FOREST SITE PREPARATION EFFECTS ON SOIL AND NUTRIENT LOSSES IN EAST TEXAS

J. P. Field, K. W. Farrish, B. P. Oswald, M. T. Romig, E. A. Carter

ABSTRACT. *Site preparation practices are frequently utilized in Southern pine ecosystems to facilitate planting and seedling establishment. Soil and nutrient losses were monitored in 12 bordered erosion plots following four site preparation treatments in a clearcut harvested loblolly pine (*Pinus taeda *L.) forest in east Texas. Three replications of four site preparation treatments were used: (1) chemical herbicide followed by prescribed fire and mechanical tillage, (2) chemical herbicide followed by prescribed fire, (3) chemical herbicide only, and (4) unprepared control. Annual soil loss from the mechanical tillage and prescribed fire treatments (1273 kg ha^{-1} and 885 kg ha^{-1}, respectively) was significantly greater than annual soil loss from the chemical herbicide and control treatments (240 kg ha^{-1} and 219 kg ha^{-1}, respectively). During the first post-treatment year, sediment concentration and overland flow increased significantly in the mechanical tillage and prescribed fire treatments with respect to control. Nutrient (N, P, K, Ca, Mg, and S) concentrations and losses in sediment and overland flow temporarily increased after the mechanical tillage and prescribed fire treatments, but not after the chemical herbicide and control treatments. Nutrient concentrations and losses for all site preparation treatments were relatively small and should have little or no effects on water quality and long-term site productivity*.

Keywords. *Erosion, Forestry, Herbicide, Nutrients, Prescribed fire, Tillage.*

Forest management practices in the Southeast U.S. often utilize site preparation treatments, such as chemical herbicide, prescribed fire, and mechanical disking or bedding, to facilitate planting and increase seedling growth and survival. In some cases, site preparation techniques disturb the protective forest floor and expose mineral soil, increasing the potential for soil and nutrient losses (Slay et al., 1987; Farrish et al., 1993). Soil and nutrient losses following forest site preparation may result in lowered site productivity and water quality degradation (Tuttle et al., 1985; Fox et al., 1986; Blackburn and Wood, 1990).

Chemical herbicides are frequently applied during site preparation operations to control competitive hardwood species and herbaceous vegetation. Research has suggested that chemical site preparation can provide better hardwood control than mechanical site preparation (Wittwer et al., 1986; Knowe et al., 1987; Griswold et al., 1989). In addition, the use of chemical herbicides alone seldom results in increased soil loss (Hansen et al., 2000) and may be viewed as a potential water quality benefit (Beasley et al., 1986). However, repeated herbicide treatments have been shown to promote nutrient leaching as a result of reduced uptake by vegetation (Slay et al., 1987).

Prescribed fire is commonly used following chemical herbicide treatments to reduce fuel loads, remove logging slash, and prepare harvested sites for pine regeneration. Fire intensity and severity has been shown to determine the extent to which soil physical properties are altered (Knoepp and Swank, 1993; Robichaud and Waldrop, 1994). Prescribed fires can also affect nutrient loss pathways such as volatilization, ash convection, overland flow, soil erosion, and leaching of fire-released nutrients (Schoch and Binkley, 1986). Studies on soil and nutrient losses following prescribed fire are limited and have produced conflicting results. Swift et al. (1993) found that light to moderate intensity fires have little or no adverse effects on soil loss from forestlands in the Southeast. However, other investigators have reported increased sediment production and soil loss under similar conditions following prescribed fire (Robichaud and Shahlaee, 1991; Robichaud and Waldrop, 1994). These reported differences are likely due to variations in soil erodibility, slope, timing of prescribed fire, amount of mineral soil exposed, and rainfall intensities.

Mechanical site preparation, including disking or bedding operations, is often utilized after chemical herbicide and prescribed fire to further facilitate planting and to promote better seedling growth and survival. Research has demonstrated that mechanical site preparation often removes or destroys the surface litter layer, exposing large amounts of mineral soil (Tuttle et al., 1985; Farrish et al., 1993). Disturbance of the surface soil by heavy machinery during mechanical site preparation generally increases the potential for soil and nutrient losses. In addition, mechanical site preparation may initially increase organic matter decomposition and consequently alter nutrient cycling (Trettin et al.,

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Article was submitted for review in March 2004; approved for publication by the Forest Engineering Division of ASAE in November 2004.

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Transactions of the ASAE

Vol. 48(2): 861−869

1996; McLaughlin et al., 2000). Mechanical site preparation has also been shown to degrade site productivity by removing the protective forest floor and nutrient-rich surface soil (Morris et al., 1983).

Intensive site preparation treatments have been shown to produce superior survival and early growth of southern pine seedlings (Pehl and Bailey, 1983). However, on sites where large amounts of soil and nutrients are displaced, studies indicate that site preparation treatments have little positive effect on pine seedling survival and growth (Glass, 1976; Pehl and Bailey, 1983). Although early survival and growth may be improved on intensively prepared sites, the potential increase for soil and nutrient losses should be minimized to maintain water quality and long-term site productivity.

Soil and nutrient losses following forest site preparation in the Southeast U.S. have been investigated previously (e.g., Beasley, 1979; Blackburn et al., 1986; Swift et al., 1993; Robichaud and Waldrop, 1994); however, the relative effects among many site preparation treatments on soil and nutrient losses are largely unknown because few studies have evaluated multiple treatments under similar soil and climatic conditions. Although several studies have investigated nutrient losses following site preparation in Southern pine ecosystems, most previous studies have focused on nutrient losses via overland flow. As a result, there is a lack of information on the relative magnitude of aqueous and sediment phase nutrient losses following forest site preparation in the Southeast. In addition, most other studies have investigated the effects of forest site preparation on soil and nutrient losses from forestlands with moderate to steep slopes, but little information is available for forestlands with slopes less than 10%. Many areas throughout the Southeast have slight slopes less than 10%; therefore, it is necessary to provide information that will aid land managers in meeting their silvicultural objectives while minimizing soil and nutrient losses from forestlands with slight slopes.

