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RESEARCH ARTICLE

Biochar as a potential tool to mitigate nutrient exports from managed boreal forest: A laboratory and field experiment

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Abstract

Forest management in drained forested peatlands can negatively affect water quality due to the increase in exports of organic matter and nutrients. Therefore, new methods to alleviate this impact are needed. In laboratory conditions, biochar has been shown to be a strong sorbent of organic and inorganic nutrients due to its high surface area and ion-exchange capacity. However, evidence of the adsorption capacity in field conditions is lacking. Here, we studied the water purification performance of two different biochar feedstocks (wood- and garden residue-based) in a 10-day laboratory experiment where we incubated biochar with runoff water collected from drainage ditches in clear-cut peatland forests. We measured changes in pH and concentrations of inorganic phosphorus (PO_4), total dissolved nitrogen (TDN), and dissolved organic carbon (DOC). The biochar with the best adsorbent capacity in the laboratory experiment was then tested in field conditions in a replicated catchment-scale experiment, where both clear-cutting and ditch cleaning were performed. We determined the nutrient concentration of water at the inlet and outlet of biochar filters placed in outflow ditches of four catchments. We found that under laboratory conditions wood-based biochar efficiently adsorbed TDN and DOC, however, it released PO_4. Furthermore, we found that the biochar filters reduced TDN and DOC concentration in field conditions. However, the percentage decrease in concentration was dependent on the initial concentrations of nutrients in the water and could be considered low. Moreover, we found that the biochar in the filters increased in TN content over the course of the experiment. This suggests that a wood-based biochar filter has the potential to be a water protection tool for reducing the export of nutrients from catchments with high nutrient concentration. And that the biochar from the ditches could be applied back to the regenerating forest catchment as a potential soil amendment, closing the nutrient cycle.

KEYWORDS

biochar, dissolved organic carbon, forest management, nitrogen, nutrient adsorption, phosphorus, water quality

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1 | INTRODUCTION

In Sweden, 15% of peatland areas are influenced by forestry (Vasander et al., 2003) and are thus affected by forest management activities such as clear-cutting harvest followed by ditch cleaning. Clear-cutting and ditch cleaning in drained forested peatlands often deteriorates water quality due to the increased export of organic matter, nutrients, and suspended solids (Joensuu et al., 2002; Kaila et al., 2014; Nieminen et al., 2017; Nieminen & Penttilä, 2004). Specifically, increased concentrations of dissolved organic matter (DOC) and nutrients such as nitrogen (N) and phosphorus (P) to downstream freshwater ecosystems could lead to notorious alterations of streams and lakes such as brownification (Kritzberg et al., 2020; Monteith et al., 2007) and eutrophication accompanied with algae blooms (Smith & Schindler, 2009).

Large areas of drained peatlands will soon reach harvest age in Sweden and Finland (Hytönen et al., 2020), increasing the risk of diffuse pollution in the near future. At present, a wide range of technologies and methods for safeguarding water resources have been used to mitigate nutrient export loads to watercourses, including sedimentation ponds and peatland buffer areas. However, these are either expensive, require large areas, or are rather inefficient in reducing dissolved nutrients export loads, especially outside the growing season (Hynninen et al., 2011; Liljaniemi et al., 2003). Consequently, new scalable tools are needed to counteract the negative effects of forest management on water quality. A promising solution to reduce nutrient exports is adsorption-based purification of runoff water using biochar has been proposed (Saarela et al., 2020). Biochar is a carbon-rich product made from any type of organic material (feedstock) by pyrolysis where the organic matter is heated at 300–800°C under low oxygen concentrations (Lehmann & Joseph, 2012). Biochar has been shown to be an effective nutrient adsorbent (Laird et al., 2010) due to its porous structure, large specific surface area, and high cation and anion exchange capacity (Ahmad et al., 2014; Gwenzi et al., 2017). Furthermore, it is also well established that the application of biochar to soils can promote soil fertility, which ultimately may enhance plant growth (Barrow, 2012; Jeffery et al., 2011). Hence, suggesting a potential circular system where nutrients successfully captured by biochar could then be applied back to forests, adding to the soil carbon stocks, and serving as a source of nutrition to trees that enhances growth (Palviainen et al., 2020).

The adsorption capacity of biochar varies with the properties of the feedstock, the pyrolysis temperature, and other manufacturing parameters (Liu et al., 2020; Zhang et al., 2020). A number of feedstocks including agricultural residues, wood biomass, manure, and solid waste have been utilized to produce biochar. Likewise, new biochar feedstocks, such as municipal garden residues, are currently reaching the market. However, the effectiveness of novel biochar feedstocks in the remediation of organic and inorganic contaminants is still uncertain (Ahmad et al., 2014). Furthermore, less attention has been focused on testing biochar as adsorbents for nutrient removal in an aqueous solution, with the available literature largely derived from laboratory experiments (Gwenzi et al., 2017). Nevertheless, existing experiments with biochar from novel feedstocks (e.g., rice straw) show different potentials in removing pollutants from water and soil environments (Luo et al., 2019). Therefore, understanding their potential and risk outside controlled experiments is a fundamental question that needs to be answered before we can apply this method as a mitigation tool for diffuse pollution from forestry.

The effectiveness of biochar in the purification of peatland runoff water has several challenges, specifically in field conditions. Biochar absorption capacity increases when the initial nutrient concentration is high, as for example in wastewater (Zhang et al., 2020) or agricultural runoff (Laird et al., 2010). Although nutrient concentration increases after clear-cutting, the concentration of solutes remains low in comparison, at least in a Nordic context (Palviainen et al., 2014). Furthermore, discharge, nutrients, and DOC concentrations vary across weather conditions and seasons in peatland forests (Mattsson et al., 2015), creating unstable conditions with high water volume and fluctuating nutrient concentrations. Unfortunately, few studies have addressed the use of biochar in water protection in peatland forests (Kakaei Lafdani et al., 2020, 2021; Saarela et al., 2020), and to our knowledge, there are no studies that have tested the biochar adsorption capacity in on-site field conditions. Therefore, in order to upscale this technology it is important to understand the effectiveness and limitations of this method in a field context.

In this study, we studied biochar as a water purification method both in controlled conditions and in field conditions. The study was conducted in two different phases; initially, we (a) evaluated the adsorption capacity of two different types of biochars (i.e., wood- and garden residue-based) and (b) assessed the effect of initial nutrient concentration on the adsorption capacity of these biochars. Subsequently, the biochar feedstock that presented the best adsorption capacity in the controlled laboratory environment was tested in field conditions. Here, we (c) tested the biochar adsorption capacity in the field under fluctuating solute concentrations, temperatures, and flowing water and (d) examined the role of average inflow solute concentration (i.e., outflow from managed catchments with different catchment characteristics) on the

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adsorption capacity. Changes in water pH, total dissolved nitrogen (TDN), phosphate (PO_4), and dissolved organic carbon (DOC) concentrations were measured throughout both experiments, as well as changes in total organic carbon (Tot-C), total nitrogen (Tot-N), and total phosphorus (Tot-P) in the biochars.

