Trollberget Experimental Area

Working report

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Background

Approximately one million km of ditches have been dug, mostly by hand, in peatlands and wet mineral soils over the last 100 years in Sweden, primarily to improve forest growth. Many ditches have resulted in new areas of productive forests, while others have only led to large-scale wetland degradation. The question now is what to do with this large number of aging forest ditches: restore them to more natural conditions, follow the forest industry's recommendation to increase ditch cleaning activities to maintain high biomass production, or leave them to develop freely? Before any informed decisions can be made, improved knowledge about the implications of the different management options for environmental and climate benefits is urgently needed.

The ditch-digging era in the first half of the 1900s resulted in one of the most widespread human-induced environmental disturbances in Sweden with largely unknown, but potentially large negative, legacy effects on soils and waters. Together with Finland, Sweden has the most drained forest landscapes in the world. When ditches age, ditch cleaning may be required to maintain forest productivity, especially during the regeneration phase in even-aged forestry to keep groundwater low and allow for aeration of seedling roots. However, there is currently limited empirical data about the consequences of this practice for hydrology, water quality and carbon dynamics under Swedish conditions, making this widespread activity questionable. Furthermore, studies from Finland suggest that ditch cleaning can be a large source of sediments, nutrients, and organic carbon to downstream waterbodies and also result in soil organic carbon degradation which has negative consequences for the greenhouse gas (GHG) balance. At the same time, enhanced tree growth following ditch cleaning results in increased uptake of CO_2, which is positive from a carbon balance perspective. Limited holistic knowledge about the overall effects on the environmental and carbon benefits cast doubt on the current strategy. Despite the risks, it has been suggested that Sweden should clean ditches on upwards of 400 000 hectares (out of ca. 2 million hectares of drained forest) to maintain forest production.

An alternative to ditch cleaning is restoration of historically drained peatlands to conditions believed to be more natural. Several governmental authorities, including the Swedish Environmental Protection Agency, the Swedish Geological Survey, and the Swedish Agency for Marine and Water Management argue that peatland restoration is a most effective way to reestablish biodiversity and reduce the likelihood of catastrophic flooding and drought stress in the future. In response to extreme weather-conditions that have occurred in recent years, most recently the exceptionally warm and dry summer of 2018, the Swedish government recently allocated 300 million SEK for peatland restoration. However, the science underpinning the desired outcomes of peatland restoration is lacking, and in fact, the limited empirical evidence from Sweden does not support that this approach necessarily is the best strategy to alleviate impacts on hydrology, nor that it is beneficial for water quality. Also, it is even more unclear what the climate consequences of such restoration strategies would be as it potentially could have harmful effects on the carbon balance and especially on the production of methane, which is a greenhouse gas with 34 times larger warming potential than CO_2 over a 100 year timeframe. In the worst case, peatland restoration to establish biodiversity could, therefore have many negative consequences on, for example, water quality and greenhouse gas production.

To overcome this lack of scientific knowledge and close the gap between science and management, Skogsstyrelsen, Västerbottens Länsstyrelse and SLU established the experimental ditch management infrastructure, called Trollberget Experimental Area (TEA) in Krycklan. TEA includes the first fully replicated and controlled experimental catchment system including restored and ditch-cleaned peatlands, as well as historical ditch networks 'left-alone' for free development. This experimental research infrastructure, initiated and funded by European Union LIFE Integrated project "GRIP on LIFE-IP" and later upgraded with funding from the Kempe Foundation and the Swedish Research Council Formas (see Appendix I) is one of the most well instrumented experiments world-wide for answering questions about the legacy and management aspect of historically ditched wetlands.

Trollberget Experimental Area

In the Trollberget Experimental Area –TEA- (64.17´N; 19.85´E) six experimental catchments have been established, with control sites in the adjacent Krycklan Catchment (www.slu.se/Krycklan). Of the six catchments, four have been harvested through clear-cut (CC) in July 2020, of which two were ditch cleaned (catchments DC1 and DC3) and two were left alone (no ditch cleaning, DC2 and DC4) during September 2021. Although we typically refer to the ditch cleaning treatment as "DC", there may be some cases that we use the term "ditch network maintenance" or "DNM". These do not refer to different treatments, but are used interchangeably. In addition, ecologically restored peatlands have been experimentally restored by blocking the ditches in fall of 2020 (WR1 and WR2).

Pretreatment measurements of all sites started in late November 2018 and have continued up to date. These measurements follow a flow adjusted sampling regime, meaning that during spring flood samples are collected as frequently as twice per week, during the growing season sampling occurs every two weeks, and during winter base-flow sampling occurs once per month. After ditch cleaning, the ditch and no ditch cleaning catchments started an intensive sampling campaign, where samples were taken twice a day for the first two weeks, every day for one week, three times a week for two weeks and once a week until snow fell (week 38 to week 45 2021).

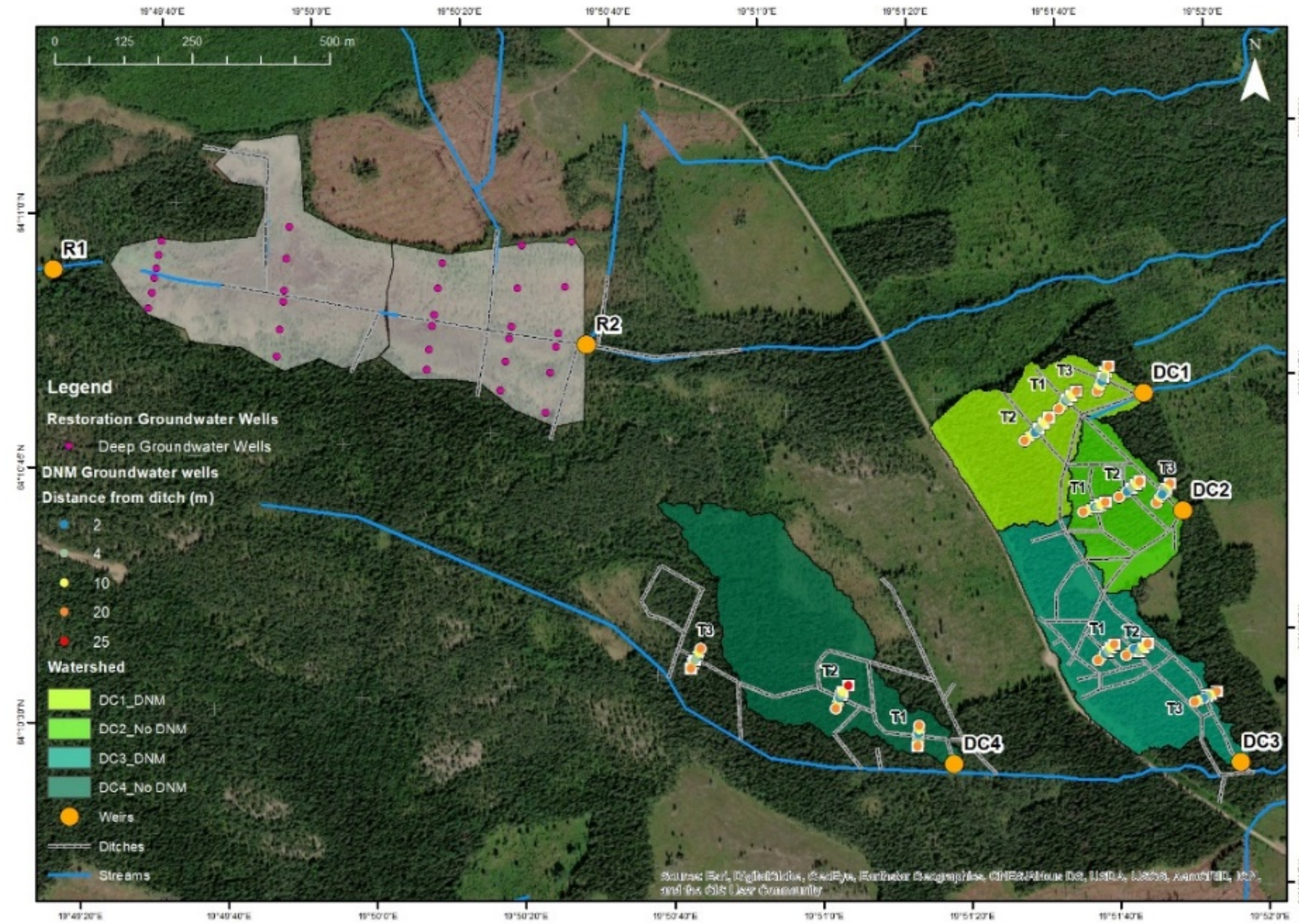

FIGURE 1 MAP OF THE TROLLBERGET EXPERIMENTAL AREA.

Water table level and discharge

Methods

Water table level (WTL)

Water table level (WTL) measurements were set up within the Trollberget wetland restoration areas called WR1 and WR2, which drain into two different directions. There are two transects in WR1 and three transects in WR2 with 6 deep wells in each reaching 4-5 meters below the surface to the mineral soil below. Approximately half of the wells are equipped with Solinst Levellogger pressure transducers to record water levels automatically across the entire year. Water table level has been recorded at hourly intervals from November 2019. For the remaining wells without loggers and to calibrate the pressure transducer measurements to actual depth to water, manual measurements have been done from the top of the well casing to the water level every two weeks during growing seasons. The raw GW data were controlled for quality and all the outliers, suspicious, and errors were removed from the dataset. All data from these wells were then averaged for further analysis. Moreover, Degerö Stormyr, a nearby natural oligotrophic mire, was used as a control site for Trollberget (restored site).

Stream discharge

Stream discharge (Q) has been monitored by recording water level at each gauging station immediately upstream of a V-notch weir with an automatic pressure transducer (hourly intervals). Moreover, manual water level observations have been done to calibrate the automatic water level data. Discharge rating curves have been derived using manual flow measurements. Daily specific discharge time-series (discharge per unit catchment area) were calculated for each catchment.

Results

Wetland restoration effects on water table

Any statistical differences in the water table before and after restoration were tested using the non-parametric Dunn's test using 0.05 as the significance level. Preliminary effects of the restoration (i.e., before and after restoration) were evident in the water table fluctuations between these two catchments (Fig. 2). Mean water table depth at the restored site rose 60% in 2022 (two years after restoration) compared to 2020 (pre-restoration year), while the control site experienced a decline in mean water table depth (-33%, $p<0.001$). The ditch blocking resulted in a long-term rise of the mean water table at the restored site from -0.2 m during the summer of 2020 to -0.08 m during the same period in 2022. In contrast, the mean water table at the control site decreased from -0.08 m in 2020, to -0.11 m in 2022. Moreover, the rise of the water table remained stable at the restored site and the difference in the water table depth between the restored and control sites decreased significantly with time. It should be noted that all the calculations are for summer and autumn (fall), and exclude the snow-free period.

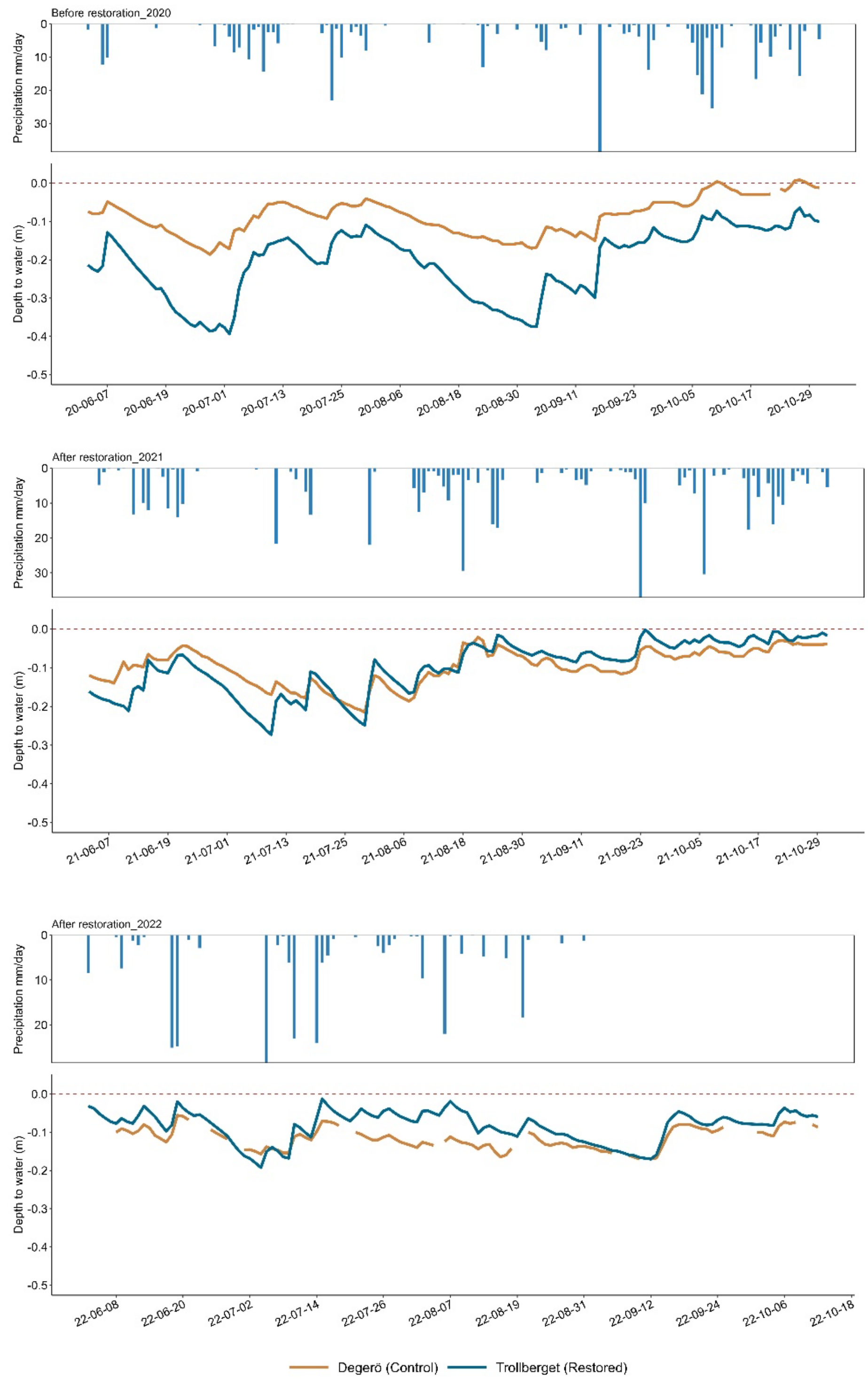

Figure 2 Water table dynamics for the control and restored sites during the same period (June-October) for the year before restoration (2020) and two years after restoration (2021 and 2022). This period was selected because data were available for all the years.

