Total Suspended Sediment Dynamic Under Managed and Unmanaged Conditions in Headwater Watersheds

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ABSTRACT

This study examined the long-term effects of timber harvesting on total suspended sediment (TSS) in the Piedmont region of North Carolina. It focuses on two headwater catchments (HF1 and HF2) at Hill Demonstration Forest that were converted from hardwoods to pines 12 years ago and continuously monitored for streamflow from 2008 to 2023, and TSS from 2010 to 2013 and 2023. In 2011, HF1 was cleared, and a 15.2-meter vegetated riparian buffer was left around the stream. Selective harvesting in the riparian buffer of HF1 reduced basal area by 27%. The harvest followed the North Carolina Neuse River Basin Riparian Buffer Rule to protect water quality. Following the clearcut, loblolly pine trees were planted in HF1. HF2 was preserved in its natural state to serve as a reference watershed. While TSS concentration did not change significantly after the clearcut from 2011 to 2013 in either watershed, TSS load in the treatment watershed increased substantially, likely due to increased total discharge and movement of in-channel legacy sediment. There were also significant relationships between precipitation and streamflow and TSS load in both HF1 and HF2 watersheds. The close relationship in sediment concentration between HF1 and HF2 indicates sediment dynamics are influenced by increasing weather extremes. Our study provides watershed land managers with important water quality information about managed and unmanaged headwaters.

Introduction

Total Suspended Sediment (TSS) is an important constituent to assess water quality and overall ecosystem health of aquatic environments (Walling, 2009; U.S. Geological Survey, n.d.). TSS concentration in streams, rivers, and lakes can be influenced by various land management practices, environmental factors, and human activities that include development and clearing (Walling, 2009). In forested watersheds, TSS levels have been found to be relatively low but peak concentrations during storms can affect aquatic species in various ways (Caldwell et al., 2023). For example, high TSS concentrations can affect water quality which can reduce water clarity or increase turbidity, thus reducing aquatic plant growth, and ecosystem dynamics (Bilotta and Brazier 2008). Understanding TSS measurements is important for describing sediment transport within forested watersheds, and to some extent, that includes overall forest health, as soil erosion from stream crossings, logging roads, and skid trails can introduce excessive sediment and nutrients to streams (Aust et al., 2011). Furthermore, TSS can serve as a transport mechanism for certain pollutants, such as phosphorus (House et al., 1998). High TSS levels may also lead to increased costs associated with the treatment of water flowing into downstream rivers, lakes, and reservoirs.

The movement of sediment is controlled in large part by precipitation, as a result stormflow generated by rainfall can increase sedimentation and TSS concentrations and exports to streams (Choquette et al., 2019). Murphy et al. (2020) found that sediment concentrations in several US streams vary with streamflow that is driven by variations in year-to-year precipitation. They also found that while disturbances to land surface can alter sediment levels and flow paths, changes in streamflow contributed to sediment trends at over half of their study sites. This work highlights the role that variations in precipitation and streamflow may have on sediment mobilization in streams and the need for additional data to refine our understanding of how precipitation influences sediment, particularly in harvested watersheds.

Forestry Best Management Practices (BMPs) are designed to protect water quality by minimizing soil disturbance and controlling erosion during timber harvesting activities and other practices. When properly implemented, BMPs like streamside management zones, stream crossings, and preharvest planning, can minimize sediment transport to streams (Ice et al., 2004). However, when BMPs are not used properly, clearcutting and associated forest activities can lead to an increase in TSS levels due to forest floor disturbance which exposes soil and can accelerate erosion (Shah et al., 2022; Ice et al., 2004). While these studies show a relationship between timber harvesting and short-term TSS increases, there are fewer studies that have defined the longer-term effects of these practices on TSS levels in forested watersheds. This gap is particularly noticeable in regions like North Carolina's Piedmont, where existing studies have mostly focused on the first few years after a harvest. This has resulted in a lack of long-term TSS changes in the years following timber removal (Bogg et al., 2017). Although paired-watershed studies that compare treated watersheds to control watersheds offer a unique approach to assess land management impacts on water quality, they are resource-intensive and require a long-term commitment (Grace, 2005; Grace and Clinton, 2007).

This study seeks to address this knowledge gap by examining TSS levels and their relationship with precipitation and streamflow over a twelve-year period at Hill Demonstration Forest – using the paired watershed approach. This method enables us to assess not only the immediate effects of the timber harvest but also the long-term condition of sedimentation, climate, and hydrology responses. By examining these extended data and relationships, this study will advance the understanding of TSS dynamics in relation to precipitation/climate and the potential effects on water quality in North Carolina’s Piedmont.

Materials and Methods

Study Sites

The standard paired watershed approach was used in the study where data was collected from 2010 to 2023 (Figure 1) (Hewlett & Pienaar, 1973). The paired watersheds are 12 ha and located at Hill Demonstration Forest (HF). They are located within the Upper Neuse River Basin watershed in northern Durham County, North Carolina and are owned and managed by North Carolina State University. HF1 served as the treatment watershed, while HF2 was the control. Prior to the harvest, both watersheds contain similar stand compositions (pine and hardwood tree compositions) and similar soil types.

Vegetation Surveys and Timber Harvest

Vegetation composition and basal area (BA) was characterized over the study period through the collection of stem count data and diameter at breast height (DBH) for overstory and understory trees from six plots in HF1 and ten plots in HF2. The treated watershed (HF1) was clear cut using typical rubber tire-mounted logging equipment from November 29, 2010 to January 19, 2011. A 15.2 m riparian buffer was maintained to protect water quality. Loblolly pine *(Pinus taeda*) was subsequently planted in HF1 in January 2012, while HF2 remained as the control, a mixed-pine hardwood stands. In December 2019, a precommercial thinning to was done to reduce competition among the pine trees. This decreased overall stand density and enhanced growth and vigor of the residual trees. The trees were hand-fallen and left on the ground to decompose. Hand-felling the trees was the most cost-effective method and the felled trees left on the ground aid in moisture retention and provide shelter for various wildlife species in the forested watershed.

