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Cumulative and discrete effects of forest harvest and drainage on the hydrological regime and nutrient dynamics in boreal catchments

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ABSTRACT

In boreal landscapes, forest management has the potential to become a major driver of surface water quality due to the large proportion of actively-used land areas and the intensity of forestry operations. In Fennoscandia, forest management is comprised of different operations during a single rotation, where final harvest by clear cutting and subsequent ditch cleaning to restore drainage capacity are among the most influential on water quality. Here, we analyzed the single and combined effect of these forest management operations on the concentrations and exports of dissolved organic carbon (DOC), dissolved organic nitrogen (DON), dissolved inorganic nitrogen (DIN) and dissolved inorganic phosphate (PO_4) in boreal Sweden. We measured groundwater table level, stream discharge, and water chemistry data continuously following experimental clear cutting and ditch cleaning applied to a historically drained forest using a before-after-control-impact (BACI) design. We used linear mixed models to test whether DOC, DON, DIN and PO_4 concentrations were affected after each individual forest management operation, and further analyzed the response of the cumulative operations. We found that after clear cutting, concentrations of organic and inorganic nutrients increased significantly. However, for catchments with ditch cleaning after clear cutting, concentrations of organic nutrients in surface water decreased to pre-disturbance levels; inorganic nutrient concentrations also decreased but less strongly than organic counterparts. Despite this effect, catchments with ditch cleaning after clear cutting still showed an increase in overall organic and inorganic nutrient exports when compared to the reference catchments and the pre-treatment period. Nevertheless, catchments without ditch cleaning showed an even higher increase in both concentration and exports of most solutes. Overall, our results suggest changes in C, N and P exports due to forest management, along with the large spatial extent of this activity, could promote biogeochemical shifts and trigger water quality deterioration in boreal streams.

1. Introduction

Even in sparsely populated regions at high latitudes, freshwater ecosystems are affected by the long-range transport and deposition of pollutants, climate change, and land management, including forestry (Laudon et al., 2011; Teutschbein et al., 2017). Additionally, due to recent shifts toward a more bio-based economy, forest biomass demand is increasing. In boreal regions, this greater demand is being met by harvesting historically drained forested peatlands (Nieminen, Piirainen, et al., 2018). In Fennoscandia alone, roughly 15 million ha of peatlands, many of which can now be classified as wet mineral soils (Ågren et al., 2024), were drained in the last century to increase forest production (Paavilainen and Päivänen, 2013), of which nearly 60 % are located within the Baltic Sea region (Sikström et al., 2020). Indeed, after Finland and Russia, Sweden has the most drained forested land in the world (Strack, 2008). Therefore, in a boreal context, extensive and intensive forest management operations could have large ecological consequences for both terrestrial and aquatic ecosystems, including short- and long-term effects on hydrological processes (Hornbeck et al., 1997; Koivusalo et al., 2008) and on the storage, availability, and export of nutrients and other pollutants (Kļaviņa et al., 2021). Thus, understanding the relationships among forest management, ongoing

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environmental change, and ecosystem functioning is critical to managing boreal forests in ways that promote sustainability and protect surface water resources.

Most waters draining production forest landscapes are generally classified as high quality (Kauffman and Belden, 2010); yet, due to the highly mechanized and intensive operations employed throughout the forest management rotation in Sweden, receiving waters are subject to a number of stressors that may impair water quality (Kuglerová et al., 2021). Production forests are typically subject to a range of management operations, including harvest, soil preparation, ditch maintenance and (re)planting, which all have the potential to impact catchment hydrology and increase loads and concentrations of carbon (C), nitrogen (N) and phosphorus (P) in runoff water (Löfgren et al., 2009) with likely consequences for receiving waters. For instance, dissolved organic carbon (DOC) plays multiple biogeochemical and ecological roles in surface waters (Schelker et al., 2012), exerting control over the acid-base chemistry (Buffam et al., 2008), influencing metal export in streams and rivers (Bishop et al., 2020), and affecting aquatic habitat and food web structure (Creed et al., 2018). Additionally, N and P are the most important limiting nutrients in both terrestrial and aquatic environments. In freshwater ecosystems, the supply of these elements can regulate productivity and food web dynamics (Eimers et al., 2009; Elser et al., 2007), but can also induce eutrophication if concentrations become too high (Smith and Schindler, 2009). Therefore, increased concentrations of C, N and P to water bodies caused by forest management are a significant environmental concern with ecological consequences and potential impacts on drinking water (Bieroza et al., 2009; Conley et al., 2009; Kritzberg et al., 2020) and agricultural water supplies (Gleick et al., 2001). Nonetheless, in Sweden, the decision regarding what to do with the large number of historical drainage ditches remains an open question: increase ditch cleaning activities to maintain the potential for forest biomass production, or leave them unmanaged? Before any informed management decision can be made, clear and data-driven information regarding the outcomes of these different options is sorely needed (Laudon et al., 2023).

In a boreal context, forest harvest by clear cutting (i.e. harvesting all trees) and maintenance of old ditches (i.e., ditch cleaning) that have lost drainage capacity are two common forestry operations that have direct effects on the water table, catchment hydrology, and consequently the export of sediment, nutrients, and DOC (Nieminen, Piirainen, et al., 2018). Extensive research has tested the effects of clear cutting on hydrology and nutrient dynamics in forest catchments, and these consistently show increases in DOC, N and P concentrations in surface waters due to disruptions in soil nutrient cycling and water balance (Nieminen et al., 2017; Shah et al., 2022). In contrast, catchment-level studies on the impacts of ditch cleaning are scarce and thus the consequences for water quality remain poorly understood. In fact, existing studies have reported conflicting results, ranging from increased nutrient and DOC exports (Nieminen, Piirainen, et al., 2018), to no significant change (Manninen, 1998) to decreases (Nieminen et al., 2010). This variability likely reflects differences in site conditions and the timescales considered (Asmala et al., 2019; Kreutzweiser et al., 2008), highlighting the need for catchment scale studies in a paired catchment design. Additionally, while clear cutting and ditch cleaning are often applied sequentially during forestry rotations, the cumulative impacts of these practices on catchment hydrology and nutrient export have been largely ignored. The vast majority of catchment studies focus on the influence of specific forestry operations on water resources in isolation (Shah et al., 2022), neglecting potential synergistic effects or interactions, particularly in the context of altered groundwater flowpaths and nutrient mobilization. Finally, despite the recognized importance of C, N and P concentrations and ratios to regulate aquatic productivity (Stetler et al., 2021), studies to date have not explored the relative influence of forest management operations on simultaneous exports of these three essential resources, including the potential seasonal imbalances.

In this paper, we test the discrete and cumulative effects of two forest management operations on hydrological processes and, consequently, the link with simultaneous C, N and P leaching from boreal catchments and the effect on total export loads to water bodies. We focus on the most influential operations to water quality, final harvest by clear cutting followed by ditch cleaning to restore drainage capacity. We asked how these operations combine to influence water quality in stream water and how such effects changes seasonally. To answer these questions, we measured groundwater table level, discharge, and water chemistry continuously in response to a catchment scale replicated clear cutting and ditch cleaning experiment at the Trollberget Experimental Area (TEA), a historically drained, shallow peated forest within the Krycklan Catchment Study (KCS) located in boreal Sweden (Laudon et al., 2021). Specifically, we used linear mixed models to test whether organic and inorganic nutrient concentrations (DOC, DON, DIN, and PO_4) increase after each discrete forest management operation and further analyzed the response of the cumulative operations.

2. Materials and methods

2.1. Study site and experimental setup

This study was conducted within the Trollberget Experimental Area (TEA), an experimental study site established in 2018 to test the effects of ditch cleaning in historically drained boreal catchments in comparison to leaving the degraded ditch networks unmanaged (Laudon et al., 2013). The TEA infrastructure is part of the Svartberget Research Station that includes the research facilities of the Krycklan Catchment Study (KCS, 64° 25′ N, 19° 46′ E), which provides long-term study sites in upland forests and served as our reference. The ~60 ha TEA is located in the boreal zone of northern Sweden (64°14 N, 19°46 E), approximately 50 km inland from the coast of the Baltic Sea (Fig. 1). The climate is typical of the 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 and −8.6 °C, respectively; Kozii et al., 2020). Snow typically covers the ground from the end of October to late April, on average for 167 days. The total annual precipitation averages 614 mm yr^{-1} of which approximately 35–50 % falls as snow and 311 mm becomes runoff (Laudon et al., 2013).

The TEA is built around replicated and controlled experimental catchments based on a BACI (before-after control-impact) approach, consisting of four side-by-side catchments (Fig. 1) with two forestry management intervention treatments (clear cutting with or without ditch cleaning) and two unharvested, but drained reference catchments in the KCS. Both the treated and reference catchments have been affected by historical ditching activity that occurred in the early 20th century to improve drainage and increase forest production (Päivänen and Hånell, 2012). The TEA experimental catchments have a drainage area ranging from 4 to 10 ha, an average tree volume prior to clear cutting of 270 m^3 ha^{-1}, and a ditch density of 166 ± 40 m ha^{-1}. The reference KCS catchments are similar, with an average tree volume of 200 m^3 ha^{-1} and a ditch density of 53 ± 20 m ha^{-1} (Laudon et al., 2021; Zannella et al., 2023). The soils have an average organic soil depth of 140 mm on podzols, with pockets of histosols. The forested reference catchments, C1 and C2 within the KCS, are 98 and 100 % forested, respectively, and are similar in terms of soil types and forest composition (Laudon et al., 2021). However, C1 is larger in comparison, with an area of 48 ha.

