EFFECTIVENESS OF TIMBER HARVESTING BMPS: MONITORING SPATIAL AND TEMPORAL DYNAMICS OF DISSOLVED OXYGEN, NITROGEN, AND PHOSPHORUS IN A LOW-GRADIENT WATERSHED, LOUISIANA

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ABSTRACT

To test effectiveness of Louisiana's voluntary best management practices (BMPs) at preventing water quality degradation from timber harvesting activities, a study with BACI design was conducted from 2006 through 2010 in the Flat Creek Watershed, north-central Louisiana. Water samples for nutrient analyses and measurements of stream flow and of in-stream dissolved oxygen (DO) were taken monthly at 7 sites: upstream and downstream of three harvested tracts, and at one control site. Harvesting occurred in 2007, with two of the tracts harvested with BMPs and the third without BMPs. One of the BMP-implemented tracts was further analyzed with intensive DO data. Preliminary results show no trend for significant changes in nutrient concentrations from harvests (with or without BMPs), and both monthly and intensive DO measurements show no DO depletion for BMP-implemented harvests. For these harvests occurring in the Flat Creek Watershed, Louisiana's current BMPs were effective in preventing water quality degradation.

INTRODUCTION

Forestry activities have the potential of introducing nonpoint sources of pollution (NPSP) into adjacent water bodies if no steps for mitigation are implemented (Binkley and Brown, 1993). Timber harvest without best management practices (BMPs) can introduce slash into adjacent stream- and river-beds; expose streams to increased direct solar radiation (causing water temperatures to increase), cause increased leaching of nutrients from watersheds (decreases nutrient uptake and increased mineralization rates); and increase sediment loads to streams due to disturbance from road-building, timber yarding, and even the increased runoff resulting from decreases in evapotranspiration. Eroded topsoil is often rich in fine decomposable organic matter that can increase stream respiration and lower aquatic dissolved oxygen (DO) concentrations. Forestry NPSP can lead to eutrophication due to excess nitrogen (N) and phosphorus (P), which both depletes and elevates DO concentrations during daily and seasonal patterns, and can potentially decrease biodiversity and even lead to toxic algal blooms.

Louisiana is divided into 12 major river basins with 475 sub-segments (watersheds). Nearly 50 percent of these watersheds are currently listed on the 303(d) list as impaired for the low DO levels in their water bodies (Xu, 2009), and nearly 25 percent are listed for excess nutrients (LDEQ, 2010). Efforts to prevent NPSP from forestry activities include the development of best management practices (BMPs) for the forestry community to follow. In 2000, the Louisiana Forestry Association, the Louisiana Department of Environmental Quality, and the Louisiana Department of Agriculture and Forestry developed a manual of Recommended Forestry Best Management Practices for Louisiana (LDEQ, 2000). The BMPs include practices that minimize erosion and sediment delivery to streams, reduce organic loads to streams, and maintain shade. Although implementation of the BMPs is currently high across various land ownerships and regions in Louisiana (Xu and Rutherford 2005), it is unknown how effective the state's forestry BMPs actually are at preventing stream water quality degradation in forested areas of Louisiana.

Over the past two decades, there have been many studies conducted to measure forestry BMP effectiveness (e.g., Martin and Hornbeck, 2000; Ice, 2004). However, to our knowledge very few studies have been conducted to test the effectiveness of Louisiana's forestry BMPs at preventing water quality degradation. Louisiana is a state with many low-gradient watersheds and streams. The topography and the subtropical climate often cause accumulation of stream

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nutrients and oxygen depletion. This study was designed to monitor the effectiveness of Louisiana's current BMPs at 1) preventing DO depletion and 2) preventing excessive increases of nitrogen and phosphorus concentrations.

