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Effects of Thinning on Hydrology and Water Quality of a Drained Pine Forest in Coastal North Carolina

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Abstract. A study was conducted to examine the effects of commercial thinning on hydrology and water quality of a 28-year old (in 2002) drained loblolly pine (Pinus taeda L.) plantation watershed (D3) using another adjacent watershed (D1) as a control. A paired watershed approach was used with data from two periods (1988-90 and 2000-02) for calibration and data from 2002-07 as the treatment period. Both of these 25 ha watersheds are located in Carteret County, North Carolina. Results showed a consistent rise in water table elevations on D3 compared to the control during the six months after 50% thinning. The water table rise of 12.6 cm on average decreased substantially by June 2007, indicating an increase in evapo-transpiration caused by increased canopy closure. Similarly, flow rates increased immediately after thinning and decreased soon thereafter. Monthly outflows on thinned watershed were generally higher in the summer-fall months compared to the control. However, the total annual outflow from the treatment was lower than the control, except for the very wet years of 2003 with extremely high rainfall (>2300 mm) and 2005, possibly indicating a hydrologic recovery due to canopy closure approximately three years after thinning. Thinning did not affect nutrient concentrations and loading rates, except for NO_3-N and total P. The increases in both of these nutrients were minor compared to the values obtained from fertilization of these stands. Results of the study indicate thinning may have only a short term (up to three years) effect on hydrology and water quality of drained pine plantation.

Keywords. Loblolly pine, Drainage Outflow, Evapotranspiration, Water Table, Nutrients

Introduction

Thinning is an important part of the silvicultural treatments imposed on managed pine plantations and is the only currently used practice to maximize productivity by potentially increasing water availability in established stands. Cregg et al. (1990) studied water relations of loblolly pine trees in southeastern Oklahoma following pre-commercial thinning. The authors reported that the thinning had a significant effect on soil water potential measured in upper 45 cm of the soil profile. The thinned plots had higher soil water potentials after thinning as compared to the control, similar to other thinned pine studies. Using data from the same site Stogsdill et al. (1992) suggested that the capacity to manage available water in loblolly pine stands by thinning is more a function of reduced interception loss and increased throughfall than reduced water use. He also stated that the effect is weather dependent. Ewel (1985) examined water quality in two central Florida cypress swamps before and after thinning in comparison with two control cypress swamps. Although the author found increased total and organic nitrogen in one swamp following thinning, after three months both thinned swamps had lower N concentrations than the controls. Using a simulation modeling approach with forestry version of DRAINMOD (McCarthy et al. (1992), McCarthy and Skaggs (1992) presented a water balance for a loblolly pine stand through its life cycle both for thinned and unthinned regimes in eastern North Carolina. Recently, Amatya et al. (2006) reported on effects of harvesting one of the treatment watersheds on the same pine plantation site. The authors reported that although the nutrient levels returned to base line conditions within three years after planting it took more than seven years for the hydrology to recovery.

Although there are adequate literature on hydrologic and water quality effects of silvicultural operations in the Southeast (Shepard, 1994; Amatya et al., 1998; 2000; 2006; Lebo and Herrmann, 1998; Chescheir et al., 2003; Grace et al., 2006; Waldbridge and Lockaby, 1994), there is only a very limited literature on experimental studies of effects of thinning on water quantity and quality for drained pine plantations in the coastal plains. In a three-year study using paired watershed approach for an artificially drained 15-year old pine plantation site on organic soils in eastern North Carolina, Grace et al. (2006) found an increase in daily drainage peak flow rates, and nutrient and sediment loadings from the thinned watershed compared to the control. The authors attributed the increases in both the drainage outflows and nutrient and sediment loadings to the reduction in evapotranspiration (ET) that resulted from thinning. In their companion study (Grace et al., 2006), the authors reported that the thinning operation reduced both the saturated hydraulic conductivity and drainable porosity, which may likely result in shallower water table depths and increased runoff for the thinned watershed. However, most of these studies have been only for a short period and did not quantify the effects of thinning over the time period for hydrologic recovery.

The main objective of this study is to analyze the effects of commercial thinning of a drained pine forest watershed (D3) on water table, drainage rates, outflows, their time distribution, and drainage water quality compared to the control watershed (D1). Data from five years of treatment (July 2002 – June 2007) were used to evaluate the thinning effects compared to the data from the first calibration period (February 1988 – March 1990) and the second calibration or pre-treatment period (February 2000 to June 2002). The treatment watershed had undergone other management treatments between March 1990 and February 2000 (Table 1). Although this study is also from a drained loblolly pine plantation in eastern North Carolina, it differs from the Grace et al (2006) study in that the soil is mineral rather than organic and the study period is much longer, extending over the period for the hydrologic recovery to base line levels.

