Sediment and Nutrient Export in Runoff from Burned and Harvested Pine Watersheds in the South Carolina Piedmont[1]

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ABSTRACT

Soil and nutrient export in ephemeral flow were studied over a 3-yr period following clearcutting three loblolly pine (*Pinus taeda* L.) watersheds (0.60–1.24 ha). Two preharvest, low-intensity prescribed fires had no effect on flow or water quality. Harvesting after the third prescribed fire significantly increased sediment concentration and export, but increases were minor compared with sediment export reported for mechanical site preparation. Nutrient concentrations varied among watershed locations because of differences in surface soil depth, but were generally unaffected by harvest. Because harvest increased runoff, nutrient export (concentration × flow) was generally increased. Results of this study show that loblolly pine stands in the erosive Piedmont physiographic region can be harvested following a series of low-intensity prescribed fires with minimal soil loss or degradation of water quality.

Additional Index Words: **erosion, prescribed fire, clearcutting, natural regeneration, water quality.**

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Federal law mandates that nonpoint-source pollution be controlled. Silvicultural activities produce varying amounts of sediment, the major water pollutant being suspended sediment associated with forest activities (Yoho, 1980; Ursic and Douglass, 1979; Van Lear and Douglass, 1983). Douglass and Van Lear (1983) showed that low-intensity prescribed fire yielded < 0.02 Mg ha^{-1} yr^{-1} sediment from ephemeral Piedmont streams, roughly equivalent to yield from undisturbed loblolly pine (*Pinus taeda* L.) watersheds. At the opposite extreme, intensive mechanical site preparation (shearing, windrowing, and disking) on steep slopes produced sediment rates as high as 9 Mg ha^{-1} yr^{-1} (Douglass and Goodwin, 1980). Less intensive mechanical site preparation produces less sedimentation. Hewlett (1979) measured sedimentation rates of 3.6 Mg ha^{-1} yr^{-1} in the Georgia Piedmont for 60 d following harvesting, chopping, and machine planting.

The high amounts of soil loss associated with mechanical site preparation in steep terrain may adversely affect productivity. Beasley (1972) stated that the maximum soil-loss tolerance for soils in the United States ranges from about 2 to 11 Mg ha^{-1} yr^{-1}. Eroded soils with unfavorable subsoils, such as many Piedmont soils, would have a tolerance of about 2 Mg ha^{-1} yr^{-1}. Because of legislative constraints, soil-loss tolerance may be established in the future as much on reducing sediment pollution as on maintaining soil productivity.

Clearcutting with seed-in-place, using prescribed fire to prepare seedbeds and control understory hardwoods prior to harvest, is a natural regeneration technique that has been successful with loblolly pine in the Coastal Plain (Lotti, 1961; Langdon, 1981) and the Piedmont (Van Lear et al., 1983). This paper presents results of these prescribed fires and the subsequent clearcutting of loblolly pine on ephemeral runoff, sediment, and nutrient export. Effects of the prescription on regeneration of loblolly pine and stormflow are covered elsewhere.

METHODS

Watershed Description

Six watersheds (0.48–2.18 ha) on the Clemson Experimental Forest in the Upper Piedmont of South Carolina were studied. Watersheds were arranged in pairs consisting of a treatment and control at three locations. Soils are Typic Hapludults formed on an eroded residium derived from granitic and gneissic materials. Much of the original loamy surface horizon was lost during decades of row-cropping, and the predominantly clay B horizon is now near the surface, especially at locations 2 (watersheds 65 and 66) and 3 (watersheds 67 and 68). The soil at location 1 (watersheds 63 and 64), probably because of past land use, was less eroded and in better hydrologic condition. Soils on the watersheds belonged to the Cecil, Pacolet, and Madison series (Typic Hapludults). Gullies formed during the period of high erosion serve as channels for today's emphemeral flow during and immediately following storm events. Channel length was < 15 m for both watersheds at location 1, whereas it ranged from 100 to 200 m for watersheds at locations 2 and 3. Slopes ranged from 10 to 16% from flume to ridgetop. Watersheds were planted to loblolly pine in 1939 and thinned twice, the last time about 10 yr prior to initiation of this study.