In this study, four commonly utilized site preparation treatments, including unprepared clearcut forest, chemical herbicide, prescribed fire, and mechanical tillage, were investigated in a harvested loblolly pine stand in east Texas under similar soil and climatic conditions to evaluated the relative effects of these treatments on soil and nutrient losses.

MATERIALS AND METHODS

STUDY SITE

The study site, composed of 12 bordered erosion plots, was located in south Cherokee County in east Texas, approximately 9 km west of Wells. The climate is characterized by long, warm summers and relatively short, mild winters. Annual precipitation of 107 cm is fairly well distributed throughout the year. Vegetation at the site prior to harvesting was loblolly pine (*Pinus taeda* L.). The area had been managed under an even-aged management system, with the last harvest in the summer of 2000. All bordered erosion plots were installed after clearcutting and prior to site preparation.

The predominant soil series at the study site was the Boswell series. These soils are classified as clayey, mixed, thermic Aquic Hapludults, with sandy loam A horizons up to 5 cm thick and clay texture Bt horizons. Soils at the study site are moderately well drained with medium runoff and slight to moderate erosion potential (NRCS, 1988). Slopes throughout the entire study area ranged from 4% to 9%. All of the erosion plots were installed on uniform slopes ranging from 5% to 6% with similar aspect to minimize any potential effects that may be attributed to differences in slope.

TREATMENT

Twelve bordered erosion plots, 1.8 m wide by 10 m in length, were installed during July 2000 in a randomized block design. The experimental design consisted of three replicated blocks with four treatments randomly assigned to each block. Within each block, slope and aspect were similar. Treatments consisted of control (unprepared clearcut forest), chemical herbicide, prescribed fire (chemical herbicide plus prescribed fire), and mechanical tillage (chemical herbicide plus prescribed fire plus simulated mechanical tillage). Control plots were established before site preparation to represent an unprepared recently clearcut forest. Herbicide plots were individually treated with Arsenal (imazapyr) and Finale (glufosinate) at an application rate of 3.8 L ha^{-1} and 2.8 L ha^{-1}, respectively. The prescribed fire treatment, designed to produce conditions of low intensity and light severity, consisted of the herbicide application followed by prescribed fire after vegetation browning. Fire temperatures at the soil surface approached 300°C, and maximum aboveground flame temperatures approached 1000°C. The mechanical tillage treatment was preformed using a rototiller to simulate disking or bedding operations. Mechanically treated plots were lightly tilled one pass along the contour to a depth of 8 cm to 12 cm.

SAMPLE COLLECTION AND ANALYSIS

Overland flow from each storm event was stored in 600-L collectors (covered livestock troughs) to calculate total overland flow volume and collect samples for sediment and nutrient analyses. Representative subsamples of overland flow were collected using 1-L high-density polyethylene (HDPE) bottles. Overland flow samples were usually collected within 24 h after each storm event to minimize evaporative water loss and nutrient transformations. Samples for anion ($NO_3^{\ -}$, $PO_4^{\ -3}$, and $SO_4^{\ -2}$) analysis were stored at 4°C until analyzed, normally within 24 h. Samples for cation ($NH_4^{\ +}$, K^+, Ca^{+2}, and Mg^{+2}) analysis were preserved with concentrated sulfuric acid to pH <2 and stored at 4°C for no more than 28 d. Nutrient concentrations in overland flow were analyzed using a Dionex ion chromatograph. Anions were analyzed in accordance with the Dionex method for analysis of 13 anions with isocratic elution (Dionex, 1996). Cations were analyzed using the Dionex method for isocratic elution of ammonium, alkali metals, and alkaline earth metals (Dionex, 1995).

Sediment in overland flow was filtered through a 0.45-μm glass-fiber filter to separate solution from the solution-suspension phase. Sediment collected from overland flow samples and the flumes was oven-dried at 60°C and recorded on a dry weight basis. Sediment was then finely ground and digested in accordance with EPA Method 1620 for total nutrient analysis (P, K, Ca, Mg, S, Na, Fe, Mn, Zn, Cu, and Al) using inductively coupled plasma atomic emission spectroscopy (ICP-AES). Sediment was also analyzed for total nitrogen (N) and carbon (C) using a Leco C/N analyzer.

A randomized block analysis of variance based on individual storm data was used to determine significant statistical differences ($P < 0.05$) in soil loss, sediment concentration, and nutrient concentrations and losses. Time was considered a subplot effect for measurements taken over time in the same plot. Analysis of variance was carried out using the general linear model procedure of SAS and the type III sums of squares (SAS, 1998). When treatment effects were significant, Duncan“s multiple range test was used to separate annual treatment means.

