https://doi.org/10.17221/32/2024-JFS

Vegetation composition, chemical element flows and their interactions in the forested riparian zone: An example from a small stream in Latvia

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Citation: Pentjuša L., Štāls T.A., Bārdule A., Lībiete Z., Gerra-Inohosa L. (2024): Vegetation composition, chemical element flows and their interactions in the forested riparian zone: An example from a small stream in Latvia. J. For. Sci., 70: 476–491.

Abstract: Riparian vegetation plays a major role in maintaining biodiversity and reducing the negative impact of nutrient leaching into aquatic ecosystems. However, the knowledge on the interactions between riparian vegetation and other environmental factors is still incomplete for planning sustainable riparian forest management. The aim of this study was to explore interactions between riparian forest ecosystem components along a small stream. Interactions between vegetation structure, chemical composition of soil and groundwater, as well as chemical element flows via litterfall and precipitation were studied in seven 50 m long transects located in the riparian forest of different characteristics along a 1.4 km river section in the northern part of Latvia. Our results showed that throughfall input of total nitrogen (TN) and potassium (K) was higher in transects with predominantly deciduous tree stands, but the concentration of TN in forest floor was higher in coniferous tree stands. At some soil layers, a positive correlation between organic soil carbon (OC) and the concentration of TN in groundwater was detected. The concentration of TN and nitrate-nitrogen ($N\text{-}NO_3^-$) in groundwater correlated positively with the deciduous tree basal area. The obtained results suggested that element flows are strongly dependent on tree species' composition and a comparatively small riparian area is able to provide diverse ecological conditions.

Keywords: above-ground litter; ground flora; groundwater; input flows; soil; throughfall precipitation

Due to increasing anthropogenic impacts, eutrophication has become one of the most significant environmental problems in recent decades, and the quality of surface water continues to deteriorate worldwide (Dupas et al. 2015; Pinay et al. 2018). For this reason, riparian protection zones, restricting economic activities and limiting management-related intervention, are established around water bodies and watercourses (Richardson et al. 2012). Thus, vegetation in the transition zone between terrestrial and aquatic systems may reduce the negative impacts of nutrient leaching and coastal erosion, at the same time preserving biodiversity and controlling water temperature and light regime (Cole et al. 2020; Ploum et al. 2021).

A fixed-width buffer zone is the simplest and most frequently implemented approach aiming at protecting surface waters (Tiwari et al. 2016). However, this practice may fail its conservation goals locally due to a large topographic variation of the riparian area and high spatial heterogeneity of riparian processes (Bren 1998; Kuglerová et al. 2014). Site-

Supported within the framework of the LIFE program integrated project 'Implementation of Latvian river basin management plans to achieve good surface water status' LIFE18 IPE/LV/000014 (LIFE GOODWATER IP).

https://doi.org/10.17221/32/2024-JFS

specific riparian management with consideration of local hydrological conditions creates more heterogeneous riparian corridors that benefit a variety of ecosystem services and mitigate negative effects caused by forestry and other anthropogenic activities (Kuglerová et al. 2014). Furthermore, it has been calculated that site-specific buffer zones are economically more profitable than the ones with a fixed width because hydrologically adapted buffers include more wet sites and forest areas of low productivity than buffers with a fixed width (Tiwari et al. 2016). Site-specific riparian management is based on hydrology as the main cause of riparian heterogeneity (Kuglerová et al. 2014). However, information about interactions between such site-specific factors as riparian vegetation structure and soil and groundwater chemical composition – important predictors for the stream water quality that should be considered before planning buffer zones – is largely missing from the studies so far (Décamps et al. 2009; Lidman et al. 2017; Franklin et al. 2019).

The impact of riparian vegetation on the biogeochemical cycles of river systems is based on the close hydrological relationships between groundwater and river water where dissolved nutrients from the areas with a higher elevation are leached into the river stream through groundwater while riparian plants provide nutrient uptake (Gregory et al. 1991; Brunke, Gonser 1997; Décamps et al. 2009). The chemical flow may differ according to the vegetation type. For example, grass buffers are significantly less effective than forest buffers at removing nitrogen and phosphorus (Mayer et al. 2005; Goudarzian et al. 2021); some tree species are better than others in uptaking nutrients and providing phytoremediation in general (Décamps 2009). There is evidence that plants with N-fixing root nodules may increase the nitrate level in leaching water (Franklin et al. 2019), but the evidence is conflicting. For instance, some studies have reported that alder stands enhance nutrient leaching (Compton et al. 2003; Cairns, Lajtha 2005), while other research recommends grey alder forests to control water quality (Mander et al. 1995; Mander et al. 1997). Riparian vegetation also affects the stream water chemistry through litterfall (Décamps et al. 2009; Franklin et al. 2019). Introduction of deciduous tree species, such as, for example, *Betula pubescens*, is suggested to improve litter quality in riparian coniferous forests (Saklaurs et al. 2022), even though birch leaf litter has generally higher concentrations of nutrients than spruce (Berg, Staaf 1987; Johansson 1995). De Schrijver et al. (2008) report that nutrient concentrations in leaves are higher compared to those in needles. However, deciduous trees are more efficient than conifers in providing rivers with shade and controlling water temperature during summer (Dan Moore et al. 2005).

The input of nutrients in the riparian forests occurs also via stemflow and throughfall (Chang, Matzner 2000; De Schrijver et al. 2008). Coniferous forests intercept more atmospheric pollutants than deciduous forests, resulting in higher nitrogen deposition on the forest floor and higher leakage of nutrients into the groundwater (De Schrijver et al. 2008). Coniferous forests can also increase forest soil acidification compared to deciduous forests (Augusto et al. 2002). However, spruce stands have lower throughfall deposition of Ca, Mg, and K than alder and birch stands (Carnol, Bazgir 2013).

In riparian zones, interactions between vegetation and soil result in significantly different groundwater chemistry (Ploum et al. 2021). The vegetation type depends on the soil characteristics, and, conversely, soil characteristics can be modified by the vegetation (Getino-Álvarez et al. 2023). The soil filtering function is an important part of ecosystem management for protecting groundwater and surface water (Keesstra et al. 2012), and riparian soil, often being the last material that groundwater is in contact with before becoming a surface water, can have a significant impact on stream water quality (Lidman et al. 2017). There are many correlations between soil properties and groundwater concentrations (McLay et al. 2001). However, the exact links between riparian soil and groundwater chemistry remain unclear. Vegetation-soil-water interactions should be considered when planning site-specific riparian buffer management, and it is especially important for water quality of small streams (Kuglerová et al. 2014). The aim of this study is to explore interactions between riparian forest ecosystem components along a small stream in Latvia, hemiboreal region of Europe. We evaluated vegetation structure and chemical composition of soil and groundwater, as well as chemical element flows via litterfall and precipitation.

MATERIAL AND METHODS

Study area. The study area was located in the north-central part of Latvia (Figure 1A–B), and comprised a 1.4 km long section of the small river Tora