Watershed Instrumentation

A 0.3-m H-flume was installed on each watershed. Runoff was calculated using the procedures described by Hibbert and Cunningham (1966) and was sampled with a 0.61-m diam Coshocton wheel set below each H-flume. Approximately 0.5% of the flow over the flume was diverted by the sampling slot in the wheel into plastic sample barrels where it was stored for weekly collection. During the winter when flow was relatively heavy, a 10:1 splitter was placed in the drainline to further reduce sample volume to about 0.05% of the total flow. Rainfall was measured at each location by a weighing intensity gauge and a standard nonrecording rain gauge.

Sample Collection and Analysis

When the runoff sample was collected for analysis, water in the storage barrel(s) was stirred to uniformly mix the suspended solids, and a 1000-mL sample was withdrawn. About 400 mL of this sample were used to determine sediment by filtration through a 0.42-μm pore fiberglass filter. Prior to filtration, 1 mL of concentrated HCl was added, and the sample was allowed to stand overnight to flocculate the fine clay colloids. Sediment weight was determined gravimetrically after drying at 105°C and was expressed as milligrams per liter.

Chemical analyses were performed by the Agricultural Chemical Services Department of Clemson University. A 250-mL aliquot of the original 1000-mL runoff sample was centrifuged at 12 340 × *g* at 9.1 cm (11 000 rpm) for 15 min to remove colloidal material. Calcium (Ca^{2+}), magnesium (Mg^{+}), potassium (K^{+}), and sodium (Na^{+}) in the supernatant were determined by atomic absorption spectrophotometry. Ammonium (NH_4^+-N) was determined spectrophotometrically by the Berthlot reaction, nitrate (NO_3^--N) by reduction of nitrate to

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nitrite and reaction with sulfanilic acid, and orthophosphate (PO_4^{3-}-P) by the molybdate blue method. Nutrient concentrations were weighted by the volume of weekly flow.

Watershed Treatment

One watershed in each of the locations was randomly selected for treatment. Low-intensity prescribed fires were applied to each treatment watershed in March 1977, September 1978, and September 1979. These burns were to control the hardwood understory consisting of small (< 50-mm ground diam) stems of black cherry (*Prunus serotina* Ehrk.), blackgum (*Nyssa sylvatica* March.), eastern red cedar (*Juniperus virginiana* L.), dogwood (*Cornus florida* L.), oak (*Quercus* spp.), and hickory (*Carya* spp.) and to prepare a seedbed for natural regeneration. Following seedfall, the overstory on watersheds 64, 66, and 68 was felled in late December 1979–early January 1980 and skidded by crawler tractor in a dendritic pattern to loading decks. Logging decks were located outside of watershed boundaries. A gravel haul road existed near the top of watersheds at locations 1 and 2 when the study was initiated. At location 3, a new haul road was established, but it was located off the watersheds. Logging slash was left in place, except on watershed 64 where essentially all above-stump biomass was carefully removed to simulate whole-tree harvesting as a part of another study. Bare soil exposure and area covered by logging slash were estimated from transects spaced at 20-m intervals across harvested watersheds.

Data Analysis

Watersheds were instrumented in 1975; after a period of stabilization, watershed calibration began in 1976. The total period of record (June 1976–September 1982) was divided into separate periods for split-plot analysis of variance tests. Earlier analyses had indicated that the first two low-intensity prescribed fires had no effect on runoff volume or water quality. However, mortality associated with an outbreak of the Southern pine beetle (*Dendroctonus frontalis* Zimm.) on watershed 68 after the first burn caused runoff and erosion from that watershed to increase significantly, as determined by the paired watershed method of analysis (Douglass and Van Lear, 1983). This apparent inconsistency in results from the randomized complete block and the paired watershed regression analysis is due to the inclusion of a source of variation in the error term of the former, which is excluded in the regression analysis on a single pair of watersheds. Therefore, the period from June 1976 until September 1979 was designated as the calibration period, but was broken into two subperiods, one prior to the beetle outbreak and one after in order to increase the sensitivity of the analysis. The third period consisted of the first year after the third burn-harvest. The last two periods are the second and third years after harvest. The tests conducted were for significant differences in mean monthly runoff, ion concentration, and ion export between treatments, periods of record, and locations. Differences between treatments within locations were determined using a *t* test. The level of significance used in all tests was 0.05.

In addition to these analyses of variance tests, the paired watershed method (Wilm, 1943) was applied to each watershed pair to determine precisely the effect of treatment on monthly water yield from individual treated watersheds. In this analysis, the calibration period was prior to the third prescribed burn-clearcut treatment on watersheds 64 at location 1 and 66 at location 2 (prior analysis indicated no effect on monthly runoff from the first two burns) and prior to the insect infestation, which caused a change in runoff on watershed 68 at location 3. The treatment period for all watersheds was the remaining period of record. The statistical testing technique was that described by Douglass et al. (1983).