The increase in the water table after restoration was significant when comparing all data combined before restoration and after ($p<0.0001$, $F=152.7$; Fig. 3), but there was no difference for the control site during the same time period. Not only was the water table higher after restoration, the restoration resulted in less water table fluctuations at the restored site during summer and autumn (more narrow distribution of data in Fig. 4 and 5). During Fall, the mean water table at the control site was not different from 2020 to 2021, whereas the restored site had a significantly higher mean water table (Figure 4). But, after the restoration, the control and restored sites had similar patterns of water table levels – both with a slight decrease in mean levels in fall of 2022 compared with 2021. During Summer, the water table at the control site was slightly lower in 2021 compared to 2020, whereas the restored site had a significantly higher mean water table due to the restoration (Figure 5). Again, after the restoration, the control and restored sites had similar patterns of water table levels – both with a decrease in mean levels in fall of 2022 compared with 2021 (Figure 5).

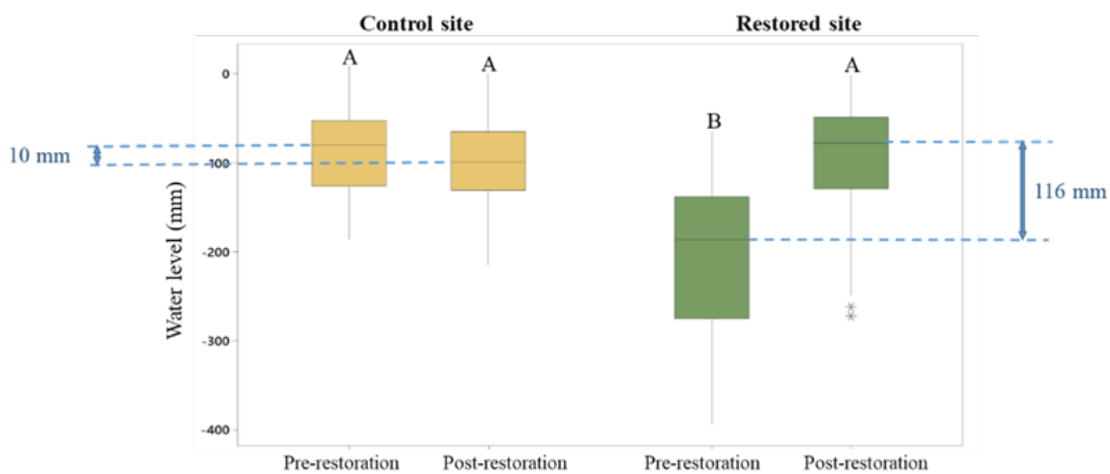

Figure 3 Box plots showing the water table changes for the period of pre-restoration (2019-2020) and post-restoration (2020-2022) for control and restored sites. Note: The line within the box represents the median and outsides of the box show the interquartile range. The whiskers represent the ranges for the bottom 25% and the top 25% of the data values. The mean value that is significantly different from the others have been shown with different letters. The significance test is based on a general linear model followed by a pairwise Bonferroni adjusted significance test. The mean difference is significant at α = 0.05.

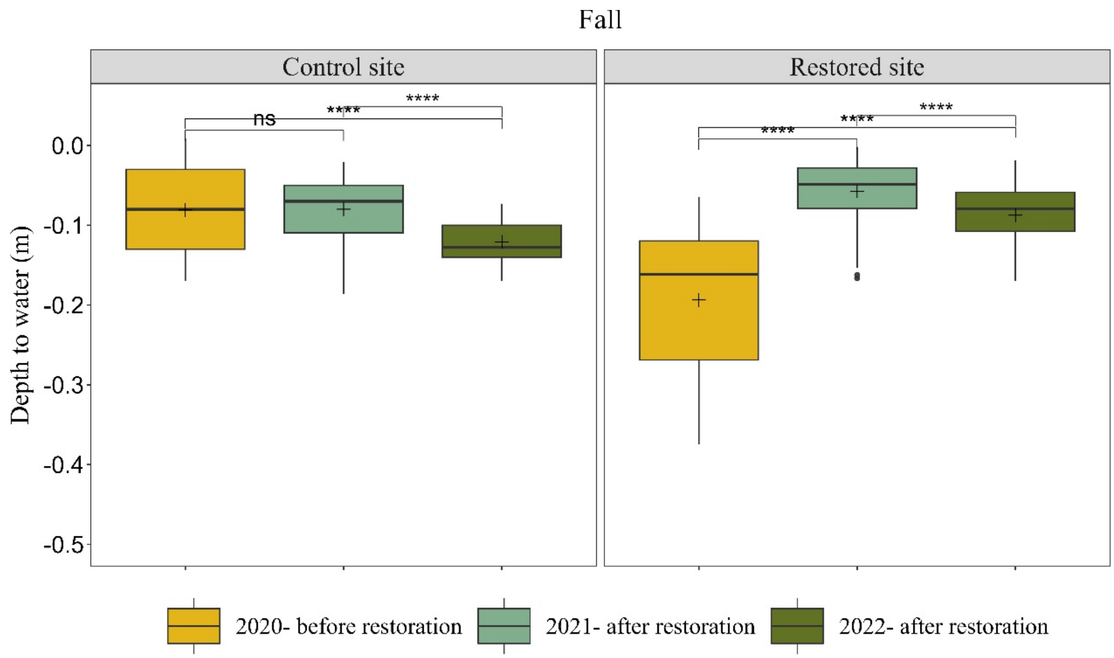

Figure 4 Box plot of water table depth (meters below ground surface) for restored and control sites for the fall season before restoration (2020) and two years after restoration (2021 and 2022). See Figure 2 for explanation of the boxes.

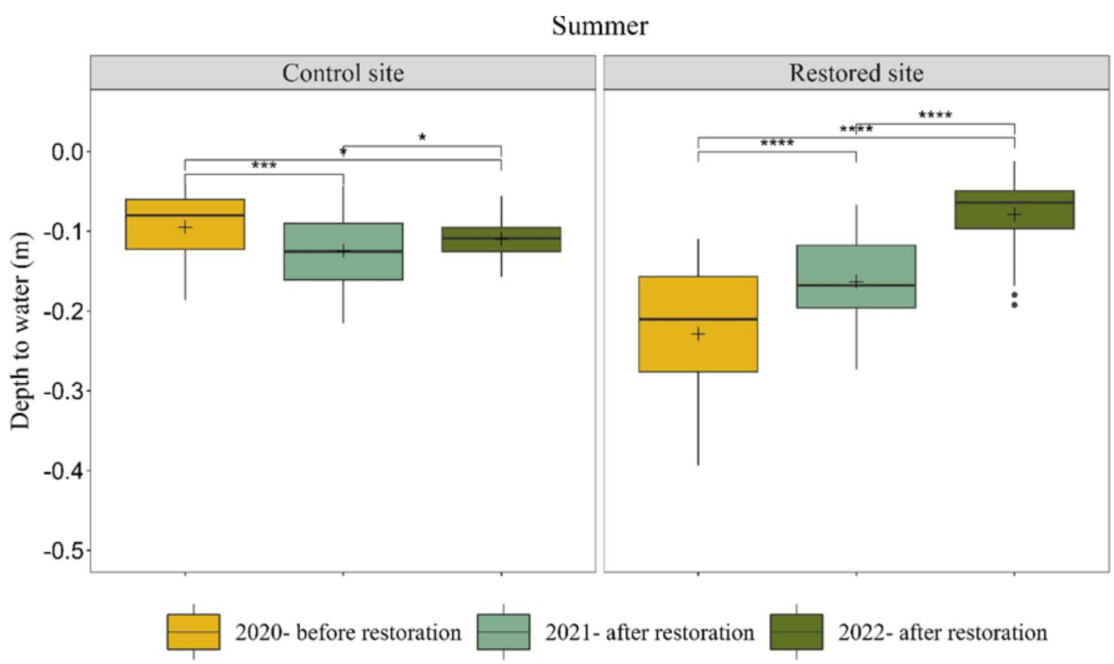

Figure 5 Box plot of water table depth (meters below ground surface) for restored and control sites for the summer season before restoration (2020) and two years after restoration (2021 and 2022). See Figure 2 for explanation of the boxes.

Wetland restoration effects on water storage

Runoff ratio

The ratio stream discharge (Q) to the precipitation (P) at a given site is called the "runoff ratio" and describes the storage capacity of a given site. One of the main goals of restoration is to increase the storage capacity of wetlands, thus, we used this as a measure of restoration success. Runoff ratios for both catchments varied from year to year (Fig. 6). A 30% decrease in runoff ratio was observed at the control site in 2022 compared to 2020, while at the restored site runoff ratio in 2022 was 18 % higher than the year before restoration (2020). For both catchments, the highest and lowest monthly runoff ratios occurred during November and July, respectively (Fig. 7). The monthly patterns between the control and restored sites were similar during 2020 and 2021. However, the pattern varied from year to year for each site. In general, after restoration, increased runoff was observed at the restored site, especially during the summer of 2022.

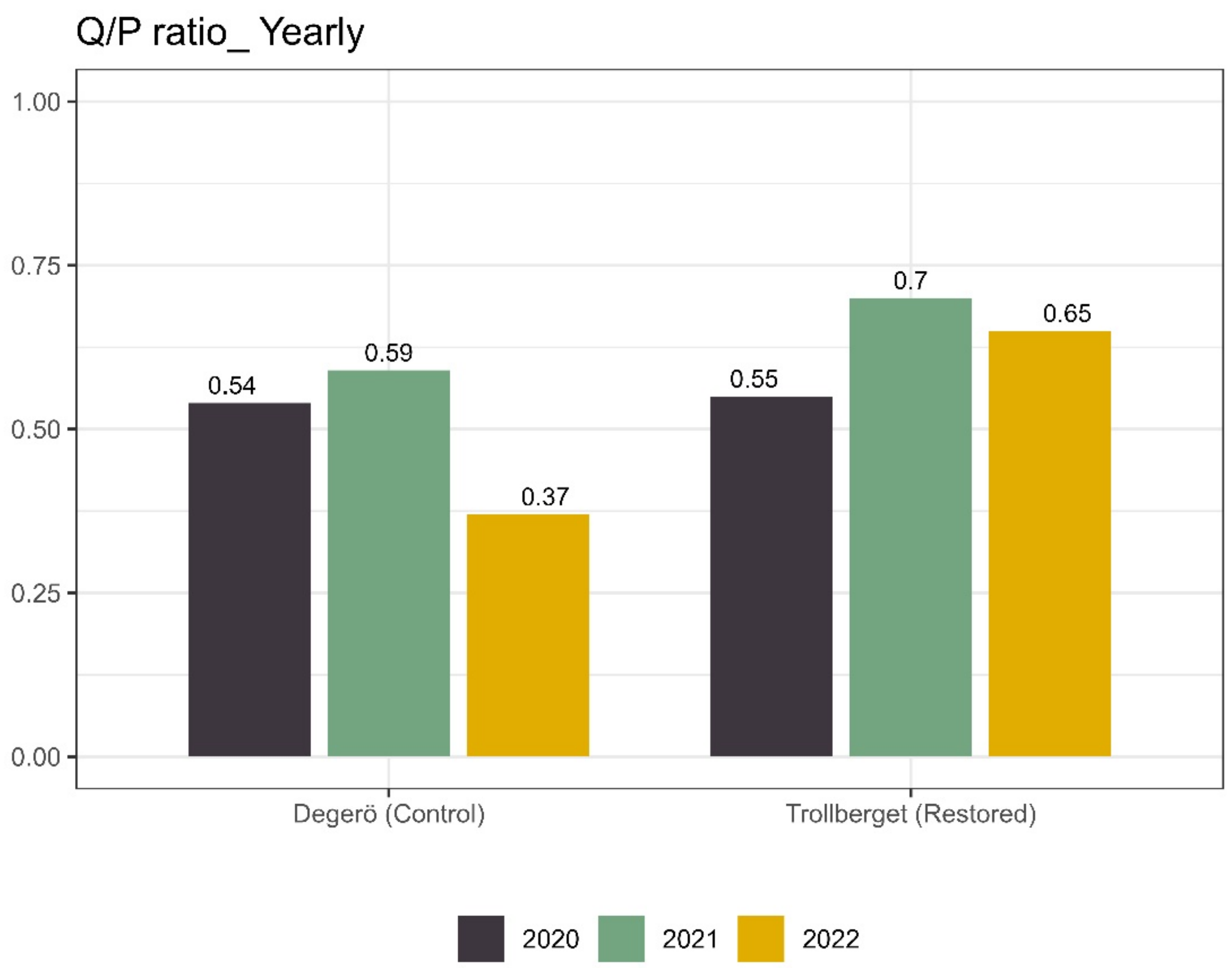

FIGURE 6 YEARLY RUNOFF RATIOS OF CONTROL AND RESTORED SITES. THERE WERE NO SIGNIFICANT DIFFERENCES AMONG SITES AND YEARS.

