMDS) statistical analysis was conducted using the metaMDS function in the 'vegan' library in R (Oksanen et al., 2001).

3 Results

3.1 Meteorological drought and soil water deficit modelling

On the OHGE site, considering the hydrological years over the recorded period from 1987 to 2023 (year running Y from 1 September to 31 August of year Y+1), 2021 was the driest year on record with a cumulated precipitation amount of 765 mm (-37% compared to the average value over the period), the second warmest year with an average annual temperature of 7.67°C (+24% compared to the average for the period – just behind 2023 with 8.4°C), and with the highest number of days with an average daily temperature above 18°C, i.e. 37 days compared to an average of 17 days. After 2003, the summer of 2022 (i.e. June to August) was the driest on record,

https://doi.org/10.5194/egusphere-2025-4622
Preprint. Discussion started: 15 October 2025
© Author(s) 2025. CC BY 4.0 License.

on a par with 2018 (with cumulative precipitation of 181 mm compared to 160 mm in 2003 and an average of 306 mm). The longest period of summer meteorological drought observed between 1987 and 2024 was 19 days in 2018, and then 17 days in 2022, 2013 and 1990. Nevertheless, the summer of 2022 was exceptional because this first drought period from 2 July to 19 July was very quickly followed by a second period of 24 days during which daily rainfall did not exceed 0.7 mm (between 21 July and 13 August 2022). It is important to notice that a rainfall of 8.9 mm, on 20 July 2022, separates those two meteorological drought events (Fig. 2.A). The particularly dry July month (10.2 mm cumulated) was amplified by the previous dry March and May months with respectively 33 mm and 36 mm cumulated, compared with the 102 mm/month usually observed on the Strengbach watershed.

To assess the impact of rainfall deficit on soil water content, BILHYDAY was used with meteorological data. The soil was divided into 5 layers of 5-5-20-30-40 cm thickness (from the surface) and the average water content (WC) in each layer is simulated. The WC of the three intermediate layers (denoted by their centers at 7.5, 20 and 45 cm) and the relative extractable soil water (REW) during the 2021-2022 hydrological year are depicted in Fig. 2.B-C. It shows that the water deficit begins in the middle of May in the 7.5cm depth layer, and the few rainy events in the first half and last week of June do not prevent it from falling to a minimum value of 0.14 in mid-July. The 20cm depth layer experienced a fairly gradual drying out from May to 22 June; after the rains at the beginning of July, the minimum water content reflecting a significant water deficit was recorded on 30 July. (Fig. 2.B). The water content remains constant and low in these layers until 16 August 2022. The water content decrease is slower in the 45cm depth layer with a minimum on 14 August 2022. Following the return of the rainy season, there is an increase in soil water content during the second half of August, particularly in the second layer, while recharge is slower for deeper layers. This is followed by a rapid rise in September, coinciding with the return of heavier rains, resulting in a value of 0.42 and 0.35 at 7.5 and 20cm depth respectively (Fig.2 B). Following the definition given by Granier et al. (1999), during the 2022 summer period, a total of 25 days of soil water deficit occurs, meaning that the relative extractable soil water dropped below the threshold of 0.4 (Fig. 2.C). Trees transpiration increases during spring and summer and reaches its maximum (2.5 mm/day) in the middle of June and then sharply decreases (Fig. 2.C). During the water stress period from mid-July to mid-August, tree transpiration reaches a very low value due to stomatal regulation, and this continues until rain returns.

https://doi.org/10.5194/egusphere-2025-4622
Preprint. Discussion started: 15 October 2025
© Author(s) 2025. CC BY 4.0 License.

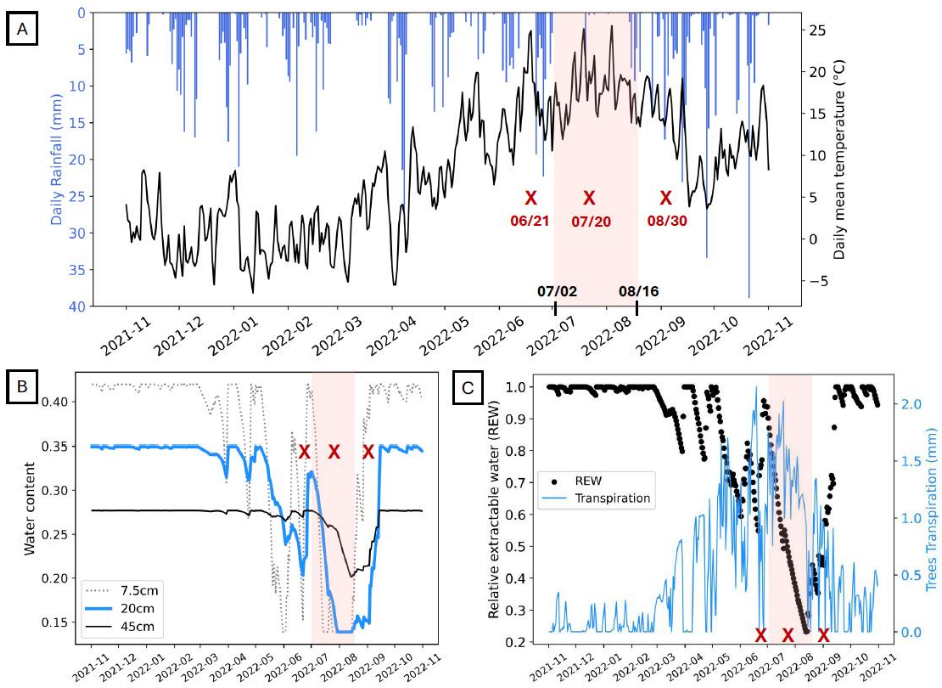


Figure 2: (A) Daily rainfall (mm) in blue bar plot and daily mean temperature (°C); (B) Simulated soil water content at 7.5 cm depth in dotted line, 20 cm in blue line, 45 cm in black line; (C) Simulated relative extractable water (REW) in black points and simulated trees transpiration in blue line. All data are plotted during the period from November 2021 to November 2022. The orange background indicates the meteorological drought period, and the red crosses indicate the date of three field soil solution sampling corresponding to the drought period (21 June 2022, 20 July 2022 and 30 August 2022).

3.2 Chemical composition of field soil solutions

The field monitoring of soil solutions concentrations in the Strengbach catchment allows observing long-term variations of major cations concentrations through the 2015-2023 period. The time series exhibits annual seasonality in the chemical signal, as well as significant anomalies (Grubbs test p-value < 10^{-2}; Table 1) during the exceptionally severe drought of summer 2022 (Fig. 3; Table 1).

https://doi.org/10.5194/egusphere-2025-4622
Preprint. Discussion started: 15 October 2025
© Author(s) 2025. CC BY 4.0 License.

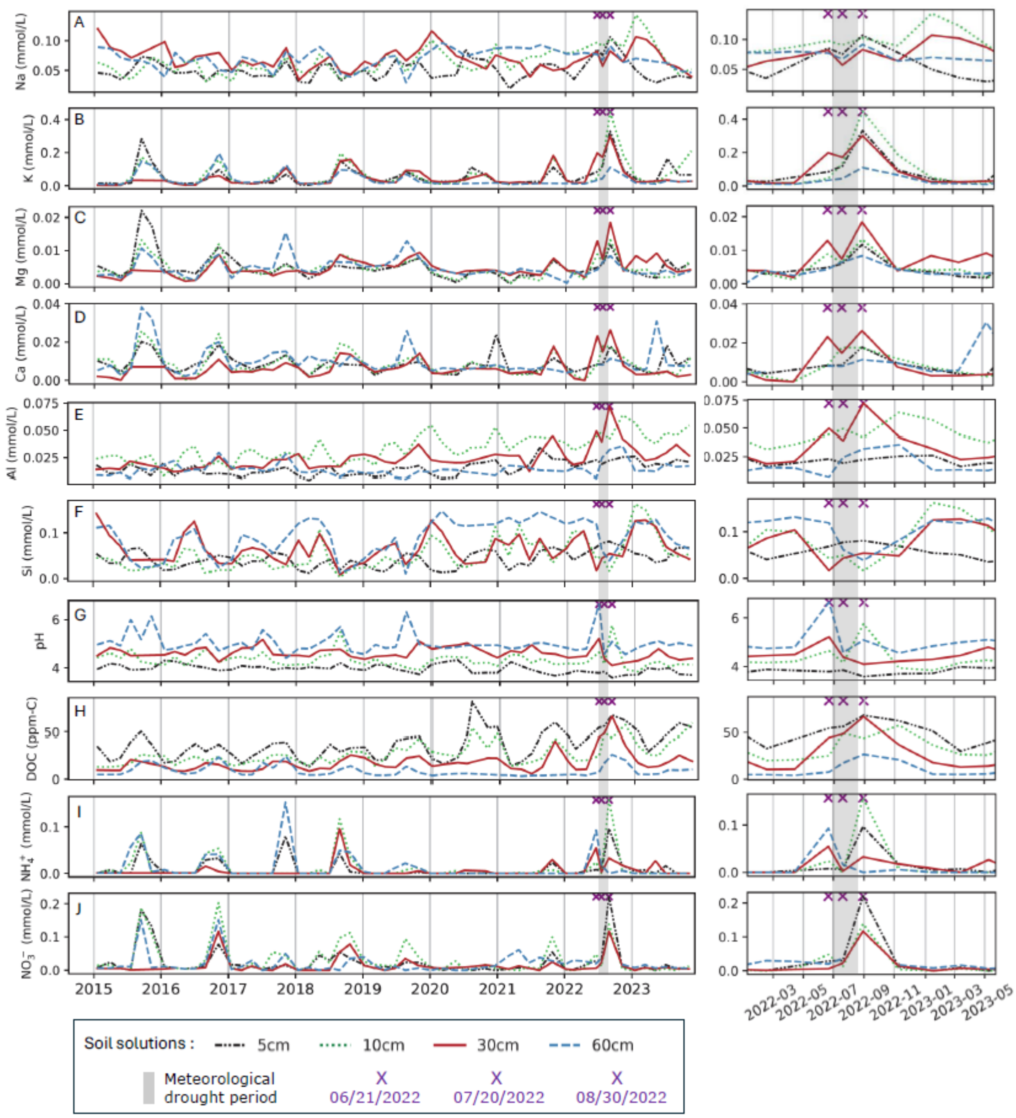


Figure 3: Soil solution cations concentrations (mmol/L) of Na^+ (A), K^+ (B), Mg^{2+} (C), Ca^{2+} (D), Al (E), Si (F), pH (G), Dissolved Organic Carbon DOC (ppm-C/L) (H), NH_4^+ (I) and NO_3^- (J) at four different depths (5, 10, 30 and 60cm) for the 2015-2023 time period. On the right side, a zoom on the 2022 hydrological year is plotted. The 2022 Meteorological drought period is represented by a grey band. The purple crosses indicate the date of three field soil solution sampling corresponding to the drought period (21 June 2022, 20 July 2022 and 30 August 2022).

https://doi.org/10.5194/egusphere-2025-4622
Preprint. Discussion started: 15 October 2025
© Author(s) 2025. CC BY 4.0 License.

	pH	Cond.	Na^+	K^+	Mg^{2+}	Ca^{2+}	Al	Si	NH_4^+	$NO3^-$	DOC
		uS/cm	mmol/L								ppm-C
Mean 2015-2023	4.6	26.7	0.070	0.049	0.005	0.006	0.024	0.066	0.006	0.014	18.13
S.D. 2015-2023	0.2	13.5	0.019	0.060	0.003	0.005	0.011	0.032	0.017	0.025	11.34
Date of outlier (2022)	08/30	08/30	X	08/30	08/30	08/30	08/30	X	06/21	08/30	08/30
Value of outlier	4.1	94.1	X	0.301	0.018	0.026	0.072	X	0.055	0.117	66.81
Grubbs test p-value	0.38	1.0e-7	X	1.9e-4	8.6e-5	4e-3	3.9e-5	X	3.2e-6	2.6e-4	9.5e-5

Table 1: Mean and Standard Deviation (S.D.) of pH, Conductivity (Cond. in µS/cm), Dissolved Organic Carbon (DOC in ppm-C), and concentrations (mmol/L) in ions (Na^+, K^+, Mg^{2+}, Ca^{2+}, Al, Si, NH_4^+ and NO_3^-) for the 2015-2023 period in the soil solutions at 30 cm depth. The third, fourth, and fifth lines correspond to the results of the Grubbs test for the 2015-2023 period, with the date of the outlier, its value and the corresponding p-value respectively. Underlined values are considered as significant outliers by the Grubbs test (p-value $< 10^{-2}$). "X" indicates that no outlier is detected during 2022 with the Grubbs test.

