Physical, Chemical, And Biological Impacts Of Intensive Forest Management On Streams Draining Watersheds In The Coastal Plain Of Alabama

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Abstract: Five watersheds drained by first-order streams and containing timber that was 80+ years old were selected to study the impacts of clearcutting and planting site preparation on water quality in the presence and absence of streamside management zones (SMZs). One watershed was maintained as a reference with no treatment while the remaining 4 were clear cut harvested. Two of the harvested watersheds were clearcut to the stream banks and two maintained 10 m SMZs on each side of the stream. Site preparation included mechanical (shearing, root-raking and windrowing) or chemical, each in the presence and absence of SMZs. Chemical site preparation was accomplished by the aerial application of a mixture of imazapyr plus glyphosate (1.12 plus 3.36 kg ai/ha). Water temperature, sediment yield, periphyton biomass, macroinvertebrate population dynamics, and herbicide off-site movement into streams were measured and differences identified as a function of the treatments versus the reference channel using Randomized Intervention Analysis (RIA). RIA identified differences in water quality among the various treatments at all stages (i.e. harvest and site preparation) of the study. In general, mechanical site preparation resulted in greater impacts on the physical, chemical and biological aspects of water quality than chemical site preparation.

Keywords: Water quality, mechanical site preparation, chemical site preparation, SMZ, buffer, streamside management zone, imazapyr, glyphosate.

INTRODUCTION

Intensive silviculture, as practiced in the southern United States, usually includes clearcut harvesting, preparation of the site for planting a new crop (site preparation), and planting. All of these operations impact water quality in streams that drain affected sites. Impacts may be classified as direct and indirect impacts. The direct impacts include sedimentation, chemical pollution (including pesticides, applied fertilizers), increases in stream temperature, and increases in solar radiation. Indirect impacts, responses to direct impacts, are perturbations to community composition and functioning in the aquatic ecosystem.

The most serious of the direct impacts arise from soil disturbances that occur during all phases of plantation establishment but are particularly important during harvest and site preparation. Rates of erosion are accelerated and if unabated may result in considerable increases in sediment in streams. This sediment significantly alters stream habitats. Removal of vegetation near streams not only exacerbates the problem of sediment delivery, but also results in increased stream temperature and increased solar radiation at the water's surface. These may result in significant

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changes in periphyton populations (Goodman et al. 2006, Kiffney et al. 2004, Minshall et al. 2001), macroinvertebrate assemblages (Rios and Bailey 2006, Wooster and Debano 2006, Kaller and Hartman 2004, Martin and Neely 2001, Bradt et al. 1999, Casper 1994, Hachmoller et al. 1991), meiofauna (Radwell and Brown 2006), trophic level functioning (Lecerf et al. 2006), and fisheries (Nakamura and Yamada 2005).

Globally natural sediment yields vary from year to year and may range from a trace to 2000 kg ha^{-1} yr^{-1} (Michael et al. 2000). Prior to the development of forestry best management practices (BMPs) sediment yields were reported to range from 22 to 14259 kg ha^{-1} yr^{-1} in the eastern United States (Yoho 1980, Patrick et al. 1984, Yorke and Ward 1986) depending on management intensity and the tools used.

Forestry BMPs recommend the use of streamside management zones (SMZs) to protect aquatic ecosystems and water quality (Michael 2004). SMZ width may vary according to stream size and intended use. SMZs reduce sediment delivery to streams and when used with herbicide instead of mechanical methods for site preparation result in sediment loading that may not be significantly different from untreated control sites (Beasley et al. 1986, Michael et al. 2000). SMZs have also been found effective in reducing herbicide movement to streams (Michael et al. 2000).

There are few reports that consider the indirect impacts of intensive forest management on aquatic ecosystems. This study was designed to quantify physical, chemical and biological changes in coastal plain first-order streams from intensively managed forest watersheds. Water temperature, sediment yield, periphyton biomass, benthic macroinvertebrate population dynamics, and off-site movement of herbicide into streams were measured and differences identified as a function of the treatments.