Stream Discharge, Precipitation, and Water Quality Measurements

In 2007, a 2-H flume was installed at the outlet of both HF1 and HF2 to provide for precision in control watershed streamflow measurements. The flume is used because it provides a standardized structure and a known relationship between water level (stage) and the flow rates (discharge) in the stream channel. Stream discharge was recorded continuously using a Sigma 900 Max water sampler equipped with a depth sensor/pressure transducer. Grab water samples were collected at least biweekly under base-flow conditions, while the Sigma sampler a flow rate of change (0.2 cfs), was used to collect stormflow samples. Precipitation was measured in an open area with a Hobo Data-Logging Rain Gauge –RG3 (Onset Corporation, Bourne, MA, USA) approximately 500 m from the outlet at HF.

The water samples were analyzed for total suspended sediment (TSS) concentration (mg/L). In the laboratory, TSS was quantified by filtering a known water volume through pre-weighed filter paper, drying, and weighing the remaining sediment to calculate the concentration of the sample. TSS load or sediment load was computed as a product of TSS concentration by streamflow volume or discharge over a given time period based on flow record and expressed as kg/ha/year.

Data Processing and Analysis

To assess the effects of timber harvesting on TSS concentrations and loads, we conducted a comparative analysis between the reference and treatment watersheds. The data were collected and analyzed across three periods: pre-harvest, year 3 postharvest (averaged over three years from 2011-2013), and year 10 postharvest (year 2023). We created bar graphs of TSS concentration and load, and streamflow measurements that included standard error bars to indicate variability. Only one year of data was available for the year 10 postharvest period. The limited data may not fully capture the variability in TSS over multiple precipitation events and years, which could lead to an underestimation or misinterpretation of the long-term relationship between rainfall and TSS. The lack of multiple years of data around the 10-year mark means that the observed correlation may not capture the typical fluctuating weather patterns for this area.

The basal area changes in the treatment watershed covered three phases: pre-harvest (2010), the loblolly pine growing period (2015-2019), and post-thinning of loblolly (2020-2023). Similarly, we determined the basal area changes in the reference watershed from pre-harvest (2010) and annually from 2014 to 2023. These data were used to evaluate the temporal effects of timber harvest and subsequent management practices on TSS/water quality conditions.

Results

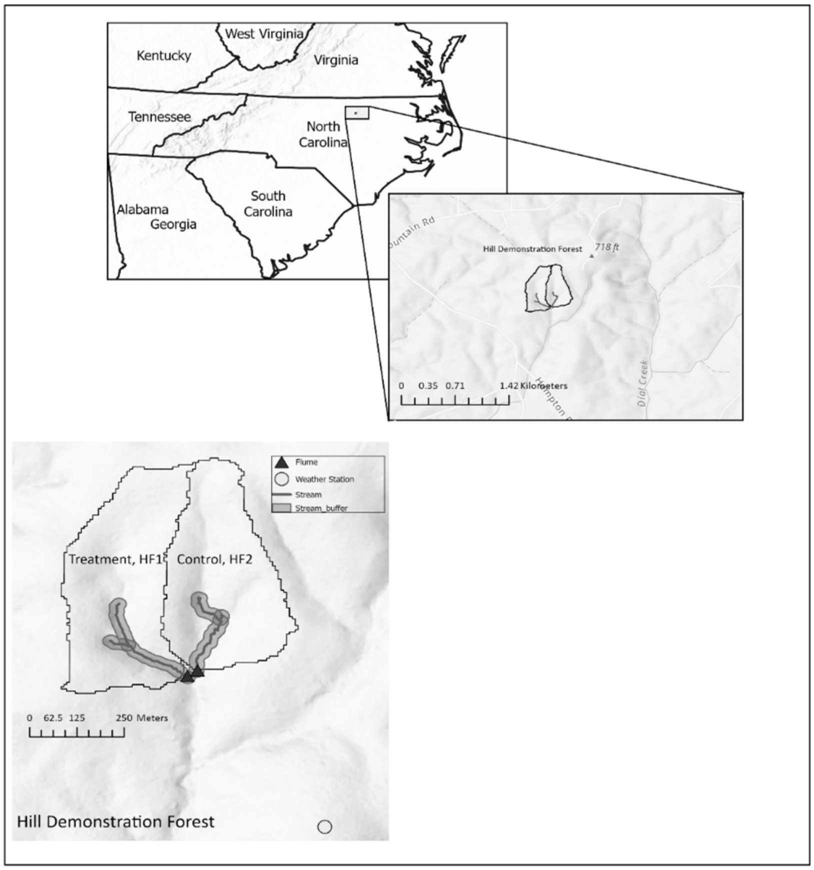

Figure 1. Paired watershed study sites at Hill Demonstration Forest (Durham County).