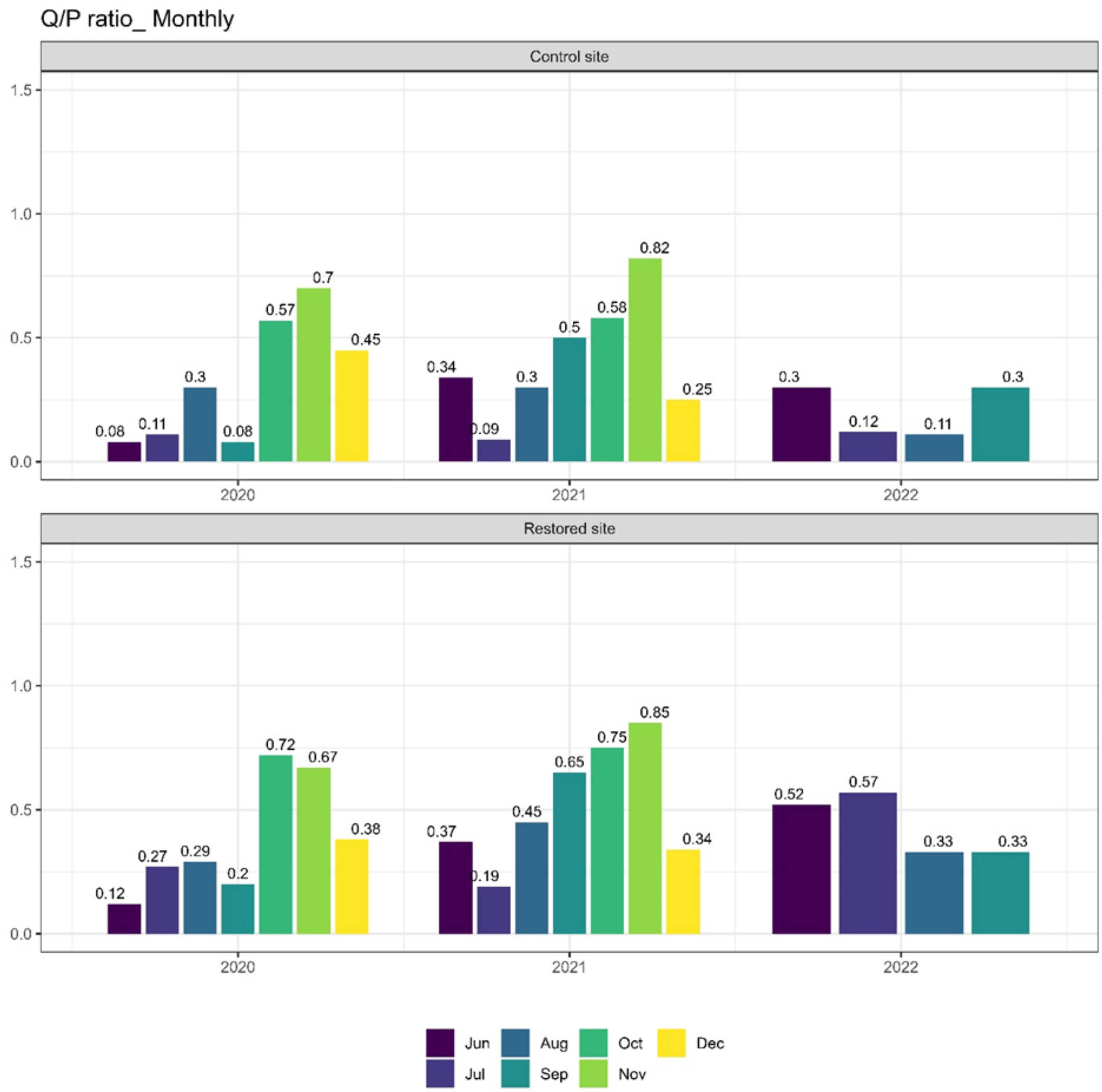

FIGURE 7 MONTHLY RUNOFF RATIOS OF CONTROL AND RESTORED SITES.

Water table threshold before activation of streamflow

A threshold relationship can be observed between the mean specific discharge (Q) and water table depth at both sites (Fig. 8). These values on the scatter plots represent the average discharge and water level for summer and autumn periods without rainfall. Before restoration, the water table threshold for activation of streamflow was -0.15 m and -0.5 m at restored and control sites, respectively. After restoration, the thresholds for control and restored sites reached -0.1 m from the ground surface. These results suggest that streamflow response at the restored site was flashier before the restoration. In addition, we have carried out the same analysis only during wet periods with rainfall occurrence (Fig. 9). At the restored site, the threshold of water table depth which activates the runoff production has increased from -0.2 m to -0.1 m after the restoration. In summary, these results suggest that the storage capacity at restored has increased after the restoration.

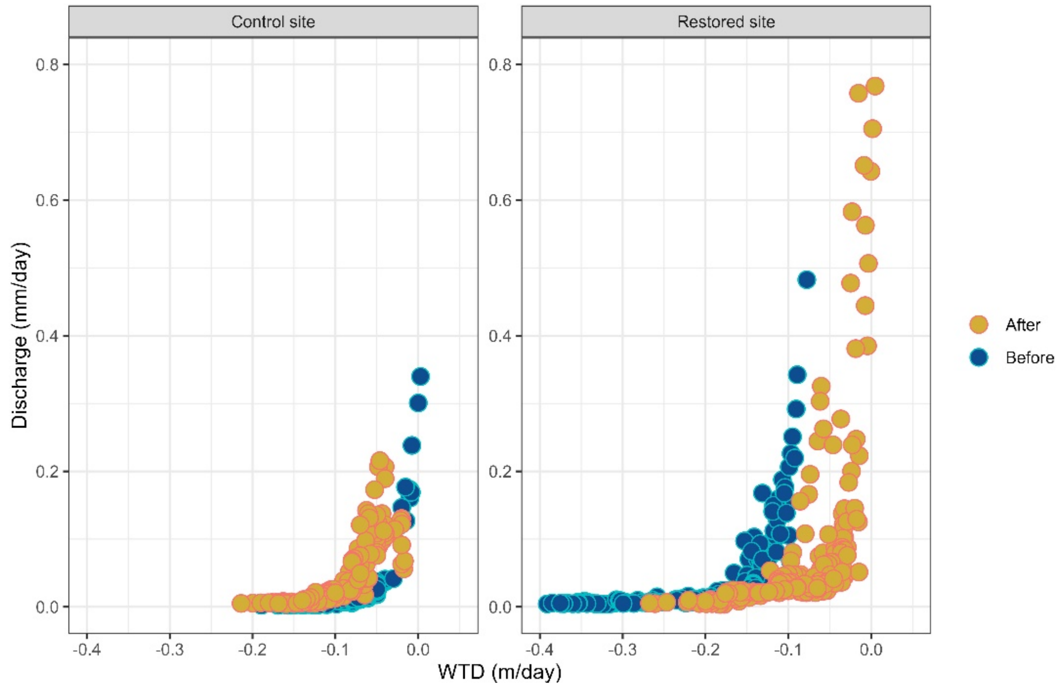

FIGURE 8 SCATTER PLOTS SHOWING THE MEAN DISCHARGE RESPONSE TO WATER TABLE CHANGE BEFORE AND AFTER RESTORATION FOR THE PERIODS WITHOUT RAINFALL.

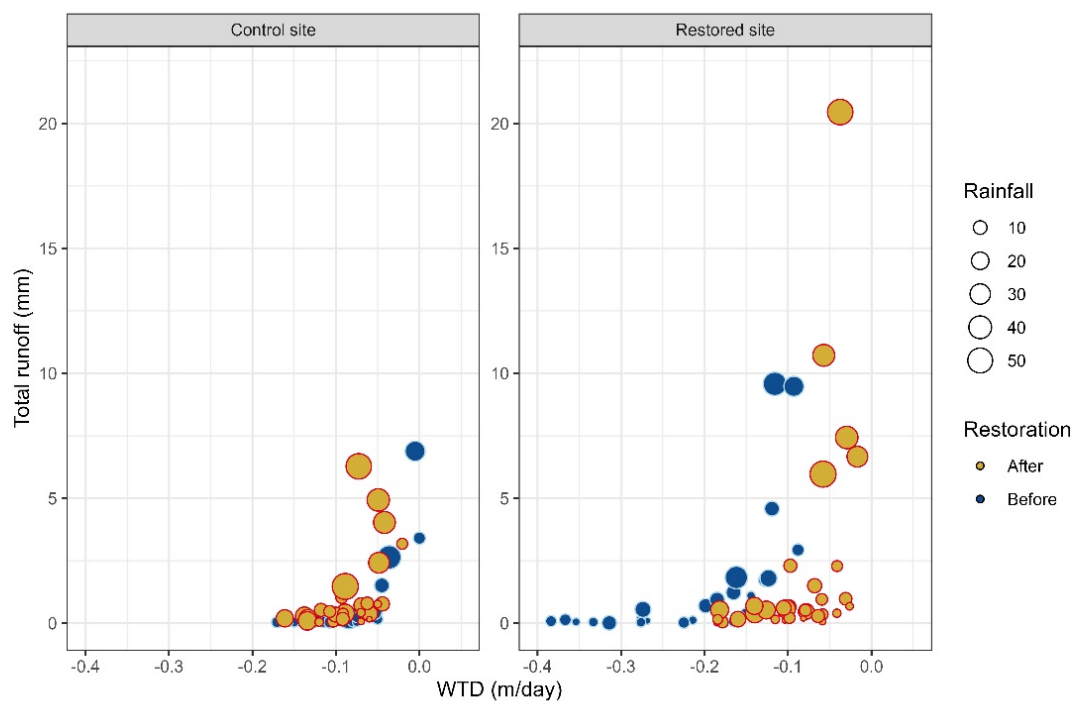

FIGURE 9 SCATTER PLOTS SHOWING THE RELATIONSHIP BETWEEN TOTAL RUNOFF AND MEAN WATER TABLE DURING RAINFALL EVENTS BEFORE AND AFTER RESTORATION.

Forest harvest and ditch cleaning effects on water table

Groundwater levels responded to both forest harvest and ditch network maintenance (DNM). As expected for all catchments the water table rise after post harvest and continued to increase only in the catchments where no DNM was conducted as opposed to the catchments where DNM was conducted where the water table on average stayed constant (Fig. 10).

