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Effects of Timber Harvest on Water Quantity and Quality in Small Watersheds in the Piedmont of North Carolina

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This paired watershed study tested the effects of timber harvest on water quantity and quality in the North Carolina Piedmont physiographic region. Four headwater watersheds at Hill Demonstration Forest (HF1, HF2, HFW1, and HFW2) and two at Umstead Research Farm (UF1 and UF2) were continuously monitored for discharge and water quality from 2007 to 2013. The HF1 and UF1 watersheds were clearcut (treatment), leaving a 15.2-m vegetated riparian buffer around the streams to protect water quality as described in the North Carolina Neuse River Basin Riparian Buffer Rule. HF2 and UF2 were uncut and used as reference watersheds. Merchantable timber was selectively removed from the riparian buffer, reducing tree basal area by 27% in HF1 and 48% in UF1. HF1 and HF2 were nested within HFW1; thus, HFW1 was considered a partial cut where 33% of the watershed area was harvested, and HFW2 was the reference. We found that discharge in treatment watersheds increased dramatically, averaging 240% in HF1 and 200% in UF1 and 40% in HFW1 during the postharvest period, 2011–2013. Total suspended sediment export in the treatment watersheds also increased significantly in HF1 after harvest, probably due to the increase of discharge and movement of in-channel legacy sediment. Stormflow peak nitrate reached its maximum concentration during the first 2 years after harvest in the treatment watersheds and then declined, corresponding to the rapid regrowth of woody and herbaceous plants in the riparian buffer and uplands. We found that 36% of the UF1 streambank trees were blown down but did not cause a measurable increase in mean daily stormflow total suspended sediment concentration. Most buffer tree blowdown occurred during the first few years after a harvest. Bioclassification of benthic macroinvertebrates indicated that stream water quality remained good/fair to excellent in the treatment watersheds after the harvest. We conclude that the temporary increases in discharge were relatively large for the Piedmont region compared with those for other regions in the southeastern United States. However, the increases in channel sediment transport and nutrient exports associated with the hydrologic change did not have a measurable impact on the indicators of aquatic invertebrate community health or bioclassification rankings.

Keywords: riparian buffer, best management practices, hydrology, water quality, North Carolina Piedmont

In the United States, the best quality water comes from forested watersheds, even when forests are managed primarily for timber production (Dissmeyer 2000, Jackson et al. 2004, Sun et al. 2004, Brown et al. 2008). However, potential sources of disturbance to the forest floor, such as access and logging roads, stream crossings, and skid trails, used for forestry activities can cause soil erosion and contribute sediment and nutrients to streams and other water bodies (Brown and Binkley 1994, Aust et al. 2011).

The paired watershed approach has been widely used for years by researchers to understand the processes of impacts of land management on watershed hydrology and water quality (Swank and Crossley 1988). The general experimental design consists of at least two watersheds, one reference and one treatment, and includes a calibration period and a treatment (i.e., timber harvest) period. Calibrating the paired watersheds requires development of a quantifiable hydrologic and water quality relationship through time between watershed pairs (US Environmental Protection Agency 1993). Preharvest calibration is a major step in assessing and

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This article uses metric units; the applicable conversion factors are: centimeters (cm): 1 cm = 0.39 in.; meters (m): 1 m = 3.3 ft; square meters (m^2): 1 m^2 = 10.8 ft^2; millimeters (mm): 1 mm = 0.039 in.; kilograms (kg): 1 kg = 2.2 lb; milligrams (mg): 1 mg = 0.015 gram; hectares (ha): 1 ha = 2.47 ac.

developing predictive models of treatment impacts in a paired watershed design (Swank et al. 2001). The length of the calibration period varies across watersheds due to different controlling factors such as watershed size, soil types, surface cover, and topography (Brooks et al. 2003).

Although the paired watershed approach represents the most rigorous method to quantify forest management effects on water quantity and quality, its applications are often costly and time-consuming. There is also a lack of scientific data and rigorous, long-term watershed-scale forest hydrologic studies in the Piedmont region. In addition, there is still some debate about site-specific design criteria for riparian buffer zones such as type of vegetation management and buffer size. For example, research has shown that when trees in riparian buffers of a certain size are exposed to high winds, blowdown can occur (Grizzel and Wolff 1998). Quantifying the role of evapotranspiration (ET) in watershed response to disturbance in Piedmont watersheds can help with the development of forestry best management practices (BMPs) for reducing stormflow and watershed degradation (Boggs and Sun 2011).

This study seeks to quantify the differences between stream discharge and water quality characteristics (e.g., total suspended sediment, nutrients, and temperature) of forested Piedmont watersheds under undisturbed conditions and clearcuts. We hypothesize that the relationships of water quantity and quality parameters between the treatment watersheds and the reference watersheds will be significantly different from the established relationship of those same watersheds in their uncut state. We also hypothesize that any changes in water quality and quantity will not result in a measurable and sustained change in the benthic bioclassification rankings. Data from this study are useful for addressing land management challenges linked to timber harvesting and other silvicultural activities in the Piedmont region in the southeastern United States.

Materials and Methods

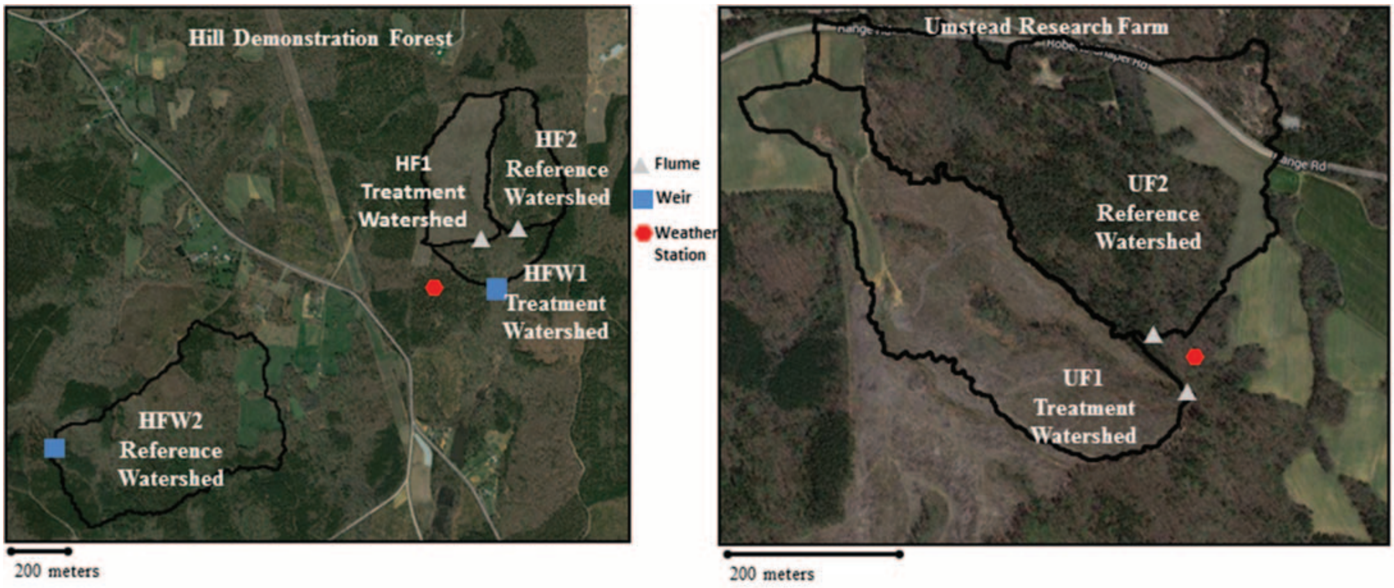
Study Sites

We used a standard paired watershed approach in this 6(+) year (2007–2013) monitoring study. Two paired watersheds were located in the Hill Demonstration Forest (HF) and Umstead Research Farm (UF). The two paired watersheds (treatment watershed HF1 versus reference HF2, treatment watershed UF1 versus reference UF2) and two other watersheds (partial treatment HFW1 versus reference HFW2) are located in the North Carolina Piedmont region (Figure 1). The HFW1 and HFW2 watershed pair was not a part of the original design, but given that the V-notch weirs were already installed in the 1960s as part of another study, we took advantage of the opportunity to monitor them. HF1 and HF2 are nested within HFW1. Therefore, HFW1 is considered a partial treatment watershed where about one-third of the total watershed area was clearcut. HF1, HF2, UF1, and UF2 range from 12 to 29 ha in size with perennial stream channels fitted for stream discharge and water quality monitoring. Dominant overstory species on these sites include red maple (*Acer rubrum*), pignut hickory (*Carya glabra*), mockernut hickory (*Carya tomentosa*), white oak (*Quercus alba*), northern red oak (*Quercus rubra*), American beech (*Fagus grandifolia*), sweetgum (*Liquidambar styraciflua),* tulip poplar (*Liriodendron tulipifera*), sourwood (*Oxydendrum arboreum*), and loblolly pine (*Pinus taeda).* HF1 and HF2 are located in the Flat River Watershed at the North Carolina State University HF in northern Durham County. UF1 and UF2 are located in the Knap of Reeds Watershed at the North Carolina Department of Agriculture and Consumer Services UF in western Granville County. We also monitored hydrology and water quality in the two larger (HFW1 and HFW2) watersheds at HF. A small portion (~10%) of HFW2 was cut before the beginning of this study, but this did not appear to alter the discharge characteristics or other conditions such that it could not serve as a reference watershed.