RESULTS AND DISCUSSION

PRECIPITATION AND OVERLAND FLOW

Total precipitation during the first post-treatment year was 160 cm, approximately 50% more than the normal annual precipitation of 107 cm. The post-treatment year consisted of 29 rainfall events, 23 of which were sufficient in duration and intensity to produce overland flow. Precipitation from the storm events that produced overland flow ranged from 26 mm to 310 mm. Overland flow from the herbicide, prescribed fire, and mechanical tillage treatments was approximately 28%, 103%, and 73% greater than the control, respectively. Three storm events that occurred during the third post-treatment month of November produced more than twice the amount of overland flow from the prescribed fire and mechanical tillage plots than from the control plots (data not shown). However, after the unusually wet period in November, differences in overland flow among treatments began to substantially diminish. This was likely due to the high antecedent soil moisture conditions in the study plots and the vigorous vegetation regrowth that occurred following the wet period. Treatment differences in cumulative overland flow remained fairly consistent after the fourth post-treatment month, except for one large storm event on 8 June (310 mm of precipitation) that produced large differences in overland flow among treatments (fig. 1). Annual overland flow following the prescribed fire and mechanical tillage treatments was significantly greater than the control treatment during the first post-treatment year (table 1). Overland flow was generally greater in the prescribed fire treatment than in the mechanical tillage treatment during the first several months following site preparation. This suggests that the mechanical tillage treatment may have temporarily increased soil infiltration rates, thus reducing the amount of overland flow from the mechanical tillage plots.

Although significant differences in overland flow were detected among the site preparation treatments, the differences among treatments might have been more apparent if not for the unusually wet post-treatment year. The high amount of precipitation during the first post-treatment year combined with the high antecedent soil moisture conditions may have reduced the potential treatment effects on overland flow. When antecedent soil moisture is high, the relative differences in stormflow among treatments may decrease. For example, Miller (1984) and Beasley et al. (1986) found no significant increases in stormflow following clearcutting treatments for unusually wet periods with high precipitation.

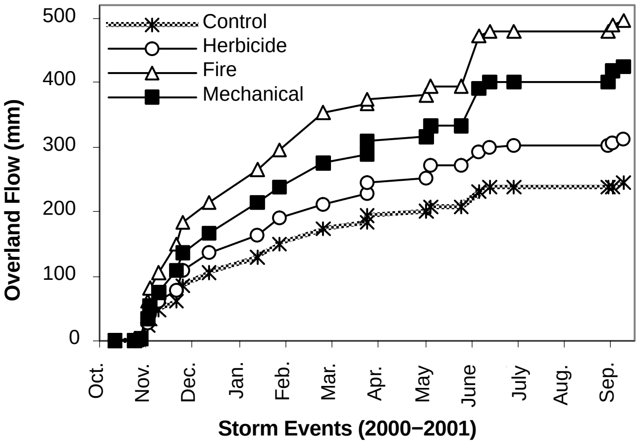

Figure 1. Cumulative annual overland flow for 23 storm events following site preparation treatment.

Table 1. Post-treatment annual overland flow, soil loss, and mean annual sediment concentration.[a]

Treatment	Overland Flow (mm)	Soil Loss (kg ha^{-1})	Sediment Concentration (mg L^{-1})
Mechanical	425 ab	1273 a	197 a
Fire	497 a	885 a	140 a
Herbicide	314 bc	240 b	64 b
Control	245 c	219 b	66 b

[a] Means within a column followed by the same letter are not significantly different ($P < 0.05$).

SOIL LOSS

Soil loss for this study is defined as the quantity of soil exported from the bordered erosion plots, not necessarily the quantity of soil transported off site. During the first post-treatment year, annual soil loss for the prescribed fire and mechanical tillage treatments was significantly greater ($P < 0.05$) than the herbicide and control treatments (table 1). Annual soil loss for the herbicide treatment was nearly identical to the control, while the prescribed fire and mechanical tillage treatments were 4.0 and 5.8 times the control, respectively (fig. 2). No significant differences in annual soil loss were detected between the prescribed fire and mechanical tillage treatments; however, annual soil loss for the mechanical tillage treatment was 44% greater than the prescribed fire treatment.

Variation in soil loss among treatments was largely related to post-treatment differences in sediment concentration rather than differences in overland flow. Annual soil loss was strongly correlated with sediment concentration ($R^2 = 0.9962$) but not with overland flow ($R^2 = 0.6572$) (fig. 3). This might have been due to the unusually wet period, which likely decreased the relative differences in overland flow among treatments.

The majority of annual soil loss during the first post-treatment year was produced by only four large storm events that occurred on 6 November, 29 November, 30 January, and 27 February. These four storm events produced over 350 mm of precipitation and accounted for 56%, 43%, 60%, and 62% of the total annual soil loss for the control, herbicide, prescribed fire, and mechanical tillage treatments, respectively. Other studies have also shown that a small number of storm events in any year frequently account for the majority of annual soil loss on clearcut and undisturbed forestlands (Miller, 1984; Blackburn et al., 1986). Although treatment differences in annual soil loss were primarily influenced by

