Timber Harvest Effects on Water Quantity and Quality in the North Carolina Piedmont: Paired Watershed Study Summary

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NOTE: This report is solely intended to report the findings and recommendations from this study, and has not undergone the peer-review process of a journal. This review does not provide official agency guidance, policy, or directive. The study in this report was implemented by scientists at the US Forest Service's Eastern Forest Environmental Threat Assessment Center (EFETAC). They have previously published their findings in a number of peer-reviewed journals, and also provided NCFS with a complete technical report. This report is intended to be a less-technical summary of the more pertinent results included in the EFETAC report, as well as providing a summary of the implications for forest management in the Piedmont region of North Carolina. For those readers that are interested in reviewing the original technical report or the published manuscripts, refer to the "Additional Resources" at the end of this document for more information.

EXECUTIVE SUMMARY

This report summarizes the findings of a long-term (6 year) study that evaluated the effects of timber harvesting on headwater streams in the Piedmont physiographic region of North Carolina. This study consisted of monitoring stream discharge and water quality in three “pairs” of similar forested watersheds. Each watershed was monitored at a specified stream location for a baseline period (~3 years). Correlation models were calibrated for each watershed pair using the baseline data. After the baseline model calibration period, timber within one watershed of each pair was harvested using a clearcut logging method (HF1, HFW1, and UF1). The other watershed in each pair served as a non-harvested reference (HF2, HFW2, and UF2). The calibrated models were used to evaluate postharvest stream conditions as compared with the anticipated conditions had the timber not been harvested. Within each harvested watershed, a nominal 50-foot wide riparian buffer zone was retained along each side of the stream, and a specified amount of timber was harvested from within the buffer zone. Selective harvest within the buffers followed North Carolina’s Neuse Buffer Rule. Streams were monitored for approximately 3 years following timber harvest.

Results of this study add to the base of knowledge regarding the effects of a timber harvest on hydrology and stream discharge, water quality, and riparian buffer characteristics. The following numbered and lettered sections summarize the study findings. Each section is followed by a summary of take-home points and recommendations for forest managers given the study results:

1. **Hydrology**
    a. Measured streamflow discharges were significantly greater than modeled estimates (estimates of the discharge had the timber not been harvested) within harvested watersheds.
    b. The additional discharge within harvested watersheds (postharvest) did not compromise water quality to the extent that would exceed North Carolina water quality standards.
    c. Increases in stream discharge compared to modeled estimates were especially notable in the watersheds that had clay soils, which naturally limit downward water infiltration and create more surface runoff.
    d. After three years of new vegetative growth following harvests, stream discharge began to return to preharvest levels.
    e. While clearcutting temporarily increased the stream discharge, the residual trees retained in the buffer zone increased their collective water use after harvest, and at least partially offset the hydrologic effects of forest removal.
    f. Ultimately, the underlying geology and soil type had a stronger influence on stream discharge than evapotranspiration, regardless of whether timber was harvested in these watersheds.

Forest Management Take-Home Points for Hydrology

- **Increased runoff not only contributes more water into the stream system, but also illustrates the need for installing and maintaining adequate BMP measures that will reduce soil erosion and sedimentation into streams.**
- **Runoff from storm events following a harvest can significantly increase in both absolute volume and duration of time, with more variation in stream discharge**

attributed to the underlying geology than vegetation. Therefore, during preharvest planning, consider potential effects of underlying geology on water yields.

- **Even though stream discharge increased notably after clearcutting, the residual trees in the riparian buffer zone increased their usage of water, and the relative increases of stream discharge began to diminish as the harvested area regrew. Prompt reforestation after a harvest will sustain timber availability and contribute towards balancing the watershed cycle back to preharvest conditions.**
- **If the forest manager has an objective of water supply management, then this increased water use by residual riparian trees may drive some of the decisions regarding whether or not to selectively harvest trees from stream buffer zones, and if so, what species of trees to retain or harvest, given that different tree species cycle water differently.**
- **The structural integrity of the streams in the two harvested watersheds remained relatively unchanged, in spite of large increased stream discharge after the harvest and the uprooting of large trees along the stream edge following storm event wind throw.**

2. **Water Quality**
   a. Watersheds exhibited sediment and nutrient loads that are similar to natural background levels from forests in other studies, and much less than other land uses. Preharvest monitoring indicated that all water quality parameters measured were within normal (background) levels for forests in the Piedmont region.
   b. No consistent increases in sediment and nutrient ***concentrations*** were observed from all monitored watersheds, with the exception of nitrate nitrogen. Note: No fertilizer was applied to watersheds. **Increased concentrations following these timber harvests did not exceed North Carolina's water quality standards.**
   c. Increased ***loads*** were relatively short-lived relative to the length of time until the next harvest.
   d. *Total nitrogen* (TN) ***loads*** significantly increased in all watersheds postharvest, but were still less than 3 lbs/ac/year in all cases. Conversely, TN ***concentrations*** were not significantly different postharvest.
      i. Postharvest mean annual *nitrate nitrogen* (NO_3-N) ***loads*** ranged from 0.17 to 1.02 lbs/ac/yr. NO_3-N stormflow ***concentrations*** peaked approximately 1.5 years postharvest and returned to preharvest levels after 2 years. Increased NO_3-N ***concentrations*** were observed in two of the three treatment watersheds postharvest, but were still well below 1.0 mg/L.
      ii. Postharvest mean annual *ammonium* (NH_4-N) ***loads*** ranged from 0.06 to 0.24 lbs/ac/yr for treatment watersheds.
      iii. Postharvest mean annual *total organic nitrogen* ***loads*** ranged from 0.92 to 1.69 lbs/ac/yr for treatment watersheds.
   e. *Total organic carbon* (TOC) ***loads*** increased 1- to 2-fold above mean annual modeled loads for two of the three watersheds. However, TOC ***concentrations*** were not significantly greater than model estimates. This was likely an effect of the timber harvest.
   f. *Total phosphorus* (TP) ***loads*** postharvest were not significantly different from modeled estimates, and were all less than 0.3 lbs/ac/yr. TP ***concentrations*** were not significantly

greater than model estimates in two of the three watersheds. In the third watershed, TP was significantly greater (0.06 mg/L [modeled] versus 0.08 mg/L [measured]).

g. *Total suspended solids* (TSS) mean annual ***loading*** rates were significantly greater than modeled levels in one harvested watershed (28.0 lbs/ac/yr [modeled] versus 84.2 lbs/ac/yr [measured]). In all cases, the post-harvest measured TSS ***loading*** rates ranged from 53 to 84 lbs/ac/yr. The increased TSS ***loading*** was likely a result of increased stream discharge dislodging and mobilizing legacy sediment. No evidence of sedimentation inputs to the streams, such as erosion gullies or sediment trails originating from the harvest areas, were observed in any of the watersheds. TSS ***concentrations*** were not significantly greater than model estimates.
h. *Stream water temperature* readings did not exceed 29°C (84.2°F), which is the maximum allowable temperature as defined by the State of North Carolina water quality standards for maintaining healthy stream habitat for aquatic life.
i. *Benthic macroinvertebrate communities* were bioclassified as Good/Fair to Excellent in the harvested watersheds, postharvest. After the harvest, changes were observed in the abundance and types of aquatic insects that were sampled. However, there was no functional degradation in the sampled aquatic life after the timber harvests in harvested watersheds.

Forest Management Take-Home Points

- **Increases in sediment and nutrient loading and concentrations may occur after a harvest. However, if best management practices are implemented and effective, these increases are of relatively short duration when compared to the long-term growth cycle of forests. Prompt reforestation after harvest will attenuate increased water flows and/or nutrient loading.**
- **Underlying soils and geology will influence the cycling of nutrients between the soil and water, especially when those nutrients are transported by rainfall-driven runoff. Foresters and resource managers should recognize the differences in their soils and implement BMPs accordingly to mitigate the potential for accelerated erosion, runoff, and sedimentation.**
- **Stream water temperatures can be moderated by retaining adequate shade-producing vegetation within the riparian zone, even with selective harvesting of large trees from the riparian area.**
- **Harvesting of timber can be compatible with sustaining and/or protecting the quality of aquatic life conditions in streams when measures are taken to protect the riparian environment.**
- **Most aquatic insects depend upon the persistence of water within the stream to sustain their life cycle. But the water must remain relatively free from sediments or other pollutants. Establishing a protective stream/riparian buffer zone can accomplish multiple objectives in protecting overall water quality and habitat conditions for aquatic organisms.**

3. **Riparian Buffer Characteristics**
   a. Even after selective harvest and removal within the riparian buffer zones, tree canopy cover in the riparian buffer met best management practices recommendations and was sufficient to shade the stream on all watersheds.
   b. The total number of stems in the riparian buffer zone did not significantly change after harvest. However, significant damage including broken tree tops and windthrown trees occurred to the residual timber in the riparian buffer zones after the harvest.
   c. After timber was selectively removed from the stream buffer zone, the ground-cover vegetation diversity increased, due to increased sunlight reaching the forest floor and promoting growth of herbaceous and bush vegetation.
   d. Soon after harvest, the layer of leaf litter got deeper and there was generally an increase in both fine and coarse woody debris.
   e. More blow-down of trees was observed in the UF1 than HF1. The UF1 site has shrink/swell clay soils, with a seasonally perched water table. The trees in the UF1 watershed were also larger and taller than those in the HF1 watershed.

Forest Management Take-Home Points

- **Harvesting of overstory trees can provide more sunlight to reach the ground and foster the growth of more diverse groundcover and shrub vegetation. Foresters and resource managers may be able to promote changes in low-growing vegetation type and structure, depending upon if and how overstory trees are removed from a riparian area.**
- **When selecting trees to retain within a riparian buffer zone, careful consideration should be taken regarding the soils, size of trees, species of trees, and potential for not leaving large, open gaps in the residual tree canopy. The intent should be to retain trees that provide long-term vegetation structure, soil stability, and stream shade; all of which contribute to protecting water quality and the overall aquatic/riparian habitat conditions**
- **Despite a lack of observed increased TSS, the practical presumption is that any major damage to streambanks from large uprooted trees on the stream edge would likely contribute to an increased future potential of streambank instability, scouring or failure; all of which would create a localized source of sediment input to the stream system.**
- **The forester, landowner, or resource manager should be offered flexibility when selecting which trees to retain and remove from a riparian buffer zone, if timber harvesting is conducted alongside the stream. If regulatory policies persist which govern the degree to which trees can be harvested alongside streams in designated watersheds, then changes to those policies may be warranted to reduce the size limits of those trees which must be retained.**
- **The Neuse Buffer Zone rule was applied in this study. This rule requires a 50 ft wide buffer with specifications on which trees may be harvested. This rule does not apply to the entire state. Please visit http://www.ncforestservice.gov/water_quality/buffer_rules.htm for additional information on what buffer rules may apply in your area.**

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Appreciation is expressed to NC State University (NCSU) and NC Department of Agriculture and Consumer Services (NCDA&CS) for their partnership and cooperation in providing access to their respective forestlands to conduct this long-term study. We especially thank David Schnake, NCDA&CS Forester; Joe Cox, former NCSU Forest Manager; and Mike Sweat, former NCSU Forester; for their site knowledge, field time, and timber sale assistance. We thank Dave Penrose and his company, Watershed Science LLC, for their participation and assistance with the macroinvertebrate monitoring component of the study.

We express our thanks and gratitude to Will Summer for his investment of time and knowledge to getting this project underway and implemented 'on the ground' during his employment with NC Division of Forest Resources (now NCFS). We also thank all the interns and support staff that has assisted with field data collection, watershed surveys, and site maintenance.

Hand felling was required in the buffer on the UF1 site. A certified chainsaw safety and felling expert (Mr. Bryan Wagner) from the Forestry Mutual Insurance Company conducted an on-site training exercise and demonstration for the logger, and assisted with the cutting and felling of trees within the NBR Zone. We thank Mr. Wagner for his assistance.

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1.0 Introduction

Forested watersheds maintain suitable water quality, even when forestlands are managed primarily for timber production. However, forest roads, skid trails, stream crossings, site preparation, and other activities that disturb the forest floor have the potential to accelerate soil erosion. Accelerated erosion may lead to increased amounts of sediment and nutrients delivered to streams during and following forest operations. Increased sediment loads may have significant effects on hydrology, hydraulics, morphology, and ecology of receiving streams.

Forestry best management practices (BMP) are methods, measures, or strategies implemented to reduce water quality impacts caused by silvicultural operations. Forestry BMPs were developed to address sediment and nutrients and are effective tools for minimizing sediment pollution that may result from silvicultural activities. Each southeastern state has a forestry BMP manual. However, each state has unique rules and regulations (see section 6.0 Additional Resources for the regulatory framework and forestry BMPs in North Carolina). The North Carolina Forest Service, among other states, continually improve and modify BMP recommendations for forest operations based on applicable research findings in their appropriate regions.

In the southeastern region of the United States, all state forestry agencies have developed BMPs that are periodically evaluated to determine their rate of usage. In addition, multiple research studies have been conducted in the southeast to determine the effectiveness of certain BMPs, with most studies focusing on the retention of protective streamside management zones (SMZs). A long history of BMP research has emphasized the importance of region specific conditions, such as soils, topography, forest management techniques, historical land uses, and other geophysical conditions, yet few research studies, relative to the number of region specific conditions, have been conducted. Several extensive reviews of forestry BMP research and implementation have been published in the peer-reviewed literature, but all reviews highlight the need for additional research.

Research in the North Carolina Piedmont is of particular interest because it is estimated that 58% of the streams are 1st-order headwater streams. Protecting these streams from degradation will help protect water quality, riparian habitat, and water resource supplies that exist further downstream. The Piedmont is an area under rapid urbanization. For example, according to the North Carolina Office of State Budget and Management, the population in Wake County, North Carolina is projected to increase from 627,000 to 1,560,000 in the next 30 years. Thus, quantifying baseline and storm runoff volumes and water quality data from forested watersheds in this region can add value to future planning, with regard to how forestry practices effect hydrology and how forests can serve a role in overall watershed protection or function.

Research in North Carolina's experimental forests, such as Coweeta Hydrological Laboratory in the Mountain region and the Hofmann Forest in the Coastal Plain region, has resulted in a long history of watershed hydrology and water quality data related to sustainability of forest and water resources following silvicultural activities. However, these region results cannot be readily applied to the Piedmont because characteristics affecting watershed hydrological processes and resulting instream water quality are often variable from region-to-region, year-to-year, and watershed-to-watershed. Since these are *in situ* studies of real-world systems, they are subject to one of the greatest sources of variability in watershed hydrology studies: precipitation patterns and other meteorological conditions (temperature, humidity, etc.). The ideal study design that accounts for this sort of variability and provides a statistically valid assessment of the experimental treatment (in this case, clearcut timber harvests) is the *paired watershed design*, and this was the approach selected for use in this study (Figure 1).

During the calibration period, both the reference and treatment watersheds are monitored for stream discharge, water chemistry, or other parameters of interest. From these data, a set of statistically significant equations are developed that can be used to predict the conditions in the *treatment watershed* based on the conditions found in the *reference watershed*. For example, during the calibration period for this study it was found that daily stream discharge in one treatment watershed ($Q_{treatment}$) could be reliably predicted using the daily discharge readings in the corresponding reference watershed ($Q_{reference}$) by using the following equation:

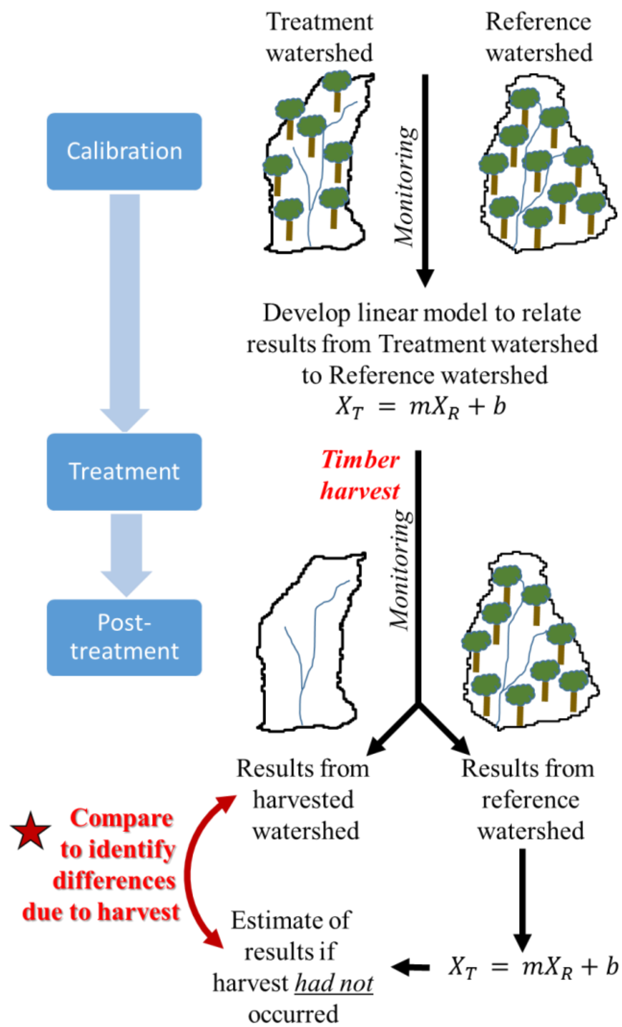


Figure 1. The paired watershed study approach.

$$Q_{treatment} = 0.81 * Q_{reference}$$

After the timber harvest, both the treatment and reference watersheds continue to be monitored, and the equations were applied to results from the *reference* watersheds to get an estimate of what the conditions would be in the *treatment* watersheds, had the timber harvests not occurred. In this way, the actual results from the treatment watershed postharvest can be compared to these estimates and any differences can be attributed to the experimental treatment (the harvest). Using the previous example, the discharge that *would* have occurred within the treatment watershed, had it not been clearcut, can be estimated by plugging the discharge from the reference watershed into the equation above. This process of calibration—developing the relationship (equation) between the watersheds, treatment, and post-treatment monitoring—was completed for discharge, sediment, and nutrient data from the study.

This type of approach accounts for annual and seasonal variability in weather, soil moisture, vegetation stress, and other factors that may affect watershed hydrology, and therefore provides a more "apples-to-apples" type of comparison under the specific weather conditions encountered during a multi-year study. To further minimize sources of variability, the paired watersheds are selected based on close proximity and similarity in soils, aspect, size, vegetation type, and other characteristics.

The objectives of this study were to quantify changes to stream discharge, water quality characteristics, and aquatic wildlife types and abundances following a clearcut timber harvest using North Carolina BMPs recommendations and appropriate North Carolina buffer rules. This study took place in the Piedmont using a paired watershed approach. Specifically, researchers asked:

1. Do forestry best management practices in the harvested watersheds maintain water quality parameters relative to the non-harvested?
2. Is watershed hydrology—as measured by discharge/precipitation ratio and total water yield—significantly different between clearcut harvested and non-harvested watersheds? If so, how long are the effects detectable?
3. If there are significant changes, do they result in significant impacts on aquatic communities and how long do they last?
4. How are riparian vegetation and groundcover affected by timber harvest?

2.0 Methods

2.1 Study Sites

A total of three watershed pairs were identified for this project in two locations: North Carolina State University's (NCSU) Hill Demonstration Forest (HF) and North Carolina Department of Agriculture and Consumer Services' (NCDACS) Umstead Research Farm (UF). Both project areas were located in the Piedmont region of North Carolina and within the Neuse River basin, approximately five miles apart. The HF sites included two pairs of watersheds in the Flat River sub-basin in northern Durham County. The remaining watershed pair in UF was located in the Knap of Reeds Creek drainage in western Granville County (Figure 2).

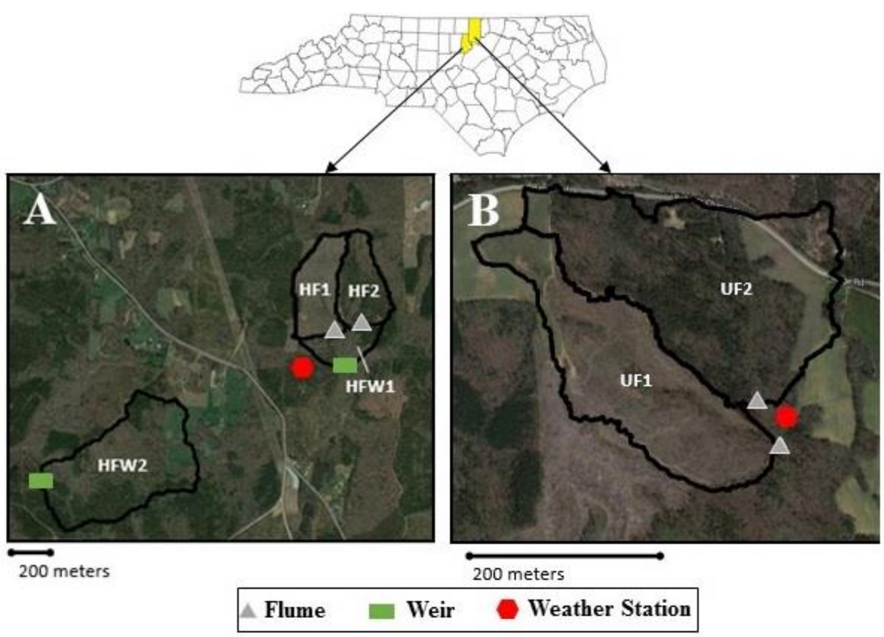


Figure 2 Approximate location of instrumented watersheds. Aerial photos taken postharvest.
A) Hill research forest (watersheds HF1, HF2, HFW1, HFW2) in Durham Co., NC.
B) Umstead Farm (UF1, UF2) in Granville Co., NC.