2 | MATERIALS AND METHODS

2.1 | Study site

Both phases were conducted in the Trollberget Experimental Area (TEA), an experimental study site established in 2018 to test best practices for forestry management and develop new methods to mitigate negative effects on freshwater ecosystems (Laudon et al., 2021). The ~60 ha site is located in the boreal zone of northern Sweden (64°14′ N, 19°46′ E), approximately 60 km from the Baltic Sea coast (Figure 1). The climate is typical for the northern boreal zone, characterized as a cold temperate humid type with short and cool summers followed by long dark winters. The 30-year mean annual air temperature (1986–2015) is +2.1°C with the highest mean monthly temperature occurring in July and the lowest in January (+14.6°C and −8.6°C, respectively; Kozii et al., 2020). Snow usually covers the ground from the end of October to late April. The total annual precipitation averages 614 mm year^{-1} of which approximately 35%–50% falls as snow and 311 mm becomes runoff (Laudon et al., 2013). At the TEA, a replicated catchment-scale approach has been established, with four side-by-side comparison catchments (Figure 1) with two treatments (clear-cut with or without ditch cleaning). Ditches were dug during the 1930s with the goal of draining forested peatlands to increase forest production (Hånell & Päivänen, 2012). To function as intended, ditches may require periodic maintenance or the cleaning out of vegetation, eroded soils, or other debris, which lowers the water table and consequently changes the nutrient dynamics on the site (Hasselquist et al., 2018; Laurén et al., 2021). The study catchments have an average size of 10 ha, an average tree volume prior to clear-cut of 270 m^3 ha^{-1}, and a ditch density of 166 ± 40 m ha^{-1}. In addition, for all catchments a weir has been installed in

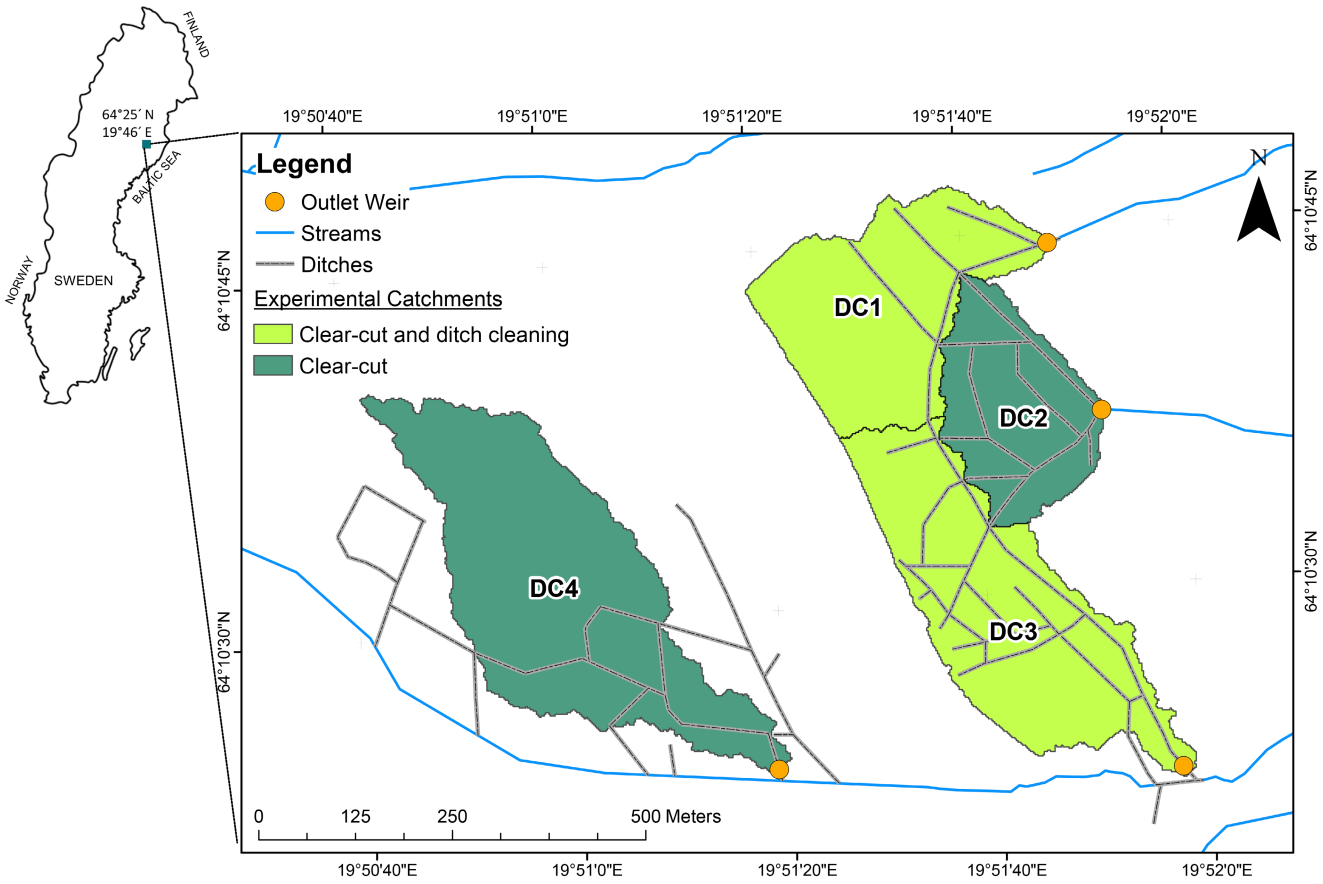

FIGURE 1 Trollberget Experimental Area (TEA) is located in northern Sweden (left). The green areas are different treatment catchments; grey lines mark the ditch networks, and the orange circles are the locations of the biochar filters and water quality monitoring sites (outlet weirs) Map lines delineate study areas and do not necessarily depict accepted national boundaries. Map lines delineate study areas and do not necessarily depict accepted national boundaries.

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the outlet ditch for water sampling and discharge measurements. In summer 2020, all four catchments were clear-cut using standard forestry practice and tree stems and branches were removed from the site (i.e., DC1, DC2, DC3, and DC4; Figure 1). In September 2021, two of the four catchments were ditch-cleaned using a 20-ton crawling excavator in DC1 and DC3, whereas the ditches were left uncleaned in DC2 and DC4 (see Laudon et al., 2021 for further details about the catchments).