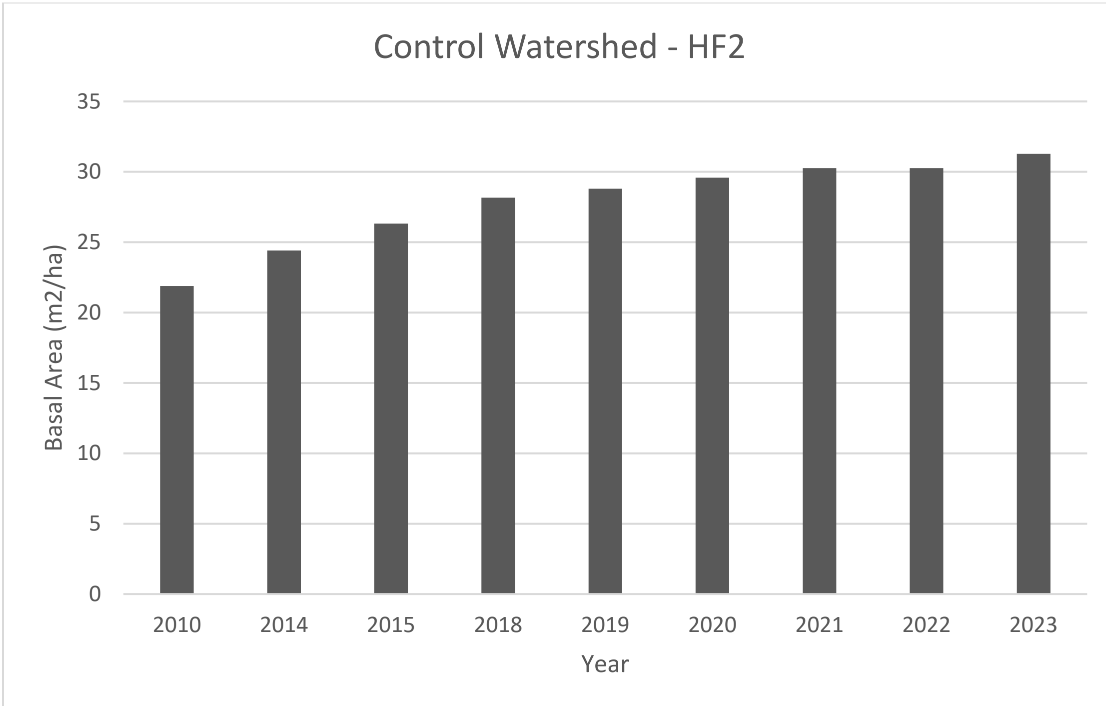

Figure 2. Basal area (m²/ha) in the control watershed (HF2) from 2010 to 2023.

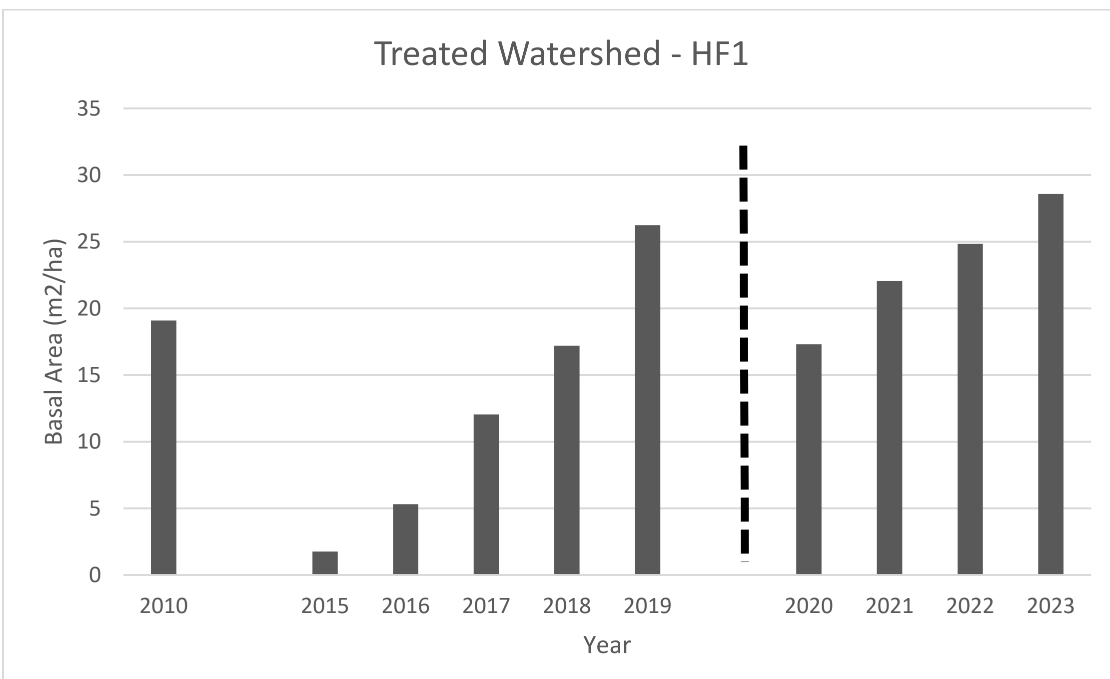

Figure 3. Basal area (m²/ha) in the treated watershed (HF1) across distinct periods: the baseline condition in 2010, mid-term growth of loblolly pine from 2015 to 2019, and continued growth from 2020 to 2023 after a precommercial thinning in December 2019.

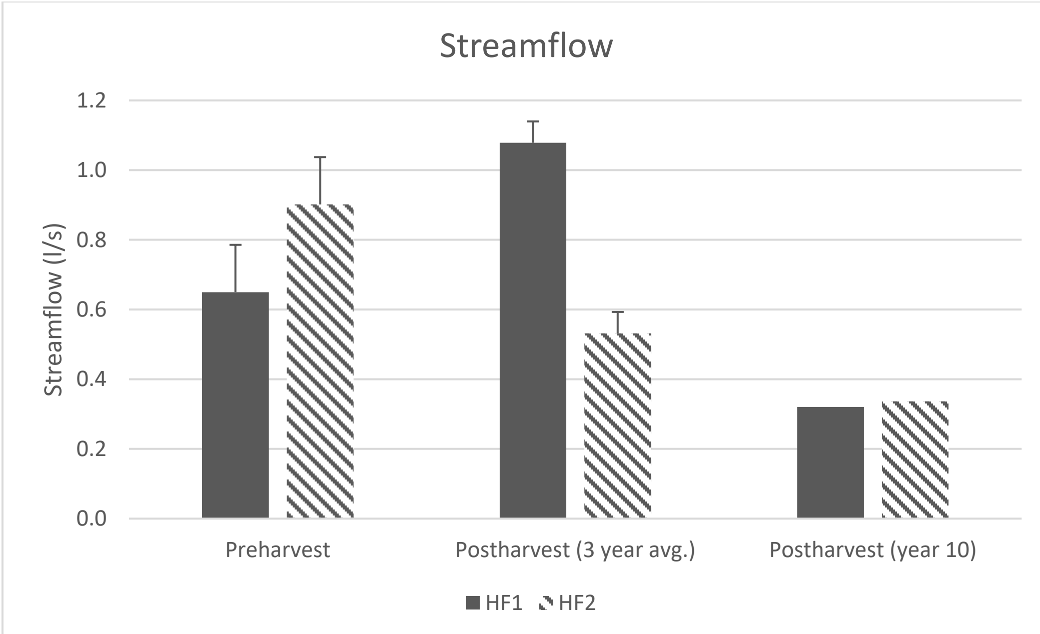

Figure 4. Streamflow (l/s) for both the treated (HF1) and control (HF2) watersheds, comparing preharvest conditions, a 3-year average postharvest, and at 10-year postharvest.