The most extreme chemical anomaly was observed at 30cm depth on 30 August 2022 with an exceptionally high conductivity (94.1 µS/cm) and high DOC (66.81 ppm-C). These values are well above the inter-annual variability and are the highest ever registered at this depth, considered as outliers by Grubbs tests with p-value about 10^{-7} and 10^{-4} respectively (Table 1). The soil solution sample of 30 August integrated the period from 20 July to 30 August and corresponds to the return of rainfall after the long dry period (Fig. 2).

This high conductivity corresponds to peaks of concentration of many ions such as K^+, H^+, Ca^{2+}, Mg^{2+}, Al, Mn^{2+}, Fe^{3+}, NO_3^-, NH_4^+, Cl^- except for Na^+, SO_4^{2-} and Si and these peaks are specially marked at 30 cm (Fig. 3). The peaks are confirmed by the Grubb tests, conducted at 30cm depth over the period 2015-2023, meaning that these maximum concentrations are outliers (Table 1). Focusing on major cations at 30cm depth, the K^+, Ca^{2+}, Mg^{2+} and Al concentrations increase twice successively between 21 June 2022 and 30 August 2022. The highest concentrations ever registered during 2015-2023 period in 30 cm depth soil solution were reached for the second peak (Table 1). K^+ concentration exhibits exceptionally high concentration also at 5 cm and 10 cm depth.

https://doi.org/10.5194/egusphere-2025-4622
Preprint. Discussion started: 15 October 2025
© Author(s) 2025. CC BY 4.0 License.

The 30 cm depth soil solution anomaly during 2022 drought is also characterized by the lowest pH of 4.1 observed on 30 August 2022 over the 2015-2023 period (Fig. 3-G). It should be noted that this anomaly of low pH happened only at 30 cm. However, high pH anomalies were observed at 30 and 60 cm on 21 June 2022 (4.1 and 6.6) and at 10 cm on 30 August 2022 with a pH equal to 5.8. Those values correspond to the maximum pH ever observed at each depth during the period 2015-2023.

For nitrogen-related ions (NO_3^-, NH_4^+), a first peak in NH_4^+ concentrations is observed on 21 June 2022 at 30 cm and 60 cm, followed by a second peak of lower concentrations on 30 August 2022 at 30 cm (Fig. 3-I). NO_3^- concentration peak of 0.117 mmol/L at 30 cm occurs only on 30 August 2022 (Fig. 3-J). For superficial soil solutions, at 5 and 10 cm depth, high concentrations were observed on 30 August 2022 for NH_4^+ (0.10 and 0.16 mmol/L respectively) and for NO_3^- (0.28 and 0.14 mmol/L respectively).

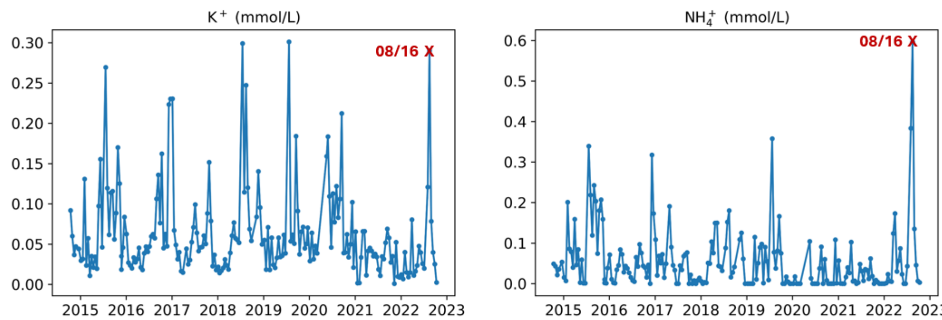


Figure 4: K^+ and NH_4^+ concentrations (mmol/L) in throughfall under spruces in the Strengbach watershed during the period 2015-2023, with the specified point of 16 August 2022 (08/16, red cross) corresponding to the period of rain return after the summer 2022 drought period.

Concentrations in throughfall are highly variable under the studied spruce plot, with numerous concentration peaks (Fig. 4). Concentrations are often higher during summer than winter. Throughfall of 16 August 2022 (red cross on Fig. 4) corresponds to the lixiviation of needle depositions after the dry period (Fig. 2-A). On this date, throughfall exhibits the highest concentration of NH_4^+ (0.597 mmol/L; Fig. 4) and particularly high concentrations of K^+ (0.290 mmol/L).

https://doi.org/10.5194/egusphere-2025-4622
Preprint. Discussion started: 15 October 2025
© Author(s) 2025. CC BY 4.0 License.

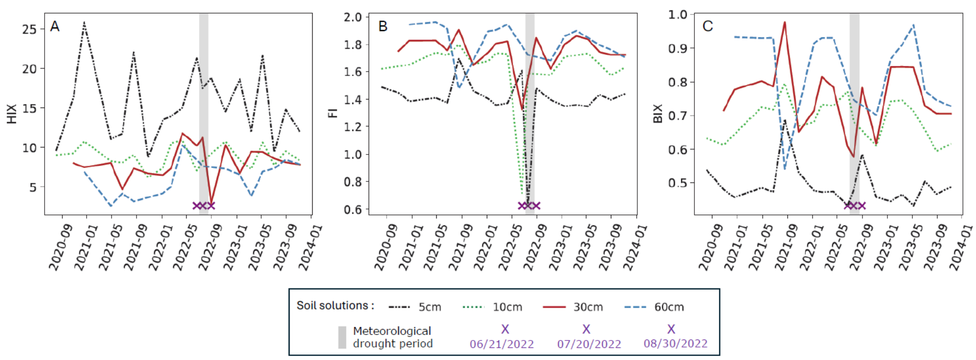


Figure 5: Fluorescence index of soil solutions from four different depths (5, 10, 30 and 60 cm) for the 2020-2023 period. HIX (A), FI (B), BIX (C). 2022 Meteorological drought period is represented by a grey band. The purple crosses indicate the date of three field soil solution sampling corresponding to the drought period (21 June 2022, 20 July 2022 and 30 August 2022).

	HIX	FI	BIX
Mean 2020-2023	8.01	1.74	0.73
S.D. 2020-2023	2.23	0.14	0.11
Date of outlier 2022	08/30	06/21	07/20
Value of outlier	2.83	1.32	0.58
Grubbs test p-value	0.21	4.8e-3	0.33

Table 2: Mean, Standard deviation, outliers dates, outliers values and corresponding Grubbs test p-value for the fluorescence index (HIX, FI, BIX) measured in soil solutions at 30 cm depth over the period 2020-2023.

The qualitative indicators of dissolved organic matter present significant anomalies during the 2022 summer drought, at 30 cm depth, with an FI of 1.32, considered as an outlier by the Grubbs test (p-value = 4.8e-3), compared with a mean value of 1.74 ± 0.14 at this depth (Fig. 5; Table 2). FI shows also an anomaly at 5 cm and 10 cm during this drought period with the lowest and atypical values of about 0.62 on 20 July 2022 and 0.72 on 21 June 2022 respectively (Fig. 5). Low BIX values of 0.60 and 0.58 on 21 June 2022 and 20 July 2022 respectively were measured whereas the average value is 0.73 ± 0.11 at 30 cm depth over the 2020-2023 period. HIX reaches a minimum value of 2.83 on 30 August 2022, only at 30 cm depth, whereas no significant anomalies are noted at any other depths.

https://doi.org/10.5194/egusphere-2025-4622
Preprint. Discussion started: 15 October 2025
© Author(s) 2025. CC BY 4.0 License.

4 Discussion

4.1 Statistical overview of drought consequences on soil solutions chemistry

In order to gain an overall view of the data, multivariate NMDS statistical analyses were carried out on the dataset of chemical measurements (pH, conductivity, Na^+, K^+, Mg^{2+}, Ca^{2+}, Al, Si, NH_4^+, NO_3^-, DOC) and during the time period 2015-2023, separating points by depth of sampling (5, 10, 30 and 60 cm). Soil solution samples from the 2022 drought (from June to November) have a statistically distinct signature only at 30 cm depth (Fig. 6). The three points between June and August, which were particularly affected by drought events, are shifted to the right of the plot along the MDS1 axis. For the other depths, only the soil solution from August 2022 exhibits atypical values. At 30 cm depth, the samples from the summer 2018, which was also a drought episode (cf. 3.1), also show statistically different coordinates. These observations sugg est that the impact of droughts on soil solution chemistry is the most important at 30 cm depth.

The NMDS scores for soil solutions at 30 cm depth show that MDS1 exhibits the highest positive value for NH_4^+, followed by NO_3^- (Table 3). This suggests a disturbance of the nitrogen cycle during the 2022 drought. K^+ and Ca^{2+} concentrations also have high scores along the MDS1 axis, indicating that the dynamics of cationic mineral nutrients are also disrupted by this event. Nutrient concentrations in the soil solution are an interesting parameter, as they are an indicator of soil capacity to supply the nutrients required for tree development. Soils of the Strengbach catchment are particularly poor in Ca and Mg (Oursin et al., 2023), resulting in trees deficiency, with visible symptoms such as yellowing of spruce needles by chlorosis, caused by Mg deficiency (Roberts et al., 1989; Probst et al., 1990). It makes Ca and Mg two critical nutrients in the studied soil. At a depth of 30 cm, the maximum concentrations of Ca^{2+} and Mg^{2+} were reached on 30 August 2022 after the drought (Fig. 3). For the other depths, concentrations were similar to those observed in other summers. Furthermore, the DOC measurement exhibited a particular peak at 30 cm (Fig. 3). Thus, soil solutions appear to be most affected by drought at a depth of 30 cm, with significantly different chemical signatures.

The highest spruce root density is found in the upper soil, from the organic layer to 20 cm depth and sharply decreases with depth (Schmid and Kazda, 2002; Borja et al., 2008). At the Strengbach watershed, the maximum root density ranges from 10 to 30 cm depth (Oursin et al., 2023). As 30 cm soil solutions sampled by zero-tension lysimetric plate integrate all the 30 cm first centimeters of the profile, this depth is key to understanding processes of tree uptake. We will therefore focus the rest of the discussion on interpreting the data

https://doi.org/10.5194/egusphere-2025-4622
Preprint. Discussion started: 15 October 2025
© Author(s) 2025. CC BY 4.0 License.

obtained at 30 cm, using data from other depths where necessary, because this depth corresponds to the data most affected by drought and to the depth of maximum water/soil/plant interactions.