Site Description

The study site (Figure 1) is located at approximately 34^{o} $48^{'}$ N latitude and 76^{o} $42^{'}$ W longitude in Carteret County, North Carolina, and is owned and managed by Weyerhaeuser Company. The research site consists of three artificially drained experimental watersheds (D1, D2, and D3), each about 25 ha in size. Topography of the site is flat and water tables are shallow. The soil is a hydric series, Deloss fine sandy loam (fine-loamy mixed, Thermic Typic Umbraquult). Each watershed is drained by four 1.4 to 1.8 m deep parallel lateral ditches spaced 100 m apart (Figure 1). Data on hydrology, soil and vegetation parameters were collected from three experimental plots (each about 0.13 ha in area) in each watershed .The three artificial watersheds were planted in 1974 at a density of 2100 trees ha^{-1} with trees separated 1.74 m apart and rows separated 2.74 m apart. Watershed D1 has served as the control treatment throughout various different studies conducted on the site since 1988 as shown in Table 1 (McCarthy et al., 1991; Amatya et al., 1996; 1998; 2000; 2003; 2006a; 2006b). Both the watersheds D1 and D3 are now 33-year old mature pine plantation that underwent pre-commercial thinning in 1981 (thinned to 988 trees ha^{-1}) and commercial thinning in the later part of the growing season in 1988 (thinned to 370 trees ha^{-1}). Additionally, watershed D3 was commercially thinned (about 50% of the biomass removed) in early July 2002 to a density of about 185 trees ha^{-1} to study the effects of the commercial thinning on hydrology and water quality on this drained pine plantation (Table 1).

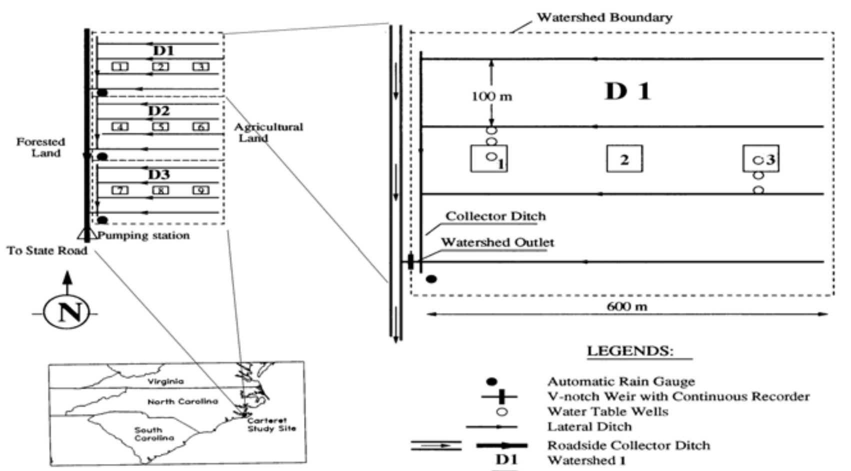


Figure 1. Location map and layout of experimental watersheds (D1 – control and D3 – treatment with thinning watersheds) at the Carteret County, NC (After Amatya et al., 2006).

Table 1. Detailed history of the pine stands at Carteret 7 site.

YEAR	EVENT
1974	Trees planted (2100 trees ha^{-1})
1980	Pre-commercial thinning (988 trees ha^{-1})
1981	Aerial Fertilization (367 kg ha^{-1} of urea)
1988 (February)	Calibration I period and study begins
1988 (October)	Commercial thinning (from 988 trees ha^{-1} to 370 trees ha^{-1})
1990 (March)	Calibration I period ends. Controlled drainage study begins on D2 and D3
1994 (December)	Controlled Drainage Study ends
1995 (July)	D2 harvested. Harvesting study begins on D2
1995 (February)	Orifice weir study begins on D3
1997 (February)	D2 Replanted. Regeneration study begins for D2
1999	Orifice weir study ends on D2
2000 (February)	Calibration II period begins
2002 (July)	D3 thinned by approximately 50% (185 trees ha^{-1}) and Thinng study begins
2005 (September 8th)	Aerial fertilization D2 and D3 (115 kg ha^{-1} and 27 kg ha^{-1} in D2 and 172 kg ha^{-1} and 41kg ha^{-1} in D3). Fertilization study begins
2007 (December)	Thinning study on D3 ends

Methods

Rainfall was measured with tipping bucket rain gauges on the western side of each watershed (Figure 1). Air temperature, relative humidity, wind speed and solar radiation were continuously measured by an automatic weather station located 800m away until 1997 after which a new station, which included a net radiometer, was installed at the center of watershed (D2). However, this station stopped functioning in September 2005 due to the damage caused by Hurricane Ophelia. A 120^o V-notched weir with an automatic stage recorder, located in a water level control structure at a depth of about 0.3 m from the bottom of outlet ditch (Figure 1), was used to continuously measure drainage outflow in each watershed. Outflows are measured only when the water level in the ditch exceeds an elevation of about 0.3 m above the ditch bottom. An additional recorder was placed downstream from the weirs in May 2005 to determine if weir submergence occurred and to correct flows in that event. In 1990, a pump was installed downstream from all three watersheds in the roadside collector ditch to prevent weir submergence during larger events. The pump assembly was renovated in late 2003 and collector ditches were cleaned in July 2004 to avoid submergence of the weirs. Water table elevations were measured by a continuous water level recorder at two locations midway between the field ditches for each watershed (Figure 1). The reader is referred to McCarthy et al. (1991) and Amatya et al. (2003b; 2000; 1996) for a detailed description of the site and other measurements including interception, lateral seepage, leaf area index (LAI), and the history of the loblolly pine stand planted in 1974.