HF streams (HF1, HF2, HFW1, and HFW2) are about 1 m wide and 30 cm deep, connected to their narrow floodplain, and have a rocky substrate. These stream channels have steep upland slopes ranging from 15 to 40% with watersheds underlain by soils that have features that are consistent with the Carolina Slate Belt (CSB) region. HF upland soils are defined as well drained with depth to water table of >2 m and tend to function in a similar capacity in the growing season and dormant season. UF streams (UF1 and UF2) are about 2 m wide and 1.5 m deep, are detached from their wide floodplain, and have sandy substrate and gentle upland slopes averaging 7%. UF watersheds are underlain by Triassic Basins (TB) soil characteristics, which are clayey with lower permeability, higher shrink swell characteristics, and thinner soil layers than Carolina Slate Belt soils (US Department of Agriculture 1971). They also generally have a 10-cm thick confining clay layer 30 cm below ground surface, which creates an impermeable condition that results in a perched water table during the dormant season. These features cause variability in how TB soils store, release, and generate water between the growing season and dormant season. TB soils cover about 3.5% of North Carolina land (Cleland et al. 2007) and extend to a small portion of South Carolina. Additional details on stream channels can be found in Boggs et al. (2013) and Dreps et al. (2014).

Management and Policy Implications

There are three distinct land provinces across North Carolina: the mountains, Piedmont, and coastal plain. Understanding how region-specific watershed hydrology responds to land management and natural disturbances can provide useful information to land managers as they set flow targets needed to maintain ecological integrity in surface waters or to design riparian buffers for water quality protection. We found that after a clearcut timber harvest with a riparian buffer zone around the streams, the percent increases in annual discharge and mean nitrate concentrations tended to be higher in the Piedmont region than in the other two regions. Our study also found that tree blowdown in the riparian buffer was more likely to occur in the Piedmont Triassic region than in the Piedmont Carolina Slate Belt region. In the Triassic region, additional management activities should be part of the preharvest planning process as they may help mitigate windthrow and uprooting of streambanks and improve the overall riparian buffer functions and flow dynamics. For example, land planners or loggers should assess whether soils have Triassic or Slate Belt characteristics to determine if they need to refrain from creating gaps and retain more windfirm species within the riparian buffer. Although there was variation in blowdown occurrences among regions, Triassic soils comprise about 3.5% of North Carolina's total land area, so any statewide implications would be low and recommendations would be localized.



	Hill Demonstration Forest				Umstead Research Farm	
	HF1	HF2	HFW1	HFW2	UF1	UF2
Watershed size (ha)	12	12	29	40	19	29
Stream length (m)	300	260	800	960	550	200
Stand type	Mixed-pine hardwood				Mixed-pine hardwood	
Stand Age (years)	35				70	
Slope (%)	13				7	
Geologic Features	Carolina Slate Belt				Triassic Basin	
Dominate Soil Series	Tatum and Appling				Helena	
Soil characteristics	Non expansive clays, no perched water, deep soils, discharges water slowly throughout the year due to large amounts of stored water in bedrock and topographic control.				Expansive clays, perched water, thin soils, discharges water slowly in growing season when soils are dry with an in-active confining clay layer, and fast in dormant season when soils are wet with an active confining layer.	

Figure 1. Aerial views of paired study watersheds and descriptive attributes.

Riparian Vegetation Surveys

To characterize vegetation composition along a 10% reach of the stream study area, 4 152-m^2 vegetation survey plots in HF1, 6 plots in HF2, 10 plots in UF1, and 4 plots in UF2 were established. Stem count, dbh of overstory trees, and canopy cover in each plot were measured annually following protocols outlined in the Carolina Vegetation Survey (Peet et al. 1998). Percent canopy cover was measured at plot center with hemispherical photography every year during the growing season. Six 1-m^2 subplots were also established in each plot to estimate percent groundcover. Visual observations for riparian buffer sediment breakthroughs or overland flow were assessed at least monthly or after large (>25 mm) storm events along the entire reach and width of the channel. Breakthroughs were determined to be one of the following: overland and sediment flowing through the riparian buffer to the channel; only overland flow moving through the riparian buffer to the channel; or evidence of overland flow or sediment moving into the riparian buffer but being dispersed before reaching the stream (Rivenbark and Jackson 2004). Field inspections in April 2013 and August 2013 revealed considerable blowdown in one of the treatment watersheds (UF1). Thus, additional vegetation surveys were taken to determine the number and diameter size of standing and windthrown stream edge trees. Stream edge trees were defined as trees having roots exposed in the stream channel. All blowdown trees had tip-up mounds with some mounds being as large as 3 m in diameter (Figure 2). If a stream edge tree had a broken top, it was not counted as blowdown.

Harvest

The entire watershed areas at both study sites were clearcut harvested using typical rubber tire-mounted logging equipment. Logging on UF1 took place between July 7 to Sept. 8, 2010, and logging on HF1 occurred from Nov. 29, 2010 to Jan. 19, 2011. In each clearcut harvest, a 15.2-m riparian buffer was retained on each side of the stream. High-value trees (trees of ≥35.6 cm dbh for pine and ≥40.6 cm for hardwood) were harvested from the riparian buffer as allowed by the Neuse River Basin Riparian Buffer Rule (NRR). Hand felling of high-value and merchantable timber within inner zone 1 (0–3 m from the stream bank) and outer zone 1 (3–9.1 m from the stream bank) of the riparian buffer was done as outlined in the NRR. On each study site, additional BMPs were deployed to prevent sedimentation and water quality pollution and to comply with the North Carolina Forest Practices Guidelines Related to Water Quality. For example, trees were skidded to the log deck without crossing the stream channel, and slash was redistributed across the upland and skid trails to limit soil distur-

Figure 2. Tip-up mound of blowdown of stream edge tree in UF1 at Umstead Research Farm, Granville County, North Carolina. Photo courtesy of Johnny Boggs, USDA Forest Service, August 2013. Pictured in photo: Neil Williams, Forestry Technician, USDA Forest Service.

bance. Site preparation for replanting included one aerial herbicide application, a bladed fireline around the watershed boundary, and a low-intensity site preparation burn that was initiated from outside of the riparian buffer. A fireline was not put around the riparian buffer. The site preparation process and hand planting operation occurred between June 2011 and January 2012 in HF1 and between July 2011 and January 2012 in UF1. Loblolly pine was planted in HF1, and shortleaf pine (*Pinus echinata*) was planted in UF1.

Stream Discharge and Water Quality Measurements

A 2-H flume was used as the flow control structure at the outlet of HF1, HF2, UF1, and UF2, and a 90° V-notch weir was used at the outlet of HFW1 and HFW2. A Sigma 900 Max water sampler with a depth sensor was used to measure and log discharge data every 10 minutes in units of liters/second. This unit was then converted to mm to normalize the watershed discharge data and to make the discharge data comparable to precipitation. Discharge data in this article are reported in mm (see Supplemental Figure S1S to convert mm back to liters). Precipitation was measured in an open area with a HOBO Datalogging Rain Gauge RG3 at HF and UF. Water quality concentrations and exports were quantified from grab and storm-based samples. Grab water samples were collected at least biweekly under baseflow conditions. The Sigma sampler was programmed to trigger based on an increase in the flow rate of change (e.g., 1.1 liters/second). Storm-based samples were collected on a stratified sampling program, intensive sampling during rising limb (6 samples in 1 hour) and less intense sampling during recession limb (6 samples over 6–10 hours) of the hydrograph. To avoid the potential to overemphasize one limb of the hydrograph (or to interpolate between measured times), a time-weighted mean concentration for each constituent was computed and then flow weighted concentrations were determined.

Water quality parameters included total suspended sediment (TSS), total organic carbon (TOC), ammonium-nitrogen (NH_4-N), nitrate-nitrogen (NO_3-N), total phosphorus (TP), total Kjeldahl nitrogen (TKN), stream temperature, and a macroinvertebrate bioclassification or biotic index. Samples were preserved with sulfuric acid to pH of <2. Water samples collected from the field were kept at 3.6° C before analysis. Constituents from each water sample were determined at the North Carolina State University Soil Science Analytical Laboratory using standard methods (Greenburg 1992). The changes in water quality parameters were initially measured in mg liter^{-1} during both stormflow and baseflow conditions. These values were then multiplied by discharge volume to determine outputs expressed as kg ha^{-1} month^{-1} and kg ha^{-1} year^{-1}. Total organic nitrogen (TON) equals TKN minus NH_4-N. Total nitrogen (TN) equals TKN plus NO_3-N. Stream temperature data were logged every 10 minutes using HOBO Pro v2 water temperature sensors.