MATERIALS AND METHODS

STUDY SITE AND DESIGN

This study was conducted from 2006-2010, in the Flat Creek watershed (Figure 1), in Winn Parish, Louisiana. This watershed covers 369 km^2 within the 41,439 km^2 Ouachita River Basin. Topography of the watershed is flat to slightly hilly, with a maximum elevation of 91 meters in the northern upland and minimum of 24 meters at the southern outlet (Saksa et al., 2010). Flat Creek is listed as having impaired water quality due to low DO and high total dissolved solids concentrations. Land use of the drainage area is predominantly forestry with some rangeland. The subtropical watershed receives about 150 cm rainfall per year. The dominant soils in the watershed are Sacul-Savannah (fine sandy loam) in the upland areas and Guyton series (silt loam) along the Turkey Creek and Flat Creek floodplains (Saksa, 2007).

First-order streams running through three forested tracts were chosen for monitoring water quality conditions within the Flat Creek watershed. For each of these tracts, two monitoring sites were established: One site immediately upstream of the forested tract, and a second site immediately downstream. An additional site in the watershed was selected to serve as a control; this site was also placed on a first-order stream in the watershed, but was not affected by any silvicultural activities during the study. The three tracts were harvested in late summer 2007. For two of the tracts, harvest occurred under Louisiana's current BMPs (between sites I3-I4, and N1-N2). These BMPs included maintaining streamside management zones (SMZ) with a basal area of 11.4 m^2 Ha^{-1} (50 ft^2 ac^{-1}) along perennial stream channels, minimizing stream crossings, limiting equipment within SMZs, constructing water bars and lateral ditches, reconstructing haul roads, restoring stream crossings, and removing slash and logging debris from stream channels (Brown and Xu, in review). The third tract was harvested using no BMPs (between sites 9up-9down). A HOBO weather station was utilized within the watershed to record continuous meteorological data such as rainfall and air temperature (Figure 1). Monthly site visits were conducted during which flow was measured (Acoustic Doppler Velocimeter, Sontec, California, USA) at each site to develop stage discharge rating curves for daily flow rate calculations.

DISSOLVED OXYGEN

In-stream measurements of water quality were made monthly at each site. These daytime "snapshot" measurements were conducted using a handheld YSI 556 (Yellow Springs Instruments, Yellow Springs, Ohio, USA), and measured numerous variables including DO concentration (mg L^{-1}) and saturation (percent). Paired t-tests (SAS analytical software) were conducted by site set (I3-I4; N1-N2; 9up-9down) on the monthly DO data. These allowed us to see any harvest-induced changes between the upstream and downstream DO relationships, by comparing pre-harvest means, and then comparing post-harvest means.

To increase resolution, and provide an additional test of BMP effectiveness at preventing DO depletion, multi-parameter water quality sondes (YSI 6920 V2, Yellow Springs Instruments, Ohio) were deployed at sites N1 and N2 in June 2006. These sondes recorded DO concentrations, temperature, conductivity, and depth at 15-minute intervals. Monthly site visits were made for calibration and maintenance of the sondes. During these monthly trips, additional water samples were taken from sites N1 and N2 for carbon and biochemical oxygen demand (BOD) analysis. Total carbon was analyzed by the Wetland Biogeochemistry Institute, Louisiana State University. The water samples for BOD analyses were kept at room temperature and analyzed for 5-day BOD (YSI 5000 dissolved oxygen meter). Paired t-tests (SAS analytical software) were performed on the DO data to compare pre-harvest relationships between N1 and N2 to post-harvest relationships. For these tests, DO measurements were averaged by day to reduce the number of observations and eliminate a falsely enhanced ρ-value. To assure that any harvest-induced changes in daily fluctuations would not be overlooked by using this daily-averaging method, the daily differences between the maximum and the minimum DO concentration were determined, and pre-harvest means were compared to post-harvest means for both sites. There were no changes in the daily differences between maximum and minimum DO concentrations from the pre- to the post-harvest at either N1 (two-sample t-test, $\rho = 0.19$) or N2 (two-sample t-test, $\rho = 0.64$). Having confirmed the suitability of the daily-averaging method, the daily averaged data were then split into two seasons: summer (May-October), and winter (November-April). Paired t-tests were also conducted on BOD, water temperature, and total carbon to search for before-and-after-harvest differences. The water temperature at each site was also averaged by month. Significance was determined by using an alpha of 0.05 in all cases except for the intensive DO concentration and saturation tests (in which the high sample number required us to use an alpha of 0.01).