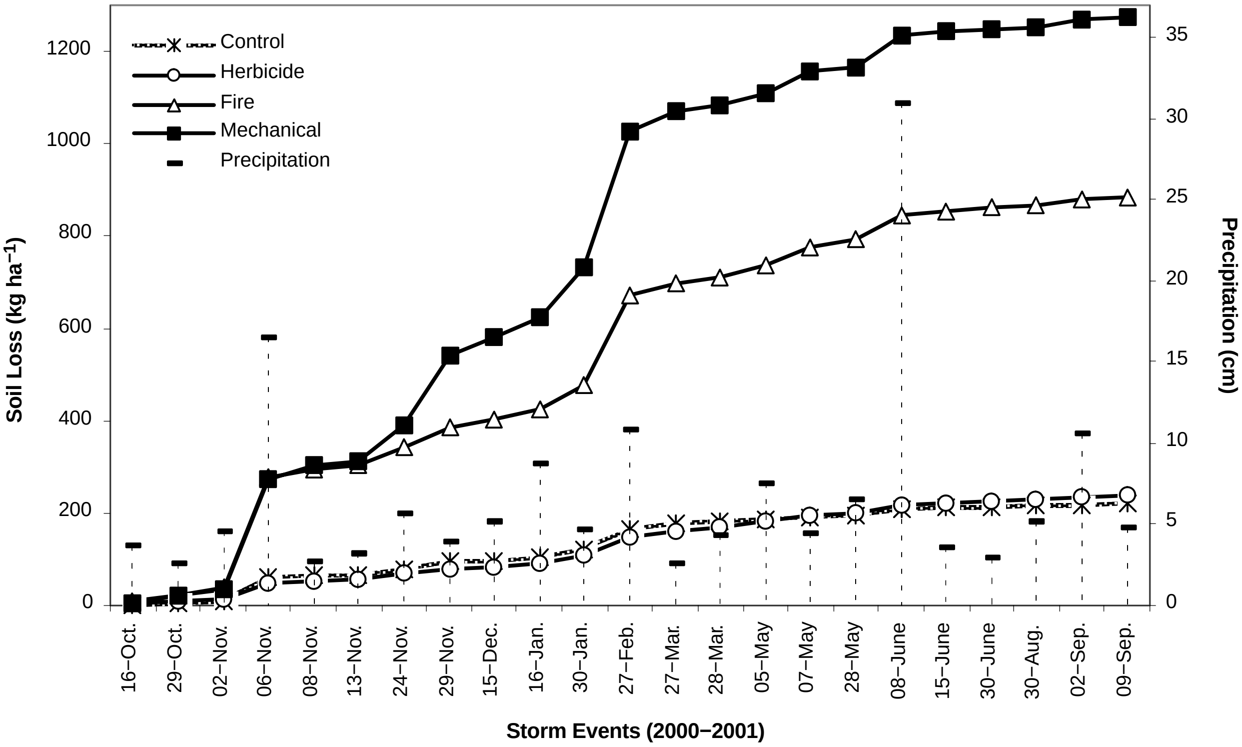

Figure 2. Precipitation and cumulative annual soil loss for 23 storm events following site preparation treatment.

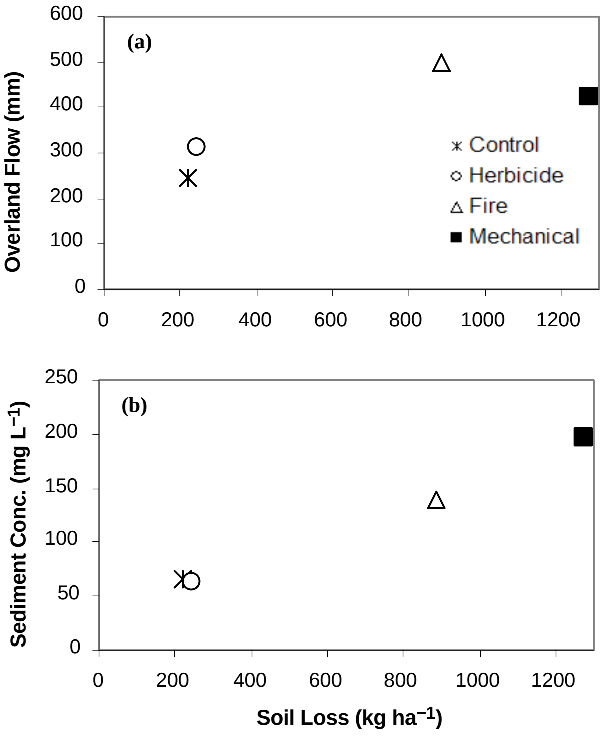

Figure 3. (a) Post-treatment annual overland flow and (b) mean annual sediment concentration as a function of annual soil loss.

a few large storm events, several small storm events produced the greatest variation in soil loss among treatments (data not shown). For example, during a small storm event on 15 December, soil loss for the prescribed fire and the mechanical tillage treatments was 8.0 and 19.4 times greater than the control, respectively. In general, differences in soil loss between the control and herbicide treatments were relatively small for most large storm events; however, three small storm events (i.e., 7 May, 28 May, and 9 September) produced more than twice the amount of soil loss from the herbicide plots than from the control plots.

Although annual soil loss was greatest for the mechanical tillage treatment (1273 kg ha^{-1}), the amount of soil loss was relatively small compared to other studies conducted on steep slopes. For example, Beasley (1979) measured soil loss exceeding 12,000 kg ha^{-1} during the first post-treatment year following mechanical site preparation on steep watersheds in the Gulf Coastal Plain. Blackburn et al. (1982) reported values more similar to this study with an annual soil loss of 2200 kg ha^{-1} for mechanically site-prepared forestlands in east Texas. Annual soil loss for the prescribed fire treatment was greater than similar plot studies in the Southeast (Robichaud and Waldrop, 1994; Field et al., 2003). These differences are likely due to variability in fire intensity and severity in addition to the unusually high amount of precipitation during this study. Although prescribed fire and mechanical tillage may increase soil loss, the effects are normally short-term and decrease rapidly due to regrowth of natural vegetation (Yoho, 1980; Farrish et al., 1993).

Annual soil loss was not significantly different between the control and herbicide treatments, despite the fact that vegetation cover in the herbicide plots was only about 20% to 30% of that in the control plots during the first few months after treatment. However, by nine months after treatment, only slight differences in vegetation cover were apparent between the control and herbicide plots. Annual soil loss following site preparation was only 10% greater in the herbicide treatment than the control treatment. The difference in soil loss between the control and herbicide treatments was likely due to reduced vegetation cover in the herbicide plots following treatment. In addition, the slight increase in soil loss resulting from the herbicide treatment may have been influenced by reduced evapotranspiration in the herbicide plots, leading to more overland flow.