Two methods of water sampling (composite using automatic water samplers ISCO-2700 and manual grab sampling) at the weir outlet of each watershed (Figure 1) have been used since late 1989. For composite sampling during specific events, 250 mL of water was collected every two hours; four consecutive samples were composited making three samples per day. All samples collected until 1994 were frozen and analyzed at the Weyerhaeuser laboratory in New Bern North Carolina. Samples collected since 1995 were analyzed in laboratories of the Soil Science Department at North Carolina State University. Grab samples were collected weekly during the flow events of the study period. Water samples were analyzed for NO_3+NO_2-N, NH_4-N, total Kjeldahl nitrogen (TKN), total phosphorus (TP), and total suspended solids (TSS). Details of procedures of event sampling and sample analysis in the laboratory were documented by Amatya et al. (1998; 2003).

Data analysis was conducted for February 1988 to March 1990 as the initial calibration period –I (CLB) and for March 2000 – June 2002 as the calibration period –II or pre-treatment (PRE) period when both the watersheds were of the same stand age and under same treatments. Thinning treatment on D3 started in late June was completed within 10 days by early July 2002 (Table 1). Number of trees of 160 per acre was reduced to 80 trees per acre resulting in a 50% removal after thinning (Joe Bergman, Personal Communications, 2002). Two TIGERCAT 728 with 48 cm (19”) cutting head cutters were used to cut the trees. The selection process the cutter used was to remove 4-5 trees every 80 feet in each row. Trees were then dropped on the ground in one direction and then three TIMBERJACKS 450 with wide tire skidders were used to haul the trees to the deck. At the deck the tree was delimbed using two delimbers and the top of the tree that is 10 cm (4”) or less was cut using two sawbucks and taken back to the forest. The log is then graded at the deck to determine if the log is GRADE (used for timber), PULP (used for paper), or HOG FUEL (used for fuel at the mill). After the completion of thinning, 88% of trees were found to be GRADE, 11% was PULP, and 1% was HOG FUEL. Two PRINTICE loaders were used to load the trees on the truck.

So five-year data from July 2002 through June 2007 was used as post-thinning (POST) period for evaluating thinning effects on hydrology. However data only through August 2005 was used for evaluating effects on water quality as another treatment with fertilization occurred on D3 in early September 2005 (Beltran 2007). Effects of thinning on the treatment watershed (D3) were determined by comparing the measured values of water table elevations, outflows, and nutrients levels with that of the expected values had the treatment not been implemented on D3. The expected values on D3 were calculated using the characteristic differences observed in water table elevations, annual outflows and outflow ratios, and nutrients between two watersheds (D1 and D3) during the calibration (CLB) and pre-treatment (PRE) periods with the corresponding measured data on the control watershed (D1) during the post-treatment (POST) years as was done in earlier studies on this site (Amatya et al., 1998; 2000; 2003). Outflow ratio is the ratio of drainage outflow to the rainfall. Student’s t-test statistics for equal samples was used to test the null hypothesis of no difference in mean monthly outflows between two watersheds for the POST periods. Both the tabular values and graphical plots were also used for analysis and interpretation

Results and Discussion

Rainfall

Annual measured data on measured rainfall, outflow, outflow ratio, and average water table elevations for the 1988-90 calibration-I, 2000-02 calibration-II (or pre-treatment), and 2002-07 thinning treatment periods are presented in Table 2.

Table 2. Measured rainfall, drainage outflow, average water table elevation for the calibration, pre-treatment, and post-treatment periods on the control (D1) and treatment (D3) watersheds.

Treatment	Period	Rainfall			Long-term	Drainage Outflow			Outflow Ratio		Water Table Elevation		
		D1	D3	D1-D3	rainfall	D1	D3	D1-D3	D1	D3	D1	D3	Difference
		mm	mm	mm	mm	mm	mm	mm	%	%	m	m	m
Calibration I	1988	1235	1199	36	1390	173	197	-24.3	0.14	0.16	1.65	1.22	0.43
	1989	1876	1768	107	1390	658	553	104.7	0.35	0.31	2.02	1.94	0.08
	1990	291	265	26	1390	140	123	17.7	0.48	0.46	2.15	2.14	0.01
Average		**1134**	**1078**	**56**	**1390**	**324**	**291**	**32.69**	**0.32**	**0.31**	**1.9**	**1.8**	**0.17**
Calibration II	2000	1533	1591	-59	1390	738	766	-27.4	0.48	0.48	1.90	1.88	0.02
(Pretreatment)	2001	852	832	20	1390	45	52	-7.1	0.05	0.06	1.26	1.21	0.05
	2002	684	698	-14	1390	21	9	12.0	0.03	0.01	1.40	1.30	0.10
Average		**1023**	**1040**	**-18**	**1390**	**268**	**275**	**-7.51**	**0.19**	**0.19**	**1.5**	**1.5**	**0.06**
Post-treatment	2002	1035	1091	-57	1390	405	342	63.2	0.39	0.31	1.92	2.04	-0.12
	2003	2331	2268	62	1390	1308	1459	-151.4	0.56	0.64	2.16	2.27	-0.11
	2004	1313	1414	-101	1390	390	325	64.7	0.30	0.23	1.72	1.80	-0.08
	2005	1777	1823	-46	1390	798	915	-117.0	0.45	0.50	1.98	2.03	-0.05
	2006	1328	1312	16	1390	247	166	81.0	0.19	0.13	1.87	1.90	-0.03
	2007	471	458	13	1390	85	55	29.5	0.18	0.12	1.60	1.66	-0.06
Average		**1376**	**1395**	**-19**	**1390**	**539**	**544**	**-5.00**	**0.34**	**0.32**	**1.88**	**1.95**	**-0.07**

Note: 1988 is from February only; 1990 is for January and February only; 2002 in Pretreatment is only through June and in Post-treatment starts from July 2002; 2007 is only through June.