2.2 | Experimental setup

2.2.1 | Experiment 1: Biochar adsorption potential in a laboratory experiment

In the laboratory phase, we tested for adsorption capacity of two different biochars, both produced by slow pyrolysis at high temperature (i.e., 600°C), known to increase the adsorption capacity (Yao et al., 2012). The wood-based biochar was produced by a local company (Vindekol AB, Vindeln Sweden) and manufactured primarily from the wood and bark of *Pinus sylvestris*, and a small portion of *Picea abies* and *Betula pendula* (hereafter referred to as "wood" feedstock; Gundale et al., 2016). The garden residue-based biochar was made from municipal garden residues, primarily shrubs and branches (hereafter referred to as "garden" feedstock) provided by a municipal company (Telge, Södertälje, Sweden). We sieved both biochar types to 4–10 mm to homogenize the material and to exclude the effect of various particle sizes of biochar in the adsorption process (Saarela et al., 2020); afterward, the biochar was dried for 12 h at 60°C. We collected 100 g of biochar from each feedstock to analyze for difference in C, N, and P contents in the biochar.

We conducted the laboratory incubation using the two biochars described above, with two different doses (3 and 12 g) to determine the effect of biochar dose on the adsorption rate and capacity and two different initial nutrient concentration in the water. Each treatment was replicated four times. In order to get two different initial nutrient concentration in water for the laboratory experiment, we collected samples from ditches draining two catchments with different landscape characteristics; one water source was a former forested, clear-cut catchment and the other was a drained peatland 1 km from TEA. After collection, the water samples were refrigerated and transported to the laboratory, upon which it was frozen until further processing. Due to a delay in the garden residue biochar delivery, the collection of runoff water was done in two different sampling occasions, May and August 2021, unfortunately resulting in slightly different initial concentrations between the wood and garden residue experimental setup. In both catchments, the average initial nutrient concentration was slightly higher in May (e.g., $6 \pm 0.5\,\mu g\,L^{-1}$ PO_4, $1 \pm 0.01\,mg\,L^{-1}$ TDN and $50 \pm 0.2\,mg\,L^{-1}$ DOC) than in August (e.g., $4 \pm 0.3\,\mu g\,L^{-1}$ PO_4, $0.5 \pm 0.02\,mg\,L^{-1}$ TDN, and $30 \pm 0.2\,mg\,L^{-1}$ DOC). Upon the start of the experiment, water was thawed, allowed to stabilize at room temperature (+20°C), standardized mixed among replicates, and kept at constant temperature throughout the experiment. We then added either 3 or 12 g biochar into 2000 mL glass jars, with four replications of each biochar dose for the two different water types. In addition, four glass jars contained only water without biochar as blank controls. Thereafter, 1500 mL of water from the field site was added to each jar and 35 mL of water was taken to measure the initial element concentration in each jar. Jars were covered with aluminum foil and placed on a platform shaker at 105 rpm for 10 days. Subsequently, 35 mL of water was sampled from each jar at the following time points: 1, 2.33, 5.5, 25, 28, 46, 49, 70, 145, 169, 196, and 215 h from the beginning of the experiment (Saarela et al., 2020). After sampling, water was filtered (0.45 µm Millipore) immediately after collection and stored in acid-washed high-density polyethylene (HDPE) bottles. Samples for DOC and TDN were refrigerated (+4°C) and analyzed within 3 days after collection. Samples for PO_4-P were frozen (−20°C) immediately after subsampling and stored for later analysis.

DOC, TDN, and PO_4 concentration change in water was measured to determine the adsorption of nutrients onto the biochar, calculated as follows (Saarela et al., 2020):

$$\mathrm{Ads}_t = \frac{\left(C_{\mathrm{ini}} V_{\mathrm{ini}} - C_t V_t\right) - \sum_{k=\mathrm{ini}}^{t} \left(C_k V_{\mathrm{sample}}\right)}{m_{\mathrm{biochar}}},$$

where Ads_t is the cumulative adsorption of the nutrient ($mg\,g^{-1}$ biochar), C_{ini} is the initial concentration of the nutrient ($mg\,L^{-1}$ or $\mu g\,L^{-1}$), V_{ini} is the water initial volume (L), C_t is the concentration of the nutrient in time t ($mg\,L^{-1}$ or $\mu g\,L^{-1}$), V_t is water volume at time t, C_k is the concentration of the nutrient in previous sampling occasion at time k, V_{sample} is the volume of water sample in each sampling occasion (35 mL), and m_{biochar} is the biochar mass (g). Moreover, cumulative adsorption was calculated for each time step during the experiment.

2.2.2 | Experiment 2: Biochar adsorption potential in field conditions

After evaluating the biochar feedstock for nutrient adsorption in the laboratory, the biochar that adsorbed the most nutrients was chosen to upscale the experiment to field conditions. The biochar was placed in jute sacks (Granngården AB, Malmö, Sweden) and placed in the

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ditches that drain the four experimental catchments (i.e., DC1, DC2, DC3, and DC4, $n = 4$). We expected different solute concentration in the runoff from the catchments with ditch cleaning and the catchments without ditch cleaning (Nieminen et al., 2018), therefore testing the effectiveness of biochar adsorption with different nutrient concentrations in field conditions. Sacks were filled with approximately 100 L of biochar and 4–5 sacks, depending on flow and geomorphology, were placed in each catchment outlet aimed to direct the ditch water flow through the biochar and to avoid bypass flow around and under the sacks. Water sampling points in the ditch were established at the weir above the biochar (inlet) and ~1 m below the biochar (outlet). Water samples were taken daily for the first 2 weeks after ditch cleaning operations (September 27–October 10) and twice a week until ditch water froze (November 3). All samples were collected in acid-washed high-density polyethylene (HDPE) bottles, filtered in the laboratory (0.45 μm Millipore) within 24–48 hours, and stored as described before for further analysis.

2.3 | Laboratory analyses

In both experiments, water quality variables were measured to determine the nutrient recovery from the runoff water. DOC and TDN concentrations were determined using the combustion catalytic oxidation method on a Shimadzu TOC VCPH analyzer (Shimadzu, Duisburg, Germany; Blackburn et al., 2017). PO_4^{3-} was accounted as the dissolved inorganic phosphorus (DIP) and was quantified colorimetrically using a Seal Analytical Autoanalyzer 3 HR and following method G-297-03 (SEAL Analytical, 2023). Water pH was measured with a pH meter (Mettler Toledo MP220). In addition, the C, N, and P concentrations in the biochars were analyzed using a Leco TruMac CN analyzer.

2.4 | Statistical analyses

All statistical analyses were conducted in R (R Core Team, 2022) and significance levels were set at $p < 0.05$ for all tests. Response variables for both experiments consisted of dissolved nutrient concentration in water ($mg\,L^{-1}$ TDN and DOC and $\mu g\,L^{-1}$ PO_4-P) and available nutrient concentration in biochar (% of Tot-C and Tot-N, and $mg\,kg^{-1}$ of Tot-P). Water quality data in the laboratory experiment were first evaluated for assumption of normality and data were logarithmic transformed when necessary to meet this assumption. First, a two-way multivariate analysis of variance (MANOVA) was used to test the effect of biochar, initial nutrient concentration in water, dose, and their interactions on dissolved nutrient concentration in water. Wilk's Lambda was used in the MANOVA to assess the significance of these main factors. Afterward, data were analyzed using a one-way analysis of variance (ANOVA), and where significance was found, Tukey's Honestly Significant Differences (HSD) post hoc comparison was used to explore differences among means in the *agricolae package* (Mendiburu, 2020). Furthermore, pH data from the laboratory experiment and Tot-N, Tot-C, and Tot-P extracted from the biochar from both experiments could not be transformed to meet the normality assumption; thus, these variables were instead analyzed with a Kruskal–Wallis nonparametric rank sum test and using Fisher's least significant difference (LSD) for the post hoc nonparametric test in the *agricolae package* (Mendiburu, 2020).