SEDIMENT CONCENTRATION

Mean annual sediment concentration for the prescribed fire and mechanical tillage treatments was significantly greater ($P < 0.05$) than the control and herbicide treatments (table 1). Sediment concentration for individual storm events was not strongly correlated with overland flow. The maximum sediment concentration of 686 mg L^{-1} was detected in the mechanical tillage plots on 27 February and was approximately 8.1, 7.1, and 4.5 times the sediment concentration in the control, herbicide, and prescribed fire plots, respectively (fig. 4). Sediment concentration was usually greatest in the mechanical tillage treatment; however, two storm events shortly following site preparation (i.e., 2 November and 6 November) produced considerably more sediment in the prescribed fire plots than in the mechanical tillage plots.

The prescribed fire and mechanical tillage treatments in this study removed slash and forest litter, exposing large amounts of mineral soil. The exposed mineral soil offered little resistance to overland flow or the effects of raindrop impact, which resulted in accelerated sheet and rill erosion. Consequently, sediment concentration and losses were greatest for the prescribed fire and mechanical tillage treatments. Sediment concentration for the control and herbicide treatments was significantly less than the prescribed fire and mechanical tillage treatments, which was largely due to the protective forest floor that remained intact after harvesting and site preparation. Mean annual sediment concentration for the control (66 mg L^{-1}) and herbicide (64 mg L^{-1}) plots was comparable to the suggested annual average of 61 mg L^{-1} for undisturbed Southern pine watersheds (Ursic, 1979).

NUTRIENT LOSSES

Total nitrogen (N) loss reported in this study equals aqueous phase NO$_2$-N, NO$_3$-N, and NH$_4$-N losses in overland flow plus sediment phase total N loss. Sediment phase total N loss accounted for the majority of total N loss for all treatments. Although sediment phase total N concentrations did not vary much among treatments, annual sediment phase total N loss was significantly greater ($P < 0.05$) for the prescribed fire and mechanical tillage treatments than for the control and herbicide treatments (table 2). Schreiber et al. (1980) reported mean annual sediment phase total N concentrations ranging from 2410 mg L^{-1} to 6080 mg L^{-1} in the southern Coastal Plain, which were similar to the concentrations in this study (table 3). Sediment phase total N concentration did not strongly correlate with overland flow or sediment concentration. Mean sediment phase total N concentration was slightly less in the prescribed fire and mechanical tillage treatments than in the control treatment. The decrease in sediment phase total N concentration following the prescribed fire and mechanical tillage treatments is likely related to the amount of organic matter consumed by the fire.

Aqueous phase NO$_2$-N, NO$_3$-N, and NH$_4$-N concentrations in overland flow varied significantly among treatments during the first post-treatment year. Nitrate-N concentration in overland flow for the prescribed fire and mechanical tillage treatments was significantly greater than for the control treatment (table 3). In addition, mean annual aqueous phase NO$_2$-N and NH$_4$-N concentrations were significantly greater than control in the prescribed fire and mechanical tillage treatments, respectively. No other significant differ-

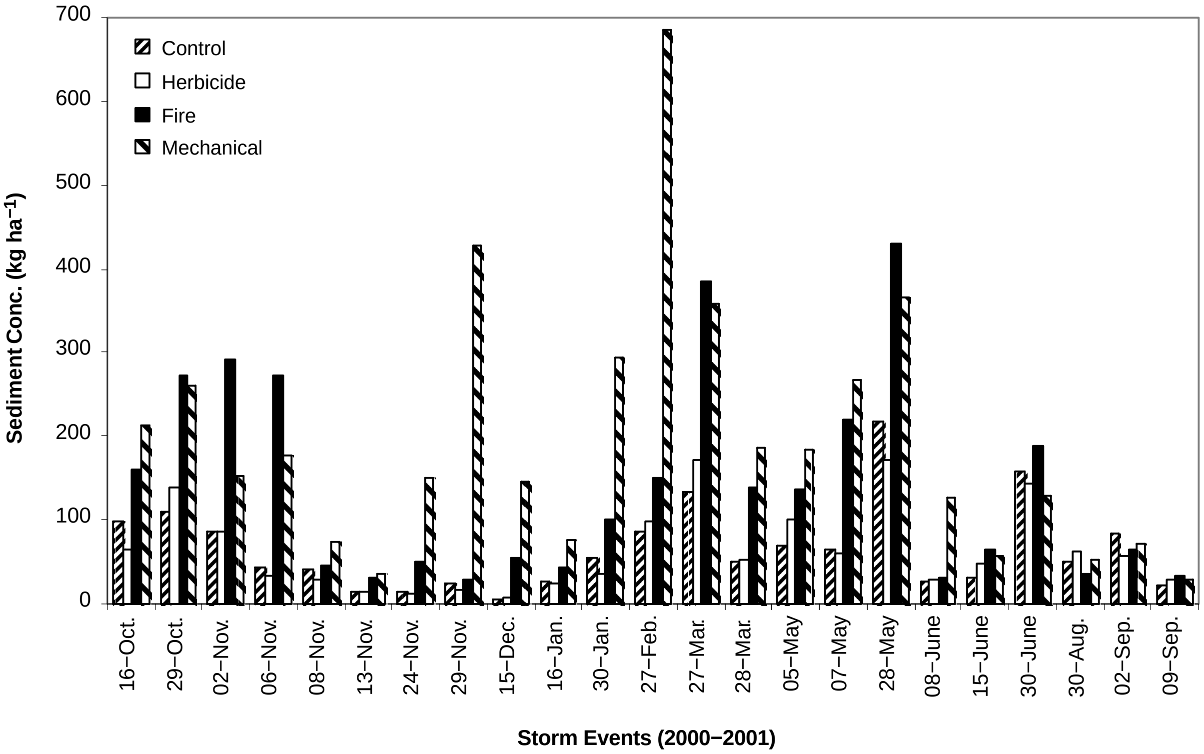

Figure 4. Sediment concentration for 23 storm events following site preparation treatment.

