Impacts of Fertilization on Water Quality of a Drained Pine Plantation: A Worst Case Scenario

Bray J. Beltran Arizona State University
Devendra M. Amatya* USDA-FS
Mohamed Youssef North Carolina State University
Martin Jones and Timothy J. Callahan College of Charleston
R. Wayne Skaggs North Carolina State University
Jami E. Nettles Weyerhaeuser Company

Intensive plantation forestry will be increasingly important in the next 50 yr to meet the high demand for domestic wood in the United States. However, forest management practices can substantially influence downstream water quality and ecology. This study analyses, the effect of fertilization on effluent water quality of a low gradient drained coastal pine plantation in Carteret County, North Carolina using a paired watershed approach. The plantation consists of three watersheds, two mature (31-yr) and one young (8-yr) (age at treatment). One of the mature watersheds was commercially thinned in 2002. The mature unthinned watershed was designated as the control. The young and mature-thinned watersheds were fertilized at different rates with Arborite (Encee Chemical Sales, Inc., Bridgeton, NC), and boron. The outflow rates and nutrient concentrations in water drained from each of the watersheds were measured. Nutrient concentrations and loadings were analyzed using general linear models (GLM). Three large storm events occurred within 47 d of fertilization, which provided a worst case scenario for nutrient export from these watersheds to the receiving surface waters. Results showed that average nutrient concentrations soon after fertilization were significantly (α = 0.05) higher on both treatment watersheds than during any other period during the study. This increase in nutrient export was short lived and nutrient concentrations and loadings were back to prefertilization levels as soon as 3 mo after fertilization. Additionally, the mature-thinned watershed presented higher average nutrient concentrations and loadings when compared to the young watershed, which received a reduced fertilizer rate than the mature-thinned watershed.

Published in J. Environ. Qual. 39:293–303 (2010).
doi:10.2134/jeq2008.0506
Published online 22 Oct. 2009.
Received 8 Dec. 2008.
*Corresponding author (damatya@fs.fed.us).
© ASA, CSSA, SSSA
677 S. Segoe Rd., Madison, WI 53711 USA

Water pollution threatens public health both directly and indirectly (USEPA, 2002). Poor water quality also threatens fish and shellfish habitat, negatively impacts commercial and recreational fisheries, causes the closure of harvestable shellfish beds, and could also have a negative impact on tourism (Bricker et al., 1999; Morand and Briand, 1996; Valiela et al., 1997; Lapointe and Bedford, 2007). The 2000 National Water Quality Inventory (NWQI) reported that nutrients were the leading pollutants in lakes and reservoirs, the fifth in rivers and streams and the eleventh in estuaries. The same report concluded that forestry activities contribute to approximately 4% of the water quality problems in all surveyed rivers and streams, and 11% in impaired waters in the same systems. Intensive management practices (IMPs) (which include, harvesting, thinning, pruning, site preparation, bedding, fertilization, herbicide application, and planting for regeneration) have increased southern timber yields by as much as 65% over standard site preparation and planting and by 100% over naturally regenerated forest (Weir and Greis, 2002). Intensive management practices affect the hydrology and water quality of downstream ecosystems by altering water, nutrients, and sediment input to these ecosystems (e.g., Amatya et al., 2006a; Grace et al., 2006). This paper reports the results of a study assessing the effects of fertilization on nutrient concentration and loading in waters drained from a pine plantation in eastern North Carolina.

Several previous studies have focused on the physiological effects (tree growth and development, absorption, and nutrient pro-

B.J. Beltran, Ph.D student, Arizona State University, Environmental Life Sciences Program,1711 S. Rural Rd., Tempe, AZ 85287. D.M. Amatya, Ph.D, P.E. Research Hydrologist, USDA-FS, Center for Forested Wetlands Research, 3734 Hwy. 402, Cordesville, SC 29434. M. Youssef, Ph.D. Assistant Professor, Dep. of Biological & Agricultural Engineering, North Carolina State Univ., Box 7625, Raleigh, NC 27695-7625. M. Jones, Ph.D. Professor, College of Charleston, Dep. of Mathematics, 66 George St., Charleston, SC 29424. T. J. Callahan, Ph.D. Associate Professor, College of Charleston, Dep. of Geology and Environmental Geosciences, 66 George St., Charleston, SC 29424. R.W. Skaggs, Ph.D., P.E. William Neal Reynolds Professor and Distinguished University Professor, Dep. of Biological & Agric. Engineering, North Carolina State Univ., Box 7625, Raleigh, NC 27695-7625. J.E. Nettles, Ph.D. Research Hydrologist, Weyerhaeuser Company, P.O. Box 2288, Columbus, MS 39704-2288. Research was performed while the first author was a M.S. student at the College of Charleston, SC.

Abbreviations: BMP, best management practice; D1, Control watershed; D2, Treatment watershed (Young); D3, Treatment watershed (Mature-thinned); GLM, general linear models; IMP, intensive management practice; TKN, total kjeldahl nitrogen; TP, total phosphorus cess, etc.) of fertilization on loblolly pine (*Pinus taeda* L.) plantations (Sampson et al., 2006; Will et al., 2006; Cough et al., 2004; Murthy and Dougherty, 1997; Vose and Allen 1991); however, few studies have investigated the effects of fertilization on stream water nutrient concentrations (Binkley et al., 1999; McBroom et al., 2008).

Binkley et al. (1999) summarized data from studies of forest fertilization around the world and reported that in general, peak concentrations of N as nitrate (NO_3–N) in stream water increase after forest fertilization with values as high as 10 to 25 mg N L^{-1}; however, all reported yearly average concentrations of NO_3–N were <5 mg N L^{-1}. Relatively high concentrations of stream-water NO_3–N tend to occur with repeated fertilization, use of ammonium nitrate rather than urea, and fertilization of N-saturated hardwood forests. Nitrogen as ammonium (NH_4–N) concentrations may also show large peaks (up to 15 mg N L^{-1}) following fertilization, but annual averages remain <0.5 mg N L^{-1}. Similarly, the same authors reported that the application of phosphate fertilizers was found to increase peak P concentrations in receiving waters to more than 1 mg P L^{-1}, but annual averages remained <0.25 mg P L^{-1}.

Previous studies at the site of this project (eastern North Carolina) evaluated the water quality impacts of drainage and related water and forest management practices. Smith (1994) concluded that the concentration of nutrients in drainage water from three watersheds with 14- to 15-yr-old pine plantations under different water management treatments were below the North Carolina water quality standards, and were in general lower than those in a receiving state highway ditch. The studies by Smith (1994) and Amatya et al. (1998) reported that nutrient concentrations on the control watershed were historically higher than on the young and the mature-thinned watershed; 1.55 and 4.04 times for NO_3–N and 1.47 and 2.45 times for total Kjeldahl N (TKN), respectively. Amatya et al. (1998) concluded that seasonal controlled drainage could be used to effectively reduce total drainage outflows and, thereby, total suspended solids (TSS) and nutrient exports from these drained forested watersheds. Amatya et al. (2003) determined that the water management using an orifice-weir at the outlet increased average annual concentration of TKN, and decreased total phosphorus (TP) and sediment concentration compared to expected results from conventional drainage. In that study it was also determined that the orifice-weir treatment did not have a significant effect on average concentrations of NO_3–N and total nitrogen (TN). Amatya et al. (2006a) concluded that fertilization applied in 1989 on a 16-yr-old watershed after commercial thinning in late 1988 increased the N and TP levels in drainage waters, but these levels were substantially reduced by 1995. In another study at this particular location Amatya et al. (2006b) argue that although harvesting of a 21-yr-old pine plantation resulted in substantial increases in both the nutrient concentrations and loadings (except for TP) the increases lasted for only 3 yr or less after harvest.