Treatment (harvested) watersheds were HF1 and UF1, with the corresponding adjoining watersheds serving as respective reference controls. Nearly 100% of the area within HF1 and UF1 was harvested. On the Hill Forest, both HF1 and HF2 are nested within a larger watershed, labeled as HFW1. About 33% of the area in the HFW1 watershed was harvested, as a result of the harvesting treatment applied to its component HF1. Also on the Hill Forest is a separate, larger watershed, labeled as HFW2. Even though a portion (~10%) of HFW2 had been harvested prior to the beginning of this study, the harvesting does not appear to have altered stream discharge or other conditions, therefore it was deemed acceptable to serve as a supplemental reference watershed. The dominant overstory timber species on all of the watersheds include(d):

- American Beech (*Fagus grandifolia*)
- Loblolly Pine (*Pinus taeda*)
- Mockernut Hickory (*Carya tomentosa*)
- Northern Red Oak (*Quercus rubra*)
- Pignut Hickory (*Carya glabra*)
- Red Maple (*Acer rubrum*)
- Shortleaf Pine (*Pinus echinata*)
- Sourwood (*Oxydendrum arboretum*)
- Sweetgum (*Liquidambar styraciflua*)
- White Oak (*Quercus alba*)
- Yellow / Tulip Poplar (*Liriodendron tulipifera*)

Several site characteristics of each watershed are shown in Table 1. The major difference between HF and UF is the corresponding ecoregional subsections, as defined by USDA-FS. Ecoregional subsection boundaries have been delineated by the USDA-FS based on local climate, vegetation, topography, surficial geology and soils, and those factors can result in distinct differences in terrain, hydrological regimes, stream channel morphology, size distribution of streambed substrates, and soil erodibility. HF watersheds (HF1, HF2, HFW1 and HFW2) were located in the Carolina Slate Belt (CSB) ecoregional subsection, which is characterized by streams that are generally shallow, connected to a narrow floodplain, have a rocky substrate, and have relatively steep upland slopes. Conversely, in the Triassic Basins (TB) ecoregional subsection, where UF watersheds (UF1 and UF2) were located, streams tend to have deeper (incised) stream channels that are detached from wide floodplains, sandy substrates, and gentle upland slopes. Some reaches of the UF streams, particularly those in UF2, appeared to have been channelized or straightened in the past, a common occurrence in the Piedmont due to legacy homestead uses or agricultural practices.

Table 1. Watershed study site characteristics.

	NCSU Hill Demonstration Forest				**NCDA&CS Umstead Research Farm**	
Watershed Label	**HF1**	**HF2**	**HFW1**	**HFW2**	**UF1**	**UF2**
Watershed Purpose	*Treatment*	*Reference*	*Nested*	*Reference*	*Treatment*	*Reference*
Watershed Location	Flat River, Durham Co.				Knap of Reeds Creek, Granville Co.	
Watershed Size (ac)	30	30	72	99	47	72
Stream Length (ft)	984	853	2,624	3,149	1,804	656
Timber Type	Mixed Pine Hardwood				Mixed Pine and Hardwood	
Timber Age	35				70	
Slope (%)	13				7	
Geologic Type	Carolina Slate Belt				Triassic Basin	
Dominate Soils	Tatum and Appling				Helena	
Soil Description	Non-expansive clays. No Perched Water. Deep Soils. Runoff is slow throughout the year due to large amounts of stored water in bedrock and topographic control.				Expansive clays. Perched water. Thin Soils. Runoff is slow in growing season when soils are dry, with an inactive confining clay layer. Runoff is fast in dormant when soils are wet with an active confining layer.	

2.2 Timber Harvests within Treatment Watersheds

Personnel from the NCDA&CS, NCFS, NC State University (NCSU) and USDA-FS worked collectively to define the timber sale area boundary, mark the property lines, designate and mark the stream buffer zones, inventory the timber to be sold, solicit and obtain timber sale bids, execute timber sale contracts, and prepare preharvest plans for each treatment watershed. A set of preharvest planning maps, aerial photos and supporting documents were provided to the timber buyers and logging contractors prior to the beginning of timber harvesting.

An on-site meeting with the timber buyer and logger was held prior to beginning the logging to explain the study and emphasize forestry BMPs. The logger was asked to fully implement applicable forestry BMPs in order to protect water quality and reduce risk of soil erosion. The logger was also asked to ensure compliance with the applicable regulations and laws outlined in the NC Administrative Code and General Statutes, including the Forestry Practice Guidelines Related to Water Quality (FPGs). Additionally, due to the study watersheds being located in the Neuse River basin, harvesting activities had to comply with the protection and preservation of riparian vegetation as stipulated in the Neuse River Basin Riparian Buffer Rules ("Neuse Buffer Rules"), rather than the more flexible recommendations for Stream Management Zones (SMZs) outlined in the NCFS BMP manual (please visit www.ncforestservice.gov to review the complete Neuse Buffer Rules). Figure 3 depicts two views of the stream buffer from UF1 watershed.

Figure 3. Photo above is the UF1 watershed, showing the Neuse Buffer Rule (NBR) Zone retained during harvest.

Photo at right shows the NBR Zone in UF1 after harvesting. The blue-painted trees mark the edge of the required 30-foot vegetated buffer. The outermost remaining 20-feet of the NBR Zone was clearcut, as permitted by the rule. Selective harvesting was conducted within the NBR Zone.

The first watershed harvested was Umstead Farm (UF1). Logging took place from July 2010 until September 2010. The Hill Forest (HF1) watershed was logged from November 2010 until January 2011. The exact scheduling of harvests was not prescribed by this study or in the timber sale contracts. The harvests were scheduled at the discretion of the timber buyer and logger.

However, the forest manager for each property retained the right to determine if the ground (soil) conditions were not suitable for logging equipment to access (i.e., if the soil was too wet, which could have resulted in site degradation from soil compaction or rutting). Generally speaking, there was very little soil compaction or rutting observed on either treatment watershed during or after logging.

No stream crossings were used on any timber harvest. The number, extent, and width of primary skid trails was kept to the minimum needed to harvest the site. In addition, the loggers were encouraged to re-distribute leftover treetops, branches, and unusable woody materials back across their main skid trails, as the logging progressed (Figure 4). This BMP is especially useful on areas of sloping terrain or when the skid trail is nearby to the stream buffer zone. This practice is intended to minimize soil compaction / rutting, reduce soil exposure, and lessen the risk of accelerated erosion. Each logger implemented this BMP; and it was especially visible in the UF1 watershed (Figure 4) where the logger had more residual woody debris available to distribute and pack down upon the main skid trails. Other BMPs employed during the study harvest included minimizing logging deck size, locating the deck away from surface water, and minimizing the size and extent of main skid trails.

Figure 4. A main skid trail on the UF1 site, looking towards the log deck. Residual tree material ("slash" or "laps") was applied on top of the skid trails throughout the logging operation.

A different logger harvested each of the watersheds. This differentiation was not prescribed by this study, but was simply a result of the timber sale agreements executed by the two respective study site Forest Managers. Both loggers used typical Piedmont ground based logging systems including: single-width, rubber-tired a grapple skidders and a rotary sawhead feller-buncher. Frequent site visits by study team participants were made to each harvest as it progressed. Figures 5 and 6 show aerial photographs of HF and UF, respectively, following timber harvests.

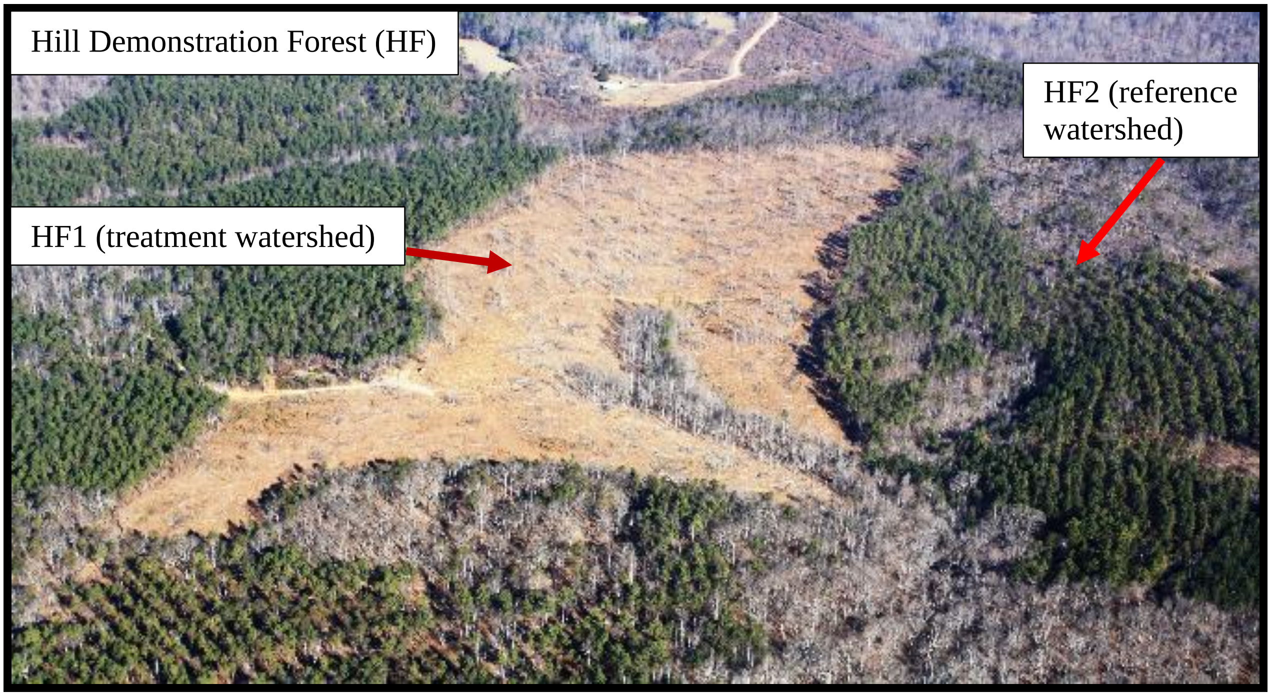


Figure 5. Aerial photo of treatment and reference watersheds in Hill Demonstration Forest study area. A 30-foot vegetated riparian buffer was left on each side and above the origins of the first-order streams in the treatment watersheds, in accordance with the requirements of the Neuse River Basin Riparian Buffer Rules. Photo was taken approximately one month postharvest.

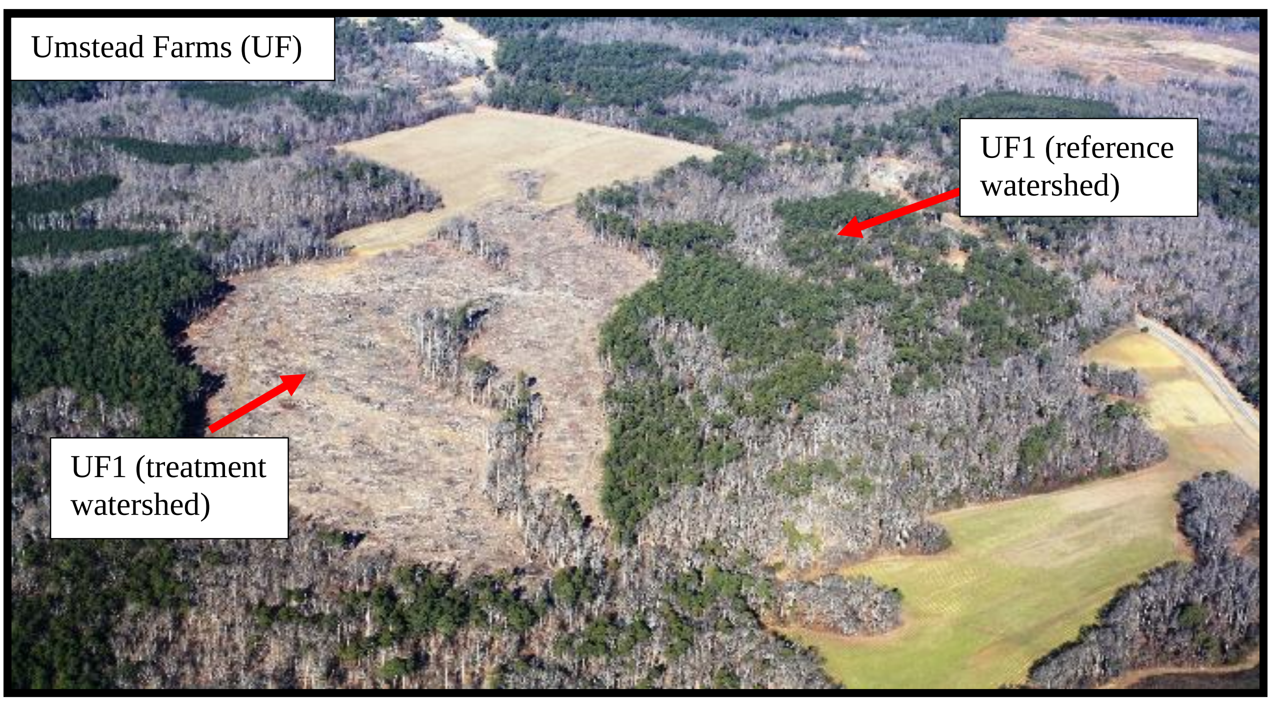


Figure 6. Aerial photo of treatment and reference watersheds in Umstead Farms study area. A 30-foot vegetated riparian buffer was left on each side and above the origins of the first-order streams in the treatment watersheds, in accordance with the requirements of the Neuse River Basin Riparian Buffer Rules. Photo was taken approximately five months postharvest.

After each harvest, silvicultural treatments were implemented by each of the watershed's forest manager. The general treatments were similar in each harvested watershed and consisted of:

- One aerial application of herbicide
- Installation of a bladed fireline around the perimeter (ridgeline) of each harvest area (Figure 7). Note: A fireline was not installed along the perimeter of the NBR Zone.
- Application of a prescribed-fire / site-preparation burn to help remove excessive logging debris and vegetative growth (Figure 7). The fire was initiated from alongside the stream in each watershed, and allowed to back-burn out from the stream's edge, through the NBR Zone, and into the cutover. No damage to residual timber within the NBR Zone was observed after the prescribed fire.
    - Note: The site prep burn was conducted before blow-down damage of trees in the UF1 NBR Zone which resulted from multiple windstorms. Had the storm-damaged timber been present, a fireline would likely have been installed along this NBR Zone to keep the fire out of the UF1 NBR Zone, to avoid the potential of the fire to ignite a significant source of woody fuel, and escape or get out of control.
- Each watershed was planted with pine seedlings, using hand tools. The HF1 site was planted with Loblolly Pine (*Pinus taeda*) and the UF1 site was planted with Shortleaf Pine (*Pinus echinata*). The decision to plant different species of pine was not prescribed by this study, and was solely at the discretion of each forest manager, to meet the respective agency's long term management objectives.
- All of these silvicultural treatments were conducted during the following period:
    - HF1: June 2011 to January 2012
    - UF1: July 2011 to January 2012

Figure 7. Installation of a fire control line around the perimeter of the UF1 site (right); the operator is installing a waterbar on the fire line. Site prep burn backing out from the Neuse Buffer Rule Zone on the UF1 site

2.3 Field Sampling Methods

Table 2 provides a summary of the metrics monitored during this study. Additional details of each category as they pertain to this study are provided in the sections below Table 2. Additional general information on watershed hydrology is provided in Appendix A.

Table 2. Summary of field data collected.

Data Category	Parameters	Frequency	Methods
Watershed hydrology			
Meteorology	Precipitation, air temperature, relative humidity, total solar radiation, wind speed, soil moisture	Sampled every 4 minutes, logged every hour	Hobo™ micrometeorological station
Stream discharge	Calculated from stage and flume/weir dimensions	10 minute intervals	2-H flumes or V-notch weirs with Sigma™ water level recorders
Stream channel geomorphology	Cross sections	Preharvest and postharvest	Land survey equipment (total station)
Evapotranspiration	Residual trees in the buffer zone	10 minute intervals	Heat dissipation (sapflow probes)
Riparian buffer vegetation			
Riparian vegetation structure	Timber overstory and midstory; groundcover survey	Preharvest and postharvest	Modified Carolina Vegetation Survey Method, with 150m^2 plots with 1 m^2 subplots
Water quality			
Water chemistry*	TSS, NO_3-N, NH_4-N, TP, TKN, TOC (all mg/L)	Bi-weekly (baseflow) and storm-initiated (stormflow)	Grab samples (baseflow) and Sigma™ automated sampler (stormflow)
Water temperature	Temperature (°C)	10 minute intervals	Hobo™ Water Temp Pro V2 Logger
Aquatic community			
Benthic macroinvertebrates	Taxa diversity, community tolerance, functional feeding groups	Biannually	Semi-qualitative method described by NCDENR-DWR, Qual4 (2012)
*Abbreviations for water chemistry measures: TSS – Total Suspended Solids; NO_3-N – nitrate nitrogen; NH_4-N – ammonium nitrogen; TP – total phosphorus; TKN – Total Kjeldahl nitrogen (organic nitrogen + ammonium); TOC – total organic carbon			

2.3.1 Watershed Hydrology Parameters

Flow control structures, such as flumes and weirs, are necessary to obtain accurate, near-continuous discharge 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 (Figure 8). Stream discharge rate (ft^3/sec, or cfs) was then recorded every 10 minutes by a Sigma™ 900 Max water sampler with a depth sensor. Precipitation (mm) was measured separately in a nearby open area at HF and UF using Hobo™ Data Logging Rain Gauge-RG3.

Figure 8. A flume and automated water sampler (left picture). A weir on the outlet of HFW1 (right picture).

To facilitate comparison of discharge to precipitation inputs, discharge measurements for each watershed were divided by their respective watershed area and reported in mm (unit used to measure precipitation). Total discharge for each watershed outlet was calculated for several time periods, including daily, monthly, and annually.

Channel geomorphology surveys were taken at three cross sections in the watersheds during both preharvest and postharvest periods (Figure 9). The stream survey protocol in general followed the *Stream Channel Reference Sites: An Illustrated Guide to Field Technique, USDA Forest Service General Technical Report RM-245* with some modification to capture features unique to these watersheds. The USDA-FS and NCFS worked in conjunction with the NCSU Department of Biological and Agricultural Engineering to complete the stream surveys. Data processing and figures showing stream cross sections during the monitoring period were completed by staff of the NCFS.

Figure 9. David Jones of NCFS (right) and a student from NCSU conduct geomorphic stream survey on one of the watershed streams.

2.3.2 Riparian Buffer Vegetation

To characterize vegetation community composition in the riparian zone, multiple plots were established, representing 10% of the total riparian area. HF1 had four plots; HF2 had six plots; UF1 had ten plots; and UF2 had four plots. Tree stem count and diameter at breast height (DBH) were measured annually, following parts of the protocol outlined in the Carolina Vegetation Survey. In addition, six subplots were established within each vegetation plot for estimation of the percent of vegetative ground cover.

Field inspections in April 2013 and August 2013 revealed considerable blowdown of overstory trees in the UF1 watershed. Thus, additional vegetation surveys were taken to determine the number and diameter size of standing and windthrown stream edge trees within the riparian area to try to characterize which species and sizes may be most susceptible to blowdown. Stream edge trees were defined as trees having roots that were naturally exposed in the stream channel.

2.3.3 Water Quality Parameters

Water quality parameters were quantified from grab and storm samples and reported as either a load or concentration (see the Note at the end of this section). Grab water samples were collected at least bi-weekly under baseflow conditions. A total of about 900 grab samples were collected over the monitoring period. Storm water samples were collected based on flow rate of change with a trigger flow point programmed in the Sigma™ 900 Max (Boggs et al. 2013). A total of 78 storms were captured over the monitoring period. The total number of storm flow samples collected during this study was approximately 5,620. Samples were analyzed for:

- Total suspended solids (TSS)
- Total organic carbons (TOC)
- Ammonium-form of nitrogen (NH_4)
- Nitrate-form nitrogen (NO_3)
- Total organic nitrogen (TON) [calculated from NH_4 and NO_3 concentrations]
- Total nitrogen (TN) [calculated from NH_4 and NO_3 concentrations]
- Total Kjeldahl nitrogen (TKN) [calculated from TON + NH_4]
- Total phosphorus (TP)
- Temperature
- Benthic macroinvertebrate biotic index (BI)
- Benthic macroinvertebrate Ephemeroptera (mayflies), Plecoptera (stoneflies), and Trichoptera (caddisflies) score (EPT)

Water samples were preserved with sulfuric acid to pH <2 and kept at 3.6°C prior to analysis. Constituents from each water sample were determined at the North Carolina State University's Department of Soil Science, Environmental and Agricultural Testing Service laboratory.

Results were reported as a concentration in mg/l. Loading (kg/ha/month, or kg/ha/year) of each constituent was then calculated as:

$$Concentration\ (mg/l) \times Discharge\ (mm/month\ OR\ \ mm/yr) \times Watershed\ area\ (ha)$$

Water sample data collection was limited at the onset of study due to a regional drought. Study watersheds experienced a 43% water deficit during the first several months of monitoring. Precipitation for this period was typically 514 mm (20.2 inches), but the study watersheds only received 296 mm (11.6 inches). This lack of precipitation reduced discharge and the number of water samples collected for chemical analysis during the early portion of study. However, an extended calibration period mitigated impact from the drought and was sufficient to develop predictive linear models necessary to fully assess treatment effects on discharge and water chemistry.

> ***Note:*** Stream water quality was measured in order to identify any changes to loading rates or instream concentrations that might occur after timber harvest. *Instream concentrations*, often measured in mg/l, are more useful for assessing potential impacts to common uses of surface water, such as supporting healthy aquatic communities, serving as public water supplies, or utility for industrial processes. *Loading*, reported as a rate (mass per unit time) and calculated from stream discharge and instream concentrations, is

often used to manage large watersheds to ensure that the maximum assimilative capacities of downstream waters (including sounds and estuaries) are not overwhelmed. Increases in sediment or nutrients can lead to deleterious impacts downstream of the source, so minimizing increases to loading over both the short- and long-term are needed to protect downstream waters. Loading and concentrations can vary greatly depending on whether the stream is carrying *baseflow* (primarily groundwater-driven discharge and tends to be relatively low) or *stormflow* (high stream discharge in response to precipitation events that includes a combination of groundwater- and runoff-driven discharge). Because of this, water samples were taken under both baseflow and stormflow conditions.