NUTRIENTS

Water samples were collected monthly at each of the sites, placed on ice, and taken to the LSU Agriculture Chemistry Lab in Baton Rouge. These samples were analyzed within 30 days for total Kjeldahl-N (TKN), ammonia, nitrate-N, and nitrite-N, total P (TP), and dissolved P. For much of the analyses, ammonia and TKN were below the detection limit. Therefore, nitrate-N and nitrite-N were added together to estimate total-N (TN). To analyze N and P data, paired t-tests were used by site set to compare upstream pre-harvest values to downstream pre-harvest values, and likewise for the post-harvest values. Again, these tests enabled us to look for changes in the up-stream and down-stream relationship due to the harvest.

RESULTS AND DISCUSSION

MONTHLY DISSOLVED OXYGEN

There was quite a large range of DO concentration and saturation monthly-measured values over the course of the 5-year study period. The lowest concentration recorded was 0.14 mg L^{-1} at site I4 during the post-harvest, and DO concentration was measured at the highest point of 12.44 during a post-harvest December monthly at site 9-down. Minimum and maximum saturation values occurred at these same two down-stream sites; with the lowest monthly measurement again occurring at site I4, and on the same date that the lowest concentration was measured. The highest DO saturation was 138.9 percent, at site 9-down, during June 2009. When measurements of supersaturation were isolated, DO saturation was over 100 percent only seven out of the 358 monthly recordings. All of these events were measured during the post-harvest, at 9Down, the site chosen to show impacts from the no-BMP harvest. Not coincidentally, the only significant harvest-induced change occurred between 9-up and 9-down (Figure 4), with there being an increase in DO downstream of the harvest. DO at the control site, I1, did not change from the pre- to the post-harvest period. Measurements of air temperature taken at the Flat Creek watershed's weather station also show no significant difference between pre-harvest monthly means and post-harvest monthly means (two-sample t-test; ρ=0.6297). Neither was there any difference between pre-harvest and post-harvest monthly sums of precipitation (two-sample t-test; ρ=0.9795).

The increase in day-time DO downstream of the no-BMP implemented timber harvest is likely due to the decreased canopy cover, and possibly slightly elevated levels of TN. The 11.4 m^2 Ha^{-1} basal area SMZ that was implemented at the BMP-harvested tracts was not installed between 9-up and 9-down; all the timber was harvested right up to the stream-banks. Following the removal of these trees, the increased sunlight availability likely acted to spur algal growth. Analysis of N/P ratios within the Flat Creek watershed, calculated as TN/TP, indicates a N-limited system—using a classification of below 20 to mean N-limited (Turner et al., 2003). The mean N/P ratio was 4.54 (±7.63) for all the sites, using all the data from both pre- and post-harvest. Before the no-BMP harvest, there was no significant difference between N/P ratios at 9-up and N/P ratios at 9-down (Figure 5). For the post-harvest period, however, 9-down had a significantly higher N/P ratio than that of 9-up. With a system as severely N-limited as this one appears, it could be that the observed spikes in TN following the harvest allowed algal blooms to form. During post-harvest monthly site-visits, we did in fact observe algae at 9-down, while none was observable at 9-up. The DO increase at 9-down following the harvest is a likely effect of these algae, and it is entirely possible that both the increase in N/P ratios and the increased insolation contributed to these blooms.

INTENSIVE DISSOLVED OXYGEN

Daily averages of DO concentrations at the intensively-monitored DO sites varied greatly over the four year period: Daily averages at the upstream site (N1) ranged from concentrations of 0.00 to 10.75 mg L^{-1}, and saturation values of 0.00 to 111.5 %. DO concentrations and saturations at the downstream site (N2) ranged from 0.00 to 10.96 mg L^{-1}, and from 0.00 to 107.9 %. For greater than 70% of the year, DO levels at both sites were below 5 mg L^{-1} (DaSilva et al., in review). Pre-harvest DO measurements (saturation and concentration) during the summer months (May - October) were not significantly different from N1 to N2 (Table 1). During November and April, DO concentration at N2 was significantly higher than that at N1. Following the harvest, both summer and winter months showed significantly higher DO saturation and concentration measurements at N2 than N1.