A study by Chescheir et al. (2003) found that mean seasonal concentrations of nutrient fractions in drainage from 50% of several study sites in eastern North Carolina were <1.5 mg L^{-1} for TN, <0.1 mg L^{-1} for NH_4–N, and <0.1 mg L^{-1} TP. For 75% of the study sites, mean seasonal concentrations in drainage water were <1.8 mg L^{-1} for TN, <0.6 mg L^{-1} for NO_3–N, <0.22 NH_4–N, and <0.08 mg L^{-1} for TP. Annual TN exports from 75% of the study sites were <6.5 kg ha^{-1}, and annual TP export from all forested sites was <0.36 kg ha^{-1}.

The aforementioned studies did not investigate the effects of fertilization rate on nutrient concentration and export from these forested watersheds. Therefore, a study to quantify the effects of fertilization rate on nutrient concentration and export was conducted and it is presented here. In this study the nutrient concentrations and loadings from two fertilized watersheds of different ages (8 and 31 yr at fertilization) were compared with an unfertilized (control) watershed (31 yr at fertilization). We hypothesized that nutrient concentrations and loadings from the fertilized pine watersheds would be significantly higher than from the unfertilized (control) pine watershed but the increase will be short lived.

Materials and Methods

The study site is located on a loblolly pine plantation owned and managed by Weyerhaeuser Company in Carteret County, North Carolina (34°48′ lat, 76°42′ long) (Fig. 1). The research site consists of three artificially drained experimental watersheds, (D1, D2, and D3) which are 24.7, 23.6, and 26.8 ha, respectively. Topography of the site is characterized by flat, shallow water table soils (McCarthy et al., 1991). The soil is a hydric series, Deloss fine sandy loam (fine-loamy, mixed, semiactive, thermic Typic Umbraquult). Each of the three experimental watersheds is drained by four 1.4 to 1.8 m deep and 2.0 m wide at the surface lateral ditches spaced 100 m apart (Fig. 1).

Additionally the soil texture is fine sandy loam (0–50 cm) and clay loam (> 50 cm), hydraulic conductivity is 3.9 m d^{-1} (auger-hole method), drainable porosity is 0.05 m/m, soil water content at saturation is 0.43 m^3 m^{-3}, soil water content at wilting point is 0.22 m^3 m^{-3}, and the restrictive layer depth is ~2.8 m (McCarthy et al., 1991). Also, the soil is extremely acid with pH ranging from 3.5 to 4.5 (S. Tian and M.A. Youssef, unpublished data, 2009). The topsoil of watershed D1 has more organic carbon (OC) than the topsoil of watersheds D2 and D3. The average OC content of the top 15 cm soil layer, measured in 2007, was 9.5% for D1, 6.9% for D2, and 5.6% for D3 (S. Tian and M.A. Youssef, unpublished data, 2009). Readers are referred to McCarthy et al. (1991) and Amatya et al. (1996) for a more detailed description of the site.

The three watersheds were planted in 1974 at a density of 2100 trees ha^{-1} (average distance between trees was 1.74 m and average distance between rows was 2.74 m). Watershed D1 (control) has served as the control treatment throughout various studies conducted on the site since 1988 (McCarthy et al., 1991; Amatya et al., 1996, 1998, 2000, 2003, 2006a, 2006b; Amatya and Skaggs, 2008). This watershed (31-yr old at the time of fertilization) underwent precommercial 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}).

Watershed D2 (young) was harvested in July 1995, and the site remained fallow until it was replanted in February 1997 with

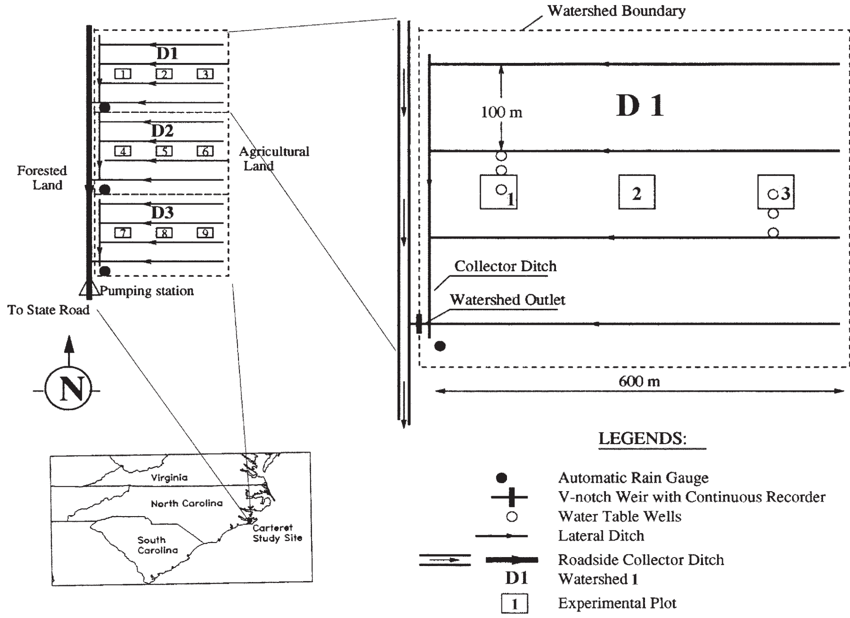

Fig. 1. Location and layout of the three experimental watersheds (D1 [control], D2 [young], D3 [mature-thinned]) at Carteret site, NC. (After Amatya et al., 2000.)

30 to 46 cm tall seedlings 1.52 m apart in rows at an average distance of 3.66 m, resulting in a density of 2100 seedlings ha^{-1} (Amatya et al., 2006a). The survival rate of this watershed was 93% and it was 8-yr old at the time of fertilization. Watershed D3 (mature-thinned) was also a mature 31-yr-old pine plantation at the time of fertilization and it received the same thinning treatment in 1988 as the control watershed. Additionally, watershed D3 was commercially thinned (about 50% of the biomass removed) in July 2002 to a density of about 185 trees ha^{-1} (Amatya and Skaggs, 2008). After monitoring for 8 yr since plantation for regeneration on the young watershed and for 3 yr since thinning on the mature-thinned watershed, both watersheds were fertilized on 8 Sept. 2005 to study the effects of fertilization on water quality drained from these pine watersheds of different ages.

The young and the mature-thinned watersheds were aerially fertilized following Weyerhaeuser procedure for this type of plantation site, tree stand age, and levels of available nutrients in the soil (Fig. 2). To avoid the areas covered by the lateral ditches (ephemeral streams), two aerial passes were made over the central 70 m of the field leaving about 15 m from the edge of the lateral ditch on either side as an unfertilized stream side management zone (SMZ). Side management zones are a type of best management practice (BMP) used in upland forests.

The treatment watersheds were fertilized with urea granules (Arborite 39–9–0) that have a coating of mono-ammonium phosphate (MAP 11–52–0) and a binder that provides N volatility control, following the agricultural format of 39% N and 9% P_2O_5. The rates applied were 303 kg ha^{-1} and 448 kg ha^{-1} of Arborite for the young and the mature-thinned watershed, respectively. Thus the young watershed received 118 kg ha^{-1} N and 12 kg ha^{-1} P and the mature-thinned watershed received 175 kg ha^{-1} N and 17 kg ha^{-1} P. Boron, a micronutrient considered deficient on some Coastal Plain sites, was also present in

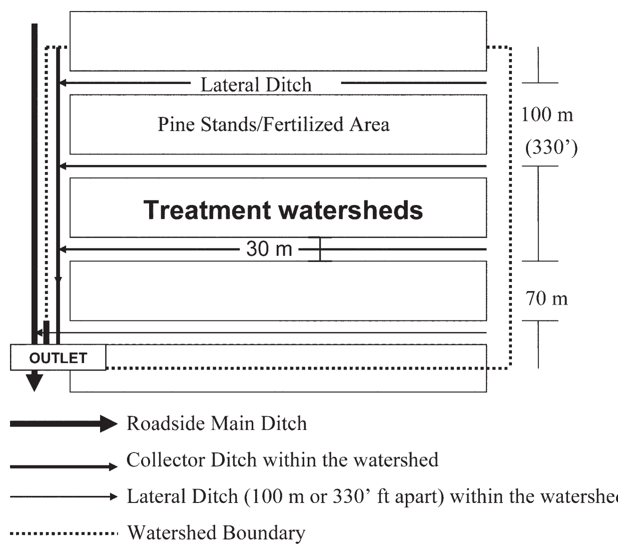

Fig. 2. Schematic of the fertilized area on the treatment watersheds.

the urea coating and the application rate was 0.38 kg ha^{-1} in the young watershed, and 0.56 kg ha^{-1} in the mature-thinned watershed. The fertilizer rate applied has performed as well as, or better (R. Campbell, personal communication, 27 May 2009), than the standard $N_{225}P_{28}$ (225 kg ha^{-1} N and 28 kg ha^{-1} P as 431 kg ha^{-1} of urea and 140 kg ha^{-1} di-ammonium phosphate [DAP]) recommended by the Forest Nutrition Coop (Fox et al., 2006) and widely used in the industry for older stands.