2.3.4 Aquatic Community Parameters

Nine benthic macroinvertebrate surveys were completed following the semi-qualitative methods outlined by NCDENR-Division of Water Resources (DWR) Biological Assessment Unit (2006) Qual4 method. This method (Figure 10) employs the use of a kick net, sweep net, leaf packs, and visual samples when sampling each stream (NCDENR, 2012). Benthic macroinvertebrate communities were sampled biennially in each study watershed in the preharvest (2 samples) and postharvest (7 samples) periods under both growing and non-growing seasons. Once samples were collected and the organisms identified, the relative abundance (rare, common, or abundant) of each taxon and its corresponding pollution tolerance values were used to calculate diversity indices and an overall bioclassification for each sample. Benthic macroinvertebrate samples were field sorted and sent to Watershed Science, LLC to be identified to the lowest possible taxonomic class. A numerical biotic index and categorical bio-classification were determined according to the NCDENR-DWR 2006 standard qualitative method. Additional analysis of functional feeding groups (FFGs) was also performed to determine if there were changes to trophic-level community structure. FFGs can be used to determine if there's an overall shift in food sources, physical, or chemical conditions in the stream.

Figure 10. Dr. Dave Penrose of Watershed Science LLC and an assistant sample for aquatic insects (left). A stonefly (*Plecoptora spp.)*, which is an indicator of excellent water quality (right).

2.3.5 Data Processing and Analysis

A statistical t-test (JMP ver.11.0, SAS 2011) was used to analyze Measured Results and Modeled Results for both TSS and all of the nutrient parameters. The t-test was selected with the significance level set to alpha (α) < 0.05 to determine which group values (Measured versus Modeled) were statistically different from each other.

Storm parameters were derived from a constant slope or standard flow separation method where water is discharged from a watershed in excess of 0.05 $ft^3/sec/mi^2/hr$ or 1.1 mm/day. The constant slope value was applied to separation analysis during 13 of 44 storms when at least 15 mm to 20 mm of measured rainfall occurred. Slope separation was terminated when total volume of discharge exceeded baseflow discharge. The average separation analysis lasted 21.2 hours during the nongrowing season (November to April) and 12.9 hours during the growing season (May to October).

3.0 Study Results

3.1 Hydrology

Overall, surface water runoff after a harvest increased. Runoff which occurred from storm events, after a harvest, significantly increased in both absolute volume and duration of time. It is important to recognize how different soils effect runoff when planning a timber harvest. Increased runoff not only contributes more water into the stream system, but also illustrates the need for installing and maintaining adequate BMP measures that will prevent, control, and manage soil erosion and sedimentation into streams that may result from increased surface runoff. A dampening effect was seen in HFW1 (where only 33% of the watershed was harvested). This demonstrated how harvest planning on a landscape scale can offset potential increases in stream discharge. This can be an important consideration for resource managers, forest owners, or downstream stakeholders.

Even though stream discharge increased notably after clearcutting, the residual trees in the stream zone increased their usage of water, and the relative increases of stream discharge began to diminish as the harvested area regrew. Assuring prompt reforestation after a harvest will sustain timber availability and contribute towards balancing the watershed cycle back to preharvest levels. If the forest manager has an objective of water supply management, then this increased water use by residual riparian trees may drive some of the decisions regarding whether or not to selectively harvest trees from stream buffer zones, and if so, what species of trees to retain or harvest, given that different tree species cycle water differently.

3.1.1 Precipitation

Table 3 shows the abbreviated version of the mean annual precipitation for the HF and UF watershed sites pre- and postharvest. Average rainfall at both sites was greater in the preharvest than postharvest. During the preharvest, 8 intense storms (greater than 1 in/hr) occurred. During postharvest monitoring, 3 intense storms (greater than 1 in/hr) occurred.

Table 3. Mean annual precipitation for each watershed site pre- and postharvest.

Site	Preharvest	Postharvest
	--------mm/yr *(in/yr)*--------	
HF	1140 *(44.89)*	1102 *(43.39)*
UF	1142 *(44.96)*	1000 *(39.37)*

3.1.2 Stream Discharge

Table 4 shows the abbreviated version of the cumulative measured stream discharge from treatment watershed. The modeled stream discharge closely matched the measured stream discharge during the preharvest calibration period for HF1, HFW1 and UF1 watersheds. This close match provided a high level of confidence that the model could realistically estimate stream discharge as if the harvest had not occurred. Thus a comparison of the modeling results against the measured data following each harvest was conducted. Following the harvests, the models predicted significantly less stream discharge (Table 4).

Table 4. Cumulative measured and modeled stream discharge from each harvested watershed. Modeled postharvest values represent the estimated discharge had the timber not been harvested.

Sites	Preharvest		Postharvest	
	Measured	Modeled	Measured	Modeled
	-----------------------(mm)----------------------			
HF1	508	510	826	249
HFW1	725	725	646	457
UF1	537	554	870	304

Detailed versions of Tables 3 and 4 can be found in Appendix B.

Significant increases in stream discharge (compared to preharvest) were observed in each of the treatment watersheds after the completion of the timber harvest (Figure 11). As shown in Tables 4 and 5 and Figure 11, the *Measured Stream Discharges Postharvest* are greater than the *Modeled Stream Discharge Without Harvest*. The actual measured stream discharges from the reference control watersheds were also significantly less during the postharvest period. The rate of change of the increased stream discharge generally began to trend lower as time passed after each harvest, as new vegetation growth re-established the evapotranspiration cycle. The annual percentage of change (increase) of stream discharge in each harvested watershed is shown in Table 5, when comparing the *Measured Discharge Postharvest* against the *Modeled Discharge Postharvest*.

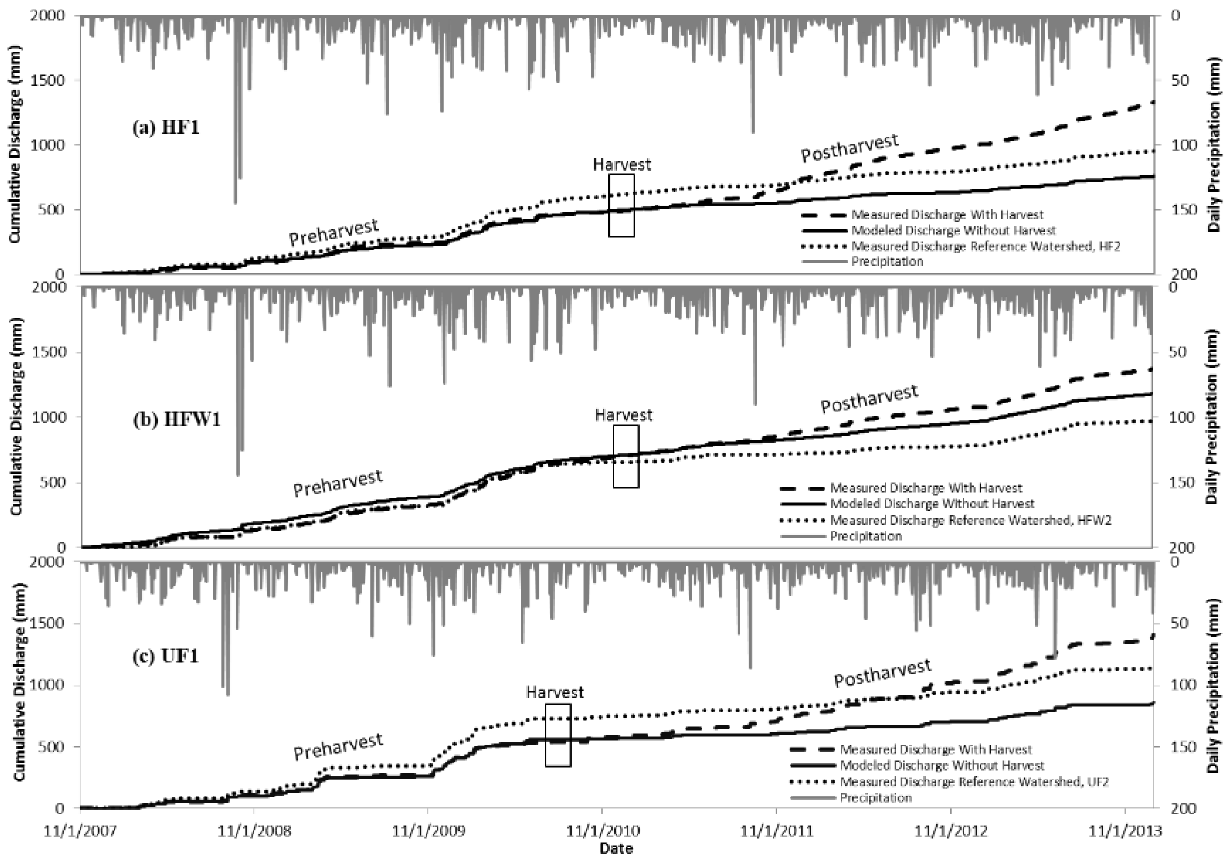


Figure 11. Study duration daily precipitation and cumulative stream discharges for measured, modeled and reference sites.

Table 5. Percent stream discharge postharvest above the modeled estimate in the harvested watersheds. Remember, the model represents the same watershed had the timber not been harvested.

Sites	Year		
	2011	2012	2013
	----------(%)----------		
HF1	263	264	192
HFW1	44	46	37
UF1	249	218	143

The relative effects of a harvest on stream discharge in HF1 and UF1 is larger than other studies have shown in other parts of southern U.S. For example, results from long-term studies at the USDA-FS Coweeta Hydrologic Laboratory in the Blue Ridge Mountains of North Carolina demonstrated up to a 400 mm/year increase in total stream discharge, which represents about a 50% relative increase in stream discharge following a clearcut timber harvest.

It is worth noting that the percentage increase of stream discharge in the HFW1 watershed was significantly lower than the results observed in each of the smaller, headwater watersheds. The HFW1 watershed included a small area of un-harvested forest downstream from the outlet of HF1. This relatively small forest area mitigated (reduced) the increased stream discharge from the HF1 harvest. Other studies have shown that when 10% or less of a forest watershed is harvested, it is unlikely that any increase in annual stream discharge will be detected.

Transpiration was measured for the residual trees that were retained in the Neuse Buffer Rule Zone (NBR) of each harvested watershed. The findings showed that, after the harvests were completed, the remaining trees within the NBR Zone cycled 43% more water than during the preharvest period. This increased water usage by the remaining trees effectively reduced the overall stream discharge by 8%, and partially mitigated the substantial increase of stream discharge otherwise observed after the harvests. A reduction in stream discharge can reduce the remobilization and transport of legacy in-channel sediments. Further studies and investigation are warranted to identify differences in water cycling between different native forest tree species, and how potential stream buffer zone management practices (including selective tree removal) may help to offset the temporary increases in stream discharge after timber is harvested from an upstream area. An additional detailed discussion of these findings can be found in the Hydrological Processes journal publication (see section 6.1, Boggs and others 2015).

Figure 12 illustrates the average monthly difference in stream discharge. This was calculated by:

Measured Stream Discharge With Harvest
(—) Modeled Stream Discharge Without Harvest
= Increased Change in Stream Discharge

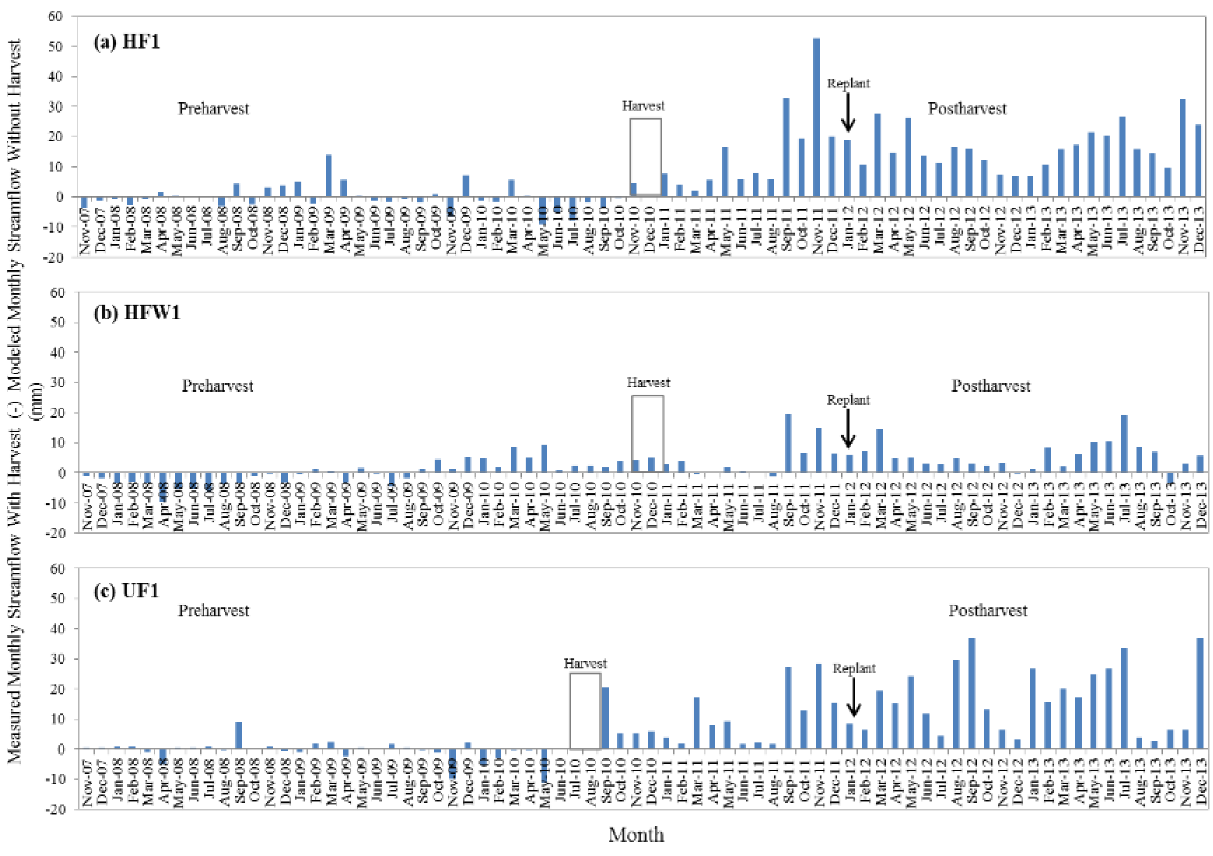


Figure 12. Difference in monthly stream discharge on the treatment watersheds when comparing measured with modeled estimates.

Monthly stream discharge increased in each treatment watershed, except for a few months at HFW1. This exception occurred when the *Measured Discharge With Harvest* was actually lower than the *Modeled Discharge Without Harvest*, resulting in a negative value. However, this margin of error (from 0.05 mm to 3 mm) is considered within the normal variability of natural systems and not considered a significant data anomaly.

As previously noted, about 33% of the HFW1 watershed was harvested (as a result of HF1 harvest), with an increased postharvest stream discharge of 65 mm/yr (about a 40% increase). This dampening effect is also seen in the cumulative discharge results that are illustrated in Figure 11.

Total discharge is a good indicator of change to overall watershed hydrology, however the data collected in this study can also be used to see if there were any changes to stormflows. The storm-based discharge results were higher in each treatment watershed during the postharvest period, as shown in Table 6. Generally, increases were observed for event duration, initial baseflow, peak rate, total discharge, and base flow. The increases were also more common during the growing season, as would be expected. For the smaller treatment watersheds (UF1 and HF1), there was a significant increase in baseflow, total stream discharge, and the discharge/precipitation ratio. This ratio reflects the "efficiency" of the watershed in terms of converting precipitation inputs to stream discharge outputs, and is also referred to as the runoff ratio or runoff coefficient. These increases were expected because removal of vegetation from the watershed results in decreases to interception and evapotranspiration and increases in surface and subsurface runoff.

Table 6. Summary of changes on stormflow characteristics postharvest in three treatment watersheds during growing and dormant (non-growing) seasons. Arrows indicate a statistically significant increase ($P < 0.05$); '--' indicates no significant change. The data for this table can be found in Appendix C at the end of this report.

Watershed	Season	Event Duration *(hours)*	Time to Peak Flow *(hours)*	Initial baseflow *(mm/day)*	Peak Rate *(mm/day)*	Total Stream Discharge *(mm)*	Baseflow *(mm)*	Stormflow *(mm)*	Discharge/ Precipitation Ratio
HF1	growing	↑	--	↑	--	↑	↑	--	↑
	dormant	--	--	↑	--	↑	↑	--	↑
UF1	growing	↑	--	↑	↑	↑	↑	↑	↑
	dormant	--	--	↑	↑	↑	--	↑	↑
HFW1	growing	↑	--	--	↑	--	--	--	--
	dormant	--	--	--	--	--	--	--	--

There were some differences between watersheds as well: changes were seen in the most characteristics in UF1, and the least in HFW1. Differences in stormflow between HF and UF sites were attributed to soil and geological differences. HF soils are thick and store water and discharge it gradually, which results in more continuous base flow across seasons when compared to UF. UF soils are thin and stream discharge is slow in growing season and fast in the dormant season. During the growing season, soils tend to be drier and the confining clay layer is generally inactive, while during dormant season, soils tend to be wet and the confining clay layer active. It appears that stormflow dynamics in response to clearcuts are controlled, at least partially, by soil features that influence hydrologic processes such as stormflow generation and soil water storage dynamics.

3.1.3 Stream Channel Geomorphology

In this study, three cross-sectional transects were established over a 3-year period for each of the watershed pairs (HF1 and HF2; HFW1 only; UF1 and UF2), with measurements taken pre- and postharvest. Transects were established and a Total Station was used to record the cross sectional data. Measurements were taken in 2010 (representing preharvest conditions), in 2011 (early postharvest), and in 2013 (late postharvest).

While this study saw increased stream discharge after the timber harvests in each treatment watershed, there were no significant changes observed in the stream channel cross sections. This would indicate that no scouring of the stream bank, undercutting of stream edge vegetation, or additional loss of stream bank structure occurred after the harvest, above and beyond any naturally-occurring stream pattern changes. There was no evidence of major stream bank failures nor measurable increases in mean daily stormflow TSS concentrations. Additionally, since no major changes in stream channel cross sections were observed, and no break-through of sediment trails in the NBR Zone were observed (in other words, no sediment trails coming from the harvested area), it can be presumed that the increases of TSS loads and concentrations during the postharvest period can be attributed to the down-stream transport of legacy in-channel sediment that was remobilized from the increased stream discharge.

3.2 Water quality

A summary of significant changes to the water quality parameters evaluated can be found in Table 7. Overall, watersheds exhibited sediment and nutrient loads that are similar to natural background levels from forests in other studies, and much less than other land uses. Total suspended solids (TSS) or nutrient loading increased (albeit minor amounts) following a timber harvest. However, the increases were relatively short-lived relative to the length of time until the next harvest. The increase in nutrients occurred almost entirely as a result of increased runoff from the landscape and the decreased uptake from trees after they were harvested. Assuring prompt reforestation after harvests will attenuate increased water flows and/or nutrient loading. Underlying soils and geology influence the cycling of nutrients between the soil and water, especially when those nutrients are transported by rainfall-driven runoff. Foresters and resource managers should recognize the differences in their soils and implement BMPs accordingly to mitigate the potential for accelerated erosion, runoff, and sedimentation. The forests in this study retained significant amounts of nitrogen that was estimated to have been deposited from the atmosphere. Even with periodic harvesting, forest management may be a viable method of managing nitrogen deposition on a landscape scale. Stream water temperatures can be moderated by retaining adequate shade-producing vegetation within the riparian zone, even with selective harvesting of large trees from the riparian area.

Table 7. Summary of significant changes to loading of total suspended sediment (TSS), total organic carbon (TOC), and nutrients during the postharvest period. A significant increase ($P < 0.05$) is indicated by ‘ ↑ ‘ and no significant increase is indicated by ‘ – ‘. ‘ N/A ‘ indicates that a statistically significant model (equation) could not be developed for this parameter/watershed combination so comparisons could not be made. The data for this table can be found in Appendix D.

Watershed	**TSS**	**TOC**	**TP**	**NH4**	**NO3**	**TN**	**TON**
HF1	↑	↑	--	--	--	↑	↑
UF1	--	↑	--	N/A	--	↑	↑
HFW1	--	--	--	--	N/A	↑	--

3.2.1 Total Suspended Solids (TSS)

Total suspended solids (TSS) were monitored under both baseflow and stormflow conditions during this study. A summary of TSS annual loads preharvest and postharvest by treatment watersheds are shown in Table 8. Detailed monthly TSS loading and concentrations for each treatment watershed can be found in Appendix E. The modeled TSS closely matched the Measured TSS during the preharvest calibration period for HF1, HFW1 and UF1 watersheds. This provided confidence that the model could realistically estimate TSS loads as if the harvest had not occurred. TSS significantly increased in the HF1 watershed (Table 8).

Table 8. Average annual measured and modeled loading rates of total suspended solids (TSS) for harvested watersheds. Modeled postharvest values represent the estimated annual TSS loading rate had the timber not been harvested. * indicates a statistically significant increase ($P < 0.05$).

Sites	Preharvest		Postharvest	
	Measured	Modeled	Measured	Modeled
	---------------------(lb/ac/yr)--------------------			
HF1	66	65	84*	28*
HFW1	74	73	53	40
UF1	83	76	57	33

Observations showed that the highest TSS loads were associated with the highest stormflow stream discharge events which resulted from heavy precipitation. There were no sediment “break-throughs” or sedimentation trails leading into the stream channels from the harvested areas. Headcutting of the origin of each stream is active, since the stream originates within the treatment watershed area. While specific measurements of pre- versus postharvest headcutting changes were not made, our observation and presumption is that the headcutting may have become more active after the harvest, due to the likelihood of increased surface water runoff coming from the harvested area (Figure 13).