Table 2. Post-treatment mean annual aqueous and sediment phase N and P losses (all values in g ha^{-1}).[a]

	Aqueous Phase				Sediment Phase		Total Loss[b]	
Treatment	NO_2-N	NO_3-N	NH_4-N	PO_4-P	Total N	Total P	N	P
Mechanical	3.7 a	81 a	129 a	3.0 a	207 a	16.5 a	421 a	19.5 a
Fire	7.6 a	80 a	123 a	1.3 a	179 a	15.6 a	390 a	16.9 a
Herbicide	0.5 a	22 ab	35 ab	1.6 a	48 b	4.0 a	106 b	5.6 a
Control	1.8 a	7 b	18 b	1.8 a	45 b	3.2 a	72 b	5.0 a

[a] Means within a column followed by the same letter are not significantly different ($P < 0.05$).

[b] Total N loss equals aqueous phase NO_2-N, NO_3-N, and NH_4-N losses plus sediment phase total N loss. Total P loss equals aqueous PO_4-P plus sediment total P.

Table 3. Post-treatment mean annual aqueous and sediment phase N and P concentrations.[a]

	Aqueous Phase (μg L^{-1})				Sediment Phase (mg L^{-1})	
Treatment	NO_2-N	NO_3-N	NH_4-N	PO_4-P	Total N	Total P
Mechanical	100 ab	1838 a	1511 a	97 a	5192 a	551 a
Fire	218 a	1704 a	1055 ab	235 a	5057 a	578 a
Herbicide	31 b	816 ab	891 ab	118 a	5012 a	492 a
Control	65 b	427 b	590 b	73 a	5648 a	466 a

[a] Means within a column followed by the same letter are not significantly different ($P < 0.05$).

ences were detected among treatments with respect to aqueous phase NO_2-N, NO_3-N, and NH_4-N concentrations. Aqueous phase NO_3-N and NH_4-N concentrations for individual storm events ranged from 0.43 mg L^{-1} to 1.84 mg L^{-1} and from 0.59 mg L^{-1} to 1.51 mg L^{-1}, respectively (data not shown).

Treatment differences in aqueous phase N losses (i.e., NO_2-N, NO_3-N, and NH_4-N) were primarily due to differences in aqueous phase N concentrations rather than differences in overland flow. Aqueous phase N losses from the prescribed fire and mechanical tillage plots were elevated with respect to the control plots for approximately nine months after treatment before leveling off to background levels in the control plots (fig. 5). Annual aqueous phase N losses for the herbicide, prescribed fire, and mechanical tillage treatments were 2.1, 7.9, and 8.0 times greater than the control treatment, respectively. Although aqueous phase N losses in this study were fairly small in magnitude, when combined with other nutrient loss pathways such as leaching and volatilization during fire, total N loss may exceed atmospheric input for several years.

Aqueous phase mean annual PO_4-P concentration was greatest in the prescribed fire treatment; however, no significant statistical differences were detected among treatments (table 3). Mean annual aqueous phase PO_4-P concentration in overland flow during the first post-treatment