During the preharvest period, two benthic surveys were completed in all six watersheds but only covered the nongrowing season because of limited sampling time. Seven postharvest surveys were taken in all watersheds and covered both growing and nongrowing seasons. Surveys were taken across seasons to capture differences in the life cycle of benthic macroinvertebrates, seasonal discharge, and climate variability. Benthic macroinvertebrate surveys were completed following the semiquantitative methods outlined by the North Carolina Department of Environmental and Natural Resources (2012) Division of Water Resources, Biological Assessment Unit Qual4 method, for which a kick net, sweep net, leaf pack, and visual samples were collected from each stream. Benthic macroinvertebrate samples were field sorted and sent to Watershed Science, LLC, to be identified to the lowest possible taxonomic class. To rate water quality condition, a bioclassification class (excellent, good, good/fair, fair, or poor) for small streams (i.e., <4.6 m wide) was assigned to each survey, which was based on the average values from Ephemeroptera, Plecoptera, and Trichoptera (EPT) taxa richness and biotic index (Lenat 1993, 2014). EPT taxa richness is the number of Ephemeroptera, Plecoptera, and Trichoptera taxa in a sample. Generally, the higher the taxa richness is, the better the water quality condition. The EPT taxon captures the full range of water quality conditions through time, whereas baseflow and stormflow samples do not fully capture conditions between samples. A mixture of both water chemistry and benthic surveys probably offers the best data to assess water quality condition.

The dominant trophic category or functional feeding group (FFG) percentages (i.e., collector gather, scraper collector, obli-

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gate scraper, shredder, predator, collector filters, and omnivore scavenger) for each macroinvertebrate species was calculated by assigning a semiquantitative value to the occurrence class: rare = 1, common = 3, and abundant = 10. The FFG percentages were used in conjunction with bioclassification and other indicators to provide additional information about the treatment effect and to assess process-level attributes about the aquatic ecosystem (Rawer-Jost et al. 2004).

Data Processing and Analysis

The experimental design consisted of a pair of watersheds (reference and treatment), a calibration or preharvest period, a treatment (i.e., tree harvest), and a postharvest period (Swank et al. 2001). In the preharvest phase (2007–2010), discharge, TSS, and the water quality parameters from the paired watersheds were calibrated.

To calibrate the watersheds, a set of linear relationship/models ($y = mx + b$) between daily discharge and monthly TSS and nutrient concentrations and exports from each pair were generated with all $P < 0.05$. Postharvest reference watershed data were then put into that linear model to predict what the treatment watershed trend would be if the harvest had not occurred. Postharvest modeled treatment data and postharvest measured reference data were compared to evaluate the treatment effect. Our paired watersheds did not have identical soil and vegetative composition and stormflow discharge. Thus, calibrating the reference watershed to the treatment watershed provided a more accurate assessment of treatment effects on discharge, water quality data, and cause-effect relationships compared with referencing the treatment watershed directly. Our 32-month calibration period developed a robust enough model for these small catchments to account for any changes or variation in climate and other factors during the postharvest period (US Environmental Protection Agency 1993). Wilm (1944, 1948) developed the following equation to determine the minimum length of calibration time required for a watershed to predict treatment effects with a reasonable level of certainty (in our study, measured and modeled discharge was within 2 SD of each other)

$$k = \frac{s_{y,x}^2\, F}{d^2}$$

where k equals the number of observations from each of the two data sets, $s_{y,x}^2$ is the SE of the estimate (y) in mm/month, the F statistic equals $F\{2 + [F/(k - 1)]\}$, and d equals the smallest noteworthy change in monthly runoff. Based on Wilm's equation calibration, watersheds (HF1 and HF2) could be calibrated in 10 months at $\alpha = 0.05$ and 32 months at $\alpha = 0.01$ (Boggs et al. 2008).

We analyzed mean annual ($n = 3$) TSS and nutrient concentrations and exports across preharvest and postharvest periods using a t-test (SAS Institute, Inc. 2011). The t-test was selected, and the significance level was set to $\alpha \leq 0.05$ to determine which group values (measured versus modeled) were statistically different from each other. Significant differences statements are $\alpha \leq 0.05$. Storm parameters were derived from a constant slope separation method where water is discharged from a watershed in excess of 1.1 mm/day as described by Hewlett and Hibbert (1967). The constant slope value was applied to the separation analysis during 13 to 44 storms when at least 15–20 mm of measured rainfall occurred. Slope separation was terminated when the total volume of discharge exceeded the baseflow discharge. The average separation analysis lasted 21.2 (SE, 3.3 hours) hours during the nongrowing season (November to April) and 12.9 (2.2) hours during the growing season (May to October).

Results

Vegetation Changes in the Riparian Buffer

The riparian buffer vegetation for the preharvest period was consistent with a basal area range found in the closed-canopy Piedmont mixed pine-hardwood riparian forests (Supplemental Table S1; Figure 1). According to the NRR, trees can be removed from the riparian buffer during logging. Selective removal of trees from the riparian buffer reduced HF1 pine and hardwood overstory basal areas by 24 and 28%, respectively. Tree removal from the riparian buffer reduced UF1 pine and hardwood overstory basal areas by 50 and 46%, respectively. The reference watershed total overstory basal area increased 13% from 2009 to 2013 in both HF2 (30.5–34.5 $\text{m}^2\ \text{ha}^{-1}$) and UF2 (36.9–41.8 $\text{m}^2\ \text{ha}^{-1}$).

There were two events of stream edge tree blowdown in UF1. One was documented on Apr. 17, 2013, in which 11% of stream edge canopy trees blew down, and the other on Aug. 28, 2013, when an additional 25% of stream edge canopy trees blew down. Trees in UF1 that were above the mean riparian buffer dbh blew down more often than trees below the mean buffer dbh, with hickory and oak species experiencing 100% blowdown within the buffer (Table 1). Pine and sweetgum experienced 50% or greater blowdown when trees were above the mean dbh. When there was more than one tree present, tulip poplar was the most windfirm tree species (i.e., those least likely to be blown down during high wind events). Tree blowdown was also documented on Mar. 14, 2014, in treatment watershed (HF1) at the HF site. This documented blowdown was outside of the water quality monitoring period for this study, and none of the windthrown trees were located at the stream edge.

Percent groundcover shifted in treatment watersheds from leaf litter dominated in 2009 (preharvest, Figure S2a) to a mixture of woody, herbaceous, and leaf litter dominated from 2011 to 2013 (postharvest, Figure S2b). Percent groundcover in reference watersheds (HF2 and UF2) remained dominated by leaf litter from 2009 to 2013 (Figures S2c and d). UF2 herbaceous groundcover increased in 2013 compared with that in other years (Figure S2d) probably due to an opening in the canopy structure around one of the riparian buffer survey plots. The higher SE (7.8%) of herbaceous groundcover in the UF site than in other plots is reflective of localized canopy openness. We did not observe sediment flowing overland and through the riparian buffer to the channel during the monitoring period at the UF or HF site.

Precipitation and Discharge

Cumulative precipitation amounts for the preharvest and postharvest periods were 3,818 and 3,256 mm at HF and 3,460 mm and 3,266 mm at UF, respectively. Measured and modeled cumulative discharges were similar during the preharvest period but increased dramatically during the postharvest period (Tables 2 and 3; Figure 3 and Supplemental Figure S3). Measured postharvest discharge increased above modeled postharvest discharge by 263, 264, and 192% in HF1, by 45, 45, and 37% in HFW1, and by 248, 218, and 143% in UF1 from 2011, 2012, and 2013, respectively. Although precipitation totals were similar between preharvest and postharvest periods, the percent discharge of precipitation decreased from preharvest to postharvest period in the reference watersheds

Table 1. Percentage of stream edge trees that blew down in treatment watershed, UF1.

Common name	Species (scientific name)	Stream edge tree dbh range (cm)	Percent of stream edge trees that blew down, larger or equal to the mean dbh (%)	Percent of stream edge trees that blew down, smaller than mean dbh (%)	Total no. of all trees tallied on stream edge, both standing and blownover	No. of stream edge trees that blew down, larger or equal to the mean dbh	No. of stream edge trees that blew down, smaller than mean dbh	Total no. of stream edge trees that DID NOT blowover
American beech	*Fagus grandifolia*	18–18	—[a]	0	2	—	0	2
Blackgum	*Nyssa sylvatica*	30–30	—	0	2	—	0	2
Elm	*Ulmus* spp.	20	—	0	1	—	0	1
Hickory	*Carya* spp.	20–33	100	0	4	1	0	3
Ironwood	*Carpinus caroliniana*	18	—	0	1	—	0	1
Oak	*Quercus* spp.	18–76	100	0	6	4	0	2
Pine	*Pinus* spp.	38–53	50	—	4	2	—	2
Red cedar	*Juniperus virginiana*	20	—	100	1	—	1	0
Red maple	*Acer rubrum*	13–20	—	25	4	—	1	3
Sourwood	*Oxydendrum arboretum*	10–15	—	0	7	—	0	7
Sweetgum	*Liquidambar styraciflua*	13–76	65	38	25	11	3	11
Sycamore	*Platanus occidentalis*	33	0	—	1	0	—	1
Tulip poplar	*Liriodendron tulipifera*	15–79	20	0	8	1	0	7

Blowdown percentage is separated into above and below mean diameter at breast height (dbh) to test whether larger trees were more vulnerable to blowdown than smaller trees. Mean stream edge tree dbh was 33 cm.