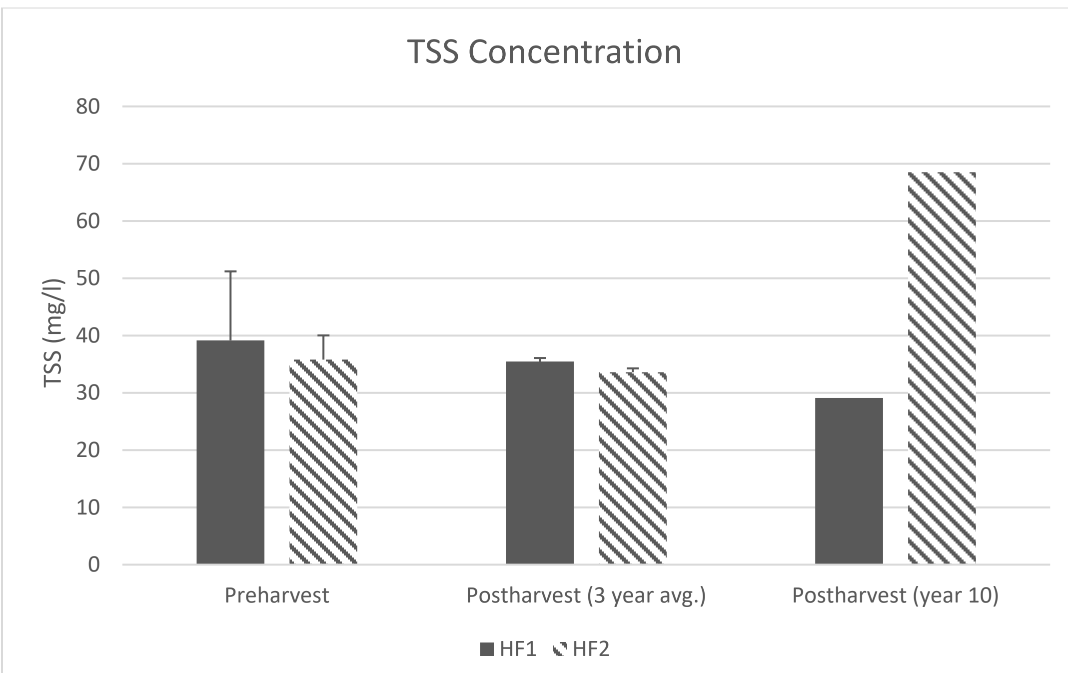

Figure 5. Total suspended sediment concentration (L/s) for both the treated (HF1) and control (HF2) watersheds, comparing preharvest conditions, a 3-year average postharvest, and at 10-year postharvest.

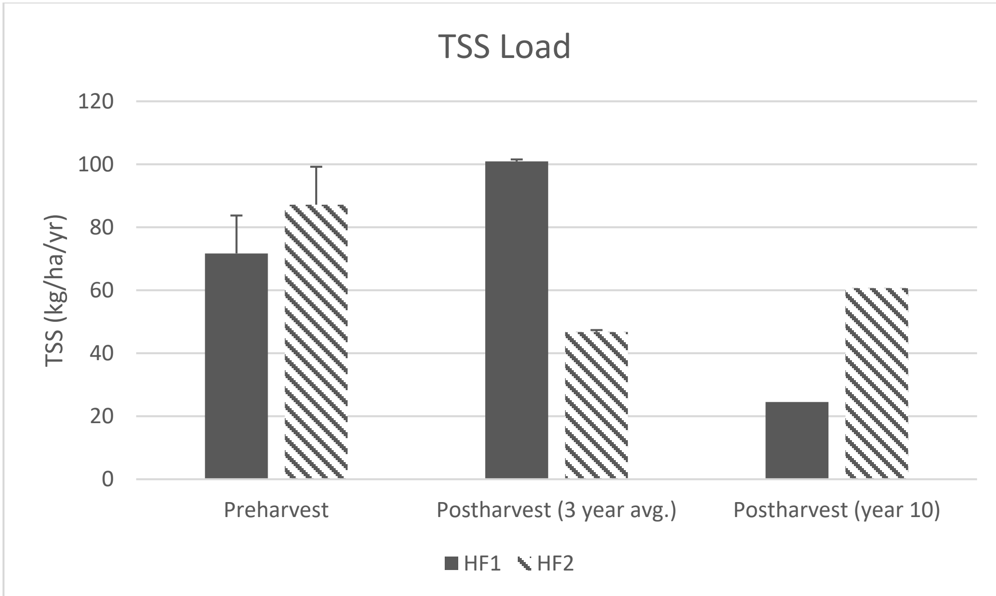

Figure 6. Total suspended sediment load (kg/ha/yr) for both the treated (HF1) and control (HF2) watersheds, comparing preharvest conditions, a 3-year average postharvest, and at 10-year postharvest.