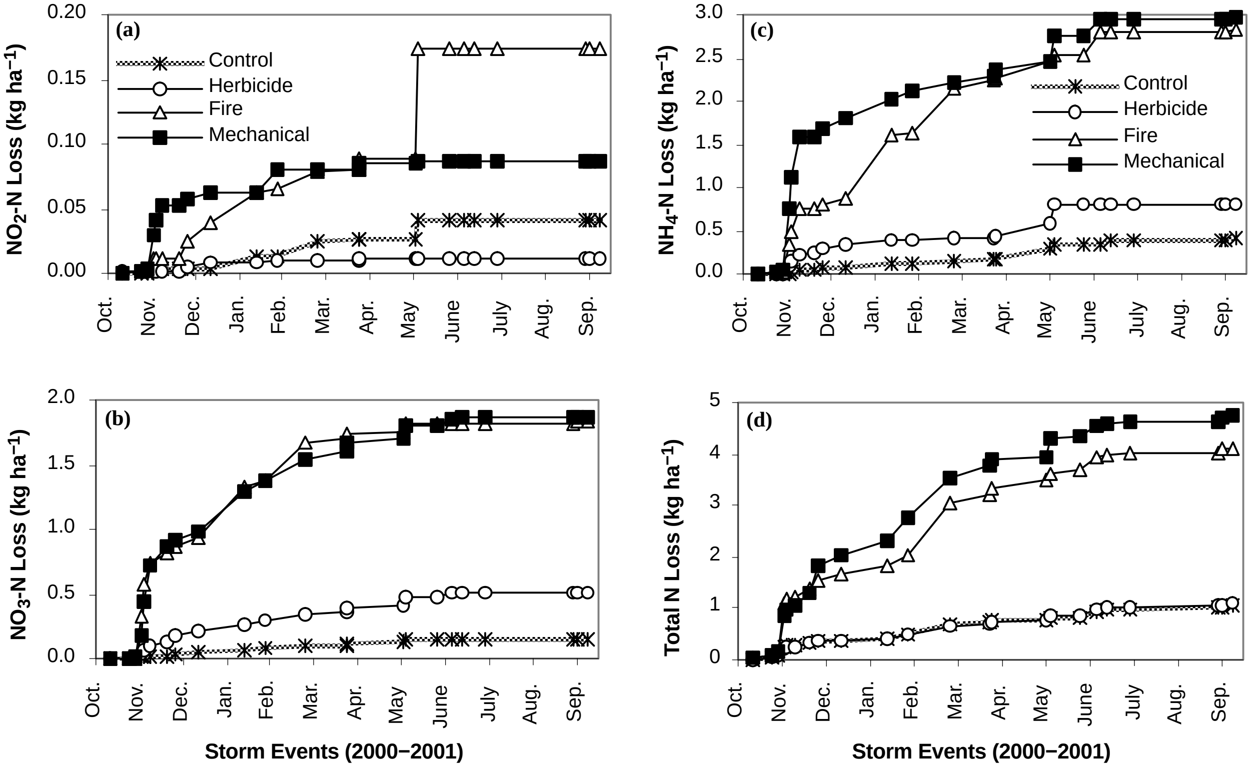

Figure 5. Cumulative aqueous phase (a) NO_2-N, (b) NO_3-N, and (c) NH_4-N losses, and (d) sediment phase total N loss during the first post-treatment year.

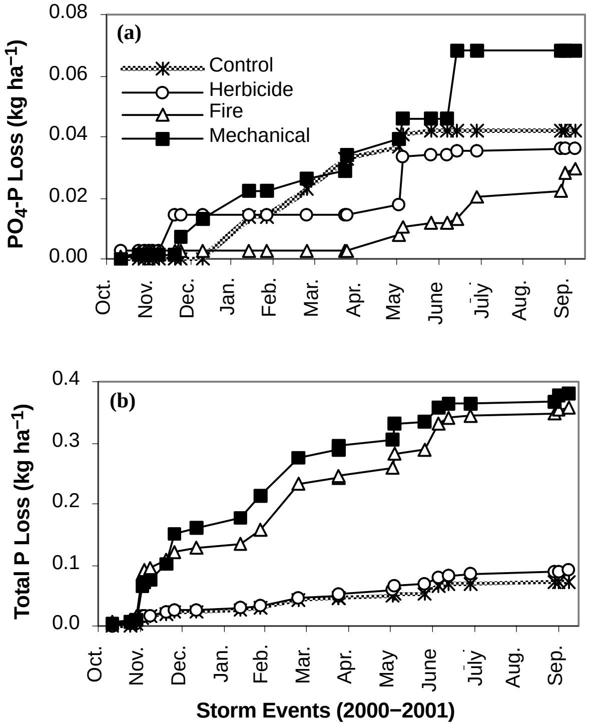

Figure 6. Cumulative (a) aqueous phase PO_4-P loss and (b) sediment phase total P loss during the first post-treatment year.

year was relatively small compared to other nutrient concentrations evaluated in this study. Phosphate-P concentration in overland flow ranged from only 0.07 mg L^{-1} to 0.24 mg L^{-1}. Large differences in aqueous phase PO_4-P concentration for individual storm events persisted throughout the study and were not correlated to treatment effects or overland flow. Sediment phase total P concentration for the prescribed fire and mechanical tillage treatments was slightly greater than the herbicide and control treatments, although these differences were not statistically significant (table 3). Cumulative aqueous phase PO_4-P and sediment phase total P losses were greatest for the mechanical tillage treatment (fig. 6). Total P loss for the mechanical tillage and prescribed fire treatments was more than three times the herbicide and control treatments (table 2). However, due to the high variability in the data, no significant differences were detected among treatments for total P loss. Aqueous phase PO_4-P loss for all treatments was relatively small compared to sediment phase total P loss.

Significant differences among treatments were detected during the first post-treatment year for aqueous phase and sediment phase K, Mg, and S losses. Treatment differences in sediment phase K, Mg, and S losses gradually converged during the last few months of the study as revegetation progressed. Mean annual aqueous phase K, Ca, Mg, and S concentrations in overland flow were not significantly different among treatments during the first post-treatment year (table 4). No significant differences were detected among treatments for aqueous phase and sediment phase Ca concentrations and losses. However, significant differences among treatments were detected in sediment phase K and Mg concentrations, as well as sediment phase K, Mg, and S losses (table 4). Aqueous phase and sediment phase K, Ca, Mg, and S concentrations and losses for individual storm events did not correlate with sediment concentration or overland flow. Treatment differences in aqueous phase nutrient losses appeared to be a function of nutrient concentrations because the treatment differences in overland flow were not great enough to account for treatment differences detected in aqueous phase nutrient losses. Aqueous phase nutrient losses in overland flow reported in this study were comparable to other studies throughout the Southeast (McClurkin et al., 1985; Van Lear et al., 1985; Mann et al., 1988).

Sediment phase Mg and S losses for the prescribed fire and mechanical tillage treatments were significantly elevated during the first post-treatment year with respect to the control and herbicide treatments. Significant differences in sediment phase K loss were also detected among treatments, with the greatest loss occurring from the mechanical tillage plots. Blackburn and Wood (1990) reported that nutrient losses following harvest and site preparation is a function of the degree of disturbance as well as the soils, vegetation, and climate characteristics. The prescribed fire and mechanical tillage treatments resulted in the greatest degree of disturbance and, as a result, had the greatest impact on sediment phase nutrient losses. Increased sediment phase K, Ca, Mg, and S losses for the prescribed fire and mechanical tillage treatments were mainly attributed to increased sediment loss because only slight differences in sediment phase K, Ca, Mg, and S concentrations were detected.