We analyzed continuous outflow and nutrient concentrations during three different periods to test our hypothesis. The three analyzed periods were: Prefertilization (January 2004–August 2005), Postfertilization A (September–October 2005), and Postfertilization B (November 2005– March 2007). During any major rain event, 250 mL of water were collected every 2 h and composited to one 1000 mL bottle, using automatic water samplers SIGMA-900 (Beltran, 2007). Additional to composite samples, grab samples (not collected at regular intervals) were collected on all three watersheds for three large storm events occurring immediately after fertilization in 2005 (Postfertilization A period). These storms were Hurricane Ophelia (14– 15 September, 208 mm rain in 38 h) and two other independent events in October (7– 8 October, 197 mm rain in 48 h; and 25 October, 46 mm rain in 21 h). All water samples were collected at the outlet of each watershed and preserved frozen until transported to the laboratory at North Carolina State University in Raleigh, NC. Laboratory analyses of NO_3–N, NH_4–N, TKN, and TP were colorimetric and done according to U.S. Environmental Protection Agency methods (USEPA, 1979).

After initial collection of all sample bottles during each event, it was later decided to composite the samples further by choosing critical samples based on sampling points on the storm hydrograph for each event (Beltran, 2007) to reduce chemical analysis cost. Another reason to composite the samples further was weir submergence at the watershed outlet for a maximum of 23 h during Hurricane Ophelia, with the downstream stage staying positive and the submergence ratio (downstream stage/upstream stage) as high as one for a very short period. A similar extent of submergence was also observed for the event on 7 to 8 October when the downstream stage was positive. A constant maximum outflow rate value (459 $m^3 h^{-1}$) for the full capacity of the submerged culvert downstream of the weir and an insignificant change in nutrient concentrations were assumed during high weir submergence.

Data Analysis

The analyzed data included rainfall, drainage outflow rates, and nutrient concentrations in drainage waters (Beltran, 2007). Outflow was estimated using standard weir equations for 120° V-notch weir and the upstream stage (head) measured continuously above the V-notch bottom. Weir submergence was detected based on the downstream stage measurements and its extent was based on the magnitude of the ratio of downstream and upstream stages. Nutrient concentration data and loading analysis for determining the effects of fertilization on the treatment watersheds at the study site were conducted using the paired watershed approach suggested by United States Environmental Protection Agency (EPA) (1993) for NPS water quality studies. This approach was previously used at the same site by Amatya et al., 1998, 2000, and 2003. In the analysis, all nutrient concentrations below the laboratory's detection limit were assumed to be at detection limit (0.1 mg L^{-1} for NH_4–N, NO_3–N, TKN; and 0.01 mg L^{-1} for TP) as a conservative estimate.

We used general linear models (GLM) (USEPA, 1993) to study the effect of fertilization on nutrient export from the treatment watersheds compared to the control. One of the assumptions in GLM procedures is the normality of the residuals. To satisfy this condition, we conducted the analysis on log-transformed data. All tests were run at a significance level of $\alpha = 0.05$. We compared nutrient (NH_4–N, NO_3–N, TP, and TKN) concentrations and loadings among the treatment watersheds and the control during the three time periods previously mentioned.

The watersheds were of different ages and possibly different biomass during the Prefertilization period due to previous harvesting and replanting of the young watershed, and commercial thinning of the mature-thinned watershed. Nonetheless, the Prefertilization period was considered as the calibration period because Amatya et al. (2006b) concluded that the difference in water tables between the young and the control watersheds was back to pretreatment levels by December 2002 and outflows on the young watershed had returned to base line levels by 2004. Similarly, hydrologic recovery possibly due to increased canopy closure seemed to have been achieved on the mature-thinned watershed by the end of the third year after thinning in July 2002 (Amatya and Skaggs, 2008). Likewise, there were no effects of thinning on the mature-thinned watershed on TN and TKN (Amatya and Skaggs, 2008).

General Linear Models Analysis

For these analyses, all of the response (treatment) and explanatory (control) variables were transformed using the natural logarithm transformation. Let *Y* represent the measured concentration of a nutrient on one of the watersheds receiving a treatment (either the young or the mature-thinned watershed) and let *X* represent the measured concentration of the same nutrient during the same time period on the control watershed. Linear models of the following type were constructed:

$$\ln(Y) = \beta_0 + \beta_1 \times \ln(X) + \beta_2 \times \mathrm{Tr} + \beta_3 \times \ln(X) \times \mathrm{Tr}$$

where *Tr* is a binary variable (0 or 1) depending on whether or not the measurements were taken during Prefertilization (1) or any of the other two periods (0). The full model *F* test tested the null hypothesis that $\beta j = 0$ for all $j = 1, 2, 3$ (Fig. 3a) vs. the alternative that at least one of these coefficients was nonzero (Fig. 3b, c, d, e, and f). Since the variable *Tr* was binary, the full model yielded two distinct linear regression models, one for each time period. Models were tested sequentially to decide if a single line model, parallel lines model, or separate slope and intercept model best fitted the data. The Type III sums of squares tests were used to determine if any of the terms provided a significant improvement in the model with the other coefficients already fitted to the model.

Note that because of the logarithmic transformation of the variables, the original relationship between *X* and *Y* must be 'decoded'. For example, the relationship $\ln(Y) = \beta_0 + \beta_1 \times \ln(X)$ was expressed as $Y = e^{\beta 0}X^{\beta 1}$. For the 'parallel lines' model with $Tr = 0$ this yielded $Y = e^{\beta 0}X^{\beta 1}$ and with $Tr = 1$ it became $Y = e^{\beta 0+\beta 2} X^{\beta 1}$. For example if $\beta_2 = \ln(k)$ then, under the condition $Tr = 1$ the mean value of *Y* was estimated to be *k* times the mean value of *Y* under $Tr = 0$.

To quantify the actual effects of fertilization on nutrient concentration and loading, expected values under no fertilization were calculated from ratios developed using the mean outflows, concentration and loading between the two treatment watersheds and control watershed during the Prefertilization period. Such an approach to quantify the average effects was also used by Amatya et al. (1998, 2003) and Lebo and Herrmann (1998). For each nutrient, expected concentration and loading (*D2 exp*. and *D3*