[a] —, tree size not present at stream edge in the riparian buffer.

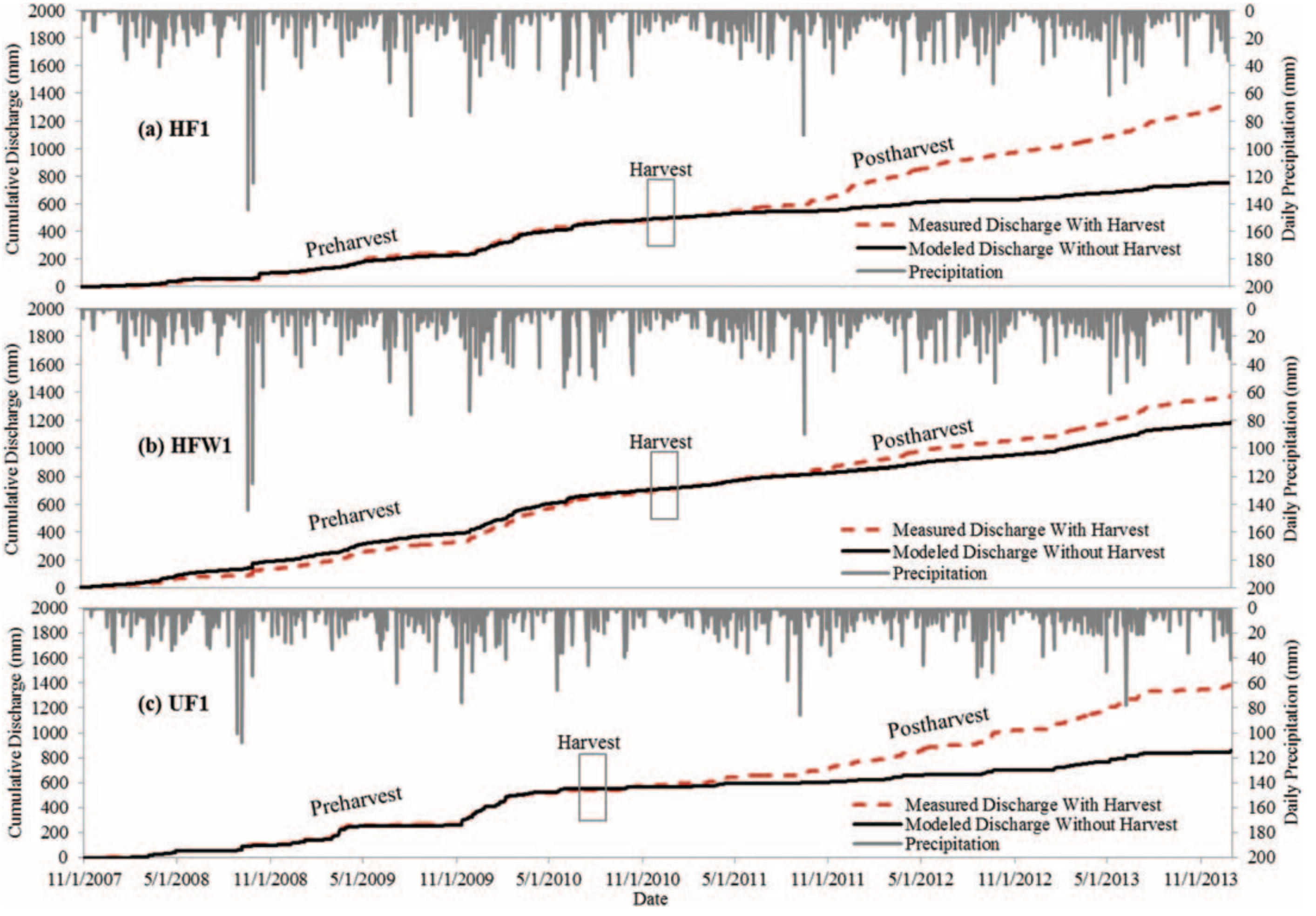

Figure 3. Daily precipitation, cumulative measured discharge with harvest, and modeled discharge without harvest in treatment watersheds over monitoring period (a) HF1, (b) HFW1, (c) UF1. Rectangle indicates tree harvest period; HF1 and HFW1 were harvested Nov. 29, 2010 to Jan. 19, 2011 and UF1 was harvested July 7, 2010 to Sept. 8, 2010.

Table 2. Measured and modeled discharge, precipitation, percent ET, and percent discharge of precipitation during preharvest and postharvest period in a timber harvest study at Hill Demonstration Forest, Durham County, NC.

Year	*n* (days)	Period	HF1 measured	HF1 modeled	HF2 measured	HFW1 measured	HFW1 modeled	HFW2 measured	Precipitation HF
			. . . .	. . . .	. . . .	(mm)	. . . .	. . . .	. . . .
2007	105	Preharvest	7	13	17	20	29	8	152
2008	366	Preharvest	117	113	142	151	199	171	1,197
2009	365	Preharvest	209	190	236	262	256	257	1,358
2010	365	Preharvest	170	190	236	286	236	226	1,096
2011	18	Preharvest	6	4	5	7	5	1	14
		Total	508	510	637	725	725	663	3,817
		ET (%) preharvest	87	87	83	81	81	83	
2011	347	Postharvest	247	68	88	175	121	62	1,002
2012	366	Postharvest	251	69	89	180	124	60	1,057
2013	365	Postharvest	327	112	142	291	212	191	1,198
		Total	826	249	318	646	457	313	3,256
		ET (%) postharvest	75	92	90	80	86	90	
						Percent discharge of precipitation			
2007	105	Preharvest	4	9	11	13	19	5	
2008	366	Preharvest	10	9	12	13	17	14	
2009	365	Preharvest	15	14	17	19	19	19	
2010	365	Preharvest	16	17	22	26	22	21	
2011	18	Preharvest	41	27	35	48	36	10	
		Mean	17	15	19	24	22	14	
2011	347	Postharvest	25	7	9	17	12	6	
2012	366	Postharvest	24	7	8	17	12	6	
2013	365	Postharvest	27	9	12	24	18	16	
		Mean	25	8	10	20	14	9	

Percent ET is estimated as (total precipitation − total discharge)/total precipitation × 100 over the preharvest and postharvest monitoring periods. Percent discharge of precipitation equals (precipitation/discharge × 100). HF1 and HFW1 harvest ended on Jan. 19, 2011. Measured discharge is cumulative flow values from the pressure transducer. Modeled discharge is cumulative flow values from the linear model that was developed during the calibration period to determine what discharge would be if the clear cut had not occurred. HF1 and HFW1, treatment watersheds; HF2 and HFW2, reference watersheds.

Table 3. Measured and modeled discharge, precipitation, percent ET, and percent discharge of precipitation during preharvest and postharvest period in a timber harvest study at Umstead Research Farm, Granville County, NC.

Year	*n* (days)	Period	UF1 measured discharge	UF1 modeled discharge	UF2 measured discharge	Precipitation UF
			. . . .	. . . . . (mm)	. . . .	. . . .
2007	105	Preharvest	2	1	3	198
2008	366	Preharvest	128	122	164	1,249
2009	365	Preharvest	281	286	372	1,307
2010	251	Preharvest	125	145	189	705
		Total	537	554	728	3,460
		ET (%) preharvest	84	84	79	
2010	114	Postharvest	52	15	23	223
2011	365	Postharvest	181	52	78	985
2012	366	Postharvest	261	82	117	967
2013	365	Postharvest	376	155	208	1,091
		Total	870	304	427	3,266
		ET (%) postharvest	75	91	88	
				Percent discharge of precipitation		
2007	105	Preharvest	1	0.3	1	
2008	366	Preharvest	10	10	13	
2009	365	Preharvest	22	22	28	
2010	251	Preharvest	18	21	27	
		Mean	13	13	17	
2010	114	Postharvest	23	7	10	
2011	365	Postharvest	18	5	8	
2012	366	Postharvest	27	8	12	
2013	365	Postharvest	34	14	19	
		Mean	26	9	12	

Percent ET is estimated as (total precipitation − total discharge)/total precipitation × 100 over the preharvest and postharvest monitoring periods. Percent discharge of precipitation equals (precipitation/discharge − 100). UF1 harvest ended on Sept. 8, 2010. Measured discharge is cumulative flow values from the pressure transducer. Modeled discharge is cumulative flow values from the linear model that was developed during the calibration period to determine what discharge would be if the clearcut had not occurred. UF1, treatment watershed; UF2, reference watershed.

Table 4. Mean values for stormflow hydrologic characteristics of treatment watersheds with harvest (measured) and without harvest (modeled) during the postharvest period.