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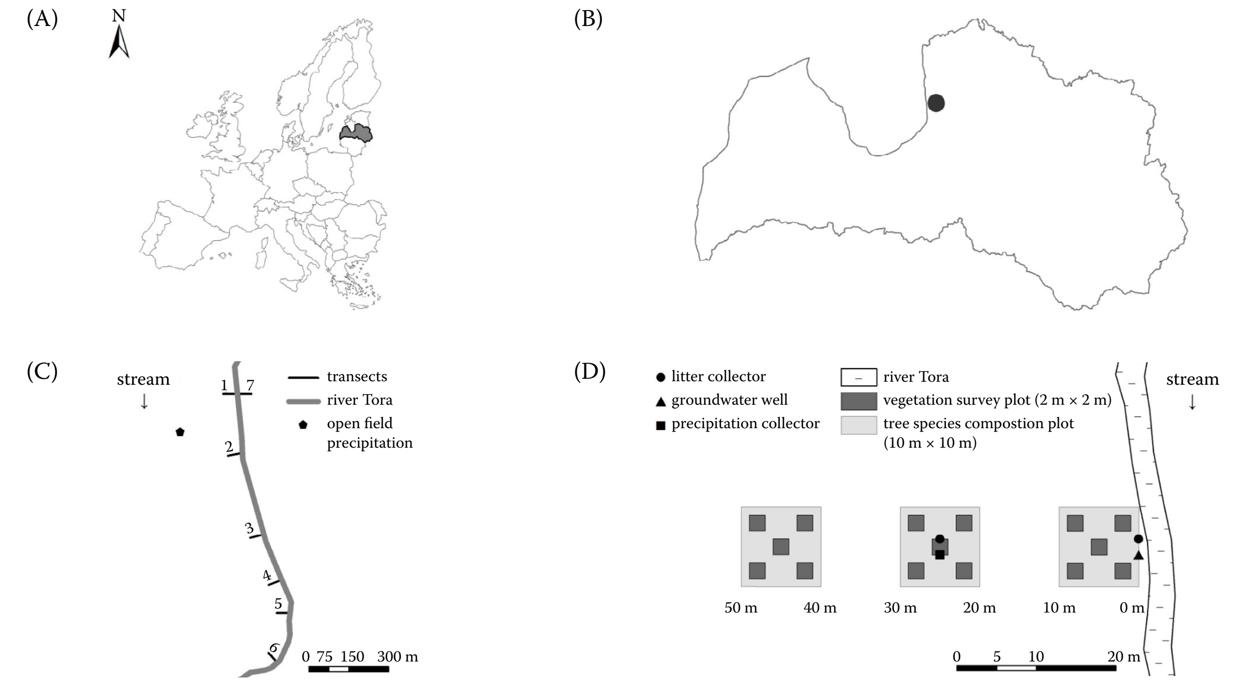

Figure 1. (A, B) Study site location; (C) study area design; (D) sampling design example in one of the transects

(total length 14.4 km) with predominantly forested catchment (65%), while 35% of the catchment basin with the total area of 40.4 km^2 is occupied by agricultural land. Most of the selected river section was straightened in 1969. The river Tora is a tributary of the river Aģe, which is classified as a water body at risk due to low hydromorphological and ecological quality (BIOR 2020). The average width of the river in the study area is 2–4 m. Our research covered 50 m of the riparian zone, in this case coinciding with the protection zone of the river Tora [according to Latvian Protection Zone Law 1997, 56/57 (771/772)]. The main focus of the study was on the right bank of the river because the conditions on the left bank were more intensely managed due to the regular removal of woody vegetation in the frames of exploitation protection zone management. On the right bank, no silvicultural management has taken place for several decades. Occasional beaver activity – vegetation removal close to the stream banks – was observed since the start of the project, but no beaver dam building. A land-use map for the surrounding area of the studied river section can be found in Figure S1 in the Electronic Supplementary Material (ESM).

The study area was located in lowland conditions, with an average elevation of 36.6 m a.s.l. The average annual air temperature in the 2020–2022 period was 7.49 °C (0.39 °C higher than the long-term average). The maximum recorded air temperature in the 2020–2022 period was 32.70 °C, and the minimum air temperature was –22.7 °C. The average annual precipitation in this period was 616 mm (85 mm lower than the long-term average; LVGMC 2024). The hyporheic zone is subject to seasonal flooding, especially during the spring snowmelt and after heavy rainfall.

Sampling design. Data were collected in seven transects that were located perpendicular to the river and represented different forest growth conditions including different forest site types, tree species composition, stand age, and forest management history (Figure 1C). The length of the transects was 50 m, coinciding with the nominal riparian protection zone of the river Tora. A tree above-ground litter collector and a groundwater well were placed at the beginning of each transect near the stream bank, and a litter collector and a precipitation collector were placed in the middle of the transect (25 m from the stream bank). In addition, one open-field rainfall collector was installed in an adjacent clearing. The placement of litter collectors and groundwater wells reflected the main goal of the study – to evaluate the situation primarily in the zone closest to the riverbank, even though the study doubtlessly would have benefitted from additional sampling 40–50 m from the stream. Along each transect, three plots (10 m × 10 m) for assess-

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ing tree species composition were placed with centres at 5 m, 25 m, and 45 m from the stream bank, i.e. 21 plots on seven transects in total. In each of these plots, five ground vegetation survey plots (2 m × 2 m) were placed (Figure 1D).

Tree species and ground vegetation survey. In each vegetation survey plot, all ground vegetation species of moss and herbaceous plants and their coverage (%) were determined. Thus, in the study area, data on ground vegetation were collected in 105 smaller plots, and data on tree stands [species, height and diameter of each tree if the diameter at breast height (*DBH*) > 10 cm] in 21 larger plots. The data on ground vegetation was collected in July 2021, and the data on tree stand structure in November 2021. Simultaneously with the ground vegetation assessment, in each of the 2 m × 2 m sample plots, the value of the leaf area index (*LAI*) characterising the shading by trees was determined with the 1/4 lens opening of the LAI-2200C measuring device (LI-COR, Inc., USA).

Sampling and analyses of environmental samples. A total of 8 precipitation collectors were installed – funnel-shaped containers with a surface area of 0.02 m^2 for the frost-free period (April–November), and pails with a 0.16 m^2 surface area for winter precipitation (December–March). The depth of the groundwater wells at the beginning of each transect is 1.5 m. Groundwater and precipitation water samples were collected throughout the year once a month. The throughfall and groundwater samples were analysed at the LVS EN ISO 17025:2018 accredited laboratory of the Latvian State Forest Research Institute Silava (LSFRI Silava) according to ISO standards for pH, dissolved organic carbon (DOC), total nitrogen (TN), nitrate-nitrogen ($N\text{-}NO_3^-$), phosphate-phosphorus ($P\text{-}PO_4^{3-}$), ammonium-nitrogen ($N\text{-}NH_4^+$), and potassium (K) concentrations. Sampling methods are summarised in Table S1 in the ESM.

The tree above-ground litter was collected in the frost-free period (April–November) once a month using 14 funnel-shaped litter traps with a collecting surface area of 0.4 m^2. In the laboratory (LSFRI Silava), litter was dried and sorted into four fractions (branches and bark; leaves and needles; fruits; other litter, such as insects and faeces). The following parameters were measured for each litter fraction: dry mass (*DM*), total carbon (TC), total nitrogen (TN), phosphorus (P) and potassium (K) concentration (Table S1 in the ESM). The results analysed in this paper include data from December 2021 to December 2022 (for water samples) and from April 2022 to November 2022 (for litter samples).

In all the three 10 m × 10 m plots of each transect, soil samples were collected in the spring of 2022 at four depths (0–10 cm, 10–20 cm, 20–40 cm, and 40–60 cm), additionally, forest floor samples were collected as well. The following parameters were determined at the laboratory (LSFRI Silava) for each collected soil sample: soil pH, organic carbon (OC), total nitrogen (TN) and total phosphorus (TP) concentration (Table S1 in the ESM). Additionally, the soil C : N ratio was calculated.

To characterise the environmental conditions of each plot, Ellenberg's indicator values of light availability (*L*), soil moisture (*F*), soil reaction (*R*), and soil fertility (*N*) based on cover of all species within a plot were calculated. The values were extracted from an existing database JUICE (Tichý et al. 2023).

Data analysis. All statistical analyses and data processing were performed in the R environment (R Core Team 2021). The normality of data distribution was tested with the Shapiro–Wilk test. Correlations (including their significance) between vegetation parameters, soil, groundwater throughfall and litter chemistry were tested using Spearman's rank correlation test [function cor.test()]. If *P* values were lower than 0.05, we considered the relationships significant. For all analyses, a 95% confidence level was used. To analyse the dependence of ground vegetation parameters and Ellenberg indicator values on the distance from the stream bank, an analysis of variance (ANOVA) was conducted. If significant differences were found, Tukey's HSD (honestly significant difference) test for multiple comparisons was used. Non-parametric Kruskal–Wallis test was used to evaluate differences in average groundwater and throughfall chemical parameters between transects. Dunn's multiple comparisons post-hoc analysis was used to assess the significance of the average concentration differences between transects.