Chemical concentrations in soil solutions are the result of a balance between inputs (throughfall, mineral dissolution, cationic exchange desorption and organic matter degradation) and outputs (plant uptake, mineral precipitation, cationic exchange adsorption and drainage). The following discussion provides an overview of the biogeochemical processes involved in the dynamics of nutrients in soil solution to understand how some of these are affected by drought.

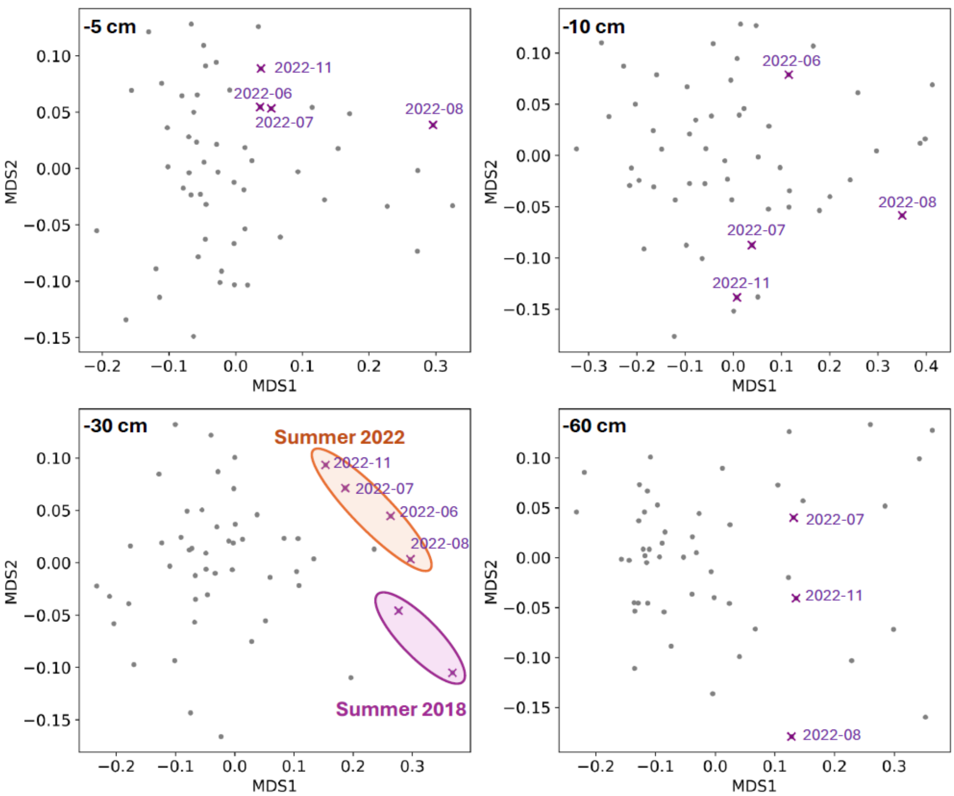


Figure 6: Plots of NMDS coordinates of soil solution samples, with separate analysis for each depth. The dates (purple crosses) correspond to soil solution samples during and after the 2022 drought. In the 30 cm figure, two crosses corresponding to the summer of 2018 are positioned on the graph. The number of crosses is lower for samples at 60 cm depths because no water is collected at this depth during certain periods of drought.

https://doi.org/10.5194/egusphere-2025-4622
Preprint. Discussion started: 15 October 2025
© Author(s) 2025. CC BY 4.0 License.

		pH	Cond.	Na^+	K^+	Mg^{2+}	Ca^{2+}	Al	Si	NH_4^+	$NO3^-$	DOC
5 cm	NMDS1	-0.072	-0.023	-0.038	0.102	0.066	0.008	-0.069	-0.035	0.603	0.239	-0.042
	NMDS2	-0.098	0.030	-0.035	0.061	-0.040	-0.017	0.054	0.071	0.150	-0.143	0.057
10 cm	NMDS1	-0.062	-0.025	-0.107	0.193	0.110	0.139	-0.114	-0.218	0.734	0.391	-0.050
	NMDS2	0.051	-0.042	0.017	-0.154	-0.008	-0.006	-0.012	0.021	0.321	0.114	-0.067
30 cm	NMDS1	-0.085	0.004	-0.097	0.204	0.040	0.143	-0.022	-0.185	0.588	0.284	0.026
	NMDS2	0.011	0.001	-0.033	0.025	-0.010	0.034	0.051	-0.019	-0.375	-0.107	0.047
60 cm	NMDS1	-0.052	0.005	-0.106	0.216	0.070	0.075	-0.041	-0.195	0.782	0.056	0.088
	NMDS2	-0.024	0.007	0.000	-0.032	-0.024	-0.060	-0.017	0.009	0.274	0.262	-0.052

Table 3: NMDS scores for the various physical and chemical parameters of soil solutions sampled at different depths (5, 10, 30 and 60 cm depths).

340

4.2 Weathering process

While most chemical concentrations show a peak during the drought of 2022, Na^+ and Si show no significant peaks (Fig. 3). Their average concentrations during the period between 21 June and 30 August 2022 are 0.074 and 0.038 mmol/L respectively, which is within the range of inter-annual variability with a mean concentration during 2015-2023 period of 0.070 ± 0.019 mmol/L and 0.066 ± 0.032 mmol/L for Na and Si respectively (Table 1). In addition, the Grubbs test also confirms that Na and Si are the only elements that do not show abnormal values (outliers) during the drought of 2022 (Table 1).

In the soils from the Strengbach catchment, sodium is mainly included in albite, a primary mineral from the granite (Fichter et al., 1998). Na is not considered to precipitate or integrate in secondary phases (Chou & Wollast, 1985). It represents only 0.6% of the cationic exchange capacity and its concentration is negligible in the litter compared to other elements (Oursin et al., 2023). Thus, the main sources of sodium in soil solution are the throughfall and the dissolution of albite. The concentrations of Na^+ in throughfall do not seem to be affected by drought, the concentration on the 16 August 2022, date of rain return after drought, is 0.033 mmol/L, which is comparable with the mean concentration of 0.042 ± 0.021. As no significant consequences of drought on Na^+ concentration in soil solution is observed, we can propose that drought does not affect albite dissolution in soil.

https://doi.org/10.5194/egusphere-2025-4622
Preprint. Discussion started: 15 October 2025
© Author(s) 2025. CC BY 4.0 License.

Moreover, the study of Oursin et al. (2023) has shown that the contribution of primary mineral weathering in the chemical signature (Ca, Mg and K concentrations) of soil solution from the same site was low and even negligible when compared with other fluxes (alteration of secondary minerals, cation exchange, litter degradation), except for Na. This lack of impact on albite dissolution may be extended to other primary minerals composing granite. So, it can be proposed that the impact of drought on the weathering of all primary minerals is negligible.

In theory, thermodynamic and kinetic of mineral dissolution depend highly on soil temperature and water content (Lasaga et al., 1994 ; Kump et al, 2000). Studies modelling the effect of climate change on future forest soil weathering rate proposed that a global increase in temperature can increase the chemical weathering. However, because of soil moisture limitation, summer droughts limit the expected gain in weathering associated with higher temperatures (Belyazid et al., 2022; Kronnäs et al., 2023). Thus, severe water deficits in soil tend to reduce weathering rates.

The concentration of Si in rain and throughfall is below the detection limit (Pierret et al., 2018) and the concentration of Si in litter is negligible compared with other elements (Oursin et al, 2023). So, Si mainly comes from mineral weathering. Hydrological modelling of soil water content (Fig. 2. B) exhibits an important diminution during June 2022 in the third layer (between 10 and 30 cm) and during August in the fourth layer (30 to 60 cm), similarly to Si concentrations with significant reduction on 21 June 2022 at 30 cm and on 30 August 2022 at 60 cm (Fig. 3 F). In addition, two minimal Si concentrations, at 30cm and 60cm depth, were observed in the summers 2018 and 2022, the two main drought events of the period 2015-2023, during which impacts on forests were observed (Gharun et al., 2024; Knutzen et al., 2025). So that we can deduce a reduction in silicate mineral dissolution due to low water content during drought. Silica is mainly controlled by clay weathering in the soil of the Strengbach catchment, as shown by geochemical modelling (Goddéris et al., 2006; Beaulieu et al., 2020). As the reduction is visible for Si and not for Na, it can be proposed that clay mineral dissolution is reduced during drought events. As the dissolution kinetic is higher for secondary minerals compared to primary, a reduction of secondary minerals dissolution should have higher consequences on the chemical composition of the solution (Drever & Clow, 1994). Thus, water deficit in soils would indeed lead to a decrease in weathering rate, as proposed by Belyazid et al. (2022) and Kronnäs et al. (2023), but only visible on secondary minerals such as clays. Silica is the only element showing a reduction in concentration during drought. However, chemical soil solutions signals show positive peaks in many elements such as K^+, Ca^{2+}, Mg^{2+} and Al (Fig. 3). These peaks cannot be explained by an expected reduction in weathering due to water deficit, which would have the opposite effect. Therefore, other processes will be discussed in the following sections.

4.3 The role of throughfall

Rainfall passing through the canopy, known as throughfall, differs from open field precipitation because of its interactions with leaf surfaces. Throughfalls integrate wet and dry atmospheric deposits as well as biological interactions with the canopy during leaves or needles leaching (Ulrich et al., 1983; Berger et al., 2008; Eisalou et al., 2013; Pierret et al., 2019; Ponette-González et al., 2020). Compared to rain, throughfalls are enriched in each chemical element. On the basis of a monitoring over the 1986-2012 period, Pierret et al. (2019) show that throughfalls under spruces are enriched by a factor of 15 for K^+, 5 for Ca^{2+} and Mg^{2+} and 2 for NH_4^+ compared to open field precipitations from the same studied site, the Strengbach catchment. K^+ in throughfalls comes mainly from biological excretion by leaves, whereas Ca^{2+} and Mg^{2+} are a mixture between wet and dry atmospheric deposits and a weak influence of biological exchanges (Lovett and Lindberg, 1984; Kopacek et al., 2009; Adriaenssens et al., 2012; Pierret et al., 2019). NH_4^+ mainly comes from atmospheric deposition, which might be from NH_3 atmospheric emission due to agricultural activities (Avila et al., 2017; Pierret et al., 2019). But NH_4^+ is involved in numerous biological processes, can also be excreted, absorbed by leaves or organisms living on the leaves (Woods et al., 2012; Ponette-González et al., 2020).

K^+ is highly affected by the biological functioning of trees. Reduction of rainfall or drought might reduce the mobility of K^+ within the canopy by decreasing foliar leaching (Sardan & Peñuelas, 2015; Schlesinger et al., 2016; Touche et al., 2024). Thus, potassium that is biologically excreted will accumulate on spruce needles. As a result, the first rains will leach these elements, leading to high concentrations in the throughfalls (Fig. 4). Thus, the exceptionally high peak in K^+ observed in soil solutions at 5, 10, and 30 cm on 30 August 2022 can be linked to the high K^+ content of throughfalls of 16 August 2022. Indeed, K^+ concentration on the 30 August 2022 soil solution at 5cm depth (integrating 20 July to 30 August period and including the rain episode of 16 August; Fig. 2) is 0.331 mmol/L, similar to the K^+ concentration in throughfall on the 16 August 2022 (Fig. 3B; 0.290 mmol/L), thus supporting the important contribution of throughfall in superficial soil solution K^+ concentration. Similar observations of K^+ concentrations peak in soil solutions at different depths have been made on drought experiments on European spruce plots (Lamersdorf et al., 1998) but also in Canadian boreal forest with very high K^+ concentrations in the soil solution at 30 cm and in throughfall, as observed by Houle et al. (2016). This vertical propagation of K^+ in the soil profile is likely driven by the increased concentrations observed in the throughfall.

https://doi.org/10.5194/egusphere-2025-4622
Preprint. Discussion started: 15 October 2025
© Author(s) 2025. CC BY 4.0 License.