Significant differences in cumulative nutrient losses (i.e., N, K, Mg, and S) were detected among the site preparation treatments during the first post-treatment year (fig. 7). Although mean annual P and Ca losses were not significantly different among treatments, cumulative P and Ca losses in the

Table 4. Post-treatment mean annual aqueous and sediment phase nutrient (K, Ca, Mg, and S) concentrations and losses.[a]

	Concentration (ppm)				Loss (g ha^{-1})			
Treatment	K	Ca	Mg	S	K	Ca	Mg	S
Aqueous Phase								
Mechanical	5.9 a	7.3 a	3.3 a	3.6 a	721 a	1230 a	606 a	176 a
Fire	5.4 a	5.5 a	3.1 a	3.6 a	594 a	795 a	531 a	153 ab
Herbicide	5.1 a	4.4 a	1.8 a	3.0 a	372 a	356 a	183 b	94 bc
Control	5.1 a	4.2 a	1.7 a	2.6 a	268 a	299 a	147 b	64 c
Sediment Phase								
Mechanical	611 ab	15900 a	1030 ab	590 a	22 a	439 a	32 a	18 a
Fire	662 a	23500 a	1150 a	549 a	18 ab	567 a	32 a	15 a
Herbicide	421 c	14800 a	665 b	443 a	4 b	127 a	5 b	4 b
Control	446 bc	19400 a	772 ab	491 a	4 b	117 a	6 b	4 b

[a] Means within a column followed by the same letter are not significantly different ($P < 0.05$).

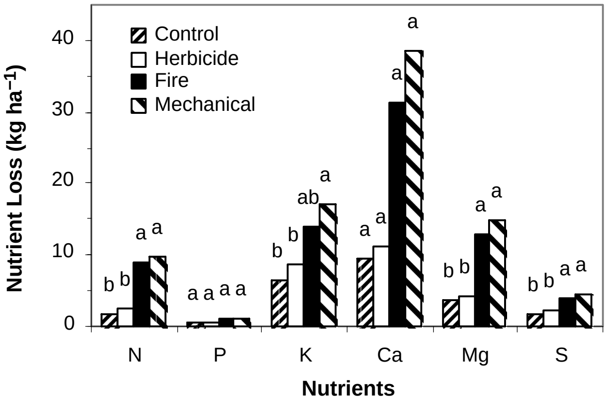

Figure 7. Cumulative annual nutrient (N, P, K, Ca, Mg, and S) losses in overland flow and sediment following site preparation treatment.

prescribed fire and mechanical tillage treatments were more than three times that of the control. Sediment phase nutrient losses were an important component of the total nutrient losses (i.e., aqueous phase and sediment phase) following site preparation treatment. Annual sediment phase N, P, and K losses averaged over all treatments accounted for approximately 48%, 83%, and 2% of the total N, P, and K losses, respectively. This implies that N and P losses in sediment constitute a substantial fraction of the total N and P losses following clearcutting and site preparation in the Southern pine region.

CONCLUSION

The prescribed fire and mechanical tillage treatments significantly increased overland flow during the first post-treatment year, which had unusually high precipitation and high antecedent soil moisture conditions. Overland flow was greatest for the prescribed fire treatment, possibly due to the presence of a less permeable surface layer that may have formed from plant resins and waxes released during the fire. Treatment differences in overland flow following site preparation may have been more apparent during a drier year with normal precipitation.

Annual soil loss and mean annual sediment concentration during the first post-treatment year were significantly greater in the prescribed fire and mechanical tillage treatments than in the control and herbicide treatments. Mechanical site preparation exposed large amounts of mineral soil, producing the greatest increase in soil loss and sediment concentration. Most mechanical site preparation operations use heavy machinery that would likely create more disturbance and expose more mineral soil than the rototiller used in this study. Real disking and bedding operations would, therefore, likely result in greater soil loss than the reported values in this study. Although the prescribed fire and mechanical tillage treatments significantly increased soil loss and sediment concentration during the first post-treatment year, annual soil loss and mean annual sediment concentration were relatively small with respect to other studies in the Southeast. Chemical herbicide site preparation was an effective method for controlling competitive species while having little or no adverse effects on soil loss and sediment concentration. No significant differences between the control and chemical herbicide treatments were detected during the first post-treatment year for all measured parameters.

Site preparation treatments that expose mineral soil and remove the protective forest floor increase the potential for nutrient losses through subsequent higher rates of soil erosion. Although the prescribed fire and mechanical tillage treatments had the greatest impact on nutrient concentrations and losses, annual nutrient losses were relatively small compared to other nutrient loss pathways (e.g., volatilization and ash convection) following intensive site preparation. Aqueous phase nutrient concentrations in overland flow were slightly elevated in the prescribed fire and mechanical tillage treatments with respect to the control; however, these increases were small in magnitude and should not degrade water quality.

Results from this study indicate significant differences in soil and nutrients losses among site preparation treatments commonly utilized in Southern pine ecosystems. Although the total amount of soil and nutrient losses reported in this study were relatively small, further reductions in these losses could be achieved by selecting site preparation methods that minimize surface soil disturbance. Site preparation can be the most significant source of soil and nutrient losses during a normal rotation period. Therefore, if land managers can meet their silvicultural objectives with minimal soil disturbance during site preparation, it would greatly reduce soil and nutrient losses while preserving long-term site productivity and water quality.

ACKNOWLEDGEMENTS

This research was financially supported by the USDA Forest Service. We would like to thank the Forest Soils Laboratory at SFASU for their field assistance. We also wish to thank the Department of Chemistry at SFASU for allowing us to use their facilities for nutrient analysis.

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