At the outlet of DC2 and DC3 catchments, a 90° V-notch weir with a water height logger was installed in November 2018 and was used for water sampling and discharge measurements. In summer 2020, all four TEA catchments were clear cut harvested using standard forestry practice and tree stems and branches were removed from the site (i.e., DC1, DC2, DC3 and DC4; Fig. 1). Approximately one year later, in September 2021, two of the four catchments were ditch cleaned using a 20-ton

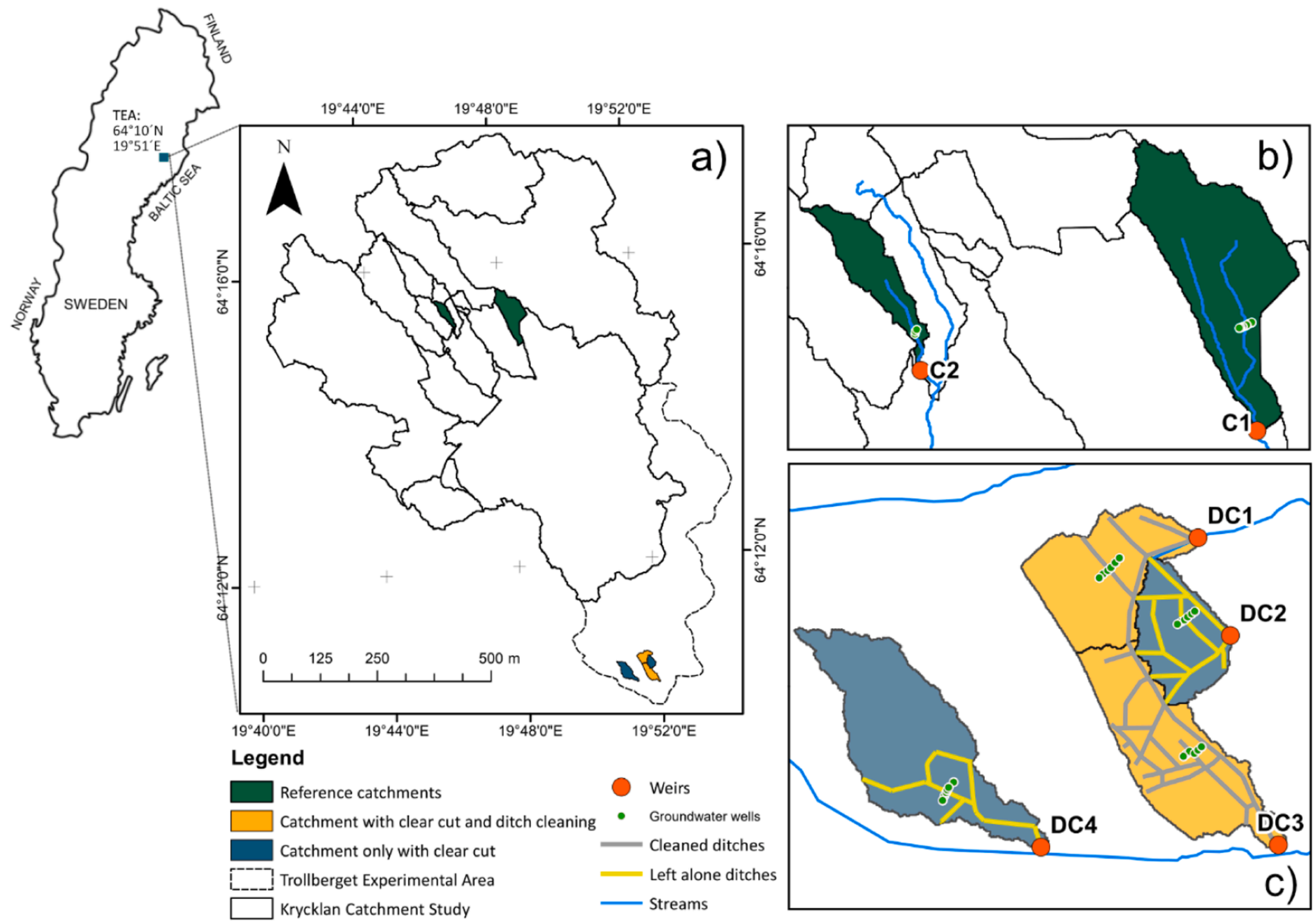

Fig. 1. The (a) Trollberget Experimental Area (TEA) including the Krycklan Catchment Study (KCS) with the (b) reference and (c) treated sub-catchments highlighted and an inset of Sweden (left). The bold grey and yellow lines denote the cleaned and left-alone ditches, respectively; delineated blue and mustard shaded areas are the different treatment catchments, green areas are the reference catchments; orange circles are the locations of water quality monitoring weirs. DC1-DC4 (in blue and mustard) are the ditch-cleaned experimental sites and C1 and C2 (in green) are the reference sites.

crawling excavator in DC1 and DC3, whereas the ditches were left uncleaned in DC2 and DC4 as reference (Laudon et al., 2021, for details about the catchments). Hereafter, the period before clear cutting will be called “pre-disturbance”, after clear cutting will be called “post-harvest” and after ditch cleaning will be called “post-drainage”. Typical ditch dimensions before cleaning at TEA were similar across the ditch cleaning catchments, on average being 500 mm (± 150) deep and 1470 mm (± 360) wide at the top. This is comparable to ditches at KCS unharvested forest reference sites, which are on average 500 mm (± 210) deep and 860 mm (± 530) wide.

2.2. Field measurements and analytical methods

Starting in 2019, pre-disturbance groundwater table level (GWL) measurements in groundwater wells as well as water samples for analysis of dissolved organic carbon (DOC), total dissolved nitrogen (TDN), nitrate (NO_3^--N), ammonium (NH_4^+-N), and phosphate or soluble reactive phosphorus (PO_4^{3-}P) were taken at the weirs in the outlets of the four treated and two reference catchments. Discharge measurements were taken only for one reference (i.e., C2) and two treated catchments (i.e., DC2 and DC3) catchments. Subsequently, the post-harvest period lasted approximately one year, starting in late August 2020, and ending after clear cutting activities were finished, until mid-September 2021, when ditch cleaning started. Finally, the post-drainage period began in late September of 2021 and lasted until June 2023, when we completed the last sampling (Figure S 1). The same protocols and sampling intensities were followed in the four experimental catchments and in the KCS reference catchments during the pre-disturbance and post-disturbance periods. GWL was measured using 36 continuously monitored (Solinst Levelogger 5) wells. For the post-harvest and post-drainage period, daily continuous data were analyzed, with 237 and 204 observations per sampling period, respectively. At all sites, GWL was measured relative to the ground surface. Furthermore, observations of water level using automatic stage loggers were made continuously at the DC2 and DC3 weir outlets. Discharge was estimated from site-specific rating curves developed using salt dilution, velocity-area, and time-volume measurements, covering most of the observed flow range (Karlsen, Grabs, et al., 2016). Year-round flow measurements were possible for one of the reference catchments (C2) where the gauging station is in a heated house. Flows during winter periods for locations without a heated gauging station were modeled according to established flow relationships (see Karlsen, Seibert et al., 2016 for further details on hydrological measurements in the KCS). Specific discharge during pre-disturbance, post-harvest and post-drainage period ranged between 0.05 and 17 mm d^{-1}, 0.05–65 mm d^{-1} and 0.01–54 mm d^{-1} for DC2, and between 0.01 and 48 mm d^{-1}, 0.11–29 mm d^{-1} and 0.07–15 mm d^{-1} for DC3, respectively. Finally, rainfall was logged every 10 minutes using a tipping bucket rain gauge (ARG 100, Campbell Scientific, USA) as part of the reference climate monitoring program at the KCS meteorological station (64°14’ N, 19°46’ E, 225 masl) (Laudon et al., 2013). For this study, the data were resampled to daily values.

The water quality sampling program was flow adjusted, following the KCS laboratory and sampling frequency protocols (Laudon et al., 2021). During high flow-spring flood periods, samples were collected twice per week, during intermediate flow conditions associated with the growing season samples were collected every 2 weeks, and during winter base-flow once per month. For the pre-disturbance, post-harvest and post-drainage period we sampled 33, 36 and 45 sampling occasions per period, respectively. All water samples were collected in acid-washed high-density polyethylene bottles, kept dark and cool during transport, and filtered in the lab (0.45 μm mixed cellulose ester (MCE) syringe filters, Millipore® within 24 h). Samples for DOC and TDN were refrigerated (+ 4°C) and analyzed within 10 d after field collection. Filtered subsamples were frozen (-20°C) immediately after subsampling and stored for later analysis of NO_3, NH_4 and PO_4. 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)). NH_4 and NO_3 were quantified colorimetrically using a SEAL Analytical AutoAnalyzer 3 (SEAL Analytical, Wisconsin, USA). NH_4 was analyzed using the Berthelot reaction to produce a blue-green-colored complex which was quantified colorimetrically at 660 nm (Method G-171–96 Rev. 12). NO_3 analysis was performed by reduction to NO_2 with a copperized cadmium coil, followed by sulfanilamide and napthylethylenediamine dihydrochloride chemistry to produce a reddish-purple azo dye; samples were analyzed colorimetrically (520–560 nm) (Method G-384–08 Rev. 2; Blackburn et al., 2017). DIN was calculated as the sum of NO_3 (including nitrite) and NH_4, and DON was calculated as the difference between TDN and DIN. PO_4 was accounted as dissolved inorganic phosphorus (DIP) and was quantified colorimetrically using a Seal Analytical Autoanalyzer 3 HR and following method G- 297–03 (SEAL Analytical, 2023). Our analytical methods have low detection levels for PO_4, NO_3 and NH_4 (0.4 μg L^{-1}, 0.3 μg L^{-1} and 0.4 μg L^{-1}, respectively), hence we excluded left censored values (below detection limit) due to the low proportion of non-detects (USEPA, 2000).