This spread of K^+ diminishes between 30 and 60 cm, probably because this cation can be sorbed, exchanged, precipitated or uptaken by trees. No other cation (Na^+, Ca^{2+}, Mg^{2+}) exhibits a maximum peak in both throughfalls and surface soil solutions (5 and 10 cm deep). This specificity of K^+ is linked to the important contribution of throughfall in K soil solution concentration compared to other elements.

NH_4^+ shows a strong positive anomaly in the throughfall for 16 August 2022, with concentrations of around 0.597 mmol/L, more than 10 times the average for the period 2015-2024 of 0.055 mmol/L (Fig. 4). This ammonium peak is also found in soil solutions at depths of 5 and 10 cm on 30 August 2022 (Fig. 3). The ammonium flux in throughfalls comes from the leaching of spruce needles during the first rain after drought, as with K. However, due to the high reactivity of ammonium and nitrogen species in general in soils (as nitrification converts ammonium into nitrite and/or nitrate), the NH_4^+ concentrations of soil solutions at 5 and 10 cm depth are significantly lower (0.075 and 0.150 mmol/L) than in throughfall (0.6 mmol/L). Thus, after a drought period, throughfall represents an important source of ammonium for soil solutions.

Since 2015, other peaks of high concentrations in the throughfall series have been observed, but not in the soil solutions (Fig. 3; Fig. 4). This highlights that an additional process must explain why, in 2022, K, Ca or Mg accumulate in soil solutions, whereas in other periods, part of the throughfall appears to be mobilized in the soil.

4.4 Vegetation uptake

Soil solutions contain elements that are essential plant nutrients such as K^+, Ca^{2+}, Mg^{2+}, NO_3^-, NH_4^+ (Ingestad, 1979). K is the most abundant cation in plant cells and a limiting element for plant growth (Leigh & Jones, 1984; Sardans & Peñuelas, 2015). Ca and Mg are also two essential nutrients for trees, found in very small quantities in Strengbach soils and maintained in sufficient concentration in the soil solution through recycling by vegetation (Ovington, 1959; Fichter, 1997; Beaulieu et al., 2020; Oursin et al., 2023). Beaulieu et al. (2020) simulate biogeochemical processes under spruce plot in the Strengbach catchment, and they estimate that tree uptake is the most important flux of Ca and Mg in the system, two times higher than the flux coming from the throughfall. In contrast to K, the uptake flux is two times lower than the flux coming from throughfall. So, trees uptake large quantities of Ca^{2+}, Mg^{2+}, K^+, NO_3^-, NH_4^+ and influence nutrient concentrations in solution. The field

https://doi.org/10.5194/egusphere-2025-4622
Preprint. Discussion started: 15 October 2025
© Author(s) 2025. CC BY 4.0 License.

data show an increase of Ca^{2+}, Mg^{2+}, K^+, NH_4^+ and NO_3^- concentrations in the soil solutions, especially at 30 cm depth, during or after the drought (Fig. 3). One hypothesis could be that these increases in concentrations are linked to a decrease in biological uptake by vegetation.

The reactions of trees to drought, such as stomate closure or reducing leaf area (needle loss), for instance, decrease water loss through transpiration and so decrease water uptake by roots (Bréda et al., 2006; Ditmarova et al., 2010, Hesse et al., 2024). The decrease in tree transpiration during the drought period, simulated by the model BILHYDAY used in this study (Fig. 2), implies a reduction in water uptake by tree roots. This has also been observed in the Strengbach watershed, with measurements of reduced sap flow during an experimental water deficit in spruce trees (Lu et al., 1995). In addition, an experimental water deficit study carried out on a spruce stand in the same Strengbach watershed showed that the composition of the xylem sap flow was lower in nutrients (Ca, Mg and K) during the water deficit period (Dambrine, 1993). So, trees take up less Ca, Mg, K during drought. Reduced nutrient uptake can explain the lower biomass concentrations found in numerous experimental water deficit studies on forest plots. For example, lower concentrations of K, B and Mg were observed after droughts in spruce needles (Nilsen, 1995), but also in the biomass of other tree species (Sardans et al., 2008; Touche et al., 2022).

Thus, the decrease in biological uptake by trees during drought may explain the maximum concentrations observed for Ca, Mg, K, nitrate and ammonium in soil solutions, particularly at a depth of 30 cm, which corresponds to the depth after the maximal root density zone, in 20 first centimeters of the mineral soil for spruces (Schmid et Kazda, 2002; Borja et al., 2008). It explains why high concentrations were found at 30 cm depth particularly for Ca and Mg, the two nutrients most impacted by trees uptake.

4.5 Organic carbon reactivity

A DOC increase is observed in soil solution at 30 cm depth during and after drought period, with a maximum concentration of 66.81 ppm-C after the rain return (Table 1; Fig. 3). On other sites, a similar DOC peak was observed under spruce plots, after a water deficit experiment at 20 cm depth (Lamersdorf et al., 1995) or after 2006 drought at 90 cm depth (Schulze et al., 2011). The DOC increase during the drought period could be induced by different organic inputs. Indeed, Gaul et al. (2008) have reported that water deficit can lead to an increase in fine root mortality up to 61%, not compensated by an increase in fine root production on a Norway spruce forest

https://doi.org/10.5194/egusphere-2025-4622
Preprint. Discussion started: 15 October 2025
© Author(s) 2025. CC BY 4.0 License.

in Germany. These root mortality, also observed in Norway spruce located in Sweden subjected to drought (Persson et al., 1995), can represent a carbon source to soil organic matter pool in a temperate ecosystem.

Moreover, another source of carbon in upper soil horizons in response to drought could come from stress and mortality in bacteria and fungi in response to water deficit as reported in many studies and so lead to a decrease in organic matter degradation (Schimel et al., 2007; Boczon et al., 2021; Gehring et al., 2017; Bogati & Walczak, 2022). Indeed, even if heterotrophic respiration is controlled by temperature in wet soils, it is limited by water deficit during dry period (Curiel-Juste et al., 2007). The degradation decrease could lead to accumulation of organic carbon in superficial soil layer. On the other hand, the high concentration of DOC observed after the rain return in soil solutions could be the result of fast-moving water and transport of DOC accumulated in superficial soil layer during drought period through soil profile. A high dissolution of organic matter would also lead to an input of other elements contained in this organic matter to the soil solution. It can therefore also contribute to an increase in Ca, Mg or K concentrations in soil solutions at 30 cm after the rain returns, in addition to other mechanisms disturbed during drought.

To better understand this modification of DOC dynamics, we use optical characterization by fluorescence. Three fluorescence indices are frequently used to characterize natural organic matter in water: the fluorescence index (FI, McKnight et al., 2001), the biological index (BIX, Huguet et al., 2009) and the humification index (HIX, Zsolnay et al., 1999).

HIX was defined by Zsolnay (1999) and Ohno (2002) and is an indicator sensitive to the quantity of aromatic molecules in solution, but also to the type of molecules, i.e., more or less aromatic, heavy, complex (Serène et al. 2025). HIX is relatively high before and during the drought in 30 cm depth soil solution (HIX = 8.01 ± 2.23). It then falls sharply when the rain returns after the long dry period (HIX = 2.83 on 30 August 2022) during the DOC peak. A similar dynamic between DOC and aromaticity during and after drought has been observed in several streams in boreal ecosystems (Tiwari et al., 2022). As these large aromatic molecules precipitate at acid pH (Swift, 1996), the decrease in pH may explain the decrease in HIX on 30 August 2022. HIX is often correlated with DOC (Pearson coefficient = 0.54 on all four depths of the plot), but the solution showing the DOC peak after the drought is relatively low in aromatic molecules, reflecting the atypical composition of this solution, reinforcing the hypothesis of a new source of organic matter coming from biological stress on soil organisms instead of usual litter decomposition.

https://doi.org/10.5194/egusphere-2025-4622
Preprint. Discussion started: 15 October 2025
© Author(s) 2025. CC BY 4.0 License.

4.6 Biological stress monitored with UV-fluorescence spectroscopy

The FI (Fluorescence Index) in superficial waters and groundwaters can be used to distinguish sources of terrestrially or microbially derived fulvic acids. McKnight et al. (2001) propose index values of 1.4 for terrestrial origin and of 1.9 for microbial origin. The FI is on average equal to 1.74 in soil solution at 30 cm depth over the period 2020-2023 (Table 2), which could highlight predominantly microbial sources of organic material. However, a decrease of FI to 1.3 is observed in June 2022 at 30 cm depth (Fig. 4), an index value consistent with predominantly terrestrial sources. The low contribution of microbial source to organic material could be explained by a reduction of fungal and bacterial activity due to low water content during the May-June period (Fig. 2.B), as mentioned in section 4.5. The index value increases to 1.8 in soil solution with the rain return, indicating a recovery of regular microbial activity (Fig. 2B).

The BIX is commonly used as a proxy of biological activity in aquatic environments (Parlanti et al. 2000; Huguet et al. 2009). High values of BIX can suggest a high biological activity and so an organic matter recently produced by microbial activity, while the low values are supposed to stem from relatively low biological activity. The BIX values decrease in soil solution at 30 cm depth during the May-June period, then increase with the rain return (Fig. 4), consistent with the FI value evolution.

The drought characterized by a decrease in soil water content from May to July (Fig. 2), leads to a DOM with a lower microbial signature which supports the hypothesis of a decrease in soil microbial and fungal activity during drought. On 30 August 2022, after the soil rewetting, the DOM had its usual microbial source signature back, which means a resumption of biological activity in the soil when water conditions become favorable again.

4.7. Nitrogen cycle disturbance during drought

While for nitrates we only observe a peak after the return of rain, for NH_4^+ we observe two distinct dynamics: high concentrations at 30 and 60 cm in June and high concentrations at 5 and 10 cm after the return of rain in August. We will explain these different temporal dynamics in chronological order.

During the water deficit period in soil (Fig. 2), a peak of NH_4^+ concentration on 21 June 2022 (Fig. 3) occurs only at 30 cm and 60 cm depth. The disturbance of nitrogen cycle during drought has been the subject of numerous historical studies, notably during experimental droughts on various spruce plots on acid soils in Europe, where canopy roofs were installed (Lamersdorf et al. 1998). They all observe high concentrations of ammonium

https://doi.org/10.5194/egusphere-2025-4622
Preprint. Discussion started: 15 October 2025
© Author(s) 2025. CC BY 4.0 License.

and dissolved organic carbon in soil solution. Gangloff et al. (2014) observe that ammonium peaks in soil solutions are also linked to specific periods of bacterial activity and to hydrological conditions, in a spruce plot from the Strengbach catchment. This supports the idea of an accumulation of organic matter during water deficit due to stress on the soil biosphere (cf. 4.5). The mortality of bacteria and fungi may release cell content that is rich in nitrogen-containing organic matter. This organic nitrogen is degraded to ammoniacal nitrogen by ammonification (Kuypers et al., 2018). The accumulation of NH_4^+ is due to the interruption of nitrification during water deficits, whereas ammonification is less sensitive, as shown by experiments on spruce soils carried out by Hentschel et al. (2007) or Chen et al. (2011). Thus, the high concentrations of NH_4^+ at deeper horizons, i.e. 30 and 60 cm depth, can be related to the punctual stress of the soil microfauna. This is consistent with the FI and BIX index showing a less microbially derived signature at the corresponding period (cf. 4.6).