Figure 13. Stream origin headcut on HF1, postharvest (left). Stream origin headcut on UF1, postharvest (right).

The estimated annual mean TSS loading rates can be multiplied to the estimated acreage for each of the watersheds, to approximate the volume of TSS that may be delivered, per year, from each watershed site.

HF1: Preharvest Measured Baseline: 30 acres (x) 66 lbs/ac/yr =	**1,980 lbs/yr**
HF1: Measured With Harvest: 30 acres (x) 84 lbs/ac/yr =	**2,520 lbs/yr**
HF1: Modeled Without Harvest: 30 acres (x) 28 lbs/ac/yr =	**840 lbs/yr**
HFW1: Preharvest Measured Baseline: 72 (x) 74 lbs/ac/yr =	**5,328 lbs/yr**
HFW1: Measured With Harvest: 72 acres (x) 53 lbs/ac/yr =	**3,816 lbs/yr**
HFW1: Modeled Without Harvest: 72 acres (x) 40 lbs/ac/yr =	**2,880 lbs/yr**
UF1: Preharvest Measured Baseline: 47 acres (x) 83 lbs/ac/yr =	**3,901 lbs/yr**
UF1: Measured With Harvest: 47 acres (x) 75 lbs/ac/yr =	**3,525 lbs/yr**
UF1: Modeled Without Harvest: 47 acres (x) 33 lbs/ac/yr =	**1,551 lbs/yr**

3.2.2 Total Organic Carbons (TOC)

Average annual loading rates of TOC increased 1- to 2-fold above mean annual modeled loads across treatment (Table 9). These increases are consistent with other similar studies and is most likely a result of timber removal. The Modeled TOC closely matched the Measured TOC during the preharvest calibration period for HF1, HFW1 and UF1 watersheds. Thus a comparison of the modeling results against the measured data following each harvest was conducted. Following the harvests, the models predicted significantly less TOC (Table 9).

Table 9. Average annual measured and modeled loading rates of total organic carbons (TOC) for harvested watersheds. Modeled postharvest values represent the estimated annual TOC loading rate had the timber not been harvested. * indicates a statistically significant increase (P < 0.05).

Sites	Preharvest		Postharvest	
	Measured	Modeled	Measured	Modeled
	---------------------(lb/ac/yr)--------------------			
HF1	8	8	12*	4*
HFW1	12	12	10	7
UF1	20	20	30*	9*

Overall, the TOC was low on all sites, both pre- and postharvest. However, there was a spiked increase of TOC in UF1 during September 2010. This was immediately following the timber harvest and occurred during an intense rainfall event. This spike normalized soon afterwards, and is attributed to the likelihood of tree leaves, pine needles, and other woody materials that were leftover from the logging having contributed to the temporary increase of available TOC through the biodegradation process, that was then mobilized into the water column of the stream. Additional detailed monthly TOC loading and concentrations for each treatment watershed can be found in Appendix F.

3.2.3 Ammonium Nitrogen (NH_4)

During the preharvest baseline calibration period, the monthly stream NH_4 measurements were near 0 lb/ac/yr. An increased peak was observed 6-8 months following harvest. This delay was expected as time is needed for ammonium to accumulate in the soil following tree removal. The average annual loading rates of NH_4 for measured and modeled treatment watersheds is shown in Table 10.

Table 10. Average annual measured and modeled loading rates of ammonium nitrogen (NH_4) for harvested watersheds. Modeled postharvest values represent the estimated annual NH_4 loading rate had the timber not been harvested. No statistically significant increases ($P < 0.05$).

Sites	Preharvest		Postharvest	
	Measured	Modeled	Measured	Modeled
	---------------------(lb/ac/yr)--------------------			
HF1	0.018	0.018	0.241	0.009
HFW1	0.012	0.012	0.062	0.005
UF1	0.012	n/a	0.080	n/a

For the HF1 and HFW1 watersheds, the calibration model was used to compare preharvest with postharvest conditions. However, for the UF1 and UF2 watershed pair, the relationship was not good enough to develop a reliable model. A reliable model is, in part, one that provides a 95% probability ($p < 0.05$) that the relationship between NH_4 in the reference watershed and NH_4 in the treatment watershed is not attributable to chance.

Overall, there was very little ammonium loading from either watershed, either before or after the harvest. Two spiked increases of NH_4 occurred in HF1 and this spike is also seen to a lesser magnitude in UF1, during 2011 and again in 2013. These are not easily attributable and are believed to be driven from external or unknown sources. No fertilizer was applied to either of these watersheds. Additional detailed monthly NH_4 loading and concentrations for each treatment watershed can be found in Appendix G.

3.2.4 Nitrate Nitrogen (NO_3)

During the preharvest baseline calibration period, the monthly stream NO_3 measurements were near 0 lbs/ac/yr. This is to be expected, as the trees in each forested watershed had high demand for nitrogen. As a result, nearly all of the available NH_4 was being taken up by the forest, leaving very little remaining to be converted into NO_3 within the soil profile. The average annual loading rates of NO_3 for measured and modeled treatment watersheds is shown in Table 11.

Table 11. Average annual measured and modeled loading rates of ammonium nitrogen (NO_3) for harvested watersheds. Modeled postharvest values represent the estimated annual NO_3 loading rate had the timber not been harvested. No statistically significant increases ($P < 0.05$).

Sites	Preharvest		Postharvest	
	Measured	Modeled	Measured	Modeled
	---------------------(lb/ac/yr)--------------------			
HF1	0.003	0.004	0.607	0.001
HFW1	0.027	n/a	0.170	n/a
UF1	0.027	0.027	1.107	0.036

For the UF watersheds, the calibration model was used to compare preharvest with postharvest conditions. However, for the HFW1 and HFW2 watershed pair, the relationship was not good enough to develop a reliable model. A reliable model is, in part, one that provides a 95% probability ($p < 0.05$) that the relationship between NO_3 in the reference watershed and NO_3 in the treatment watershed is not attributable to chance.

Within 6 to 8 months after the timber harvest, an increase of nitrate was seen, but the annual loading remained below 2 pounds/acre. This delayed response is not uncommon, since time is needed for the NH_4 to accumulate in the soil (due to a lack of consumption by trees), and thus contribute to the nitrification process in the soil. In addition, the decomposition of leaves, needles, and tree branches further contributes nitrogen into the soil, adding to the pool for NO_3 development. Overall, NO_3 levels remained low, and levels returned to preharvest conditions within three years after the harvest.

Peak stormflow nitrate concentrations were observed in each of the harvested watersheds, but measured nitrate concentrations did not exceed the State of North Carolina water quality standard of 10 mg/L for designated water supply watersheds [rule 15A NCAC 02B .0212 to .0218]. The data show that UF1 produced more frequent and stronger peak concentrations, likely due to the rapid runoff of water from rain events that results from the confining clay of the Triassic Basin geology underlying the UF watersheds. To place things into context, only about 4% of North Carolina is comprised of Triassic Basin soils, so the results from this study may not easily predict nitrate concentrations after timber harvests in other areas of the state. Additional detailed monthly NO_3 loading and concentrations for each treatment watershed and peak stormflow NO_3 concentrations can be found in Appendix H.

3.2.5 Total Phosphorus (TP)

As seen in other studies, relative changes in TP closely follow the changes of TSS loads, due to the fact that phosphorous often binds with small sediment particles (Brady, 1990). During the postharvest silvicultural practices, no fertilizer was applied to either HF1, HFW1, or UF1. The average annual loading rates of TP for measured and modeled treatment watersheds is shown in Table 12. The Modeled TP closely matched the Measured TP during the preharvest calibration period for HF1, HFW1 and UF1 watersheds, thus providing confidence that the model can realistically estimate TP loads as if the harvest had not occurred, and thus compare the modeling results against the actual data that was collected. Additional detailed monthly TP loading and concentrations for each treatment watershed can be found in Appendix I.

Table 12. Average annual measured and modeled loading rates of total phosphorus (TP) for harvested watersheds. Modeled postharvest values represent the estimated annual TP loading rate had the timber not been harvested. No statistically significant increases ($P < 0.05$).

Sites	Preharvest		Postharvest	
	Measured	Modeled	Measured	Modeled
	---------------------(lb/ac/yr)--------------------			
HF1	0.143	0.134	0.277	0.054
HFW1	0.152	0.152	0.187	0.098
UF1	0.170	0.170	0.196	0.080

The estimated annual mean TP loading rates can be applied to the estimated acreage for each of the watersheds, to approximate the volume of TP that may be delivered, per year, from each watershed site.

HF1: Preharvest Measured Baseline: 30 acres (x) 0.143 lbs/ac/yr =	**4.3 lbs/yr**
HF1: Measured With Harvest: 30 acres (x) 0.277 lbs/ac/yr =	**8.3 lbs/yr**
HF1: Modeled Without Harvest: 30 acres (x) 0.054 lbs/ac/yr =	**1.6 lbs/yr**
HFW1: Preharvest Measured Baseline: 72 acres (x) 0.152 lbs/ac/yr =	**11.0 lbs/yr**
HFW1: Measured With Harvest: 72 acres (x) 0.187 lbs/ac/yr =	**13.5 lbs/yr**
HFW1: Modeled Without Harvest: 72 acres (x) 0.098 lbs/ac/yr =	**7.0 lbs/yr**
UF1: Preharvest Measured Baseline: 47 acres (x) 0.17 lbs/ac/yr =	**8.0 lbs/yr**
UF1: Measured With Harvest: 47 acres (x) 0.196 lbs/ac/yr =	**9.2 lbs/yr**
UF1: Modeled Without Harvest: 47 acres (x) 0.08 lbs/ac/yr =	**3.8 lbs/yr**

3.2.6 Total Nitrogen (TN)

Average annual TN loads from all watersheds were low during the baseline calibration period, remaining below 2 lbs/ac/yr for the preharvest period. During the postharvest silvicultural practices, no fertilizer was applied to either HF1, HFW1, or UF1. The average annual loading rates of TN for measured and modeled treatment watersheds is shown in Table 13. The Modeled TN closely matched the Measured TN during the preharvest calibration period for HF1, HFW1 and UF1 watersheds, thus providing confidence that the model can realistically estimate TN loads as if the harvest had not occurred, and thus compare the modeling results against the actual data that was collected (Table 13). Additional detailed monthly TN loading and concentrations for each treatment watershed can be found in Appendix J.

Table 13. Average annual measured and modeled loading rates of total nitrogen (TN) for harvested watersheds. Modeled postharvest values represent the estimated annual TN loading rate had the timber not been harvested. * indicates a statistically significant increase ($P < 0.05$).

Sites	Preharvest		Postharvest	
	Measured	Modeled	Measured	Modeled
	---------------------(lb/ac/yr)--------------------			
HF1	1.062	1.044	2.338*	0.642*
HFW1	1.222	1.213	1.142*	0.633*
UF1	1.392	1.392	2.793*	0.794*

After the harvest, several spikes of TN loads were observed that are attributed to pulses of Nitrate (NO_3) mobilization from stormflow stream discharge events which resulted from heavy precipitation.

The estimated annual mean TN loading rates can be applied to the estimated acreage for each of the watersheds, to approximate the volume of TN that may be delivered, per year, from each watershed site. See below.

HF1: Preharvest Measured Baseline: 30 acres (x) 1.062 lbs/ac/yr =	**32 lbs/yr**
HF1: Measured With Harvest: 30 acres (x) 2.338 lbs/ac/yr =	**70 lbs/yr**
HF1: Modeled Without Harvest: 30 acres (x) 0.642 lbs/ac/yr =	**19 lbs/yr**
HFW1: Preharvest Measured Baseline: 72 acres (x) 1.222 lbs/ac/yr =	**88 lbs/yr**
HFW1: Measured With Harvest: 72 acres (x) 1.142 lbs/ac/yr =	**82 lbs/yr**
HFW1: Modeled Without Harvest: 72 acres (x) 0.633 lbs/ac/yr =	**46 lbs/yr**
UF1: Preharvest Measured Baseline: 47 acres (x) 1.392 lbs/ac/yr =	**65 lbs/yr**
UF1: Measured With Harvest: 47 acres (x) 2.793 lbs/ac/yr =	**131 lbs/yr**
UF1: Modeled Without Harvest: 47 acres (x) 0.794 lbs/ac/yr =	**37 lbs/yr**

For the majority of study period, at this location, atmospheric deposition of nitrogen was estimated to be 10.5 lbs/ac/yr (11.8 kg/ha/yr). Using this estimate, the overall average TN loading rates measured from each treatment watershed site can be used to estimate nitrogen retention, both pre- and postharvest:

HF1: Preharvest nitrogen retention: **90%** Postharvest nitrogen retention: **78%**
UF1: Preharvest nitrogen retention: **85%** Postharvest nitrogen retention: **68%**

3.2.7 Total Organic Nitrogen (TON)

The average annual loading rates of TON for measured and modeled treatment watersheds is shown in Table 14. The Modeled TON closely matched the Measured TON during the preharvest calibration period for HF1, HFW1 and UF1 watersheds, thus providing confidence that the model can realistically estimate TON loads as if the harvest had not occurred, and thus compare the modeling results against the actual data that was collected.

Table 14. Average annual measured and modeled loading rates of total organic nitrogen (TON) for harvested watersheds. Modeled postharvest values represent the estimated annual TN loading rate had the timber not been harvested. * indicates a statistically significant increase ($P < 0.05$).

Sites	Preharvest		Postharvest	
	Measured	Modeled	Measured	Modeled
	---------------------(lb/ac/yr)--------------------			
HF1	1.044	1.017	1.490*	0.633*
HFW1	1.187	1.178	0.920	0.590
UF1	1.356	1.354	1.686*	0.705*

3.2.8 Stream Water Temperature

Stream water temperatures across all of the watersheds were very similar during the preharvest baseline calibration period. Monthly maximum highs averaged around 25°C in the HF sites and around 24°C on the UF sites. There was no significantly different increase in stream water temperatures for any of the sites during the growing season, when comparing preharvest conditions with postharvest conditions. The maximum monthly stream temperatures did not exceed the 29°C (84.2°F) maximum as defined in North Carolina water quality standards for Class C waters in the mountains and upper piedmont [rule 15A NCAC 02B .0211(3)(j)]. Additional detailed monthly maximum stream water temperatures for each watershed can be found in Appendix K.

3.2.9 Benthic Macroinvertebrate Communities

Macroinvertebrates are ideal indicators of stream health because they vary in sensitivity to water pollution. There are certain aquatic insects which require clean, clear water to thrive and cannot tolerate sedimentation or other polluting factors in the water column. Macroinvertebrates provide an integrated index of water quality over longer periods of time and are easy and relatively cheap to collect. Overall, the Bioclassification ratings and Biotic Index scores from the watershed sites indicated that water quality in the streams was not adversely effected following timber harvesting. The ratings and scores generally remained “Good/Fair” to “Excellent” at both HF1 and UF1. However, species-specific macroinvertebrate abundance and percentage of trophic categories did change over the monitoring period. Results for each watershed pair are briefly discussed below, and a summary of results is shown in Table 15. See appendix L for a summary of all the sampling results and appendix M for average functional feeding group percentages during the postharvest period.

The metrics used to evaluate macroinvertebrate communities in this study include:

- <u>Taxa Richness</u> of *Ephemeroptera* spp. (mayfly); *Plecoptera* spp. (stonefly), and *Trichoptera* spp. (caddisfly), which collectively are referred to as the EPT Taxa Richness. This metric simply counts the number of each EPT taxa in the sample. The higher the EPT score, the better the water quality.
- <u>Biotic Index (BI)</u>. This uses the presence or absence of a suite of pollution-tolerant and pollution intolerant organisms to make conclusions about the stream’s water quality. A

biotic index assigns higher scores to streams with more pollution-intolerant organisms, which tend to have better water quality

- Stream Bioclassification. This categorization of streams is based on the average values of the EPT Taxa Richness and the Biotic Index. Labels include one of the following: Excellent, Good, Good/Fair, Fair, or Poor.
- Mean Functional Feeding Group (FFG). This categorizes each type of insect according to the type of material it feeds upon, and how it feeds. These FFG percentages were sorted only during the postharvest period.

Table 15. Bioclassification based on benthic macroinverebrate (stream insect) community assessments. The background shading provides a visual indication of similar rating categories.

Study phase	**Sampling date**	**Hill Forest**				**Umstead Farms**	
		HF1 (treatment)	***HF2 (reference)***	***HFW1 (treatment)***	***HFW2 (reference)***	***UF1 (treatment)***	***UF2 (reference)***
Preharvest	**1/1/2010**	Good	Excellent	Excellent	Excellent	Good	Good
	4/1/2010	Excellent	Excellent	Excellent	Excellent	Good	Excellent
Postharvest	**3/1/2011**	Good/Fair	Good	Excellent	Good	Good/Fair	Good/Fair
	7/1/2011	Excellent	Excellent	Excellent	Fair	Good	Fair
	2/1/2012	Good	Good	Excellent	Excellent	Good	Good
	7/1/2012	Excellent	Excellent	Excellent	Good	Good	Good/Fair
	2/1/2013	Excellent	Good	Excellent	Good	Excellent	Fair
	6/1/2013	Excellent	Excellent	Excellent	Excellent	Excellent	Good
	1/1/2014	Excellent	Excellent	Excellent	Good	Good	Good

3.2.9.1 HF1 and HF2 Aquatic Life Conditions

The preharvest EPT Taxa Richness in HF1 was less than HF2, and this pattern persisted after the timber harvest. Taxa Richness results changed across seasons. For example, during the postharvest sampling, both HF1 and HF2 had lower EPT score in the growing season, than when compared with non-growing season samples. This would be expected to some degree, as stream flow and available water for habitat was generally lower during the growing season, when forest evapotranspiration was at its full extent; and water temperatures were higher. Ultimately, there was no significant degradation of the aquatic habitat conditions in HF1 after the harvest, when compared with the reference control HF2. Biotic Index values were not significantly different between pre- or postharvest periods. The only noteworthy decline in Bioclassification was from the first sample taken after the timber harvest (about 7 months afterwards), but even then the Bioclassification remained in the "Good/Fair" category, and improved over time. Functional Feeding Group sorting showed that Shredders dominated in this pair of watersheds after the harvest, comprising nearly 30% of the sampled insects.

3.2.9.3 HFW1 and HFW2 Aquatic Life Conditions

The preharvest EPT Tax Richness in HFW1 was better than HFW2, and this pattern persisted after the timber harvest. Taxa Richness results changed across seasons. For example, during the postharvest sampling HFW1 and HFW2 had lower EPT score in the growing season, than when compared with non-growing season samples. The likely reasons behind these differences were noted in the previous section for HF1 and HF2. This presumption may be corroborated by the July 2011 sampling from HFW2, which had its lowest monthly stream discharge discharge, and its lowest EPT Taxa Richness. In later years, the samples from HFW2 scored a higher EPT score, and the stream discharge was also more abundant. This trend would suggest that the decrease in EPT score for HFW2 was due to the lack of water in the stream system, and not because of a degradation of the stream water quality. Both the EPT and Biotic Index scores were statistically different between pre- and postharvest periods, with a slight decrease in quality, but this was observed for both the HFW1 treatment watershed and HFW2 reference watershed. Bioclassification for HFW1 was “Excellent” throughout the study period. Functional Feeding Group sorting showed that Shredders dominated in this pair of watersheds after the harvest, comprising nearly 25% of the sampled insects.

3.2.9.4 UF1 and UF2 Aquatic Life Conditions

The preharvest EPT Taxa Richness in the UF1 and UF2 watersheds did not show a sustained pattern, with a higher EPT score being observed in each of the watersheds, depending upon which sample is analyzed. During the postharvest sampling, the EPT score in UF1 consistently was higher than the control reference UF2, with some individual scores changing across seasons. This may suggest that the additional stream discharge resulting from the UF1 harvest may have improved overall aquatic life conditions, as compared with preharvest conditions. As seen in the HFW2, the July 2011 stream discharge discharge in UF2 was at its lowest, and its EPT score from that time period was also the lowest score observed during the study. The UF1 and UF2 locations were the only sites in the study where examples of *Maccaffertium (S) femoratum* were observed in the samples. This mayfly species is tolerant of low-flow stream systems. Biotic Index values were not significantly different between pre- or postharvest periods. Bioclassification for the UF1 site ranged from “Good” to “Excellent”, and for UF2 it ranged from “Poor” to “Good”. Functional Feeding Group sorting showed that Collector-Gatherers dominated in this pair of watersheds after the harvest.

3.3 Riparian Buffer Characteristics

Each treatment watershed (HF1 and UF1) was harvested in a manner that retained a protective stream buffer zone that met the requirements of the Neuse River Basin Riparian Buffer Zone Rule, called a NBR Zone in this report. Selective harvesting of trees was conducted within the NBR Zone. Data was collected on the trees within the NBR Zone and the overall groundcover vegetation characteristics.

After the harvest, tree canopy cover met BMP recommendations and was sufficient to shade the stream on all watersheds. The total number of stems in the Neuse Buffer Rule Zone (NRB) did not significantly change after harvest. However, significant damage to the residual timber in the NBR Zones occurred after the harvest. The damage seen in the study is similar to occurrences of blown-down trees that were retained within NBR Zones of other harvests observed by NCFS personnel across central North Carolina, since the NBR Zone rule was adopted.

Harvesting of overstory trees provided more sunlight to reach the ground and foster the growth of more diverse groundcover and shrub vegetation. Foresters and resource managers may be able to promote changes in low-growing vegetation type and structure, depending upon if and how overstory trees are removed from a riparian area. Soon after harvest, the layer of leaf litter got deeper and there was generally an increase in both fine and coarse woody debris. This increased litter and debris may retain more moisture within the soil surface; or conversely, if dried out, could result in increased fuel loading if a wildfire or prescribed fire burns through the riparian area.