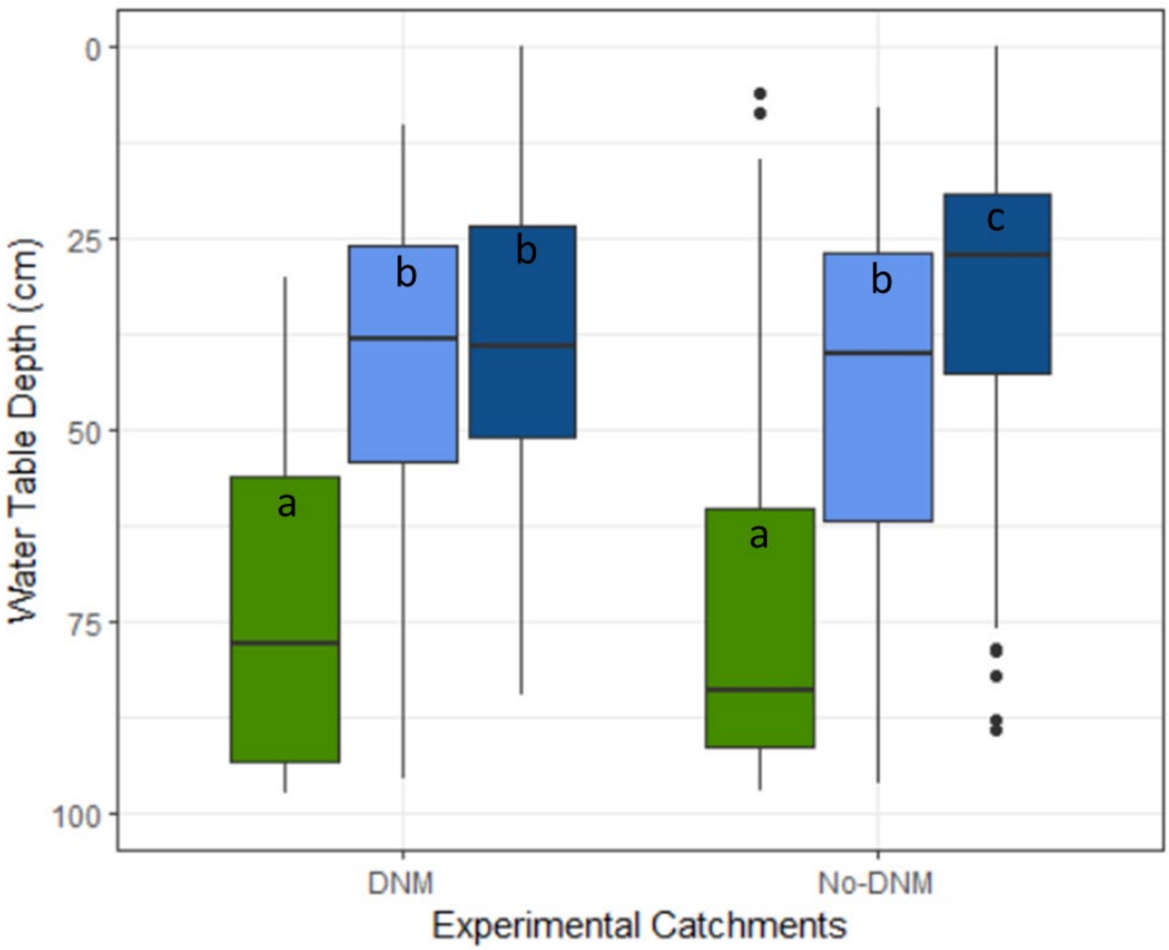

FIGURE 10 GROUNDWATER LEVEL DIFFERENCES BETWEEN DNM AND NO-DNM AFTER DIFFERENT TREATMENTS IN TEA. DNM SHOWS DATA FROM SIX WELLS (THREE DIFFERENT DISTANCES FROM DITCH), WITHIN THREE TRANSECTS IN TWO CATCHMENTS (DC1 AND DC3); NO-DNM SHOWS DATA FROM SIX WELLS (THREE DIFFERENT DISTANCES FROM DITCH), WITHIN THREE TRANSECTS IN TWO CATCHMENTS (DC2 AND DC4). SEPARATE SMALL LETTERS INDICATE SIGNIFICANT DIFFERENCES BETWEEN ALL TREATMENTS AND CAMPAIGN TIME ($P<0.05$). NOTICE GROUNDWATER TABLE DEPTH IS SHOWN IN CM AND WITH INVERSE Y-AXIS. THE BOUNDARIES OF THE BOXES REPRESENT THE 25TH AND 75TH PERCENTILES, THE SOLID LINE WITHIN THE BOX MARKS THE MEDIAN. THE WHISKERS REPRESENT THE 10TH AND 90TH PERCENTILES.

Nutrients: PO_4, DIN, and DON

Methods

Runoff water is being collected at the outlet of each catchment and analyzed total dissolved nitrogen (TDN), nitrate (NO_3^-) ammonium (NH_4), dissolved inorganic nitrogen (DIN= NO_3 + NH_4), dissolved organic nitrogen (DON = TDN-DIN), and phosphate or soluble reactive phosphorus (PO_4), among many others at the frequency described above. In addition, groundwater level was sampled every two weeks in snow free seasons. The groundwater well network setup is made up of transects with three wells at three different distances from the ditch (2m, 10m, 20m) on both sides and three transects at each catchment. All infrastructure in TEA can be found in Figure 1.

Results

Wetland restoration effects on nutrients

There were significant initial differences between the two catchments draining the restored wetland (WR1 and WR2) for PO_4 ($p < 0.01$), DIN ($p<0.001$) and DON ($p<0.05$) (Fig. 11). For PO_4 and DIN, the median concentration was higher for WR1 (3 µg l^{-1} and 86 µg l^{-1}, respectively) than for WR2 (1 µg l^{-1} and 24 µg l^{-1}, respectively). For DON the pattern was opposite, being WR2 (504 µg l^{-1}) higher than WR1 (439 µg l^{-1}) (Fig. 11). Furthermore, our control site also had significantly different nutrient concentrations from our restoration sites, but results do show that in the time period before and after restoration there is no significant difference in concentration of PO_4, DIN and DON (Fig 11).

We did not find significant effect ($p<0.05$) from the wetland restoration (i.e. comparing pre-and post-restoration) for DIN and DON but we did find a significant increase for PO_4 after restoration (Fig 12).

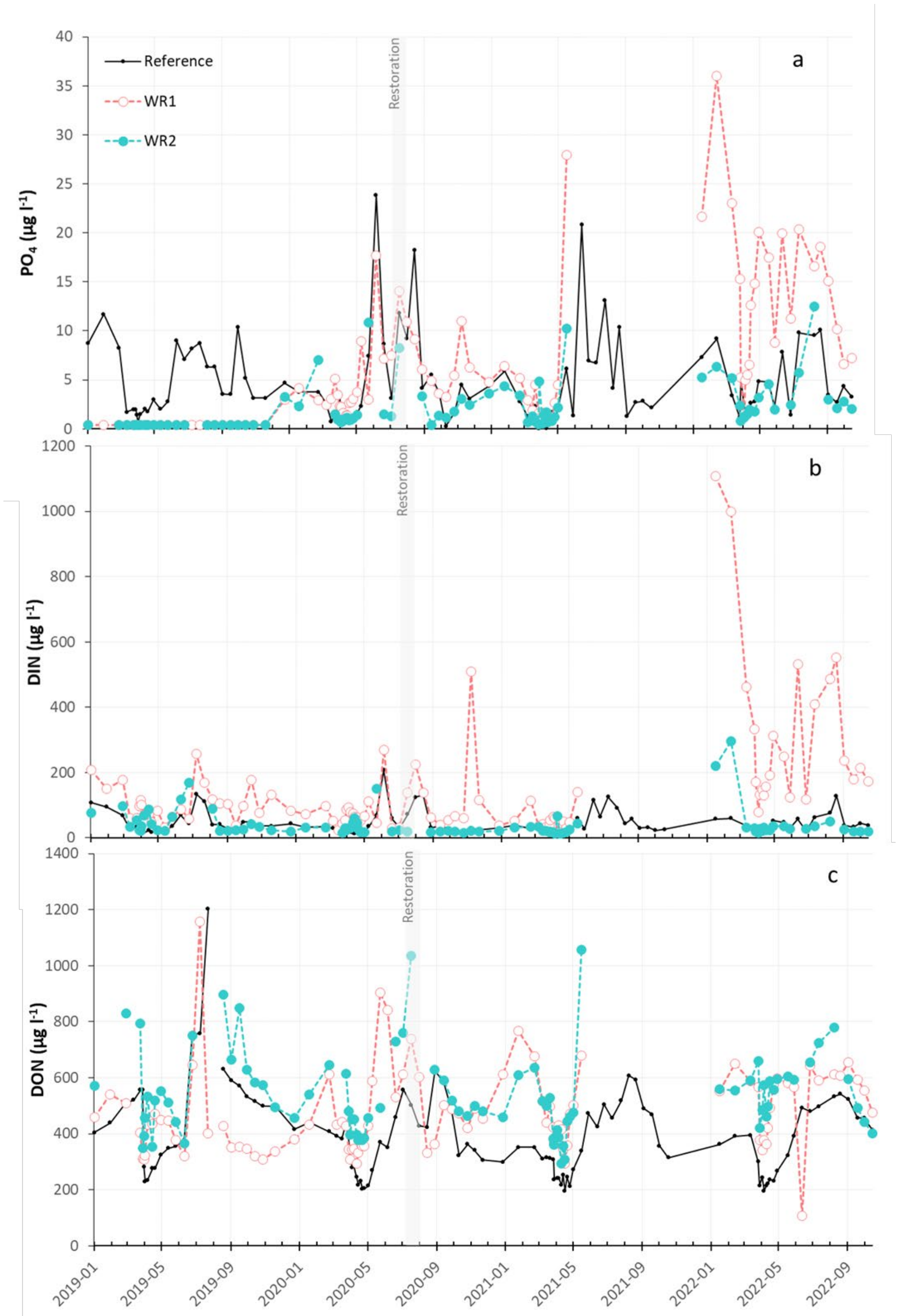

FIGURE 11 TIME SERIES OF ORGANIC AND INORGANIC NUTRIENTS FOR THE PERIOD 2019-2022. (A) PO4, (B) DIN AND (C) DON CONCENTRATION FOR THE TWO OUTLETS (WR1 AND WR2) OF THE RESTORED WETLAND AT TEA AND THE REFERENCE WETLAND LOCATED IN THE KCS. GREY VERTICAL BAR MARKS THE TIME THAT RESTORATION WAS COMPLETED.

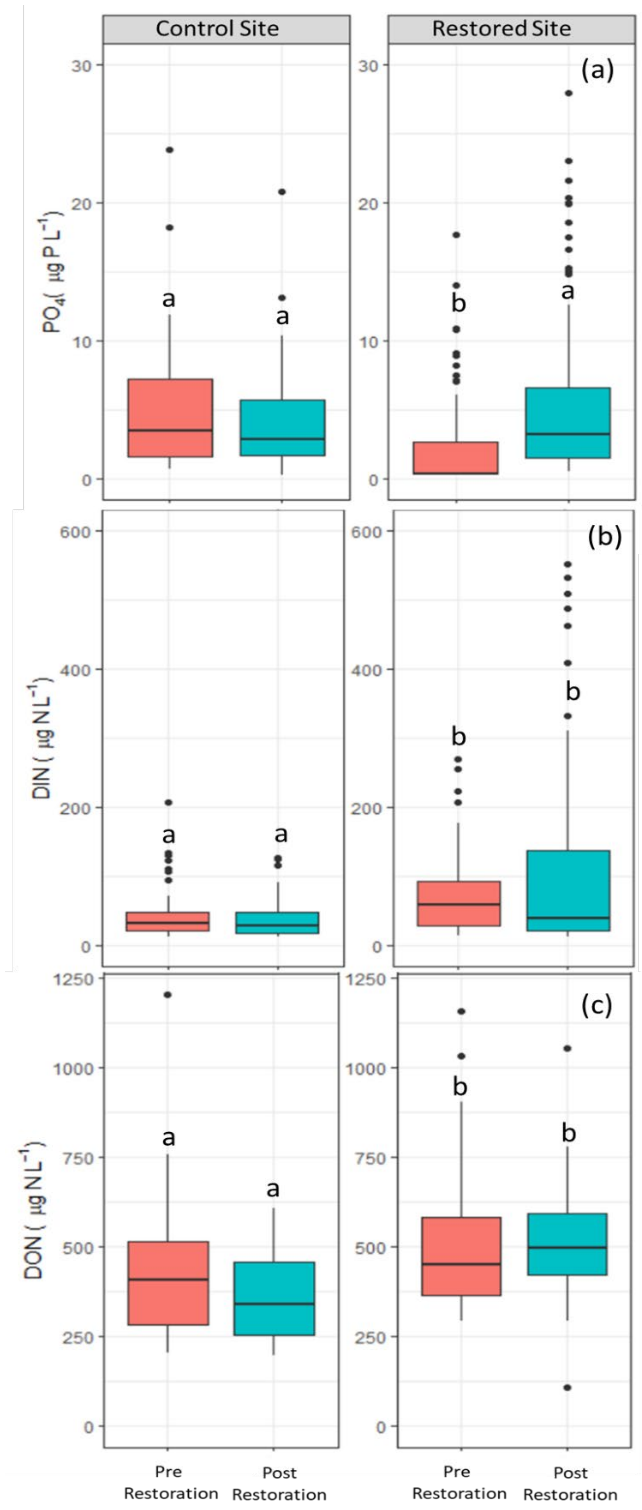

FIGURE 12 SURFACE WATER CONCENTRATION DIFFERENCES OF ORGANIC AND INORGANIC NUTRIENTS PRE AND POST RESTORATION AT TEA: (A) PO4, (B) DIN AND (C) DON. DNM SHOWS DATA COMBINED FROM THE OUTLET OF THE TWO SIDES OF THE RESTORED MIRE (I.E., WR1 AND WR2) AND CONTROL IS OUR REFERENCE SITE IN THE KCS. DIFFERENT LETTERS INDICATE SIGNIFICANT DIFFERENCES BETWEEN TREATMENT AND TREATMENT TIMING (PRE AND POST RESTORATION; P<0.05). THE BOUNDARIES OF THE BOXES REPRESENT THE 25TH AND 75TH PERCENTILES, THE SOLID LINE WITHIN THE BOX MARKS THE MEDIAN. THE WHISKERS REPRESENT THE 10TH AND 90TH PERCENTILES.

Forest harvest and ditch cleaning effects on nutrients

All four experimental catchments have responded to both forest harvest and ditch network maintenance (DNM), with an increase in inorganic and organic nutrients in surface water across all (Figures 13 and 14).

Post forest harvest, median PO_4 (DC1, 331%, DC2, 612%, DC3, 718% and DC4 89%), DIN (DC1, 346%, DC2, 399%, DC3, 166% and DC4, 5%) and DON (DC1, 27%, DC2, 27%, DC3, 50% and DC4 16%,) concentrations were higher in all four catchments when compared to pre-harvest (Table 1).

After DNM treatment, the catchments *without* DNM (only forest harvest) had on average higher concentrations ($p<0.05$) of PO_4 (18.1 ±2 μg l^{-1}), DIN (749.5 ±42 μg l^{-1}) and DON (1314.8 ± 47 μg l^{-1}) in surface water (Figure 13). Furthermore, the catchments *without* DNM had the highest percent increase for PO_4, DIN and DON, at least within this two-year period after the DNM treatment, having an increase of 457%, 1183 % and 88%, respectively (Table 1).