After the rain returns (30 August 2022), the NH_4^+ concentrations presented peaks in soil solutions at 5 and 10 cm depths. This can be related to the throughfall inputs as mentioned above (cf. 4.3). At the same time, high nitrate concentrations were observed in soil solutions at all depths (Fig. 4). After soil rewetting, conditions become favorable for nitrifying bacteria: high ammonium concentration, high pH, high temperature and sufficient water content. This leads to significant development of nitrifying populations at 30 cm depth, as observed by Krüger et al. (2021) after the 2018 drought under a beech plot. This resulted in high nitrification after rain returned, leading to the observed high NO_3^- concentrations in soil solutions. In addition, nitrate accumulation in soil solutions is also enhanced by the lower tree uptake (cf. 4.4).

Thus, periods of water deficit and the first episodes of rain returns, by modifying bacterial activity, severely disrupt the cycle of nitrogen and nitrogen nutrients (NH_4^+ and NO_3^-) concentrations in soil solutions.

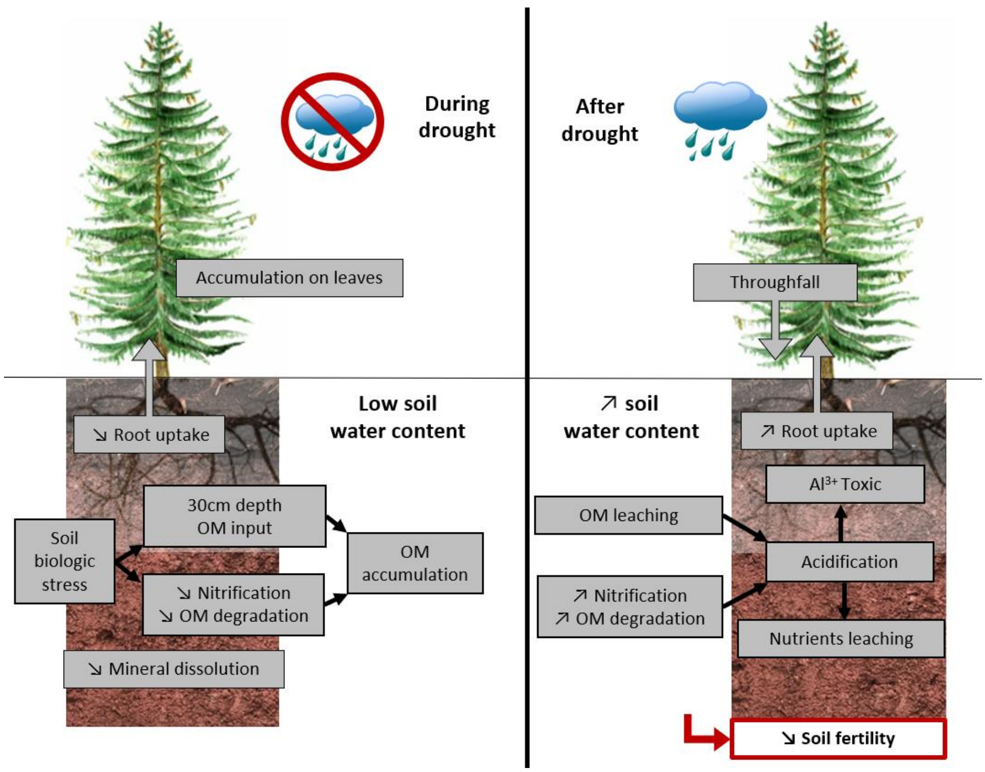
4.8. Acidification

The most acidic pH (4.1) recorded in soil solution at 30 cm depth during the 2015-2023 monitoring period was observed on 30 August 2022. In contrast, a significantly higher pH (5.2) was measured on June 21, coinciding with low soil moisture content (Fig. 2). The ammonification consumes protons and consequently increases pH (Kuypers et al., 2018). This process likely explains the highest pH of the 2015-2023 period at 30 cm with a value of 5.21 observed on 21 June 2022 (Fig. 3). Conversely, the low pH corroborates with exceptionally elevated nitrate concentrations observed in August (Fig. 3) because nitrification is acidifying (Kuypers et al., 2018). The sharp pH variation illustrates the strong influence of the nitrogen cycle on the pH of those soil solutions. In addition, this

https://doi.org/10.5194/egusphere-2025-4622
Preprint. Discussion started: 15 October 2025
© Author(s) 2025. CC BY 4.0 License.

low value of pH can also be related to the high DOC concentration, which is the highest ever measured at 30 cm depth (Fig. 3). Indeed, DOC is composed mainly of organic acids, contributing to acidification (Strobel et al., 2001).

Furthermore, this acidification has consequences for the dynamics of some elements in the soil, as protons can desorb cations from soil exchangeable surface, in particular Al^{3+}, Ca^{2+}, Mg^{2+} and K^{+} (Ulrich et al., 1980; Fest et al., 2005; Meng et al., 2019). This process resulted in the release of those cations into soil solution and likely contributed to the elevated concentrations in solution at 30 cm depth (Fig. 3). This is especially noticeable with Al concentrations, with the highest concentration ever observed during the 2015-2023 period at 30 cm depths on 30 August 2022 (Fig. 3). It raises issues for tree health, as Al^{3+} is toxic in high concentrations (Ulrich et al, 1980; De Wit et al, 2001). The desorption of cationic nutrients such as Ca^{2+}, Mg^{2+} and K^{+} is of particular concern in acid soils that are already low in cationic nutrients, such as those in the Strengbach catchment (Dambrine et al., 1998).



https://doi.org/10.5194/egusphere-2025-4622
Preprint. Discussion started: 15 October 2025
© Author(s) 2025. CC BY 4.0 License.

Figure 6: Graphical summary of drought perturbation on soil solution chemistry and soil reactivity with grey boxes representing biogeochemical processes and a red box representing the consequences of drought on soil fertility.

Conclusion

The summer drought of 2022 was the most severe ever recorded at the observatory of the Strengbach catchment since 1986. Ten years of monitoring at the spruce plot has made it possible to identify and characterize the main geochemical disturbances in soil solutions (in terms of major elements, dissolved organic matter and its indicators) linked to both drought and the effects of the first rains, as well as the consequences for nutrient biogeochemical cycles and for the whole functioning of the forest ecosystem.

We focused our discussions on soil solutions at 30 cm depth because they are the most affected and represent the preferential depth for root uptake. The 2022 drought caused a significant increase in DOC and ion concentrations in soil solutions (K^+, Ca^{2+}, Mg^{2+}, Al^{3+}, NH_4^+, NO_3^-) and atypical values of fluorescence index HIX, FI and BIX. The consequences of drought on biogeochemical processes can be separated into two time periods: during drought and after drought.

The impact of drought on primary mineral dissolution seems negligible, whereas the decrease in water content in soil induced a decrease in secondary mineral weathering such as clays. During drought, because of the decrease in water content in soil, the trees uptake of water and nutrients is also reduced. The exceptionally dry belowground conditions cause an important biological stress on soil microfauna and an important decrease in microbial activity and mortality of bacteria, fungi and roots. Organic matter thus accumulates in the soil to a depth of 30 cm. Nitrification is also reduced, resulting in an accumulation of NH_4^+ and an increase in pH in soil solutions.

After drought, the return of rainfall will lixiviate the accumulated atmospheric depositions and biological recretion on spruce needles. It results in high concentrations in throughfall, particularly for K^+ and NH_4^+. The increase of soil water content lixiviates the organic matter accumulated during the dry period and induces the highest DOC (66 ppm-C) ever registered at 30 cm deep since 2015. In addition, the degradation of organic matter also generates an important flux of Ca, Mg and K to soil solutions. Sufficient water content, high NH_4^+ and high temperature trigger nitrification to reactivate and produce high NO_3^- concentration in solution. As organic matter degradation and nitrification are acidifying processes, it results in the lowest pH (4.1) ever registered at 30 cm

https://doi.org/10.5194/egusphere-2025-4622
Preprint. Discussion started: 15 October 2025
© Author(s) 2025. CC BY 4.0 License.

during the 2015-2023 period. This acidification leads to a desorption of soil cationic nutrients from the clay-humic complex. Thus, immediately after the rains return, the soil solutions at 30 cm depth had the highest concentrations of nutrients (K^+, Ca^{2+}, Mg^{2+}, NH_4^+, NO_3^-) for the 2015-2023 period. It also generates a very high concentration of desorbed Al^{3+}, which is toxic for trees. This acidification will therefore lead to the migration of nutrients and then to a decline in the fertility of forest soils, which is particularly worrying in already nutrient-poor acidic soils such as those in the Strengbach watershed.

In addition to the water deficit that threatens spruces with severe physiological consequences, drought also induces nutrient loss and so accelerates forest decline and fragility. Climate forecasts predict an increase in the frequency and intensity of droughts in the Vosges (Soubeyroux et al., 2020), which will increase mortality in spruce forests that are particularly non-resilient to drought. This aggravation of forest decline by drought suggests a negative feedback loop that could exacerbate climate change by reducing the carbon storage capacity of forests and by releasing carbon due to tree mortality. Spruce trees, already weakened by nutrient-poor soils and bark beetle attacks, appear to be poorly adapted in temperate regions to drought conditions, which are likely to recur. Forest management must take this into account to achieve more sustainable forests.

Data availability

Data concerning soil solutions are not yet available online. However, weather data and data on the chemistry of throughfall are available on the BDOH platform: https://bd-ohge.unistra.fr/OHGE/

Author contribution

AS, MCP and EB designed the study. MNP produces soil solution fluorescence measurements. BB processed meteorological data and produced hydrological simulations. AS ran statistical analysis. AS interpreted data and wrote the manuscript. MCP, EB, BB and MNP commented the manuscript.

Competing interest

The authors declare that they have no conflict of interest.

Acknowledgements

https://doi.org/10.5194/egusphere-2025-4622
Preprint. Discussion started: 15 October 2025
© Author(s) 2025. CC BY 4.0 License.

We acknowledge all the team of the *Observatoire hydrogéochimique de l'environnement*: Solenn Cotel, Colin Fourtet, Anthony Julien and Alain Hernandez for field sampling and laboratory analysis.

Financial support

This research has been supported by the *Ecole Nationale du Génie de l'Eau et de l'Environnement* (ENGEES), the *Région Grand-Est*, and EC2CO/INSU-CNRS project REFORESTATION.

References

Adriaenssens, S., Hansen, K., Staelens, J., Wuyts, K., De Schrijver, A., Baeten, L., Boeckx, P., Samson, R., Verheyen, K.: Throughfall deposition and canopy exchange processes along a vertical gradient within the canopy of beech (Fagus sylvatica L.) and Norway spruce (Picea abies (L.) Karst). Sci. Total Environ., 420, 168–182, https://doi.org/10.1016/j.scitotenv.2011.12.029, 2012.