A previous reference-stream study in Louisiana found that DO concentrations in Louisiana were limited by natural conditions (Ice and Sugden, 2003), including low velocity streams, bottoms high in organic matter, and high temperatures. Our study seems to underscore this point, as DO was below 5 mg L^{-1} for the great majority of both pre- and post-harvest. The significant increases in DO seen for both seasons are surprising in light of our findings on total carbon (TC), and BOD. During pre-harvest, TC was not significantly different between N1 and N2 (paired t-test; ρ=0.8025), but following the harvest TC at the downstream site was significantly higher than upstream TC (paired t-test; ρ=0.0059). A harvest-induced BOD increase was also recorded, with there being no difference between N1 and N2 pre-harvest BOD means (paired t-test; ρ=0.874), but a significantly higher BOD at N2 for the post-harvest period (paired t-test; ρ=0.002). When we averaged water temperature by month, and compared the sites, we saw a change in the relationship going from no difference during the pre-harvest (paired t-test; ρ=0.6675) to a slightly elevated (about 1°C) monthly water temperature mean downstream of the harvest. This 1°C increase was, however, significant (paired t-test; ρ<0.0001). This combination of factors-- the observed increase in DO following the harvest, and the seemingly contradictory increases in TC, BOD, and water temperature-- is unusual. Many studies have found decreases in DO caused by increasing TC, BOD, and/or water temperature (Binkley and Brown, 1993; Ensign and Mallin, 2001). The reduction in evapotranspiration following the harvest may have resulted in increases in groundwater reaching the stream; this excess groundwater could have increased turbulence, subsequently raising reaeration. This possibility is supported by our monthly stream-flow measurements: Before the harvest, there was no difference between N1 and N2 (paired t-test; ρ=0.0898). Post-harvest, however, showed N2 with higher stream-flow than N1 (paired t-test; ρ=0.0211).

NUTRIENTS

Nutrient concentrations for all sites remained low over the duration of the study: TP ranged from a low of 0.01 mg L^{-1} to a high of 0.661 mg L^{-1}; TN ranged from a low of 0.02 mg L^{-1} to a high of 1.234 mg L^{-1}. This TN range is well below the EPA recommended limits of 10 ppm for nitrate-N, and 1 ppm nitrite-N (nitrite-N concentrations never went above 0.0323 mg L^{-1}). Our analyses showed no statistically significant differences in the TN concentrations between any up-stream and down-stream sites either before or after harvest (whether BMPs were implemented or not; Figure 2). There was a significant decrease in TN at the control site, I1, from pre- to post-harvest (two sample t-test; ρ=0.0065). There also appears to be a change in the relationship between TN concentrations at 9-up and 9-down following the harvest, but this apparent increase was not significant (paired t-test; ρ= 0.0759). This relatively high post-harvest mean (0.26 mg L^{-1}) at 9-down was belied by a median of only 0.114 mg L^{-1}; the elevated mean was mostly due to the first two months following harvest, where TN at 9-down was 1.14 and 2.17 mg L^{-1}, respectively. The only statistically significant differences in TP were between post-harvest I3 and I4 concentrations (paired t-test; ρ=0.042), with I4 having higher post-harvest TP concentrations (Figure 3). The overall relationship between I3 and I4 appears nearly unchanged, however, since I4 had consistently experienced higher TP concentrations during the pre-harvest period.