RESULTS AND DISCUSSION

Runoff

Harvesting the stands in late December–early January of 1979–1980 increased monthly runoff over control watersheds (Table 1). The magnitudes of the increases were greatest at locations 2 and 3 (i.e., where the harvested watersheds had well-defined channels [high drainage density] and shallow surface soil [< 100 mm]). The monthly runoff response to harvest was small on watershed 64, which had a lower drainage density and deeper, permeable surface soils more conducive to deep seepage than to direct runoff.

Monthly runoff varied significantly between treatments, locations, and periods. Ephemeral runoff before treatment was least at location 1, an area with the deepest residual soil and least ephemeral channel development. Prescribed burning did not affect runoff during the preharvest period at locations 1 or 2. However, tree mortality during subperiod 2 (Nov. 1978–Dec. 1979) from a bark beetle attack on watershed 68 caused a significant increase in runoff on this watershed.

The impact of the bark beetle attack was greater than would have been expected from mortality of trees on only 20% of the watershed area (Fig. 1). However, mortality occurred just above the flume where ephemeral channels were deeply incised. Surface and subsurface flow reached the channels quickly in this impacted area and the increased flow was significant.

A more precise measure of the treatment effect on runoff from individual watersheds can be obtained using the paired watershed approach, which regresses monthly flow of treatment and control watersheds. Deviations in monthly runoff of harvested watersheds from those predicted from paired control watersheds are shown in Fig. 1. The large positive deviations in response to the beetle kill on watershed 68 and all treated watersheds after harvest are unmistakable and reflect increased direct runoff (i.e., channel precipitation, overland flow, and subsurface stormflow) during storms. These increases result from evapotranspiration reduction, higher soil moisture, and lower available moisture storage. However, these increases reflect only the increase in stormflow, not the total increase in yield to streamflow and groundwater. Hewlett (1979) found that in the Georgia Piedmont, clearcutting loblolly pine stands followed by roller chopping and machine planting increased stormflow from small storms by 27% and doubled peak flows. Clearcutting had a much smaller

Table 1. Average monthly rainfall and runoff as affected by treatment and period.

	Calibration				After harvest					
	Subperiod 1		Subperiod 2		1st Year		2nd Year		3rd Year	
Treatment	Precip.	Runoff	Precip.	Runoff	Precip.	Runoff	Precip.	Runoff	Precip.	Runoff
	mm									
Control	115.8	8.2a*	143.9	10.3a	116.7	10.2a	80.1	2.7a	108.8	7.6a
Harvest	115.8	10.4a	143.9	15.0a†	116.7	18.1b	80.1	5.7a	108.8	14.4b

* Means within columns followed by the same letter are not significantly different at the 0.05 level.

† At location 3, a *t* test indicated a significant increase in runoff during this period caused by a bark beetle attack (see also Fig. 1).

Table 2. Sediment concentrations and export in runoff from harvested and control watersheds in the Piedmont of South Carolina.

Treatment	Calibration: Sub-period 1	Calibration: Sub-period 2	After harvest: 1st Year	After harvest: 2nd Year	After harvest: 3rd Year
	Mean weighted concentration				
	mg L⁻¹				
Harvest	35	39	72*†	29	25
Control	28	20	19	10	10
	Soil export				
	kg ha⁻¹ yr⁻¹				
Harvest	41.5	73.9	151.1*†	23.4	49.1
Control	26.8	24.3	19.6	3.0	8.6

* Significantly greater than control at the 0.05 level during this period.
† Significantly greater at the 0.05 level than all other harvest means except subperiod 2.

effect on hydrologic response to large storms. In our study, stormflow volume increased from about 70 to 200% following harvest for storms with flows > 109 L s^{-1} km^{-2} (Douglass et al., 1983). These small watersheds have less storage opportunity than larger watersheds, which probably acounts for the larger response.

The second year after harvest was an extremely dry year (i.e., precipitation was only 67% of normal) and ephemeral flow was small on both treatment and control watersheds. The increase in ephemeral flow on harvested watersheds during the drought was small and supports Hewlett and Douglass's (1968) observation that "it takes water to fetch water." That is, little of the evapotranspirational savings that accrue from harvest will be flushed through to the stream until the drought ends. Rainfall was near normal during the third year after harvest and the increase in monthly flow was significantly higher than during the drought from all harvested watersheds (Fig. 1).