Anderegg, W.R.L., Kane, J.M., Anderegg, L.D.L.: Consequences of widespread tree mortality triggered by drought and temperature stress. Nat. Clim. Change, 3, 30–36, https://doi.org/10.1038/nclimate1635, 2013.

Anderegg, W. R. L., Trugman, A. T., Badgley, G., Konings, A. G., and Shaw, J.: Divergent forest sensitivity to repeated extreme droughts, Nat. Clim. Chang., 10, 1091–1095, https://doi.org/10.1038/s41558-020-00919-1, 2020.

Avila, A., Aguillaume, L., Izquieta-Rojano, S., García-Gómez, H., Elustondo, D., Santamaría, J.M., Alonso, R.: Quantitative study on nitrogen deposition and canopy retention in Mediterranean evergreen forests. Environ. Sci. Pollut. Res., 24, 26213–26226, https://doi.org/10.1007/s11356-017-8861-4, 2017.

Beaulieu, E., Pierret, M.-C., Legout, A., Chabaux, F., Goddéris, Y., Viville, D., Herrmann, A.: Response of a forested catchment over the last 25 years to past acid deposition assessed by biogeochemical cycle modeling (Strengbach, France). Ecol. Modell., 430, 109124, https://doi.org/10.1016/j.ecolmodel.2020.109124, 2020.

Belyazid, S., Akselsson, C., Zanchi, G.: Water limitation in forest soils regulates the increase in weathering rates under climate change. Forests, 13, 310, https://doi.org/10.3390/f13020310 , 2022.

Berger, T.W., Untersteiner, H., Schume, H., Jost, G.: Throughfall fluxes in a secondary spruce (Picea abies), a beech (Fagus sylvatica) and a mixed spruce–beech stand. For. Ecol. Manage, 255, 605–618, https://doi.org/10.1016/j.foreco.2007.09.030, 2008.

Boczoń, A., Hilszczańska, D., Wrzosek, M., Szczepkowski, A., Sierota, Z.: Drought in the forest breaks plant–fungi interactions. Eur. J. For. Res., 140, 1301–1321, https://doi.org/10.1007/s10342-021-01409-5, 2021.

Bogati, K., Walczak, M.: The Impact of Drought Stress on Soil Microbial Community, Enzyme Activities and Plants. Agronomy, 12, 189, https://doi.org/10.3390/agronomy12010189, 2022.

Borja, I., De Wit, H.A., Steffenrem, A., Majdi, H.: Stand age and fine root biomass, distribution and morphology in a Norway spruce chronosequence in southeast Norway. Tree Physiol., 28, 773–784, https://doi.org/10.1093/treephys/28.5.773, 2008.

Bréda, N., Huc, R., Granier, A., Dreyer, E.: Temperate forest trees and stands under severe drought: a review of ecophysiological responses, adaptation processes and long-term consequences. Ann. For. Sci., 63, 625–644, https://doi.org/10.1051/forest:2006042, 2006.

Brioschi, L., Steinmann, M., Lucot, E., Pierret, M.C., Stille, P., Prunier, J., Badot, P.M. : Transfer of rare earth elements (REE) from natural soil to plant systems: implications for the environmental availability of anthropogenic REE. Plant Soil, 366, 143–163, https://doi.org/10.1007/s11104-012-1407-0, 2013.

Cenki-Tok, B., Chabaux, F., Lemarchand, D., Schmitt, A.-D., Pierret, M.-C., Viville, D., Bagard, M.-L., Stille, P.: The impact of water–rock interaction and vegetation on calcium isotope fractionation in soil- and stream waters of a small, forested catchment (the Strengbach case). Geochimica et Cosmochimica Acta, 73, 2215–2228, https://doi.org/10.1016/j.gca.2009.01.023, 2009.

Chen, Y.-T., Borken, W., Stange, C.F., Matzner, E.: Effects of decreasing water potential on gross ammonification and nitrification in an acid coniferous forest soil. Soil Biol. and Biochem., 43, 333–338, https://doi.org/10.1016/j.soilbio.2010.10.020, 2011.

Chou, L., Wollast, R.: Steady-state kinetics and dissolution mechanisms of albite. Am. J. Sci., 285 (10), 963 – 993, https://doi.org/10.2475/ajs.285.10.963, 1985.

Ciais, Ph., Reichstein, M., Viovy, N., Granier, A., Ogée, J., Allard, V., Aubinet, M., Buchmann, N., Bernhofer, Chr., Carrara, A., Chevallier, F., De Noblet, N., Friend, A.D., Friedlingstein, P., Grünwald, T., Heinesch, B., Keronen, P., Knohl, A., Krinner, G., Loustau, D., Manca, G., Matteucci, G., Miglietta, F., Ourcival, J.M., Papale, D., Pilegaard, K., Rambal, S., Seufert, G., Soussana, J.F., Sanz, M.J., Schulze, E.D., Vesala, T., Valentini, R. : Europe-wide reduction in primary productivity caused by the heat and drought in 2003. Nature, 437, 529–533, https://doi.org/10.1038/nature03972, 2005.

Copernicus Climate Change Service (C3S): European State of the Climate 2022, https://doi.org/10.24381/gvaf-h066, 2023, last access: 19 august 2025

Curiel Yuste, J., Baldocchi, D.D., Gershenson, A., Goldstein, A., Misson, L., Wong, S.: Microbial soil respiration and its dependency on carbon inputs, soil temperature and moisture. Global Change Biol., 13, 2018–2035, https://doi.org/10.1111/j.1365-2486.2007.01415.x, 2007.

Dambrine, E., Carisey, N., Pollier, B., Granier, A.: Effects of drought on the yellowing status and the dynamics of mineral elements in the xylem sap of declining spruce (Picea abies L.). Plant Soil, 150, 303–306, https://doi.org/10.1007/BF00013028, 1993.

Dambrine, E., Pollier, B., Poszwa, A. et al. Evidence of current soil acidification in spruce stands in the Vosges Mountains, north-eastern France. Water Air Soil Pollut., 105, 43–52, https://doi.org/10.1023/A:1005030331423, 1998.

De Wit, H. A., Mulder, J., Nygaard, P. H., and Aamlid, D.: Testing the aluminium toxicity hypothesis: a field manipulation experiment in mature spruce forest in Norway, in: Acid rain 2000, edited by: Satake, K., Shindo, J., Takamatsu, T., Nakano, T., Aoki, S., Fukuyama, T., Hatakeyama, S., Ikuta, K., Kawashima, M., Kohno, Y., Kojima, S., Murano, K., Okita, T., Taoda, H., Tsunoda, K., and Tsurumi, M., Springer Netherlands, Dordrecht, 995–1000, https://doi.org/10.1007/978-94-007-0810-5_13, 2001.

Deng, L., Peng, C., Kim, D.-G., Li, J., Liu, Y., Hai, X., Liu, Q., Huang, C., Shangguan, Z., Kuzyakov, Y.: Drought effects on soil carbon and nitrogen dynamics in global natural ecosystems. Earth Sci. Rev., 214, 103501, https://doi.org/10.1016/j.earscirev.2020.103501, 2021.

Drever, J. and Clow, D.: Weathering rates in catchments, in: White, A. and Brantley, S. ed. *Chemical Weathering Rates of Silicate Minerals*, edited by De Gruyter, Berlin, Boston, pp. 463-484. https://doi.org/10.1515/9781501509650-012, 1995.

Ditmarova, L., Kurjak, D., Palmroth, S., Kmet, J., Strelcova, K.: Physiological responses of Norway spruce (Picea abies) seedlings to drought stress. Tree Physiol., 30, 205–213. https://doi.org/10.1093/treephys/tpp116, 2010.

Eisalou, H.K., Şengönül, K., Gökbulak, F., Serengil, Y., Uygur, B.: Effects of forest canopy cover and floor on chemical quality of water in broad leaved and coniferous forests of Istanbul, Turkey. For. Ecol. Manage., 289, 371–377, https://doi.org/10.1016/j.foreco.2012.10.031, 2013

FAO: Global Forest Resources Assessment 2020: Main report. Rome. https://doi.org/10.4060/ca9825en, 2020

Faranda, D., Pascale, S., Bulut, B.: Persistent anticyclonic conditions and climate change exacerbated the exceptional 2022 European-Mediterranean drought. Environ. Res. Lett., https://doi.org/10.1088/1748-9326/acbc37, 2023.

Fest, E.P.M.J., Temminghoff, E.J.M., Griffioen, J., Van Riemsdijk, W.H.: Proton buffering and metal leaching in sandy soils. Environ. Sci. Technol., 39, 7901–7908, https://doi.org/10.1021/es0505806, 2005.

Fichter, J., Dambrine, E., Turpault, M.-P., Ranger, J.: Base cation supply in spruce and beech ecosystems of the Strengbach catchment (Vosges Mountains, N-E France). Water Air Soil Pollut., **104**, 125–148, https://doi.org/10.1023/A:1004966302517, 1997.

Forzieri, G., Dutrieux, L. P., Elia, A., Eckhardt, B., Caudullo, G., Taboada, F. Á., Andriolo, A., Bălăcenoiu, F., Bastos, A., Buzatu, A., Dorado, F. C., Dobrovolný, L., Duduman, M., Fernandez-Carrillo, A., Hernández-Clemente, R., Hornero, A., Ionuț, S., Lombardero, M. J., Junttila, S., Lukeš, P., Marianelli, L., Mas, H., Mlčoušek, M., Mugnai, F., Nețoiu, C., Nikolov, C., Olenici, N., Olsson, P., Paoli, F., Paraschiv, M., Patočka, Z., Pérez-Laorga, E., Quero, J. L., Rüetschi, M., Stroheker, S., Nardi, D., Ferenčík, J., Battisti, A., Hartmann, H., Nistor, C., Cescatti, A., and Beck, P. S. A.: The Database of European Forest Insect and Disease Disturbances: DEFID2, Global Change Biology, 29, 6040–6065, https://doi.org/10.1111/gcb.16912, 2023.

Frank, S. D.: Review of the direct and indirect effects of warming and drought on scale insect pests of forest systems, Forestry: An International Journal of Forest Research, 94, 167–180, https://doi.org/10.1093/forestry/cpaa033, 2021.

Gangloff, S., Stille, P., Schmitt, A.-D., Chabaux, F.: Impact of bacterial activity on Sr and Ca isotopic compositions (87Sr/86Sr and δ44/40Ca) in soil solutions (the Strengbach CZO). Procedia Earth and Planet. Sci., 10, 109–113, https://doi.org/10.1016/j.proeps.2014.08.038, 2014.

Gaul, D., Hertel, D., Borken, W., Matzner, E., Leuschner, C.: Effects of experimental drought on the fine root system of mature Norway spruce. For. Ecol. and Manage., 256, 1151–1159, https://doi.org/10.1016/j.foreco.2008.06.016, 2008.

Gehring, C. A., Swaty, R. L., and Deckert, R. J.: Mycorrhizas, drought, and host-plant mortality, in: Mycorrhizal mediation of soil, Elsevier, 279–298, https://doi.org/10.1016/B978-0-12-804312-7.00016-4, 2017.

Gessler, A., Schaub, M. and McDowell, N.G.: The role of nutrients in drought-induced tree mortality and recovery. New Phytol, 214: 513-520, https://doi.org/10.1111/nph.14340, 2017.

Gharun, M., Shekhar, A., Xiao, J., Li, X., Buchmann, N.: Effect of the 2022 summer drought across forest types in Europe. Biogeosciences, 21, 5481–5494, https://doi.org/10.5194/bg-21-5481-2024, 2024.