For the field experiment, we used a linear mixed-effect model (LMM) to analyze differences in the concentration of PO_4, DOC, and TDN between the inlet and the outlet. The analysis was performed using lme model from the *nlme package* (Pinheiro et al., 2022). The LMM provided a nonparametric approach to explain variability in the response variables by fixed effects (factors that were included in the study design) and random effects, which accounted for factors that were not part of the study design, but possibly affected variability in the concentration of PO_4, DOC, and TDN between the inlet and the outlet. The fixed effects considered in this study were the biochar treatment (inlet–outlet) and sampling time (i.e., day number); the random effects included were catchment ID and sampling time to account for repeated measures.

3 | RESULTS

3.1 | Laboratory experiment: Biochar adsorption potential in a controlled environment

The initial concentration of total C, N, and P in the two biochars showed significant ($p < 0.05$) differences (Figure 2). The garden residue biochar had higher concentrations of N ($0.5 \pm 0.01\%$) and P ($1288.6 \pm 4.1\,mg\,kg^{-1}$), but lower concentration of C ($73.2 \pm 2.4\%$) compared with the wood biochar ($0.09 \pm 0.003\%$ of N, $55.5 \pm 11.5\,mg\,kg^{-1}$ of P and $85.7 \pm 0.5\%$ of C).

In the laboratory experiment, the results of the multivariate analysis of variance showed that there was a statistically significant effect of biochar feedstock ($p < 0.01$) and initial nutrient concentration ($p < 0.01$) on the combined nutrient variables (PO_4, TDN, and DOC).

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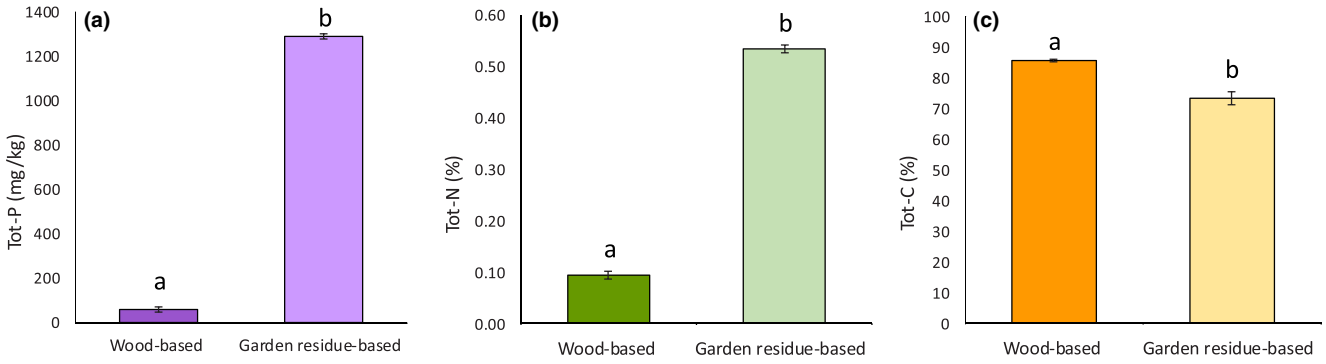

FIGURE 2 P (a), N (b), and C (c) concentrations in wood and garden residue biochar. Letters indicate significant differences between nutrient concentrations of the different biochars ($p < 0.05$, $n = 4$).

Specifically, the wood biochar significantly ($p < 0.05$) decreased the concentrations of TDN and DOC of the ditch water, while the garden residue biochar did not significantly decrease ($p > 0.05$) the TDN concentration and even released DOC ($p < 0.05$) to the ditch water. Conversely, both the wood and garden residue biochars increased ($p < 0.05$) the PO_4 in the water (Figure 3). By the end of the experiment, the higher dose (i.e., 12 g) of wood biochar significantly decreased ($p < 0.05$) the concentration of DOC and TDN in ditch water (Figure 3b,c,f,g), on average by 8% and 15%, respectively. A lower dose of wood biochar (i.e., 3 g) significantly reduced the TDN concentration when the initial N concentration was higher (Figure 3b); however, it did not significantly affect ($p > 0.05$) the concentration of other elements in the water (Figure 3c,e–g). Here, the reduction in TDN concentration was slightly higher when the initial N concentration in water was higher and for DOC the stronger decrease occurred when the initial C concentration in the water was lower. The higher dose (i.e., 12 g) of garden residue biochar adsorbed C and reduced the concentration of DOC ($p > 0.05$) by 17% in ditch water when the initial C concentration was higher (Figure 3k) but significantly released DOC when the initial C concentration was lower (Figure 3o). Neither doses of garden residue biochar significantly changed the concentration of TDN (Figure 3j,n). In addition, the higher dose of the wood biochar released PO_4 into the water, significantly increasing ($p < 0.05$) the concentration of PO_4 from 2.2 to 11 $\mu g\,P\,L^{-1}$ when the initial P concentration in the ditch water was higher (Figure 3a). Likewise, the garden residue biochar released P into the ditch water and increased ($p < 0.05$) the concentration of PO_4 by 111 and by 289 $\mu g\,P\,L^{-1}$ when the initial concentration of P was low and high, respectively. It is worth highlighting that the increase in PO_4 concentration in water was much higher from the garden residue biochar compared with the wood biochar. Finally, the addition of both wood and garden residue biochar increased ($p < 0.05$) the pH of the ditch water, for both high and low doses. Yet again, the garden residue biochar had a larger effect, increasing pH from 5.0 to 7.0, with the lower biochar dose and up to 8.0 with the higher dose of biochar (Figure 3l,p). The wood biochar reached pH of 5.5 and 5.8 with the higher biochar dose, respectively (Figure 3d,h).

