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Influence of harvesting on biogeochemical exchange in sheetflow and soil processes in a eutrophic floodplain forest

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Abstract

Floodplain forests contribute to the maintenance of water quality as a result of various biogeochemical transformations which occur within them. In particular, they can serve as sinks for nutrient run-off from adjacent uplands or as nutrient transformers as water moves downstream. However, little is known about the potential that land management activities may have for alteration of these biogeochemical functions. This paper examines the effects of three harvesting regimes (unharvested control, clearcut, and partial cut) on the physical and chemical parameters within the Flint River floodplain located in southwestern Georgia, USA. Data presented in this paper were collected during the year following initiation of the harvesting treatments which occurred in September of 1993. Sheetflow water chemistry (total suspended solids (TSS), total dissolved solids (TDS), nitrate (NO_3^-), phosphate (PO_4^{3-}), sulfate (SO_4^{2-}), calcium (Ca^{2+}), potassium (K^+), magnesium (Mg^{2+}), ammonium (NH_4^+), total phosphorous (P), total nitrogen (N), total carbon (C), dissolved organic carbon (DOC)), sedimentation rates, depth of soil oxidation after flooding, saturated hydraulic conductivity, and bulk density were measured. During the year immediately after treatment installation, alterations in some of the physical and chemical properties (TDS, NO_3^-, total P, and K^+) of floodwaters crossing harvest plots were detected. Soil oxidation depths, saturated hydraulic conductivity and bulk density also changed with treatment. The meaning of the changes detected is uncertain but they suggest the nature of potential changes in nutrient spiralling and non-point source cumulative effects that may occur within a managed watershed. Second-year data may offer an interesting comparison of sheetflow chemistry and sedimentation changes between vegetated and non-vegetated conditions.

Keywords: Wetland forests; Silviculture; Water chemistry

1. Introduction

Floodplain forests represent critically important ecotones between aquatic and terrestrial ecosystems and, consequently, they are highly valued by society (Mitsch and Gosselink, 1993). Maintenance of water quality is dependent on the interaction of the hydrologic pattern and the biogeochemical transformations which occur within these systems (Hammer, 1989; Hammer and Bastian, 1989). The biogeochemical transformation functions which can occur include retention of (phosphate) PO_4^{3-}, conversion of (nitrate) NO_3^- to gaseous forms, transformation of inorganic to organic forms of nutrients, and export of (dis-

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solved organic carbon) DOC. The functions associated with these ecotones are well-known and potentially include high vegetation productivity and maintenance of water quality. The floodplains of some rivers in the southeastern United States have been likened to kidneys in terms of their ability to cleanse waters with which they come in contact (Meyer, 1990).

The high net primary productivity sometimes associated with floodplains (Sharitz and Mitsch, 1993) has long attracted the interest of timber managers and that interest appears to be increasing in the southern United States (McWilliams, 1992). While uncertainties exist regarding the potential for changes to occur in some floodplain forest functions following harvesting (Conner, 1994; Walbridge and Lockaby, 1994), a number of studies have examined the potential for a harvested floodplain site to act as a source of inorganic chemicals and sediment (Lockaby et al., 1994; Shepard, 1994). Those studies have generally concluded that there is little likelihood of a harvested floodplain site acting as a source of inorganic nutrients to the extent that environmental quality is jeopardized. Some studies have shown little potential for such a site to act as a non-point source of sediment (Lockaby et al., 1994) while others have reported the potential for considerable sediment export in association with ditching and road building in wet hardwood stands (Askew and Williams, 1984). These differences among studies are related primarily to the type of harvest and to the design of any associated road system.

The biogeochemical transformations which occur within a floodplain forest are considered to be important functions provided by these ecosystems. For example, Brinson (1993) has shown that unaltered floodplains may act as both a sink and a transformation zone for inorganic (nitrogen) N delivered via sheetflow and lateral flow from uplands. Although the interest in maintaining floodplain functions in managed systems is high, we know of no studies which have examined the potential for land management to alter the nature of the biogeochemical transformation functions for which these systems are so noted (Elder, 1985; Scott et al., 1990). For example, an understanding of how management can and does affect these functions is lacking despite our increasing awareness of the cumulative influence of land management activities within watersheds on downstream water quality (Johnston, 1994). Consequently, the objectives of this study were to focus on biogeochemical transformation functions by examining (1) the manner in which the chemical and physical composition of sheetflow might be altered by contact with a harvested versus a non-harvested floodplain, (2) the potential for a newly harvested floodplain to act as a sink versus as a source of sediment, and (3) associated soil impacts.