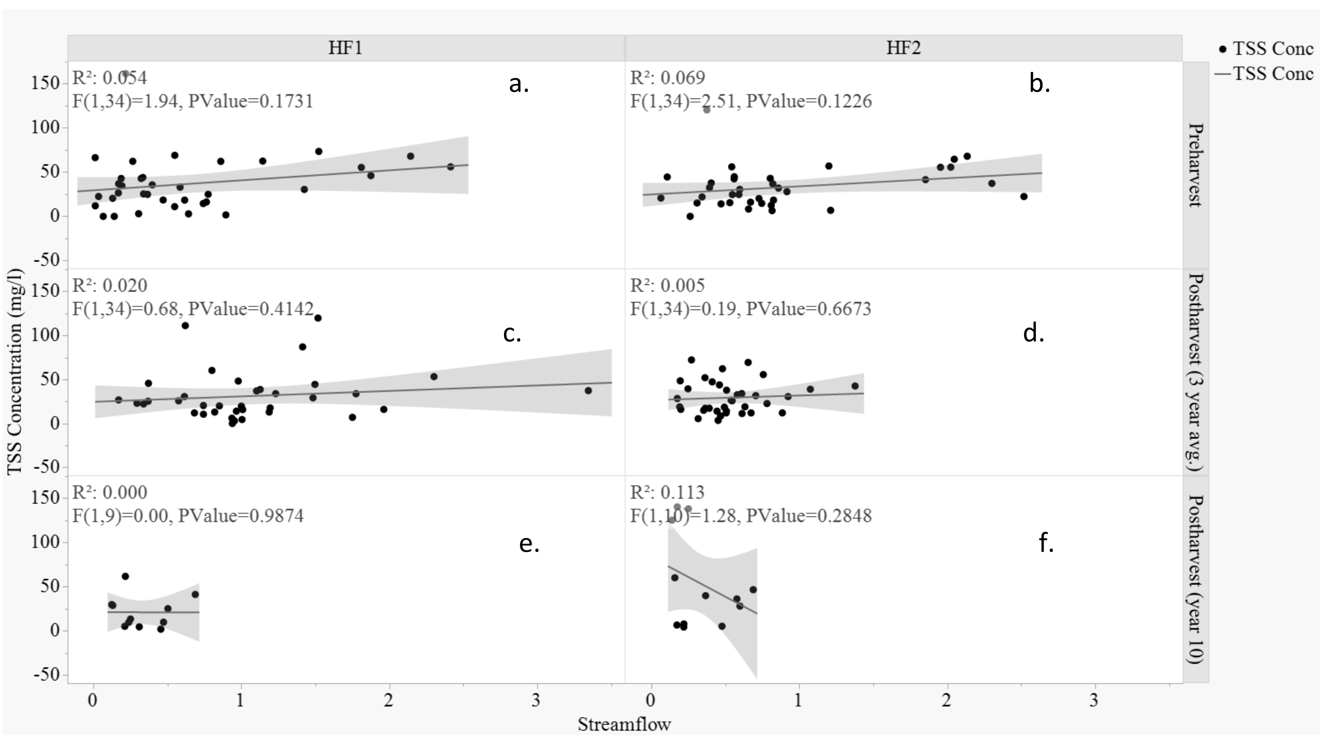

Figure 7. Comparison of mean monthly streamflow (L/s) and total suspended sediment (TSS) concentration (mg/l) for treated (HF1) and control (HF2) watersheds during preharvest a. and b.; post-harvest (3-year average) c. and d.; and at year 10 postharvest d. and e., respectively. The linear regression line is shown. The shaded area depicts 95% confidence interval for the trend.

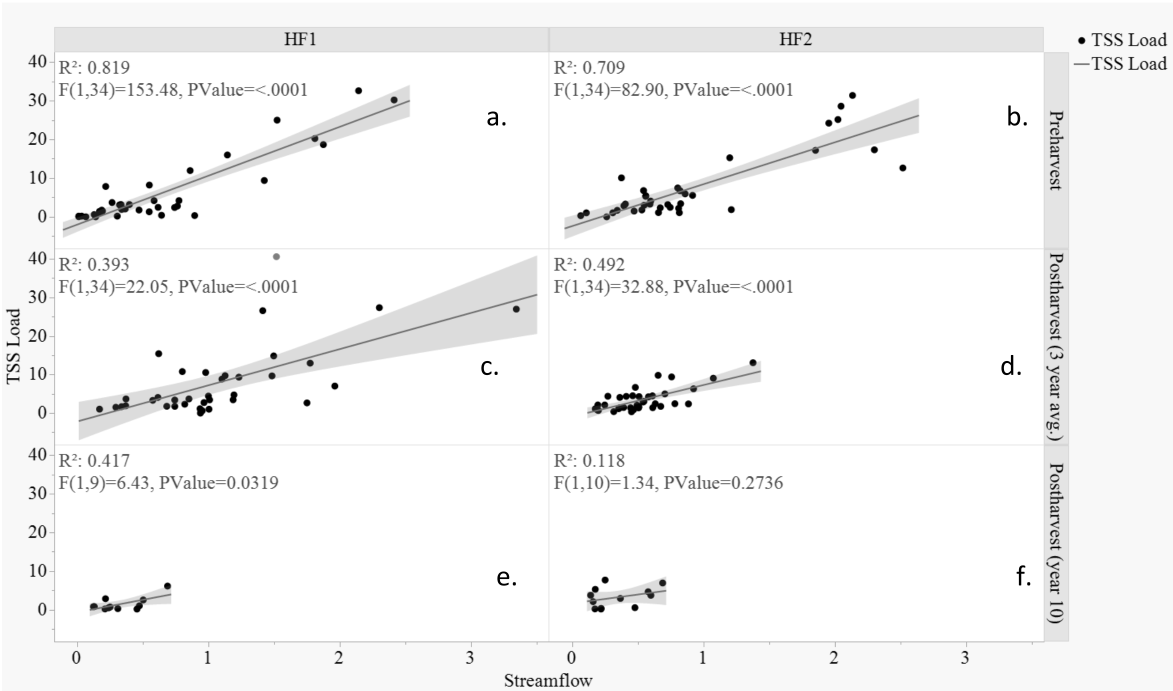

Figure 8. Comparison of mean monthly streamflow (L/s) and monthly total suspended sediment (TSS) load (kg/ha/month) for treated (HF1) and control (HF2) watersheds during preharvest a. and b.; post-harvest (3-year average) c. and d.; and at year 10 postharvest d. and e., respectively. The linear regression line is shown. The shaded area depicts 95% confidence interval for the trend.