Regarding temporal responses to biochar addition in the laboratory experiment, our results show that, for all elements, with a higher initial solute concentration in water and the addition of a lower wood biochar dose, the cumulative adsorption is higher, being the highest 2.5 $mg\,C\,g\,biochar^{-1}$, 0.05 $mg\,N\,g\,biochar^{-1}$ and 1.1 $\mu g\,P\,g\,biochar^{-1}$, for DOC, TDN and PO_4, respectively (Figure 4). However, for PO_4 and in some time steps for TDN, solutes were released from biochar to the water when we added a high wood biochar dose and the initial concentration was higher. Both for the wood and garden residue biochar, the cumulative adsorption of DOC was higher when the lower dose was added, reaching the peak adsorption at 145 h after the start of the experiment for the wood biochar (Figure 4c,f) and at 169 for the garden residue biochar (Figure 4i). For the garden residue biochar, the release of all solutes happened at some or multiple points with all treatments, showing a strong release pattern for PO_4 and TDN when the initial solute concentration was higher and for DOC when the initial C concentration was lower. Specifically, the garden residue biochar released between 9.2 and 29.8 $\mu g\,P\,g\,biochar^{-1}$ of PO_4, between 0.01 and 0.05 $mg\,N\,g\,biochar^{-1}$ of TDN, and between 0.1 and 2.7 $mg\,C\,g\,biochar^{-1}$ for DOC. Furthermore, both the wood and garden biochar adsorbed and released N when the initial N concentration was lower. Note that unfortunately, due to sampling difficulties, we did not have a high initial concentration for TDN when the garden residue biochar was tested.

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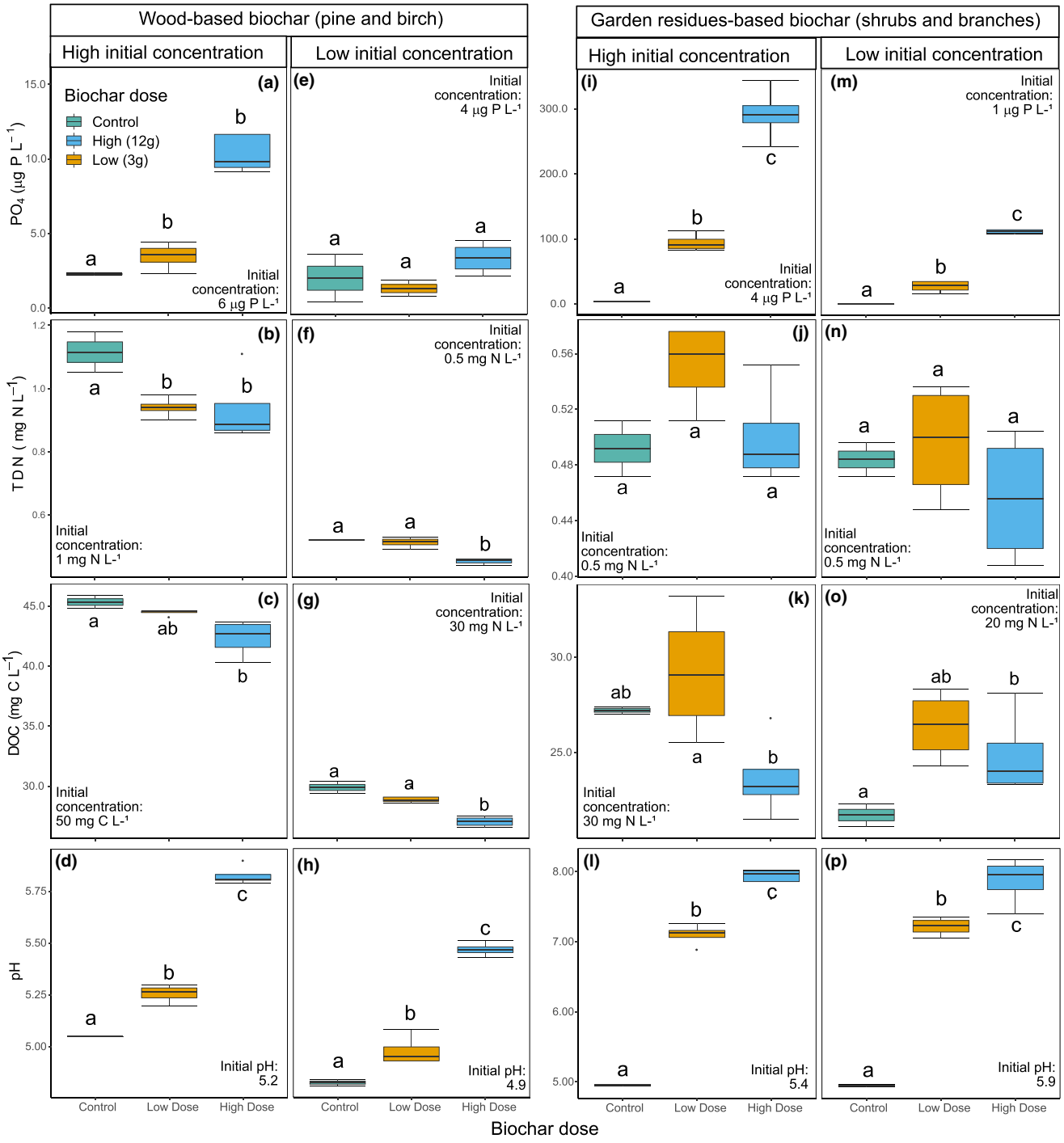

FIGURE 3 Effect of different doses of two different biochar feedstock in water with low and high solute concentration in laboratory conditions. Wood biochar (a–h) in higher initial solute concentration (a–d) and lower initial solute concentration (e–h) and garden residue biochar (i–p) in higher initial solute concentration (i–l) and lower initial solute concentration (m–p). Letters indicate significant differences between biochar doses ($p < 0.05$). Colors represent the different biochar doses added (control = 0 g, low = 3 g, high = 12 g). The solid line in box plots is the median value, box extents are the interquartile range (IQR), and whiskers show the minimum and maximum data points. Note that the scales for the *y*-axes show different magnitudes of concentrations.

Overall, the wood biochar demonstrated the highest potential to adsorb nutrients from stream water, specifically, for TDN and DOC removal. Our results also showed that the adsorption capacity increased when the initial nutrient concentration in water was higher. In contrast, nutrient release from the garden biochar into the stream water was higher (i.e., PO_4 and DOC). These differences justified the use of wood biochar for the second experiment, where biochar was tested at the catchment level in the field.