2. Methods

2.1. Study area

The site chosen for the study was a portion of the Flint River floodplain near Ft. Valley, Georgia, owned by Georgia–Pacific Corporation. As is the case with many river floodplains in the southeastern United States, much of the western portion of that floodplain was utilized for agriculture from approximately the mid-19th to the mid-20th centuries and, consequently, that usage has influenced the present condition of floodplain hydrology, soils, microrelief, and vegetation. A system of dikes (presently discontinuous owing to erosion) runs parallel to the river and resulted in the formation of better drained soils and level microrelief compared to non-diked areas. As a result, sheetflow is only minimally channelized over these areas. Soils are dominated by Inceptisols and overstory vegetation consists of an uneven-aged stand of *Quercus* spp., *Liquidambar styraciflua* L., and *Acer rubrum* L. that originated around 1950. A typical hydrograph for previously diked areas is shown in Fig. 1.

In areas that were never diked, such as the eastern portion of this tract, soils are more poorly drained and inundation periodicities and durations are higher. Overstory vegetation is dominated by *Nyssa* spp. and *Fraxinus* spp.

The Flint River is a high gradient, redwater system originating in the Georgia Piedmont and, consequently, deposition of fertile alluvium is high compared to that of blackwater river floodplains in the Southeast. Extractable phosphorus (P) levels in Flint floodplain soils average $20\,mg\,kg^{-1}$, a value much above the deficiency level for all floodplain hard-

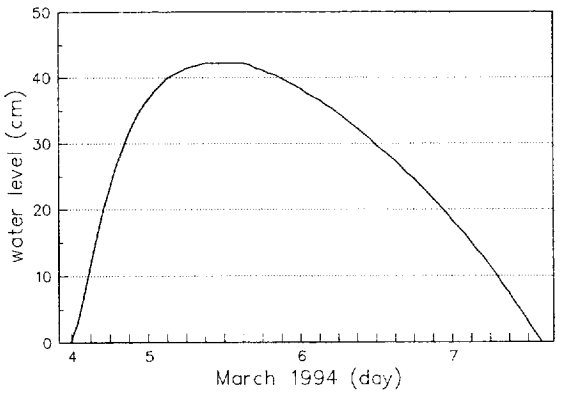

Fig. 1. Hydrograph for single flooding event in previously diked areas on Flint River floodplain near Ft. Valley, Ga.

woods with the exception of *Populus deltoides* Bartr. ex Marsh. (H. Kennedy, US Forest Service, Stoneville, MS, personal communication).

2.2. Study installation

Three harvesting treatments were installed in a randomized complete block design with two blocks occurring in the better drained areas (west plain) and one in the more poorly drained portions (east) (Fig. 2). Harvest treatments included (1) unharvested controls, (2) total clearcut, and (3) partial cut, i.e. 90% basal area removal. Felling was accomplished using shears and logs were removed with articulated-frame, rubber-tired skidders. Plots were square and approximately 8 ha in size. Plot placement was determined by the need to insure that sheetflow entering plots had not been in contact with other plots or harvest roads. Treatments were installed in September, 1993 during a period of dry soil conditions.

2.3. Field sampling

In order to assess changes in sheetflow chemistry and physical properties during contact of waters with treatment plots, pairs of automated water samplers were situated 30 m upstream from and 30 m inside the downstream margin of treatment plots. The distance over which floodwaters were in contact with plot surfaces (i.e. the distance between paired samplers) was approximately 300 m. These samplers were designed to initiate activity upon contact of rising floodwaters with an activation switch secured on the soil surface. Samplers then withdrew a 50 ml sample every hour until the 2.5 L bottle was filled or until the sampler was deactivated by falling floodwaters. Sample bottles were collected after each of the four major flood events that occurred during the winter and spring following treatment installation.

Steel welding rods were placed in treatment plot centers in order to assess changes in depths of soil oxidation following treatment installation (Bridgham et al., 1991). Twelve rods were installed to a depth of about 78 cm in late 1993 and were withdrawn and measured in summer 1994 after the flooding season had ended.