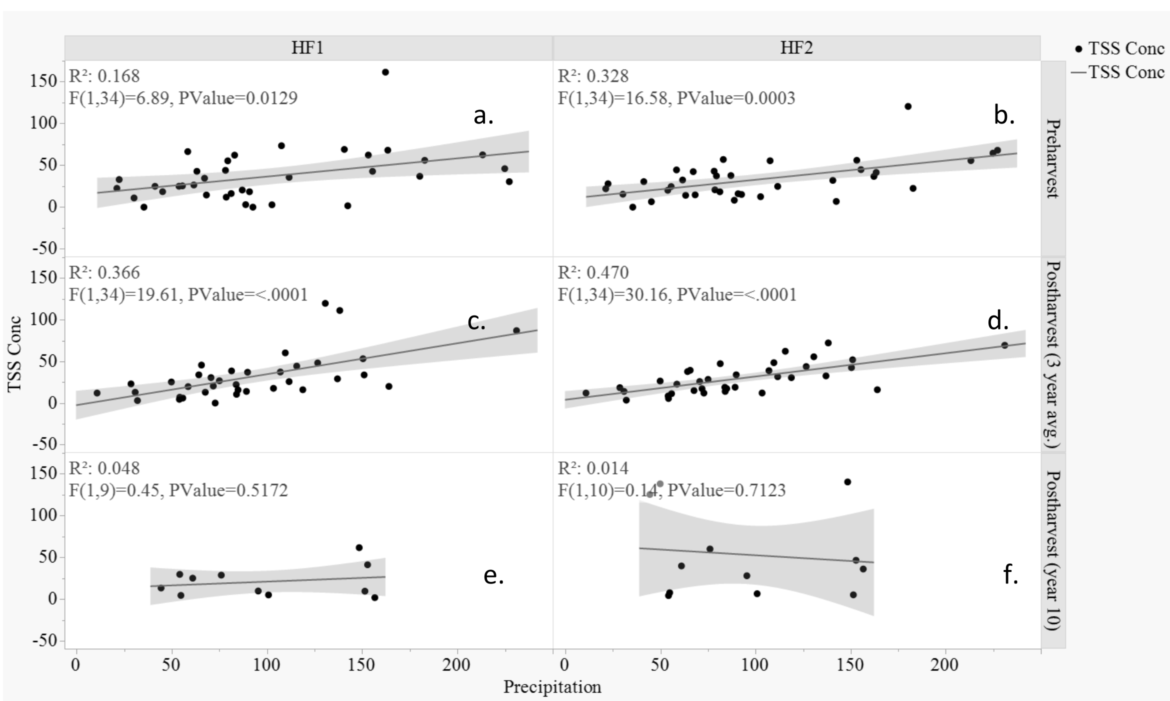

Figure 9. Comparison of monthly precipitation (mm) and mean monthly total suspended sediment (TSS) concentration (mg/l) for treated (HF1) and control (HF2) watersheds during preharvest a. and b.; post-harvest (3-year average)

c. and d.; and at year 10 postharvest d. and e., respectively. The linear regression line is shown. The shaded area depicts 95% confidence interval for the trend.

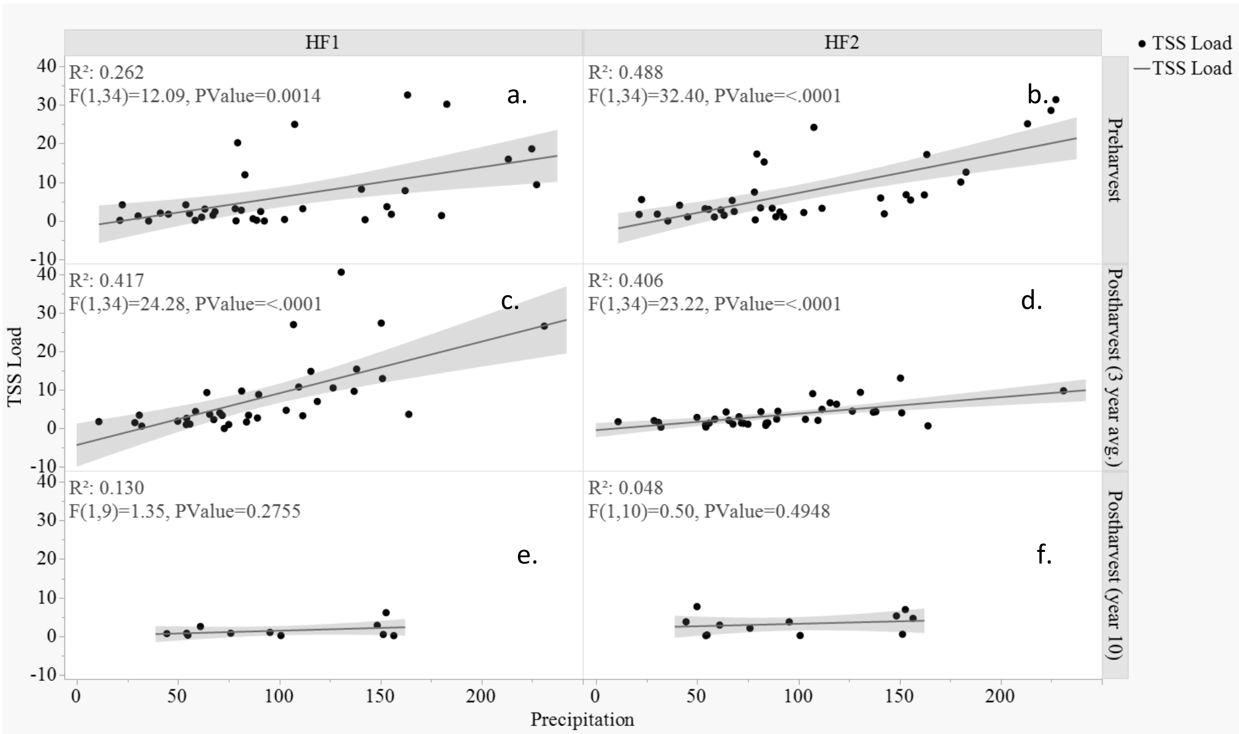

Figure 10. Comparison of monthly precipitation (mm) and total suspended sediment (TSS) load (kg/ha/month) for treated (HF1) and control (HF2) watersheds during preharvest a. and b.; post-harvest (3-year average) c. and d.; and at year 10 postharvest d. and e., respectively. The linear regression line is shown. The shaded area depicts 95% confidence interval for the trend

Basal Area

The initial basal areas (BA) were 22 m^2/ha and 19 m^2/ha in the control watershed and treatment watersheds, respectively (Figures 2 & 3). The control watershed exhibited a consistent, gradual increase in annual BA, reaching a maximum of 31 m^2/ha in 2023. In the treatment watershed, after the harvest and planting of loblolly pine in 2012, BA reached 2 m^2/ha in 2015 and then increased exponentially to 27 m^2/ha in 2019. Following the thinning in 2019, BA was reduced by 34%. BA begins to increase in subsequent years and reached a maximum of 29 m^2/ha in 2023.