Soil Export

Sediment concentrations in runoff from control watersheds were less than from harvested watersheds throughout the study, although the difference was small during the early part of the calibration period (Table 2). As the study progressed, sediment concentrations on the control watersheds steadily decreased. Apparently erosion and sedimentation from the plowed fire lines around both control and treated watersheds prior to the first burn, as well as channel disturbance during flume installation, accounted for relatively high initial sediment levels from all watersheds. Fire lines were plowed to delineate watershed boundaries and to keep fire within the burned watersheds. Before the second and third burns prior to harvest, fire lines were hand raked so soil disturbance was not great. As time progressed, these fire lines gradually stabilized, thereby accounting for the decreasing trend in sediment levels on control watersheds. On harvested watersheds, this trend was masked by effects of the bark beetle attack and harvest.

Sediment concentration in runoff differed significantly among locations. At location 3, channel exposure resulting from the bark beetle attack resulted in increased sediment levels at watershed 68 about 1.2 yr prior to

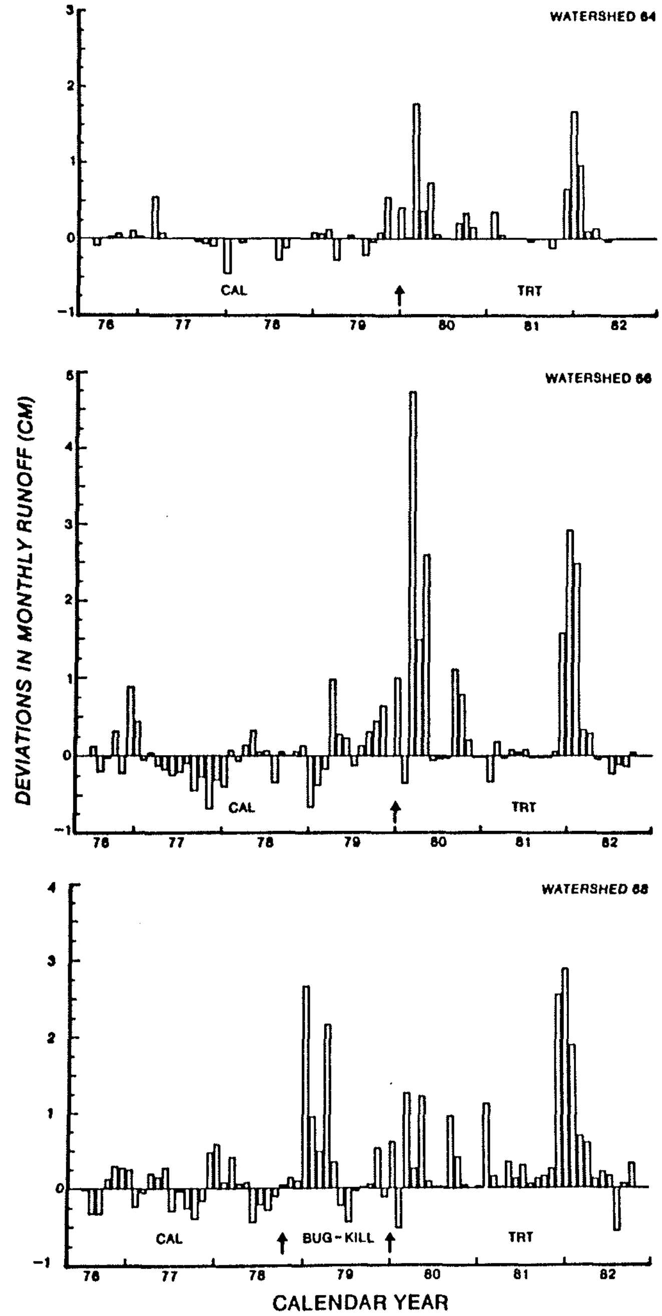

Fig. 1. **Effects of bark beetle attack and harvest on deviations in monthly runoff.**

harvest. Sediment concentrations in this watershed averaged 68 mg L^{-1} after beetle infestation compared with 21 mg L^{-1} for its paired control watershed. Watershed 68 had a long (174 m), deeply incised gully network that had developed prior to stand establishment. Sediment concentration increased as protective litter in and around the channel decomposed and washed away without replacement.