Saturated hydraulic conductivity was measured on clearcut plots only using the excavation method (Amoozegar and Warrick, 1986) in association with

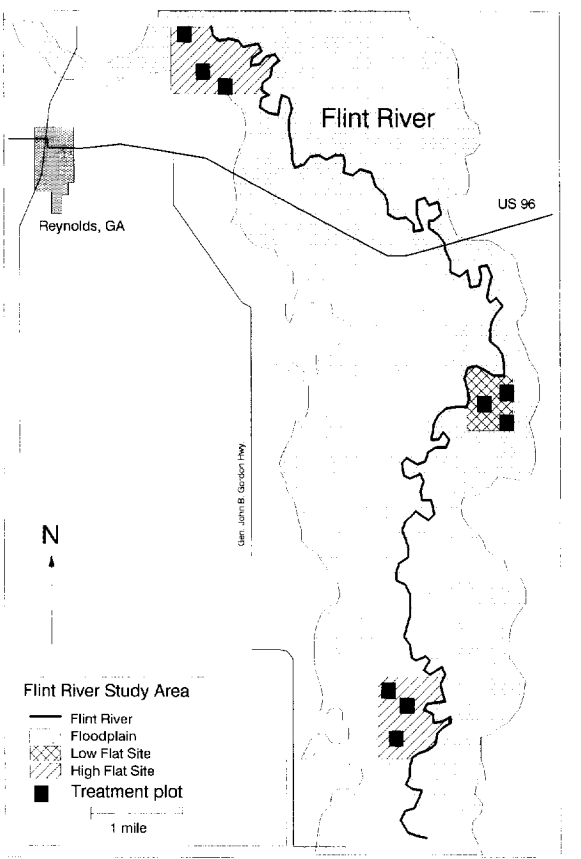

Fig. 2. Location map of the study site including three blocks and treatment plots within blocks.

the following soil disturbance classes: undisturbed; disturbed with litter remaining; and within ruts. Bulk density was measured using collection and drying of soil cores (collected to a 5 cm depth) on partial harvest and clearcut plots in conjunction with the same soil disturbance classes. Bulk density cores were collected immediately following harvests and saturated hydraulic conductivity was measured during late spring, 1994.

Twenty feldspar clay marker horizons were established within each treatment plot located within the three blocks. Feldspar clay horizons have been used successfully to determine sediment deposition in marshes (Baumann et al., 1984; Cahoon and Turner, 1989) and in wetland forests (Conner et al., 1986). The plots were 0.5 m^2 in size and were established during November and December 1993. Two soil cores from each marker horizon were collected in June 1994 using a 2.54 cm diameter soil probe. Soils on the clearcut plot of the eastern block were very wet, and consequently, it was difficult to extract soil cores. As a result, only two samples were collected from that experimental unit. In September 1994, following a 500-year flood which occurred in July, 1994, a second set of soil cores was collected from each marker horizon. At that time, a 5 cm diameter, bevelled PVC pipe and a sliding hammer were used to collect a soil core from each marker horizon. The cores were sealed with hot wax to prevent disturbance of the upper layer of soil, frozen, and cut in half (vertically) with a band saw in order to expose the demarcation line of the feldspar clay. Again, the clearcut plot of the eastern block was too wet to allow collection of intact soil cores. Sediment deposition was measured to the nearest millimeter as the amount overlying the marker horizon.

2.4. Laboratory analysis

Water samples collected with automated sippers were analyzed using the following methods: NO_3, PO_4 and sulphate (SO_4) using ion chromatography (Dionex HPIC AS4A separator column); calcium (Ca), potassium (K) and magnesium (Mg) using interconductive argon plasma (ICAP); ammonium (NH_4) using steam distillation; total N and total C using a Leco CNS analyzer; DOC using a Rosemount–Dohrmann DC-80 analyzer on filtered samples; and total suspended solids (TSS) using gravimetric determination.

3. Results and discussion

Owing to flow modifications associated with the installation of a harvest road study near clearcut plots, water samples from those plots have been excluded from the sheetflow comparisons. Two-way ANOVAs were used to compare sheetflow concentrations on a pre-treatment versus post-treatment contact basis for control and partial harvest treatments. Contact of floodwaters with unharvested control plots resulted in decreases in Ca and Mg and increases in NO_3 but no statistically significant ($P < 0.10$)

Table 1
TSS, TDS, NH_4, NO_3, PO_4, SO_4, Ca, K, Mg, total N, total C, DOC, total P ($mg\,l^{-1}$) and pH compared in floodwaters prior to and after contact with unharvested and partial plots on Flint River floodplain

Location	TSS	TDS	NH_4	NO_3	PO_4 [a]	SO_4	Ca	K	Mg	total P	total N	total C	DOC	pH
Unharvested														
Pre	30.0	31.4	0.16	0.08	0.85	2.11	3.76	1.72	1.11	0.06	500.0	1100.0	41.3	5.90
Post	24.0	26.3	0.00	0.23	3.12	2.28	2.51	1.83	0.73	0.08	233.3	1000.0	47.2	5.86
$P > F$	0.63	0.11	0.51	0.06	0.24	0.84	0.10	0.35	0.07	0.15	0.13	0.68	0.77	0.67
Partial														
Pre	10.9	36.5	0.18	0.11	3.29	2.90	3.04	2.18	1.02	0.16	225.0	850.0	51.4	5.79
Post	19.8	29.2	0.00	0.39	3.12	2.34	1.99	1.43	0.45	0.07	425.0	1225.0	30.8	5.98
$P > F$	0.28	0.07	0.36	0.05	0.94	0.58	0.35	0.05	0.16	0.06	0.35	0.14	0.49	0.32