More blow-down was observed in the UF1 NBR Zone. This site has shrink/swell clay soils, with a seasonally perched water table. The trees in the UF watershed were also larger and taller than those in the HF watershed. While there were no observations of negative impacts to water quality resulting from the blown-down timber, impacts remain unknown on the long term forest health, wildfire fuel loading, tree regeneration potential, and overall aesthetics of the residual riparian forest areas.

3.3.1 Tree Spacing, Count, and Canopy Cover Changes

Table 16 summarizes the results of the preharvest and postharvest surveys of the trees within the Neuse Buffer Rule (NBR) Zone for each watershed. Harvesting of overstory trees within the NBR Zone on HF1 resulted in an approximate 20% to 25% reduction in pine tree basal area, and an approximate 30% reduction in hardwood tree basal area. Harvesting of overstory trees within the NBR Zone on UF1 resulted in an approximate 50% reduction in pine tree basal area, and an approximate 45% reduction in hardwood tree basal area. The basal area of all remaining residual overstory trees within the NBR Zone, after harvesting, was nearly identical at both HF1 and UF1, consisting of approximately 100 square feet/acre of basal area. The number of midstory tree stems generally decreased in each NBR Zone, when comparing preharvest with postharvest surveys (Table 16). Canopy cover in the NBR Zone decreased after the selective harvesting in HF1 and UF1, but still remained well above the recommendations found in the North Carolina Forestry BMP Manual (retain 50% shade).

Table 16. Tree density, basal area, and canopy cover in the riparian buffers, preharvest and postharvest. Harvests occurred in 2010. Values were converted from the original metric units (stems/ha, m^2/ha) and rounded to the nearest whole number. Rounding may result in slight differences from the percentages shown in the text, which were calculated using the unrounded data in metric units.

	Overstory (Pine)		**Overstory (Hardwood)**		**Total Overstory (Pine + Hardwood)**		**Midstory (all spp.)**	**Total stems (Overstory + Midstory)**	**Canopy Cover**
	Stems per Acre	*Basal Area (sq.ft. / ac)*	*Stems per Acre*	*Basal Area (sq.ft. / ac)*	*Stems per Acre*	*Basal Area (sq.ft. / ac)*	*Stems per Acre*	*Stems per Acre*	*Percent*
HF1 (treatment)									
2009 (preharvest)	38	27	186	112	224	139	964	1,188	90
2011 (1 yr. postharvest)	23	20	159	81	182	101	907	1,089	69
2012 (2 yr. postharvest)	23	21	156	74	178	95	941	1,119	72
2013 (3 yr. postharvest)	23	23	163	80	186	102	845	1,031	79
HF2 (reference)									
2009	100	60	173	73	272	133	1,168	1,440	93
2011	100	62	173	76	272	139	1,115	1,388	92
2012	100	65	179	78	279	143	1,016	1,295	95
2013	100	69	179	81	279	150	916	1,195	93
UF1 (treatment)									
2009 (preharvest)	32	68	162	122	194	189	1,013	1,207	85
2011 (1 yr. postharvest)	13	34	138	65	151	99	906	1,057	71
2012 (2 yr. postharvest)	13	34	138	68	151	101	940	1,092	70
2013 (3 yr. postharvest)	13	35	127	68	141	103	1,285	1,426	72
UF2 (reference)									
2009	0	0	193	161	193	161	587	779	86
2011	0	0	179	166	179	166	558	737	91
2012	0	0	186	175	186	175	817	1,003	90
2013	0	0	186	182	186	182	584	770	91

3.3.2 Changes in Groundcover Vegetation

The preharvest vegetation surveys revealed that the groundcover of the Neuse Buffer Rule (NBR) Zone in all watersheds was dominated by leaf litter, and the depth of the leaf litter in the NBR Zone of HF1 and UF1 were essentially the same, at approximately 1 cm deep (Figure 14). After selective harvesting and a prescribed fire, the depth of the leaf litter varied from year to year in both of the treated NBR Zones, with an average of 1.1 cm depth in HF1 and 1.4 cm depth in UF1. A notable increase of leaf litter depth was seen in the year following the timber harvest in both NBR Zones of HF1 and UF1, but this depth rapidly decreased in the subsequent years after harvest and approached the preharvest depths of around 1 cm after three years postharvest (Figure 14).

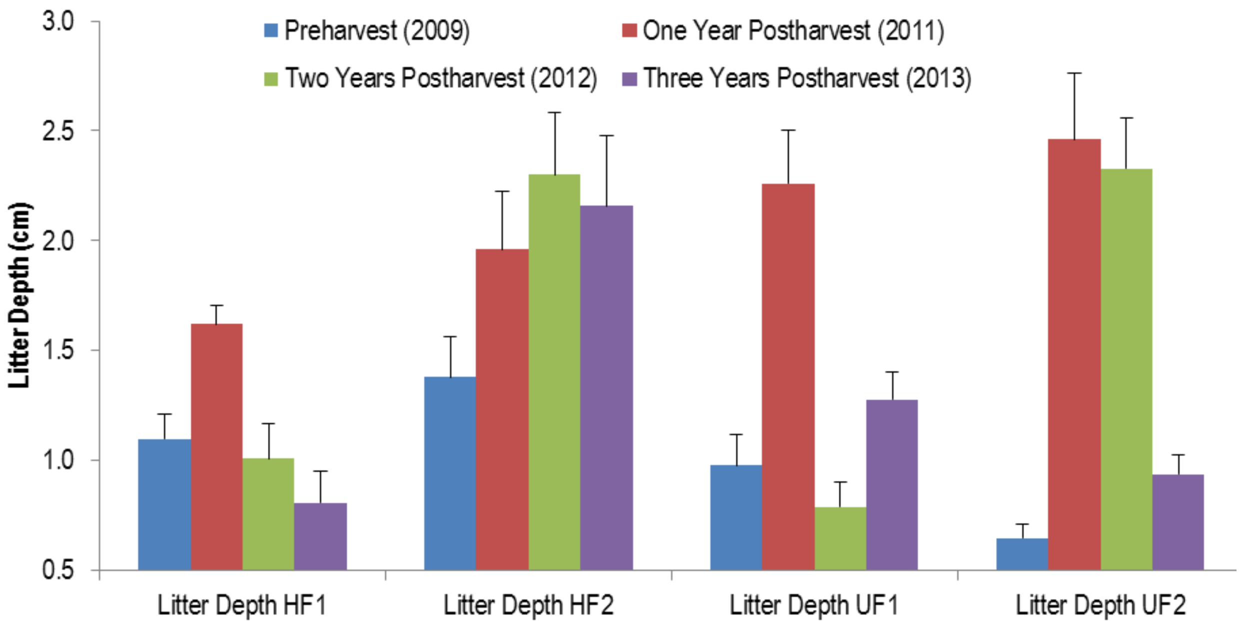


Figure 14. Depth of leaf and needle litter measured pre- and postharvest.

The surveys conducted after the harvest showed that the vegetation in each of the harvested NBR Zones (HF1 and UF1) had become a mixture of woody plants, herbaceous vegetation and leaf litter. Surveys that were done after the treatment watersheds were harvested showed that the two control reference watershed NBR Zones (HF2 and UF2) continued to be dominated by leaf litter, with an exception noted in UF2. This exception showed an increase in herbaceous vegetation growth that likely resulted from a naturally-occurring opening in the canopy that existed in one of the vegetation sample plots. These results are illustrated in Figures 15.

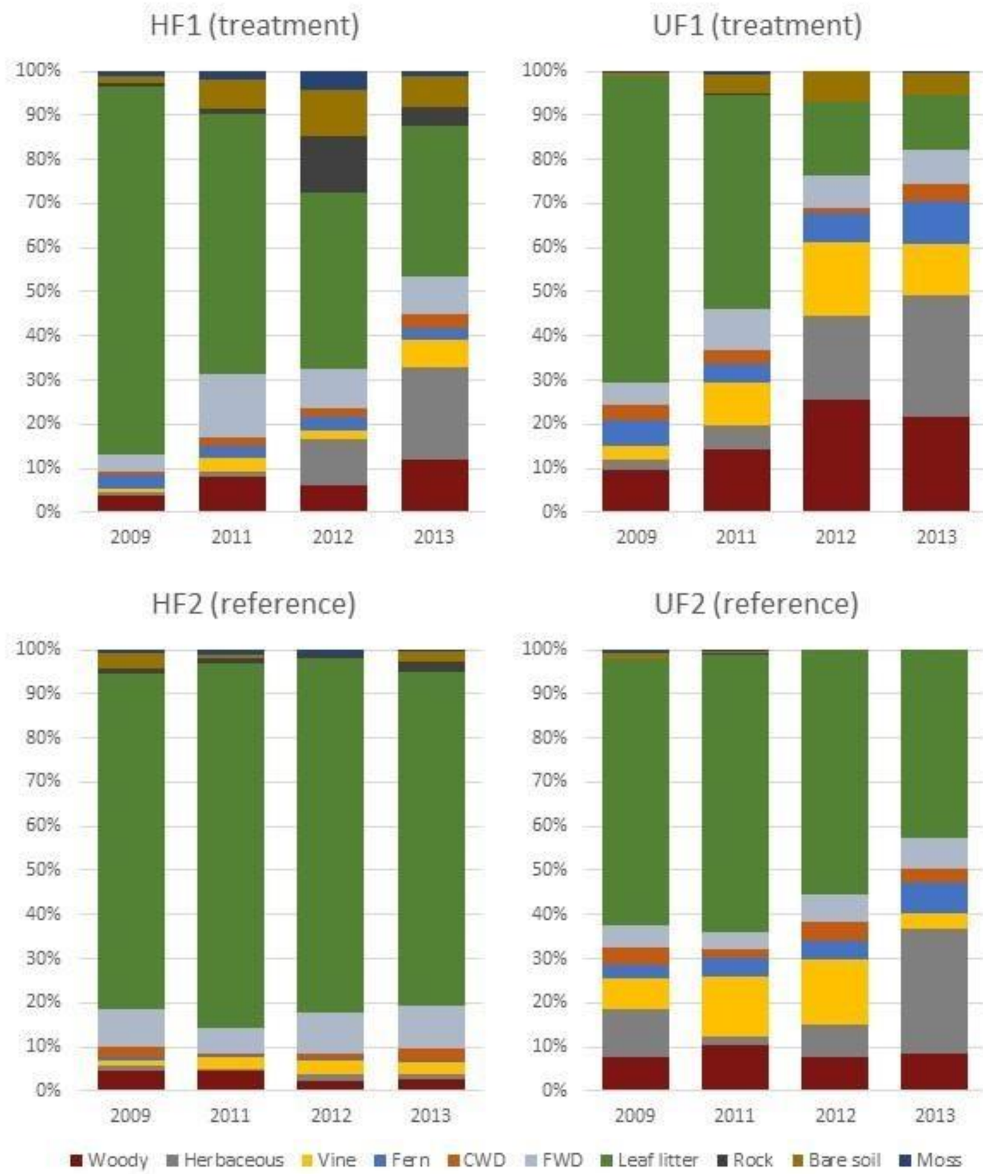


Figure 15. Percent groundcover by type in treatment (top row) and reference (bottom row) watersheds. (CWD—coarse woody debris; FWD—fine woody debris).

3.3.3 Blowdown of Timber within the Neuse Buffer Rule (NBR) Zone

In 2012 and 2013, two separate damaging windstorms occurred over the watershed study sites, resulting in significant blowdown of several large residual live trees on the UF1 site that were required, by rule, to be retained within the NBR Zone (reference state rule 15A NCAC 02B .0233).

While some small trees on the HF1 site were observed to be blown-over from these storms, overall that site did not experience the same degree of disturbance as seen on the UF1 site. Interestingly, another windstorm in 2014 incurred more significant blowdown disturbance in the

NBR Zone of HF1. However, for the purposes of this study, data collection ceased at the end of 2013 and therefore this most recent HF1 blowdown was not evaluated.

While these windstorms at first were concerning, regarding how the disturbance may negatively influence the outcomes of this study, the project study team decided to take the opportunity to assess the blowdown damage in the NBR Zone of the UF1 site and determine if any observational trends or possible conclusions could be drawn from the disturbance. Earlier studies have documented that most blowdown occur after the first few years following a timber harvest, and this observation held true for the blowdown on UF1, having occurred within two years after the timber was harvested.

In total, the NBR Zone of UF1 had approximately 36% (24 of 66) of its stream edge trees blown down from these windstorms. After the blowdown, there was no measurable change in the TSS concentrations from UF1 stormflow water samples when compared with the other treatment watersheds (HF1 and HFW1) that did not experience the windstorm disturbance. A field examination in April 2013 of the UF1 site showed that the trees did not blow down in any consistent direction. There was no evidence of twisting damage to the trees that would indicate a tornado. The bole of most all of the wind-thrown trees were intact and were not split or broken. The speculation is that either down-burst winds or storm-induced directional gusts caused the wind disturbance. Of the 12 wind-thrown trees that were assessed on that field exam, the trees were blown down at multiple compass reading directions between a 50° reading and a 230° reading, with each tree laying at a unique compass reading direction. In fact, two large conjoined/forked sweetgum trees blew down in nearly exactly opposite directions (150°difference) from each other, with one tree laying across and over the stream channel and the other tree laying outwards, pointing away from the stream channel (Figure 16).

Figure 16. Two conjoined 15” DBH sweetgum trees blown down in nearly opposite directions on left-bank of stream edge in Neuse Buffer Rule Zone of UF1. Photo taken April 2013.

Despite the visually disruptive appearance of the significant amount of blowdown in the NBR Zone of UF1, coupled with the extensive streambank uprooting from the blown-down trees, and a presumptive belief that a negative impact to water quality would result, there would seem to be a natural resiliency to this type of disturbance that prevented additional sedimentation impacts to the stream water quality. This resiliency is possibly founded upon the increased amount of herbaceous and low-growing woody vegetation that grew after the selective harvest of overstory trees in the NBR Zone. Other researchers have proposed that an increase in this type of ground-covering vegetation can provide soil stability. However, data in this study does not indicate how rapid this apparent natural resiliency would deteriorate if blowdown exceeded 36%, or if the location of trees or circumstances of the windstorm were different from what actually occurred. In addition, it is unclear if impacted streambanks (from uprooted trees) would be more susceptible to structural failure and subsequent contribution of sediment loads.

Three factors may have contributed to the significant amount of disturbance on the UF1 site, as compared with the HF1 site: 1) tree size, 2) tree species, and 3) soils. Additional results of tallied stream edge trees in the Neuse Buffer Rule Zone of the treatment watershed UF1, following harvest can be found in Table 17.

Table 17. Tally of stream edge trees in the Neuse Buffer Rule Zone of the UF1 treatment watershed following harvest. Mean DBH for stream edge trees was 13 inches. (--) indicates that a tree of that size for that species was not present at stream edge. Tree Latin names are listed below the table.

Species	Total Number of All Trees Tallied on Stream Edge, both Standing and Blown-Over	Range of Tree DBH (inches)	Number of Stream Edge Trees that Blew Down, Larger or Equal to the Mean DBH	Number of Stream Edge Trees that Blew Down, Smaller than Mean DBH	Total Number of Stream Edge Trees that Did Not Blow Over
American Beech	2	8 - 8	--	0	2
American Sycamore	1	13	0	0	1
Blackgum	2	12 - 12	--	0	2
Eastern Red Cedar	1	8	--	1	0
Elm spp.	1	8	--	0	1
Hickory spp.	4	8 - 13	1	0	3
Ironwood	1	7	--	0	1
Oak spp.	6	7 - 30	4	0	2
Pine spp.	4	15 - 21	2	--	2
Red Maple	4	5 - 8	--	1	3
Sourwood	7	4 - 6	--	0	7
Sweetgum	25	5 - 30	11	3	11
Tulip/Yellow Poplar	8	6 - 31	1	--	7
All species	**66**	4 - 31	**19**	**5**	**42**

American Beech = *Fagus grandifolia*, American Sycamore = *Platanus occidentalis*, Blackgum = *Nyssa sylvatica*, Eastern Red Cedar = *Juniperus virginiana*, Elm = *Ulmus* spp., Hickory = *Carya* spp., Ironwood = *Carpinus caroliniana*, Oak = *Quercus* spp., Pine = *Pinus* spp., Red Maple = *Acer rubrum*, Sourwood = *Oxydendrum arboreum*, Sweetgum = *Liquidambar styraciflua*, Tulip/Yellow Poplar = *Liriodendron tulipifera.*

3.3.3.1 Tree Size

The first factor is the overall size of the residual trees within each of the Nesuse Buffer Rule Zones:

- The average DBH of the trees retained in the NBR Zone on the HF1 site was approximately 9.5 inches.
- The average DBH of the trees retained in the NBR Zone on the UF1 site was approximately 13 inches.

Observations showed that trees in the UF1 streamside area that had a DBH larger than average were blown down more often than were trees that had a DBH smaller than the average. This supports the intuitive conclusion that larger diameter trees (which often are also taller) are less wind-firm than smaller trees. About 20% of the blown-down trees were smaller than the 14-inch DBH limit for harvesting stated in the NBR rule (i.e., the high value trees). About 60% of the blown-down trees were those which had primary roots exposed in the stream channel, and were not allowed to be harvested, regardless of their DBH, as prescribed by the NBR Zone rule.

3.3.3.2 Tree Species

When examining tree species, Yellow/Tulip Poplar (*Liriodendron tulipifera*) trees were the most wind-firm of when considering all trees with a DBH larger than the mean DBH of all trees in the UF1 NBR Zone. A cursory assessment indicated that the following possible hierarchy of wind-firmness between tree species for this site, of those trees which had a DBH larger than the average found in the NBR Zone.

In order from **most wind-firm to least wind-firm**, this study observed:

Yellow/Tulip Poplar >> Sweetgum >> Pine *spp.* >> Hickory *spp.* >> Oak *spp.*

By comparison, a study in southwestern Georgia observed that among trees that were blown down from wind storm events, the average DBH was approximately 13 to 14 inches. The two predominant species of trees retained in the SMZ were Yellow Poplar and Swamp Tupelo. In that study, Yellow Poplars exhibited more frequent blow-down.

3.3.3.3 Soils

The final potential factor in blowdown was the *soil type*. The soils of the UF watershed pairs are shallow and dense, with an impervious clay layer that restricts deep root growth and may result in trees being more susceptible to wind-throw. Conversely, the soils at the HF watershed pairs are deeper and well drained, allowing for deeper penetration by tree roots and likely providing firmer anchoring of the trees due to increased rooting capacity. The UF watershed soils were also generally wetter after the watershed harvest, as compared with soils of the HF watershed site. Wetter soils tend to have weaker strengths than drier soils. This can result in trees being more prone to blown-downs from strong winds. This phenomenon can be seen during tropical storms which produce saturated soils from heavy rains, coupled with strong winds.

4.0 Conclusions and Recommendations

The 6-year study provides valuable information for forest management in the Piedmont region. Forest vegetation plays an important role in water and nutrient cycles/balances. This study supports the premise that forest management that follows recommended best management practices in the Piedmont region does not adversely affect water quality or site productivity. Overall the study provides a better understanding of how Piedmont watersheds cycle water and nutrients across growing and dormant season, how riparian buffers function, and how to apply the most appropriate best management practices for protecting water resources. The following bullets summarize the take-home points and forest management recommendations:

- Increased runoff not only contributes more water into the stream system, but also illustrates the need for installing and maintaining adequate BMP measures that will prevent, control, and manage soil erosion and sedimentation into streams.

- The relative increase in stream flow varies dependent upon vegetation. Runoff from storm events following a harvest can significantly increase in both absolute volume and duration of time. However, more variation in stream discharge is associated with the underlying geology than vegetation. Therefore, preharvest planning with an understanding of the underlying geology is critical step for managing forestlands.
- Even though stream discharge increased notably after clearcutting, the residual trees in the riparian buffer zone increased their usage of water, and the relative increases of stream discharge began to diminish as the harvested area regrew. Prompt reforestation after a harvest will sustain timber availability and contribute towards balancing the watershed cycle back to preharvest conditions.
- If the forest manager has an objective of water supply management, then this increased water use by residual riparian trees may drive some of the decisions regarding whether or not to selectively harvest trees from stream buffer zones, and if so, what species of trees to retain or harvest, given that different tree species cycle water differently.
- The structural integrity of the streams in the two harvested watersheds remained relatively unchanged, in spite of increased stream discharge after the harvest and the uprooting of large trees along the stream edge.
- While increases in sediment and nutrient loading and concentrations may occur after a harvest, these increases are of relatively short duration (if best management practices are implemented and effective) when compared to the long-term growth cycle of forests. Assuring prompt reforestation after harvest will attenuate increased water flows and/or nutrient loading.
- Underlying soils and geology will influence the cycling of nutrients between the soil and water, especially when those nutrients are transported by rainfall-driven runoff. Foresters and resource managers should recognize the differences in their soils and implement BMPs accordingly to mitigate the potential for accelerated erosion, runoff, and sedimentation.
- Stream water temperatures can be moderated by retaining adequate shade-producing vegetation within the riparian zone, even with selective harvesting of large trees from the riparian area.
- Harvesting of timber can be compatible with sustaining and/or protecting the quality of aquatic life conditions in streams when measures are taken to protect the riparian environment.
- Most aquatic insects depend upon the persistence of water within the stream to sustain their life cycle. But the water must remain relatively free from sediments or other pollutants. Establishing a protective stream/riparian buffer zone can accomplish multiple objectives in protecting overall water quality and habitat conditions for aquatic organisms.
- Harvesting of overstory trees can provide more sunlight to reach the ground and foster the growth of more diverse groundcover and shrub vegetation. Foresters and resource managers may be able to promote changes in low-growing vegetation type and structure, depending upon if and how overstory trees are removed from a riparian area.
- When selecting trees to retain within a riparian buffer zone, careful consideration should be taken regarding the soils, size of trees, species of trees, and potential for not leaving large, open gaps in the residual tree canopy. The intent should be to retain trees that

provide long-term vegetation structure, soil stability, and shade; all of which contribute to protecting water quality and the overall aquatic/riparian habitat conditions

- Despite a lack of observed increased TSS over the study period, the practical presumption is that any major damage to streambanks from large uprooted trees on the stream edge would likely contribute to an increased future potential of streambank instability, and scouring or failure; all of which would create a localized source of sediment input to the stream system. Therefore, forestry BMPs should always be implemented to prevent windthrow and uprooting of streambanks to ensure that the riparian buffer function is not compromised.
- Forester, landowner, or resource manager should be offered flexibility when selecting which trees to retain and remove from a riparian buffer zone, if timber harvesting is conducted alongside the stream. If regulatory policies persist which govern the degree to which trees can be harvested alongside streams in designated watersheds, then changes to those policies may be warranted to reduce the size limits of those trees which must be retained.