Rainfall in 1990 is only for the period January 01 to March 20 (end of the calibration). Annual rainfall varied over a wide range during the study period. The rainfall of 2330 mm (on D1) in year 2003 (which included Hurricane Isabelle) was the highest of the 20-years (1988-2007) of record at this site. Years 1989, 2002, 2003, and 2005 had much higher than normal rainfall (Beltran, 2007). Annual total rainfall recorded during the calibration periods indicated that D1 received approximately 5% more rain on average than D3. The PRE period was slightly drier than the CLB period, mostly because of 2001 which had the lowest recorded rainfall during the period of record. Both the CLB and PRE periods had lower average rainfall than the long-term regional average of 1390 mm (Morehead City, NC 50-year dataset, 1950-2000). During the pre-treatment and post-treatment periods, however, D3 received about 2% and 3% on average, respectively, more rain than D1. Average annual rainfall for the POST period was above the 1391 mm regional average indicating it as a wet period. Although monthly rainfall between D1 and D3 were highly correlated (R^2> 0.98) for all three periods, it was more consistent between PRE and POST periods than the CLB period. This was likely due to different type of gauges and data loggers used in the calibration-I compared to calibration-II and post-treatment periods.

Water Table Elevation (WTE)

Calibration-I and pretreatment periods show a consistent pattern of lower water table elevation in D3 compared to D1 with negative values of (D3-D1) as shown in Figure 3. On average, the water table in D1 was approximately 5 cm higher than D3 during the CLB and PRE periods. After the thinning in June 2002, water table elevation patterns reversed indicating a response of the treatment. Water table elevations rose quickly in watershed D3 after thinning in early July 2002, averaging 12.6 cm higher than D1 in the first 6 months. This was a rise of 17.2 cm, on average, compared to –4.6 cm for the CLB and PRE periods. This was consistent with Grace et al. (2006) results who also reported deeper WTEs on the control watershed due to higher ET. However, the average difference in WTE steadily declined in the following four years (2003=11.2 cm, 2004=7.4 cm, 2005=4.7 cm, 2006 = 2.7 cm) (Table 1; Figure 4), suggesting increasing ET as the canopy closed on the thinned watershed (D3). The average difference in WTE between the treatment (D3) and the control (D1) increased back to 6.2 cm for January-June of 2007. This was attributed to much drier conditions of this spring-early summer period compared to the same period in previous years. This is consistent with the findings of Grace et al (2006) who reported greater increases in water table elevations of thinned watershed during the spring and summer periods when ET demands are high. These data showed that five years after the thinning the water table on the treatment watershed (D3) had not completely recovered to pre-thinned conditions. The LAI data measured more than two years after 50% thinning (until end of 2004) of this watershed was still reduced by 17% (Sampson et al., 2008) shows that the canopy was not closed at least until the beginning of 2005.

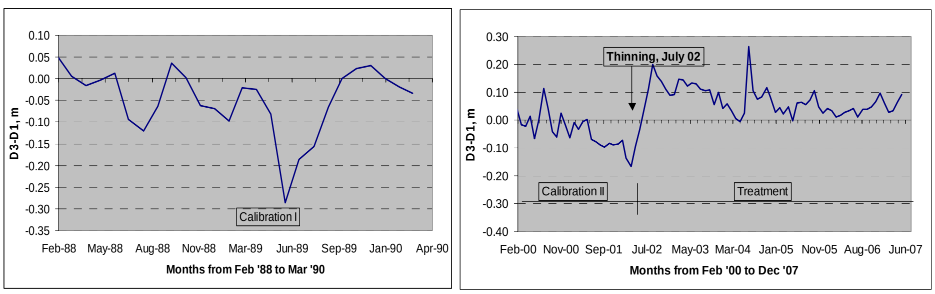


Figure 3. Average difference in monthly water table elevations (WTE) measured on D3 (treatment) and the D1 (control) for the first calibration (1988-90) (left plot), pre-treatment (2000-02) and the post-treatment (2002-07) period (right plot).

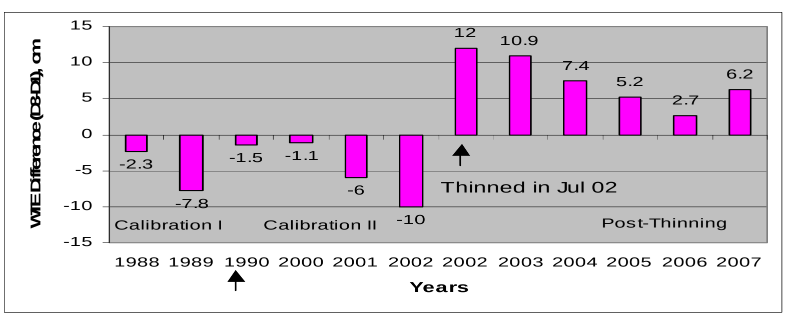


Figure 4. Average difference in annual water table elevation (WTE) measured on D3 (treatment) and D1 (control) for the CLB (1988-90), PRE (2000-02) and the POST (2002-07) periods.