Sediment concentration averaged 72 mg L^{-1} during the first year after harvest of the three watersheds, about four times that of control watersheds (19 mg L^{-1}) during the same period (Table 2). Concentrations were highest (139 mg L^{-1}) during the first year after harvest

Table 3. Bare soil exposure and coverage of logging slash on three harvested loblolly pine watersheds in the Piedmont.

Watershed	Treatment	Bare soil	Logging slash cover
		%	
64	Simulated whole-tree harvest (above-stump)	47	6
66	Conventional stemwood harvest	23	37
68	Conventional stemwood harvest	21	27

on the beetle-infested watershed, a fact attributed to the exposed channel previously described, which was further aggravated by harvest.

During the second and third years after harvest, sediment concentrations progressively declined. During the second year, the drought year, concentrations were lower than during the first portion of the calibration period on two of the three harvested watersheds. However, sediment concentrations on control watersheds also dropped below calibration period levels as fire plow lines around the watersheds stabilized. After 3 yr, sediment concentrations from two of the harvested watersheds are approximately at preharvest levels. Sediment concentration in the third harvested watershed, which suffered the beetle infestation and had the longer channel degradation, was still significantly higher than its control. This watershed will require more time to recover to pretreatment levels.

The product of sediment concentration and flow is defined as soil export. During the latter part of the calibration period, soil export increased to an average of 74 kg ha^{-1} yr^{-1} on watersheds to be harvested (Table 2). This increase is again due to the bark beetle attack on watershed 68, which not only exposed the channel and resulted in higher turbidity, but also increased flow. This combined effect raised soil export to 147 kg ha^{-1} yr^{-1} on watershed 68 during period 2 or about four times that of the other watersheds to be harvested. Soil export from the other two watersheds to be harvested was similar to that of period 1.

During the first year after harvest, soil export increased to 151 kg ha^{-1} yr^{-1}, nearly eight times that of the control watersheds (Table 2). This increase is the result of increased flow and increased sediment concentrations following harvest. Erosion and sedimentation increased after harvest because of overland flow on skid trails and exposed mineral soil on the relatively steep slopes and perhaps increased channel erosion.

During the second year following harvest, soil export from harvested watersheds was below that of the early calibration period for treated watersheds. Significantly lower surface runoff, coupled with decreasing sediment concentration during the drought year, produced this decline. However, soil export rose to just above early calibration period levels during the third year after harvest, a year of nearly average rainfall.

The increase in soil export from harvested watersheds, while significant, should be kept in perspective. During the first postharvest year, sediment export averaged only about 0.15 Mg ha^{-1} yr^{-1}. This amount is almost insignificant compared with the nearly 9 Mg ha^{-1} yr^{-1} measured by Douglass and Goodwin (1980) from intensive mechanical site preparation (sheared, windrowed, and disked) in the North Carolina Piedmont and the 13 Mg ha^{-1} yr^{-1} from similar treatment in the Virginia Piedmont (Fox et al., 1983). Not only are actual levels of sedimentation low from the regeneration methods used in this study, but the duration of the elevated sediment levels appears to be short-term, perhaps < 5 yr until sediment concentrations from harvested watersheds reach those of control watersheds, except where management activities reactivate old gully systems. Low sediment levels following harvest are attributed to small amounts of mineral soil exposed to erosion (21–47%), plus the fact that logging slash covered 27 to 37% of the two steeper watersheds (Table 3).

Table 4. Mean weighted concentrations of ions in runoff from harvested and control watersheds in the Piedmont of South Carolina.

Period and treatment	NO_3^--N	NH_4^+-N	PO_4^{3-}-P	Ca^{2+}	Mg^{2+}	K^+	Na^+
				mg L^{-1}			
Calibration Subperiod 1							
Harvest	0.04	0.05	0.008	0.54	0.49	0.93	0.59
Control	0.05	0.05	0.005	0.56	0.50	1.00	0.53
Calibration Subperiod 2							
Harvest	0.05	0.05	0.019	0.88	0.53	1.03	1.00
Control	0.04	0.07	0.021	0.85	0.53	1.09	0.85
After harvest Year I							
Harvest	0.03	0.01	0.005	0.70	0.49	1.11	0.70
Control	0.02	0.01	0.003	0.69	0.50	0.94	0.79
After harvest Year II							
Harvest	0.05	0.05*	0.016	0.89	0.65	1.31	0.35
Control	0.22	0.13	0.022	1.14	0.74	1.50	0.62
After harvest Year III							
Harvest	0.01	0.01	0.013	0.80	0.44	1.13	0.43
Control	0.03	0.04	0.020	0.89	0.48	1.01	0.48

* Significantly different from control at the 0.05 level within this period.