5.0 Lessons Learned

A long term study of this scope requires significant planning, funding, dedicated personnel, operational/project management, and resourcefulness to adapt to unexpected challenges that arise. This section of the report is presented as a tool to identify some lessons learned in the spirit of continuous improvement for future paired forest watershed and BMP studies. This section follows a generally-accepted format for after-action reviews that are commonly conducted by forestry/wildland fire agencies after managing complex incidents.

5.1 Project Successes

- A literature review of other studies was conducted, to identify how a study in North Carolina may contribute to filling a gap in the knowledge base regarding timber harvest effects on hydrology and water quality.

- Funding was secured by the NCFS at a time when water quality project grant funds were more readily accessible. If this study had to be replicated today in North Carolina, the project team is confident that funding would not be available, due to reduced budgets and changes in national and state-level program priorities.

- Research staff from the USDA-FS (SRS, EFETAC) was enlisted via contractual agreement with the NCFS to develop the study plan and implement the study on a day-to-day basis, including all data collection and analysis. The USDA-FS team is located nearby, and is more qualified and experienced in managing watershed research studies and large amounts of data than is the NCFS. This partnership was crucial, with the USDA-FS fully investing in its successful completion by contributing significant personnel time and resources. A large factor in the project's success was the assignment by USDA-FS of one existing permanent employee to serve as the lead project manager, with assistance from his colleagues. This provided continuity from year to year, and from one phase of the study to another; while also providing a single point-of-contact for NCFS and the Forest Managers.

- A quality assurance / quality control (QA/QC) plan was developed by the project team. This plan was submitted to and approved by the NCDENR-DWR, on behalf of the USEPA, before data collection was initiated. This QA/QC plan was required as a condition of the Nonpoint Source Section 319-Grant award contract that funded the majority of this study.

- Two peer-reviewed journal articles were published, and two Masters theses were developed as part of the baseline (preharvest) monitoring of the watersheds. This documentation contributes to the base of scientific knowledge and fostered professional development for the authors.

- Multiple supplemental study investigations arose from out of the core watershed study project, including partnerships with N.C. State University and the University of North Carolina at Chapel Hill.

- The study sites served as an ideal, real-time, outdoor classroom and educational venue for college students to learn about forestry and hydrology. Conducting annual field tours and outdoor lab exercises exposed the students to how research findings make their way to practical applications.

- The two landowner organizations and their respective Forest Manager were fully invested and cooperative with allowing the study to be conducted on their organization's forestland. Changes to their management schedule were made to accommodate this study and each Forest Manager welcomed the study as part of diversifying their overall management objectives, while promoting their respective programs. The NCFS executed a memorandum-of-agreement (or similar document) with each landowner organization to serve as documentation of expectations for each entity and the expected study timeline.

- The watershed study sites are in close proximity to each other, which makes for more efficient use of time for traveling, collecting water samples, checking on the study sites, conducting field tours, or resolving issues.

- An on-site planning meeting was held with the timber buyer, logger, Forest Manager, and project study team before the start of timber harvesting on each watershed site. Maps were provided and expectations outlined for the logger. The NBR Zone and harvest area boundary were marked by the project study team prior to the logging, so they would be clearly visible. Frequent site visits were made by the Forest Manager, members of the project study team and local field personnel of the NCFS while logging was ongoing. Both of the loggers were very cooperative and overall the harvests went reasonably well.

5.2 Potential Improvements

- Could have provided a more flexible timeline to execute the contractual agreement between the NCFS and USDA-FS; and with a contractor to install the flumes. These administrative tasks consumed nearly one year which resulted in a delay of implementing the start of the project, after funding was secured and certified by the NCFS.

- Could have done a better job of recognizing the soil erodibility of each watershed, at the location where the 2-H flumes were installed, and more closely supervised the installation of the flumes by the contractor. After some of the first few stormflow events, stream water began to undermine the apparatus on the UF site. Quick action was taken to plug the gaps and assure that no stream discharge bypassed the flume for the remainder of the study (Figure 17).

Figure 17. Concrete being added to the entry throat of a flume to keep the streamflow from bypassing under or around.

- Should have established more consistent communications between NCFS, USDA-FS, and each Forest Manager to identify potential problems before they occurred and make sure the landowner's field agents felt more fully invested and involved with the study. One example includes an inadvertent planting of an exotic woody-stemmed grass in portions of the agricultural fields which exist in the upper reaches of one pair of watersheds, soon after the study's data collection began. The exotic plants were also fertilized after planting, but that fertilizer application was not sufficient to warrant concern from the project team about data integrity. The exotic plants were removed from the study site soon afterwards and the fields were left fallow for the duration of the study, except for periodic mowing.

5.3 Project Challenges

5.3.1 Regional Drought at the Onset of the Study's Data Collection Period

The preharvest, baseline monitoring period was extended, and the harvest schedule was pushed forward. This extended period allowed for sufficient samples to be collected and a calibration model to be developed. Flexibility from the Forest Managers allowed the timelines to be shifted.

5.3.2 Protecting, Troubleshooting, and Maintaining Field Apparatus and Sampling Equipment

At the onset of the study, informational signs were posted at each water sampling station that explained the study and included contact information. Each study site is on public land, and is a registered hunting gameland, and there was concern about vandalism or theft of equipment. Through the duration of this study, there was no observed or known incidents of damage, vandalism, or theft of any equipment. For three of the sites, the NCFS fabricated a heavy steel containment box with a locking lid to house the automated water sampler (Figure 18). This box kept the sampler out of site and protected from potential vandalism or theft.

Figure 18. An informational sign and protective containment box on one of the watershed study sites.

For troubleshooting and maintaining the electronic equipment, a backpack and bin of tools, replacement batteries and common replacement parts was taken to each site, each time water samples were collected. To assure continuous operation, batteries were swapped-out each time samples were collected. There was very little disruption in data collection and each water sampler worked well.

5.3.3 Keeping Flumes Free from Sediment Accretion

In-channel mobilization of legacy sediments resulted in an accumulation of sediment on the base of each flume, in each watershed. Periodically, this sediment was shoveled out of the flume to assure a constant geometric configuration to obtain accurate stream discharge readings. We did not expect the degree to which sediment would mobilize, even during the preharvest baseline monitoring period. Sediment accumulation was especially notable in the UF watersheds.

5.3.4 Turbidity Meters Did Not Perform as Anticipated

The meters did not meet the needs of this study for continuously monitoring in-stream suspended sediment. Sensor problems included recalibration issues and fouling (from both physical and biological sources), resulting in faulty turbidity readings (Figure 19). The manufacturer's suggested protocols for installation in shallow streams was followed, to no avail. In April 2010 the turbidity meters were removed from all of the study sites. While no turbidity results are available from this study, turbidity is often closely correlated with TSS. Inquiries with other researchers, prior to installing the meters, may have

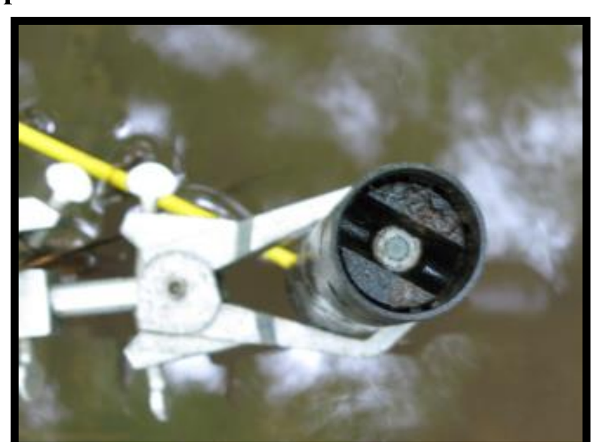


Figure 19. A turbidity meter that was installed for this study, showing fouling of the optical sensor by algae and sediment build-up.

resulted in a better level of expectations as to the performance of this equipment.

5.3.5 Not All Trees Were Harvested by the Logger on One of the Treatment Watershed Sites

On the HF1 site, there were numerous (hundreds) very small diameter, relatively short (unmerchantable) trees left standing after the timber was cut and removed. These leftover stems were manually felled by students and members of the study project team within a few weeks after logging was completed, to assure evapotranspiration data from the postharvest period accurately reflected the outcomes from a 'complete' harvest of all timber (aside from retained trees in the riparian zone).

5.3.6 Off-road Equipment Drove through the Neuse Buffer Rule Zone on One of the Treatment Watershed Sites

In the late Fall of 2012, the UF Forest Manager was notified by a contractor, after the fact, of an exploratory mission by the contractor who was hired by the federal government to locate potential unexploded ordnance in the area immediately surrounding an active military installation, which abuts the UF watershed site. The contractor operated a small mobile piece of equipment (believed to be a tracked skid-steer loader or similar machine) on transects across the property, and drove the machine through the UF1 NBR Zone and crossed the stream in at least two locations that could be identified. The impact to the NBR Zone and the stream were considered minimal by NCFS personnel after inspecting the site soon after notification was received. On one crossing, a small area of soil was exposed on the left bank, and coarse woody debris was partially obstructing stream discharge (photos below). Dead grass stems were applied to the exposed soil and the woody debris was removed by hand. The other crossing did not require remedial work.

Figure 20. Unauthorized crossing of the stream on the UF1 site (left). The same crossing after debris removal and vegetation material was applied to cover the exposed soil.

5.3.7 Personnel Turnover in NCFS Interrupted Project Continuity and Communication

Through the duration of this study, the staff position in the NCFS who was assigned to this study was vacated and back-filled three times, sometimes with lengthy gaps of vacancy (measured in months). Fortunately, the lead project manager at the USDA-FS who handled the day-to-day operations of this study remained in place for the entire duration. The rotation of NCFS personnel likely caused gaps in communication between NCFS and USDA-FS, regarding the development, review, communication style, and sharing of outreach products and publications; and overall awareness by NCFS of what was going on regarding the project's status, including additional studies or investigations that arose from the core watershed project.

6.0 Additional Resources

6.1 Study Technical Report

US Forest Service, 2015. Effects of Timber Harvest on Water Quantity and Quality in the NC Piedmont. Available online at http://www.treesearch.fs.fed.us/pubs/49155

6.2 Peer-reviewed publications and presentations from this study

Many of the following papers and presentations are available from EFETAC's project web page as well as the EFETAC Publications page.

Boggs, J.L., G. Sun, S.G. McNulty, W. Swartley, E. Treasure, and W. Summer. 2009. Temporal and spatial variability in North Carolina piedmont stream temperature. In: Proceedings of 2009 American Water Resources Association Spring Specialty Conference. May 4-6, 2009. Anchorage, AK.

Boggs, J.L., G. Sun, D.G. Jones, S.G. McNulty. 2013. Effect of soils on water quantity and quality in Piedmont forested headwater watersheds of North Carolina. Journal of American Water Resources Association.

Boggs, J., G. Sun, J.-C. Domec, S.G. McNulty, and E. Treasure. 2015. Clearcutting upland forest alters transpiration of residual trees in the riparian buffer zone. Hydrological Processes. http://www.treesearch.fs.fed.us/pubs/48028

Dreps, C., A.L. James, G. Sun, J.L. Boggs. 2014. Water balances of two Piedmont headwater catchments: Implications for regional hydrologic landscape classification. Journal of American Water Resources Association.

6.3 Regulatory framework for forestry in NC

NCFS Best Management Practices Manual:

www.ncforestservice.gov/water_quality/bmp_manual.htm

Regulations applicable to forestry operations in NC:

http://www.ncforestservice.gov/water_quality/water_quality.htm

Appendix A. Watershed hydrology.

In forestry operations and other land-clearing activities, the removal of vegetation (particularly woody vegetation) can have a number of effects on watershed hydrological processes (See the water cycle figure below). Components (precipitation, interception, transpiration, evaporation, flow, and uptake) if this cycle make up the water "budget" for a watershed. Much like a personal budget for your household, the water budget accounts for how much is coming in and where it is being "spent". For example, water could be considered "spent" if it is returned to the atmosphere through evaporation and transpiration or carried to streams where it leaves the watershed as stream discharge. Water can also be "saved" by being transferred for storage in soils and groundwater. In addition to its use in examining a watershed's water budget, stream discharge is also used to determine *loading*—the total mass of a material that is exported from the watershed over a certain time period—for certain water quality measures such as sediment or nutrients.

Removal of vegetation reduces the amount of water returned to the atmosphere through evapotranspiration (ET) and may also reduce surface roughness, which would increase the speed at which water can travel downslope to nearby streams. The net effect of vegetation removal is that more water is converted from precipitation to stream discharge (water flowing in the channel) from the watershed. The time it takes for water movement through the system occurs slower under vegetated conditions.

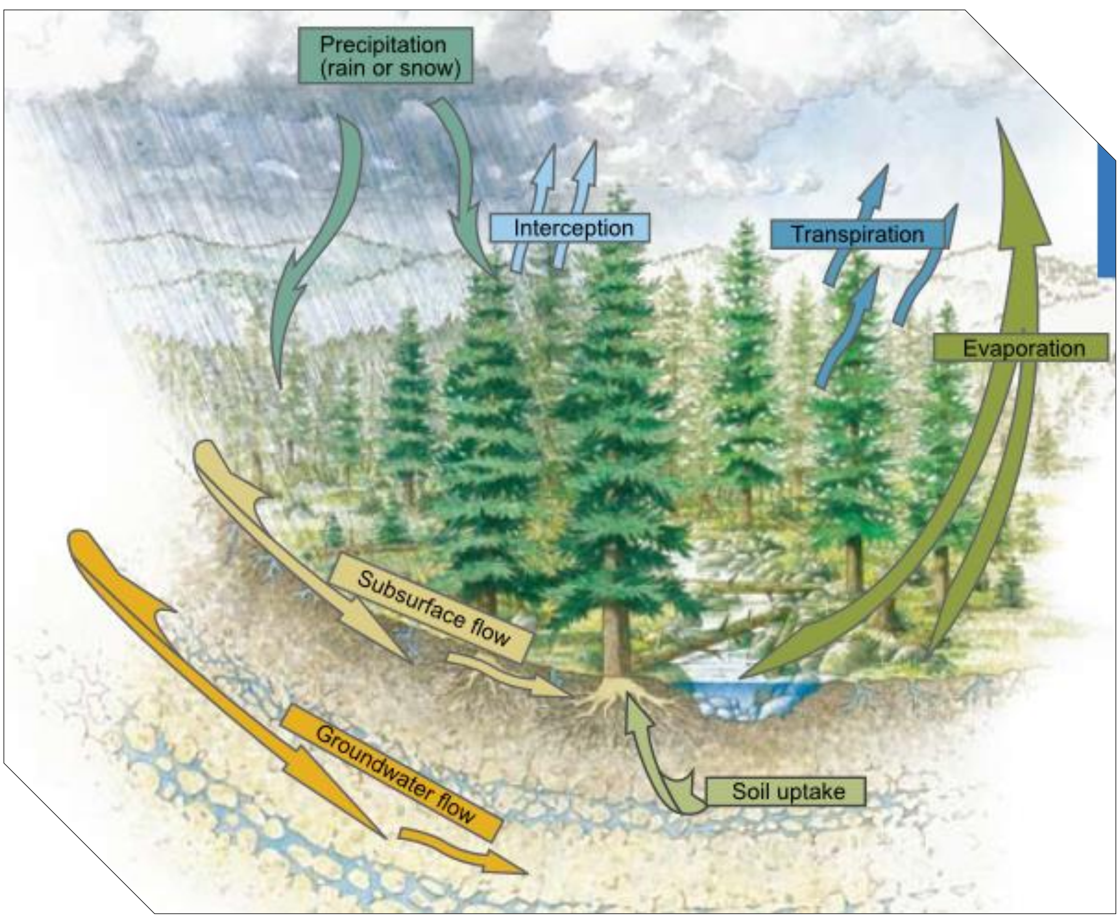


Image courtesy of idahoforests.org

Appendix B. Stream discharge and total precipitation at (A) Hill Forest (HF) and (B) Umstead Farm (UF) in English units.

(A) Stream discharge and total precipitation at Hill Forest (HF) converted to English Units

Year	n (days)	Period	HF1 Measured	HF1 Modeled	HF2 Measured	HFW1 Measured	HFW1 Modeled	HFW2 Measured	Precipitation
			Daily Stream Discharge for the Year (U.S. Gallons/Day)						(inches)
2007	105	Preharvest	2,138	3,971	5,193	6,109	8,858	2,444	5.98
2008	366	Preharvest	10,253	9,902	12,444	13,232	17,439	14,985	47.13
2009	365	Preharvest	18,365	16,695	20,738	23,022	22,495	22,583	53.46
2010	365	Preharvest	14,938	16,695	20,738	25,131	20,738	19,859	43.15
2011	18	Preharvest	10,691	7,127	8,909	12,473	8,909	1,782	0.55
		Total	**56,385**	**54,391**	**68,021**	**79,967**	**78,438**	**61,652**	**150.28**
2011	347	Postharvest	22,830	6,285	8,134	16,175	11,184	5,731	39.45
2012	366	Postharvest	21,995	6,047	7,799	15,774	10,866	5,258	41.61
2013	365	Postharvest	28,734	9,842	12,478	25,570	18,629	16,783	47.17
		Total	**73,559**	**22,173**	**28,411**	**57,519**	**40,679**	**27,772**	**128.23**

(B) Stream discharge and total precipitation at Umstead Farm (UF) converted to English Units

Year	n (days)	Period	UF1 Measured	UF1 Modeled	UF2 Measured	Precipitation
			Daily Stream Discharge for the Year (U.S. Gallons/Day)			(inches)
2007	105	Preharvest	957	479	1,436	7.80
2008	366	Preharvest	17,573	16,749	22,515	49.17
2009	365	Preharvest	38,684	39,372	51,211	51.46
2010	251	Preharvest	25,024	29,027	37,836	27.76
		Total	**82,237**	**85,627**	**112,998**	**136.18**
2010	114	Postharvest	**22,920**	**6,612**	**10,138**	**8.78**
2011	347	Postharvest	26,210	7,530	11,295	38.78
2012	366	Postharvest	35,832	11,258	16,063	38.07
2013	365	Postharvest	51,762	21,338	28,634	42.95
		Total	**136,724**	**46,737**	**66,129**	**128.58**

$$\frac{\text{mm}}{\text{days}} * \frac{0.001\ \text{m}}{1\ \text{mm}} * \frac{4047\ \text{m}^2}{1\ \text{ac}} * \frac{watershed\ ac}{1} * \frac{1000\ \text{L}}{1\ \text{m}^3} * \frac{0.26417\ \text{Gal}}{1\ \text{L}} = \text{Gallons per Day}$$

Appendix C. Mean values for stormflow hydrologic characteristics of the harvested watersheds.

Watershed	Season	Num. of Storms	Event Duration	Begin Flow	Peak Rate	Time Peak	Total Stream Discharge	Baseflow	Stormflow	Precipitation	Discharge / Precip Ratio
			(hours)	*(mm/day)*	*(mm/day)*	*(hours)*	*(mm)*	*(mm)*	*(mm)*	*(mm)*	
HF1 measured	growing	40	**11.00 (1.32)**	**0.70 (0.13)**	9.43 (3.44)	2.75 (0.58)	**1.65 (0.53)**	**0.53 (0.11)**	1.12 (0.44)	24.90 (1.98)	**0.05 (0.01)**
HF1 modeled	growing	40	**6.37 (0.82)**	**0.19 (0.04)**	5.11 (0.90)	2.02 (0.41)	**0.61 (0.25)**	**0.13 (0.04)**	0.49 (0.21)	22.50 (1.74)	**0.02 (0.01)**
HFW1 measured	growing	44	**10.38 (1.08)**	0.56 (0.09)	**7.82 (2.18)**	2.48 (0.36)	1.36 (0.39)	0.43 (0.09)	0.92 (0.31)	**23.71 (1.67)**	0.05 (0.01)
HFW1 modeled	growing	33	**7.49 (0.97)**	0.48 (0.06)	**2.59 (0.59)**	1.86 (0.15)	0.59 (0.18)	0.27 (0.06)	0.33 (0.12)	**18.77 (1.72)**	0.03 (0.01)
UF1 measured	growing	36	**17.21 (1.68)**	**0.35 (0.07)**	**41.60 (7.94)**	3.52 (0.51)	**7.17 (1.48)**	**0.69 (0.11)**	**6.48 (1.39)**	25.86 (2.76)	**0.24 (0.04)**
UF1 modeled	growing	33	**9.96 (1.72)**	**0.07 (0.02)**	**14.12 (3.97)**	2.47 (0.52)	**2.69 (0.87)**	**0.23 (0.06)**	**2.47 (0.82)**	21.08 (2.54)	**0.09 (0.02)**
HF1 measured	dormant	23	23.48 (8.05)	**0.79 (0.18)**	5.24 (1.60)	5.64 (1.14)	**2.11 (0.68)**	**0.86 (0.19)**	1.25 (0.51)	23.05 (2.51)	**0.07 (0.01)**
HF1 modeled	dormant	23	10.75 (1.30)	**0.32 (0.05)**	3.65 (0.59)	4.31 (0.88)	**0.72 (0.13)**	**0.28 (0.07)**	0.44 (0.08)	20.33 (1.74)	**0.03 (0.00)**
HFW1 measured	dormant	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	dormant	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	dormant	20	25.47 (2.34)	**0.48 (0.11)**	**33.01 (6.62)**	6.29 (1.07)	**9.03 (1.92)**	1.33 (0.29)	**7.70 (1.72)**	22.97 (2.75)	**0.33 (0.04)**
UF1 modeled	dormant	19	21.38 (2.46)	**0.24 (0.07)**	**13.58 (2.79)**	6.13 (1.08)	**4.65 (0.99)**	0.79 (0.16)	**3.85 (0.85)**	21.78 (2.77)	**0.19 (0.03)**

Note 1: **Bold Numbers** indicate significance ($p < 0.05$) when comparing results of *Measured with Harvest* versus *Modeled without Harvest*, within each watershed and in each season. Standard error is in parenthesis.