Flow rates and Monthly Drainage Outflows

There was a clear response showing higher peak drainage rates from thinned watershed D3 compared to control watershed D1 for the first event of July 26 (Day 207), 2002 immediately after thinning (not shown). This was consistent with water table rise as discussed above. Interestingly, despite a rise in water table on D3 for other late summer and fall events of 2002, there was no similar response of increase in outflow rates. Flow rates came back to previous conditions by end of 2002 with higher outflow rates from control watershed compared to thinned watershed D3. This could, possibly, have been due to a relatively wet period with high water table elevations such that ET was not limited in the thinned watershed (Amatya and Skaggs, 2003). This is possibly the reason, there was no increase in total outflow for the later part of 2002. This is contrary to results reported by Grace et al. (2006) for a pine forested watershed on organic soils in eastern NC. However, their results were obtained for the relatively dry summer-fall of 2001 and winter-spring of 2002 when large increases in outflows were observed after thinning. The dry periods in this study occurred for the pre-thinning period. The Grace et al (2006) study extended for only 1.8 years after thinning may not have had opportunity to observe results for conditions similar to those reported here.

Monthly outflow differences (D3-D1) for the calibration-I, pretreatment, and post-treatment periods are shown in Figure 5. As with the water table elevations no clear pattern was observed in monthly outflow differences during the CLB and PRE periods. Although there were some positive differences with higher outflows on the treatment watershed (D3) during the CLB and PRE periods the large negative values with higher D1 outflows in 1989 and near zero or zero flows for the rest of the period including May 2001 to February 2002 yielded an average value of –2.7 mm with higher values on D1 on average for this period. Accordingly, the regression with a zero intercept gave D3Flow = 0.94*D1Flow.

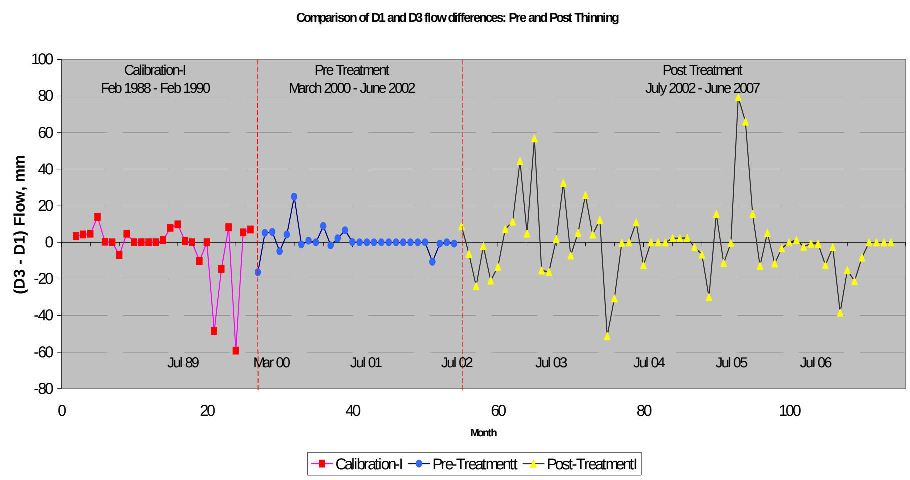


Figure 5. Difference of monthly outflows measured on D1 (control) and D3 (treatment) for the first calibration (1988-90) and pre-treatment (2000-02) periods and the post-treatment (2002-07) period.

Interestingly, soon after thinning the differences were found to be negative with lower outflows on D3 than the control for all the months except for relatively dry month of July in 2002. The slope of regression was only 0.85. However, in the wet years of 2003 and 2005 most of the months yielded positive D3-D1 values as high as 79 mm and 66 mm for September and October 2005, respectively. The regression lines yielded much higher slopes of 1.13 in 2003 and 1.17 in 2005, respectively, compared 0.94 for the CLB and PRE periods. Although these large increases were possibly attributed to reduced canopy interception for the thinned watershed (D3) and reduced ET, some of these flow increases on D3, especially for the months of April-June, September, and December in 2003 and September and October in 2005 occurred during weir submergence when the measured flow estimates were adjusted. By the mid-year 2007, however, the differences were mostly negative or only small positive values indicating decreasing effects of thinning on monthly drainage outflows. For example, the total outflow from D3 (55 mm) from Jan to March in 2007 was still lower compared to 85 mm from D1. Note that there was non flow in both watersheds after March 2007. Along with the continuing decline in difference in water table elevations until 2006 (Figures 3 and 4), the decrease in outflows since late 2005 indicates that the hydrology is essentially recovering to conditions prior to thinning in this watershed. This was also indicated by the regression slopes of 0.63 and 0.65 for the monthly flows in 2006 and the first-half of 2007, respectively, compared to 0.94 during the CLB and PRE periods. Except for the wet years of 2003 and 2005 (Table 2), all measured average monthly outflows for each of the years after thinning since July 2002 were less than the expected average values predicted by the regression equations for the CLB and TRT periods. Results were somewhat complicated by some periods of weir submergence, which increased the uncertainity of measured flows for those periods in 2003 and 2005. Although the difference in mean monthly outflow of 121.6 mm on the thinned watershed (D3) compared to 108.9 mm on the control (D1) was just significant (α = 0.05) in 2003, the difference of 76.3 mm for D3 compared to 66.5 mm for the control (D1) in 2005 was not significant using the Student's t-tests.