A potentially important confounding issue is that the catchments that were "left alone" (only forest harvest, no DNM) showed somewhat higher concentrations before clear-cut and before ditch cleaning for DON, thus future analyses should take into account different starting conditions.

In comparison, for inorganic N and P and for the catchments where DNM treatment was applied, the effects of forest harvest (CC) seem to have been larger than that of DNM (the percent change was higher; Table 1).

TABLE 1. MEDIAN CONCENTRATION AND PERCENT CHANGE IN NUTRIENT CONCENTRATIONS OF SURFACE WATER AFTER FOREST HARVEST WITH CLEAR-CUT METHOD (CC), AND CLEAR-CUT + DITCH CLEANING (DNM).

	Treatment Combinations	**PO_4 μg l^{-1}**	**PO_4 % change**	**DIN μg l^{-1}**	**DIN % change**	**DON μg l^{-1}**	**DON % change**
DC1+DC3	Before CC	0.8		18.8		324.7	
	After CC	4.5	446.4	101.9	443.4	439.9	35.5
	After CC+DNM	11.8	160.0	340.5	234.2	629.9	43.2
DC2+CD4	Before CC	0.9		29.8		567.8	
	After CC	3.2	243.4	58.4	96.3	700.8	23.4
	After CC+ no DNM	18.1	457.2	749.4	1183.0	1314.8	87.6

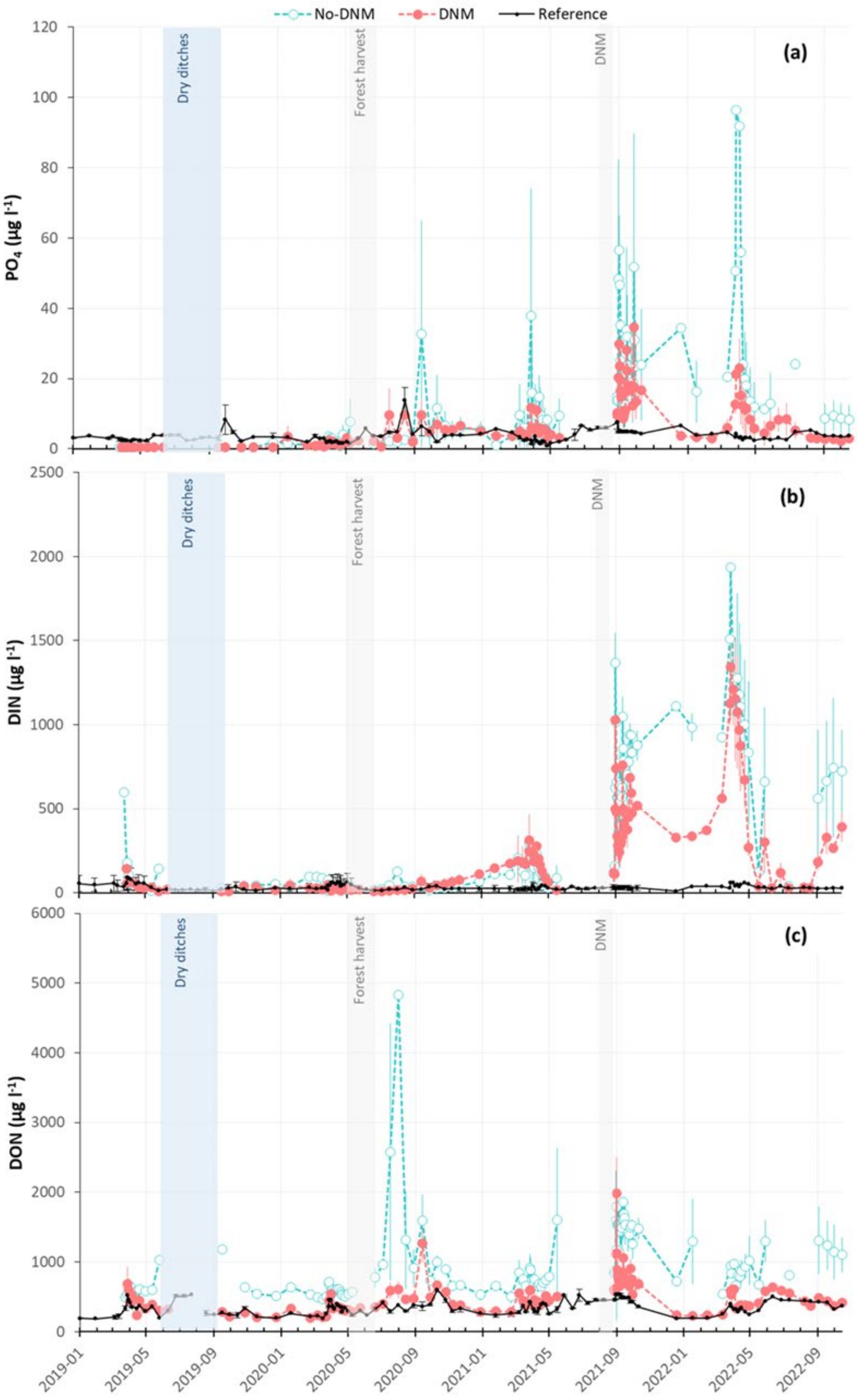

FIGURE 13 TIME SERIES OF ORGANIC AND INORGANIC NUTRIENTS FOR THE PERIOD 2019-2022. (A) PO4, (B) DIN AND (C) DON CONCENTRATION FOR THE FOUR EXPERIMENTAL DITCH CLEANING CATCHMENTS AT TEA. CATCHMENT DC1 AND DC3 ARE AVERAGED AS THE DITCH CLEANING (DNM), DC2 AND DC4 ARE AVERAGED AS NO DITCH CLEANING (NO-DNM) WITH ± 1SE AND REFERENCE IS OUR CONTROL SITE IN THE KCS. DIFFERENT SHADED VERTICAL BARS REPRESENT THE TIMING OF EVENTS (DROUGHT) OR TREATMENTS.

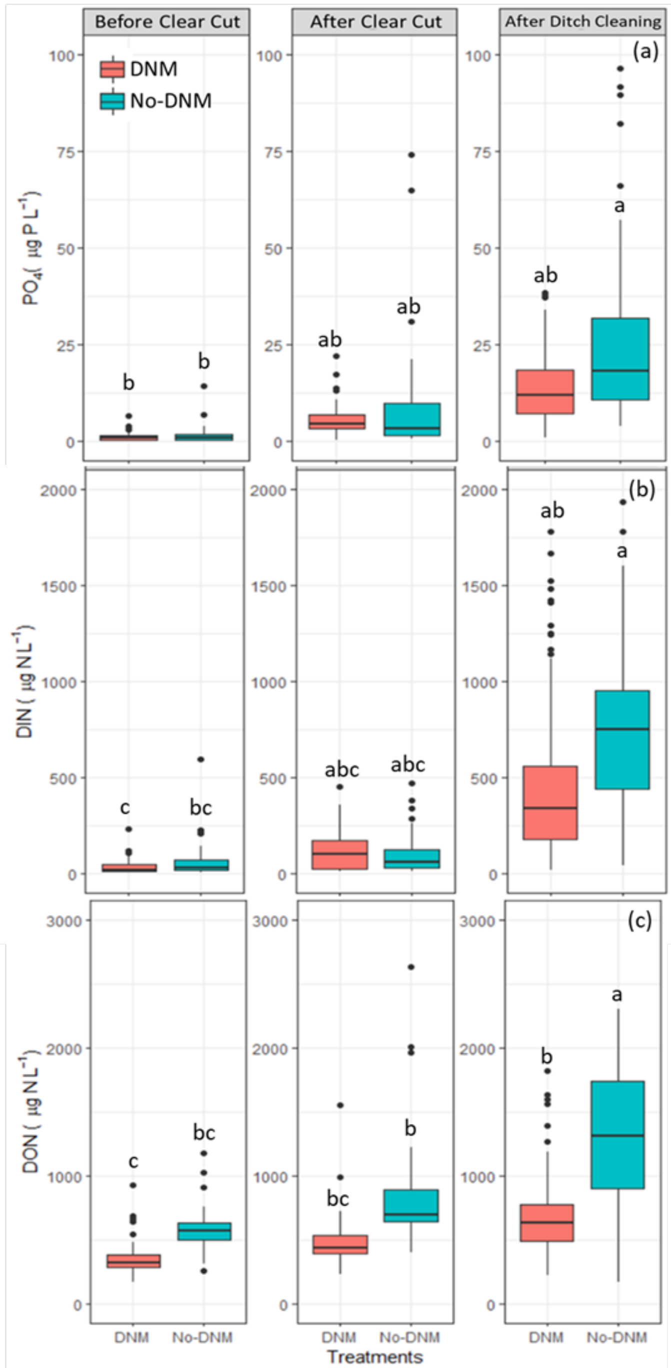

Figure 14 Surface water concentration differences of organic and inorganic nutrients after different treatments at TEA: (a) PO4, (b) DIN and (c) DON. DNM shows data combined from the outlet of the two catchments where ditch cleaning happened (i.e., DC1 and DC3); No-DNM shows data combined from the outlet of the two catchments where ditch cleaning did not happen (i.e., DC2 and DC4). PLEASE NOTE that DNM actually only occurred in the panel on the far right called "after Ditch Cleaning;" all other panels show the pre-treatment time period. Different letters indicate significant differences between all treatments (DNM) and treatment timing (Before any treatments, after CC, but before DNM, and after CC and DNM; $p<0.05$).

Carbon

Methods

Sampling for concentrations of dissolved organic carbon (DOC), dissolved inorganic carbon (DIC) and methane (CH_4) were conducted in six ditches within the Trollberget Experimental Area (TEA), two in the wetland restoration area (WR1-2) and four in the ditch cleaning area (DC1-4). Sampling was performed every second week during summer and fall and more intensively during spring flood, significant hydrological events and following the ditch cleaning operations that were conducted in late September 2021. Sampling during the winter occurred monthly and depending on the winter conditions. DOC samples were collected in 250 mL polyethylene bottles and transported dark and cold to the lab. DOC analysis was performed using a Shimadzu TOC-CPCH (Laudon et al., 2011). Samples for DIC and CH_4 were taken by using a 10 mL syringe and injecting 5 mL of ditch water into a sealed 22.5 mL glass vial. The vials were prior to sampling evacuated and filled with N_2 at atmospheric pressure and prefilled with 0.1 ml 85 % H_3PO_4 to shift the carbonate equilibrium toward CO_2. Headspace CO_2 and CH_4 concentrations were analyzed on a gas chromatograph equipped with a methanizer and flame ionization detector (GC-FID). In-situ ditch concentrations of DIC and CH_4 were calculated from headspace concentrations considering water and headspace volumes and temperature-dependent equations. For further details concerning DIC and CH_4 sampling and analysis see Wallin et al. (2010; 2014).

Evaluation of aquatic carbon (C) concentrations were made in order to detect effects of different management operations (i.e., clear cut harvest, ditch cleaning and wetland restoration). Data were evaluated to compare pre- and post- operations, both on the full data set as well as for individual seasons. The different seasons were defined as follow: spring, 20/03–20/06; summer, 21/06– 22/09; autumn, 23/09 – 21/12 and winter, 21/12 – 20/03). Any statistical differences in aquatic carbon concentrations between pre- and post-operations and between different sites were tested using the non-parametric Dunn´s test using 0.05 as the significance level.

Results

Wetland restoration effects on carbon

There were clear differences in aquatic carbon chemistry between the two wetland restoration sites, WR1 and WR2 (Figure 15). For DOC, the median concentration was higher ($p<0.001$) in WR2 (32 mg L^{-1}) than in WR1 (26 mg L^{-1}) during the full study period. For DIC and CH_4, the pattern was the opposite, with higher ($p<0.001$) median concentrations observed in WR1 (7.3 mg L^{-1} and 137.2 µg C L^{-1}, respectively) than in WR2 (3.3 mg L^{-1} and 9.5 µg C L^{-1}, respectively). Notable was the much higher (about ten times higher) median CH_4 concentrations observed in WR1 than in WR2.

Preliminary effects of the restoration (i.e., comparing pre- and post- restoration) were identified among the different C components. Median DOC and CH_4 concentrations at WR1 were higher (21% and 288%, respectively; $p<0.001$) during the period after the restoration, but not at WR2. In contrast, no change in DIC concentration was identified after the restoration at both sites. On a seasonal scale, higher median DOC concentrations post-restoration were observed during autumn (58%, $p=0.001$) and winter (21%, $p=0.037$) at WR1. Median CH_4 concentrations at WR1 were higher after the restoration during autumn (155%, $p=0.032$), spring (289%, $p<0.001$), winter (241%, $p=0.037$) and especially during summer (618%, $p<0.001$), when it peaked from 272.6 to 1958.2 µg L^{-1}. No significant change between pre- and post-restoration median DIC concentrations was observed at WR1. On the other hand, post-restoration DIC concentrations were lower (-41%, $p=0.031$) during summer at WR2.