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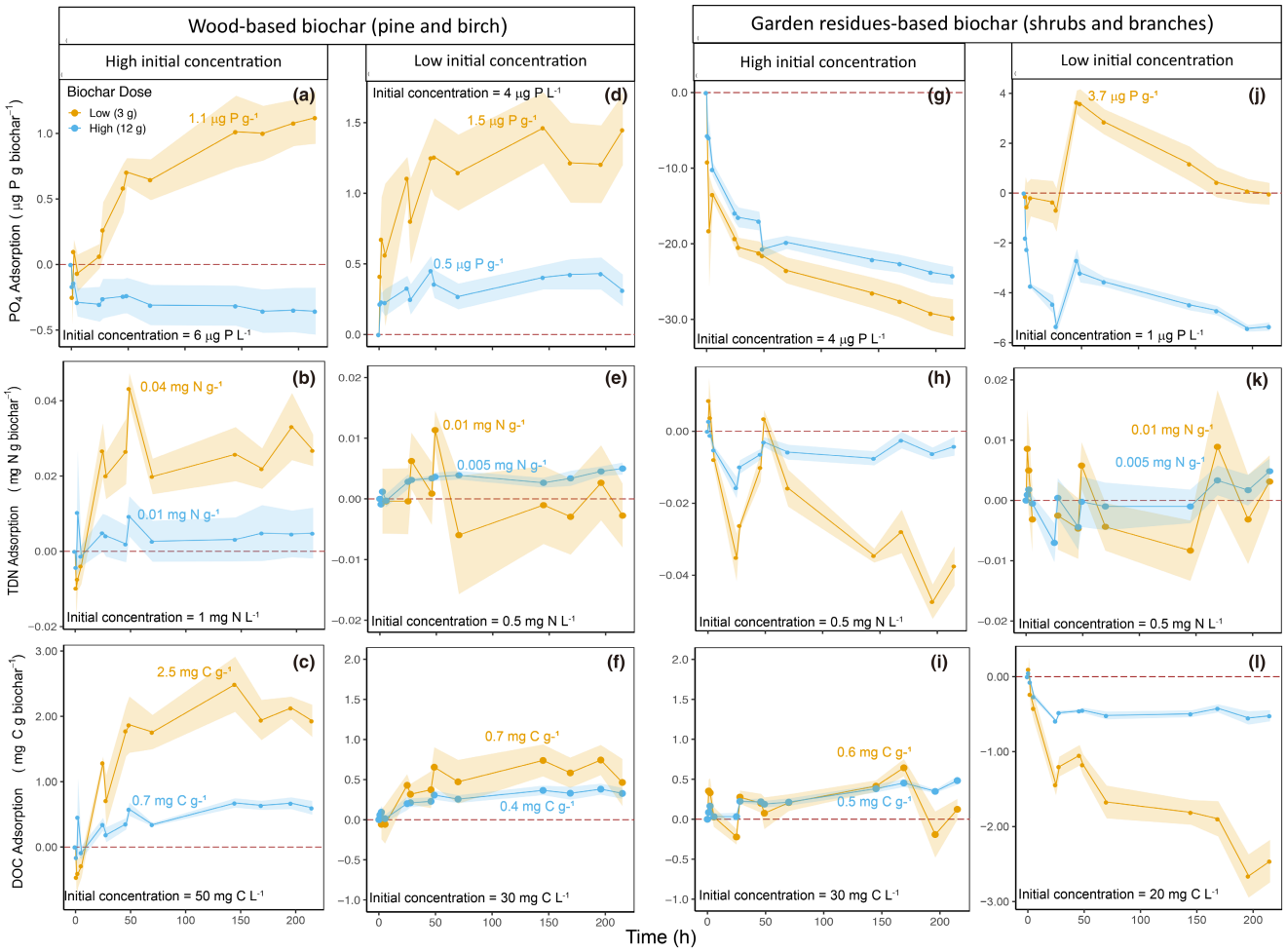

FIGURE 4 Cumulative adsorption by two doses of two biochar feedstock in the laboratory experiment that included water with low and high solute concentrations. The left side of the figure includes adsorption in wood biochar (a–f) in higher initial solute concentration (a–c) and lower initial solute concentration (d–f) and (g–l). The right side of the figure shows adsorption in garden residue biochar in higher initial solute concentration (g–i) and lower initial solute concentration (j–l). Colored numbers indicate the time step and highest adsorption capacity. Colored circles represent the average between replicates and shadowed area is the standard error. Values over zero indicate adsorption, while values below zero indicate release.

3.2 | Field experiment: Biochar adsorption potential in field conditions

The efficiency of wood biochar to remove DOC and TDN in the field was dependent on the initial concentration of the incoming water ($p < 0.05$), suggesting that the higher the concentration of DOC and TDN in the inlet, the higher the removal. Experimental catchment DC4 had the highest inlet concentration of TDN (2.6 mg N L^{-1}) and DOC (95.6 mg C L^{-1}) and was the only site where the water collected at the outlet (downstream) of the biochar filter had a significantly lower mean concentration ($p < 0.05$, Table 1) compared with the inlet (Figure 5b,c). For DC4, the mean percent of removal over the length of the experiment was 7% for TDN and 6% for DOC, with a maximum removal of 20% and 15%, respectively. In DC1-3, sites with lower inlet solute concentrations, the biochar did not significantly reduce TDN or DOC. Furthermore, there was no statistical difference ($p > 0.05$) between the inlet and outlet concentration for PO_4 in any of the experimental catchments; thus, the biochar filter did not remove PO_4. In fact, at DC4, there was an average increase in PO_4 concentration after the biochar filter of 2.4% (Table 1). Finally, the biochar filters did not significantly change the water pH ($p > 0.05$) in any of the experimental catchments, remaining on average acidic (i.e., 4–5).

Furthermore, we analyzed the nutrient content of the wood biochar before and after the field experiment (Figure 6) and found that the N content of the biochar had increased ($p > 0.05$) from 0.1% (±0.01) before the biochar filters were placed in ditches to 0.14% (±0.03) after they had been in ditches for 2 months, with no statistical difference between catchments ($p > 0.05$). Thus, there was an average increase of 45% in the N content of the biochar.

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TABLE 1 Average inlet concentration of PO4, TDN, and DOC for all experimental catchments at TEA.

	Mean inlet concentration ± SE	Mean outlet concentration ± SE	Mean removal	*p*-value
PO_4	**($\mu g\,P\,L^{-1}$)**	**($\mu g\,P\,L^{-1}$)**	**(%)**	
DC1	17.9 ± 1.3	17.5 ± 1.4	−2	n.s.
DC2	31.7 ± 3.1	30.8 ± 3.3	−3	n.s.
DC3	12.5 ± 1.1	11.6 ± 1.2	−7	n.s.
DC4	10.7 ± 0.8	11.0 ± 0.9	+2	n.s.
TDN	**($mg\,N\,L^{-1}$)**	**($mg\,N\,L^{-1}$)**	**(%)**	
DC1	0.9 ± 0.04	0.9 ± 0.04	0	n.s.
DC2	1.9 ± 0.08	1.8 ± 0.08	−1	n.s.
DC3	1.3 ± 0.06	1.3 ± 0.05	−2	n.s.
DC4	2.6 ± 0.03	2.4 ± 0.02	−7	**<0.01**
DOC	**($mg\,C\,L^{-1}$)**	**($mg\,C\,L^{-1}$)**	**(%)**	
DC1	35.3 ± 1.0	34.9 ± 1.1	−1	n.s.
DC2	69.0 ± 1.6	68.0 ± 1.2	−1	n.s.
DC3	41.5 ± 1.3	40.8 ± 1.2	−2	n.s.
DC4	95.6 ± 1.4	89.7 ± 1.7	−6	**<0.01**

Note: Percent removal is calculated in each time step and averaged. Negative values represent removal and positive values represent release. *p*-value is based on linear mixed-effect model for PO4, DOC, and TDN. The bold values show the significance level, $p < 0.01$.

However, the percent of C and P in the biochar did not change over the course of the field experiment ($p > 0.05$).