Annual Outflows and Outflow (Runoff-Rainfall)Ratios

Difference in annual drainage outflows between the control (D1) and the treatment (D3) during the CLB and PRE periods in Table 2 varied from –7 mm in driest year 2001 to 105 mm in a wet year (1989). The average difference was 12.6 mm, indicating a larger outflow from the control when the trees were in the same stage and condition. Although thinning in July 2002 did not increase outflow from D3 compared to D1 in the later half of 2002 because conditions were relatively dry, it did increase outflows for wet years 2003 and 2005. The annual outflow ratio (ratio of outflow to rainfall) on D3 in 2003 was 0.64 compared to 0.56 for D1 and 0.50 compared to 0.45 for D1 in 2005). Both of these outflow ratios (0.64 and 0.50) were higher than the calculated expected values of 0.55 for 2003 and 0.44 for 2005, respectively. The total outflows for both 2006 and half-year of 2007 were much lower than that for the control indicating a trend towards hydrologic recovery due to increased ET (i.e. the canopy closure).

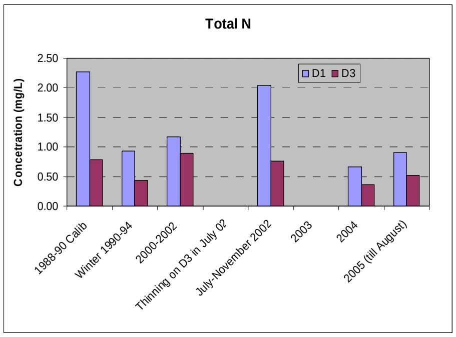
Water Quality

Nutrients Concentrations: Measured average nutrient concentrations on both D1 and D3 watersheds for the 1988-90 calibration (CLB) and three pre-thinning (PRE) periods since March 2000 to June 2002 are presented in Table 3. Average nutrient concentrations (on D1) of 2.3 mg L^{-1} for total nitrogen (TN), 0.93 mg L^{-1} for NO_3-N, and 1.34 mg L^{-1} for TKN were the highest observed during the calibration and two pre-treatment years of 2000 and 2001. These values were at least 2.5 to 4 times greater than the levels observed for the same nutrients on the treatment (D3) although these data represent the post-fertilization periods on both the watersheds in spring of 1989 (Amatya et al., 1998; Beltran, 2007). As an example a plot for TN concentrations for all periods is shown in Figure. 5 (left). However, total phosphorus (TP) concentrations on D3 were slightly higher than on D1 for the CLB and the winters of 1990-94, but were about the same for the 2000-02 PRE period (Fig. 5, right). Details of data for the CLB and 1990-94 winter periods can be found in Amatya et al (1998). As a result of long dry period from early summer of 2001 to early summer of 2002 flows were low to negligible (Table 2). Consequently, there was only one sample collected on D1 and D3 on April 11, 2002 that yielded a very high value of 3.4 mg L^{-1} for NO_3-N on the treatment watershed (D3) compared to only 0.3 mg L^{-1} for the control. Although this might be a possibility due to a first flush effect of nitrification of deposited organic materials (as NH_4-N itself was very low) it was assumed to be an outlier and not included in the analysis.

Table 3. Measured and expected nutrient concentrations and loadings (per period shown) for the D1 and D3 watersheds for CLB, PRE, and four POST periods after thinning in early July 2002.