Note 2: "Discharge / Precip Ratio" is the relative extent to which the Total Stream Discharge transported (discharged) the Precipitation. Multiply the figure by (x 100) to obtain a percentage.

Appendix D. Mean annual measured and modeled water quality constitute loads (A) and concentrations (B).

A: Mean Annual Measured and Modeled Water Quality Constituent Loads

		HF1		HFW1		UF1	
Period	Constituents	Measured	Modeled	Measured	Modeled	Measured	Modeled
		(lbs / ac / yr)					
Pre-harvest	TSS	66.201	65.487	73.607	73.160	83.331	76.015
	TOC	8.387	8.297	12.402	12.312	19.807	19.807
	NH_4	0.018	0.018	0.012	0.012	0.012	--
	NO_3	0.003	0.004	0.027	--	0.027	0.027
	TP	0.143	0.134	0.152	0.152	0.170	0.170
	TN	1.062	1.044	1.222	1.213	1.392	1.392
	TON	1.044	1.017	1.187	1.178	1.356	1.356
Post-harvest	TSS	**84.224**	**28.015**	53.354	39.703	75.391	32.922
	TOC	**12.312**	**3.836**	10.082	6.959	**29.175**	**8.833**
	NH_4	0.241	0.009	0.062	0.005	0.080	--
	NO_3	0.607	0.001	0.170	--	1.017	0.036
	TP	0.277	0.054	0.187	0.098	0.196	0.080
	TN	**2.338**	**0.642**	**1.142**	**0.633**	**2.793**	**0.794**
	TON	**1.490**	**0.633**	0.919	0.598	**1.686**	**0.705**

B: Mean Monthly Measured and Modeled Water Quality Constituent Concentrations

		HF1		HFW1		UF1	
Period	Constituents	Measured	Modeled	Measured	Modeled	Measured	Modeled
		(mg / L)					
Pre-harvest	TSS	36.8 (5.1)	35 (3.1)	27.9 (2.9)	26.7 (2.2)	33.7 (4.1)	32.5 (3.2)
	TOC	6.1 (0.6)	6.2 (0.3)	5.7 (0.3)	5.7 (0.3)	10.2 (1.0)	9.6 (0.6)
	NH_4	0.03 (0.02)	0.04 (0.02)	0.01 (0.005)	0.01 (0.003)	0.01 (0.01)	0.01 (0.003)
	NO_3	0.01 (0.01)	0.00 (0.00)	0.02 (0.01)	--	0.03 (0.02)	0.01 (0.01)
	TP	0.08 (0.01)	0.07 (0.01)	0.06 (0.01)	0.06 (0.005)	0.07 (0.01)	0.06 (0.01)
	TN	0.71 (0.09)	0.69 (0.05)	0.52 (0.05)	0.50 (0.03)	0.66 (0.08)	0.66 (0.05)
	TON	0.67 (0.09)	0.64 (0.04)	0.5 0(0.04)	0.48 (0.03)	0.61 (0.07)	0.60 (0.05)
Post-harvest	TSS	31.1 (4.5)	34.3 (2.5)	23.8 (2.9)	23.2 (1.7)	33.4 (2.8)	29.9 (2.1)
	TOC	4.6 (0.4)	5.5 (0.4)	4.8 (0.4)	5.2 (0.3)	**12.8 (2.0)**	**8.0 (0.4)**
	NH_4	0.08 (0.03)	0.03 (0.01)	**0.02 (0.01)**	**0.01 (0.002)**	0.03 (0.01)	0.04 (0.01)
	NO_3	**0.13 (0.04)**	**0.01 (0.01)**	0.06 (0.03)	--	**0.48 (0.11)**	**0.02 (0.002)**
	TP	0.09 (0.02)	0.07 (0.01)	0.07 (0.01)	0.06 (0.01)	0.08 (0.01)	0.06 (0.01)
	TN	0.81 (0.10)	0.64 (0.05)	0.52 (0.06)	0.44 (0.02)	**1.30 (0.16)**	**0.73 (0.07)**
	TON	0.60 (0.07)	0.60 (0.04)	0.43 (0.05)	0.43 (0.03)	**0.79 (0.09)**	**0.58 (0.04)**

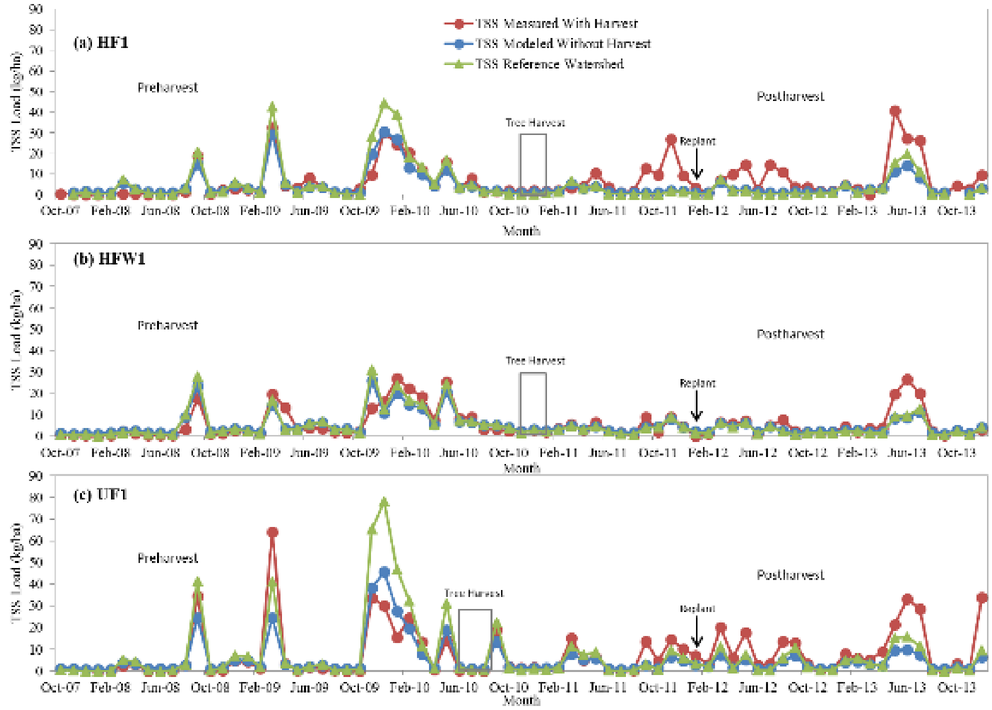
Note 1: **Bold** Numbers indicate significance ($p < 0.05$) from t-test between Measured and Modeled, within Watershed and Period. Standard Error is in parenthesis.

Note 2: (--) indicates that the predictive model was not good enough to develop a reliable modeled value, (ie: probability statistic = 0.43 for NO3 in HFW1 and 0.62 for NH4 in UF1.)

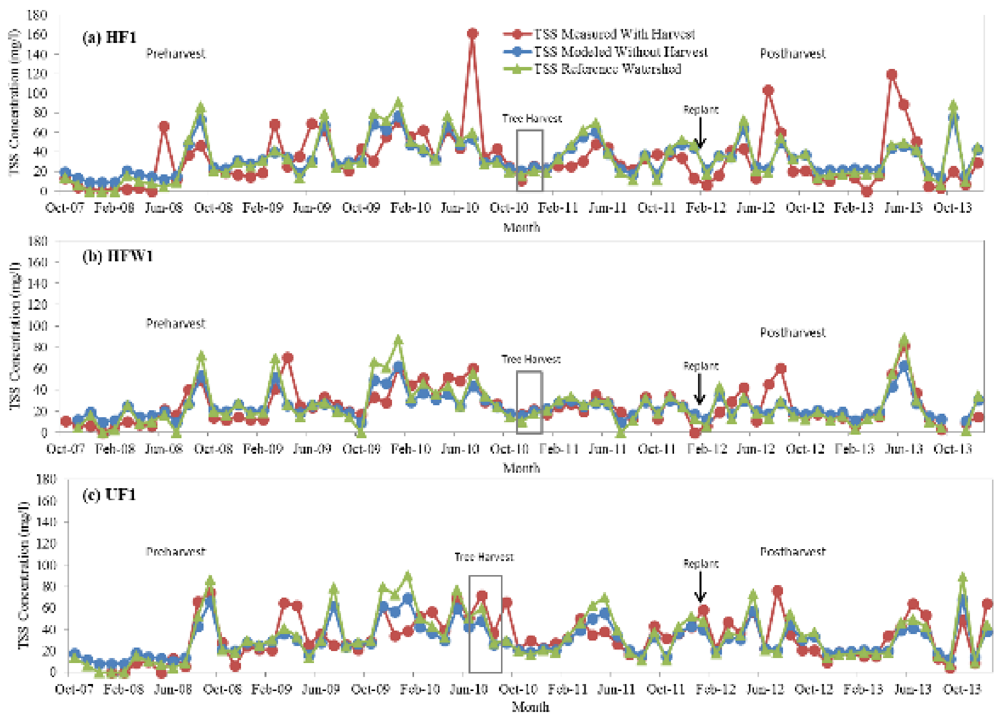
Note 3: TSS: Total Suspended Sediment. TOC: Total Organic Carbon. NH_4: Ammonium. NO_3: Nitrate. TP: Total Phosphorus. TN: Total Nitrogen. TON: Total Organic Nitrogen

Note 4: For the sake of brevity, Standard Error was not included in table A when converting from metric to English units. See section 6.1 for published data.

Appendix E. Average monthly loading (A) and concentrations (B) of Total suspended solids (TSS) for the duration of this study (includes both baseflow and stormflow).

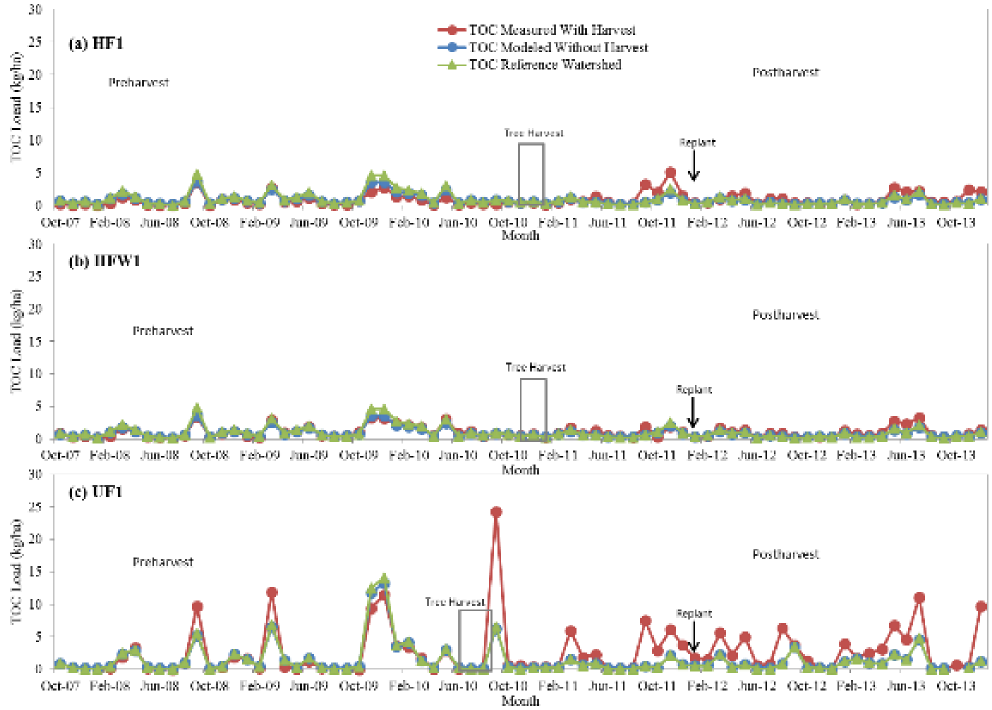


(A) Average monthly loading (kg/ha) of TSS for the duration of this study (includes both baseflow and stormflow).

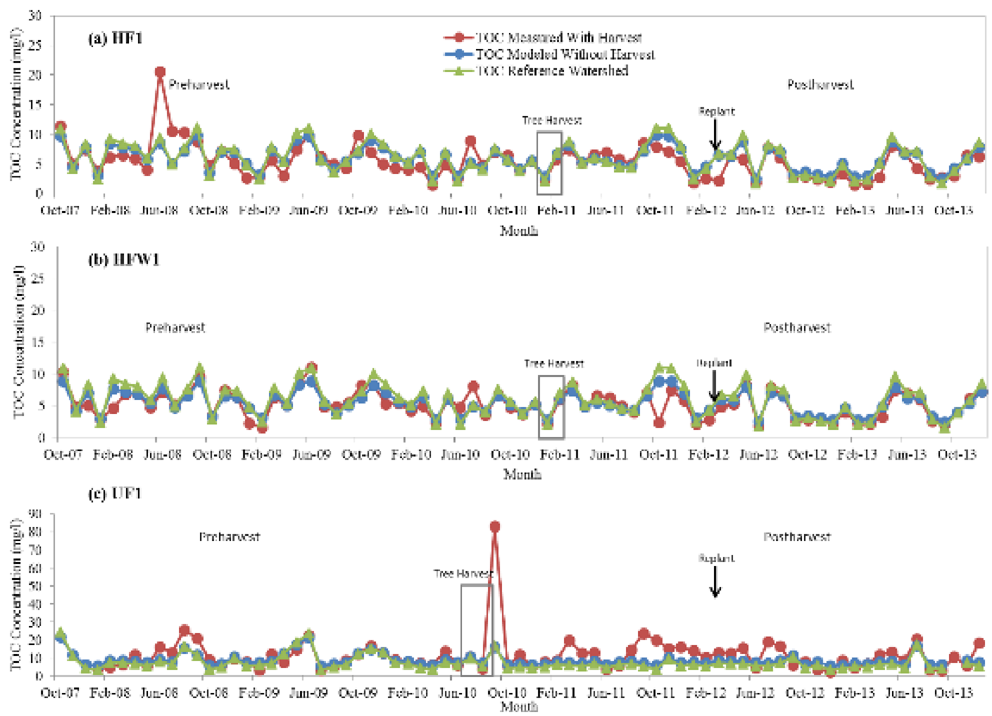


(B) Average monthly concentration (mg/L) of TSS for the duration of this study (includes both baseflow and stormflow).

Appendix F. Average monthly loading (A) and concentrations (B) of Total Organic Carbon (TOC) for the duration of this study (includes both baseflow and stormflow).

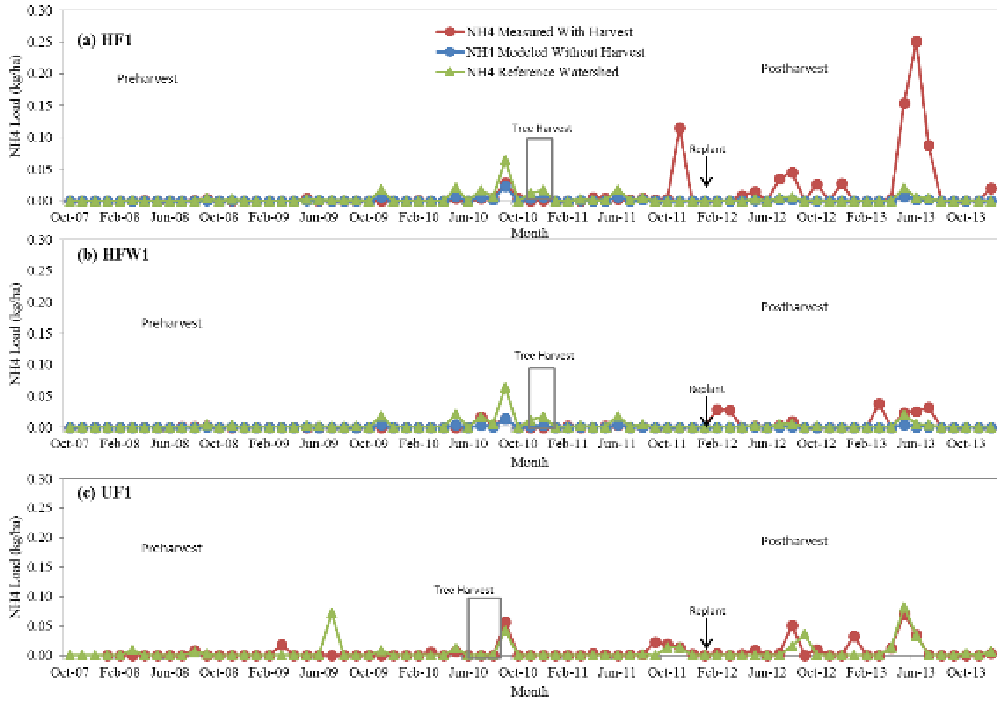


(A) Average monthly loading (kg/ha) of TOC for the duration of this study (includes both baseflow and stormflow).

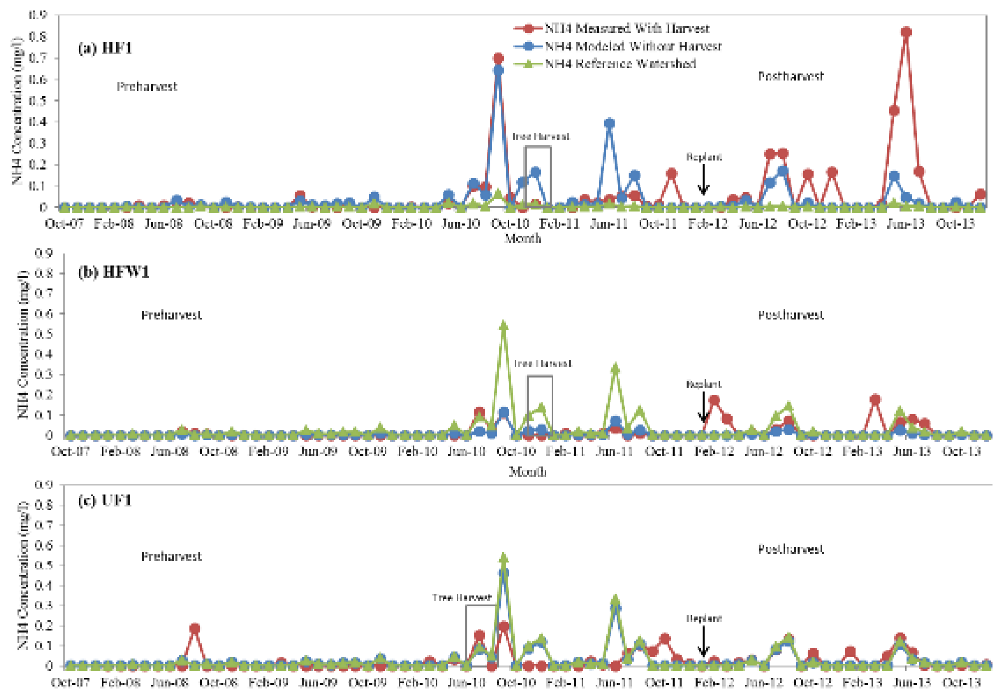


(B) Average monthly concentration (mg/L) of TOC for the duration of this study (includes both baseflow and stormflow).

Appendix G. Average monthly loading (A) and concentrations (B) of Ammonium Nitrate (NH_4) for the duration of this study (includes both baseflow and stormflow).

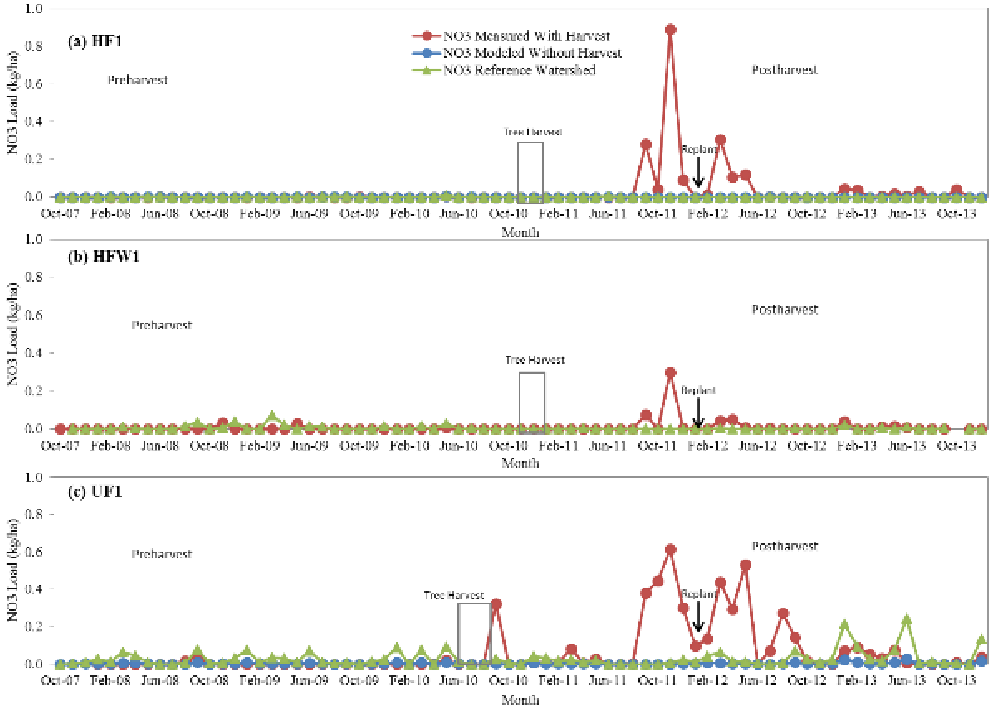


(A) Average monthly loading (kg/ha) of NH_4 for the duration of this study (includes both baseflow and stormflow).