MATERIALS AND METHODS

Study site

This study was conducted between 1993 and 1995 at the Alabama Agricultural Experiment Station, Lower Coastal Plain Substation, located in Wilcox County about 2.5 km north of the city of Camden, Alabama. Five small, topographically well-defined watersheds (WS1…WS5) were identified, each drained by a perennial first-order stream. Smithdale and Bama soils, sandy loams derived from marine and fluvial sediments eroded from the Appalachian and Piedmont plateaus, are characteristic of these lower Coastal Plain areas. Prior to harvest, all watersheds contained mature loblolly pine stands (>80 years old) with a typical mixed hardwood understory (Marshall 1999). One watershed was maintained as an undisturbed reference, the remaining four were clear-cut harvested. Of the four clear-cut watersheds, two were clear-cut to the banks of the 1st order streams draining them while the remaining two were left with 11 m (35-ft) SMZs protecting the streams. All streams were about 1 m wide with small reaches approaching 2 to 3 m in width. Base flow water depth ranged from less than 5 cm where the streambed was wide, to about 30 cm in areas where the channel was narrow. Each stream was typical of small-undisturbed coastal plain streams with a dense canopy and trees growing close to the banks of each stream. Stream beds were mainly sandy under shallow pools and composed of sand, gravel and some cobble in riffles. Channels were deeply incised with steep mud banks along most of the stream. Experimental treatments were randomly assigned to each watershed (Table 1).

Table 1. Characteristics and treatments applied to the watersheds in this study near Camden, AL.

Watershed	Total Area (ha)	Clearcut (ha)	SMZ	Site Preparation
WS1	16.6	No Treatment	No Treatment	No Treatment
WS2	20.2	14.4	No	Chemical
WS3	18.6	14.4	Yes	Chemical
WS4	50.2	14.8	No	Mechanical
WS5	26.2	13.4	Yes	Mechanical

Watersheds were instrumented with standard recording rain gauges located near the center of each treated area. Stream discharge was gauged continuously at the output end of 0.5 m rectangular weirs attached to long rectangular approaches. The gauging weirs were placed in the stream near the downstream edge of the clearcut in each watershed. Flumes were equipped with air and water temperature probes, Keller PSI pressure transducers, Campbell CR10 data loggers and ISCO 3700 automatic water samplers. Stream velocity, total discharge, water temperature, herbicide concentrations and total suspended solids data were obtained from samples collected by these automatic samplers.

Treatments

Clearcut harvesting was conducted during February and March 1995 from WS2, WS3, WS4 and WS5 using a circular saw-head feller-buncher, rubber-tired skidders and a deck loader. Between 17-21 August 1995, WS4 and WS5 were mechanically site prepared by shearing, root raking, and windrowing. On 30 August 1995, WS2 and WS3 were chemically treated with a mixture of Arsenal AC®, a.i. imazapyr [2-[4,5-dihydro-4-methyl-4-(1-methylethyl)-5-oxo-1H-imidazol-2-yl]-3-pyridinecarboxylic acid] and Accord®, a.i. glyphosate [N-(phosphonomethyl)glycine], in the form of its isopropylamine salt. Labeled rates of Arsenal AC®, Accord® and a surfactant were mixed to provide an equivalent of 1.12-kg/ha of imazapyr, 3.36-kg/ha of glyphosate and 0.28-kg/ha of nonionic surfactant. The herbicide mixture was applied by helicopter using a microfoil spray system to help ensure accurate application and minimum drift. On 21 November 1995, a prescribed burn was conducted on the four harvested watersheds using an incendiary mix dropped from a helicopter with an aerial drip torch, and on the ground using hand held drip torches. Each clearcut was planted with loblolly pine in January 1996.

Sample collection

Samples of water and sediment were collected from all watersheds, transported to the laboratory, and frozen until analyzed. Samples collected from the untreated control watershed were used mainly in analytical methods development, freezer storage stability studies, and for quality control. Water was intensively sampled by prearranged timed sequence and stream flow according to precipitation events. During storm runoff, samples were collected every 15 minutes. Base flow samples were collected hourly.

Periphyton, and macroinvertebrate sampling was conducted at fixed sampling locations in each stream. A single sampling station was located in the reference stream upstream of the flume. Two stations were established in each of the other four streams; one inside the clearcut area above the flume, and one downstream from the flume. Each station included a stream reach of about 100 m. Streams were sampled twice per season from August 1993 to December 1995.

Water temperature was measured at 5 minute intervals at the sampling weirs throughout the study. Periphyton and macroinvertebrates were sampled using PVC core samplers as described by Cross et al. (2006) at least one week after heavy rains to allow those communities to recover from any scouring effects that might have resulted from the increased discharge.

Analytical methods

Water samples were analyzed for imazapyr by solid phase extraction/high performance liquid chromatography and enzyme linked immunosorbent assay (ELISA) using the method described by Fischer and Michael (1997) with a method detection level of 0.8 micrograms L^{-1}. Glyphosate was not analyzed in these samples although samples may have contained glyphosate, especially on the day of application (Newton et al. 1994).