Nutrient Export

Treatment had no significant effect on concentration of any ion studied, with the exception of NH_4^+-N (Table 4). During the second year after harvest, NH_4^+-N concentrations were significantly higher on control than on harvested watersheds. This difference is apparently caused by increased nitrification rates on harvested watersheds (Van Lear, 1983, unpublished data), which reduces NH_4^+-N levels. The relatively high concentrations of all nutrients in the second year after harvest are apparently related to a concentrating effect of reduced flow during the drought year. High nutrient concentrations were most evident on uncut watersheds where flow was most reduced.

Both NH_4^+-N and NO_3^--N mean concentrations varied widely from month to month. A multitude of soil and climatic factors affect mineralization and nitrification rates (Alexander, 1977), thereby affecting concentrations of these elements in stormflow. Studies are in progress to determine relationships among these factors and NH_4^+-N or NO_3^--N concentrations. No significant differences were detected in average NH_4^+-N or NO_3^--N concentrations among the three locations.

Concentrations of K^+, Ca^{2+}, Mg^+, and Na^+ were not significantly affected by harvest. Potassium (K^+) concentration in runoff averaged the highest over the duration of the study, while Mg^+ concentrations were generally lowest. Calcium (Ca^{2+}) and Na^+ concentrations were intermediate between the two. There were significant locational differences in cation concentrations for all cations, except K^+, probably reflecting mineralogical and soil depth differences among sites. Top soil depth varied among locations because of differences in past land use. Calcium (Ca^{2+}) concentrations in runoff from moderately eroded location 1 averaged about 80 to 100% greater than those from highly eroded locations 2 and 3, perhaps indicating the effect of the more fertile A horizon on nutrient concentration in runoff. Most of the runoff measured in our flumes is rapid subsurface flow above the fine-textured B horizon. Primarily because of locational differences, the treatment × location interaction was significant for Ca^{2+}, Mg^+, and K^+, but not for Na^+.

Although ion concentrations were not greatly affected by treatment, ion concentrations did differ by locations and time periods. Concentrations were generally higher in runoff at location 1, where the more fertile surface soil was deepest. Concentrations were also higher during the droughty second year after harvest. Regrowth of legumes and other herbaceous vegetation, as well as pine seedlings and surviving hardwood sprouts, was rapid following harvest and aided in maintaining tight nutrient cycling.

As a result of increased runoff, export of all ions, except NO_3^--N and NH_4^+-N, increased after the beetle kill and/or timber harvest (Table 5). The extreme variability in concentrations of these two ions masked any treatment effect with regard to export. Because runoff was significantly different among locations and periods, almost all interactions were significant.

CONCLUSIONS

Mature loblolly pine plantations can be harvested in the Southern Piedmont following a series of low-intensity prescribed fires with only minor impacts on water quality of ephemeral streams. Elevated sediment concentrations and export occur after harvest, but the magnitude and duration of these effects are relatively insignificant when compared with those of intensive mechanical site preparation that are often used prior to artificial regeneration. Relatively low levels of sedimentation following harvest are attributed to the fact that gravel haul roads were well away from stream channels, little mineral soil was exposed by the preharvest burns or the track-type skidder, and logging slash was left in place on the more erosive watersheds. Sediment levels in this study are similar to those reported by Ursic and Douglass (1978) for harvesting effects in pine stands in Mississippi, and much less than those found by Hewlett (1979) and Douglass and Goodwin (1980) for harvesting and mechanical site preparation in the Piedmont.

Table 5. Nutrient export from harvested and control watersheds in the Piedmont of South Carolina.