Streamflow

Preharvest streamflow measured 0.62 L/s for HF1 and 0.8 L/s in HF2 (Figure 4). Three years postharvest, streamflow increased substantially in HF1 (1.1 L/s) compared to control HF2 (0.5 L/s). However, by ten years postharvest, streamflow had decreased to an average of 0.3 L/s in both HF1 and HF2.

Total Suspended Concentration and Load

TSS concentration was similar between the treatment and control watershed during preharvest and postharvest (3-year average) (Figure 5). Both watersheds decreased during the 10-year postharvest period when compared to the 3-year average, with HF1 exhibiting the most significant decrease.

Before the harvest, the TSS load was 75 kg/ha/yr for HF1 and 82 kg/ha/yr for HF2 (Figure 6). Three years following the harvest, sediment yield increased to 100 kg/ha/yr in HF1 and decreased to 50 kg/ha/yr in HF2. Ten years postharvest, the load declined to an average of 15 kg/ha/yr in both HF1 and HF2.

Streamflow versus TSS

Streamflow varied less in post-harvest (year 10) than the other periods (Figures 7 and 8). The R^2 values across pre- and post-harvest phases indicate weak correlations between TSS concentration and streamflow (Figure 7). For instance, HF1 and HF2 in the pre-harvest period (2010) display low R^2 values (0.05 and 0.07, Figures 7a and 7b, respectively), indicating minimal TSS variation attributable to streamflow. Post-harvest values remain similarly low, with insignificant p-values across both watersheds.

In contrast to TSS concentration, HF1 and HF2 exhibit strong correlations between TSS load and streamflow in the pre-harvest period ($R^2 = 0.82$ and 0.71, respectively). Post-harvest (3-year average) R^2 values are weaker (0.42 for HF1, 0.12 for HF2) with significant p values, indicating a more shattered dataset and reduced TSS load dependency on streamflow in the treated watershed post-clearcut.

Precipitation versus TSS

Precipitation varied less in post-harvest (year 10) than the other periods (Figures 9 and 10). The R^2 values indicate stronger relationships between TSS concentration and precipitation, particularly during post-harvest phases. HF1 and HF2 pre- and post-harvest show positive correlations between TSS concentration and precipitation (Figure 9a, b, c and d). HF1 and HF2 pre- and post-harvest exhibit statistically significant relationships between TSS load and precipitation (Figure 10a, b, c, and d).

Discussion

Timber Harvest and TSS dynamics

In both postharvest year 3 and year 10, TSS concentration patterns in HF1 closely matched those in HF2 (Figure 5), which indicates that the effects of timber harvesting on sediment concentrations were slightly moderated over time. In year 3 postharvest, however, the TSS load in HF1 was higher due to increased streamflow following the harvest (Figure 6). This increase aligns with measured streamflow changes (figure 4), where vegetation removal reduces evapotranspiration which leads to more flow and sediment mobilization (Shah et al., 2022). However, when TSS load in postharvest year 3 was plotted against streamflow and precipitation, the relationships were similar to those observed in HF2. This suggests that while streamflow volume increased, the relationship between TSS and streamflow did not significantly deviate from the control, indicating that the rise in TSS load was driven primarily by increased flow rather than a higher sediment yield per unit of flow/concentration. This weak relationship in this study between streamflow and TSS concentration (Figure 7) aligns with findings from broader sediment trend studies in U.S. rivers, where stable, forested watersheds with intact vegetation show limited TSS response to streamflow (Walling, 2009; U.S. Geological Survey, n.d.).

Role of Precipitation in Sediment Mobilization

The relationship between TSS concentration and precipitation indicated higher R^2 values than streamflow, especially in postharvest year 3 and preharvest phases in both the unmanaged and managed watersheds (Figure 7 vs Figure 9). These findings align with research that suggests precipitation, rather than streamflow, is likely a dominant factor in the movement of sediment in streams (Murphy et al., 2020).

The Caspar Creek studies also emphasize the role of precipitation as a direct driver of sediment movement, with sediment levels remaining elevated postharvest, particularly during storm events (Ziemer, 1998; Lewis et al., 2001; Cafferata & Spittler, 1998). Similarly, high R^2 values in HF1 in year 3 postharvest highlight the importance of precipitation in sediment mobilization following harvest (Figures 9c and 10c). Our analysis of TSS concentration versus streamflow showed consistently low R^2 values across both watersheds in pre- and postharvest conditions, indicating that streamflow alone poorly predicts TSS concentration (Figure 7). However, TSS load versus streamflow showed stronger correlations in the preharvest period, with R^2 values of 0.82 for HF1 and 0.71 for HF2 (Figure 8a and 8b), suggesting that while streamflow has limited effect on TSS concentration, it significantly impacts total sediment transport, particularly following storm events.

Effectiveness of Riparian Buffer

The similar TSS load-streamflow relationships between HF1 and HF2 across the study periods highlight, in part, the role of BMPs and natural recovery in reducing sediment effects. Vegetation regrowth over time likely decreased erosion potential by reducing streamflow which allowed flow in HF1 to exhibit TSS load patterns to HF2 by year 10. While BMPs provide long-term stability by minimizing soil disturbance and erosion, their effectiveness can be moderated by precipitation intensity. For example, in HF1, BMPs may have mitigated TSS concentrations postharvest, but the close TSS-precipitation relationship suggests that intense future precipitation events may still lead to elevated TSS transport despite the proper implementation of forestry BMPs.