2.3. Data analysis and statistical methods

The GWL and discharge hydrographs were created to visually assess the differences between reference and treatment sites. Specifically, continuous GWL data from all the wells were averaged to obtain one single time series to facilitate this comparison. Additionally, seasonal background information was included in the time series. Note that seasons were defined on the basis of local air temperature measured at the center of the KCS using World Meteorological Organization standards (Laudon et al., 2013). Accordingly, spring begins when average air temperature reaches above 0°C for five consecutive days and the maximum temperature is still below 20°C. Summer begins when the 5-day mean temperature rises above 10°C for 10 consecutive days. Autumn begins when the mean daily temperature falls below 10°C and the minimum temperature is below 0°C, and winter starts when daily mean temperature is below 0°C for five consecutive days. To capture and illustrate the general pattern of nutrient concentration in the outlet weir after treatments, a Generalized Additive Model (GAM) was applied using the "ggplot" package in R (Wickham, 2016). Finally, for all sites, annual export was estimated using daily discharge and interpolated (daily) stream concentration data. Daily concentration of stream nutrients was estimated via linear interpolation to gap fill between sampling occasions. Daily export was then calculated as the product of the interpolated daily concentration and the specific daily discharge. Daily values were summed to estimate cumulative daily exports (mg ha^{-1}). The discrepancy in downstream exports between linearly interpolated daily data and daily data based on discharge-dependent regression models has been shown to be low (<10 %), given the sampling frequency in this study (Laudon et al., 2004; Wallin et al., 2013). To assess the impact of forest management on the streamflow regime, we used a Flow Duration Curve (FDC) approach and focused primarily on identifying and comparing baseflow conditions during pre-disturbance, post-harvest, and post-drainage periods. To do this, we used the 'hydroTSM' R package, which partitions the FDC into three segments based on flow exceedance probabilities (Smakhtin, 2001). The first segment represents high flows (0–20 % exceedance probabilities of flow), while the middle segment characterizes mid-range flows (20–70 %), namely, flows initiated by moderate rainfall events. The third segment (70–99 %) is related to the sustainability of baseflow in the dry period (Karimi et al., 2024).

The statistical design used in this study follows a BACI experimental design that has been used previously for hydrological studies in the same study site (Laudon et al., 2023). To compare treatments and reference GWL and nutrient concentrations, at each sampling occasion, we calculated a standardized metric for each variable, which was the difference in mean value of treatment (DC2 and DC4, DC1 and DC3) minus reference (C1 and C2). Accordingly, positive values indicate that the GWL or nutrient concentration is greater for the treated compared to reference catchments, whereas negative values indicate the opposite. Linear mixed effect models (LMM) provided a parametric approach to evaluate whether forest management interventions (i.e., clear cut and ditch cleaning) resulted in significant response in standardized GWL, base flow, concentration of PO_4, DIN, DON and DOC. We carried out a separate analysis for each contrast group (e.g., catchments with clear cut compared through the different periods, Table S 1-S 6), otherwise the model would have been too complex. LMM models were fitted using the restricted maximum likelihood (REML) method in the lme function from the *nlme package* (Pinheiro et al., 2022). The model was specified as:

$$y \quad = \quad \beta_0 + \quad \beta_1 treatment + u_1 \quad + \epsilon$$

where y represents the response vector (i.e., the standardized response in hydrology and water quality parameter); β_0 represents the fixed-effect intercept, corresponding to the reference concentration level of each treatment; β_1 is the fixed-effect coefficient for the effect of the forest management intervention (i.e., clear cut and ditch cleaning); u_1 is the random effect of time and ϵ represents the residual error, assumed to follow a normal distribution. Afterwards, if the fixed effects were significant, we performed post hoc pairwise comparisons using the emmeans function from the emmeans package (Lenth et al., 2023) to test for significant differences ($p < 0.05$) between forest management interventions. All statistical analyses, data manipulation, summary statistics, and plotting were conducted in R (R Core Team, 2022) and significance levels were set at $p < 0.05$ for all tests.

3. Results

3.1. Effect of forest management interventions on catchment hydrology

3.1.1. Groundwater table level

The GWL was similar among all catchments and controls in the pre-disturbance period. DC1 and DC3 had a median GWL of 3 ± 0.9, which was 2 ± 0.6 cm lower than the reference catchments (DC2 and DC4; Fig. 2a.1). After clear cutting, GWL significantly rose in all treated catchments to an average of 26 ± 0.8 cm above the reference GWL ($p < 0.05$; Fig. 2a.2; Table S 1). GWL subsequently significantly decreased post-drainage compared to post-harvest in catchments with ditch cleaning (returned to 5 ± 0.6 cm below the GWL of the reference catchment; Fig. 2a.3), while the GWL of catchments without ditch cleaning remained higher than reference catchments (5 ± 0.6 cm above the GWL of the reference catchments, Fig. 2a.3). Furthermore, the effect of both forest management operations and natural variation due to precipitation and seasons was apparent in the GWL hydrograph (Fig. 3). Specifically, the median GWL in the reference catchments was relatively similar between the pre-disturbance and post-harvest period (-54 ± 0.9 and −56 ± 0.8 cm, respectively); however, it rose during the post-drainage period (to −39 ± 0.6 cm); due to high precipitation (Fig. 3a). In comparison, the catchments with clear cutting and with or without ditch cleaning had similar median GWL in the pre-disturbance period

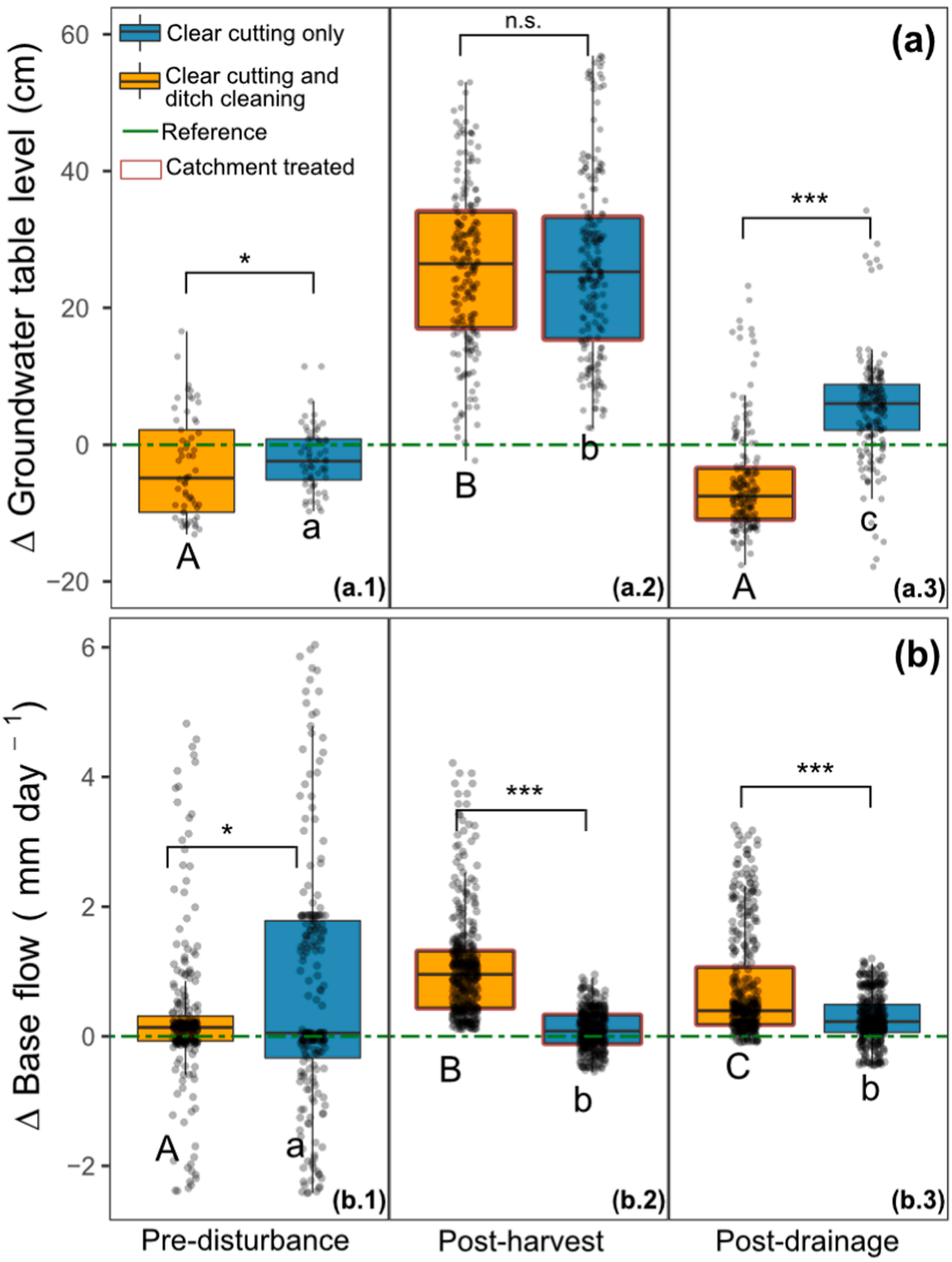

Fig. 2. Difference in (a) groundwater table level (GWL) and (b) base flow between treatment and reference catchments before and after interventions. The difference was computed as treatment minus reference, thus positive values indicate that the GWL or base flow is greater at the treated catchments than at the reference catchments, while negative values indicate the opposite. Black circles represent individual data points. **denotes significant difference ($p < 0.01$) and ***denotes significant difference ($p < 0.001$), between treatments during each intervention period between treatments; different uppercase letters indicate significant difference ($p < 0.05$) for catchments with clear cutting and ditch cleaning after each intervention; and different lower case letters indicate significant difference ($p < 0.05$) for catchments with clear cutting but without ditch cleaning after each intervention. Green dotted line denotes the zero reference. Solid line in box plots is the median value, box extents are the interquartile range (IQR) and whiskers show the 1.5IQR value.