4 | DISCUSSION

We tested different feedstocks of biochars, both in the laboratory and in the field conditions as a method to reduce nutrient exports to water courses from managed forested catchments. Forest management activities such as clear-cut, commonly occur across high-latitude landscapes and typically affect DOC, N, and P exports affecting trends of brownification and eutrophication downstream.

4.1 | Adsorption capacity of two feedstock biochars in a controlled environment

Our results from the controlled laboratory experiment showed that higher doses of wood biochar effectively adsorbed TDN and DOC, although with lower cumulative adsorption, and released PO_4. The garden residue biochar also released PO_4 and was not efficient in the adsorption of any nutrient. Our results support previous studies, where feedstock is one of the key parameters controlling the adsorption properties (Ahmad et al., 2014) and nutrient adsorption capacity (Gai et al., 2014). The reduction in DOC and TDN concentration in solution could be explained by a wood biochar with large specific surface area, high porosity, and active sites on the adsorbent surface interacting with the arriving organic molecules from DOC and the organic part of TDN (i.e., dissolved organic nitrogen DON) (Lee et al., 2018). TDN reduction can also be explained by the capacity of the biochar to adsorb ammonium (NH_4^+) and nitrate (NO_3^-), as TDN is a combined measure of the inorganic (i.e., NH_4^+ and NO_3^-) and the organic fraction of N (i.e., DON). Specifically, biochars are known to be an effective adsorbent for NH_4 (Yin et al., 2017) because of its negative surface charges due to carboxylate and phenolate groups (Liang et al., 2006), which enhances the ability to adsorb and retain cations (Gai et al., 2014; Novak et al., 2009). However, the NO_3^- adsorption capacity of biochar is less clear, with comparable studies showing somewhat opposite effects, such as 2 out of 13 biochars absorbing NO_3 (Yao et al., 2012), none of the biochar types being able to adsorb NO_3 (Hollister et al., 2013) or even release of $NO_3^-$from the biochar to solution (Gai et al., 2014). Nevertheless, Kakaei Lafdani et al. (2021) found NO_3^- adsorption by wood biochar from clear-cut boreal forest runoff, arguing that the discrepancy in results could be explained by pyrolysis conditions and different initial N concentrations (Gundale & DeLuca, 2006). Furthermore, our results showed that for both biochar feedstocks, PO_4^{3-} was not only not adsorbed, but showed a net release back to the water. This may be attributed to the solubilization of ash residue enriched with P, given that the pyrolysis temperature for the preparation of both biochar samples was lower than the required 700–800°C temperature for P volatilization

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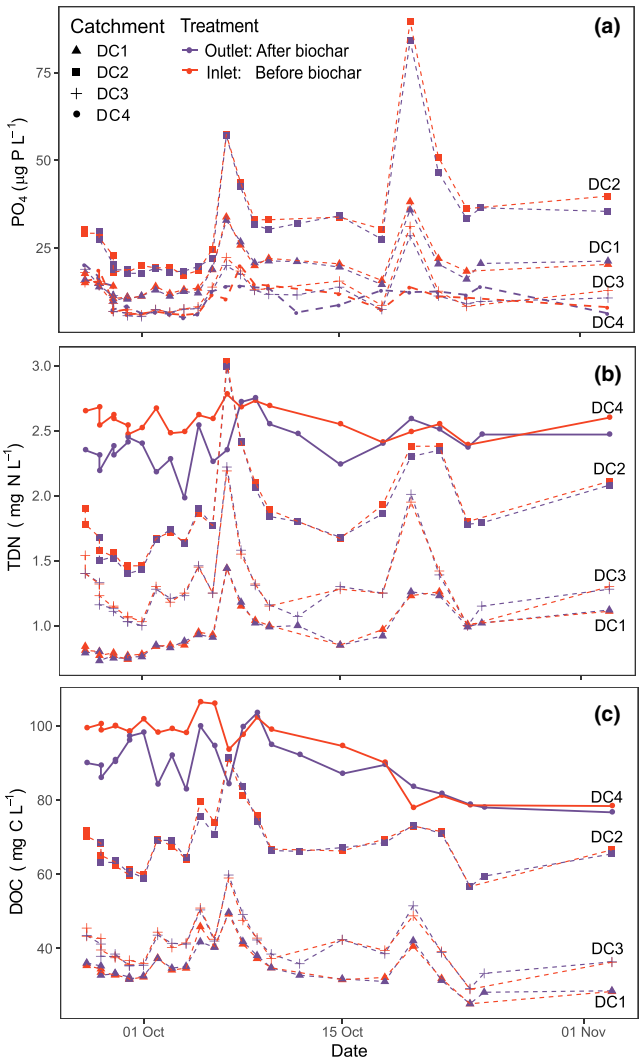

FIGURE 5 Nutrient concentrations of water from the inlet and outlet of the biochar filter for each experimental catchment. Solid lines represent a significant difference between inlet (red) and outlet (purple) over time of the experimental catchments according to the LMM ($p < 0.5$). The dotted lines represent non-significant relationships. Shape of the points identifies catchments, where circle is DC4, triangle DC1, square DC2, and cross DC3.

(Deluca et al., 2015). However, Yao et al. (2011) did find the removal of PO_4^{3-} from aqueous solution by biochar converted from anaerobically digested sugar beet. Both types of biochar used in our study, in higher and lower doses, increased pH significantly, turning the solution basic, and therefore, potentially improving further the adsorption of organic nutrients into the biochar (Ahmad et al., 2014) by increasing the net negative charge on the surface due to the dissociation of phenolic-OH group (Xu et al., 2011).

The laboratory experiment also showed that wood biochar has the potential to mitigate the environmental impact of forestry by removing organic C and N from run-off waters. Specifically, the reduction in DOC is gaining more importance in boreal freshwater ecosystems due to an ongoing brownification trend, with implications to the structure and function of aquatic ecosystems (Kritzberg et al., 2020). Furthermore, the reduction in N export would decrease the risk of eutrophication of freshwater ecosystems, as N and P are the main limiting elements to regulate aquatic productivity and accompanied algal bloom (Smith & Schindler, 2009). However, we also found that the novel garden residue biochar has the potential to increase the concentration of P in solution, consequently becoming a risk to freshwater ecosystems, by increasing the concentration of a main limiting nutrient (P) that could trigger eutrophication processes in receiving waterways. Therefore, to upscale a specific novel feedstock to field conditions as a mitigation tool for nutrient leaching from anthropogenic activities it is of utmost importance to consider an array of possible collateral effects.