Timber harvest without BMPs induced an immediate spike in monthly measurements of TN for the first two months (October and November 2007) following the harvest, but no such increases were seen from either of the down-stream sites of harvests with BMPs (I4 and N2). This indicates that the timber harvesting BMPs employed during this study were successful at preventing excess TN from reaching the streams. The only significant change in TP occurred at one of the two tracts harvested under BMPs. This change may not be attributable to the harvest; the uncertainty is due to the fact that there was no significant change in TP relationships between the up-stream and down-stream sites for the no-BMP implemented harvest. The pre-harvest TP mean at 9-up was observably--though not significantly--lower than that of 9-down, while for the post-harvest period this relationship was observably reversed. The fact that timber harvest without BMPs did not significantly increase TP makes it difficult to say that the slight but significant increase at one of the two BMP-implemented tracts was due to harvesting. All measured values over the duration of this study were below current EPA recommended limitations.

CONCLUSIONS

This study monitored changes of dissolved oxygen and nutrient concentrations in the headwater streams of a low-gradient, subtropical watershed from 2006 through mid-2010. During the period, timber harvest was conducted at three tracts near the monitored streams in order to evaluate effectiveness of Louisiana's current forestry BMPs in maintaining water quality conditions. The results showed that BMPs were effective in keeping dissolved oxygen levels from decreasing below pre-harvest levels. They also showed no significant increases in TN from the two BMP-implemented harvests, though there were spikes in TN from the non-BMP implemented tract. At two out of three of the tracts there were no significant differences in TP concentrations between pre-harvest and post-harvest. At the remaining tract, a BMP-implemented tract, there was a slight but significant increase from pre- to post-harvest TP. Overall, however, there was no clear harvest-caused trend in nutrient concentrations either with or without BMPs.

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Table 1—Dissolved oxygen saturation (%) and concentration (mg L^{-1}) means and standard deviations at sites N1 and N2 during summer (May-October) and winter (November-April) months. Paired t-tests were used, and * indicates significant difference between up-stream and down-stream sites over the same time period (α=0.01)

		Pre		Post	
		N1 ± std	**N2 ± std**	**N1 ± std**	**N2 ± std**
DO %	*Summer*	14.0 ± 20.0	16.8 ± 19.8	9.20 ± 17.6 *	12.9 ± 20.0*
	Winter	39.9 ± 34.1 *	44.1 ± 33.1 *	38.8 ± 25.4 *	44.8 ± 26.8 *
DO mg/L	*Summer*	1.49 ± 1.97	1.44 ± 1.68	0.84 ± 1.63 *	1.16 ± 1.83 *
	Winter	4.33 ± 3.83 *	4.77 ± 3.75 *	4.24 ± 2.87 *	4.87 ± 3.04 *