Watershed	Season	No. of storms	Event duration	Beginflow	Peak rate	Time peak	Total discharge	Baseflow	Stormflow	Preciptation	D/P ratio
			hr	. . . . . (mm/day)		hr	. (mm/storm) .				
HF1 measured with harvest	Growing	40	11.00 (1.32)[a]	0.70 (0.13)[a]	9.43 (3.44)	2.75 (0.58)	1.65 (0.53)[a]	0.53 (0.11)[a]	1.12 (0.44)	24.90 (1.98)	0.05 (0.01)[a]
HF1 modeled without harvest	Growing	40	6.37 (0.82)[a]	0.19 (0.04)[a]	5.11 (0.90)	2.02 (0.41)	0.61 (0.25)[a]	0.13 (0.04)[a]	0.49 (0.21)	22.50 (1.74)	0.02 (0.01)[a]
HFW1 measured with harvest	Growing	44	10.38 (1.08)[a]	0.56 (0.09)	7.82 (2.18)[a]	2.48 (0.36)	1.36 (0.39)	0.43 (0.09)	0.92 (0.31)	23.71 (1.67)[a]	0.05 (0.01)
HFW1 modeled without harvest	Growing	33	7.49 (0.97)[a]	0.48 (0.06)	2.59 (0.59)[a]	1.86 (0.15)	0.59 (0.18)	0.27 (0.06)	0.33 (0.12)	18.77 (1.72)[a]	0.03 (0.01)
UF1 measured with harvest	Growing	36	17.21 (1.68)[a]	0.35 (0.07)[a]	41.60 (7.94)[a]	3.52 (0.51)	7.17 (1.48)[a]	0.69 (0.11)[a]	6.48 (1.39)[a]	25.86 (2.76)	0.24 (0.04)[a]
UF1 modeled without harvest	Growing	33	9.96 (1.72)[a]	0.07 (0.02)[a]	14.12 (3.97)[a]	2.47 (0.52)	2.69 (0.87)[a]	0.23 (0.06)[a]	2.47 (0.82)[a]	21.08 (2.54)	0.09 (0.02)[a]
HF1 measured with harvest	Nongrowing	23	23.48 (8.05)	0.79 (0.18)[a]	5.24 (1.60)	5.64 (1.14)	2.11 (0.68)[a]	0.86 (0.19)[a]	1.25 (0.51)	23.05 (2.51)	0.07 (0.01)[a]
HF1 modeled without harvest	Nongrowing	23	10.75 (1.30)	0.32 (0.05)[a]	3.65 (0.59)	4.31 (0.88)	0.72 (0.13)[a]	0.28 (0.07)[a]	0.44 (0.08)	20.33 (1.74)	0.03 (0.00)[a]
HFW1 measured with harvest	Nongrowing	19	14.77 (2.19)	0.64 (0.05)	3.74 (0.66)	5.32 (1.12)	1.50 (0.46)	0.70 (0.18)	0.80 (0.28)	20.22 (2.32)	0.06 (0.01)
HFW1 modeled without harvest	Nongrowing	13	14.68 (2.55)	0.55 (0.05)	3.03 (0.77)	5.76 (1.21)	1.34 (0.44)	0.66 (0.20)	0.68 (0.25)	15.43 (2.94)	0.08 (0.02)
UF1 measured with harvest	Nongrowing	20	25.47 (2.34)	0.48 (0.11)[a]	33.01 (6.62)[a]	6.29 (1.07)	9.03 (1.92)[a]	1.33 (0.29)	7.70 (1.72)[a]	22.97 (2.75)	0.33 (0.04)[a]
UF1 modeled without harvest	Nongrowing	19	21.38 (2.46)	0.24 (0.07)[a]	13.58 (2.79)[a]	6.13 (1.08)	4.65 (0.99)[a]	0.79 (0.16)	3.85 (0.85)[a]	21.78 (2.77)	0.19 (0.03)[a]

Measured stormflow parameters are values from the pressure transducer. Modeled stormflow parameters are values from the linear model that was developed during the calibration period to determine what stormflow would be if the clear cut had not occurred. Standard errors are in parentheses.

[a] *t*-test to determine significant difference ($P < 0.05$) between measured with harvest versus modeled without harvest within watershed and season.

due to fewer (8 versus 3) intense storms (≥ 25.4 mm/hour) and smaller discharge events. These factors probably led to greater amounts of deep seepage and water storage during postharvest than during preharvest in the reference watersheds.

Stormflow characteristics changed after harvest in all treatment watersheds (Table 4). Measured growing season stormflow duration with harvest was significantly higher than that of modeled growing season stormflow duration without harvest in all watersheds. Measured growing and nongrowing season beginflow and discharge to precipitation ratios in the treatment watershed were significantly higher than modeled beginflow and discharge to precipitation ratio in both HF1 and UF1. This indicated that growing and nongrowing season soils were wetter after harvest in HF1 and UF1. Measured peak rate of stormflow was significantly higher than the modeled peak rate in UF1 during both growing and nongrowing seasons and both were significantly higher in HFW1 only during the growing season. Measured total discharge increased significantly above the modeled total discharge in HF1 and UF1 during both the growing and nongrowing seasons. In UF1, the growing and nongrowing season stormflow increased significantly.

Mean Annual, Peak Nitrate, and Daily Stormflow Water Quality Concentration

Mean annual measured preharvest TSS and nutrient concentrations were not significantly different from mean annual modeled preharvest concentrations in either watershed (Table 5). All values were within background levels for forests or near the detection limits. Mean annual measured TP, TN, and TON concentrations were highest in HF1 compared with those for HFW1 and UF1. UF1 had a higher mean annual measured TOC concentration than the other treatment watersheds.

Mean annual measured NO_3-N concentration during the postharvest period was statistically higher than mean annual modeled NO_3-N concentration in both HF1 and UF1 with NO_3-N reaching 0.13 mg liter^{-1} in HF1 and 0.45 mg liter^{-1} in UF1 (Table 5). Mean annual measured TP concentration was significantly higher than the modeled value in UF1 during the postharvest period. Mean annual measured TSS, TOC, NO_3-N, TN, and TON concentrations were higher in UF1 than in HF1 and HFW1.

The stream nitrate concentration peaked during the postharvest period at 4.9 mg liter^{-1} in HF1, at 4.5 mg liter^{-1} in HFW1, and at 6.9 mg liter^{-1} in UF1 (Supplemental Figure S4). By the mid-2012 postharvest period, NO_3-N peak concentrations in the treatment watersheds were near preharvest peak concentrations. The mean daily stormflow TSS concentrations in the treatment watersheds were similar between preharvest, postharvest, and blowdown periods (Supplemental Figure S5).

Mean Annual Export of TSS and Nutrients

Mean annual measured TSS and nutrient export values during the preharvest period were not significantly different from mean annual modeled preharvest exports in all watersheds (Table 6). In the postharvest period, all mean annual measured constituents were higher than the mean annual modeled constituents in all treatment watersheds. However, mean annual measured TN was the only water quality parameter that was significantly higher than the mean annual modeled value across all treatment watersheds. The measured TSS load increased significantly from the modeled TSS in HF1. Although not significant, measured TSS load also increased from modeled TSS in HFW1 and UF1. Mean annual measured TOC and TON increased significantly above mean annual modeled

Table 5. Mean annual measured and modeled TSS and nutrient concentrations during preharvest and postharvest periods in the treatment watersheds.

Period	Constituents	HF1		HFW1		UF1	
		Measured	Modeled	Measured	Modeled	Measured	Modeled
		(mg liter^{-1})					
Preharvest	TSS	36.8 (0.02)	35 (0.04)	27.9 (9.7)	26.7 (5.2)	35.7 (9.3)	33.8 (6.4)
	TOC	6.1 (6.4)	6.2 (2.9)	5.7 (0.9)	5.7 (0.5)	10.0 (0.96)	9.5 (0.96)
	NH_4-N	0.03 (0.3)	0.04 (0.4)	0.01 (0.02)	0.01 (0.03)	0.01 (0.007)	0.01 (0.005)
	NO_3-N	0.01 (0.01)	0 (0.01)	0.02 (0.06)		0.03 (0.013)	0.01 (0.002)
	TP	0.08 (0.005)	0.07 (0.00)	0.06 (0.02)	0.06 (0.01)	0.07 (0.009)	0.06 (0.01)
	TN	0.71 (0.004)	0.69 (0.002)	0.52 (0.13)	0.50 (0.08)	0.66 (0.05)	0.67 (0.05)
	TON	0.67 (0.06)	0.64 (0.004)	0.5 (0.12)	0.48 (0.06)	0.62 (0.049)	0.59 (0.04)
Postharvest	TSS	31.1 (0.06)	34.3 (0.01)	23.8 (0.7)	23.2 (1.2)	33.6 (0.8)	28.6 (2.3)
	TOC	4.6 (0.3)	5.5 (1.1)	4.7 (0.8)	5.2 (0.5)	15.1 (3.9)	8.2 (0.3)
	NH_4-N	0.08 (0.4)	0.03 (0.4)	0.02 (0.03)	0.01 (0.01)	0.04 (0.005)	0.06 (0.036)
	NO_3-N	0.13 (0.01)[a]	0.00 (0.002)[a]	0.06 (0.05)		0.45 (0.156)[a]	0.01 (0.005)[a]
	TP	0.09 (0.04)	0.07 (0.00)	0.07 (0.02)	0.06 (0.01)	0.08 (0.001)[a]	0.06 (0.004)[a]
	TN	0.81 (0.01)	0.64 (0.004)	0.52 (0.08)	0.44 (0.08)	1.37 (0.20)	0.82 (0.17)
	TON	0.6 (0.07)	0.6 (0.02)	0.43 (0.06)	0.43 (0.07)	0.89 (0.17)	0.60 (0.03)

The predictive model was not good enough to develop a reliable modeled value (i.e., probability statistic = 0.43 for NO_3-N in HFW1 and 0.62 for NH_4-N in UF1). Measured concentrations are mean values from water samples collected during baseflow and stormflow. Modeled concentrations are mean values from the linear model that was developed during the calibration period to determine what load would be if the clearcut had not occurred. HF1 and HFW1 were harvested from Nov. 29, 2010, to Jan. 19, 2011, and UF1 was harvested July 7, 2010, to Sept. 8, 2010. Standard errors are in parentheses.