CLB, PRE and POST Periods	Water-shed	NO3-N Measur mg L^{-1}	NO3-N Expect mg L^{-1}	TKN Measur mg L^{-1}	TKN Expect mg L^{-1}	Total N Measur mg L^{-1}	Total N Expect mg L^{-1}	Total P Measur mg L^{-1}	Total P Expect mg L^{-1}	NO3-N Measur kg ha^{-1}	NO3-N Expect kg ha^{-1}	TKN Measur kg ha^{-1}	TKN Expect kg ha^{-1}	Total N Measur kg ha^{-1}	Total N Expect kg ha^{-1}	Total P Measur kg ha^{-1}	Total P Expect kg ha^{-1}
CLB	D1	0.93		1.34		2.27		0.03		5.34		6.15		11.49		0.38	
1988-90	D3	0.23		0.55		0.78		0.04		0.88		1.79		2.67		0.37	
PRE	D1	0.48		1.09		1.57		0.02		8.00		13.40		21.40		0.22	
2000	D3	0.12		0.79		0.91		0.02		2.00		7.40		9.40		0.27	
PRE	D1	0.08		0.43		0.51		0.01		0.04		0.15		0.19		0.00	
2001	D3	0.02		0.56		0.58		0.01		0.01		0.23		0.24		0.01	
PRE	D1	N/A		N/A		N/A		N/A		N/A		N/A		N/A		N/A	
Jan 02-Jun 02	D3	N/A		N/A		N/A		N/A		N/A		N/A		N/A		N/A	
POST	D1	0.35		1.69		2.04		0.03		1.77		3.63		5.40		0.12	
Jul 02 -Dec 02	D3	0.15	0.15	0.61	1.03	0.76	1.13	0.02	0.04	0.44	0.39	1.49	2.29	1.93	3.46	0.13	0.17
POST	D1	0.26		N/A		N/A		0.03		3.56		N/A		N/A		0.36	
2003	D3	0.17	0.12	N/A	N/A	N/A	N/A	0.07	0.04	0.88	0.78	N/A	N/A	N/A	N/A	0.54	0.50
POST	D1	0.29		0.38		0.67		0.03		1.94		1.33		3.27		0.04	
2004	D3	0.16	0.13	0.20	0.23	0.36	0.37	0.05	0.04	0.48	0.43	0.54	0.84	1.02	2.09	0.19	0.06
POST	D1	0.51		0.40		0.91		0.09		2.73		1.38		4.11		0.23	
Jan 05-Aug 05	D3	0.29	0.23	0.23	0.24	0.52	0.50	0.08	0.11	0.67	0.60	0.56	0.87	1.23	2.63	0.28	0.32

Measured nutrient concentrations on both D1 and D3 watersheds and the calculated expected values on D3 (had it not been thinned) for the four post thinning periods since July 2002 are presented in Table 3. The measured average concentrations during the CLB and the PRE periods for the treatment (D3) and the control (D1) used to derive the mean calibration factors (D3:D1) for calculating the expected concentration values on D3 using the measured data on D1 for the post-thinning periods were 0.45, 0.61, 0.55, and 1.19 for NO_3-N, TKN, TN, and TP, respectively. Data for the 2004-05 period are also recently reported by Beltran (2007). The average measured nutrient concentrations of NO_3-N, TKN, TN, and TP were just 0.15, 0.49, 0.64, and 0.02 mg L^{-1}, respectively, for 105 samples collected intensively on the thinned watershed (D3) for events that occurred soon after the thinning. Even the corresponding maximum concentrations were just 0.48, 0.95, 1.43, and 0.04 mg L^{-1}, all of which are much lower than generally observed for agricultural lands in the region (Amatya et al., 1998). Although measured average NO_3-N and total P concentrations on thinned watershed (D3) continued to be higher than the expected values until 2005 (except for TP soon after harvesting and in 2005), these increased values (< 0.3 mg L^{-1} for NO_3-N and 0.07 mg L^{-1} for TP) were low compared to the values reported for the agricultural lands in the region. There was no effect of thinning on TKN concentration as all measured values were lower than the expected for all other periods, except for 2003 when data were not available. TN showed only a small increase in 2005.



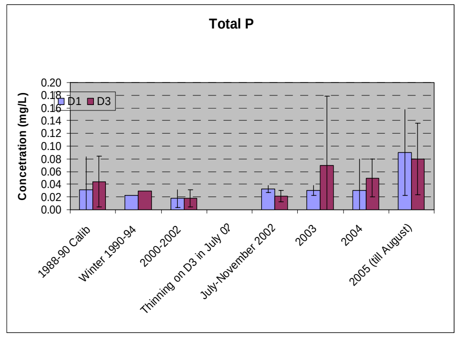


Figure 6. Comparison of mean total N (left) and total P (right) concentrations between the control (D1) and treatment (D3) watersheds for the CLB, PRE, and POST thinning periods.

However, these measured POST nutrient concentrations on the thinned watershed were somewhat higher than those measured during the same years (2002 to 2003) on the adjacent watershed (D2), which was replanted in 1997 after harvest in mid-1995 (Amatya et al., 2006). In that study the authors found no effect of harvest three years after panting for regeneration. In a recent study Beltran (2007) reported a significant increase in all nutrient concentrations measured in drainage outflow that occurred during three major events (September-October) on the treatment watershed (D3) soon after fertilization on September 2005. Those average concentrations for NO_3-N, TKN, TN, and TP were 1.39, 1.49, 2.88, and 0.10 mg L^{-1}, respectively. These results suggest that the fertilization has much more effect on drainage water quality than the silvicultural treatments like thinning and harvesting.

Nutrient Loadings: Measured average nutrient loadings on both D1 and D3 watersheds for the 1988-90 calibration (CLB) and three pre-thinning (PRE) periods since March 2000 to June 2002, and four post-thinning (POST) periods are presented in Table 3. The loading rates are for the periods shown in the first column of Table 3. For example, only 2001, 2003, and 2004 have the loadings on an annual basis. Data also show the calculated expected loadings for the four POST periods. Due to the higher concentrations of NO_3-N and TN measured on the control (D1) in the PRE (2000) than all POST periods (Table 3), the loading rates as high as 8.0 and 21.4 kg ha^{-1} yr^{-1} in 2000 obtained for these nutrients were the highest of all the periods analyzed herein. These loading rates are also much higher than the values of 2.05 and 3.73 kg ha^{-1} yr^{-1} of NO_3-N and TN, respectively, reported by Grace et al. (2006) for their 18-month (November 1999 to April 2001) calibration period in their study of thinning a pine stand on organic soils in eastern North Carolina. The primary reason was the large difference in outflows in 2000 between these two studies. Grace et al. (2006) obtained outflows of only 144 mm for control and 151 mm for treatment in 2000 compared to 738 mm for control and 766 mm for the treatment in this study. Apparently, the 2000 precipitation of more than 1533 mm at this site (Table 2) was at least 373 mm higher than at the Grace et al. (2006) site (1160 mm). This comparison indicates that rainfall (and possibly its distribution not analyzed herein) and the resulting outflow is a primary driver in nutrient loading rates.