RESULTS

Forest stand and ground vegetation. In total, five tree species (*Betula pendula*, *Picea abies*, *Fraxinus excelsior*, *Alnus incana*, *Ulmus glabra*) were recorded along the studied transects in the canopy layer, with *Alnus incana* dominating the stream bank (0–10 m distance from the stream, Figure 2).

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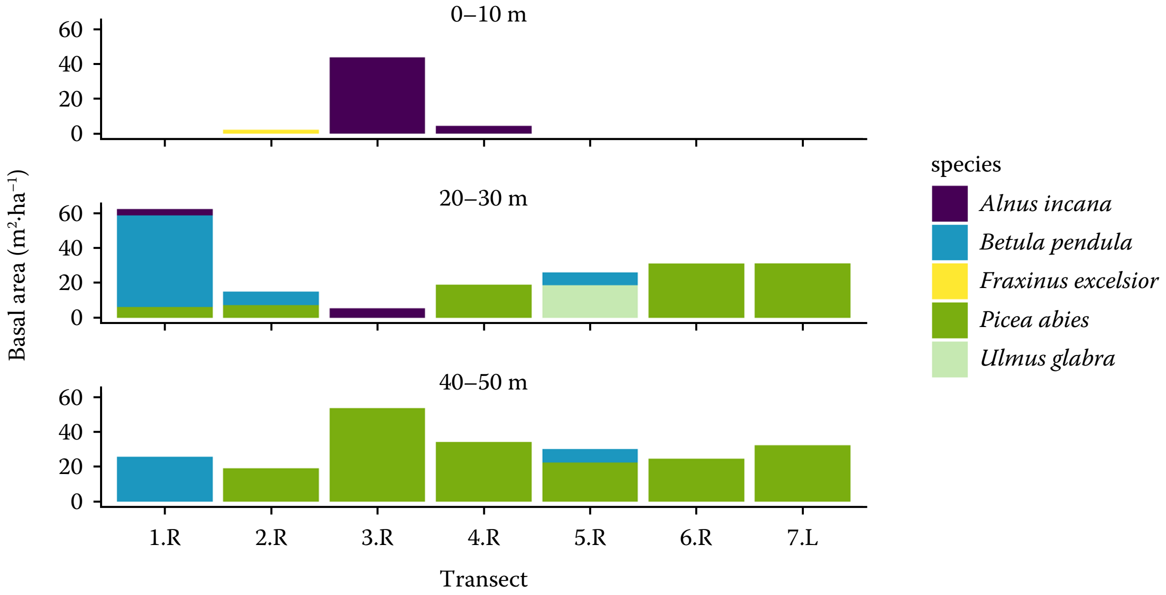

Figure 2. Basal area of tree species ($m^2 \cdot ha^{-1}$) of each plot along the studied transects at different distances from the stream (0–10 m, 20–30 m, 40–50 m)

The transect is identified by a number and a letter indicating its location on the right (R) or left (L) bank of the stream

Further from the stream (20–50 m distance), the species composition shifted towards a higher share of *Picea abies*, with the exception of the first transect, where *Betula pendula* was the dominant species. The total basal area varied from 0 $m^2 \cdot ha^{-1}$ in four plots near the stream to 62.4 $m^2 \cdot ha^{-1}$ (Figure 2). The average *LAI* value in the tree measurement plots varied from 0 near the stream to 11.5 further from the stream bank (Figure 3) and differed significantly between transects (Kruskal–Wallis,

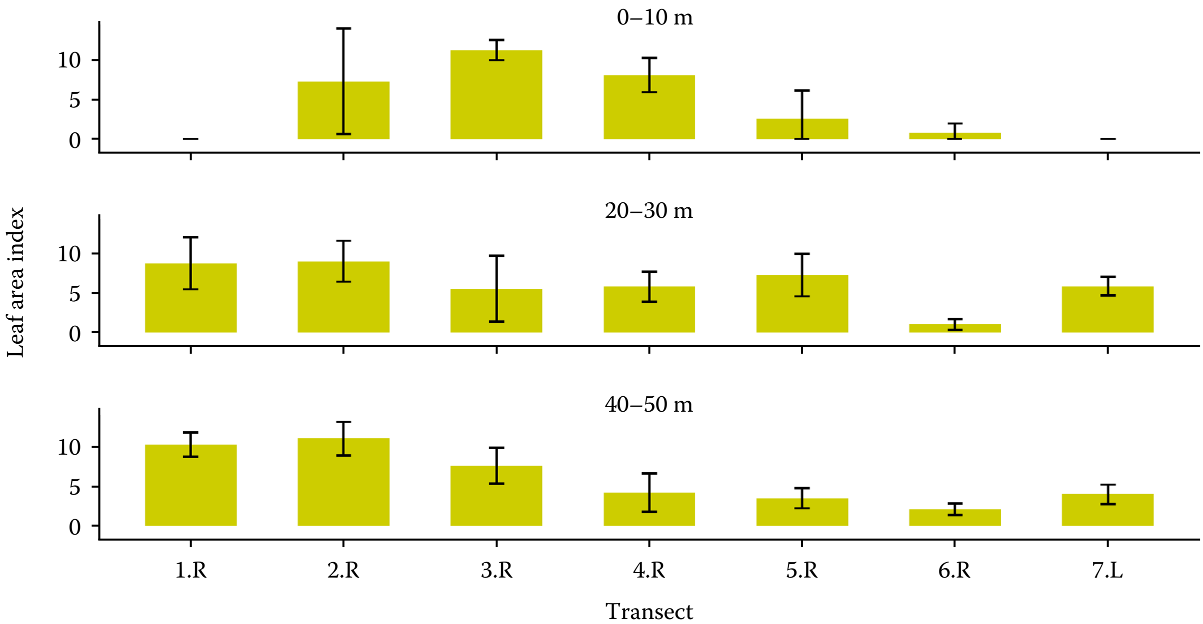

Figure 3. Leaf area index of each studied plot along the established transects at different distances from the stream (0–10 m, 20–30 m, 40–50 m)

Error bars – standard error; the transect is identified by a number and a letter indicating its location on the right (R) or left (L) bank of the stream

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P < 0.0001). The absence of trees in the close proximity of the river is explained by periodic flooding and occasional vegetation removal by beavers.

In total, 126 ground vegetation species were recorded along the studied transects (111 species of herbaceous plants and 15 species of bryophytes). The cover of bryophytes varied from 0% in the plots along the stream bank to 62.5% in the plots further from the stream bank, while the cover of herbaceous plants varied from 5.3% in the plots further from the stream bank to 100% in the plots along the stream bank.

Both bryophytes and herbaceous plant cover showed statistically significant differences depending on the plot distance from the stream bank (ANOVA, P < 0.0001). Herbaceous plant cover was significantly higher in the plots along the stream bank than in the plots further from the stream (Tukey's HSD, P = 0.0012, P < 0.0001), but there was no significant difference between both further distances (20 m and 50 m from the stream) (Tukey's HSD, P = 0.4411). Bryophytes cover showed no difference between the plots near the stream bank and the plots in the middle of transect (Tukey's HSD, P = 0.6157), but it was significantly higher in the third plot, most distant from the stream (Tukey's HSD, P = 0.0031, P < 0.0001). Cover of both studied ground vegetation groups significantly differed also between transects (ANOVA, P < 0.0001, P = 0.0008).

The distance of the plot from the stream bank showed a significant effect on the Ellenberg indicator values for plots (Figure 4). F (moisture) values were significantly different and higher in the plots along the stream bank than in the plots further from the stream (Tukey's HSD, P < 0.0001). N (nutrient) values were significantly higher near the stream compared to the third plot at 45 m distance from the stream (Tukey's HSD, P = 0.0076), but L (light) and R (soil pH) values had no significant differences (ANOVA, P > 0.05). Plot values did not differ significantly between transects (ANOVA, P > 0.05).