[a] *t*-test to determine significance ($P < 0.05$) between measured and modeled values within the watershed and period.

Table 6. Mean annual measured and modeled TSS and nutrient loads during preharvest and postharvest periods in the treatment watersheds.

Period	Constituents	HF1		HFW1		UF1	
		Measured	Modeled	Measured	Modeled	Measured	Modeled
		(kg ha^{-1} yr^{-1})					
Preharvest	TSS	74.2 (23.9)	73.4 (18.5)	82.5 (29.1)	82.0 (15.6)	93.4 (27.4)	85.2 (23.5)
	TOC	9.4 (1.3)	9.3 (1.2)	13.9 (1.9)	13.8 (1.4)	22.2 (7.3)	22.2 (7.9)
	NH_4-N	0.02 (0.01)	0.02 (0.01)	0.013 (0.01)	0.013 (0.01)	0.013 (0.003)	
	NO_3-N	0.003 (0.001)	0.004 (0.001)	0.03 (0.01)		0.03 (0.02)	0.03 (0.001)
	TP	0.16 (0.06)	0.15 (0.04)	0.17 (0.04)	0.17 (0.03)	0.19 (0.09)	0.19 (0.08)
	TN	1.19 (0.39)	1.17 (0.23)	1.37 (0.35)	1.36 (0.33)	1.56 (0.66)	1.56 (0.56)
	TON	1.17 (0.39)	1.14 (0.23)	1.33 (0.35)	1.32 (0.32)	1.52 (0.67)	1.52 (0.56)
Postharvest	TSS	94.4 (14.8)[a]	31.4 (9.6)[a]	59.8 (13.9)	44.5 (3.3)	84.5 (25.9)	36.9 (7.0)
	TOC	13.8 (2.2)[a]	4.3 (0.6)[a]	11.3 (1.8)	7.8 (0.8)	32.7 (4.1)[a]	9.9 (1.8)[a]
	NH_4-N	0.27 (0.12)	0.01 (0.002)	0.07 (0.03)	0.006 (0.001)	0.09 (0.02)	
	NO_3-N	0.68 (0.33)	0.001 (0.001)	0.19 (0.1)		1.14 (0.46)	0.04 (0.02)
	TP	0.31 (0.1)	0.06 (0.01)	0.21 (0.1)	0.11 (0.02)	0.22 (0.06)	0.09 (0.02)
	TN	2.62 (0.26)[a]	0.72 (0.14)[a]	1.28 (0.18)[a]	0.71 (0.07)[a]	3.13 (0.56)[a]	0.89 (0.24)[a]
	TON	1.67 (0.21)[a]	0.71 (0.14)[a]	1.03 (0.17)	0.67 (0.07)	1.89 (0.40)[a]	0.79 (0.15)[a]

The predictive model was not good enough to develop reliable modeled value (i.e., probability statistic = 0.43 for NO_3-N in HFW1 and 0.62 for NH_4-N in UF1). Measured loads are mean values from water samples collected during baseflow and stormflow multiplied by discharge. Modeled loads are mean values from linear model that was developed during the calibration period to determine what load would be if the clearcut had not occurred. HF1 and HFW1 were harvested Nov. 29, 2010 to Jan. 19, 2011, and UF1 was harvested July 7, 2010 to Sept. 8, 2010. Standard errors are in parentheses.

[a] *t*-test to determine significance ($P < 0.05$) between measured and modeled values within the watershed and period.

values in both HF1 and UF1. Modeled postharvest loads were lower than modeled preharvest loads for all constituents in all treatment watersheds because percent discharge of precipitation was smaller during the postharvest period than during the preharvest period.

Benthic Macroinvertebrates

Preharvest water quality bioclassification ranged from good to excellent in all treatment watersheds (Table 7). Postharvest bioclassification in harvested sites ranged from good/fair to excellent, whereas those in the reference sites ranged from fair to excellent. In the preharvest period, mean nongrowing season EPT taxa richness and biotic index values were not significantly different between any treatment and reference watershed pair. In the postharvest period, both mean growing season and nongrowing season EPT taxa richness increased (improved) significantly in HFW1 compared with that for HFW2 and in UF1 compared with that for UF2. The biotic index decreased or improved significantly in HFW1 compared with that in HFW2 during the nongrowing season. The dominant FFG or trophic category was similar between treatment and reference watersheds during the postharvest period (Figure 4). For example, the highest FFG percentage was for shredders in the HF1 and HF2 pair (29 and 27% of the total macroinvertebrates in the samples, respectively) and the HFW1 and HFW2 pair (25 and 26%, respectively). Collector gatherers FFG was the highest in the UF1 and UF2 pair (21 and 33%, respectively).

Stream Temperature

Preharvest monthly maximum stream temperature values were 24.8° C in HF1, 22.4° C in HF2, 25.8° C in HFW1, 24.5° C in HFW2, 23.5° C in UF1, and 24.1° C in UF2. After the harvest, monthly maximum

Table 7. EPT taxa richness, biotic index, and bioclassification in treatment and reference watersheds during preharvest and postharvest periods.

		Preharvest			Postharvest								
Watershed	Index	January 2010	April 2010	Mean nongrowing	March 2011	July 2011	February 2012	July 2012	February 2013	June 2013	January 2014	Mean growing	Mean nongrowing
HF1 (treatment)	EPT taxa richness	13	16	14.5 (1.5)	9	8	11	9	16	7	12	8.0 (0.6)	12.0 (1.5)
HF2 (reference)	EPT taxa richness	21	17	19.0 (2.0)	14	10	14	12	12	9	15	10.3 (0.9)	13.8 (0.6)
HFW1 (treatment)	EPT taxa richness	24	22	23.0 (1.0)	20	11	20	12	20	11	14	11.3 (0.3)[a]	18.5 (1.5)[a]
HFW2 (reference)	EPT taxa richness	20	17	18.5 (1.5)	17	2	11	4	13	7	11	4.3 (1.5)[a]	13.0 (1.4)[a]
UF1 (treatment)	EPT taxa richness	16	12	14.0 (2.0)	19	10	20	11	14	10	12	10.3 (0.3)[a]	16.3 (1.9)[a]
UF2 (reference)	EPT taxa richness	18	10	14.0 (4.0)	10	0	12	1	12	4	10	1.7 (1.2)[a]	11.0 (0.6)[a]
HF1 (treatment)	Biotic index	4.5	3.3	3.9 (0.60)	5.2	4.0	4.8	4.2	4.2	3.6	4.1	3.9 (0.19)	4.6 (0.26)
HF2 (reference)	Biotic index	3.8	3.0	3.4 (0.40)	4.9	3.2	4.8	3.7	4.7	3.8	3.9	3.6 (0.18)	4.6 (0.22)
HFW1 (treatment)	Biotic index	3.9	3.4	3.7 (0.25)	4.1	3.3	4.0	3.8	3.7	3.6	3.9	3.6 (0.15)	3.9 (0.08)[a]
HFW2 (reference)	Biotic index	4.1	2.8	3.5 (0.65)	4.6	6.3	4.2	4.5	4.4	3.0	4.3	4.6 (0.95)	4.4 (0.08)[a]
UF1 (treatment)	Biotic index	4.8	4.8	4.8 (0.00)	5.4	4.8	4.7	4.9	4.1	4.1	5.1	4.6 (0.27)	4.8 (0.28)
UF2 (reference)	Biotic index	4.5	4.0	4.3 (0.25)	5.4	6.6	4.5	5.4	6.3	4.6	5.2	5.5 (0.59)	5.3 (0.36)
HF1 (treatment)	Bioclassification	Good	Excellent		Good/fair	Excellent	Good	Excellent	Excellent	Excellent	Excellent		
HF2 (reference)	Bioclassification	Excellent	Excellent		Good	Excellent	Good	Excellent	Good	Excellent	Excellent		
HFW1 (treatment)	Bioclassification	Excellent	Excellent		Excellent	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent		
HFW2 (reference)	Bioclassification	Excellent	Excellent		Good	Fair	Excellent	Good	Good	Excellent	Good		
UF1 (treatment)	Bioclassification	Good	Good		Good/fair	Good	Good	Good	Excellent	Excellent	Good		
UF2 (reference)	Bioclassification	Good	Excellent		Good/fair	Fair	Good	Good/fair	Fair	Good	Good		

Criteria for North Carolina biotic index for small streams (<4 m wide): excellent, <4.3; good, 4.3–5.1, good/fair, 5.2–5.8; fair, 5.9–6.9; poor, >6.9. In the postharvest period, the mean nongrowing season includes March 2011, February 2012, February 2013, and January 2014 and the growing season included July 2011, July 2012, and June 2013. Standard errors are in parentheses.