Goddéris, Y., François, L.M., Probst, A., Schott, J., Moncoulon, D., Labat, D., Viville, D.: Modelling weathering processes at the catchment scale: The WITCH numerical model. Geochimica et Cosmochimica Acta, 70, 1128–1147, https://doi.org/10.1016/j.gca.2005.11.018, 2006.

Gomez, D. F., Riggins, J. J., and Cognato, A. I.: Bark beetles, in: Forest entomology and pathology, edited by: D. Allison, J., Paine, T. D., Slippers, B., and Wingfield, M. J., Springer International Publishing, Cham, 299–337, https://doi.org/10.1007/978-3-031-11553-0_10, 2023.

Granier, A., Bréda, N., Biron, P., and Villette, S.: A lumped water balance model to evaluate duration and intensity of drought constraints in forest stands, Ecological Modelling, 116, 269–283, https://doi.org/10.1016/S0304-3800(98)00205-1, 1999.

Hentschel, K., Borken, W., and Matzner, E.: Leaching losses of inorganic N and DOC following repeated drying and wetting of a spruce forest soil, Plant Soil, 300, 21–34, https://doi.org/10.1007/s11104-007-9385-3, 2007.

https://doi.org/10.5194/egusphere-2025-4622
Preprint. Discussion started: 15 October 2025
© Author(s) 2025. CC BY 4.0 License.

Hesse, B.D., Hikino, K., Gebhardt, T., Buchhart, C., Dervishi, V., Goisser, M., Pretzsch, H., Häberle, K.-H., Grams, T.E.E.: Acclimation of mature spruce and beech to five years of repeated summer drought – The role of stomatal conductance and leaf area adjustment for water use. Sci. Total Environ., 951, 175805, https://doi.org/10.1016/j.scitotenv.2024.175805, 2024.

Houle, D., Lajoie, G., Duchesne, L.: Major losses of nutrients following a severe drought in a boreal forest. Nat. Plants, 2, 16187, https://doi.org/10.1038/nplants.2016.187, 2016.

Huguet, A., Vacher, L., Relexans, S., Saubusse, S., Froidefond, J. M., and Parlanti, E.: Properties of fluorescent dissolved organic matter in the Gironde Estuary, Org. Geochem., 40, 706–719, https://doi.org/10.1016/j.orggeochem.2009.03.002, 2009.

Institut national de l'information géographique et forestière (IGN), Mémento 2024 : Inventaire forestier national., https://inventaire-forestier.ign.fr , 2024.

Ingestad, T.: Mineral Nutrient Requirements of *Pinus silvestris* and *Picea abies* Seedlings. Physiol. Plant., 45: 373-380, https://doi.org/10.1111/j.1399-3054.1979.tb02599.x, 1979.

Kleber, M., Bourg, I.C., Coward, E.K., Hansel, C.M., Myneni, S.C.B., Nunan, N.: Dynamic interactions at the mineral–organic matter interface. Nat. Rev. Earth Environ., 2, 402–421, https://doi.org/10.1038/s43017-021-00162-y, 2021.

Knight, C.G., Nicolitch, O., Griffiths, R.I., Goodall, T., Jones, B., Weser, C., Langridge, H., Davison, J., Dellavalle, A., Eisenhauer, N., Gongalsky, K.B., Hector, A., Jardine, E., Kardol, P., Maestre, F.T., Schädler, M., Semchenko, M., Stevens, C., Tsiafouli, M.A., Vilhelmsson, O., Wanek, W., De Vries, F.T.: Soil microbiomes show consistent and predictable responses to extreme events. Nat., 636, 690–696, https://doi.org/10.1038/s41586-024-08185-3, 2024.

Knutzen, F., Averbeck, P., Barrasso, C., Bouwer, L.M., Gardiner, B., Grünzweig, J.M., Hänel, S., Haustein, K., Johannessen, M.R., Kollet, S., Müller, M.M., Pietikäinen, J.-P., Pietras-Couffignal, K., Pinto, J.G., Rechid, D., Rousi, E., Russo, A., Suarez-Gutierrez, L., Veit, S., Wendler, J., Xoplaki, E., Gliksman, D.: Impacts on and damage to European forests from the 2018–2022 heat and drought events. Nat. Hazards Earth Syst. Sci., 25, 77–117. https://doi.org/10.5194/nhess-25-77-2025, 2025.

Komsta L.: outliers: tests for outliers, https://doi.org/10.32614/CRAN.package.outliers, 2022.

Kopáček, J., Turek, J., Hejzlar, J., Šantrůčková, H.: Canopy leaching of nutrients and metals in a mountain spruce forest. Atmos. Environ., 43, 5443–5453. https://doi.org/10.1016/j.atmosenv.2009.07.031, 2009.

Kronnäs, V., Lucander, K., Zanchi, G., Stadlinger, N., Belyazid, S., and Akselsson, C.: Effect of droughts and climate change on future soil weathering rates in Sweden, Biogeosciences, 20, 1879–1899, https://doi.org/10.5194/bg-20-1879-2023, 2023.

Krüger, M., Potthast, K., Michalzik, B., Tischer, A., Küsel, K., Deckner, F.F.K., Herrmann, M.: Drought and rewetting events enhance nitrate leaching and seepage-mediated translocation of microbes from beech forest soils. Soil Biol. Biochem., 154, 108153. https://doi.org/10.1016/j.soilbio.2021.108153, 2021.

Kump, L. R., Brantley, S. L., and Arthur, M. A.: Chemical weathering, atmospheric CO_2, and climate, Annu. Rev. Earth Planet. Sci., 28, 611–667, https://doi.org/10.1146/annurev.earth.28.1.611, 2000.

Kuypers, M.M.M., Marchant, H.K., Kartal, B.: The microbial nitrogen-cycling network. Nat. Rev. Microbiol., 16, 263–276, https://doi.org/10.1038/nrmicro.2018.9, 2018.

Lasaga, A. C., Soler, J. M., Ganor, J., Burch, T. E., and Nagy, K. L.: Chemical weathering rate laws and global geochemical cycles, Geochimica et Cosmochimica Acta, 58, 2361–2386, https://doi.org/10.1016/0016-7037(94)90016-7 , 1994.

Leigh, R.A. and Wyn Jones, R.G.: A hypothesis relating critical potassium concentrations for growth to the distribution and functions of this ion in the plant cell. New Phytol., 97, 1-13, https://doi.org/10.1111/j.1469-8137.1984.tb04103.x, 1984.

https://doi.org/10.5194/egusphere-2025-4622
Preprint. Discussion started: 15 October 2025
© Author(s) 2025. CC BY 4.0 License.

Lévesque, M., Walthert, L., Weber, P.: Soil nutrients influence growth response of temperate tree species to drought. Journal of Ecology, 104, 377–387, https://doi.org/10.1111/1365-2745.12519, 2016.

Lovett, G.M., Lindberg, S.E.: Dry deposition and canopy exchange in a mixed Oak forest as determined by analysis of throughfall. J. Appl. Ecol. 21, 1013, https://doi.org/10.2307/2405064, 1984.

Lu, P., Biron, P., Bréda, N., Granier, A.: Water relations of adult Norway spruce (Picea abies (L) Karst) under soil drought in the Vosges mountains: water potential, stomatal conductance and transpiration. Ann. For. Sci. 52, 117–129, https://doi.org/10.1051/forest:19950203, 1995.

McKnight, D.M., Boyer, E.W., Westerhoff, P.K., Doran, P.T., Kulbe, T., Andersen, D.T.: Spectrofluorometric characterization of dissolved organic matter for indication of precursor organic material and aromaticity. Limnol Oceanogr 46, 38–48, https://doi.org/10.4319/lo.2001.46.1.0038, 2001.

Meng, C., Tian, D., Zeng, H., Li, Z., Yi, C., Niu, S.: Global soil acidification impacts on belowground processes. Environ. Res. Lett. 14, 074003, https://doi.org/10.1088/1748-9326/ab239c, 2019.

Muhr, J., Goldberg, S.D., Borken, W., Gebauer, G.: Repeated drying–rewetting cycles and their effects on the emission of CO_2 , N_2 O, NO, and CH_4 in a forest soil. Z. Pflanzenernähr. Bodenk. 171, 719–728, https://doi.org/10.1002/jpln.200700302, 2008.

Lamersdorf, N. P., Beier, C., Blanck, K., Bredemeier, M., Cummins, T., Farrell, E. P., Kreutzer, K., Rasmussen, L., Ryan, M., Weis, W., and Xu, Y.-J.: Effect of drought experiments using roof installations on acidification/nitrification of soils, For. Ecol. Manage., 101, 95–109, https://doi.org/10.1016/S0378-1127(97)00128-X, 1998.

Nilsen, P.: Effect of nitrogen on drought strain and nutrient uptake in Norway spruce Picea abies (L.) Karst.) trees, Plant Soil, 172, 73–85, https://doi.org/10.1007/BF00020861, 1995.

Ohno, T., Fernandez, I.J., Hiradate, S., Sherman, J.F.: Effects of soil acidification and forest type on water soluble soil organic matter properties. Geoderma, 140, 176–187. https://doi.org/10.1016/j.geoderma.2007.04.004, 2007.

Oksanen, J., Simpson, G. L., Blanchet, F. G., Kindt, R., Legendre, P., Minchin, P. R., O'Hara, R. B., Solymos, P., Stevens, M. H. H., Szoecs, E., Wagner, H., Barbour, M., Bedward, M., Bolker, B., Borcard, D., Carvalho, G., Chirico, M., De Caceres, M., Durand, S., Evangelista, H. B. A., FitzJohn, R., Friendly, M., Furneaux, B., Hannigan, G., Hill, M. O., Lahti, L., McGlinn, D., Ouellette, M.-H., Ribeiro Cunha, E., Smith, T., Stier, A., Ter Braak, C. J. F., Weedon, J., and Borman, T.: vegan: Community Ecology Package, https://doi.org/10.32614/CRAN.package.vegan, 2001.

Oursin, M., Pierret, M.-C., Beaulieu, É., Daval, D., Legout, A.: Is there still something to eat for trees in the soils of the Strengbach catchment? For. Ecol. Manage., 527, 120583, https://doi.org/10.1016/j.foreco.2022.120583, 2023.

Ovington, J.D.: The calcium and magnesium contents of tree species grown in close stands. New Phytologist, 58, 164–175, https://doi.org/10.1111/j.1469-8137.1959.tb05348.x, 1959.

Parlanti, E.: Dissolved organic matter fluorescence spectroscopy as a tool to estimate biological activity in a coastal zone submitted to anthropogenic inputs, Org. Geoch., 2000.

Persson, H., Von Fircks, Y., Majdi, H., Nilsson, L.O.: Root distribution in a Norway spruce (*Picea abies* (L.) Karst.) stand subjected to drought and ammonium-sulphate application, in: Nutrient uptake and cycling in forest ecosystems, edited by: Nilsson, L.O., Hüttl, R.F., Johansson, U.T., Developments in Plant and Soil Sciences, 62, Springer, Dordrecht, https://doi.org/10.1007/978-94-011-0455-5_17, 1995.

Pierret, M.-C., Cotel, S., Ackerer, P., Beaulieu, E., Benarioumlil, S., Boucher, M., Boutin, R., Chabaux, F., Delay, F., Fourtet, C., Friedmann, P., Fritz, B., Gangloff, S., Girard, J.-F., Legtchenko, A., Viville, D., Weill, S., Probst, A.: The Strengbach catchment: a multidisciplinary environmental sentry for 30 years. Vadose Zone Journal, 17, 1–17, https://doi.org/10.2136/vzj2018.04.0090, 2018.