(-42 ± 0.6 and −41 ± 0.6 cm), but then rose similarly in all catchments after clear cutting (to −32 ± 0.6 and −33 ± 0.3 cm). However, in the post-drainage period, the GWL in the catchment with ditch cleaning reached the lowest GWL (-47 ± 0.6 cm), while the GWL in the catchments without ditch cleaning also decreased (-36 ± 0.6 cm).

Finally, forest management operations also had differentiated effects on seasonal GWL (Fig. 4, Table S 7); however, except for autumn, these effects generally followed the overall trend (i.e., rising after clear-cutting and decreasing after ditch cleaning). The highest increase of GWL occurred in summer post-harvest period, with an average increase of 46 %, yet with variable catchment responses. Similarly, after clear cutting, the spring and winter GWL increased in all catchments. However, DC1 and DC3 showed a median increase of 8 % during spring and an increase of 11 % during winter, whereas DC2 and DC4 showed a median increase of 39 % during spring and 27 % during winter. Furthermore, during the post-drainage period, the highest percent change was observed during winter, where the GWL decreased 20 % more in the catchments with ditch cleaning and 8 % more during summer. Conversely, autumn GWL rose by 21 and 51 % during the post-drainage period in catchments with and without ditch cleaning, respectively.

3.1.2. Runoff

Median and high runoff showed no significant change during the

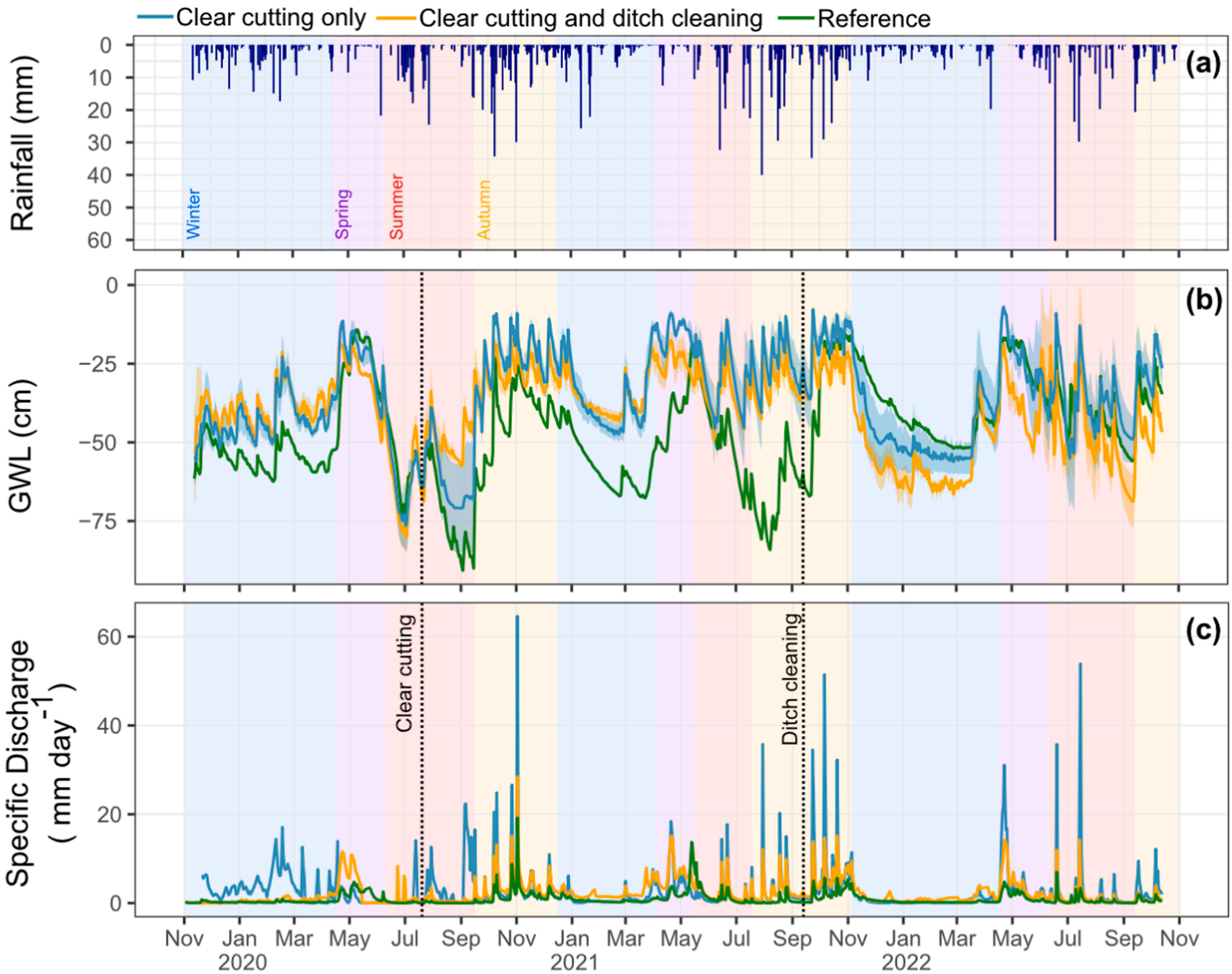

Fig. 3. (a) Daily precipitation at the KCS meteorological station (b) median groundwater table level (GWL) for the [green line] reference catchments (C1 and C2), [yellow line] catchments with clear cut and ditch cleaning (DC1 and DC3), [blue line] catchments with only clear cut (DC2 and DC4) with ± 1SE shaded in gray, yellow and blue, respectively; and (c) specific discharge for the [green line] reference catchment (C2), [yellow line] catchment with clear cut and ditch cleaning (DC3), [blue line] catchment with only clear cut (DC2). Background colors delineate seasons.

periods after forest management operations. However, when considering only the change in median base flow, we found a difference in treated catchments after clear cut and a decrease in base flow in the ditch cleaned catchment during the post-drainage period ($p < 0.05$, Fig. 2b and Table S 2). Catchment DC3 (i.e., with ditch cleaning) had base flow higher than the reference throughout the study period; pre-disturbance (0.2 ± 0.04 mm day^{-1}), after clear cut (1.0 ± 0.04 mm day^{-1}) and after ditch cleaning (0.4 ± 0.04 mm day^{-1}). Interestingly, the increase in median base flow after clear cut was higher for DC3 (1.0 ± 0.04 mm day^{-1}) than for DC2 (0.1 ± 0.01 mm day^{-1}), even though both were treated equally at this time. Median base flow for DC2 (i.e., without ditch cleaning in the post-drainage period), was different between pre-disturbance and post-harvest periods (0.1 ± 0.13 mm day-1, $p < 0.05$), with median base flow becoming less variable after clear cutting (0.1 ± 0.01 mm day^{-1}) and during the post-drainage period (0.2 ± 0.02 mm day^{-1}) (Fig. 2).

The runoff hydrograph showed differences between seasons and catchments (Fig. 4), with the highest median runoff during spring after clear cutting (6.2 ± 0.5 and 2.7 ± 0.5 mm day^{-1} for DC3 and DC2, respectively), and during autumn after ditch cleaning, when DC3 reached a median runoff of 5.4 ± 0.5 mm day^{-1} and DC2, the catchment without ditch cleaning, reached a median runoff of 4.6 ± 0.5 mm day^{-1}. Furthermore, base flow also showed strong seasonality and different effects after forest management operations depending on the season (Fig. 4). For example, summer base flow showed an increase by a factor of 10 after clear cut in both catchments DC3 and DC2; however, after ditch cleaning, DC3 base flow decreased to 0.2 ± 0.02 mm day^{-1} and did not change for DC2, the catchment without ditch cleaning. Conversely for autumn base flow, both catchments increased in the post-drainage period relative to the reference catchment, but flow increased 40 % more in the catchment without ditch cleaning (increased by 20 % with and 60 % without ditch-cleaning).