Correlation analysis showed significant interactions between ground vegetation and forest stand. Herbaceous plant cover had a moderately strong and negative correlation (r_s = –0.5352, P = 0.0124) with leaf area index, while moss cover had a moderately strong and positive correlation with coniferous tree basal area (r_s = 0.4944, P = 0.0227). Moss cover also showed significant and negative correlations with Ellenberg indicator values of F, R, and N (r_s < –0.4, P < 0.05).

Throughfall and tree above-ground litter. In all transects, tree above-ground litter biomass was lower near the stream bank than further from the stream, and litter fraction of leaves and needles accounted for the majority of the above-ground litter biomass (Figure 5). Tree above-ground litter biomass

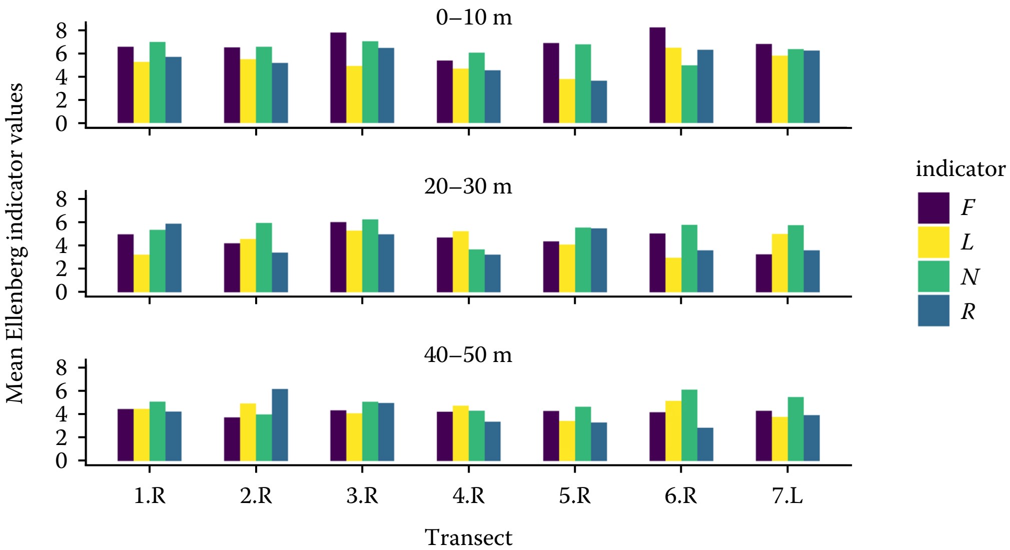

Figure 4. Ellenberg indicator values of each studied plot along the established transects at different distances from the stream (0–10 m, 20–30 m, 40–50 m)

F – soil moisture; L – light availability; N – soil fertility; R – soil reaction; the transect is identified by a number and a letter indicating its location on the right (R) or left (L) bank of the stream

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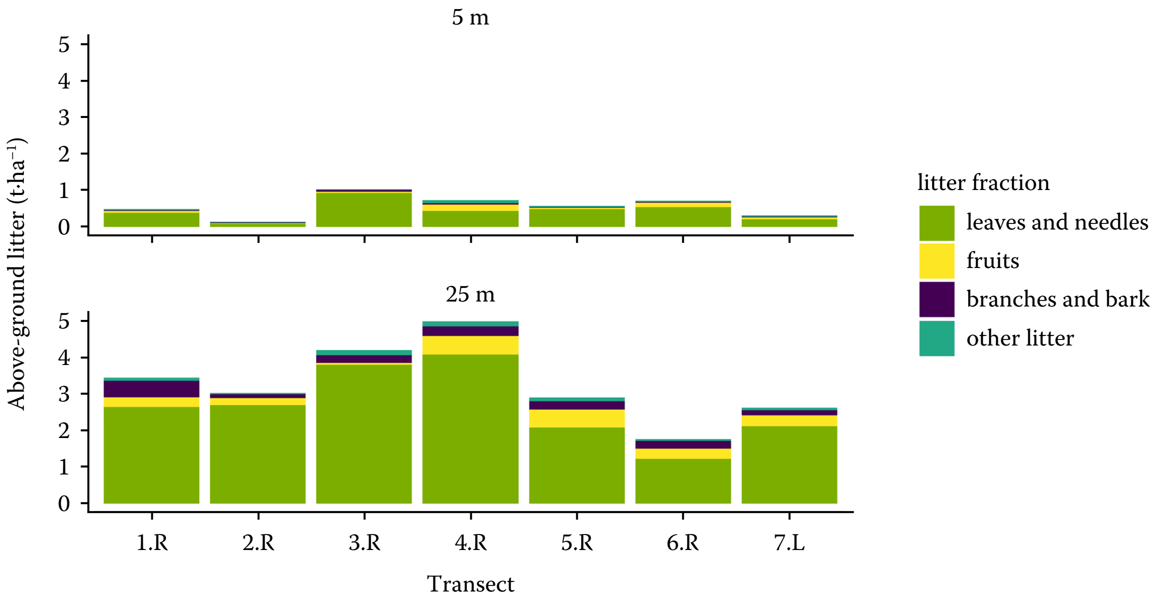

Figure 5. The total study period (April–November) tree above-ground litter biomass (t·ha^{-1}) of four fractions (leaves and needles, fruits, branches and bark, other litter) in two sampling points on each transect (5 m and 25 m from the stream bank)

The transect is identified by a number and a letter indicating its location on the right (R) or left (L) bank of the stream

varied from 0.15 t·ha^{-1} to 1.05 t·ha^{-1} in the plots near the stream and from 1.76 t·ha^{-1} to 5.01 t·ha^{-1} in the plots further from the stream bank. Leaves and needles were the dominant litter fraction at all sampling points, making up 80% of the total litter biomass.

In all plots near the stream bank, element (C, N, P, and K) input with litter was lower than in the plots further from the stream (Figure 6). During the study period (April–November), C input through tree above-ground litter ranged from 79.2 kg·ha^{-1} (2.1.R) to 715.2 kg·ha^{-1} (4.2.R), N input ranged from 3.2 kg·ha^{-1} (2.1.L) to 24.9 kg·ha^{-1} (3.2.R), P input ranged from 5 kg·ha^{-1} (2.1.L) to 28 kg·ha^{-1} (4.2.L), and K from 1.4 kg·ha^{-1} (2.1.L) to 14.8 kg·ha^{-1} (4.2.L).

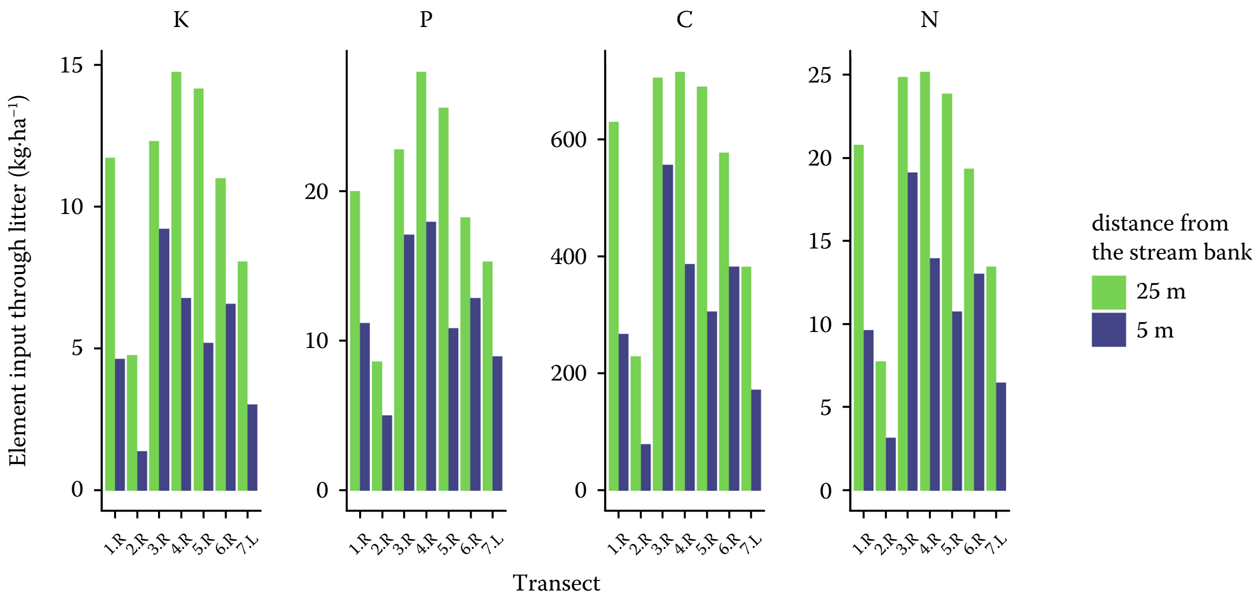

Figure 6. The total study period element (K, P, C, N) input (kg·ha^{-1}) with tree above-ground litter in two sampling points on each transect (5 m and 25 m from the stream bank)