Pierret, M.-C., Viville, D., Dambrine, E., Cotel, S., and Probst, A.: Twenty-five year record of chemicals in open field precipitation and throughfall from a medium-altitude forest catchment (Strengbach - NE France): An obvious response to atmospheric pollution trends, Atmospheric Environment, 202, 296–314, https://doi.org/10.1016/j.atmosenv.2018.12.026, 2019.

Ponette-González, A.G., Van Stan II, J.T., Magyar, D.: Things seen and unseen in Throughfall and stemflow. In: Van Stan, II, J., Gutmann, E., Friesen, J. Precipitation partitioning by vegetation. Springer, Cham., https://doi.org/10.1007/978-3-030-29702-2_5, 2020.

Poszwa, A., Wickman, T., Dambrine, E., Ferry, B., Dupouey, J.-L., Helle, G., Schleser, G., and Breda, N.: A Retrospective isotopic study of spruce decline in the Vosges Mountains (France), Water, Air and Soil Pollution: Focus, 3(1), 201-222, https://doi.org/10.1023/A:1022176025379, 2003.

Probst, A., Dambrine, E., Viville, D., Fritz, B.: Influence of acid atmospheric inputs on surface water chemistry and mineral fluxes in a declining spruce stand within a small catchment (Vosges massif, France). J. Hydrol., 116, 101-124, https://doi.org/10.1016/0022-1694(90)90118-H, 1990.

Probst, A., Viville, D., Fritz, B., Ambroise B., Dambrine E.: Hydrochemical budgets of a small forested granitic catchment exposed to acid deposition: The strengbach catchment case study (Vosges massif, France). Water Air Soil Pollut 62, 337–347, https://doi.org/10.1007/BF00480265, 1992.

Probst, A., Fritz, B., Viville, D.: Mid-term trends in acid precipitation, streamwater chemistry and element budgets in the Strengbach catchment (Vosges mountains, France). Water, Air and Soil Pollution, 79, 39-59, https://doi.org/10.1007/BF01100429, 1995.

Quirion, B. R., Domke, G. M., Walters, B. F., Lovett, G. M., Fargione, J. E., Greenwood, L., Serbesoff-King, K., Randall, J. M., and Fei, S.: Insect and Disease Disturbances Correlate With Reduced Carbon Sequestration in Forests of the Contiguous United States, Front. For. Glob. Change, 4, 716582, https://doi.org/10.3389/ffgc.2021.716582, 2021.

Roberts, T. M., Skeffington, R. A., and Blank, L. W.: Causes of type 1 spruce decline in Europe, Forestry, 62, 179–222, https://doi.org/10.1093/forestry/62.3.179-a, 1989.

Rodríguez-Calcerrada, J., Li, M., López, R., Cano, F.J., Oleksyn, J., Atkin, O.K., Pita, P., Aranda, I. and Gil, L.: Drought-induced shoot dieback starts with massive root xylem embolism and variable depletion of nonstructural carbohydrates in seedlings of two tree species. New Phytol, 213: 597-610, https://doi.org/10.1111/nph.14150, 2017.

San-Miguel-Ayanz, J., Durrant, T., Boca, R., Maianti, P., Liberta`, G., Jacome Felix Oom, D., Branco, A., De Rigo, D., Suarez-Moreno, M., Ferrari, D., Roglia, E., Scionti, N., Broglia, M., Onida, M., Tistan, A. and Loffler, P.: Forest fires in Europe, Middle East and North Africa 2023, Publications Office of the European Union, Luxembourg, https://doi.org/10.2760/8027062, 2024.

Saintonge, F.-X., Gillette, M., Blaser, S., Queloz, V., & Leroy, Q. : Situation et gestion de la crise liée aux scolytes de l'Épicéa commun fin 2021 dans l'est de la France, en Suisse et en Wallonie. Revue forestière française, 73(6), 619–641, https://doi.org/10.20870/revforfr.2021.7201, 2022.

Sardans, J., Peñuelas, J., Ogaya, R.: Drought's impact on Ca, Fe, Mg, Mo and S concentration and accumulation patterns in the plants and soil of a Mediterranean evergreen Quercus ilex forest. Biogeochemistry, 87, 49–69, https://doi.org/10.1007/s10533-007-9167-2, 2008.

Sardans, J., Peñuelas, J. : Potassium: a neglected nutrient in global change. Global Ecology and Biogeography, 24, 261–275, https://doi.org/10.1111/geb.12259, 2015.

Serène, L., Mazzilli, N., Batiot-Guilhe, C., Emblanch, C., Gillon, M., Babic, M., Dupont, J., Simler, R., and Blanc, M.: Questioning calculation and interpretation of fluorescence indices in natural waters studies, J. Hydrol., 650, 132524, https://doi.org/10.1016/j.jhydrol.2024.132524, 2025.

Schimel, J., Balser, T.C., Wallenstein, M.: Microbial stress-response physiology and its implications for ecosystem function. Ecology, 88, 1386–1394, https://doi.org/10.1890/06-0219, 2007.

Schlesinger, W.H., Dietze, M.C., Jackson, R.B., Phillips, R.P., Rhoades, C.C., Rustad, L.E., Vose, J.M.: Forest biogeochemistry in response to drought, Global Change Biol., 22, 2318–2328, https://doi.org/10.1111/gcb.13105, 2016.

Schmied, G., Hilmers, T., Mellert, K.-H., Uhl, E., Buness, V., Ambs, D., Steckel, M., Biber, P., Šeho, M., Hoffmann, Y.-D., Pretzsch, H. Nutrient regime modulates drought response patterns of three temperate tree species. Sci Total Environ., 868, 161601, https://doi.org/10.1016/j.scitotenv.2023.161601, 2023.

Schmid, I., Kazda, M.: Root distribution of Norway spruce in monospecific and mixed stands on different soils. For. Ecol. and Manage., 159, 37-47, https://doi.org/10.1016/S0378-1127(01)00708-3, 2002.

Schulze, K., Borken, W., Matzner, E.: Dynamics of dissolved organic 14C in throughfall and soil solution of a Norway spruce forest. Biogeochemistry, 106, 461–473, https://doi.org/10.1007/s10533-010-9526-2, 2011.

Senf, C., Buras, A., Zang, C.S., Rammig, A., Seidl, R.: Excess forest mortality is consistently linked to drought across Europe. Nat Commun, 11, 6200, https://doi.org/10.1038/s41467-020-19924-1, 2020.

Sorel, M., Mittelberger, S., Berne, C., Ribes, A.: Bilan climatique de l'année 2022. La Météorologie, 120, 2-4, https://doi.org/10.37053/lameteorologie-2023-0002, 2023, last access : 19 August 2025

Soubeyroux, J.-M., Bernus, S., Core, L., Drouin, A., Dubuisson, B., Etchevers, P., Gouget, V., Josse, P., Kerdoncuff, M., Samacoits, R et Tocquer, F.: Les nouvelles projections climatiques de référence Drias 2020 pour la métropole, http://www.drias-climat.fr/document/rapport-DRIAS-2020-red3-2.pdf, 2021, last access : 19 August 2025

Strobel, B. W., Hansen, H. C. B., Borggaard, O. K., Andersen, M. K., and Raulund-Rasmussen, K.: Composition and reactivity of DOC in forest floor soil solutions in relation to tree species and soil type, Biogeochemistry, 56, 1-26, https://doi.org/10.1023/A:1011934929379, 2001.

Strohmenger, L., Ackerer, P., Belfort, B., and Pierret, M. C.: Local and seasonal climate change and its influence on the hydrological cycle in a mountainous forested catchment, J. Hydrol., 610, 127914, https://doi.org/10.1016/j.jhydrol.2022.127914, 2022.

Swift, R.S.: Organic matter characterization, in: Methods of soil analysis, edited by: Sparks, D.L., Page, A.L., Helmke, P.A., Loeppert, R.H., Soltanpour, P.N., Tabatabai, M.A., Johnston, C.T., Sumner, M.E., https://doi.org/10.2136/sssabookser5.3.c35, 1996.

Tiwari, T., Sponseller, R.A., Laudon, H.: The emerging role of drought as a regulator of dissolved organic carbon in boreal landscapes. Nat. Commun., 13, 5125, https://doi.org/10.1038/s41467-022-32839-3, 2022.

Touche, J., Calvaruso, C., De Donato, P., and Turpault, Mp.: Five successive years of rainfall exclusion induce nutritional stress in a mature beech stand, For. Ecol. Manage., 507, 119987, https://doi.org/10.1016/j.foreco.2021.119987, 2022.

Touche, J., Calvaruso, C., De Donato, P., and Turpault, M.-P.: Drought events influence nutrient canopy exchanges and green leaf partitioning during senescence in a deciduous forest, Forest Ecosystems, 11, 100173, https://doi.org/10.1016/j.fecs.2024.100173, 2024.

Ulrich, B.; Mayer, R.; Khanna, P. K.: Chemical changes due to acid precipitation in a loess-derived soil in central Europe, Soil Sci., 130(4), 193-199, https://doi.org/10.1097/00010694-198010000-00005, 1980

Ulrich, B.: Interaction of forest canopies with atmospheric constituents: SO2, alkali and earth alkali cations and chloride, in: Ulrich, B., Pankrath, J.: Effects of Accumulation of Air Pollutants in Forest Ecosystems, edited by: Springer, Dordrecht, 33–45, https://doi.org/10.1007/978-94-009-6983-4_2, 1983.

Vose, J. M., Miniat, C. F., Luce, C. H., Asbjornsen, H., Caldwell, P. V., Campbell, J. L., Grant, G. E., Isaak, D. J., Loheide, S. P., and Sun, G.: Ecohydrological implications of drought for forests in the United States, For. Ecol. Manage., 380, 335–345, https://doi.org/10.1016/j.foreco.2016.03.025, 2016.

Wagner, Y., Volkov, M., Nadal-Sala, D., Ruehr, N. K., Hochberg, U., and Klein, T.: Relationships between xylem embolism and tree functioning during drought, recovery, and recurring drought in Aleppo pine, Physiol.Plant., 175, 13995, https://doi.org/10.1111/ppl.13995, 2023.

Weed, A. S., Ayres, M. P., and Hicke, J. A.: Consequences of climate change for biotic disturbances in North American forests, Ecol. Monogr., 83, 441–470, https://doi.org/10.1890/13-0160.1, 2013.

Winter, C., Nguyen, T. V., Musolff, A., Lutz, S. R., Rode, M., Kumar, R., and Fleckenstein, J. H.: Droughts can reduce the nitrogen retention capacity of catchments, Hydrol. Earth Syst. Sci., 27, 303–318, https://doi.org/10.5194/hess-27-303-2023, 2023.

https://doi.org/10.5194/egusphere-2025-4622
Preprint. Discussion started: 15 October 2025
© Author(s) 2025. CC BY 4.0 License.

Woods, C., Hunt, S., Morris, D., Gordon, A.: Epiphytes influence the transformation of nitrogen in coniferous forest canopies. Boreal Environ. Res., 17. 411-424, 2012.

Zsolnay, A., Baigar, E., Jimenez, M., Steinweg, B., Saccomandi, F.: Differentiating with fluorescence spectroscopy the sources of dissolved organic matter in soils subjected to drying, Chemosphere, 38, 45-50, https://doi.org/10.1016/S0045-6535(98)00166-0, 1999.