Sediment was analyzed gravimetrically by filtration followed by oven drying at 103-105 C and weighing. Sediment was totaled for each day and expressed as total mass lost per hectare per day for each watershed.

Periphyton

The chlorophyll content of periphyton was determined and algae biomass estimated following the trichromatic method (APHA 1995). Pigment extraction and sample handling was conducted in subdued light to avoid degradation of chlorophyll. Optical density (OD) of each sample was measured at 630, 647 and 750 nanometers using a Beckman DU-50 Series Spectrophotometer and related to biomass through a correlation coefficient.

Macroinvertebrate communities

Macroinvertebrate samples were preserved in formalin, rinsed and then stored in 70% ethyl alcohol until identified, sorted and counted using a stereomicroscope and standard taxonomic keys (Merritt and Cummins 1996; Wiggins 1996; Edmunds et al. 1977; Bednarik and McCafferty 1979; Stewart and Stark 1988; and Wiederholm 1983). Macroinvertebrates were assigned to functional feeding groups (FFGs) based on classification by Merritt and Cummins (1996). The following categories were included: filtering collectors (FC), gathering collectors (GC), scrapers (SC), shredders (SH), predators (P) and piercers (PI). Macroinvertebrates from both pool and riffle habitats were combined for analysis of total densities. Densities for each core sample were expanded to number of organisms m^{-2}. Taxa richness was calculated for each sample as well as the EPT index, based on the number of taxa within the orders Ephemeroptera, Plecoptera and Trichoptera (Plafkin et al., 1989). Analysis of taxa richness, community structure and diversity was conducted with selected dates that included four dates before harvest, two dates between harvest and site preparation and two dates after site preparation. The diversity of macroinvertebrate communities was calculated using the Shannon-Weaver index (H') (May 1975).

Statistical analysis

Calculations for each replicate were averaged and used to evaluate macroinvertebrate differences among the sites, before and after harvest, and before and after site preparation. Values for the replicates from each station were averaged and analyzed statistically. The nature and scale of this study qualified it as a whole-ecosystem experiment. Replicating whole ecosystems is seldom possible. A statistical method designed to address such experiments is Randomized Intervention Analysis (RIA). This method detects changes in a "manipulated ecosystem" relative to an undisturbed reference ecosystem (Carpenter et al. 1989). RIA indicates whether a change has occurred or not, however it does not demonstrate that the disturbance was the cause of the change. Parallel observations from the reference and manipulated streams were paired in time spanning periods before and after disturbance. A computer program designed for RIA (Carpenter et al. 1989) analyzed all measurement means. When data did not fit the RIA program, a Tukey's test was used to statistically compare differences among means at the 0.05 probability level for all tests of significance. Chlorophyll-a and macroinvertebrate data values were logarithmically transformed to stabilize variance. The biological and physicochemical data collected between August 1993 and February 1995 provided the pre-disturbance database that was compared against the same variables measured during post-harvest (March to August 1995) and post-site preparation (September to December 1995).

RESULTS AND DISCUSSION

Water temperature

Comparison of stream water temperature post-harvest and post-site preparation for treated watersheds with that observed in the reference watershed is given in Table 2. Comparisons made using the RIA technique showed that temperature rose significantly post-harvest for both of the watersheds without SMZs. Following site preparation water temperature was significantly higher on the chemically site prepared watershed without an SMZ while the mechanically site prepared watershed without an SMZ had water temperatures that were not significantly different than the reference. On this watershed, in the months following harvest and site preparation riparian vegetation recolonized the stream banks rapidly reaching a height of approximately 2 m.

Table 2. RIA analysis of stream temperature for the periods post-harvest and post-site preparation for four clearcut harvested watersheds. Comparisons were made with the undisturbed reference watershed (WS1) and differences between the treated watersheds and the reference were significant (S) or not significant (NS) at the 0.05 probability level.

Watershed And Treatment	Post-Harvest	Post-Site Preparation
WS2 Chemical No SMZ	S	S
WS3 Chemical With SMZ	NS	NS
WS4 Mechanical No SMZ	S	NS
WS5 Mechanical With SMZ	NS	NS

Davies-Colley and Rutherford (2005) have considered the characteristics of SMZ vegetation that protect water quality. They found that as the ratio of SMZ vegetation height to stream width approaches 10, shading maximizes near 100% but as the ratio approaches 0.1 shading decreases to nearly 0 (i.e. amount of light received by stream increases). At a ratio of 2 (eg for 2 m tall vegetation and a 1 m wide stream like that of WS4) shading would be approximately 70-80 percent of maximum and would greatly affect the amount and quality of light reaching the stream surface. It was probably the shading provided by this vegetation that protected water temperature. Thus, even a small amount of low vegetation on small 1st order streams like those in this study can provide for protection of water temperature from insolation.