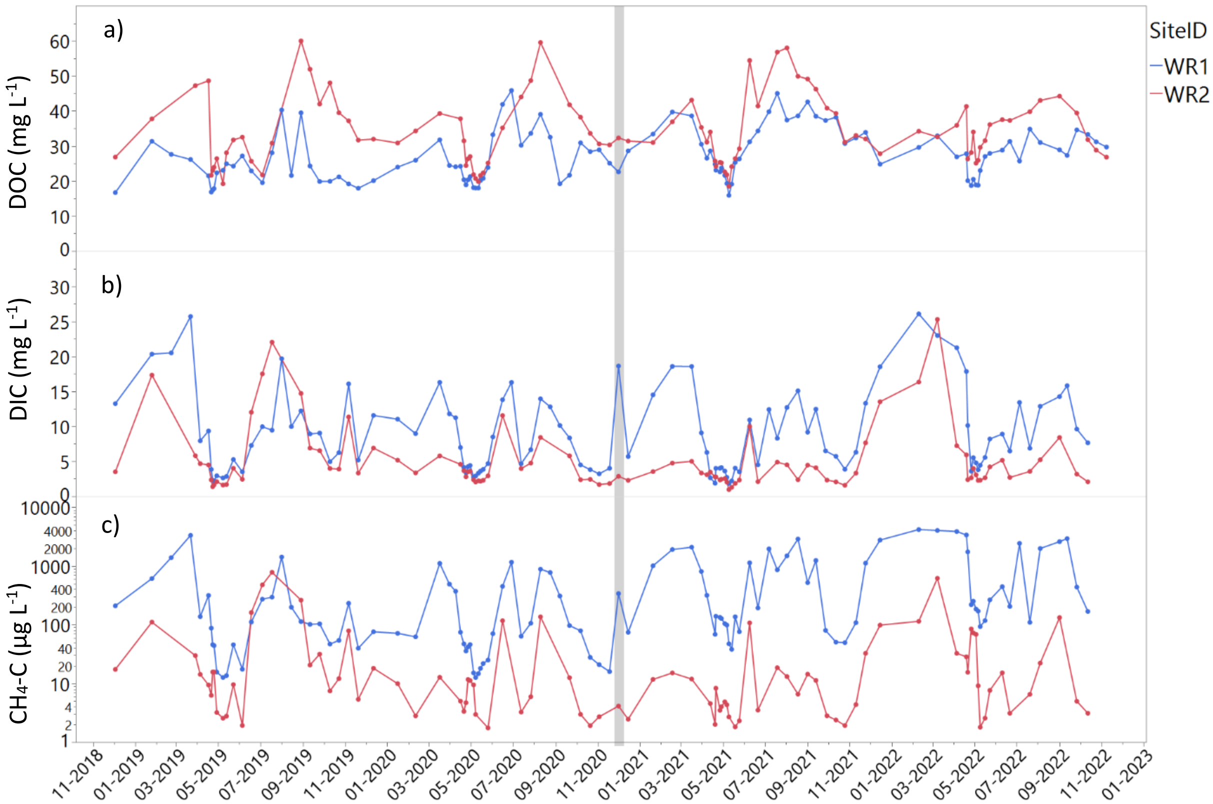

FIGURE 15. CONCENTRATION TIME-SERIES OF A) DOC, B) DIC AND C) CH_4 FOR THE TWO DRAINING STREAMS OF THE WETLAND AT TEA. THE GREY BAR INDICATES THE PERIOD WHEN THE WETLAND WAS RESTORED (*GREY BAR MARKS THE DATE WHEN RESTORATION WAS CONDUCTED*: NOVEMBER 27TH, 2020). NOTE THE LOG SCALE ON THE Y-AXIS FOR CH_4-C CONCENTRATIONS.

Forest harvest and ditch cleaning effects on carbon

For the ditch cleaning part of the study, two different operations were conducted, first a clear-cut forest harvest that was conducted in July/August 2020 and second, the ditch cleaning in September 2021.

There were clear effects on all aquatic C species following the clear-cut (Figure 16). Post-harvest median ditch DOC concentrations were higher in all four monitored catchments (DC1, 53%, DC2, 73%, DC3, 81% and DC4, 148%) ($p<0.0001$) when compared to the pre-harvest period. On a seasonal scale, median spring DOC concentrations were higher after the clear-cut in DC2 (34%), DC3 (38%) and DC4 (21%) ($p<0.0001$) compared to pre-harvest conditions, but not in DC1. DC3 was the only site that displayed higher summer median DOC concentration (67%, $p=0.03$) following clear-cut. During autumn, higher post-harvest median DOC concentrations were observed in DC1 (146%, $p=0.021$), DC3 (225%, $p=0.001$) and DC4 (202%, $p=0.003$). Worth to note is the extremely high DOC concentrations measured after the clear-cut in DC4, which peaked at 292 mg L^{-1} directly after the harvest. For DIC, post-harvest median concentrations were higher at DC1 (21%, $p=0.015$), DC2 and DC3 (22% and 24%, respectively, $p<0.001$) compared to pre-harvest conditions. On a seasonal scale, median post-harvest DIC concentrations were higher during the spring period at DC2 (14%, $p=0.014$). In addition, after the clear-cut, median autumn DIC concentrations were higher (39%, $p=0.02$) at DC3. Very high concentrations of DIC were observed in DC4 during the summer periods over the whole study period (14.8, 19.5 and 21.5 mg L^{-1} in the summer of 2019, 2020 and 2021, respectively).

Following the ditch cleaning operations that were conducted at DC1 and DC3, no significant change in ditch DOC concentration occurred with respect to the period before ditch cleaning but after the clear-cut. It is worth noting that during the days immediately after ditch cleaning was conducted, DOC concentrations peaked at 103.5 mg C L^{-1} in DC1, 98.6 mg C L^{-1} in DC2 and 76.2 mg C L^{-1} in DC3. However, these sharp increases in DOC concentrations, even at DC2 where ditches were not cleaned, could be likely controlled by the hydrology and ascribed to the heavy rainfalls that occurred simultaneously with the ditch cleaning operations. In contrast, DIC median concentrations decreased by 11% ($p=0.013$) and 23% ($p=0.0005$) after the ditch cleaning at DC1 and DC3, respectively. Together, the DIC concentrations in the cleaned ditches of DC1 and DC3 were lower (18%, $p<0.0001$) compared to the pre-ditch cleaning period. Post-cleaning CH_4 concentrations at DC3 decreased by 28% ($p=0.02$) when compared to the pre-cleaning but after-clear-cut concentrations, but no significant change in CH_4 was observed at DC1.

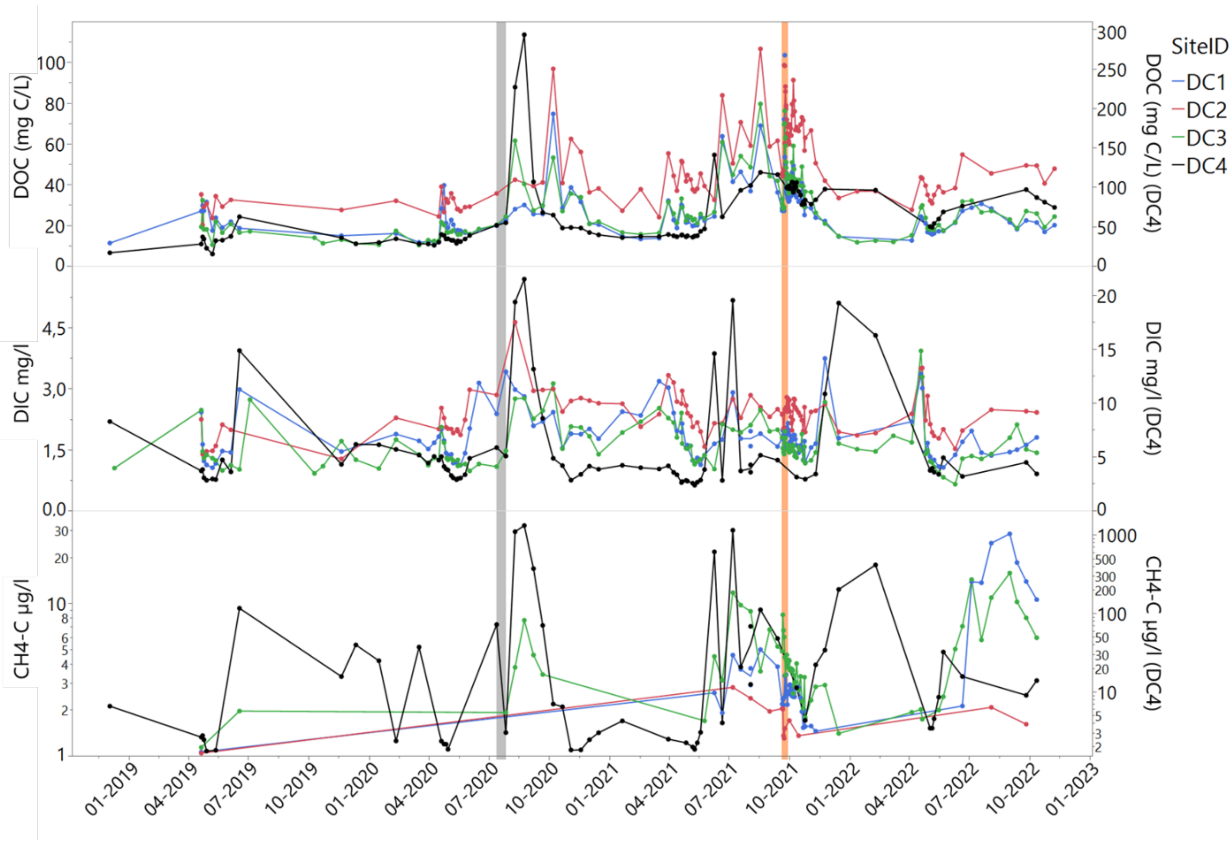

FIGURE 16 TIME SERIES OF A) DOC, B) DIC AND C) CH4 CONCENTRATIONS FOR THE FOUR DITCHES DRAINING THE DC CATCHMENTS OF THE TEA: DC1-4. THE GREY BAR INDICATES THE PERIOD WHEN THE CLEAR-CUTTING OCCURRED (JULY/AUGUST 2020) AND THE ORANGE BAR INDICATES THE PERIOD WHEN THE DITCH CLEANING (SEPTEMBER 2021) WAS CONDUCTED. NOTE THAT CH_4 CONCENTRATION IS EXPRESSED ON A LOG SCALE FOR ALL SITES AND DC4 IS ON 2ND-Y-AXIS AS IT HAS A MUCH HIGHER RANGE OF CONCENTRATIONS.

Mercury

Methods

The sampling of total mercury (THg) and methyl-mercury (MeHg) included the six TEA catchments mostly followed the other water quality sampling schedule. Concentrations of THg and MeHg in these six catchments were also compared to concentrations in untreated reference forest catchments in Krycklan and Degerö (Ref). Sampling of THg and MeHg in ditches, were conducted at around 15 occasions each year.

As THg and MeHg are highly sensitive for contamination, we used trace clean methods in the field and laboratory. Single use gloves were used when collecting water for THg and MeHg analysis. Ditch water was collected in Teflon (THg) and high-density polyethylene (MeHg) bottles, after rinsing in ditch water three times. Samples were stored dark and cool during transport to the laboratory. Samples for THg analyses were preserved with concentrated suprapur HNO3, and samples for MeHg analyses were directly delivered to Umeå University. THg concentrations were analyzed at IVL and MeHg concentrations were analyzed by the chemistry department at Umeå University.

Results

Wetland restoration effects on mercury

Wetland restoration were conducted in the R1 and R2 catchments in late autumn 2020, just before the first snow. The wetlands filled up with water during the spring flood in 2021. No clear wetland restoration effect could be detected from the preliminary data so far (Figure 17 and 18). However, there is a tendency towards increasing concentrations of THg in the restored catchments. Our hypothesis is that MeHg, rather than THg, will increase after wetland restoration, due to elevated MeHg formation in flooded soils. However, also THg mobilization may increase if more Hg is mobilized from soils during flooding.