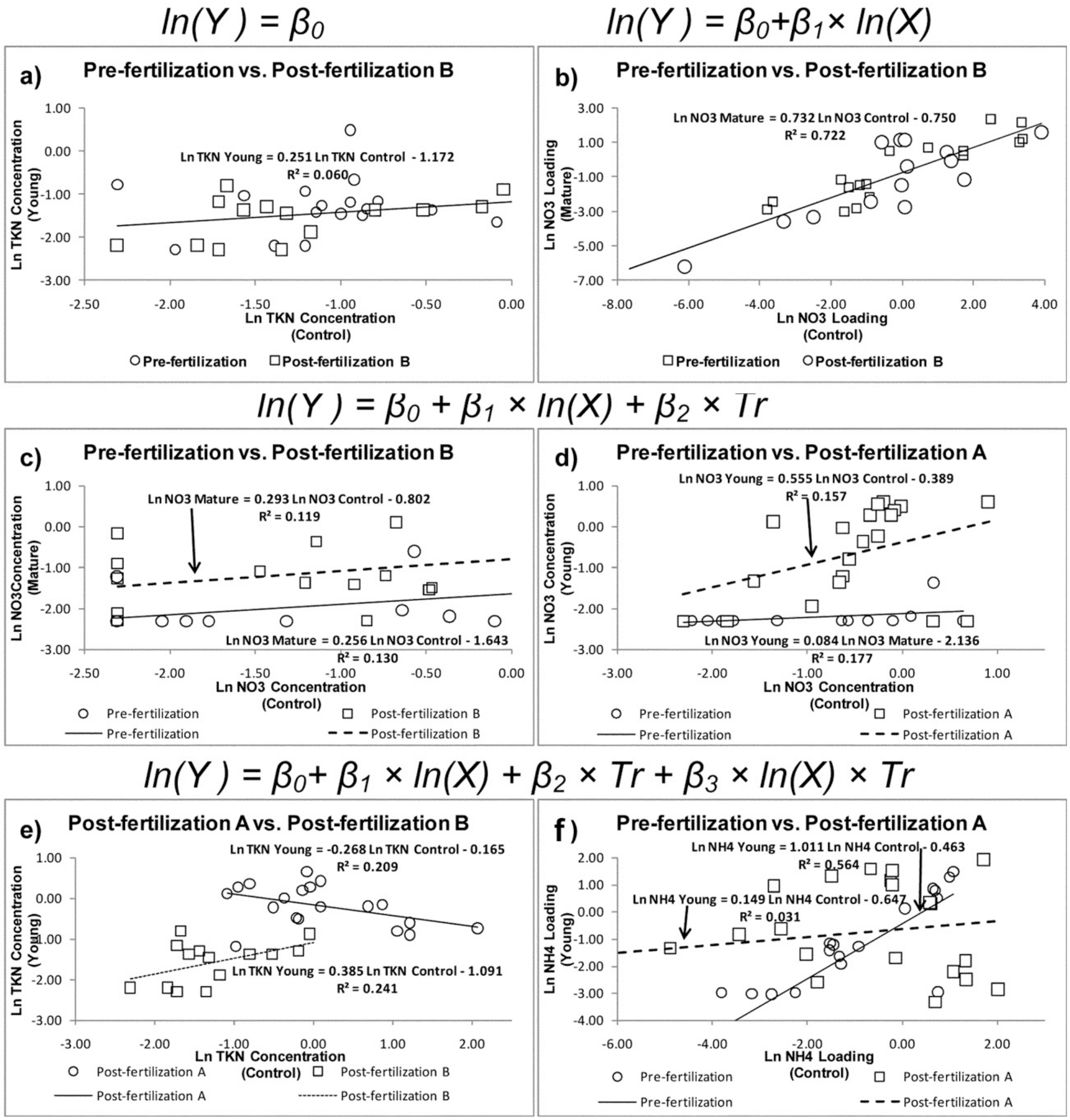

Fig. 3. Different general linear model (GLM) scenarios, (a) Overall model is not significant and does not have any predicting power over the data, $\beta j = 0$ for all j = 1, 2, 3; (b) Single line model is significant, $\beta_1 \neq 0$; (c) Parallel line model and single line model are significant, β_1 and $\beta_2 \neq 0$; (d) only Parallel line model is significant $\beta_2 \neq 0$; e) Separate slopes and intercepts model is significant, $\beta_3 \neq 0$ (lines do not cross); (f) Separate slopes and intercepts model is significant, $\beta_3 \neq 0$ (lines cross). The model's fit is sequential and a significant difference of one coefficient from zero means that that model gives more predictive power over the data with the previous model(s) already fitted.

exp.; had the treatment watersheds not been fertilized) during the treatment period was calculated using the following formulas that include the measured value on the control watershed (D1 meas.):

$$\text{D2 exp.} = [\text{D2(prefert)}/\text{D1(prefert)}] \times \text{D1 meas.}$$

$$\text{D3 exp.} = [\text{D3(prefert)}/\text{D1(prefert)}] \times \text{D1 meas.}$$

The expected values (D2 exp. and D3 exp) were then compared to the actual measured values after fertilization to determine if there was a significant increase in nutrient concentration or loading after the treatment was applied. This analysis when combined with the GLM Procedures provided the average actual amount or percentage increase, if any, in nutrient concentration and loading for the Postfertilization A and B periods. These average actual amount or percentage increases were then used to evaluate the statistical significance of the models and, the difference in both slopes and/or intercepts of the regression for Prefertilization and the Postfertilization A and B periods. Effects on nutrient loading were analyzed using the same methods used to analyze nutrient concentration.

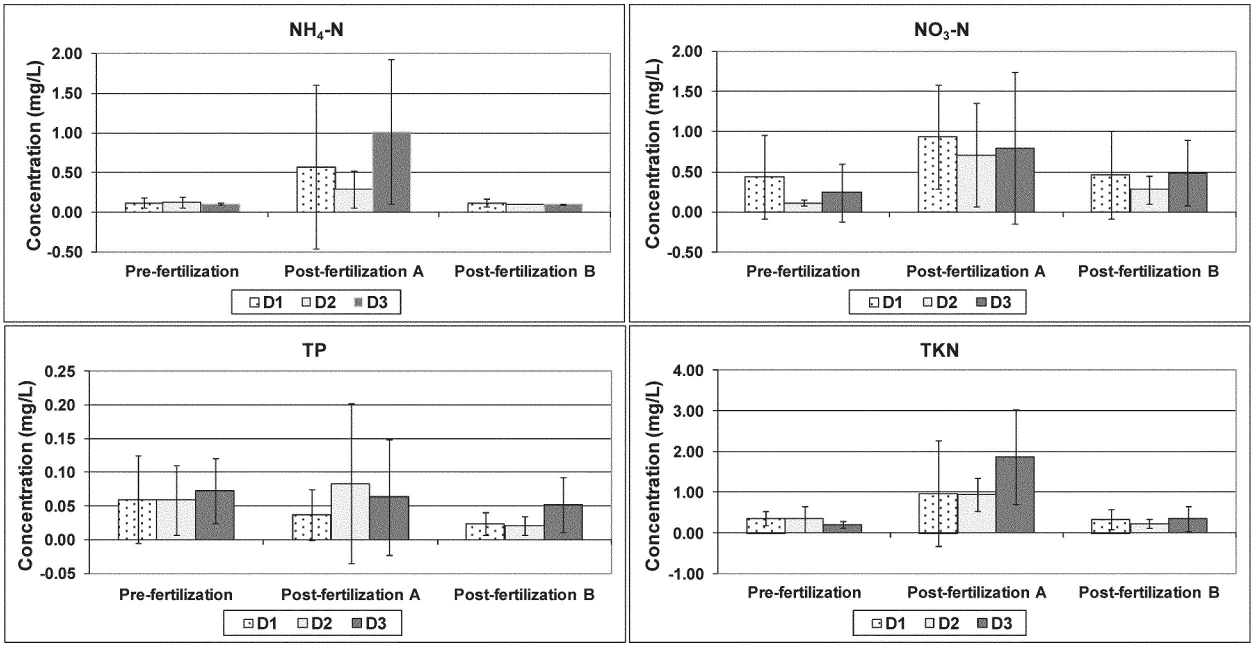

Fig. 4. Measured average nutrient concentrations during Prefertilization, Postfertilization A, and Postfertilization B periods. Watersheds: D1-control, not fertilized; D2-young, fertilized; D3-mature-thinned, fertilized (1.5 more fertilizer than D2).

Results and Discussion

Three large storm events occurred soon after fertilization of the treatment watersheds on 8 Sept. 2005. They were a 5-yr 24-h rain event (208 mm) just 6 d after fertilization, a 2-yr event (197 mm) 29 d after fertilization, and a third event 47 d after fertilization (46 mm in 21 h). These rain events provided the opportunity to analyze a worst case scenario for postfertilization nutrient export from these drained forests. As a result of the rains, storm outflow immediately followed the fertilizer application and caused a significant increase in concentrations and loadings of NH_4–N, NO_3–N, and TKN in the treatment watersheds (Fig. 4 and 5). The mature-thinned watershed presented higher nutrient concentrations and loadings than the young watershed (Fig. 4 and 5). The difference in nutrient export from the two treatment watersheds was not equivalent to the difference in the rate of fertilizer application to the two treatment watersheds. These findings are further discussed below.