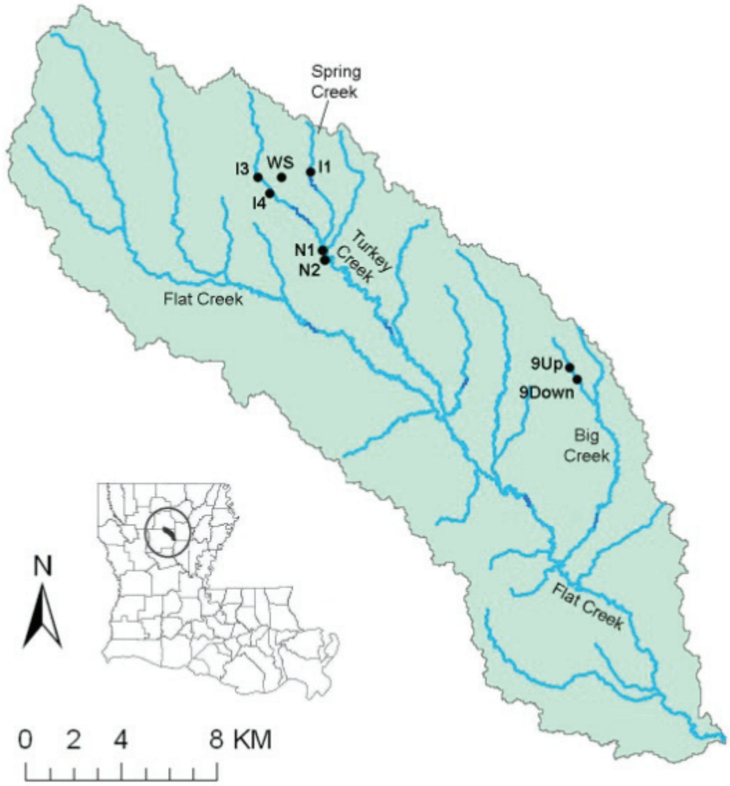

Figure 1—The Flat Creek Watershed, with labeled sites, including the weather station (WS).

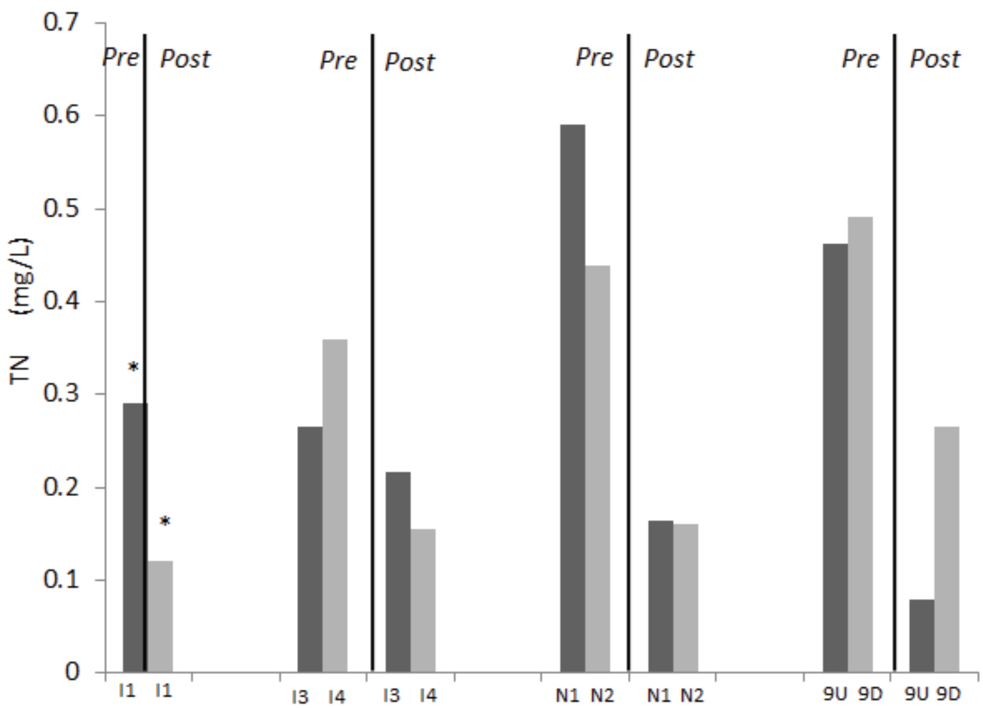

Figure 2—Total nitrogen (TN) means for each site during both pre- and post-harvest periods. Paired t-tests were conducted on I3-I4, N1-N2, and 9U-9D, while a two sample t-test was used on site I1 to test for significant differences (α=0.05; significance indicated by *).