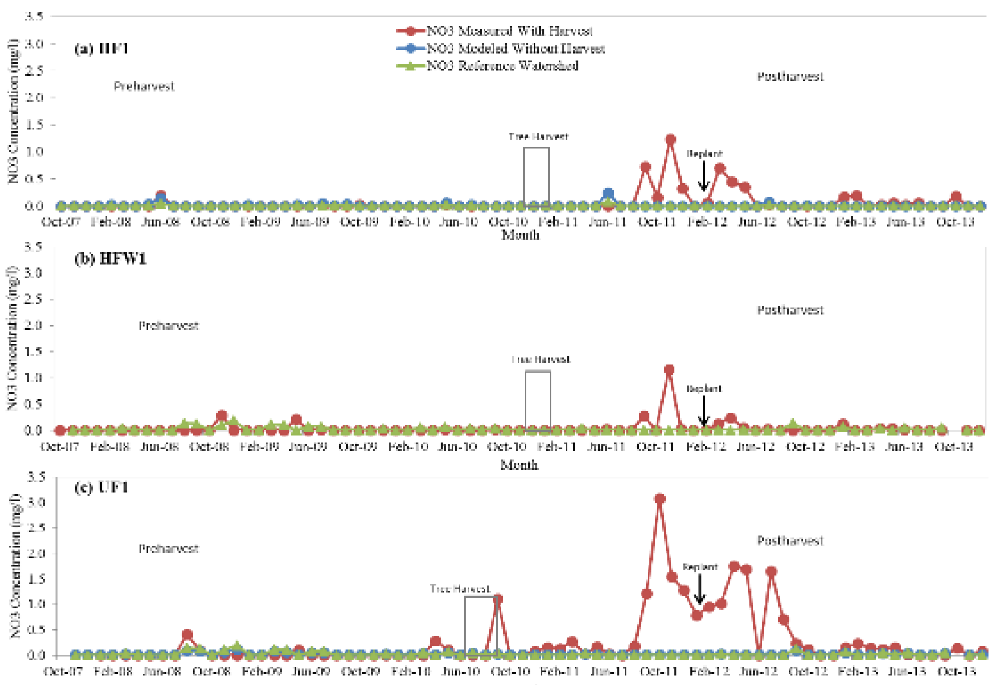


(B) Average monthly concentration (mg/L) of NH_4 for the duration of this study (includes both baseflow and stormflow).

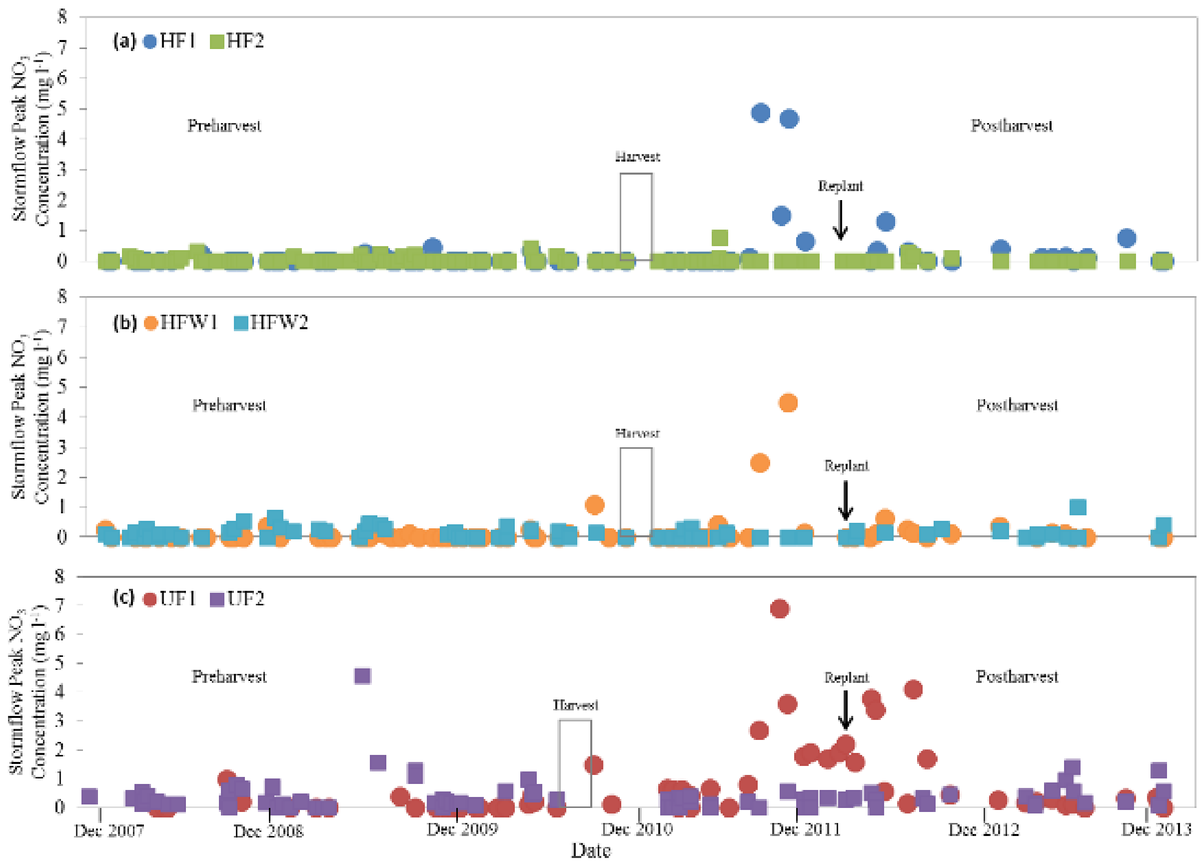
Appendix H. Average monthly loading (A) and concentrations (B) of Nitrate Nitrogen (NO_3) for the duration of this study (includes both baseflow and stormflow). (C) Peak stormflow NO_3 concentrations (mg/L) for the duration of this study.



(A) Average monthly loading (kg/ha) of NO_3 for the duration of this study (includes both baseflow and stormflow).

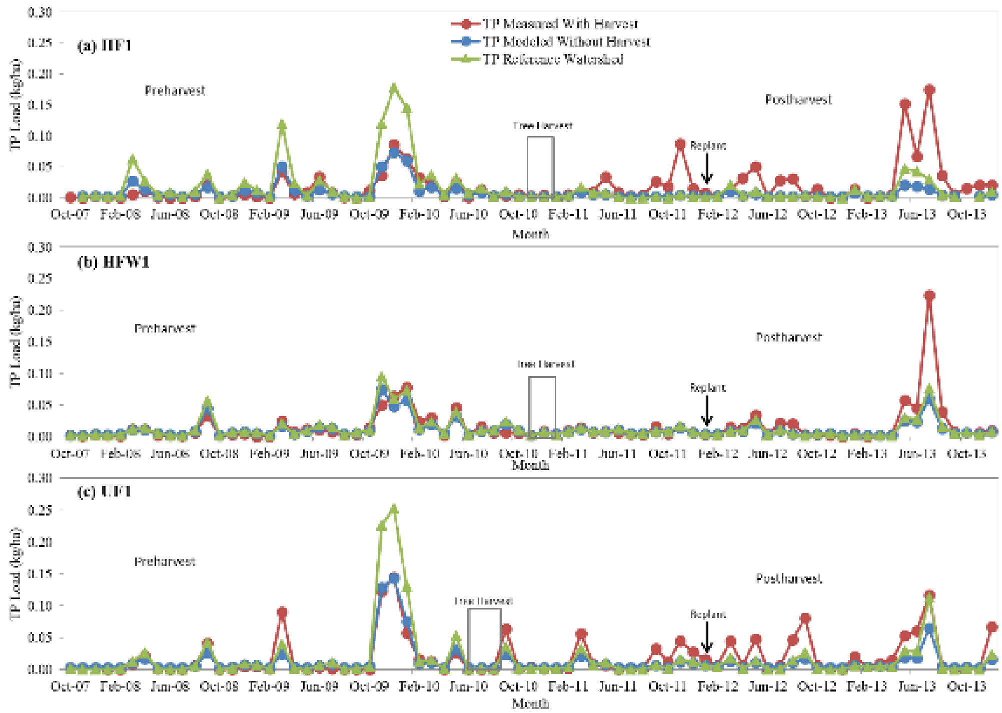


(B) Average monthly concentration (mg/L) of NO_3 for the duration of this study (includes both baseflow and stormflow).

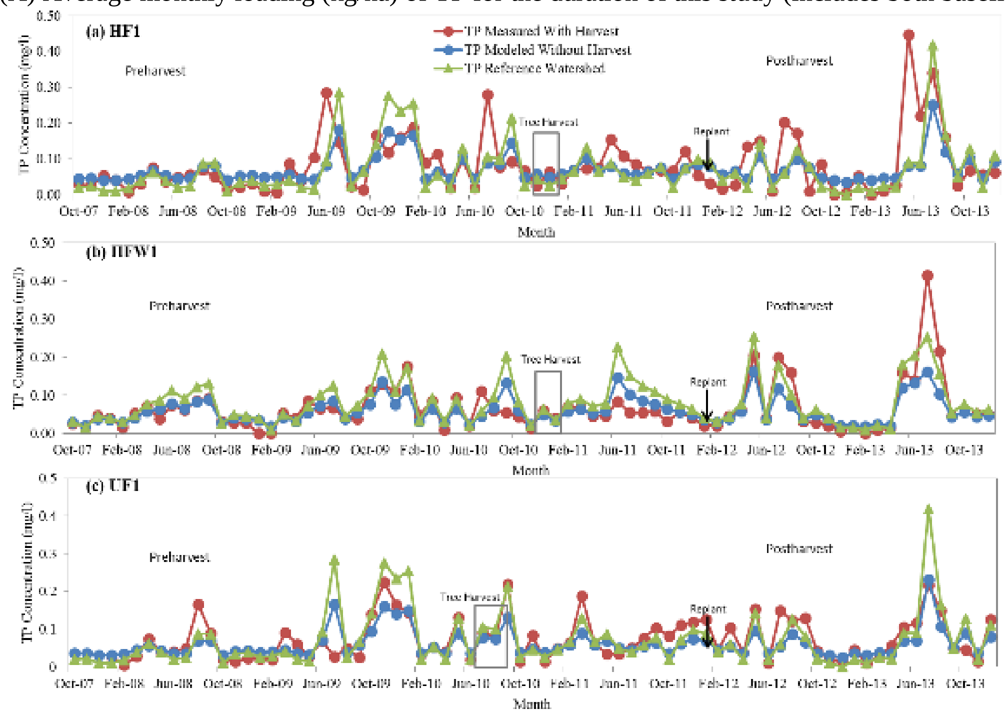


(C) Peak stormflow NO_3 concentrations (mg/L) for the duration of this study.

Appendix I. Average monthly loading (A) and concentrations (B) of Total Phosphorous (TP) for the duration of this study (includes both baseflow and stormflow).

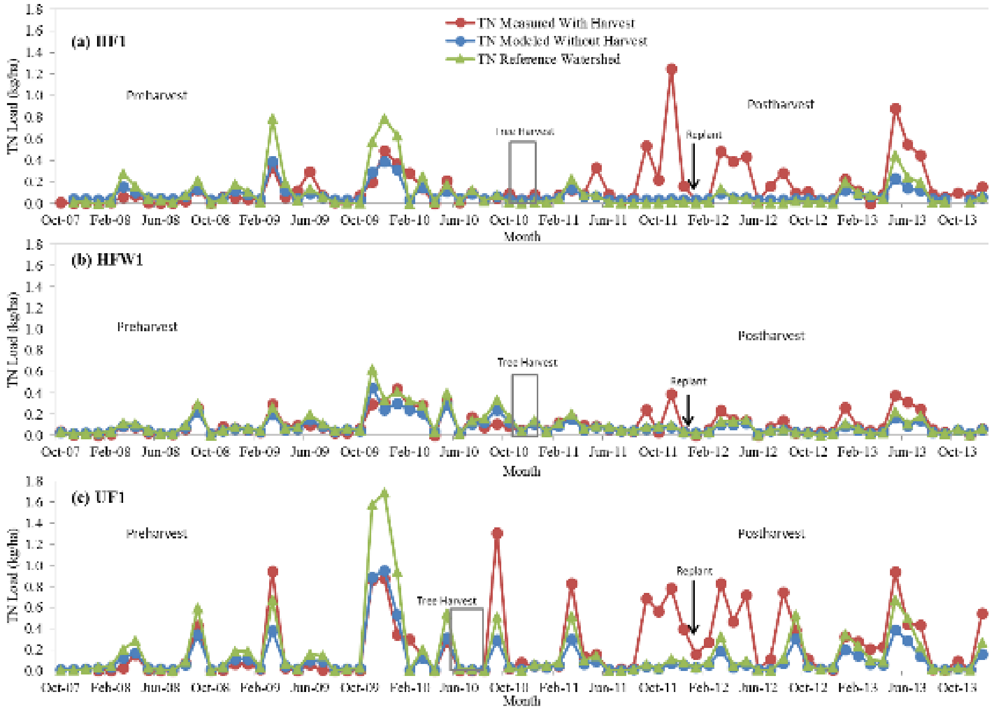


(A) Average monthly loading (kg/ha) of TP for the duration of this study (includes both baseflow and stormflow).

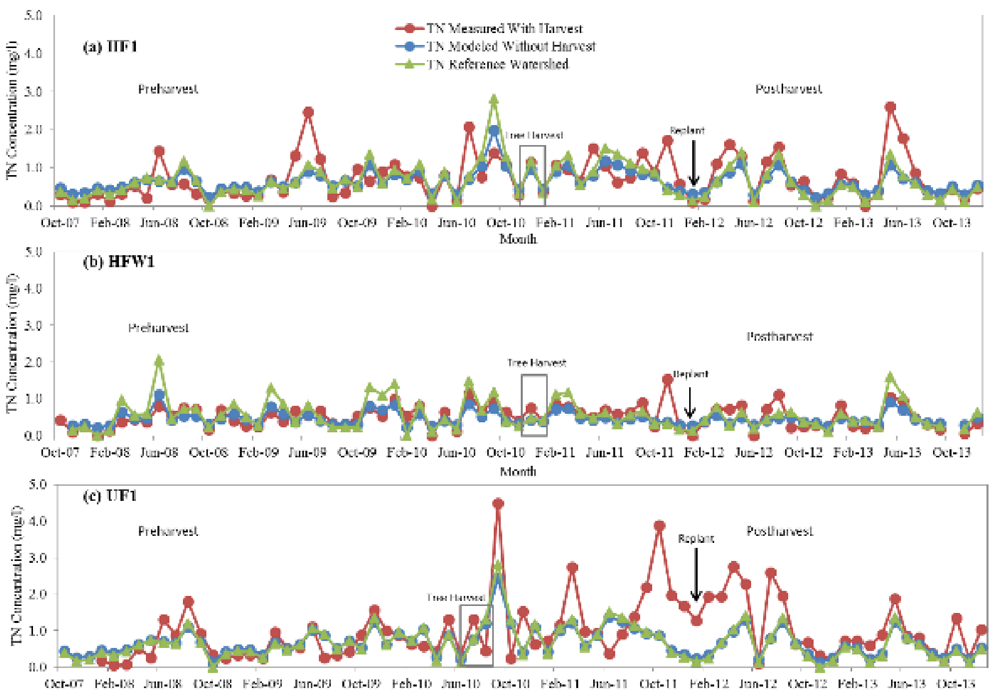


(B) Average monthly concentration (mg/L) of TP for the duration of this study (includes both baseflow and stormflow).

Appendix J. Average monthly loading (A) and concentrations (B) of TN for the duration of this study (includes both baseflow and stormflow).

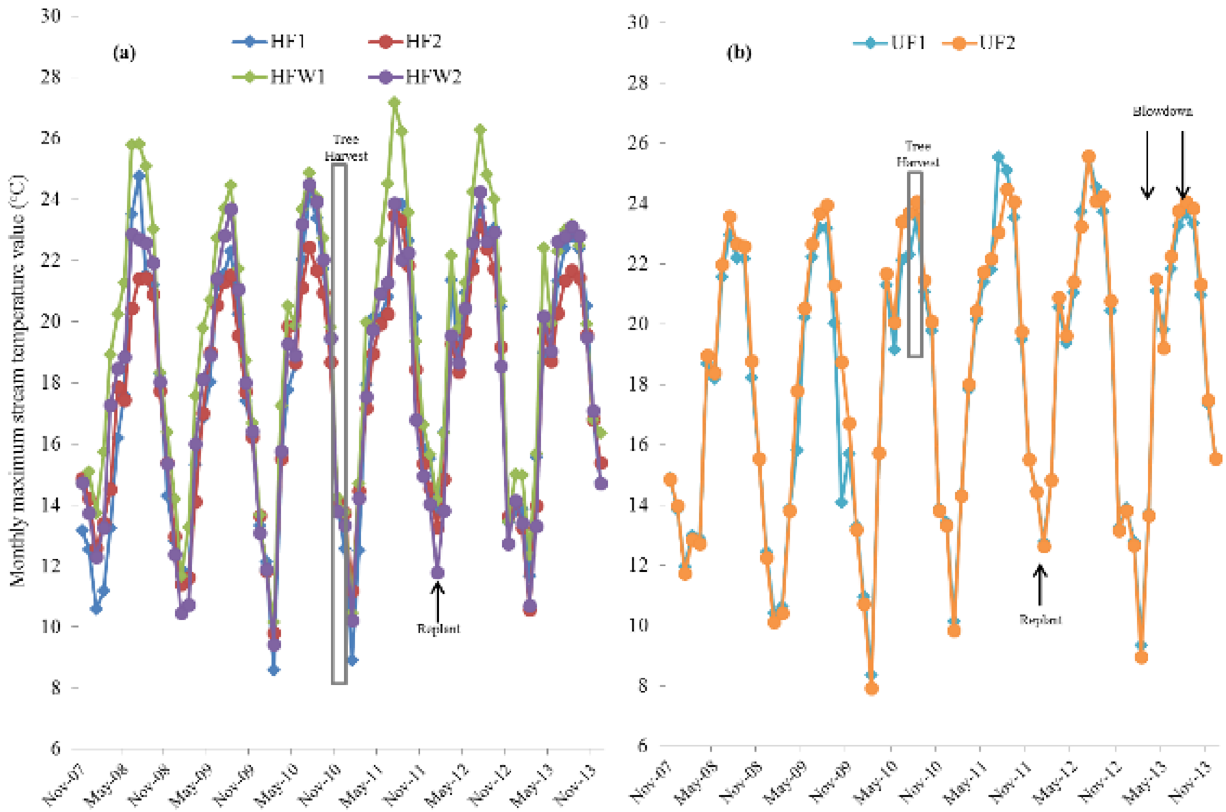


(A) Average monthly loading (kg/ha) of TN for the duration of this study (includes both baseflow and stormflow).



(B) Average monthly concentration (mg/L) of TN for the duration of this study (includes both baseflow and stormflow).

Appendix K. Monthly maximum stream water temperatures for each watershed.



Appendix L. Results of sampling for benthic macroinvertebrates during preharvest and postharvest periods.

		Preharvest			Postharvest								
Watershed	**Index**	**January 2010**	**April 2010**	**Mean Non-Growing Season**	**March 2011**	**July 2011**	**February 2012**	**July 2012**	**February 2013**	**June 2013**	**January 2014**	**Mean Growing Season**	**Mean Non-Growing Season**
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)**	**18.5 (1.5)**
HFW2 (reference)	EPT Taxa Richness	20	17	18.5 (1.5)	17	2	11	4	13	7	11	**4.3 (1.5)**	**13.0 (1.4)**
UF1 (treatment)	EPT Taxa Richness	16	12	14.0 (2.0)	19	10	20	11	14	10	12	**10.3 (0.3)**	**16.3 (1.9)**
UF2 (reference)	EPT Taxa Richness	18	10	14.0 (4.0)	10	0	12	1	12	4	10	**1.7 (1.2)**	**11.0 (0.6)**
HF1 (treatment)	Biotic Index	4.5	3.3	3.9 (0.60)	5.2	4	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	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	3.8	3.7	3.6	3.9	3.6 (0.15)	**3.9 (0.08)**
HFW2 (reference)	Biotic Index	4.1	2.8	3.5 (0.65)	4.6	6.3	4.2	4.5	4.4	3	4.3	4.6 (0.95)	**4.4 (0.08)**
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	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		

Note 1: EPT is the abbreviation for *Ephemeroptera* spp. (mayfly), *Plecoptera* spp. (stonefly), and *Trichoptera* spp. (caddisfly).
For EPT Tax Richness values, a larger number is better.

Note 2: Criteria for North Carolina Biotic Index (BI) for small streams (< 4 meters wide) are:
Excellent < 4.3, Good 4.3 to 5.1, Good-Fair 5.2 to 5.8, Fair 5.9 to 6.9, and Poor > 6.9.
Therefore, for BI values, a lower number is better.

Note 3: **Bold** numbers indicate statistical significant difference from t-test ($p < 0.05$) between Reference and Treatment watersheds, comparing Pre- and Post-Harvest periods, and when comparing Growing Season with Non-Growing Season. Standard Error is in parenthesis.

Appendix M. Mean functional feeding group (FFG) percentages of sampled insects for each watershed during postharvest period.