The transect is identified by a number and a letter indicating its location on the right (R) or left (L) bank of the stream

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For all throughfall precipitation chemical parameters, except pH and concentration of inorganic forms of nitrogen ($N\text{-}NH_4^+$ and $N\text{-}NO_3^-$), the average annual concentration in the open field was significantly lower compared to the sampling plots in forest stands located at 25 m distance from the stream bank (Kruskal–Wallis, $P < 0.05$). Annual input of TN and $N\text{-}NO_3^-$ was the highest in the first and fifth transects where deciduous tree species were dominant. Also, the annual input of DOC and K was the highest in the first transect and lowest in the open field (Figure 7).

Correlation analysis showed strong and statistically significant interactions between throughfall precipitation, litter and forest stand parameters. Annual throughfall precipitation input of K and TN correlated strongly and positively with deciduous tree basal area ($r_s > 0.8$, $P < 0.01$). Throughfall input of $P\text{-}PO_4^{3-}$ and average concentration of TN, $N\text{-}NO_3^-$, $P\text{-}PO_4^{3-}$, and K correlated positively and strongly with leaf area index ($r_s > 0.8$, $P < 0.05$). Throughfall input of K also showed a significant and negative correlation with coniferous tree basal area ($r_s = -0.7568$, $P = 0.0489$). No statistically significant correlation was detected between any of the analysed throughfall or litter parameters and ground vegetation, nor between litter element (K, P, C, N) input and any of the analysed parameters of the forest stand ($P > 0.05$). Only above-ground litter biomass correlated positively with total tree basal area ($r_s = 0.66$, $P = 0.0102$).

Soil. Some soil chemistry parameters showed significant differences depending on the sampling distance from the stream bank and transects,

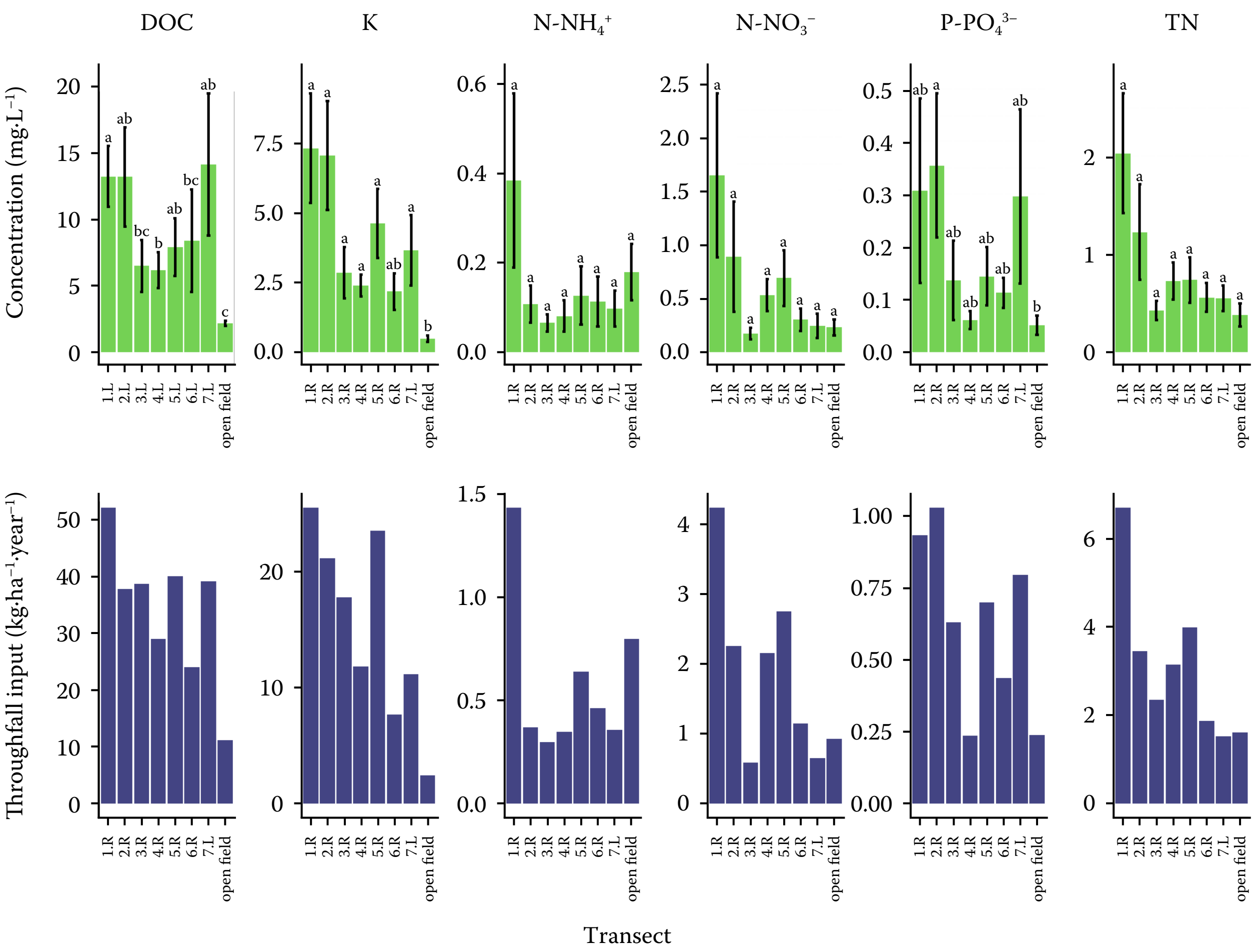

Figure 7. Average element concentrations (mg·L^{-1}) and annual input (kg·ha^{-1}·year^{-1}) with throughfall precipitation (January–December) in each transect at 25 m distance from the stream bank, including the sampling point in the open field

a–c – statistically significant differences between transects at the 0.05 level; DOC – dissolved organic carbon; TN – total nitrogen; error bars – standard error; the transect is identified by a number and a letter indicating its location on the right (R) or left (L) bank of the stream

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as well as on the sampling depth (Figure 8). For example, pH and TP concentrations were significantly different between transects (Kruskal–Wallis, $P < 0.0001$) and higher closer to the stream (5 m from the stream bank), than at 45 m distance (Dunn's, $P < 0.0001$). The depth of the sample had a significant effect on the amount of OC and TN, thus affecting the C:N ratio as well (Kruskal–Wallis, $P < 0.0001$). The C:N ratio and concentrations of OC and TN were significantly higher (Dunn's, $P < 0.001$) in forest floor samples and the first two depths (0–10 cm, 10–20 cm) than in the deepest analysed layer (40–60 cm).