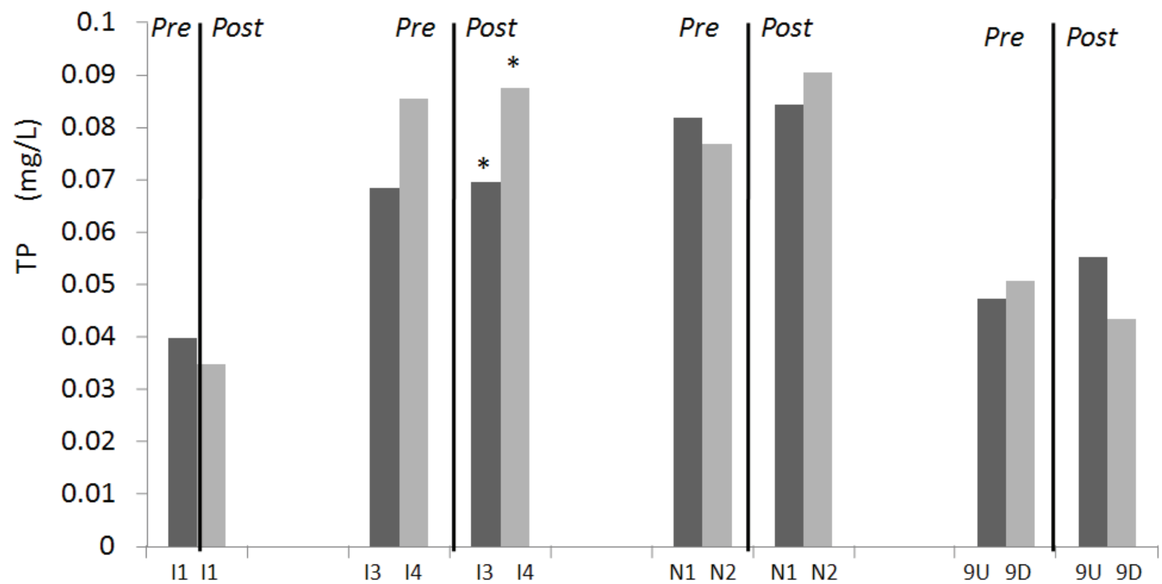

Figure 3—Total phosphorus (TP) means for each site during both pre- and post-harvest periods. Paired t-tests were conducted on I3-I4, N1-N2, and 9U-9D, while a two sample t-test was used on site I1 to test for significant differences (α=0.05; significance indicated by *).