Note that the loadings of 5.3 and 11.5 kg ha^{-1} NO_3-N and TN in CLB period (Table 3), however, are for 2-year (March 1988 to February 1990) period. Nitrate loadings on the control were four to six times higher than on the treatment (D3) during both the CLB and PRE periods. A similar pattern for NO_3-N was obtained by Grace et al. (2006). However, with one exception, TKN and total N were about two to four times higher on the control than the thinned watershed (D3) during the same periods. The exception was in 2001 when the treatment (D3) yielded about 80% higher TKN and about 30% higher TN than the corresponding loadings on the control. The higher loadings from D3 were due to both the higher concentrations (Table 3) and slightly higher outflow (Table 2) compared to the control watershed (D1).

Data in Table 3 also show the measured loading rates for all nutrients from the thinned watershed (D3) compared with their corresponding expected loading rates calculated using the calibration factors from the calibration-I (CLB) and pre-thinning (PRE) periods. To compare the loading rates for the POST periods on an annual basis, the measured loadings for six-month of July-December 2002 should be doubled and the values for the first 8 months of 2005 should be multiplied by 1.5. Clearly, measured annual NO_3-N loadings were higher than the expected for all POST periods since soon after the thinning. The increase was only about 13% in the first July 2002-December 2002 period and 2003 followed by about 12% in 2004 and 2005. However, the extrapolated highest NO_3-N loading rate of 1.0 kg ha^{-1} yr^{-1} for 2005 was less than about 3.0 kg ha^{-1} yr^{-1} (4.97 kg ha^{-1} for 20 months) obtained by the Grace et al study. Apparently, thinning did not have any effects on both the TKN and total N loadings (Table 3) at this study site. Total P yielded mixed results with increased loads only in 2003 and 2004. These results are in contradiction with the results obtained by Grace et al. (2006) who reported increases in both TKN and phosphorus and decrease in NO_3-N loadings in their study of thinning a pine stand on organic soils. There are two factors that might have influenced the results in these two studies. Higher drainage outflow rates from the thinned watershed (D3) in 2003 may result in increased nitrate concentrations and loading rates. A long period during May 2001 to December 2002 after thinning in April 2002 in Grace et al study had relatively dry periods without outflows as opposed to wet periods after July 2002 and all 2003 in this study. Consequently, the total outflow in 2002 for this site varied from 351 mm (D3 – treatment) to 426 mm (D1 - control) compared to only 168 mm (control) and 326 mm (treatment) for the Grace et al study. Secondly, the organic soils on Grace et al study may naturally yield higher TKN (NH_4-N + Organic N) concentrations (data not reported), especially due to the first flush effects after a long dry spell.

Summary and Conclusions

A study was conducted to examine the effects of commercial thinning on hydrology and water quality of a 28-year old (in 2002) drained loblolly pine (*Pinus taeda* L.) plantation (watershed D3) using an adjacent watershed (D1) as a control. A paired watershed approach was used with data for two periods (1988-90 and 2000-02) for calibration and 2002-07 for the treatment period. Treatment watershed D3 was thinned in late June of 2002 by removing approximately 50% of the basal area. Thinning treatment on watershed D3 increased water table elevations by as much as 13 cm on average for the first six months after thinning due to increased throughfall (reduced interception) and reduced ET, after which it continued to decline, suggesting increasing ET by canopy closure. Flow analysis suggested that thinning effect was very short-lived and was dependent upon the antecedent conditions. There was a significant increase in mean monthly flow only in 2003 and no significant effects were observed in outflows thereafter. On an annual basis also both the annual outflow and outflow ratio increased only in 2003 and 2005 compared to the expected values and the outflows decreased thereafter indicating a trend to hydrologic recovery due to canopy closure.

Thinning did not have any effect on drainage water nutrient levels in the first-six months although the NO_3-N concentrations continued to increase for three years thereafter compared to the expected values. Total P increased for two years after thinning. There was no effect on TKN concentrations and the total N showed only a small increase in 2005 three years after thinning. Similar results were obtained for the nutrient loadings for the post-thinning periods with a continuous 11-12% increase only in NO_3-N loadings until 2005 and total P increase only until 2004. There was no effect on TKN and total N loadings.

In general, the increases in some of the nutrient concentrations and loading rates reported here are much lower than those observed for the post-fertilization events on the same treatment watershed in later part of 2005. These results tend to confirm previous other studies which indicate only short term and minor effects on drainage water quality to this type of silvicultural treatment.

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