3.2. Effect of forest management operations on nutrient fluxes

3.2.1. Nutrient concentration

The concentration of most nutrients (i.e., PO_4, DON and DOC) in ditch water increased significantly ($p < 0.05$, Table S 3, S 5 and S 6) post-harvest in all treated catchments compared to the pre-disturbance period; however the increase in DIN concentration was not significant ($p > 0.05$, Fig. 5, Table S 4 and S 8). Furthermore, during the post-drainage period, the organic nutrient concentration (i.e., DON and DOC) in the catchments with ditch cleaning decreased to pre-disturbance levels, while in the catchments with no ditch cleaning the

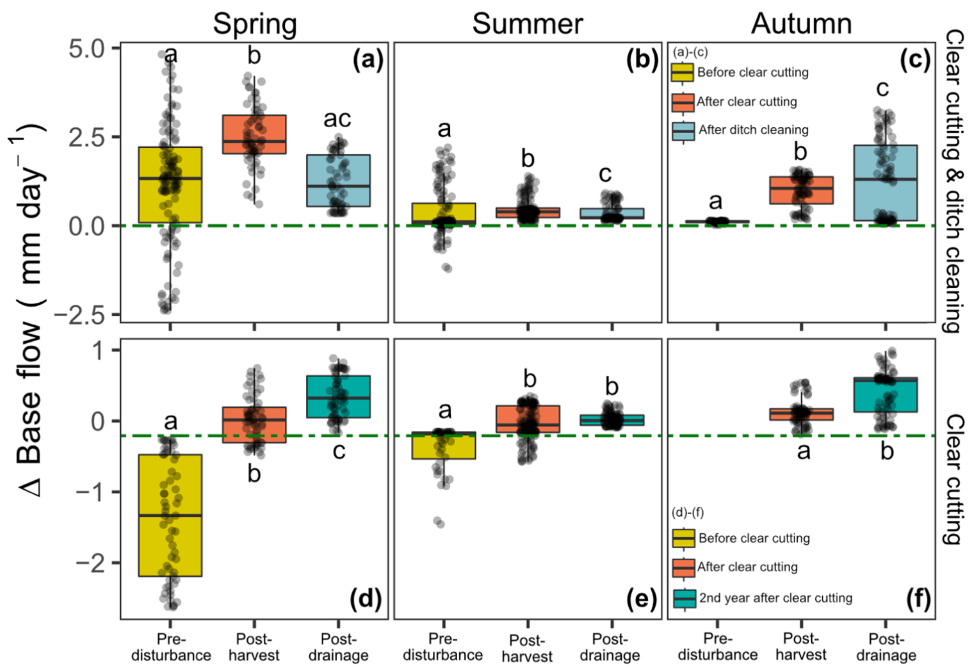

Fig. 4. Difference in base flow between treatment and reference catchments before and after forest management operations for (a and d) spring, (b and e) summer, and (c and f) autumn. The difference was computed as treatment minus reference, thus positive values indicate that the base flow is greater at the treated catchments than at the reference catchments, while negative values indicate the opposite. Different lower case letters indicate significant difference ($p < 0.05$) between interventions. Green dotted line denotes the zero reference. Black circles represent individual data points. Solid line in box plots is the median value, box extents are the interquartile range (IQR) and whiskers show the 1.5IQR value.

concentration remained higher (Fig. 5c and d and Table S 8). By comparison, during the post-drainage period, PO_4 and DIN concentrations increased for sites without ditch cleaning, whereas PO_4 remained unchanged and DIN concentration significantly increased with ditch cleaning (Fig. 5a and b and Table S 8). Here, we also found a difference in DIN speciation, such that during the post-drainage period, NH_4 increased ($p < 0.05$) in the catchment with ditch cleaning but increased even further in the catchments without ditch cleaning (Figure S 2a). NO_3 showed the opposite pattern, with a higher increase ($p > 0.05$) in the catchments with ditch cleaning, compared to the catchments without ditch cleaning (Figure S 2b).

Regarding temporal responses to forest management operations, we found that after clear cutting, the concentration of organic nutrients had greater seasonal fluctuations compared to the reference catchment, peaking during the growing season immediately after clear cut. Additionally, we observed higher peaks in the non-drained catchments compared to the catchments that would eventually be drained (Fig. 6, Table S 9). Yet, DON and DOC returned to almost pre-disturbance concentrations during winter-spring a year following ditch cleaning. Here, spring DON median concentration decreased to 395.1 ± 25 μg N L^{-1} compared to pre-disturbance concentration of 327.9 ± 19 μg N L^{-1}. Likewise, spring DOC median concentration decreased to 18.5 ± 0.9 compared to pre-disturbance concentration of 17.0 ± 1 mg C L^{-1}. Inorganic nutrients responded at different times after clear cutting: PO_4 concentrations started increasing in the autumn immediately following harvest, while DIN increased during the spring after clear cutting (Fig. 6; Table S 9). After one year, autumn and winter PO_4 concentration decreased in the catchments with ditch cleaning (i.e., DC1 and DC3), while PO_4 concentration continued increasing through autumn and winter in the catchments without ditch cleaning. Effects on DIN were more persistent, with concentrations peaking again during spring in the post-drainage period in catchments both with and without ditch cleaning; however, this peak was greater in catchments without ditch cleaning (Fig. 6; Table S 9).

3.2.2. *Nutrient exports*

Over the study period, the catchment with only clear cutting had the highest cumulative exports of all nutrients (i.e., DIN, PO_4, DON and DOC), followed by the catchment with clear cut combined with ditch cleaning, and then the reference catchment (Fig. 7). The greatest increase was for DIN, which, when compared to the reference catchment, showed a 75-fold increase in exports in the catchment with only clear cutting and a 58-fold increase in the catchment with both clear cutting and ditch cleaning. Similarly, the catchment with only clear cutting had the highest increase for PO_4, DON and DOC, which increased by 20-fold, 8-fold and 6-fold, respectively. For the catchment with clear cutting and ditch cleaning combined, these three solutes showed a less dramatic response, with a 4-fold, 4-fold and 3-fold increase in exports, respectively. In terms of cumulative export during this period, the catchment with only clear cut exported 0.6 kg P ha^{-1}, the catchment with clear cut and ditch cleaning exported 0.1 kg P ha^{-1}, and the reference catchment exported 0.03 kg P ha^{-1} of PO_4. For inorganic and organic nitrogen, the catchment with only clear cutting exported 9.1 and 27.6 kg N ha^{-1}, the catchment with clear cut and ditch cleaning exported 7.0 and 13.8 kg N ha^{-1} and, the reference catchment exported 0.12 and 3.5 kg N ha^{-1}, respectively. For DOC, the reference catchment exported 226 kg C ha^{-1}, the catchment with clear cut and ditch cleaning exported 700 kg C ha^{-1} and the catchment with only clear cut exported 1463 kg C ha^{-1}.

Forest management operations increased the total exports of all nutrients and all treated catchments had higher exports in the post-harvest and post-drainage period, compared to the pre-disturbance period (Table 1). The total exports of DON and DOC were lower both for the catchments with ditch cleaning and those without during the post-drainage period when compared to the post-harvest period. Yet, this decrease was greater for the catchments with ditch cleaning: −41 % for DON and −48 % for DOC, compared to −16 % for the catchments without ditching. Similarly, total export of PO_4 post-drainage compared to the clear cut period was lower in the catchments with ditch cleaning, and in the catchment without ditch cleaning the total exports were higher. By contrast, DIN showed the opposite pattern, with exports