The chemistry of all soil layers, including forest floor, showed a statistically significant correlation with some of the forest stand characteristics and litter chemical parameters. Forest floor concentration of OC had a positive, moderately strong and significant correlation with the total tree basal area ($r_s > 0.4$, $P < 0.05$) and a strong, positive correlation with the basal area of coniferous trees ($r_s > 0.6$, $P < 0.05$), but TN of the forest floor had a significant correlation only with the basal area of coniferous trees ($r_s > 0.4$, $P < 0.05$). Forest floor pH correlated negatively with coniferous tree basal area ($r_s = -0.6041$, $P = 0.0037$), but the C:N ratio correlated positively with coniferous tree basal area ($r_s = 0.7236$, $P = 0.0002$). Leaf area index had a positive and moderately strong correlation ($r_s = 0.5054$, $P = 0.0194$) with the C:N ratio of soil at 0–10 cm depth and a negative, moderately strong correlation with the concentration of TN in soil at 20–40 cm depth. The concentrations of OC and TN in the deepest analysed soil layer (40–60 cm) correlated negatively with the total tree basal area in the plot ($r_s > 0.4$, $P < 0.05$).

The chemistry of soil layers did not show any statistically significant correlation with throughfall

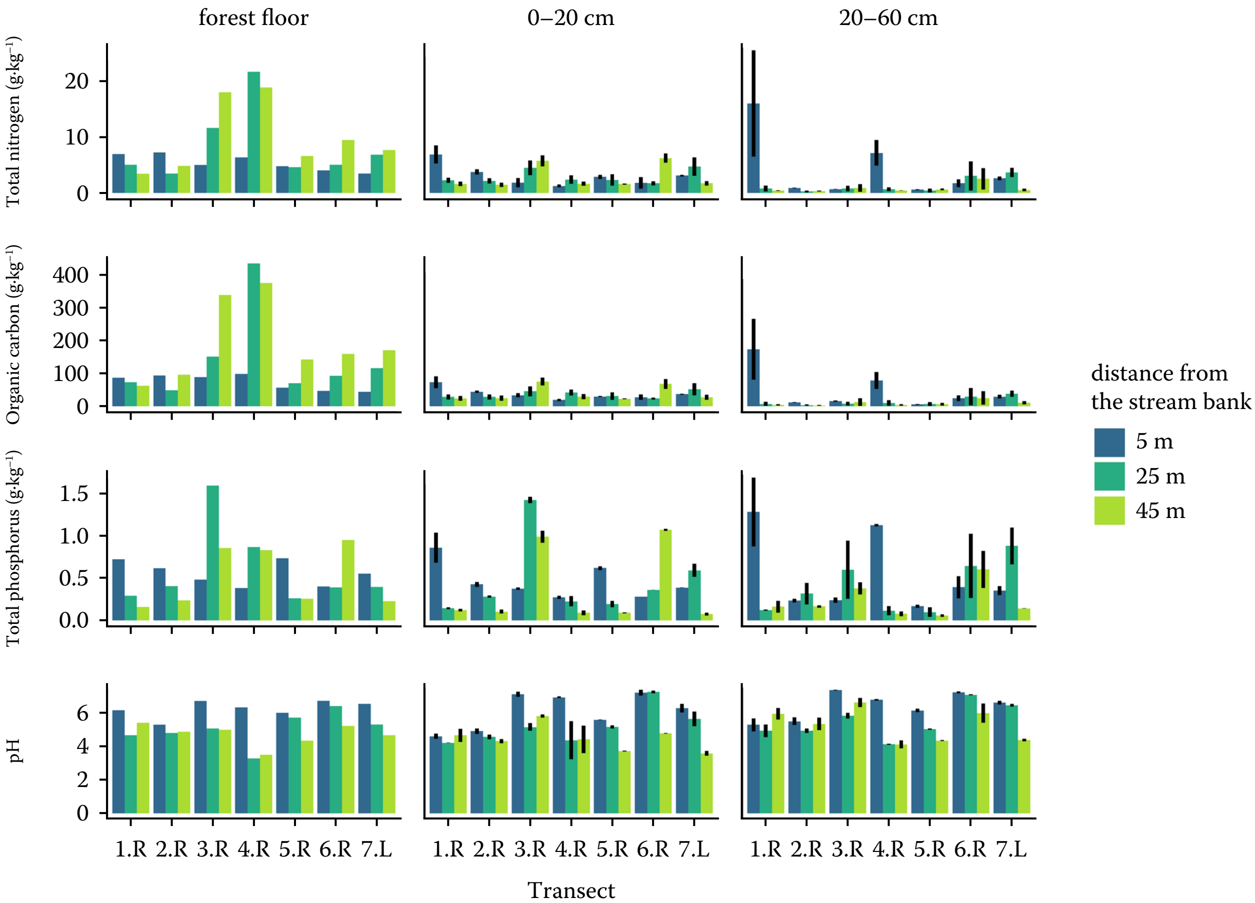

Figure 8. pH and concentrations of total nitrogen, organic carbon and total phosphorus (g·kg^{-1}) at forest floor in two depths (0–20 cm, 20–60 cm) along the established transects at different distances from the stream bank (5 m, 25 m, 45 m)

Error bars – standard error; the transect is identified by a number and a letter indicating its location on the right (R) or left (L) bank of the stream

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precipitation chemical parameters and elements' annual input. However, the C : N ratio of forest floor correlated significantly and positively with litter input of C, N, P, and K ($r_s > 0.5$, $P < 0.05$).

Some of the soil layers had significant correlations also with ground vegetation. The pH of forest floor and soil at 20–40 cm and 40–60 cm depth had a negative, moderately strong correlation with bryophyte cover ($r_s < -0.5$, $P < 0.01$). Bryophyte cover correlated significantly also with the concentration of TN and OC in the forest floor ($r_s > 0.5$, $P < 0.01$), while herbaceous plant cover correlated positively with the pH of soil at 0–10 cm depth ($r_s = 0.5287$, $P = 0.0137$) and the concentration of TN and OC of soil at 40–60 cm depth ($r_s > 0.5$, $P < 0.01$).

The chemistry of all soil layers correlated significantly also with Ellenberg indicator values of the studied plots. Ellenberg moisture values (*F*) had a positive correlation with the pH of the forest floor and the pH of soil at 0–10 cm and 10–20 cm depth ($r_s > 0.5$, $P < 0.05$). *F* correlated positively also with the concentration of OC and the C : N ratio ($r_s > 0.5$, $P < 0.05$). Ellenberg indicator values of soil nutrients (*N*) correlated positively with TN concentration in soil at 10–20 cm and 40–60 cm depth ($r_s > 0.4$, $P < 0.05$) and negatively with the C : N ratio of forest floor and soil at 0–10 cm depth ($r_s < -0.6$, $P < 0.01$). Ellenberg soil reaction *R* values correlated positively with the pH of the forest floor and soil at 20–40 cm depth ($r_s > 0.4$, $P < 0.05$).

Groundwater. The annual average DOC concentration in the groundwater had the largest variation of all elements, ranging from 14.58 mg·L^{-1} (2.R) to 23.79 mg·L^{-1} (1.R), but the average concentration of TN varied from 0.22 mg·L^{-1} (6.R) to 3.24 mg·L^{-1} (1.R). The N-NO_3^- concentration varied from 0.03 mg·L^{-1} (6.R) to 2.62 mg·L^{-1} (1.R), N-NH_4^+ – from 0.03 mg·L^{-1} (7.L) to 0.13 mg·L^{-1} (1.R), and K ranged from 0.36 mg·L^{-1} (3.R) to 1.13 mg·L^{-1} (6.R). The average concentration of P-PO_4^{3-} had little variation – from 0.024 mg·L^{-1} (3.R) to 0.029 mg·L^{-1} (4.R).

The results of the Kruskal–Wallis test indicated no significant differences among the average concentrations of DOC ($P = 0.3711$) and P-PO_4^{3-} ($P = 0.5153$) between transects. The average value of groundwater pH and average concentrations of TN, N-NO_3^-, N-NH_4^+, and K differed significantly between transects ($P < 0.05$). Figure 9 represents differences between transects based on Dunn's test.