Nutrient Concentration

The control watershed was not fertilized but interestingly an increase in NO_3–N, NH_4–N, and TKN concentration was also observed in this watershed after fertilization (Fig. 4). After careful analysis of data and recorded field notes it was ruled out that this increase was the result of fertilizer drift during fertilization. Higher nutrient concentrations in the control watershed should not be considered an anomaly as this has been reported previously (Smith, 1994; Amatya et al., 1998). Also, we attributed the nutrient concentrations increases in the control watershed during Postfertilization A to the flushing phenomenon, where mineralized N and dissolved organic N were leached to the shallow groundwater and the receiving surface water by the storm events. This suggested that a significant portion of the increase in N concentrations and loading on the treatment watersheds might not have even been caused by fertilization; therefore, the effects of fertilization might be even smaller than shown here.

Intrawatershed comparison shows that the average nutrient concentration of NH_4–N, NO_3–N, and TKN increased during Postfertilization A compared to the other analyzed time periods (Fig. 4). Also, peak nutrient concentrations were higher during Postfertilization A than during Postfertilization B for both treatment watersheds (Table 1). A comparison between treatment watersheds during Postfertilization A showed that measured peak concentrations on the mature-thinned watershed were 5.6, 1.9, 0.96, and 3.3 times higher than on the young watershed for NH_4–N, NO_3–N, TP, and TKN, respectively. This indicated that measured peak concentrations were not linearly correlated with the difference in fertilizer application rate (1.5 times more fertilizer to the mature-thinned watershed than to the young watershed). Also, NH_4–N, NO_3–N, and TKN average nutrient concentrations were higher on the mature-thinned watershed than on the young watershed by 3.5, 1.1, and 2.0 times, respectively. On the other hand, TP average concentration was lower on the mature-thinned watershed (0.06 mg L^{-1}) than on the young watershed (0.08 mg L^{-1}).

In addition, average nutrient concentration results supported the findings of Binkley et al. (1999) in which peak nutrient concentration after fertilization were much higher than the average values. Also, average nutrient concentrations during Postfertilization A (Fig. 4) were slightly higher than the ones reported by Chescheir et al. (2003) for 75% of study sites on forests in eastern North Carolina. During Postfertilization B, all nutrients, except for NO_3–N, were below the reported values for 50% of the study sites in the same area.

Nitrogen as nitrate concentration was always below the EPA drinking water standard of 10 mg N L^{-1} (USEPA, 2009), even during Postfertilization A, when the maximum average

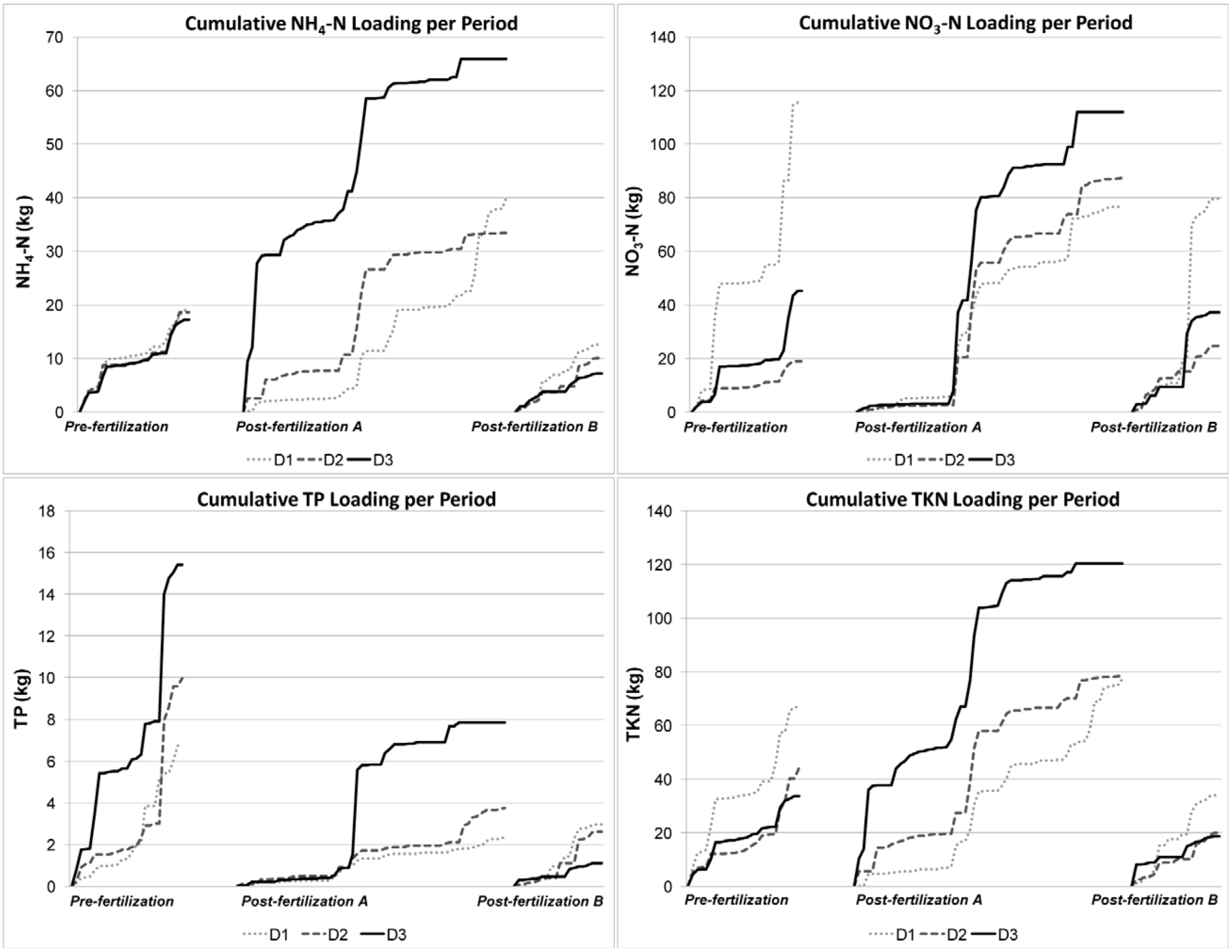

Fig. 5. Cumulative nutrient loading measured on a weekly to biweekly basis on watersheds D1 (control), D2 (young), and D3 (mature-thinned) during the analyzed periods (a) NH4–N, (b) NO3–N, (c) TP, and (d) TKN. The control watershed was not fertilized. Watersheds: D1-control, not fertilized; D2-young, fertilized; D3-mature-thinned, fertilized (1.5 more fertilizer than D2).

Table 1. Measured peak nutrient concentrations (mg L–1) on all three watersheds during the study period. Watersheds: D1-control, not fertilized; D2-young, fertilized; D3-mature-thinned, fertilized (1.5 more fertilizer than D2).

Period	Nutrient	D1 measured peak concentration	D2 measured peak concentration	D3 measured peak concentration
			mg L^{-1}	
Prefertilization (Jan. 2004–Aug. 2005)	NH_4–N	0.37	0.41	0.15
	NO_3–N	1.90	0.25	1.60
	TP	0.18	0.19	0.18
	TKN	0.92	1.60	0.47
Postfertilization A (Sept.– Oct. 2005)	NH_4–N	6.00	0.84	4.7
	NO_3–N	2.5	2.20	4.20
	TP	0.16	0.46	0.44
	TKN	8.00	1.90	6.20
Postfertilization B (Nov. 2005– Mar. 2007)	NH_4–N	0.29	0.10	0.11
	NO_3–N	2.3	0.66	1.60
	TP	0.06	0.60	0.11
	TKN	0.96	0.44	1.40

(0.80 mg NO_3–N L^{-1}) and peak (4.20 mg NO_3–N L^{-1}) nutrient concentration values in the mature-thinned watershed were the highest. Both the maximum average (1.02 mg NH_4–N L^{-1}) and peak (4.70 mg NH_4–N L^{-1}) concentrations of NH_4–N, which happened during Postfertilization A, were within the accepted values by the EPA (USEPA, 1999). The relatively high mobility of the ammonium cation could be explained by the extremely high soil acidity (soil pH between 3.5 and 4.5).