[a] PO_4 means are higher than those of total P because one flood event was associated with very high PO_4 levels but was not analyzed for total P.

changes in concentrations of other indices (Table 1). However, contact of floodwaters with partial harvest plots induced statistically significant ($P < 0.10$) decreases in total dissolved solids (TDS), K, and total P. As with the unharvested controls, the partial harvests displayed source behavior for NO_3^-. On the control plots, concentration differences that were close to statistical significance included suggestions of TDS and total N detention and source behavior for total P. Similarly, on the partially harvested areas, there were suggestions of Mg retention and source activity in the case of total C. While Table 1 represents concentration data only, we suggest that those data reflect the possibility that load changes occur as well. This is because the potential for changes in sheetflow volume to occur is low as floodwaters move across only 300 m of floodplain that was carefully selected to avoid influx from lower-order streams, sloughs, and run-off from adjacent uplands.

The ability of forested floodplains to transform inorganic forms of nutrients to organic forms (Elder, 1985) is one of the more important functions of these systems. That ability, in an undisturbed floodplain that is fully occupied by vegetation, is probably linked to vegetative and/or microbial assimilation.

In the Flint system, significant decreases occurred in Ca and Mg as waters passed over 300 m of unharvested floodplain and similar trends are suggested by TDS and total N behavior. This probably represents removal of mineral and organic particulates from the water column as sheetflow passes over the floodplain surface. Similar reductions in sediment load have been observed by Peterjohn and Correll (1984). Nitrate source behavior on those same areas is likely driven by normal stimulation of nitrification as temperatures rise in late winter and spring.

There is similar evidence of filtration (or settling of mineral particulates) from the sheetflow column passing over the partially harvested plots. Reductions in TDS, K, P, and possibly, Mg support that assertion. As in the case of the unharvested areas, nitrate source activity is again observed. It is interesting to note that the magnitude of the latter in terms of concentration is close to that measured in sheetflow from unharvested areas. Also interesting (and reasonable) is the suggestion ($P > 0.14$) of source activity for total C as floodwater crosses an area with much coarse, woody debris.

Although regeneration areas usually act as deposition sites during flooding (Scott et al., 1990; Aust and Lea, 1992), that effect is primarily associated with high stem densities in young, naturally regenerated stands. No regeneration had occurred on the harvested plots at the time these data were collected (during the winter and spring immediately following harvests) and, thus, it is reasonable that TSS deposition was not observed.

Comparisons among treatments for depth of soil oxidation indicate that clearcut plots exhibited reduced conditions at shallower depths (Table 2). There were no differences between partial cuts versus controls although partially harvested plots were numerically less oxidized than controls. These results are predictable since, under most forest conditions, the loss of evapotranspiration via canopy removal causes soil water table levels to rise.

Soil impacts were directly related to the intensity of soil disturbance (Table 3). Saturated hydraulic conductivity was reduced by almost 90% in ruts associated with logging equipment traffic. Moderately disturbed areas exhibited reductions of 50–70%. These results approximate those reported following skidder operations in a similar river system by Aust and Lea (1992). Bulk densities were significantly increased in the most severe disturbance class (Table 3) although bulk densities were not elevated to the extent that is generally associated with tree growth reductions (Lockaby and Vidrine, 1984). The intermediate disturbance class actually has a lower bulk density than the undisturbed class. This is probably due to the fact that samples only 5 cm deep were collected making it possible that disturbance unrelated to harvesting equipment (movement of logs,

Table 2
Depth of soil oxidation as measured by iron rod technique compared among harvest treatments on Flint River floodplain

Treatment	Depth (cm)
Control	52 a
Partial	49 a
Clearcut	38 b

Column means followed by the same letter are not statistically different at the $P < 0.05$ level.

Table 3
Saturated hydraulic conductivity (1 m) and bulk density (0–7.6 cm) compared among soil disturbance classes on Flint River floodplain

Treatment	Saturated hydraulic conductivity (cm h^{-1})	Bulk density (Mg m^{-3})	Percentage of area
Undisturbed	14.9 a	0.95 a	20
Disturbed with litter	7.5 b	0.88 b	32
Rut	1.7 c	1.04 c	5

Column means followed by the same letter are not statistically different at the $P < 0.05$ level.

tree tops, etc.) may have disrupted the upper layer of soil.