Implications of Climate Variability and Watershed Management

Understanding the relationship between precipitation and TSS is crucial for predicting future effects of climate variability, especially when considering extreme weather events. Climate models are projecting more intense rainfall events, which could mean managed and unmanaged forested watersheds will likely face greater sediment mobilization. Insights from studies like ours, which examine TSS responses over long periods, are essential for informing adaptive watershed management strategies that address sediment conditions over the long-term. Our findings highlight the important role of precipitation, land management, and forestry BMPs in regulating sediment dynamics and the importance of maintaining forest buffers and ground cover to effectively manage TSS concentrations and loads postharvest.

Conclusion

We found that while timber harvesting has minimal long-term effects on TSS concentrations and loads, the streamside management zone seems to have protected water quality by maintaining stable TSS concentrations before and after harvest. In addition, this study provides important information about the interactions between streamflow, precipitation, and sediment in Piedmont watersheds with significant relationships observed between precipitation and sediment. Given these linkages and the projected increases in precipitation frequency and intensity for this region, existing riparian buffers may need to be reevaluated to ensure continued protection of water quality from sedimentation. Protecting headwater streams will be important for downstream waterways in which cumulative effects from multiple harvested watersheds could affect aquatic habitats and water resources. Future research should focus on how extreme precipitation patterns might influence TSS dynamics, the cumulative effects of repeated harvest cycles on sediment transport, and site-specific buffer designs to optimize their benefits. Long-term studies are invaluable in furthering our understanding of the complex interactions between water quality and forest disturbances.

References

Aust, W. M., Carroll, M.B., Bolding, M.C., & Dolloff, C. A. (2011). Operational Forest Stream Crossings Effects on Water Quality in the Virginia Piedmont, Southern Journal of Applied Forestry, Volume 35, Issue 3, Pages 123–130, https://doi.org/10.1093/sjaf/35.3.123.

Bilotta, G.S., & Brazier, R.E. (2008). Understanding the influence of suspended solids on water quality and aquatic biota. Water Research; 42: (12): 2849-61. doi: 10.1016/j.watres.2008.03.018.

Boggs, J., Sun, G., & McNulty, S. (2015). Effects of timber harvest on water quantity and quality in small watersheds in the Piedmont of North Carolina. Journal of Forestry, 114(1), 27-40.

Boggs, J., Sun, G., & McNulty, S. (2016). Paired forested watershed experiments in the Piedmont of North Carolina (General Technical Report SRS-XXX). Southern Research Station, U.S. Department of Agriculture Forest Service.

Boggs, J., Sun, G., & McNulty, S. 2017. The effects of stream crossings on total suspended sediment in North Carolina Piedmont forests. Journal of Forestry: 12 pages. DOI:10.5849/jof.2016-059

Cafferata, P. H., & Spittler, T. E. (1998). Logging impacts of the 1970s vs. the 1990s in the Caspar Creek Watershed. USDA Forest Service General Technical Report PSW-GTR-168.

Caldwell, P. V., Martin, K. L., Vose, J. M., Baker, J. S., Warziniack, T. W., Costanza, J. K., Frey, G. E., Nehra, A., & Mihiar, C. M. (2023). Forested watersheds provide the highest water quality among all land cover types, but the benefit of this ecosystem service depends on landscape context. Science of The Total Environment, 163550. 10.1016/j.scitotenv.2023.163550.

Choquette, A. F., Hirsch, R. M., Murphy, J. C., Johnson, L. T., & Confesor Jr., R. B.: (2019). Tracking changes in nutrient delivery to western Lake Erie: Approaches to compensate for variability and trends in streamflow, J. Great Lakes Res., 45, 21–39.

Hewlett, J. D., & Pienaar, L. V. (1973). Design and analysis of the catchment experiment. In E. H. White (Ed.), Symposium on use of small watersheds in determining effects of forest land use on water quality (pp. 88-106). University of Kentucky.

House, W. A., Jickells, T. D., Edwards, A. C., Praska, K. E. & Denison, F. H. (1998). Reactions of phosphorus with sediments in fresh and marine waters. Soil Use and Management 14, 139–146.

Ice, G. G., Stednick, J. D., & Berg, N. H. (2004). The influence of timber harvesting on water quality and sediment transport. Forest Science, 50(2), 168-178.

Krammes, J. S., & Burns, J. W. (1973). Road construction on Caspar Creek watersheds: Ten-year report on impact. USDA Forest Service Research Paper PSW-93.

Lewis, J., Reid, L. M., & Ziemer, R. R. (2001). The Caspar Creek water balance. In R. R. Ziemer (Ed.), Proceedings of the Seventh Federal Interagency Sedimentation Conference (Vol. 1, pp. VII-54–VII-61).

Murphy, J. C. (2020). Changing suspended sediment in United States rivers and streams: linking sediment trends to changes in land use/cover, hydrology and climate, Hydrol. Earth Syst. Sci., 24, 991–1010, https://doi.org/10.5194/hess-24-991-2020.

Shah, N.W., Baillie, B. R., Bishop, K., Ferraz, S., Högbom, L., & Nettles, J. (2022). The effects of forest management on water quality. Forest Ecology and Management. 522: 120397. https://doi.org/10.1016/j.foreco.2022.120397.

U.S. Geological Survey. (n.d.). Sediment and Suspended Sediment. Water Science School, USGS.

U.S. Geological Survey. (n.d.). Suspended-sediment concentration and suspended-sediment discharge: Theory, use, and analysis. U.S. Department of the Interior, Washington, D.C.

Walling, D. E. (2009). The impact of global change on erosion and sediment transport by rivers: current progress and future challenges. UNESCO, Paris.

Ziemer, R. R. (1998). Caspar Creek watershed study: The California context. USDA Forest Service General Technical Report PSW-GTR-168, pp. 41–53.