Period and treatment	NO_3^--N	NH_4^+-N	PO_4^{3-}-P	Ca^{2+}	Mg^+	K^+	Na^+
	kg ha⁻¹ yr⁻¹						
Calibration Subperiod 1							
Harvest	0.058	0.070	0.011	0.61	0.60	1.22	0.67
Control	0.055	0.055	0.005	0.48	0.46	0.94	0.52
Calibration Subperiod 2							
Harvest	0.091	0.099	0.038*	1.51	0.93	2.01	1.75*
Control	0.050	0.085	0.023	0.94	0.59	1.24	1.07
After harvest Year I							
Harvest	0.068	0.019	0.010	1.41*	0.99*	2.52*	1.43*
Control	0.028	0.012	0.004	0.72	0.53	1.02	0.87
After harvest Year II							
Harvest	0.025	0.033	0.013	0.54	0.43	1.01	0.22
Control	0.048	0.032	0.006	0.24	0.18	0.34	0.20
After harvest Year III							
Harvest	0.024	0.022	0.025	1.27	0.74	2.16	0.67
Control	0.028	0.033	0.017	0.72	0.40	0.86	0.43

* Significantly different from control at the 0.05 level within this period.

Nutrient concentrations in runoff are not significantly increased on these sites by low-intensity burns and clearcutting. Because of an increase in flow following harvest, nutrient export is increased, but hardly at a rate to cause concerns about site quality deterioration.

Upland Piedmont soils are fragile and highly susceptible to erosion damage, as over 100 yr of soil abuse amply demonstrate. Forest managers should strive to prevent loss of the thin, nutrient-rich surface horizon for both timber growth and water quality considerations. Stand establishment techniques used in this study demonstrate one regeneration alternative that protects both soil and water resources.

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Yields and Leaf Elemental Composition of Cotton Grown on Sludge-Amended Soil[1]

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ABSTRACT

A 3-yr field study was conducted to determine the effects of land application of anaerobically digested, air-dried sewage sludge on growth of upland cotton (*Gossypium hirsutum* L.). Cotton lint yields obtained with sludge rates from 20 to 80 Mg/ha were comparable with those obtained by area farmers employing conventional fertilizer practices. Rates of 80 Mg/ha had no significant effect on lint yields, although lint/seed ratios tended to decrease with increased sludge rate for all years. After 3 yr of sludge application, the leaf and seed concentrations of Cd, Zn, Ni, and Cu were not significantly different from those on the fertilized check plots. Leaf concentrations of Cd were higher than seed concentrations, but the reverse trend was true for Zn, indicating that Zn may not be directly useable as a model for Cd behavior in cotton.

Additional Index Words: **sewage sludge, heavy metals, zinc, cadmium, plant phytotoxins.**

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Major cities in the southwestern USA produce large quantities of anaerobically digested, air-dried sewage sludge, which can conveniently be utilized as a fertilizer amendment. Upland cotton (*Gossypium hirsutum* L.) is a major summer crop in the southwest, and hence sludge could be used as a source of nutrients and as a soil amendment to physically improve land planted to upland cotton.

Modest amounts of sewage sludge have been shown to improve the physical condition of mineral soils (Epstein, 1975) and supply significant amounts of N and P and various other nutrients and micronutrients. However, excessive amounts of sludge can supply too much nutrient for crop production, reducing yields as well as lowering crop quality (Epstein, 1973). The other major hazard of sludge utilization for crop production is that of excess toxic metals, in particular Cd, Zn, Ni, and Cu (CAST, 1976, 1980). The major economic product from cotton production is the cotton fiber, from which potential hazards to man are low in regard to toxic metals. However, cotton seed may subsequently be used for oil production for human consumption and the residue used for animal feed. Potential hazards to the food chain thus exist from use of cotton seed grown on sludge-amended soils, although seed metal concentrations would be expected to be significantly lower than leaf metal concentrations (CAST, 1980).

Nitrogen is the nutrient that has the greatest effect on cotton yields (Tucker and Tucker, 1968). A 1972 survey of selected southwestern cotton growers showed that on an average, 155 kg N/ha was applied.[3] However, applications of 280 kg N/ha have been shown to significantly decrease cotton yields relative to yields from plots receiving 140 kg N/ha[4]. In general then, a moderate N supply is needed for optimum yields of cotton.

Phosphorus is less often applied to cotton fields in the southwest since cotton yield response to P is limited; but when it is applied, the rate of application is usually about 33 kg P/ha.[3] Some studies have shown that 56 kg N/ha and 49 kg P/ha produced significantly greater yields than N alone.[5] Potassium is usually not limited in most of the cotton-growing areas of the arid and semiarid southwest, since soils naturally contain large amounts of available K (Kamprath and Welch, 1968).

Since N is needed for optimum cotton yields and organic matter concentrations in southwestern soils are low, sludge amendments to land planted with cotton should prove beneficial. The objective of this field study

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