[a] *t*-test to determine significance ($P < 0.05$) between mean treatment versus mean reference EPT (Ephemeroptera [mayfly], Plecoptera [stonefly], and Trichoptera [caddisfly]) taxa richness and biotic index values of each watershed pair (HF1 versus HF2, HFW1 versus HFW2, and UF1 versus UF2) during preharvest and postharvest periods and across the nongrowing season or growing season.

stream temperature spiked during the first two growing seasons in HFW1 and during the first growing season only in UF1 (Supplemental Figure S6a and b). Unexpectedly, a spike in temperature was not observed in the other treatment watershed, HF1, during the postharvest period.

Discussion

Discharge Response to Harvesting

Understanding regional site-specific water resource responses to timber removal and other land disturbances can help land managers set flow targets to reduce stormflow and watershed degradation and manage general streamflow dynamics. When ET is reduced through clearcut harvesting, discharge has been shown to increase by 370 mm (60%) in the mountains (Johnson and Kovner 1954), 91 mm (99%) in the coastal plain of North Carolina (Amatya et al. 2006), and 250 mm (55%) in the Piedmont of South Carolina (Williams et al. 2000) during the 1st year. During the 1st year after harvest in our study, we found that discharge increased more dramatically after forest removal compared with the values in these studies. Discharge increased 180 mm (263%) over modeled discharge rates in HF1 and 129 mm (248%) over modeled discharge rates in UF1. We believe this large increase in annual discharge postharvest is driven primarily by the type of topography and climatic conditions found in our study catchments and their effects on ET. ET was estimated to be about 80% of the annual water budget for our study sites. In contrast to the results for the Piedmont, Sun et al. (2002) reported that annual ET was 70% of precipitation for a coastal plain pine plantation and 47% of precipitation in a hardwoods watershed at Coweeta in the mountains of North Carolina. Post and Jones (2001) reported that ET in mountainous regions in the United States ranged from about 36 to 50% of the water budget. Thus, when our watersheds were clearcut, a large response in discharge was expected because the tree hydrologic ET pump was removed from the system.

The effect of the disturbance on discharge was less when a smaller portion of our Piedmont watershed was disturbed. For example, HFW1 experienced 33% tree removal from the watershed (HF1 experienced 92% timber removal) that resulted in an increase in discharge of 54 mm (45%) during the first year after harvest. On a 10% forest removal basis (54 mm × 10/33% = 16.4 mm year^{-1} in HFW1 and 180 mm year^{-1} × 10/92%=19.6 mm in HF1), the uncut portion of HFW1 dampened the effect on discharge from the cut area, HF1, during year 1 by 20% (i.e., 19.6 mm −16.4 mm/16.4 mm). However, the capacity to buffer against the effects of a clearcut on streamflow may depend on the distance of the disturbance from the stream channel. Based on a simulation study using Visualizing Ecosystems for Land Management Assessments (VELMA), Abdelnour et al. (2011) reported that a 20% clearcut area near the catchment divide resulted in an average annual discharge increase of 53 mm, whereas a 20% clearcut near the stream resulted in an average annual discharge increase of 92 mm. Stednick (1996) reported that when 20% or less of a watershed was harvested, it was unlikely that any increase in annual discharge would be detected. In addition, an increase in peak flow may be undetectable in harvested areas of less than 29% (Grant et al. 2008) or 32% of removal of the basal area (Bent 1994). We detected an increase in peak rate in all treatment watersheds with the largest differences between measured versus modeled occurring in the growing season.

Water Quality Response to Harvesting

The significant increases in NO_3-N concentrations in both HF1 and UF1 after harvest were below levels considered harmful to biological integrity (Binkley et al. 1999, Boggs et al. 2013) but were generally higher than values found in the North Carolina mountains (Clinton 2011), Alabama coastal plain (Lockaby et al. 1994), or South Carolina coastal plain (Askew and Williams 1986) or Piedmont (Williams et al. 2000).

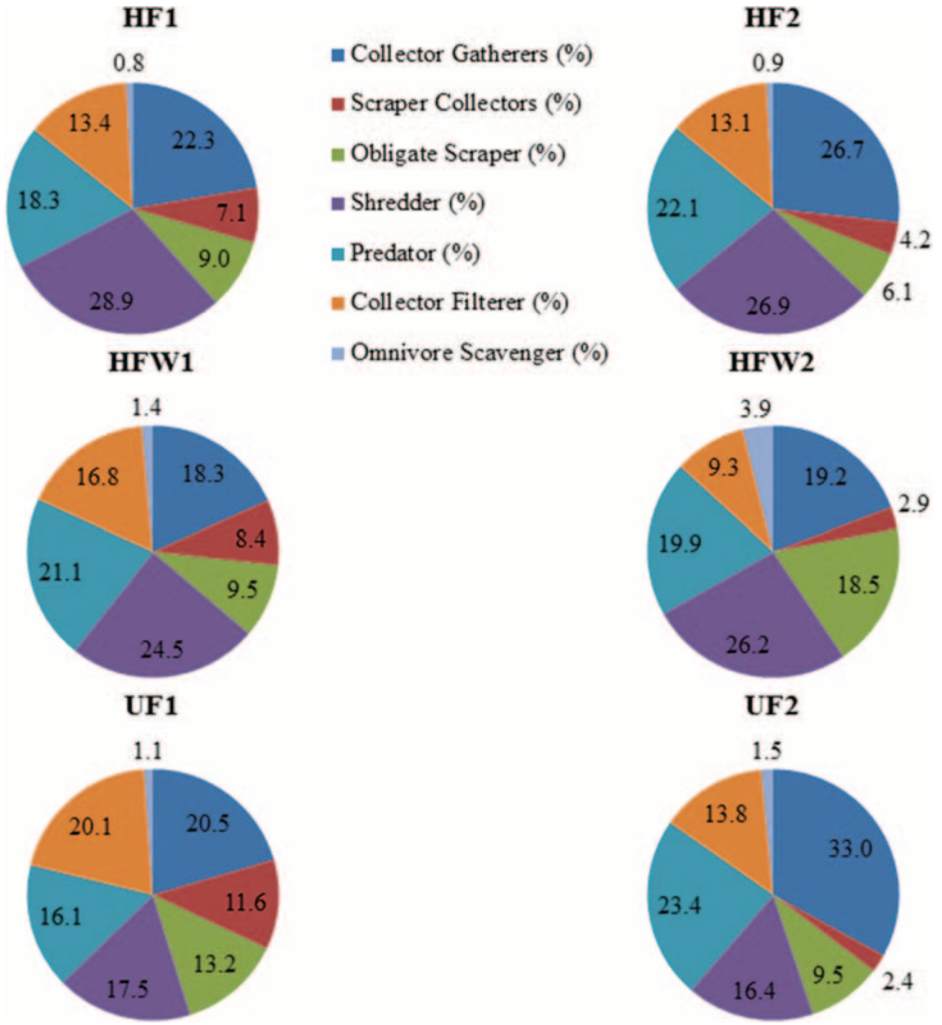

Figure 4. Mean functional feeding group percentages in treatment versus reference (HF1 versus HF2, HFW1 versus HFW2, and UF1 versus UF2) watersheds during the postharvest period, 2011–2013.

Quantifying nutrient values in the North Carolina Piedmont after a harvest may not only help to document stream quality responses to disturbances but can also provide further context for managing water resources through improved planning and treatment strategies across regions. Nitrate peaks in our study were probably driven by a reduction in plant nitrogen uptake that left the highly mobile nitrate anions vulnerable to flushing during storm events (Hornberger et al. 1994). UF1 had considerably more nitrate spikes than HF1 and HFW1 (Supplemental Figure S4) because of the rapid lateral and increased stormflow that occur in these TB soils. UF1 stormflow, peakflow, and total discharge increased significantly in the postharvest period in both growing and nongrowing seasons, increasing the potential to quickly mobilize accumulated nitrate to the stream channel. Increases in peak NO_3-N were delayed by 6–8 months from the time of harvest. This delay is not uncommon as time is needed for ammonium to accumulate in the soil after reduced demand by the trees, and time is also needed for nitrifying populations to increase with the increasing soil ammonium. In addition, time is needed for root systems and slash to decay and release additional N back into the soil. However, despite the pulse increases, NO_3-N levels remained low. By mid-2012, the regrowth of woody and herbaceous plants is what probably reduced stormflow peak NO_3-N concentrations to preharvest levels in all treatment watersheds. HFW1 demonstrated a greater capacity to retain nitrate compared with that for HF1 and UF1 because a much smaller percentage of HFW1 was disturbed. Although the UF1 site exhibited the highest peak NO_3-N concentrations over a relatively short period, the TB soils found on the UF1 site only comprise 3.5% of North Carolina's total land area (Cleland et al. 2007), so any impacts would be localized.