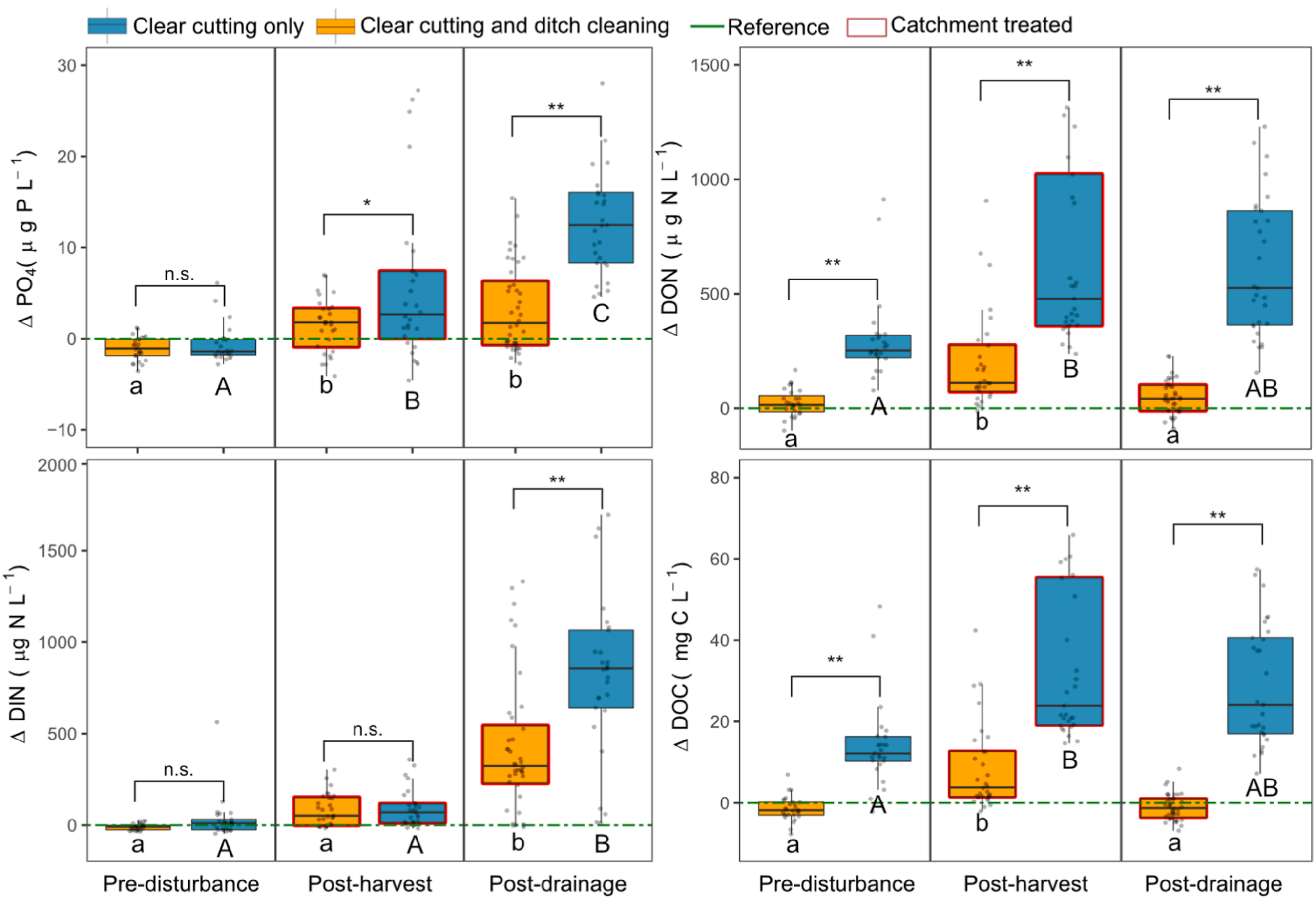

Fig. 5. Difference in nutrient concentration between treatment and reference catchments before and after interventions for PO_4 (a), DIN (b), DON (c) and DOC (d). The difference was computed as treatment minus reference, thus positive values indicate that the nutrient concentration is greater at the treated catchments than at the reference catchments, while negative values indicate the opposite. Black circles represent individual data points. **denotes significant difference ($p < 0.01$) between treatments during each intervention period; different uppercase letters indicate significant difference ($p < 0.05$) for catchments with clear cutting and ditch cleaning after each intervention; and different lower case letters indicate significant difference ($p < 0.05$) for catchments with clear cutting but without ditch cleaning after each intervention. Green dotted line denotes the zero reference. Solid line in box plots is the median value, box extents are the interquartile range (IQR) and whiskers show the 1.5IQR value.

continuing to increase post-drainage relative to post-harvest, regardless of whether catchments had ditch cleaning. Still, in this case, there was again a smaller percent increase in export for the catchments with ditch cleaning, + 68 %, compared to + 210 % for the catchments without ditch cleaning.

In the post-harvest period, autumn remained the season with the highest exports of all organic and inorganic nutrients (i.e., PO_4, DIN and DON, DOC). However, during the post-drainage period, spring became the season with the highest exports of PO_4 in the catchment without ditch cleaning and the season with the highest exports of DIN in the catchments with and without ditch cleaning. Further, winter was the season with the lowest exports of organic nutrients after clear cut; however, in the post-drainage period, summer became the season with the lowest exports in the catchment with ditch cleaning. For the inorganic nutrients, the season with the lowest exports differed between the treated catchments even when both were only clear cut; summer was lowest for PO_4 in catchment DC3, while winter was lowest in catchment DC2. Similarly, for DIN after clear cut, summer had the lowest exports in catchment DC3, while winter was lowest in DC2; however, during the post-drainage period summer also became the season with the highest exports in the catchment without ditch cleaning (i.e., DC2). Finally, seasonal exports followed the same overall pattern as the concentrations, where the catchments without ditch cleaning had the higher exports, even in the pre-disturbance period or after clear cut (Fig. 7).

4. Discussion

In a Fennoscandian context, forest management includes a number of different operations during the rotation cycle, of which final harvest by clear cutting followed by ditch cleaning to restore drainage capacity in wet areas are the two operations with the most potential to influence water quality (Shah et al., 2022). Consistent with many other studies (Nieminen et al., 2017), we found that clear cutting resulted in a significant increase in the concentrations and hydrological export of all organic and inorganic nutrients (Löfgren et al., 2009; Palviainen et al., 2014). However, for catchments with ditch cleaning, concentrations of organic nutrients in surface waters decreased to pre-disturbance levels. For inorganic nutrients, ditch cleaning did not result in a return to pre-disturbance levels, but did have a mitigating effect on both concentrations and exports.

4.1. GWL change as a main driver for organic and inorganic nutrient mobilization

Changes in hydrological processes in response to forest harvesting are well documented and largely reflect the effects of decreased transpiration on the GWL (Laudon et al., 2011; Nieminen et al., 2017). In boreal landscapes, a rise in the GWL can be expected to follow clear cutting, though the magnitude and duration of this increase varies

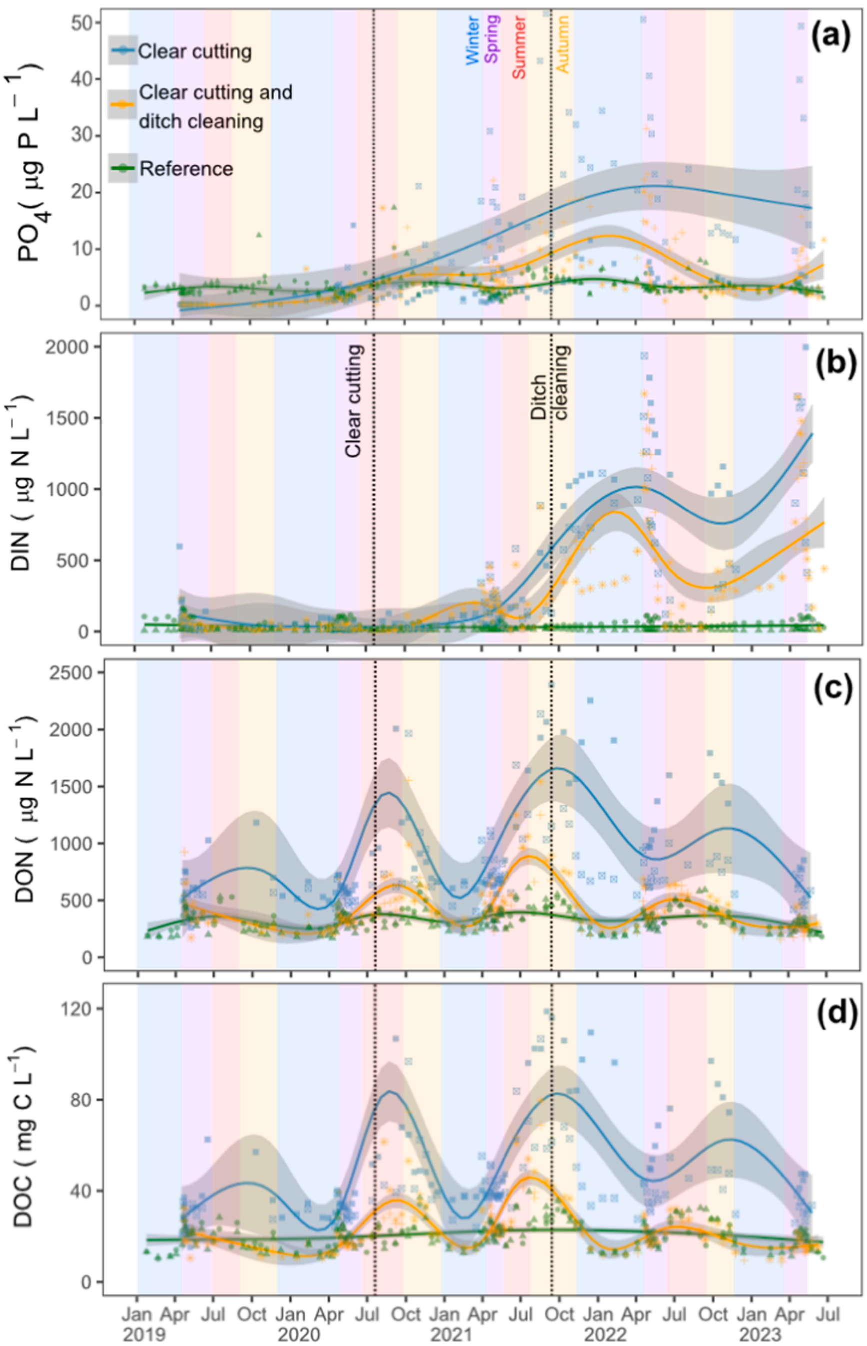

Fig. 6. Time series of organic and inorganic nutrients for the pre-disturbance, post-harvest and post-drainage period shown with a general additive model (GAM). (a) PO_4, (b) DIN, (c) DON and (d) DOC for catchments with clear cutting and ditch cleaning shown with yellow line (i.e., DC1 and DC3), catchments with only clear cutting shown with blue line (i.e., DC2 and DC4) and reference catchments shown with green line (i.e., C1 and C2). Background colors delineate seasons.

depending on landscape position, soil type and texture, soil and till depth, and current and previous climatic conditions (wet vs. dry periods) (Wei et al., 2022). For example, aspen harvesting in Alberta's boreal forest during dry conditions did not significantly increase GWL (Thompson et al., 2018), while simulations of aspen harvesting in the same region during wet conditions suggested the potential for significant increases (e.g., 1.0–3.5 m; Carrera-Hernández et al., 2011). Our results are generally in line with this overall pattern: the GWL rose on average 10 cm after clear cutting, reaching approximately a GWL of −32 cm on average. This increase was smaller in magnitude when compared to other studies at similar latitudes where the GWL increased by 20–30 cm in response to clear cutting (Kaila et al., 2014; Sarkkola et al., 2013). Such differences are likely related to variation in peat layer depth and slope among studied catchments (Koivusalo et al., 2008).