Atmospheric deposition was not considered to be a major input of nutrients into the water draining out of these water-

Table 2. Comparison between expected mean nutrient concentrations (mg L⁻¹) under no treatment (fertilization) and the measured mean nutrient concentrations (mg L⁻¹) after fertilizer was applied. Treatment watersheds (WS): D2-young, D3-mature-thinned (1.5 more fertilizer than D2).

Period	Nutrient	WS	Measured concentration	Expected concentration	Percent increase/ decrease
			mg L^{-1}		%
Post-Fertilization A (September– October 2005)	NH_4–N	D2	0.29	0.59	–50
		D3	1.02	0.49	108
	NO_3–N	D2	0.71	0.24	196
		D3	0.80	0.52	53
	TP	D2	0.08	0.04	109
		D3	0.06	0.05	27
	TKN	D2	0.94	0.91	3
		D3	1.87	0.56	234

sheds as NH_4–N and NO_3–N concentrations did not respond to the fluctuations in atmospheric deposition of nutrients reported by the National Atmospheric Deposition Program (NAPD) in the area (http://nadp.sws.uiuc.edu/, July 2007). Also, in this case, N input through deposition was insignificant when compared to N input through fertilization.

Table 2 shows the expected and the measured mean concentrations on the treatment watersheds during Postfertilization A when nutrient concentrations were considerably higher. Except for NH_4–N on the young watershed, which was 50% lower than the expected concentration, all other measured mean nutrient concentrations were higher than the expected mean value had fertilization not occurred on the treatment watersheds.

Average nutrient concentrations during each of the three periods analyzed were further normalized by outflow (Table 3) to obtain outflow-weighted concentrations. It is important to normalize average nutrient concentrations by outflow because there would probably be more samples or data during a wet year (or period) than during dry periods. Outflow-weighted nutrient concentrations also show a substantial increase in nutrient concentrations right after fertilization on both treatment watersheds (Table 3). This effect is not present as early as 3 mo after fertilization (Table 3). During the Postfertilization A period, outflow-weighted concentration increased several folds for all nutrients, except for TP which varied slightly (±0.01 mg L^{-1}) on all three watersheds (Table 3). Nitrogen as nitrate was the nutrient which responded the most with as much as ten times increase on the young watershed during Postfertilization A when compared to the Prefertilization period (Table 3). This could be possibly due to the relatively rapid nitrification of NH_4^+ (formed during hydrolysis of the urea fertilizer) to NO_3^- which is highly susceptible to leaching due to its negative charge and high mobility. The low response of TP is attributed to the ability of P as phosphate to be held by soils through both electrostatic and nonelectrostatic mechanisms; P usually does not leach in most soils (Sparks, 2003).

The difference in the outflow-weighted nutrient concentrations between the treatment watersheds (Table 3) were well within expected ranges given the tree biomass differences between the two treatment watersheds. The average nutrient response rates of the mature-thinned watershed were 1.9, 1.2, 2.0, and 1.4 times higher than the young watershed for NH_4–N, NO_3–N, TP, and TKN, respectively. This result is consistent with the peak nutrient concentration discussed earlier. Additionally, average outflow-weighted nutrient concentrations for both treatment watersheds during Postfertilization B are very similar to their prefertilization levels (Table 3), except for NO_3–N. Also, the difference in concentrations between the two treatment watersheds (2.3 times higher on the mature-thinned watershed) is equivalent to the difference during the Prefertilization period.

We found that the average calculated nutrient concentrations (Table 4) using the GLM models (Fig. 3) of NH_4–N, NO_3–N, and TKN during the Postfertilization A were significantly higher (α = 0.05) from the prefertilization period on both treatment watersheds. Additionally, except for NO_3–N, which was significantly higher (α = 0.05) than the Prefertilization period on both treatment watersheds, the average calculated concentrations (Table 4) from the GLM models (Fig. 3) during the Postfertilization B were not significantly different from the Prefertilization period and were only detected during the period from 15 Sept. to 31 Oct. 2005 (Postfertilization A). Since the storm outflow events immediately followed fertilizer application and because the fertilizer applied was NH_4–based, the overall portion of the applied fertilizer that was immediately lost through leaching during Postfertilization A was relatively small. As nitrification of the added NH_4–N proceeded with time, more NO_3–N became available for leaching, which persisted for a few months during Postfertilization B.

Nutrient Loading

Nutrient loadings were determined for all three watersheds for the same three periods as for the nutrient concentrations described in the previous section. Unlike nutrient concentration, the average nutrient loading (kg ha^{-1}) was not consistently higher during the Postfertilization A period than during either of the two analyzed periods. Similarly, peak loading values were not consistently higher during Postfertilization A.

Because the analyzed periods were all of different length in time, nutrient loading rates were normalized by time (Table 5). This allowed for a comparison among all periods to determine the effect of fertilization on nutrient loading. Total drainage outflow (in millimeters) per watershed during each period is presented in Table 5 along with the total mass of nutrients leaving each watershed (kg ha^{-1} yr^{-1}). Table 5 shows substantial increases in nutrient loading from the treatment watersheds for the Postfertilization A period compared to the other two periods and to the control watershed. Although the nutrient loading is reported in kg ha^{-1} yr^{-1}, it is important to consider that the values presented here are an extrapolation. None of the analyzed periods were exactly 1 yr long, in particular Postfertilization A which was only 0.24 yr long. The values were reported in this manner to normalize the data and make accurate comparisons.

Calculated dissolved inorganic nitrogen (DIN) (NH_4–N, NO_3–N) loading (Table 5) during Postfertilization A was substantially higher than the value (6.5 kg ha^{-1} yr^{-1}) for 75% of the

Table 3. Outflow-weighted average nutrient concentration (mg L^{-1}) in each watershed during all analyzed periods. Watersheds (WS): D1-control, not fertilized; D2-young, fertilized; D3-mature-thinned, fertilized (1.5 more fertilizer than D2).

Period†	WS	Period length	Outflow	Outflow-weighted average nutrient concentration			
				NH_4–N	NO_3–N	TP	TKN
		yr	mm	mg L^{-1}			
Prefertilization (Jan. 2004– Aug. 2005)	D1	1.59	740	0.10	0.63	0.04	0.37
	D2	1.60	742	0.11	0.11	0.06	0.25
	D3	1.59	645	0.10	0.26	0.09	0.19
Postfertilization A (Sept.– Oct. 2005)	D1	0.24	335	0.49	1.01	0.03	0.95
	D2	0.23	322	0.44	1.15	0.05	1.03
	D3	0.23	302	0.82	1.39	0.10	1.49
Postfertilization B (Nov. 2005– Mar. 2007)	D1	1.41	402	0.13	0.80	0.03	0.34
	D2	1.41	427	0.10	0.24	0.03	0.20
	D3	1.41	296	0.10	0.56	0.02	0.25

† Periods vary in length as data might have been collected at different times and/or intervals at times.

Table 4. Calculated average nutrient concentration (mg L^{-1}) on the treatment watersheds (D2 and D3) from the measured average nutrient concentration (mg L^{-1}) on the control watershed (D1) using the linear equations developed with the general linear models (GLM) models. Watersheds: D1-control, not fertilized; D2-young, fertilized; D3-mature-thinned, fertilized (1.5 more fertilizer than D2).