4.2 | Biochar to adsorb nutrients in field conditions

In the field experiment, we found that our biochar filter was only effective at the removal of TDN and DOC when there was a high initial solute concentration. This is likely due to an increase in adsorption in response to the increased N availability in the water which improves the adsorption of nitrogen compounds onto biochar surfaces (Saarela et al., 2020). These results are consistent with our laboratory experiment results and results obtained by others (Kakaei Lafdani et al., 2021; Saarela et al., 2020), where in controlled environments, the higher adsorption rate was found when the solute initial concentration in water was higher. Yet, even in the catchment with the higher solute concentration, the percentage of N removed was low (7%) compared with other studies, where the biochar was shown to reduce 58% of the TN concentration (Kakaei Lafdani et al., 2020). Or, even compared with the increase in DOC and TN after clear-cut (i.e., an average increase of 42% ± 8 and 56% ± 12, respectively) in our study sites (Laudon et al., 2023). However, the observed low adsorption capacity might be an artifact of our filter setup, particularly when compared with other configurations such as horizontally oriented columns with longer residence time (Kakaei Lafdani et al., 2020). Moreover, contrary to our results in the laboratory experiment, the biochar filters did not change the pH of the water flow in any of the experimental catchments. This discrepancy suggests that a biochar filter design with a longer residence time could be beneficial in enhancing pH levels and increasing nutrient adsorption capacity.

Finally, our results agree with other studies that establish the potential of wood biochar as a water protection

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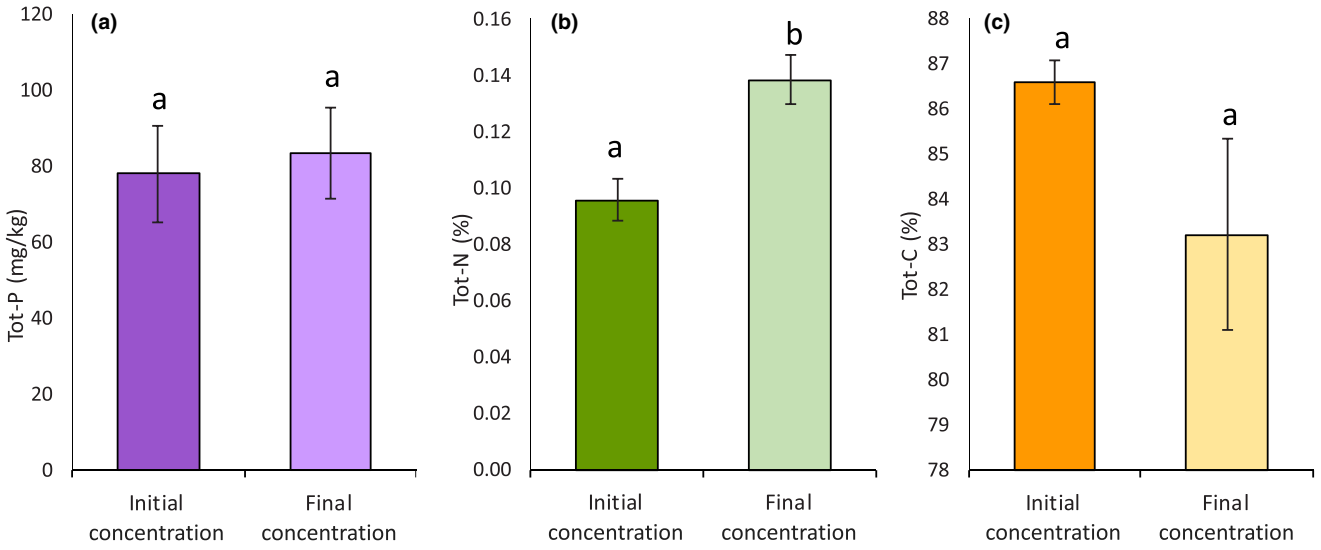

FIGURE 6 Concentration of P (a), N (b), and C (c) of the wood biochar before and after exposure to runoff water. Different letters indicate significant differences between nutrient concentrations in the biochar ($p < 0.05$).

tool, specifically for the retention of soluble nutrients (Lee et al., 2018; Zhang et al., 2020). However, using the wood biochar on-site with a simple setup for the removal of C, N, and P from runoff water in managed peatland forests could be challenging if the initial solute concentration leaching from the catchment is not high enough and discharge fluctuates over time. Yet, further efforts could be directed toward designing a better biochar filter with longer residence times. Ultimately, our study supports previous findings that a biochar filter in field conditions could be a feasible method for purifying runoff water with elevated nutrient concentration (Kaetzl et al., 2019; Perez-Mercado et al., 2019), with the potential for the most benefit in remediation of forestry outflows with higher nutrient concentrations or in agricultural and wastewater outflows with considerably higher concentrations. However, further development is needed to optimize the system and achieve greater reduction in dissolved nutrients.

4.3 | Closing the nutrient cycle

It is well established that biochar addition to soils can promote soil fertility and improve soil properties, which ultimately may enhance the growth of plants and trees (Biederman & Harpole, 2013; Jeffery et al., 2011; Palviainen et al., 2020). Pingree et al. (2022) suggests that the increase in plant growth in boreal environments after biochar addition is likely due to direct nutrient supply from biochar, hence a higher biochar nutrient content could be beneficial. Our results showed that the biochar N content increased significantly after 2 months of functioning as adsorption-based water purification. Therefore, by filtering ditch water, the biochar has the potential to become a soil amendment in boreal ecosystems with widespread terrestrial N limitation (Högberg et al., 2017); as nutrients (i.e., N) adsorbed onto the biochar are easily available for plants when placed in soil (Taghizadeh-Toosi et al., 2012). This would promote a closed nutrient cycle in boreal forest management, where nutrients leached from the catchment due to forest management activities such as clear-cut could be reincorporated to soils in the catchment and enhance forest productivity (Gundale et al., 2016). In summary, undesirable contaminants in aquatic ecosystems (i.e., C and N) can be transformed into desirable nutrients in the forest system, which could be used to promote growth and therefore C capture. Nevertheless, even though our field results revealed that our biochar filter reduces TDN and DOC concentration from outflows, the percentage decrease is dependent on initial concentrations of nutrients in water and could be considered low. Therefore, further research is needed to design an improved biochar filter to mitigate the impact of forest management on boreal aquatic ecosystems. Finally, although not suited for use in cleaning ditch water, the garden residue biochar used in the laboratory experiment could also present potential as a soil amendment, since it has relatively high levels of N and P as well as released PO_4, TDN, and DOC back to the solution. Yet, more research should be done to establish the desorption capacity of garden residue biochar in soils.

AUTHOR CONTRIBUTIONS

Virginia Mosquera: Conceptualization; data curation; formal analysis; funding acquisition; methodology; project administration; visualization; writing – original draft; writing – review and editing. **Michael Gundale:**

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Conceptualization; funding acquisition; writing – review and editing. **Marjo Palviainen:** Conceptualization; funding acquisition; methodology; writing – review and editing. **Annamari Laurén:** Conceptualization; funding acquisition; methodology; writing – review and editing. **Hjalmar Laudon:** Conceptualization; funding acquisition; writing – review and editing. **Eliza Maher Hasselquist:** Conceptualization; funding acquisition; methodology; project administration; visualization; writing – original draft; writing – review and editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interests.

DATA AVAILABILITY STATEMENT

Data on laboratory and field experiment can be available upon request to the authors.

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