Sedimentation rates varied significantly with block and with treatments in June. At that time, the average sedimentation rate was greater in the poorly drained eastern block (5 mm) as compared to the better drained western blocks (2.8 and 1.7 mm). The greater sediment deposition which occurred within the more poorly drained block is due to the longer inundation periods which occurred in that area. Rates of sediment deposition were also significantly higher on the unharvested plots than on either the partial or clearcut harvest treatments (Table 4). The presence of undisturbed litter layers in the present study probably accounts for the higher rates of cumulative sedimentation on the unharvested areas during the period between October 1993 and June 1994. In general, most of the resistance to surface water flow within wetlands is due to the presence of emergent vegetation (Kadlec, 1990).

Following the 500-year flood which occurred in July 1994 sedimentation rates varied significantly by block but not with treatment. Again, owing to extremely wet soil conditions, no soil cores were collected from the clearcut treatment in the wetter, eastern block. Sedimentation rates which occurred within the more poorly drained eastern block were again significantly ($P < 0.05$) greater (8 mm) than those which occurred in the two better-drained western blocks (3 mm in both blocks). This was again probably due to a longer period of inundation at the wetter eastern block. No significant ($P < 0.05$) differences in sedimentation rates occurred with treatment (Table 4). It is very possible that the occurrence of very deep floodwaters (river flood stage equal to 3.35 m; river stage reached at least 8.02 m during this flood) negated the influence of vegetation on sediment filtration and allowed greater sediment deposition across all three treatments within each of the blocks. Kadlec (1990) states that depth of floodwater also affects water velocity and this may be important for interpretation of the data collected in September 1994.

Table 4
Sedimentation rates (mm per flooding season) on Flint River floodplain

Treatment	Rate	
	June 1994	September 1994
Control	4.6 a	4.4 a
Partial	2.3 b	4.6 a
Clearcut	1.6 b	2.4 a

Column means followed by the same letter are not statistically different at the $P < 0.05$ level.

Few data on the effects of harvesting on sediment deposition in floodplains are available. An exception is the study by Aust (1989) within the Mobile Delta in Alabama. In that study, steel rods placed in a grid pattern in the soil were used to estimate deposition. Sedimentation rates did not vary significantly among treatments the first year after harvest. However, following natural regeneration, the harvested plots exhibited greater rates in the second year. These results were related to increased roughness on harvest plots during the second year.

4. Conclusions

In the first year following treatment installation, the harvest treatments imposed have had measurable influence on some functions and characteristics of the Flint River floodplain. Harvest influences include (1) alterations in some of the physical and chemical properties (specifically TDS, NO_3, total P and K) of

floodwaters crossing harvest plots, (2) decreases in the depth of soil oxidation, (3) decreases in saturated hydraulic conductivity and increases in bulk density, and (4) decreases in sedimentation. Changes in the depth of soil oxidation, bulk density, and saturated hydraulic conductivity were quite predictable while alterations in sheetflow chemistry and sedimentation were less expected.

The meaning of these changes is uncertain since, in some cases, effects are somewhat subtle. In the cases of sheetflow chemistry and sedimentation, changes probably have little direct importance in terms of immediate water quality impacts. Rather, their chief value lies in suggesting the nature of potential changes in nutrient spiralling and non-point source cumulative effects that may occur within a managed watershed: topics which are increasingly important as we strive to improve our understanding of the role of wetlands within landscapes. Partial harvesting resulted in increased concentrations of several components of sheetflow and decreased sedimentation rates at one sample date indicating the possibility that land management may have the potential to affect downstream water quality.

The importance of soil bulk density, saturated hydraulic conductivity, and oxidation data stems from their linkage to factors which control vegetation productivity. As discussed, the bulk density data presented here are probably not biologically significant in terms of potential effects on vegetation growth. The decreased soil oxidation depths are probably highly transitory and should dissipate as evapotranspiration increases during vegetation re-establishment. The biological implications of the increases in saturated hydraulic conductivity are uncertain since we know of no reports relating alterations in saturated hydraulic conductivity to tree growth responses.

It is important to keep in mind that these data were collected during the first year following harvests and prior to the re-establishment of the natural regeneration. In that sense, they may prove to be transitory. Additional data of the same nature will be collected during the second year (i.e. after the growing space has become re-occupied). Those data should provide an interesting comparison of sheetflow chemistry and sedimentation changes between vegetated versus non-vegetated conditions.

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