Some of the measured water quality loads were not significantly different from modeled loads during the postharvest period because discharge and climate variability increased with increasing exports (Table 6). Despite this statistical limitation, it is still informative to discuss the annual load patterns because they indicate the amount of nutrient impact on the ecosystem. Mean annual measured TN load was the only parameter that increased significantly above mean annual modeled load values in all treatment watersheds. Mean annual measured TP, TOC, and TSS loads increased 1- to 2-fold above mean annual modeled loads across treatments. These increases are consistent with effects of timber removal on sediment and nutrient yields from headwater catchments (Arthur et al. 1998, Fraser et al. 2012). In addition, changes in TP export tend to follow changes in TSS export given that phosphorus often attaches to small particles of sediment (Brady 1990). The increases in TSS and nutrient exports in the treatment watersheds were probably driven by the large increase in discharge in response to the clearcut harvest (Swank and Vose 1994, McBroom et al. 2008) and movement of in-channel legacy sediment during preharvest (Boggs et al. 2013) and postharvest periods (J.L. Boggs, USDA Forest Service, unpubl. data, Sept. 8, 2010 to Dec. 31, 2013). Given that postharvest discharge and NO_3-N concentration spikes declined each year and corresponded to increased ET and plant growth, TSS, ammonium, and other nutrient exports will probably match preharvest levels within the next 5 years. Overall, our results showing that temporary increases in discharge were accompanied by increased in-channel sediment transport and nutrient exports but did not measurably impact indicators of aquatic invertebrate communities align with those of other timber harvesting studies (Table 8).

The macroinvertebrate bioclassification rankings indicated that stream quality remained good/fair to excellent in the treatment watersheds during the postharvest period (Table 7). However, some reference watersheds had bioclassification scores that ranked from fair to a maximum of good/fair. These reference watershed scores were often linked to low discharge periods during the growing season that drove down the presence of certain indicator aquatic species. For example, the UF2 July 2011 survey had the

Table 8. Comparison of postharvest discharge, sediment, and nitrate in paired watershed timber harvesting studies.

Study	Treatment	Location	Discharge	Sediment	NO_3-N	Sediment	NO_3-N	Conclusions
			(mm yr^{-1})	. . (mg $liter^{-1}$)	. .	. (kg ha^{-1} yr^{-1})	.	
This study								
HF2	Control	North Carolina/ Piedmont	105	29	0.003	41	0.002	Temporary increases in discharge were accompanied by increased in-channel sediment transport and nutrient exports but were not sufficiently disruptive to impact aquatic life and ecological integrity.
HFW2	Control		105	22	0.001	33	0.02	
UF2	Control		130	34	0.29	56	0.36	
HF1, 15.2-m buffer	Clearcut with buffer		280	31	0.13	94	0.67	
HFW1, 15.2-m buffer	Clearcut with buffer		215	24	0.06	61	0.19	
UF1, 15.2-m buffer	Clearcut with buffer		262	33	0.48	101	1.37	
Fraser et al. (2012)								
Control	Control	Georgia/Piedmont				418		SMZ greatly reduced the water quality effects of clearcutting.
12–21-m buffer	Clearcut with buffer					1,067		
Clinton 2011								
Control	Control	North Carolina/ Mountains		16	0.04			Stream nitrate concentration increased only in the no buffer site. Total suspended solids concentration increased only slightly above that for the reference site.
10-m buffer	Clearcut with buffer		32	0.05				
30-m buffer	Clearcut with buffer			8	0.02			
No buffer	Clearcut without buffer			24	0.12			
McBroom et al. (2008)								
. . .SW3, SW5, SW8	Control	Texas/East	14			42		Sediment load increased with discharge. First year sediment loss was higher on intensive watershed than conventional watershed but not to loads that would degrade or impact water quality.
. . .SW2, SW4, SW9	Clearcut/conventional prep with BMPs		78			111		
. . .SW1, SW6, SW7	Clearcut/intensive prep with BMPs		98			225		
Williams et al. (2000)								
Kenamore One	Control	South Carolina/ Piedmont	458	114	0.03	522	0.16	Increases in discharge were accompanied by increases in sediment and nutrient exports. Sediment loads without BMPs can be 10-fold higher than loads with BMPs according to Hewlett (1979).
Holley Springs, 12.2-m buffer	Clearcut with BMPs		709	98	0.08	894	0.58	
Ramsey Bridge, 12.2-m buffer	Clearcut/herbicide with BMPs		677	95	0.09	647	0.60	
Kenamore Two, 12.2-m buffer	Clearcut/mechanical and thin with BMPs		902	90	0.14	802	0.81	
Arthur et al. (1998)[a]								
Watershed A	Control	Kentucky/Cumberland Plateau	490		1.0	30	0.24	Harvested watersheds had higher discharge and concentrations of nitrate and other nutrients compared with those for the control. Regrowth of vegetation reduced nutrient losses within 3 years of harvest.
Watershed B, 15.2-m buffer	Clearcut with BMPs		600		1.8	250	1.91	
Watershed C	Clearcut without BMPs		650		2.0	300	2.18	
Kochenderfer et al. (1997)								
Haddix	Clearcut with BMPs	West Virginia/Allegheny Plateau			1.45	58		Sediment loads returned to preharvest levels by the 3rd postharvest year.

[a] Sediment and nutrient values were averaged across all postharvest years.

lowest EPT taxa richness and was the lowest discharge month (0.13 mm) compared with any other month. The UF2 bioclassification for July 2011 was fair, whereas the UF1 bioclassification was good and had a measured discharge of 2.3 mm. UF1 without harvest discharge (based on a model from the calibration period) would have been 0.11 mm. This suggests that the additional discharge in UF1 after the harvest may have improved stream habitat for benthic macroinvertebrates beyond what would have been observed without harvest. However, the dominant FFG (i.e., collector gatherers in UF and shredders in HF) in the treatment and reference watersheds remained the same, and the distribution of FFG in the watershed pairs was similar after harvest (Figure 4). Jackson et al. (2007) also found that macroinvertebrate groups did not decline significantly after harvest. This suggests that any increase or fluctuations in discharge or nutrient concentrations probably did not pose any risk to water quality, despite differences in bioclassification scores between our watershed pairs during certain surveys.

Riparian Buffer Vegetation

Our study is consistent with findings from previous work indicating that blowdown occurs during the first few years after a harvest under normal weather events or patterns (Moore 1977, Jackson et al. 2007). In UF1, 36% of stream edge trees blew down during two windstorm events in the third postharvest year. There was no measurable change in UF1 mean daily TSS concentrations in stormflow water samples compared with those in treatment watersheds without blowdown, HF1 and HFW1 (Supplemental Figure S5). Grizzel and Wolff (1998) found a similar result where 33% of buffer trees were windthrown but did not produce a significant amount of additional sediment to the headwater stream channel. They also noted that any sediment delivered to streams from windthrown trees was small relative to the amount stored in the channel. There appears to be some degree of riparian buffer resiliency to the windthrow disturbance that protected water quality in UF1. The resiliency is possibly the result of the increase in herbaceous and woody vegetation growth as HF1 herbaceous plant coverage increased from 0.8% preharvest to 21% postharvest, and UF1 herbaceous plant coverage increased from 2.1 to 28% over the same time period (Figure S2). This additional coverage and plant root structure could provide groundcover protection and soil stability in the riparian buffer (Wynn and Mostaghimi 2006). Streambank failure could occur in the future in UF1 because the edge function of the riparian buffer had been compromised, which may cause excessive sedimentation to occur. Therefore, forestry BMPs and measures should always be implemented to prevent windthrow and uprooting of streambanks to ensure that the riparian buffer function is not compromised.

Different tree blowdown patterns between UF1 and HF1 were probably caused by differences in tree size, species, and soil characteristics at our study sites (Steinblums et al. 1984, Sinton et al. 2000, Steil et al. 2009). The UF1 riparian buffer trees were larger (30 cm) than the HF1 riparian buffer trees (23.8 cm). Trees in UF1 that were above the mean riparian buffer dbh blew down more often than trees below the mean dbh (Table 1), suggesting that larger trees were less windfirm than smaller trees. For trees above a mean riparian buffer dbh of 33 cm and in cases where more than one tree was present, the order for most windfirm species to least windfirm species appears to be tulip poplar > sweetgum > pine spp. > hickory spp. = oak spp. Although there was variation in blowdown occurrences among regions (Triassic versus Carolina Slate Belt), TB soils comprise about 3.5% of North Carolina's total land area, so any statewide implications would be low and recommendations would be site-specific.

Conclusions

Our 6-year study has resulted in important findings in forest hydrology, nutrient exports, and vegetated riparian buffer functions in Piedmont watersheds. Among similar studies in the region, this paired watershed study provides a complete assessment of hydrology and water quality responses to timber harvesting. We conclude that forest vegetation removal plays a more significant role in affecting water balances and mean and peak nitrate concentrations in this region than in the mountains and coastal plains. However, overall stream water quality in the Piedmont was not negatively affected by increases in discharge, nutrient loading, and stream edge tree blowdown. The knowledge gained from this project will be useful to land managers. It should provide a better understanding of how Piedmont watersheds store, release, and discharge water and nutrients across growing and dormant seasons, how riparian buffers function, and how to apply the most appropriate timber harvest management practices for protecting water resources across regions.

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