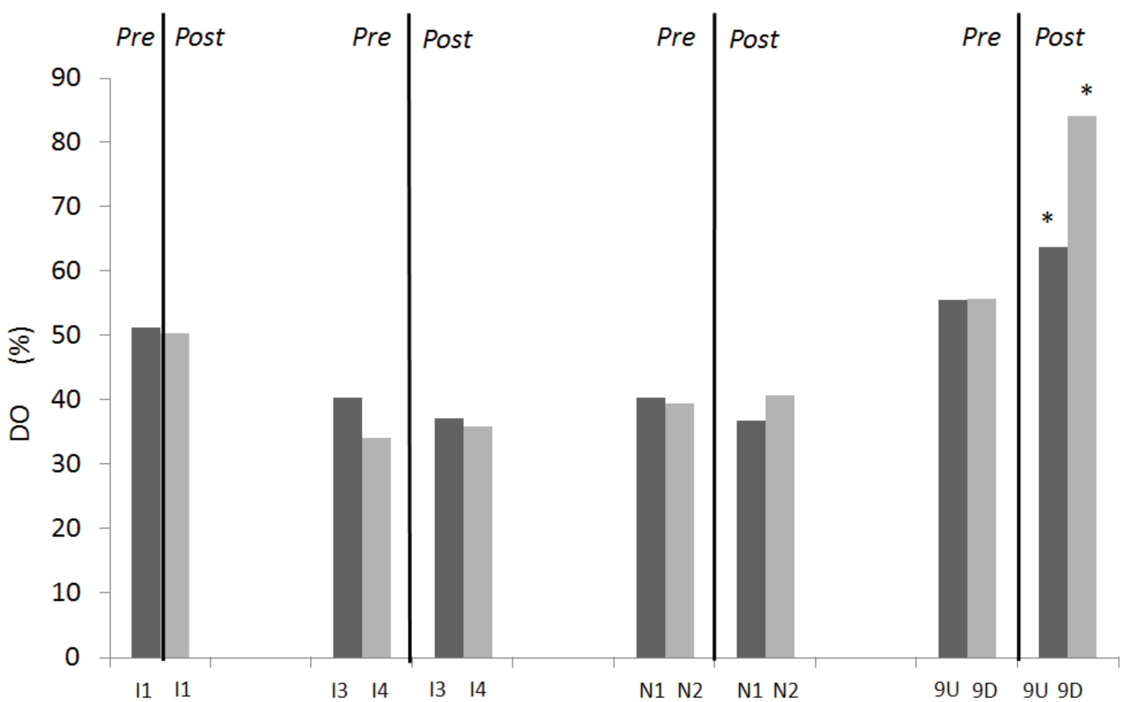

Figure 4—Monthly in-stream dissolved oxygen saturation (%) means at each site, for the pre- and the post-harvest periods. Paired t-tests were conducted on I3-I4, N1-N2, and 9U-9D, while a two sample t-test was used on site I1 to test for significant differences (α=0.05; significance indicated by *).

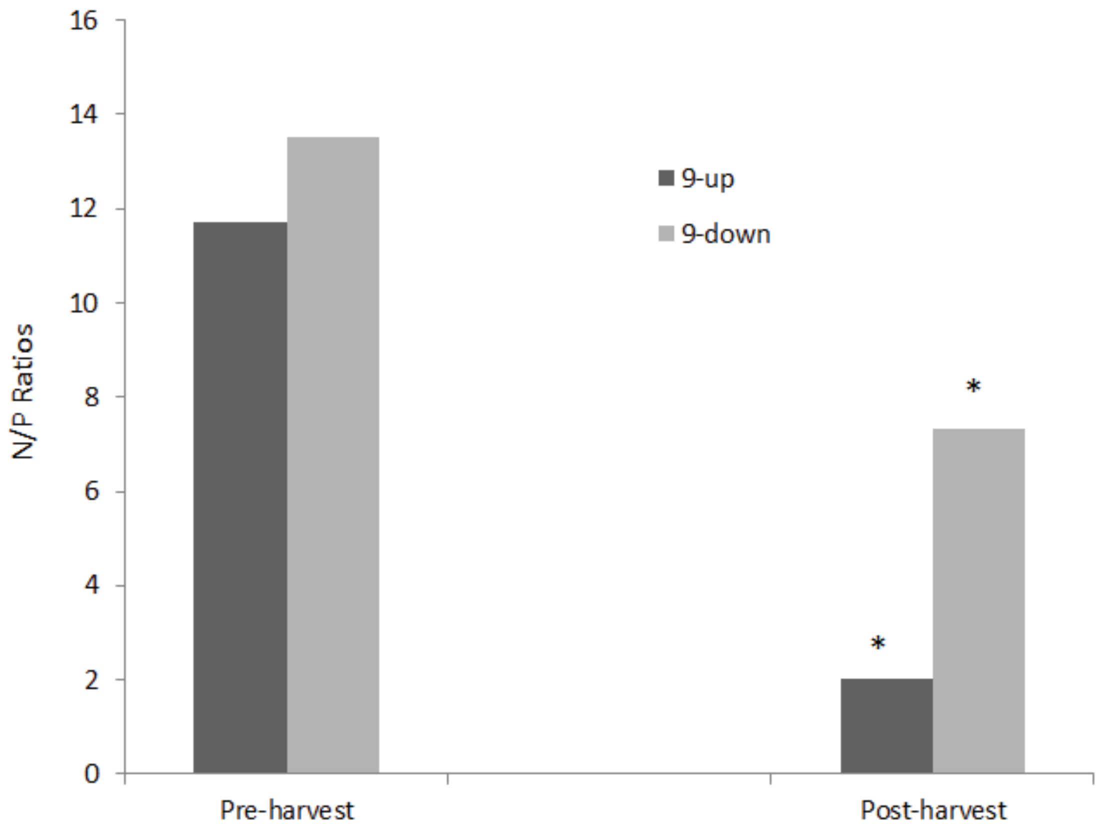

Figure 5—Pre- and post-harvest means of monthly N/P ratios at sites 9-up and 9-down. Paired t-tests were conducted for both time periods to test for differences between the upstream and downstream sites (α=0.05; significance indicated by *).