The effectiveness of various sizes of buffers on mediating air and stream temperatures have been reported (Boothroyd et al. 2004, Meleason and Quinn 2004, and Quinn et al. 2004, Wilkerson et al 2006). Boothroyd et al. (2004) found no statistically significant differences in stream temperature when comparing clearcut sites with those with buffers of either pine or native vegetation but stream temperature sampling was not systematic. Meleason and Quinn (2004) considered the effect of 5 and 30 m SMZs on air temperature and found air temperature in a 5 m SMZ was not significantly different than that of 30 m SMZs. In Maine (USA), Wilkerson et al. (2006) found a small but insignificant summer stream temperature difference for streams protected by 11 m SMZs compared to untreated controls. In most cases normal or insignificantly different stream temperatures are re-established within 100 m downstream of clearcuts. Clearly, SMZs protect streams from significant variations in temperature from their pre-disturbance conditions but the width of the SMZ required may not be as great as previously thought. For 1st order streams, it appears that as few as 5 m of SMZ width (Meleason and Quinn 2004) in which the vegetation is 10 m in height can provide nearly 100 percent of predisturbance stream shading (Davies-Colley and Rutherford 2005). In this study, vegetation just 2 m in height apparently gave considerable shading protection to the 1st order stream in WS4.

<u>Sediment</u>

Eroded soil becomes sediment when it is delivered into stream channels. Erosion was studied on this site by Marshall (1999). He found post-site preparation erosion was not significantly different between two different slope classes (10-15 degrees and 20-25 degree) on chemically treated clearcut watersheds, but on mechanically treated watersheds the 20-25 degree slopes were more than three times as eroded as on 10-15 degree slopes. Erosion was also much higher on clearcut watersheds than on the reference, but the erosion which occurred on mechanically treated clearcuts was ~493 times that on the reference and only 9 times greater on chemically treated watersheds than on the reference (P=0.0001 using Duncan's Multiple Range Mean Separation test). Following a prescribed burn to remove slash from the clear cuts, erosion increased to 49 (chemically treated) and 1154 (mechanically treated) times that observed on the reference.

Some eroded soil ends up in streams as sediment. Sediment concentrations were monitored in stream samples collected by automatic samplers on this site during each storm over a two year period (Michael et al. 2000). Prior to any disturbance, average storm flow sediment concentrations from the watersheds to be mechanically treated were 2.25 times greater than observed on the herbicide treated watersheds. Following clearcut harvesting, differences in sediment yields were reduced to only 1.7 greater. Site preparation was conducted in late August 1995 and the first post-site preparation storm came 1 month later in September 1995. Sediment concentrations in flow from the mechanically treated watersheds increased to 4.98 times that from the herbicide treated. Not only were individual sample sediment concentrations higher on the mechanically treated watersheds, they did not decrease as rapidly as those from the herbicide treated watersheds during storms.

Periphyton biomass

Algal production in small streams is highly variable and a function of quantity and quality of canopy cover, temperature, aspect, and nutrient availability. Disturbances proximal to streams frequently alter these characteristics and this is especially true when forests are clearcut harvested. Chlorophyll-*a* increases were observed in all the experimental streams in this study and were undoubtedly a consequence of the clearcut disturbance (Table 3). The smallest increases were observed in WS3 where an SMZ was observed. Periphyton populations were already high in this watershed due to the near constant and favorable temperature regime produced by the springs feeding this stream. Significant increases in periphyton were observed in WS3 (chemical, no SMZ) and in WS5 (mechanical, SMZ). Clearly the direct introduction of imazapyr and glyphosate during site preparation did not have a negative impact on periphyton growth. The small increases in WS4 (mechanical, no SMZ) may be due to the rapid colonization of stream banks by riparian vegetation and the shading that afforded. Disturbance of seed banks usually stimulates this response which was not observed in WS5 (mechanical, SMZ) where there was no similar riparian disturbance. This interpretation is supported by the findings of Kiffney et al. (2004). They report that incident light is more important than temperature and a 30 m SMZ did not provide better protection than 10 m. Davies-Colley and Rutherford (2005) reported that as vegetation height/stream width ratio approaches 10, shading maximizes near 100% but as ratio approaches 0.1 shading decreases to nearly 0. It is not unusual for disturbed seed banks in riparian soils to respond quickly producing vegetation up to 5 m in height significantly shading stream surfaces from insolation.