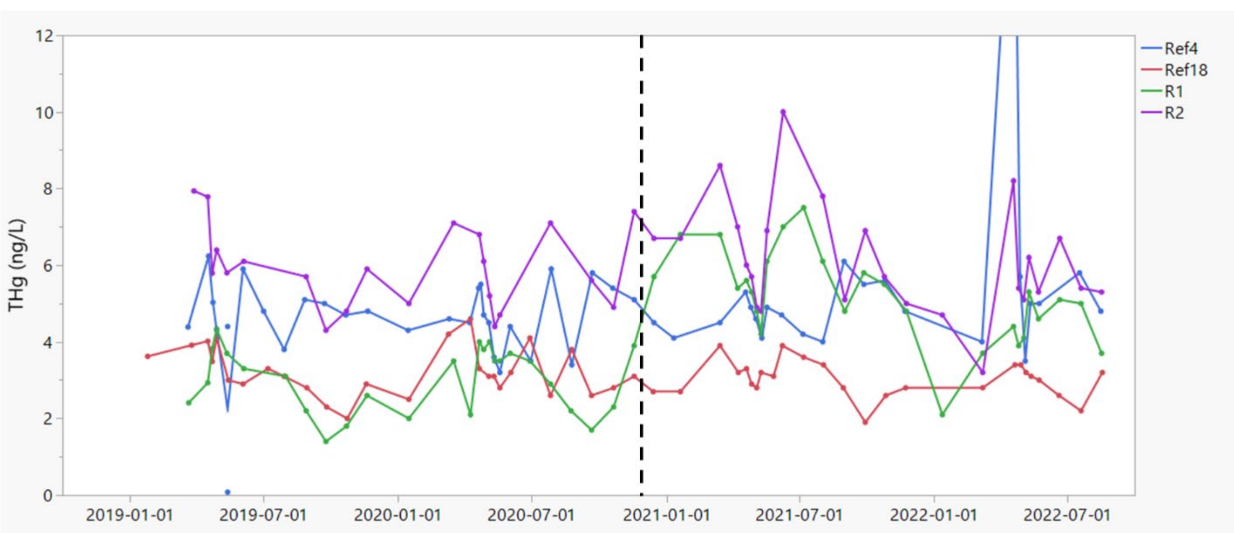

FIGURE 17 CONCENTRATIONS OF THG IN THE CATCHMENTS WERE WETLANDS WERE RESTORED (R1 AND R2), AND THE REFERENCE CATCHMENT WITH NON-RESTORED WETLANDS (REF4 AND REF18). THE DASHED VERTICAL LINE SHOWS THE TIMING OF THE WETLAND RESTORATION

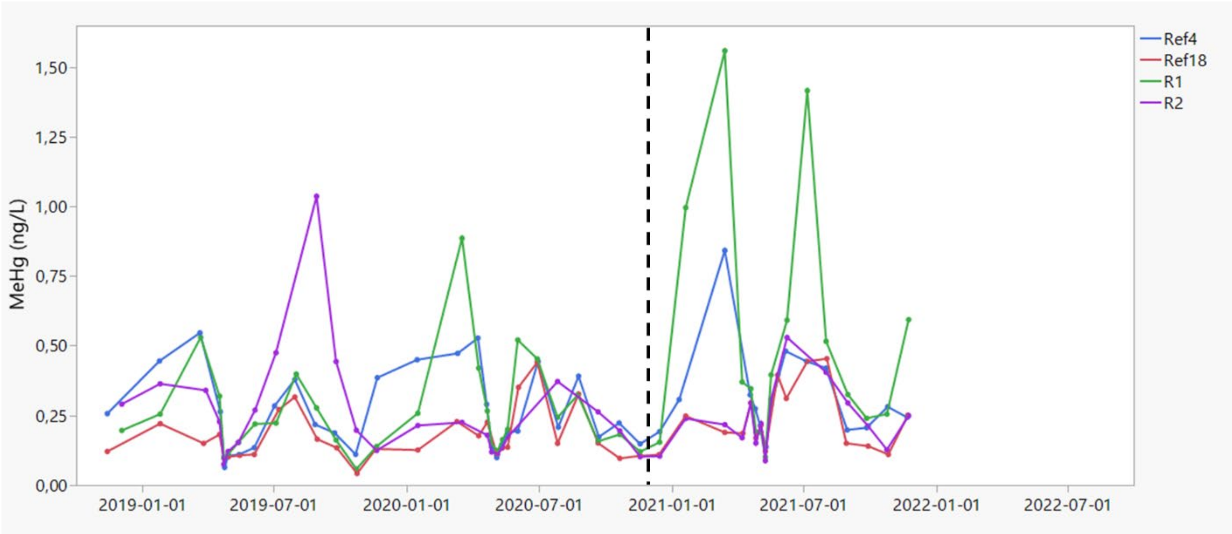

Figure 18 Concentrations of MeHg in the catchments where wetlands were restored (R1 and R2), and the reference catchment with non-restored wetlands (Ref4 and Ref18). The dashed vertical line shows the timing of the wetland restoration.

Forest harvest and ditch cleaning effects on mercury

Preliminary results indicate that concentrations of both THg and MeHg were elevated, at least during some periods, in some of the clear cut areas after harvest, while concentrations in reference catchments did not change (Figure 19 and 20). Concentrations of MeHg were rather high (up to 6 ng/L) in some of the harvested areas during late summer of 2020 and 2021. The ditch cleaning (autumn 2021) may potentially worsen the situation by increasing the mobilization of THg and MeHg into the ditch channel. For THg we have data for the around 10 months following ditch cleaning. However, there is no indication so far of on additional increase of THg concentrations after ditch cleaning compared to after harvest only. Further sampling will evaluate the effect of ditch cleaning on THg and MeHg concentrations and exports.

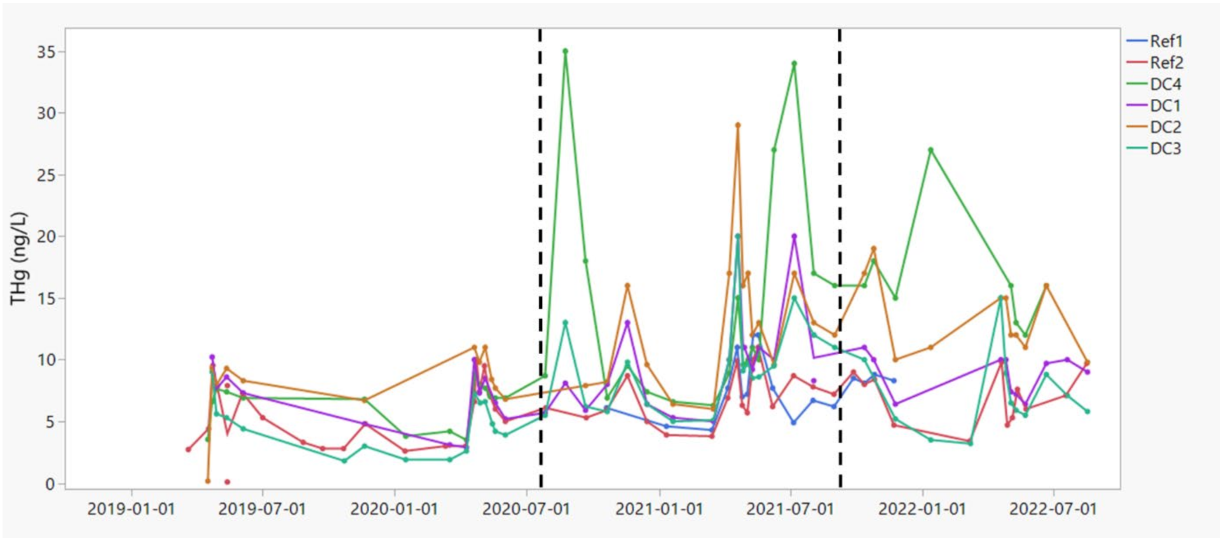

FIGURE 19 CONCENTRATIONS OF THG IN THE HARVESTED AND DITCH CLEANED CATCHMENTS (DC1 AND DC3), THE HARVESTED ONLY CATCHMENTS (DC2 AND DC4), AND THE REFERENCE CATCHMENT WITH GROWING FOREST (REF1 AND REF2). THE DASHED LINES MARK THE FOREST HARVEST (2020) AND DITCH CLEANING (2021).

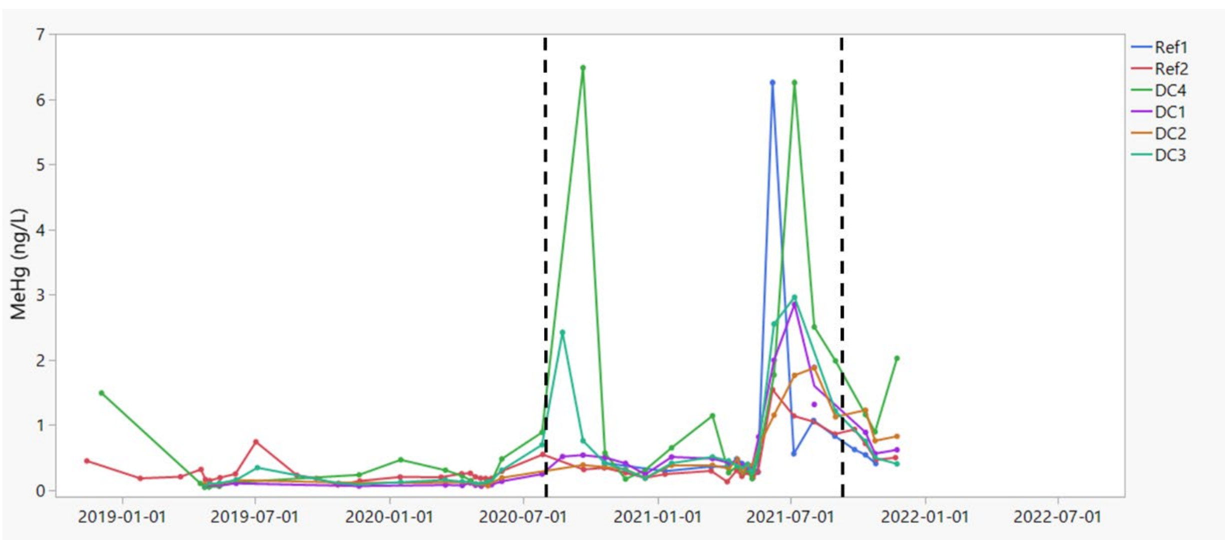

FIGURE 20 CONCENTRATIONS OF MEHG IN THE HARVESTED AND DITCH CLEANED CATCHMENTS (DC1 AND DC3), THE HARVESTED ONLY CATCHMENTS (DC2 AND DC4), AND THE REFERENCE CATCHMENT WITH GROWING FOREST (REF1 AND REF2). THE DASHED LINES MARK THE FOREST HARVEST (2020) AND DITCH CLEANING (2021).

Total Suspended Solids

Methods

Total suspended solids (TSS) have been collected since November of 2018 on the same schedule as all other water quality measurements. Samples were collected in two, 250mL bottles, for a total sample of 500mL. Samples were frozen until filtering in the lab using the international standard protocol for Total Suspended Solids (p 540 D, PHYSICAL & AGGREGATE PROPERTIES (2000)).

Wetland restoration effects on TSS

Preliminary results show that peaks in export of TSS in the restored wetland catchments (WR1 + WR2) were less common after the ditches were blocked (Figure 21), presumably because the flow was less flashy and had less power to transport sediments. This did translate into a significant difference in TSS exported before and after restoration (Figure 22), but further analysis needs to be done to be sure of this.

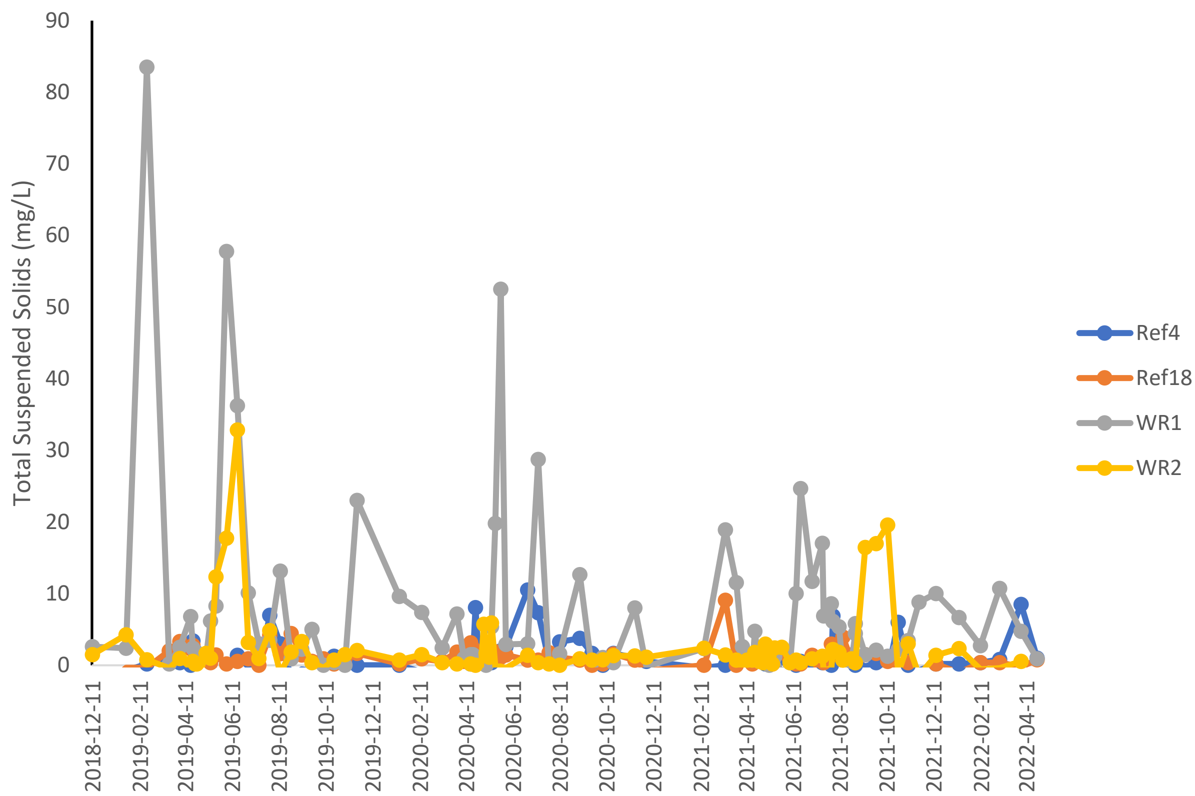

FIGURE 21 CONCENTRATIONS OF TOTAL SUSPENDED SOLIDS (MG/L) IN THE CATCHMENTS WERE WETLANDS WERE RESTORED (WR1 AND WR2), AND THE REFERENCE CATCHMENTS WITH NON-RESTORED WETLANDS (REF4 AND REF18). THE DASHED VERTICAL LINE SHOWS THE TIMING OF THE WETLAND RESTORATION. RESTORATION OCCURRED IN NOVEMBER 2020.