Period	Nutrient	D1 measured average nutrient concentration	D2 calculated average nutrient concentration	D3 calculated average nutrient concentration
		mg L^{-1}		
Prefertilization (Jan. 2004–Aug. 2005)	NH_4–N	0.12	0.11	0.10
	NO_3–N	0.44	0.11	0.16
	TP	0.06	0.05	0.06
	TKN	0.37	0.25	0.20
Postfertilization A (Sept.– Oct. 2005)	NH_4–N	0.57	0.24	0.44
	NO_3–N	0.93	0.65	1.15
	TP	0.04	0.05	0.04
	TKN	0.98	0.85	1.44
Postfertilization B (Nov. 2005– Mar. 2007)	NH_4–N	0.12	0.10	0.10
	NO_3–N	0.47	0.29	0.36
	TP	0.02	0.02	0.03
	TKN	0.34	0.22	0.29

Table 5. Outflow (mm) and total nutrient load (kg ha–1 yr–1) per watershed during the study period. Watersheds (WS): D1-control, not fertilized; D2-young, fertilized; D3-mature-thinned, fertilized (1.5 more fertilizer than D2).

Period	WS	Period length	Outflow	NH_4–N	NO_3–N	TP	TKN
		yr	mm	kg ha^{-1} yr^{-1}			
Prefertilization (Jan. 2004– Aug. 2005)	D1	1.59	740	0.48	2.94	0.17	1.70
	D2	1.60	742	0.51	0.53	0.26	1.17
	D3	1.59	645	0.41	1.06	0.36	0.79
Postfetilization A (Sept.– Oct. 2005)	D1	0.24	335	6.72	13.97	0.41	13.09
	D2	0.23	322	6.12	16.05	0.69	14.38
	D3	0.23	302	10.90	18.53	1.29	19.87
Postfertilization B (Nov. 2005– Mar. 2007)	D1	1.41	402	0.36	2.28	0.08	0.98
	D2	1.41	427	0.30	0.74	0.08	0.60
	D3	1.41	296	0.21	1.18	0.03	0.51

study sites reported by Chescheir et al. (2003). Our calculated yearly loading amounts during Postfertilization B were below the DIN value reported by that same study. Total P loading rates from the treatment watersheds during Postfertilization A (Table 5) were also higher than the annual TP loading from all forested sites (0.36 kg ha^{-1} yr^{-1}) reported by the same authors. During Postfertilization B, except for NO_3–N, nutrient loadings were below levels during prefertilization (Table 5), which indicates that the increase in nutrient loadings were short lived as initially hypothesized and nutrient loadings were back to pretreatment levels as early as 3 mo after fertilization. This is also an indication that fertilization is the main cause of the nutrient increase in the water draining from the treatment watersheds.

Figure 5 illustrates the cumulative nutrient loadings during each analyzed period. A change in cumulative loading patterns is observed in all nutrients, except TP during Postfertilization A. The NH_4–N cumulative loading pattern (Fig. 5a) was very similar among the control and the treatment watersheds during the Prefertilization period. This pattern changed during Postfertilization A with the treatment watersheds having larger cumulative loading values than the control; except for the last 5 d of the period when the control watershed had higher val-

Table 6. Expected (exp.) total nutrient loading (kg ha^{-1} yr^{-1}) compared to measured (meas.) nutrient loading (kg ha^{-1} yr^{-1}) in the treatment watersheds after Prefertilization. Expected outflow (mm) is also presented. Treatment watersheds (WS): D2-young, D3-mature-thinned (1.5 more fertilizer than D2).

			NH_4–N		NO_3–N		TP		TKN	
Period	WS	Exp. outflow	Exp.	Meas.	Exp.	Meas.	Exp.	Meas.	Exp.	Meas.
		mm	kg ha^{-1} yr^{-1}							
Postfertilization A (Sept.– Oct. 2005)	D2	309	7.18	6.12	2.51	16.05	0.62	0.69	9.00	14.38
	D3	284	5.69	10.90	5.04	18.53	0.86	1.29	6.07	19.87
Postfertilization B (Nov. 2005– Mar. 2007)	D2	410	0.38	0.30	0.41	0.74	0.13	0.08	0.67	0.60
	D3	278	0.30	0.21	0.82	1.18	0.18	0.03	0.45	0.51

ues than the young watershed (Fig. 5a). Prefertilization patterns are observed again during the Postfertilization B period. The cumulative loading pattern of NO_3–N (Fig. 5b) shows the control watershed had much larger cumulative loading values than the treatment watersheds during Prefertilization. This pattern was reversed during the Postfertilization A (Fig. 5b) with both treatment watersheds having larger cumulative nutrient loadings than the control. As with NH_4–N, NO_3–N cumulative loading patterns returned to Prefertilization behavior during Postfertilization B. The cumulative loading of TP was higher on the treatment watersheds than the control during the Prefertilization and Postfertilization A periods (Fig. 5c). The control watershed's cumulative loading was higher than the treatment watersheds, during Postfertilization B, and the levels on the mature-thinned watershed were significantly lower during this period (Fig. 5c). TKN cumulative loading (Fig. 5d) shows the same behavior as NO_3–N. Taking into account that the outflow (Table 4) during Postfertilization A was less than half than during the Prefertilization period and similar to the outflow during Postfertilization B, but that the nutrient loadings during Postfertilization A were greater than during the other two analyzed periods, it is safe to assume that the nutrient loading increase was an effect of fertilization rather than an increase in outflow.

Expected nutrient loadings for the treatment watersheds after fertilization are presented in Table 6. Except for NH_4–N on the young watershed (15% lower), measured nutrient loadings were higher than the expected values on both the watersheds during Postfertilization A. Measured loading for NO_3–N, TP, and TKN on the young watershed were 6.4, 1.1, and 1.6 times higher than expected, respectively. The mature-thinned watershed yielded loading values that were 1.9, 3.7, 1.5, and 3.3 times higher than the expected for NH_4–N, NO_3–N, TP, and TKN, respectively.

Although we argue that the differences in nutrient loading between the two treatment watersheds, and to the control are due to the differences in nutrient concentrations during Postfertilization A we cannot unquestionably conclude that. Due to weir submergence, which caused some inaccuracy in outflow calculation (Beltran, 2007) a direct outflow comparison could not be made during Postfertilization A to unquestionably determine if the nutrient loading difference was due to the change in nutrient concentration in the water or to the difference in total outflow on the treatment watersheds. Nevertheless, and although there were differences in the biomass of the tree stands, the water tables and outflows were not significantly different and back to baseline levels at the beginning of the study (Amatya et al., 2006a). This led us to conclude that the increase in nutrient loading was due to fertilizer addition not differences in outflow. Also, our results are consistent with those found by McBroom et al. (2008) in East Texas, where they found that nutrient export increased after fertilization and nutrient loss rates were observed only for the first few storms after fertilizer application.

Summary and Conclusions

This study was conducted using 39 mo (January 2004–March 2007) of data from a pine plantation site in the coastal plain of North Carolina to evaluate the effects of fertilizer addition (8 Sept. 2005) on nutrient concentration and loading in the drainage waters of two artificially drained watersheds with different stand ages using a paired watershed approach. Rain conditions after fertilization provided a great opportunity to analyze a worst case scenario for nutrient concentration increase and export from the fertilized pine plantations, however we submit this study might not be effective in analyzing the long-term effects of fertilizer application. This is because we believe that three major rain events soon after fertilization removed all excess nutrients and did not allow anytime for the system to store nutrients in the soil and have the excess nutrients leach naturally into the drainage waters.

Peak nutrient and average concentrations in the drainage waters of the pine plantations increased significantly shortly after their fertilization (Postfertilization A period), yet this effect was short lived. We consider this was the direct result of fertilization because the trees did not have time to absorb the fertilizer. However, N concentrations were still below the EPA standard for drinking water during this period of elevated concentrations. Nutrient loadings also increased due to fertilization but loading rates were at or well below pretreatment levels starting as soon as 90 d after fertilization. Therefore, we deem these results important for forest managers in the Atlantic and Gulf Coastal Plain, as they show that site-specific fertilization as a BMP in drained low gradient coastal pine plantations is an effective method that should continue to be used to help safely meet the increase in wood products demand in the United States.

Acknowledgments

We would like to thank the National Council for Air and Stream Improvement Inc. (NCASI) for funding this project through a cooperative grant/agreement between the Forest Service Southern Research Station and the College of Charleston. Also, many thanks are due to Dr. Chip Chescheir and Wilson Huntley (North Carolina State University) for water quality sample processing at the university's laboratory. Weyerhaeuser staff Cliff

Tyson, Sandra McCandless, and Joe Bergman (formerly) for their invaluable help on field data collection and management, and finally Dr. Wendell Gilliam (retired, North Carolina State University) for comments and input.