The increase in GWL is biogeochemically significant because it forces water tables into soil layers with elevated nutrient concentrations, which can promote leaching of solutes (Nieminen et al., 2017; Stewart et al., 2022). Specifically, in our experimental catchments, where the entire catchment area was clear cut, the mechanism governing higher transport of organic nutrients, DON and DOC shortly after clear cutting seems to be related to an increase in the lateral flow through more surficial soil horizons (Lupon et al., 2023; Schelker et al., 2012) due to an increase in GWL. This response is generally consistent with increases in DON and DOC concentrations and hydrological conductivity near the soil surface where soil organic matter storage is greatest (Bishop et al., 2004). Beyond this direct hydrological effect, increases in GWL may also

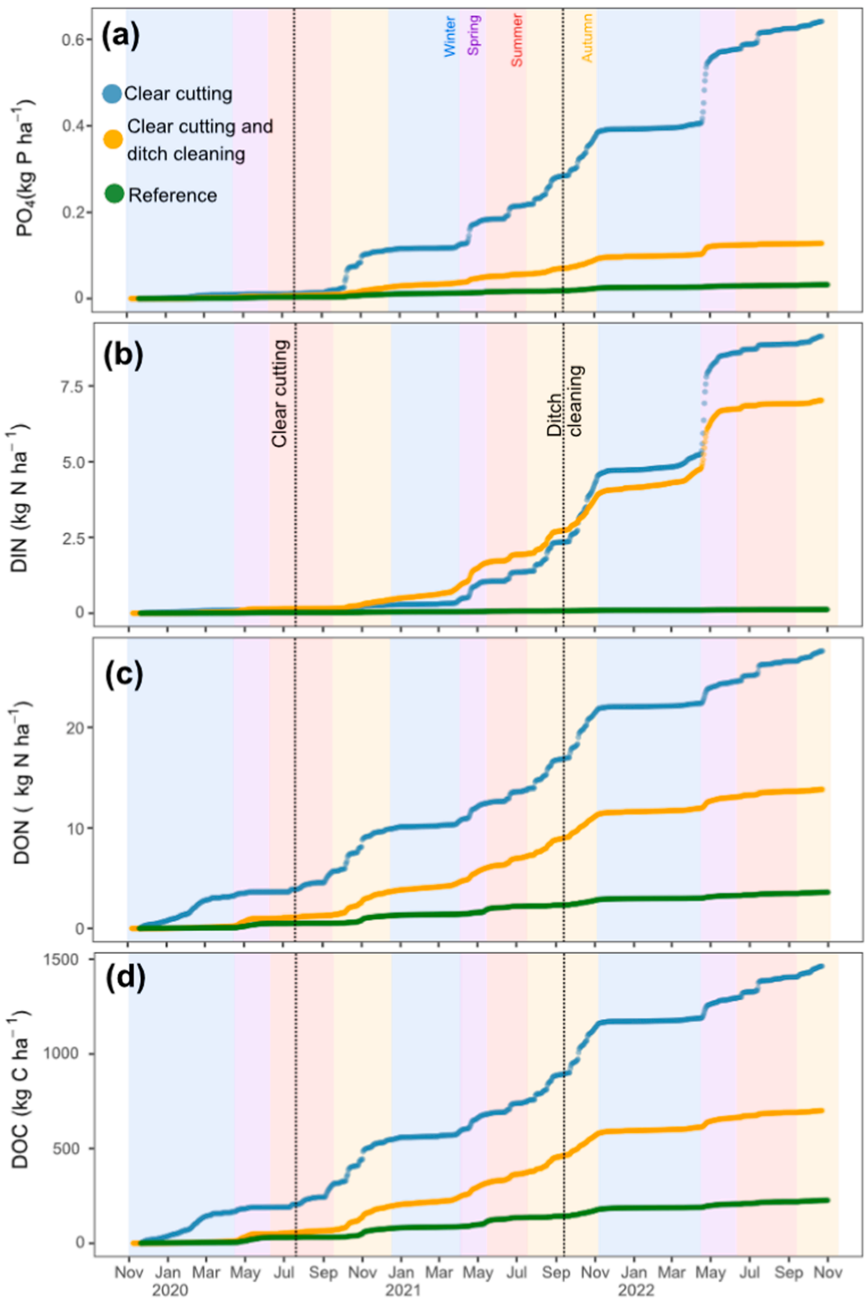

Fig. 7. Time series of organic and inorganic nutrients cumulative exports for the pre-disturbance, post-harvest and post-drainage period. (a) PO_4, (b) DIN, (c) DON and (d) DOC for catchments with clear cutting and ditch cleaning shown with yellow line (i.e., DC3), catchments with only clear cutting shown with blue line (i.e., DC2) and reference catchments shown with green line (i.e., C2). Background colors delineate average seasons.

drive typically oxic soils and peat toward anoxia, which can induce shifts in biogeochemical processes that increase element mobility and further promote solute losses (Åström et al., 2005). Similarly, the rise in GWL appears to also be the key-factor for increased PO_4 concentration in surface water. This response is likely due to a combination of highly soluble P and relatively low aluminum (Al) and iron (Fe) content in surface soil layers, as well as anoxic P-mobilization, which together may increase the potential for rising GWL to transfer P laterally while also limiting re-sorption in soils (Kaila et al., 2014, 2016).

While the rise in GWL is one of the clearest consequences of clear cutting on drained soils, other factors that act in concert to drive nutrient losses from catchments during the post-harvest period are likely more responsible for the overall magnitude of response (Shah et al., 2022). Specifically, clear cutting can increase soil nutrient concentrations by elevating soil temperature, altering soil microbial communities, and enhancing microbial processes such as mineralization and nitrification, which are enhanced by warmer and moister conditions (Futter et al., 2010; Jerabkova et al., 2011). Additionally, increases in soil nutrient concentrations following harvest also result from the dramatic losses in nutrient demand by vegetation (Jerabkova et al., 2011), but also from the direct disturbance of soils associated with using heavy machinery (Ågren et al., 2015) and the loss of natural buffers to nutrient export by removing the riparian trees lining ditches (Nieminen, Piirainen, et al., 2018). Interestingly, clear cutting seemed to have a delayed effect on DIN mobilization, as our results only showed a large increase in DIN concentrations and flux during the next growing season following clear cutting. Specifically, our results showed that the increase of DIN during the post drainage period in the catchments with only clear cutting was

Table 1
Treatment effects on total exports (**Δ** is calculated as treatment minus reference) of PO_4, DIN, DON and DOC during the period after each forest management operation.

		Δ PO_4	**Δ DIN**	**Δ DON**	**Δ DOC**
		(kg P ha^{-1})	**(kg N ha^{-1})**	**(kg N ha^{-1})**	**(kg C ha^{-1})**
Catchment with clear cutting and ditch cleaning (DC3)	**Pre-disturbance**	0.003	0.1	0.6	24
	Post-harvest	0.05	2.5	6.1	296
	Post-drainage	0.04	4.2	3.6	154
Catchment with clear cutting (DC2)	**Pre-disturbance**	0.01	0.1	3.4	174
	Post-harvest	0.26	2.2	11.2	578
	Post-drainage	0.34	6.8	9.4	485
		Δ PO_4 (% change)	**Δ DIN (% change)**	**Δ DON (% change)**	**Δ DOC (% change)**
Catchment with clear cutting and ditch cleaning (DC3)	**Poat-harvest to post-drainage**	−10 %	68 %	−41 %	−48 %
Catchment with clear cutting (DC2)	**Post-harvest to post-drainage**	33 %	210 %	−16 %	−16 %

driven by the increase on NH_4. Such a response seems to be attributed to a combination of the loss of plant nutrient demand during growing season (Hughes and Quinn, 2019), but also a decrease in soil N mineralization after clear cutting due to the increase in GWL (Schelker et al., 2016). Finally, the effect of increased nutrient exports after clear cutting might be a highly local phenomenon and as such, increases due to an individual clear cut are no longer observed at larger catchment scales (Deval et al., 2021; Schelker et al., 2016; Shah et al., 2022).

4.2. Mitigation effect by ditch cleaning on organic and inorganic nutrient concentration

Due to the increase in GWL after clear cutting, ditch cleaning is used to restore drainage capacity of old ditches, which lowers the GWL, increases aeration of the rooting zone and potentially improves tree regeneration and growth (Sikström et al., 2020). As expected, we found a significant decrease in GWL after ditch cleaning, on average decreasing 14 cm and reaching an average of 50 cm below the surface of the ground. This decrease typically is thought to alter peat physical properties such as the degree of humification and bulk density (Menberu et al., 2016) and lower the hydraulic conductivity (Jutebring Sterte et al., 2021). The resulting changes in physical properties of catchments after ditching affect the hydrological functioning of these ecosystems (Holden et al., 2004), including the patterns and strength of hydrological connections between land and water during different runoff conditions (Jencso and McGlynn, 2011). Indeed, we found a decrease in base flow in the ditch cleaned catchments, thus confirming a change in key hydrological patterns and water residence time of the system (Holden, Chapman, and Labadz, 2004; Nieminen, Palviainen, et al., 2018). Furthermore, the decrease in GWL is typically thought to increase the peat oxidation depth and promote faster rates of mineralization due to aeration of soil layers with subsequent increase in soil nutrient concentrations (Härkönen et al., 2023); nonetheless, the decrease in GWL also changes the vertical position of subsurface lateral flow paths, and therefore rates of nutrient mobilization to streams (Macrae, Devito, Strack, and Waddington, 2013).