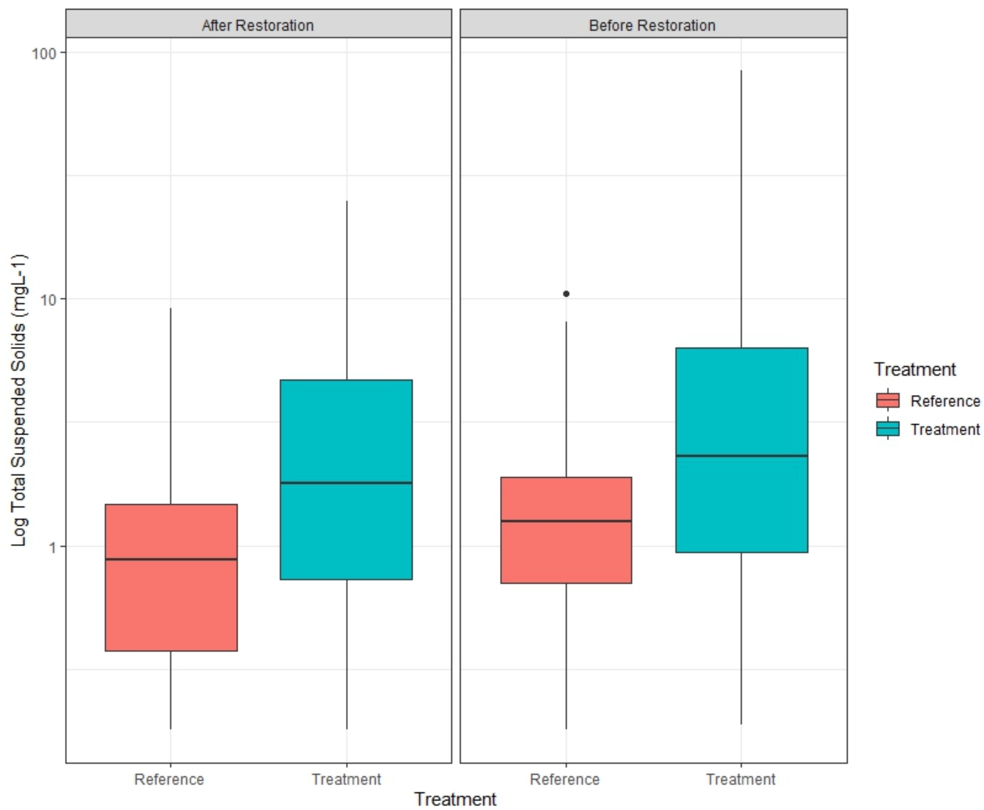

FIGURE 22 CONCENTRATION OF TOTAL SUSPENDED SOLIDS (MG PER LITER) AFTER THE RESTORATION TREATMENT WAS APPLIED AT TEA. "TREATMENT" INCLUDES DATA COMBINED FROM THE OUTLET OF THE TWO CATCHMENTS THAT WERE ECOLOGICALLY RESTORED (I.E., WR1 AND WR2); "REFERENCE" INCLUDES DATA COMBINED FROM THE OUTLET OF TWO CONTROL, UNIMPACTED CATCHMENTS (I.E., SITE 4 AND DEGERÖ(SITE 18). PLEASE NOTE THAT RESTORATION ACTUALLY ONLY OCCURRED IN THE PANEL ON THE LEFT CALLED "AFTER RESTORATION." THE PANEL ON THE RIGHT IS FROM THE TIME PERIOD BEFORE RESTORATION OCCURRED. PRELIMINARY DATA ANALYSIS SUGGESTS THAT RESTORATION DOES NOT AFFECT TSS.

Forest harvest and ditch cleaning effects on TSS

Preliminary results show that peaks in TSS concentrations occurred after both forest harvest in August 2020 as well as ditch cleaning in September 2021 (Figure 23). The peaks were more frequent after ditch cleaning, particularly in DC3, but not as large as those after the forest harvest. But, these peaks were not outside the range of concentrations of TSS found during flood events, for example in spring at Ref1 (Figure 23). When data were combined into the time periods of "Before CC" (before any treatments were applied anywhere), "After CC" (after the Trollberget catchments were clear cut), and "After CC+DNM" (after DC1 + DC3 were ditch cleaned), we can see stronger patterns emerge (Figure 24). With this analysis, we found that ditch cleaning tended to have higher concentrations of TSS after the combined effects of clear cutting and ditch cleaning (far right panel), whereas clear cutting alone did not produce higher concentrations of TSS than the reference conditions.

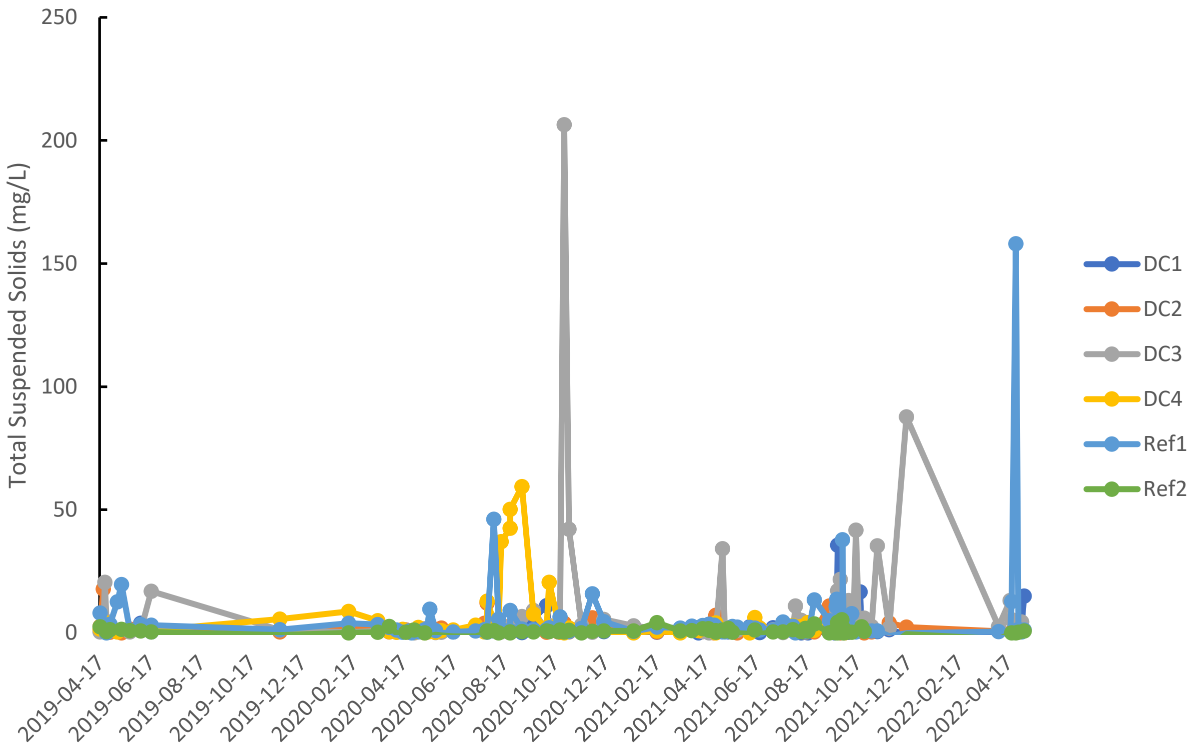

FIGURE 23 CONCENTRATIONS OF TOTAL SUSPENDED SOLIDS (MG/L) IN THE HARVESTED AND DITCH CLEANED CATCHMENTS (DC1 AND DC3), THE HARVESTED ONLY CATCHMENTS (DC2 AND DC4), AND THE REFERENCE CATCHMENTS WITH GROWING FOREST (REF1 AND REF2). THE DASHED LINES MARK THE TIMING OF THE FOREST HARVEST (2020) AND DITCH CLEANING (2021).

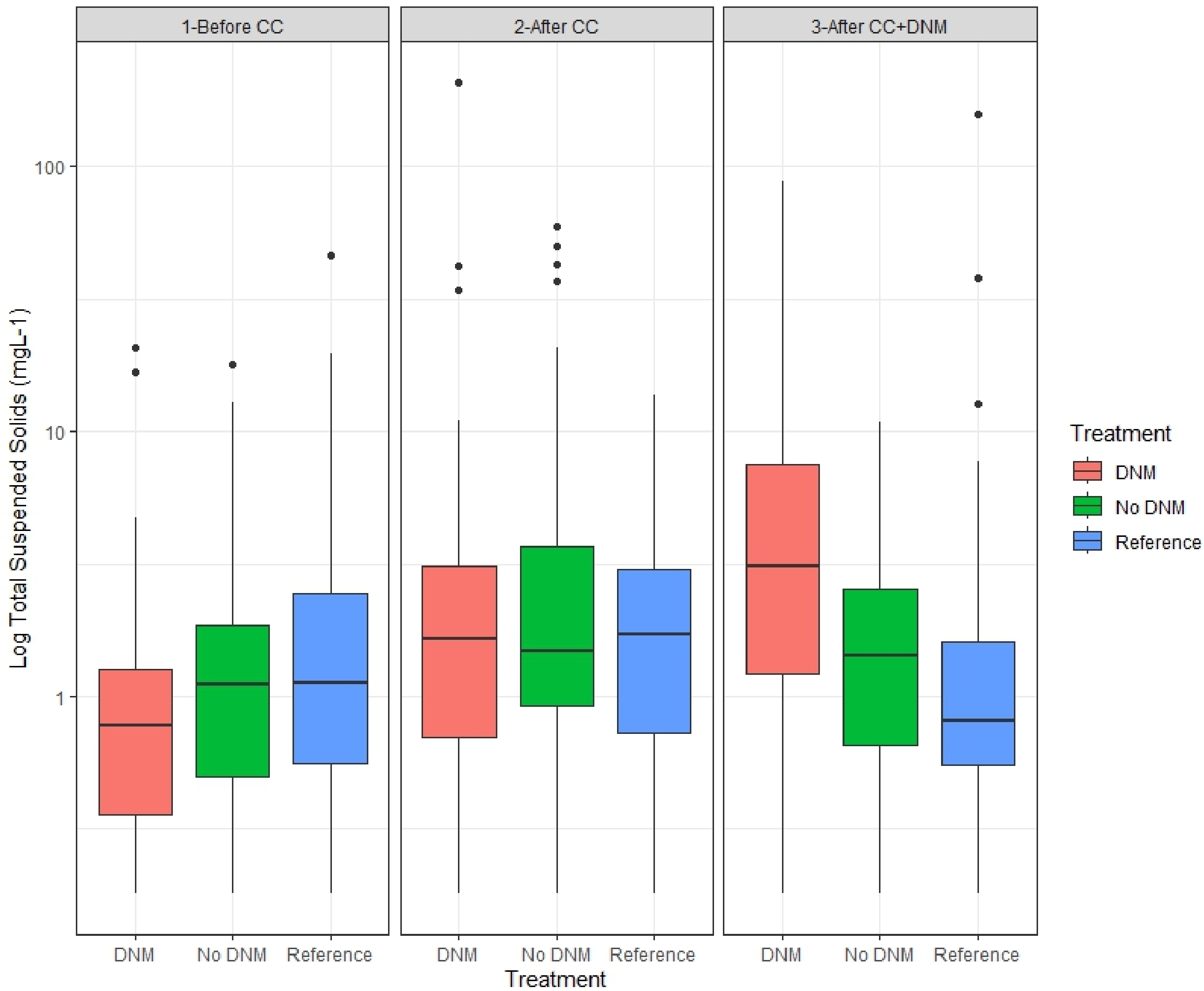

FIGURE 24 CONCENTRATION OF TOTAL SUSPENDED SOLIDS (MG PER LITER)AFTER DIFFERENT TREATMENTS AT TEA. DNM SHOWS DATA COMBINED FROM THE OUTLET OF THE TWO CATCHMENTS WERE DITCH CLEANING WAS APPLIED (I.E., DC1 AND DC3); NO-DNM SHOWS DATA COMBINED FROM THE OUTLET OF THE TWO CATCHMENTS WHERE DITCH CLEANING DID NOT HAPPEN (I.E., DC2 AND DC4); AND REFERENCE IS A COMBINATION OF TWO CONTROL CATCHMENTS WITH IN KRYCKLAN THAT WERE NEVER HARVESTED OR DITCH CLEANED (I.E. SITES 1 AND 2). PLEASE NOTE THAT DNM ACTUALLY ONLY OCCURRED IN THE PANEL ON THE FAR RIGHT CALLED "AFTER CC + DNM;" ALL OTHER PANELS SHOW THE PRE-TREATMENT TIME PERIOD IN CATCHMENTS THAT WOULD EVENTUALLY GET THOSE TREATMENTS. PRELIMINARY DATA ANALYSIS SUGGESTS THAT THERE IS A TREND TOWARDS THE DITCH CLEANED SITES HAVING HIGHER CONCENTRATIONS OF TSS THAN THE REFERENCE SITES, AFTER THAT TREATMENT WAS APPLIED (FAR RIGHT PANEL).

GRIP on LIFE

NATUR VÅRDS VERKET

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