Table 3. Mean chlorophyll-a (mg m^{-2}) before site preparation (11/93, 12/93, 10/94, 12/94, n=12) and after site preparation (10/95, 12/95, n=6) and percentage increase from stage to stage for the reference stream and the sites within each clearcut watershed.

Treatment	Pre-Disturbance (mg m^{-2})	Post-Disturbance (mg m^{-2})	Percent Increase
Undisturbed Reference	1.3	1.3	0
Chemical, No SMZ	0.8	9.3*	1063
Chemical, SMZ	6.5	16.7	157
Mechanical, No SMZ	1.2	6.6	450
Mechanical, SMZ	0.2	3.6*	1700

* significantly different by RIA at the p=0.05 level.

Benthic macroinvertebrates

Like periphyton, population densities of benthic macroinvertebrates in streams are highly variable. However, an ANOVA test for samples taken during the predisturbance period revealed no significant ($p < 0.05$) differences between macroinvertebrate densities at stations within and below the areas to be treated in these experimental watersheds.

Following harvest, densities inside the clearcut area from WS4 and WS5 were significantly higher ($p<0.05$) than those found in the reference stream WS1, whereas densities in WS2 and WS3 were not statistically different from WS1 based on RIA (Table 4).

Table 4. Benthic macroinvertebrate density based on RIA did not differ from the untreated reference stream populations following site preparation indicating significant but temporal effects during harvest were a result of the harvesting method used ($p<0.05$).

Treatment	Post-Harvest	Post-Site Preparation
Chemical, No SMZ	NS	NS
Chemical, SMZ	NS	NS
Mechanical, No SMZ	S	NS
Mechanical, SMZ	S	NS

There were no significant differences in richness, diversity, and structure of benthic macroinvertebrate populations between the treated watersheds and the undisturbed reference watershed during the entire study.

Off-site movement of herbicide

Movement of imazapyr off site was measured in storm- and base-flow from the herbicide treated watersheds and is presented in Table 5. The maximum concentration in streams was observed during the period of application (WS2, 264 µg L^{-1}; WS3, 0.551 µg L^{-1}). The stream draining

Table 5. Effect of an 11 m SMZ on offsite movement of imazapyr from treated watersheds expressed as total grams for each week and as percent of the amount applied to each watershed.

Weeks Post-Application	WS2 No SMZ	WS2 Percent Of Applied	WS3 With SMZ	WS3 Percent Of Applied
1	7.57	0.047	0.05	0.0003
2	2.15	0.013	0.00	0.0000
3	1.57	0.010	0.00	0.0000
4	1.90	0.012	0.00	0.0000
5	34.12	0.212	1.87	0.0120
6	343.08	2.127	308.75	1.9140
Total Moved Off Site	390.39	2.421	310.67	1.9260

WS2 received more imazapyr from direct application than that of WS3 where the SMZ afforded nearly complete protection. It is not known how much glyphosate was in streamflow during and immediately following the application. It is likely that the maximum instantaneous concentration which occurred as a result of direct spraying was approximately 792 µg L^{-1} (application rate was three times the rate for imazapyr). Subsequent offsite movement of glyphosate was not measured. Movement of imazapyr was greatest from the stream not protected by an SMZ and occurred as a function of precipitation events. After 5 weeks, 18 times as much imazapyr had moved off the site without an SMZ as had moved off the SMZ protected site indicating that SMZs afford considerable protection both during and in the weeks after application. The occurrence of Hurricane Opal on 3-4 October 1995, however, was overwhelming and the unprotected stream released only a slightly greater amount of imazapyr than the stream protected by an SMZ. The maximum imazapyr stormflow concentrations were similar for No SMZ (58 µg L^{-1}) and the SMZ stream (56 µg L^{-1}) during this hurricane. The total amount moving off the treated watersheds was small in comparison to the amount applied (WS2, 2.4%; WS3, 1.9%).

Clearly the impacts of the herbicide offsite movement on macroinvertebrates and periphyton were insignificant (Tables 3-4). Concentrations observed in this study were more than 1000 times lower than the amounts reported in SERA (2004) to affect fish and periphyton. Fowlkes et al. (2003) found that application of up to 100 times the label recommendations in cypress domes had no impact on macroinvertebrate communities.

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