After ditch cleaning, we observed a decrease in the concentration of all organic nutrients in the outflow ditch water, but a somewhat lessened effect on inorganic nutrient concentration. Specifically, DOC and DON declined to almost pre-disturbance after ditch cleaning, which likely reflects the combined effect of (1) the water table having been lowered enough to not interact with the upper organic soil layer with its easily releasable, high organic nutrient concentrations (Nieminen, Piirainen, et al., 2018) and (2) the greater fraction of lateral water flowing through deeper soil layers with positively charged mineral soil oxohydroxides that yield less organic material and could, in fact, act as sorption sites for the negatively charged organic moieties (Åström et al., 2001). Inorganic nutrients behaved differently than organic counterparts, most likely reflecting distinct biogeochemical processes involved in their production and mobilization. For example, after ditch cleaning, PO_4 concentrations remained similar to levels before ditch cleaning, while concentrations in the catchments without ditch cleaning increased significantly. Here, the lower GWL likely increased oxygen in peat and mineral soil layers, which may increase adsorption of PO_4 by Fe and Al and consequently reduce concentrations in transport (Kaila et al., 2014; Laudon et al., 2023). Conversely, while we found an increase in DIN concentrations in the catchments with and without ditch cleaning, this increase was greater in the catchments without ditch cleaning. Such patterns could also be explained by the difference in lateral flow due to changes in GWL, as clear cutting likely mobilized N near the soil surface and this pool could become inaccessible when the GWL dropped following ditch cleaning (Nieminen, Palviainen, et al., 2018). Moreover, by understanding the different effects of GWL change on NO_3 and NH_4, we could further interpret how ditch cleaning may have altered the net N balance (Åström et al., 2005). Specifically, the increase of nitrate in response to ditch cleaning likely reflects increased nitrification rates due to oxygenated soil layers and higher nitrate mobilization, while the mitigated increase of ammonium could be related to a greater accumulation of mineralized NH_4 in the post-harvest period in more surficial soils that become disconnected as the water table drops (Kaila et al., 2016). Finally, our results showed a mitigating effect of ditch cleaning in addition to a previous effect from clear cut, however other studies that have addressed ditch cleaning in isolation have instead shown an increased transport of organic matter (Finér et al., 2021), DOC (Kļaviņa et al., 2021), P (Nieminen, Palviainen, et al., 2018) and N, particularly NH_4 (Joensuu et al., 2002) to receiving water bodies.

4.3. Cumulative effect of forest management on organic and inorganic nutrient exports and implications for downstream aquatic ecosystems

During the typical Fennoscandia forestry rotation cycle, each forest management operation is individually associated with several physicochemical consequences; however, as one follows the other, the effects on water quality could be additive or reversible. For example, it has been shown that soil preparation typically accelerates the effects on water quality and aquatic ecology of clear cut and is therefore considered an additive effect (Kuglerová et al., 2021). As an example of a reversible effect, our results showed that ditch cleaning could help mitigate, or even reverse, the effect of clear cut on organic and inorganic exports, as the highest exports of all organic and inorganic nutrients were reached by the catchments without ditch cleaning. This reversible effect on the total organic and inorganic C, N and P export seems to be a joint effect of lower nutrient concentration and a decrease in base flow as both concentration and water fluxes act simultaneously on exports (Schelker et al., 2012). However, it is important to note that while ditch cleaning may temporarily mitigate the negative consequences of clear cut on nutrient exports, the long-term effects of drainage (i.e., first time ditching and/or ditch cleaning) could eventually lead to increased levels of DOC (Nieminen, Sarkkola, Sallantaus, Hasselquist, and Laudon, 2021), total P (Nieminen, Sallantaus, Ukonmaanaho, Nieminen, & Sarkkola, 2017), and Total N (Räike, Taskinen, & Knuuttila, 2020).

Indeed, although ditch cleaning did show a short-term mitigating effect on nutrient exports following clear cutting, catchments with ditch cleaning still showed an increase in organic and inorganic nutrient exports when compared to both the reference catchments and the pre-disturbance period.

These increases in organic and inorganic nutrients after forest management operations could have important effects on water quality and the aquatic ecosystem, contributing to brownification due to an increase of DOC or downstream eutrophication due to an increase of N and P in receiving water bodies (Nieminen et al., 2021; Smith and Schindler, 2009). Ultimately, an increase in the supply of C, N and P from upland catchments to freshwater ecosystems has important ecological consequences (Cloern, 2001; Creed et al., 2018) which can influence ecosystem services such as fish biomass production and other recreational values (Smith and Schindler, 2009; van Dorst et al., 2019), but also the provision of drinking water (Lavonen et al., 2013; Smith et al., 2006). Furthermore, we observed seasonal differences in nutrient concentrations after forest management; for example, organic nutrients increased during the growing season, PO_4 concentrations rose in autumn, and DIN concentrations increased in spring following both after clear cut and ditch cleaning. These distinct seasonal responses could have effects in aquatic ecosystems by altering the natural seasonal patterns in the stoichiometry of C, N and P (i.e., the organic energy and inorganic building blocks) supplied by natural ecosystems (Mosquera et al., 2023).

4.4. Forest management operations in a changing climate

At high latitudes, global climate models predict alteration in seasonal attributes, such as shorter and warmer winters (Teutschbein et al., 2015), wetter autumns with more variable precipitation events, both in intensity and frequency (Teutschbein et al., 2018), drier summers with hydrological droughts (Spinoni et al., 2018) and longer growing seasons (Barichivich et al., 2013) all of which have consequences for the timing and magnitude of nutrient uptake, production, and mobilization in soils. Here, we highlight that in northern Fennoscandia, widespread forest management co-occurs with climate change, potentially creating a synergistic effect on rates of nutrient cycling, increased exports and further impacts on aquatic ecosystems (Mattsson et al., 2015). For example, we found a strong decrease in summer base flow after ditch cleaning, which could be intensified by future summer droughts (Sørensen et al., 2009). Special attention should be focused on autumn changes, when we found that GWL is the highest and base flow increased in the catchments regardless of ditch cleaning. Likewise, we found that organic nutrient concentration increased the most after clear-cut during autumn, while inorganic nutrient concentration peaked during spring. These seasonal effects might be altered further in the future due to ongoing climate change, where wetter autumns and more variable precipitation events could potentially change infiltration rates and GWL (Teutschbein et al., 2018), or where shorter warmer winters could affect spring flood dynamics (Teutschbein et al., 2015) and nutrient mobilization. Moreover, it is possible that the ongoing global warming trend (IPCC, 2023) will intensify the increase in nutrient exports to aquatic ecosystems. Aaltonen et al. (2021) found that long-term temperature sum (i.e., the sum of daily mean temperatures above 5°C) correlated with an increase in all nutrient concentrations and exports from a managed compared to unmanaged forest. Specifically, a warmer climate likely accelerates decomposition of soil organic matter (Laurén et al., 2019) and increases biomass production and the length of growing season, leading to higher release and potential transport of DOC, TN and TP (Aaltonen et al., 2021). Nevertheless, several studies in the boreal region also suggest that inorganic N and P concentrations are decreasing in forest streams over time (Deininger et al., 2020; Lucas et al., 2016; Mosquera et al., 2022), indicating that other ecosystem responses to climate change may instead tighten terrestrial nutrient cycles, which could have an opposing response in aquatic ecosystems.

5. Conclusion

We studied the effect of different forest management interventions on hydrology, C, N and P in waters discharging from drained peatland forests. To our knowledge, this is the first study on the combined effect of clear cut and ditch cleaning in Sweden, and while it largely corroborates previous findings from elsewhere, it also raises concerns regarding the impact of intensive forestry practices on water quality, particularly in a changing climate. We found that, while ditch cleaning did mitigate some of the negative consequences of clear cutting on nutrient exports, forest management interventions never-the-less increased nutrient concentrations in waters discharging from these drained forests. We suggest that forest management, combined with climate change, may alter C, N and P exports, potentially leading to biogeochemical shifts that could compromise water quality in boreal streams. Furthermore, intensive forestry operations might disrupt the natural seasonal stoichiometry of C, N and P supplied to aquatic ecosystems. Finally, continued observation following experiments like ours is crucial to understand whether/how catchment dynamics may change over time toward greater net nutrient export following ditch cleaning, as observed in long-term studies. Overall, understanding the combined effects of climate change and intensive land management on aquatic ecosystems is an important research goal, requiring close collaboration between forester managers and scientists.

CRediT authorship contribution statement

Mosquera Virginia: Writing – review & editing, Writing – original draft, Visualization, Formal analysis, Data curation, Conceptualization. **Laudon Hjalmar:** Writing – review & editing, Writing – original draft, Project administration, Funding acquisition, Conceptualization. **Karimi Shirin:** Writing – original draft, Formal analysis, Data curation. **Sponseller Ryan:** Writing – review & editing, Writing – original draft, Visualization, Formal analysis. **Hasselquist Eliza:** Writing – review & editing, Writing – original draft, Visualization, Project administration, Funding acquisition, Formal analysis, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.foreco.2025.122605.

Data availability

Data will be made available on request.

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