Correlation analysis showed significant interactions between groundwater chemistry and soil, forest stand and ground vegetation parameters. The average concentrations of TN and N-NO_3^-

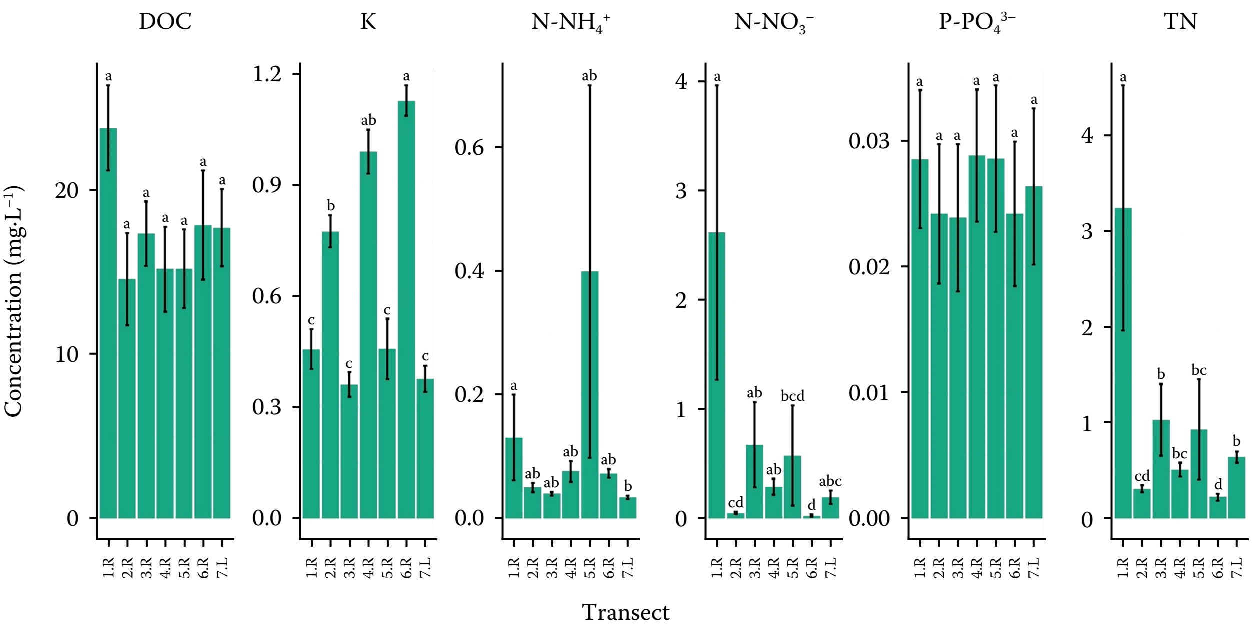

Figure 9. Average concentrations of elements in groundwater (mg·L^{-1}) in each transect

a–d – statistically significant differences between transects at the 0.05 level; DOC – dissolved organic carbon; TN – total nitrogen; error bars – standard error; the transect is identified by a number and a letter indicating its location on the right (R) or left (L) bank of the stream

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in groundwater had a positive, strong correlation ($r_s > 0.6$, $P < 0.05$) with deciduous and total tree basal area in the transects. However, the total tree basal area had a strong, negative correlation ($r_s > 0.6$, $P < 0.05$) with the average groundwater concentration of K. No relationships were found between groundwater chemistry and litter inputs. The concentration of DOC in groundwater correlated strongly and negatively ($r_s > 0.6$, $P < 0.05$) with bryophytes cover.

Groundwater chemistry showed statistically significant correlations with some of the analysed soil layers. The concentration of DOC correlated positively with the concentration of OC and TN in the soil at 10–20 cm depth ($r_s > 0.8$, $P < 0.05$) and with the concentration of TP and TN at 20–40 cm depth ($r_s > 0.7$, $P < 0.05$).

DISCUSSION

The interactions of different ecosystem components in a forested riparian zone of a small stream in our study were characterised by vegetation composition, element concentrations in soil and groundwater and input via throughfall precipitation and tree above-ground litter. Our results showcase the diversity in forest structure and ground vegetation composition of the riparian zone even in a comparatively small area, potentially impacting element flows and related water quality issues. When it comes to water quality, the main focus is on the problem of eutrophication and, therefore, on nutrients, including elements such as N, P, and K. However, in our study, we also analysed the flow of carbon, due to its impact on water pH and its key role in the abundance of the microbial communities by regulating the biogeochemical changes in the water (Schindler, Krabbenhoft 1998; Sterte et al. 2022).

Vegetation composition. In our study, a 50 m buffer zone reflected different ecological conditions, especially showing significant differences closer to and further from the stream, thereby affecting the distribution of nutrients essential for eutrophication. That could be recorded as the response in vegetation composition. We found higher nutrient concentrations in the soil (total P and total N values), as well as higher herbaceous plant cover and higher Ellenberg nitrogen values closer to the stream, indicating better growing conditions in the ecotone. According to the Ellenberg values, the plots closer to the stream were characterised also by higher moisture. Higher vascular plant cover was best explained by such environmental variables as total N in the soil and humidity (Zelnik, Čarni 2013). Our results showed that herbaceous cover was predicted by canopy cover expressed as a negative correlation between *LAI*, consistent with earlier findings that opening has a positive effect, while cover has a negative effect (Dormann et al. 2020). Our study confirms that Ellenberg nitrogen values correlate with soil parameters and could serve as a useful tool for habitat calibration (Schaffers, Sýkora 2000; Dzwonko 2001). However, we did not find the same result for Ellenberg light values. It could be explained by the fact that three of the seven plots closest to the stream bank had trees, thus shading the ground vegetation.

Closed forest areas located mostly further from the stream contained conditions favourable for higher bryophyte diversity, which could be explained by lower pH values – compared to vascular plants, bryophytes have a higher preference for acidic substrates (Tyler, Olsson 2016). Bryophyte cover also significantly differed between transects in plots located further from the stream, confirming that bryophyte cover was higher where coniferous trees were dominant in the tree layer. Although Ellenberg plot values did not differ significantly between transects, differences in soil TP concentrations and pH, as well as groundwater pH and average concentrations of TN, $N\text{-}NO3^-$, $N\text{-}NH4^+$, and K between transects were significant and, together with differences in moss and herbaceous plant cover, indicate diverse ecological conditions in our study site.

Element input flows. Throughfall and litterfall are the major pathways for elements to return from forest canopies to soil (Hojjati et al. 2009). Throughfall inputs include a large amount of dry deposition in addition to that in bulk precipitation and are deposited with dust on the canopy, leading to an increased concentration of nitrogen and phosphorus in throughfall compared to bulk precipitation (Qualls 2020). In our study, for all throughfall precipitation chemical parameters, except pH and the concentration of inorganic forms of nitrogen ($N\text{-}NH_4^+$ and $N\text{-}NO_3^-$), there was a significantly lower average annual concentration in the open field compared to the forest, indicating forest impact on throughfall chemistry, and potentially also on stream water quality, because it is well-known

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that species composition of the riparian forest can affect stream water quality (Kominoski et al. 2011; Saklaurs et al. 2022).

Our results demonstrated that the throughfall input of TN and K was higher in deciduous tree stands, showing that nutrient deposition generally is higher in deciduous stands than in coniferous stands, while the input of K correlated negatively with the coniferous tree basal area. These findings are not in accordance with findings reported by De Schrijver et al. (2008), who observed higher interception capacity of N and higher throughfall deposition input of K in coniferous forests than in deciduous forests, suggesting that higher interception capacity can explain higher throughfall deposition and that causal factors are the generally lower height and leaf area index in deciduous stands. However, in our study, the *LAI* had a significant and positive correlation with the deciduous tree basal area. *LAI* also correlated positively with the average throughfall concentration of TN, N-NO_3^-, P-PO_4^{3-}, and K and the input of P-PO_4^{3-}. Augusto et al. (2002) also suggested that the capacity of trees to intercept atmospheric deposition depends on various factors, including *LAI*. Differences in leaf area index in our study may contribute to variations in throughfall input. However, it must be acknowledged that monthly measurements of the leaf area index would provide more accurate results because of seasonal variations in throughfall chemical composition (Bhat et al. 2011). This variation will be analysed in the further steps of our study when long-term data will be collected.