References

Amatya, D.M., J.W. Gilliam, R.W. Skaggs, M. Lebo, and R.G. Campbell. 1998. Effects of controlled drainage on forest water quality. J. Environ. Qual. 27:923–935.

Amatya, D.M., J.D. Gregory, and R.W. Skaggs. 2000. Effects of controlled drainage on storm event hydrology in a loblolly pine plantation. J. Am. Water Resour. Assoc. 36:175–190.

Amatya, D.M., and R.W. Skaggs. 2008. Effects of thinning on hydrology and water quality of a drained pine forest in coastal North Carolina. *In* E.W. Tollner and A. Saleh (ed.) 21st Century Watershed Technology: Improving Water Quality and Environment, Proc. Int. Conf., Concepcion, Chile. 29 Mar.–3 Apr. 2008. ASABE Publ. 701P0208cd. ASABE, St. Joseph, MI.

Amatya, D.M., R.W. Skaggs, C.D. Blanton, and J.W. Gilliam. 2006a. Hydrologic and water quality effects of harvesting and regeneration on a drained pine forest. p. 537–551. *In* T.M. Williams and J.E. Nettles (ed.) Proc. of the Int. Conf. on Hydrology and Management of Forested Wetlands, New Bern, NC. 8–12 Apr. 2006. ASABE Publ. 701P0406. ASABE, St. Joseph, MI.

Amatya, D.M., R.W. Skaggs, and G.W. Gilliam. 2006b. Hydrology and water quality of a drained loblolly pine plantation in coastal North Carolina. p. 15–26. *In* T.M. Williams and J.E. Nettles (ed.) Proc. of the Int. Conf. on Hydrology and Management of Forested Wetlands, New Bern, NC. 8–12 Apr. 2006. ASABE Publ. 701P0406. ASABE, St. Joseph, MI.

Amatya, D.M., R.W. Skaggs, and J.D. Gregory. 1996. Effects of controlled drainage on the hydrology of a drained pine plantation in the North Carolina Coastal Plains. J. Hydrol. 181:211–232.

Amatya, D.M., R.W. Skaggs, and J.E. Hughes. 2003. Effects of an orifice and a weir on the hydrology and water quality of a drained forested watershed. Southern J. Appl. For. 27:130–142.

Beltran, B.J. 2007. Impacts of fertilizer additions on water quality of a drained pine plantation, lower coastal plain of North Carolina. M.S. thesis. Environmental Studies Program, College of Charleston, Charleston, SC.

Binkley, D., H. Burnham, and H.L. Allen. 1999. Water quality impacts of forest fertilization with nitrogen and phosphorus. For. Ecol. Manage. 121:191–213.

Bricker, S.B., C.G. Clement, D.E. Pirhalla, S.P. Orlando, and D.R.G. Farrow. 1999. National estuarine eutrophication assesment: Effects of nutrient enrichment in the nation's estuaries. NOAA, Natl. Ocean Serv., Special Projects Office and the Natl. Centers for Coastal Ocean Sci., Silver Spring, MD.

Chescheir, G.M., M.E. Lebo, D.M. Amatya, J. Hughes, J.W. Gilliam, R.W. Skaggs, and R.B. Herrmann. 2003. Hydrology and water quality of forested lands in eastern North Carolina. Tech. Bull. 320. North Carolina Agric. Res. Serv., North Carolina State Univ., Raleigh.

Cough, C.M., J.R. Seiler, and C.A. Maier. 2004. Short-term effects of fertilization on loblolly pine (*Pinus taeda* L.) physiology. Plant Cell Environ. 27:876–886.

Fox, T.R., H.L. Allen, T.J. Albaugh, R. Rubilar, and C.A. Carlson. 2006. Forest fertilization in southern pine plantations. Better Crops 90:12–15.

Grace, J.M., III, R.W. Skaggs, and G.M. Chescheir. 2006. Hydrologic and water quality effects of thinning loblolly pine. Trans. ASABE 49:645–654.

Lapointe, B.E., and B.J. Bedford. 2007. Drift Rhodophyte blooms emerge in Lee County, Florida, USA: Evidence of escalating coastal eutrophication. Harmful Algae 6:421–437.

Lebo, M.E., and R.B. Herrmann. 1998. Harvest impacts on forest outflow in coastal North Carolina. J. Environ. Qual. 27:1382–1395.

McBroom, M.W., R.S. Beasley, and M. Chang. 2008. Water quality effects of clearcut harvesting and forest fertilization with best management practices. J. Environ. Qual. 37:114–124.

McCarthy, E.J., R.W. Skaggs, and P. Farnum. 1991. Experimental determination of the hydrologic components of a drained forested watershed. Trans. ASAE 34:2031–2039.

Morand, P., and X. Briand. 1996. Excessive growth of Macroalgae: A symptom of environmental disturbance. Bot. Mar. 39:491–516.

Murthy, R., and P.M. Dougherty. 1997. Effect of carbon dioxide, fertilization and irrigation on loblolly pine branch morphology. Trees (Berlin) 11:485–493.

Sampson, D.A., R.H. Waring, C.A. Maier, C.M. Gough, M.J. Ducey, and K.H. Johnsen. 2006. Fertilization effects on forest carbon storage and exchange, and net primary production: A new hybrid process model for stand management. For. Ecol. Manage. 221:91–109.

Smith, K.L. 1994. Assessing water quality impacts of forest management activities in Pocosin wetlands in eastern North Carolina. M.S. thesis. Univ. of Georgia. Athens.

Sparks. Donald L. 2003. Environmental soil chemistry. 2nd ed. Elsevier Sci., San Diego, CA.

U.S. Environmental Protection Agency. 1979. Methods for chemical analyses of water and wastes. EPA-600/4–79–020. USEPA, Environmental Monitoring and Support Lab., Cincinnati, OH.

U.S. Environmental Protection Agency. 1993. Paired watershed study design. EPA- 841-F-93–009. USEPA, Office of Water, Washington, DC.

U.S. Environmental Protection Agency. 1999. 1999 Update of ambient water quality criteria for ammonia. EPA822-R- 99–014. Available at http://www.epa.gov/waterscience/criteria/ammonia/99update.pdf (accessed December 2007; verified 4 Sept. 2009). USEPA Office of Water, Office of Sci. and Technol., Washington, DC.

U.S. Environmental Protection Agency. 2009. National primary drinking water regulations. EPA-816-F-09–004. Available at http://www.epa.gov/safewater/consumer/pdf/mcl.pdf (verified 15 Sept. 2009). USEPA, Washington, DC.

U.S. Environmental Protection Agency. 2002. National water quality inventory–2000 report: U.S. Environmental Protection Agency Office of Water Report EPA-841-R-02–001. Available at http://www.epa.gov/305b/2000report (accessed July 2007; verified 4 Sept. 2009). USEPA, Washington, DC.

Valiela, I., J. McClelland, J. Hauxwell, P.J. Behr, D. Hersh, and K. Foreman. 1997. Macroalgal blooms in shallow estuaries: Controls and ecophysiological and ecosystem consequences. Limnol. Oceanogr. 42:1105–1118.

Vose, J.M., and H.L. Allen. 1991. Quantity and timing of needlefall in N and P fertilized loblolly pine stands. For. Ecol. Manage. 41:205–219.

Weir, D.N., and J.G. Greis. 2002. Southern forest resource assessment: Summary report. Gen. Tech. Rep. SRS-54. U.S. Department of Agric. Forest Serv., Southern Res. Stn., Asheville, NC.

Will, R.E., D. Markewitz, R.L. Hendrick, D.F. Meason, T.R. Crocker, and B.E. Borders. 2006. Nitrogen and phosphorus dynamics for 13 year-old loblolly pine stands receiving complete competition control and annual fertilizer. For. Ecol. Manage. 227:155–168.