We found that tree above-ground litter biomass correlates positively with the total tree basal area. Bārdule et al. (2021) found similar results in spruce and birch stands, concluding that stand basal area is the most significant factor influencing annually produced biomass of tree above-ground litter. While our results did not show interactions between any of the forest stand characteristics and litter element input, so we cannot discuss how these inputs differed between coniferous and deciduous trees, Bārdule et al. (2021) found a higher carbon concentration in the above-ground litter of birch than in spruce above-ground litter. While in our study the throughfall input of N, P, and K in coniferous tree stands along the stream was lower than in deciduous stands, it must be considered that litter also accounts for a large amount of element input. For example, the input of TN through litter in all transects was many times higher than the throughfall input of TN. Our results were similar to those found by Carnol and Bazgir (2013), but different from Hojjati et al. (2009), who reported that litterfall and throughfall made a relatively similar total nitrogen input. Unlike nitrogen, the input of K through litter was lower than the throughfall input of K. Scheer (2009), Hojjati et al. (2009) and Carnol and Bazgir (2013) found similar results, emphasising that throughfall is the main flux for K to the soil surface in the forest, and nutrient inputs are driven by species-specific properties. However, it should be noted that our results, like the others, are affected by the regional climate and site-specific properties. Hansen et al. (2009) concluded that such site-related factors as the annual increment of the stand, soil nutrient status and nitrogen deposition regime affect the amount of total litterfall significantly.

Soil. Cools et al. (2014) suggested that tree species are the main factor explaining C:N ratios in European forest soils, and species with high lignin and low nitrogen content in litter (conifers) decompose more slowly, subsequently impacting the C:N ratio of forest floor, making it higher. In our study, the C:N ratio of forest floor and the first analysed soil layer (0–10 cm) had a positive correlation with the coniferous tree basal area, which in turn correlated negatively with the pH of forest floor, indicating the effect of coniferous trees on soil properties. The range of the C:N ratio in all the analysed soil layers was narrower compared to the forest floor, indicating a decreasing effect of the tree species on the C:N ratio with increasing depth. Cools et al. (2014) explain similar results about decreasing organic matter content and tree root density with increasing soil depth. Based on our results, the parameters of the forest stand primarily impacted the forest floor rather than deeper soil layers. A similar pattern of results was mentioned by Augusto et al. (2002), indicating that the impact of vegetation on soil characteristics is often significant only in the forest floor and the first 10 cm of topsoil, or near the roots.

Our results on soil chemistry in the plots near the stream bank showed no differences in nutrient concentrations between soil layers, contrary to the plots further from the stream. While no carbon concentration decrease from the surface to deeper layers was detected by the stream, it was found in the plots further from the stream bank. Tērauda (2008) and

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Getino-Álvarez et al. (2023) found similar results in pine and mixed pine-beech forests not located near the river, explaining these results with more effective nutrient retention due to larger amount of plant roots, as well as higher biological activity of the soil. However, our findings indicate different soil ecological processes near the stream bank.

Although Fischer et al. (2019) suggested that the correlation between vegetation and soil is closest for the top 10 cm of soil, we made these correlations with all the analysed depths. Forest floor and the first depth (0–10 cm) chemistry showed similar results of correlation with the Ellenberg N values to those observed by Ewald and Ziche (2017). In our study area, the Ellenberg indicator values for plots indicated reduced herbaceous plant cover and increased moss cover in drier conditions. Moss cover was also lower in fertile conditions, but higher in more acidic environments, suggesting the effect of coniferous trees on the soil pH.

Soil pH can affect the availability of nutrients in the soil and affect productivity (Szymura et al. 2014). Our results, consistent with the findings of Hong et al. (2019), show that coniferous trees may contribute more to soil acidification than deciduous trees. Burgess-Conforti et al. (2019) did not find significant differences between soil pH in coniferous and deciduous stands but found that the concentration of TN in forest floor of the coniferous stand is significantly higher than in deciduous tree stand, which is similar to our results, as we found a positive correlation between the coniferous tree basal area and the concentration of TN in forest floor.

In several transects, some analysed elements in the soil, for example, total N and total P, tended to have higher concentrations in the sampling plots closest to the bank. At the same time, the nutrient input with litter in these plots was generally lower than further from the stream. This suggests other possible nutrient sources, most likely sediment and organic material deposition with floodwater. While we did not monitor this aspect specifically, this is one of the possible explanations for the nutrient concentration differences.

Groundwater. Riparian zones or near-stream areas are terrestrial interfaces that control groundwater inputs to streams (Ploum et al. 2021), and such local riparian conditions as vegetation and soil chemistry are important for riparian groundwater chemistry (Sterte et al. 2022). Although De Schrijver et al. (2008) revealed a higher nitrate seepage into groundwater in coniferous forests compared to deciduous, our results revealed a positive correlation between the average concentration of TN and N-NO_3^- in groundwater and the total tree and deciduous tree basal area. De Schrijver et al. (2008) also mentioned that the dominant cause of nitrate seepage flux to groundwater might be the throughfall N deposition. In our study, it was not possible to correlate throughfall chemistry with groundwater chemistry due to only one precipitation receiver on the transect; however, the throughfall input of TN was higher in deciduous tree stands.

A positive correlation between riparian soil OC and TN and groundwater DOC in the riparian zone suggests that soil, depending on its type and chemical composition, also can be an important source of nutrients, enriching the riparian groundwater with nitrogen and carbon. Although many studies indicate increased leaching of nitrogen compounds from grey alder stands (Compton et al. 2003; Cairns, Lajtha 2005), in the riparian zone of the river Tora, the grey alder stand is able to effectively retain nutrients, likely due to the fact that the stand is still growing and thus consuming nutrients. According to a study carried out in southeast Estonia, the average carbon and TN content in the soil of an old riparian grey alder stand was significantly higher than in a young grey alder stand (Mander et al. 2015).

Even though our results revealed that stream riparian zones dominated by deciduous trees can act as a source of nitrogen, the nitrate-nitrogen concentration in groundwater did not exceed the limit value (11.3 mg N-$NO_3^-\cdot L^{-1}$) that is mentioned in the Nitrates Directive (EC 1991), indicating efficient nitrogen retention capacity of the forested buffer zone of the river Tora. It must be emphasised that the lower nutrient input amount from the coniferous forest stand by itself does not necessarily mean that coniferous tree species are better for stream water quality. It is known that forest stands dominated by conifers can reduce the aquatic macroinvertebrate community by providing lower-quality litter (Naiman, Décamps 1997; Jonsson et al. 2017). Furthermore, the fact that we did not find any correlation between soil and throughfall precipitation shows that a higher input of elements does not necessarily lead to higher nutrient stocks in forest floor and, thus, higher leaching risks to adjacent water ecosystems.

https://doi.org/10.17221/32/2024-JFS

CONCLUSION

The studied riparian zone provides diverse environmental conditions supporting a wide variety of ecosystem functions which differently affect element flows and vegetation structure. Element flows (nutrient input) are strongly dependent on tree species composition and distance from the stream bank. Our results support the idea that a comparatively small riparian area can provide diverse ecological conditions and contribute to the efforts to increase biodiversity across different ecosystems, including managed forests. The identified interactions between vegetation composition and chemical element flows in the studied forested riparian zone highlighted the potential to impact chemical element flows including nutrient leaching into groundwater and watercourses by targeted management. Alteration of vegetation structure and composition can substantially change ecosystem functions and subsequently impact water quality. Our results suggest that a targeted and site-specific riparian management approach should involve maintaining or creating mixed riparian forest stands with deciduous and coniferous tree species along the stream banks. This would create a varied canopy structure, providing different niches for flora and fauna, thereby enhancing both ecological integrity and water quality in riparian areas. Our study, though small in scale, provides data on the potential impacts of riparian zone management on various ecosystem components, thus adding to the overall knowledge of diverse aspects of riparian ecosystem functioning.

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Received: April 22, 2024
Accepted: July 2, 2024
Published online: September 12, 2024