CHANGES IN ORGANIC MATTER AND NUTRIENTS IN FOREST FLOOR AFTER APPLYING SEVERAL REPRODUCTIVE CUTTING METHODS IN SHORTLEAF PINE-HARDWOOD STANDS

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Abstract—This study was initiated to determine the effects of various regeneration cutting methods on forest floor mass and nutrient content in shortleaf pine-hardwood communities in the Ouachita and Ozark National Forests. Clearcutting generally altered forest floor concentrations of N, P, and S as well as loss on ignition by increasing the amount of herbaceous vegetation and by mixing mineral soil with the forest floor. Reductions in forest floor concentrations of Mg and Mn were evident in regeneration methods that favored pines and excluded hardwoods (pine single-tree selection and pine shelterwoods). Changes were due to the overall lower concentrations of these nutrients in pine foliage than in hardwood foliage and a reduction of Mn in both pine and hardwood foliage after harvesting. Thus reductions in forest floor Mn appeared not only to be related to changes in stand composition but also reduced soil availability and/or tree uptake. Reductions in Mn content after harvesting were between 22 and 52 percent. Reduction of the other nutrients were generally less than 20 percent.

INTRODUCTION

Timber harvesting and associated silvicultural practices has the potential to significantly alter nutrient cycling and organic matter decomposition in forest ecosystems (Yin and others 1989; Montagnini and others 1989; Kimmins 1996; Barnes and others 1998). Tree and vegetation removal reduces annual inputs of litter to the forest floor until such time that aboveground biomass recovers to pre-harvested levels (Kimmins 1996). This reduction in annual inputs is partially offset at the time of harvesting by a substantial one-time flux of woody materials and decomposable tissues added to the soil surface in the form of logging debris and unmerchantable woody material. The reduction of annual inputs and addition of harvesting debris not only impacts the amount but type of organic matter inputs to detritus food chains resulting in the modification of organic matter decomposition and the availability of nutrients in the forest floor and soil. Nutrient mineralization, like decomposition, changes with the modification of organic matter and carbon inputs after harvesting. Removal of forest canopies can also alter nutrient mineralization and decomposition in temperate forests by increasing available water and soil temperature. Increasing soil temperature occurs after harvesting due to the increased insolation after canopy removal (Waide and others 1987; Liechty and others 1992). A reduction in the amount of canopy also reduces transpiration resulting in an increase in soil moisture availability (Liechty and others 1992). Depending on original ambient conditions and the magnitude of change in temperature and moisture, alteration of ambient conditions can either increase microbial efficiency and population levels or decrease microbial activity (Waide and others 1987). Reductions in decomposition or mineralization can also occur if nutrient concentrations are decreased below pre-harvest levels by addition of carbon rich, nutrient poor organic material.

The need to design and develop alternative regeneration strategies for shortleaf pine (*Pinus echinata* Mill.)-hardwood forests in the Ouachita Mountains has stimulated land managers to question how silvicultural practices affect long-term sustainability and productivity. One of the keys to answering this question is a better understanding of the degree to which these strategies alter nutrient cycling and decomposition. We have attempted to evaluate the effect of harvesting and composition manipulation on these processes by quantifying changes in forest floor mass, nutrient contents, nutrient concentrations, and organic matter 3.5 years after application of several regeneration cutting methods as part of the USDA Forest Service's Phase II Ecosystems Management Study. Our objectives were to quantify changes in the: (1) amount and composition of forest floor, and (2) nutrient concentration and content of forest floor. This information will then be used to address if potential long-term changes in nutrient and organic matter in these ecosystems could occur.

METHODS

Study Sites and Design

Relatively undisturbed, mature, shortleaf pine (*Pinus echinata* Mill.)-hardwood stands occurring on generally south facing slopes in the Ouachita Mountains of Arkansas and Oklahoma were selected for study. A detailed description of the study area and its vegetation is provided in Baker (1994) and Guldin and others (1994). Baker (1994) describes the selection criteria for stands and provides an overview of the full array of thirteen overstory treatments that were performed in the summer of 1993. Six of these thirteen treatments were selected for forest floor sampling in this study. The six treatments selected were: clearcut (CC), pine shelterwood (PSW), pine-hardwood shelterwood (PHSW), pine single-tree selection (PSTS), pine-hardwood single-tree selection (PHSTS), and unharvested control (UC). These treatments provided a broad range of disturbance levels but also allowed us to evaluate the effects of different levels of hardwood retention on nutrient cycling. A total of 24 stands, 4 from each of the 6 treatments, were

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Table 1— Mean preharvest (1993) and postharvest (1997) basal area (m^2 ha^{-1}) of conifer and hardwood trees greater than 10 cm d.b.h. for each treatment

	Preharvest		Postharvest	
Treatment	Conifer	Hardwood	Conifer	Hardwood
	- - - - - - - -	- - - - - *m^2 ha^{-1}*	- - - - - -	- - - - - -
CC	19.2	6.7	< 0.1	0.9
PSW	19.8	6.7	9.3	1.2
PHSW	25.6	6.4	8.2	3.2
PSTS	20.0	9.7	14.2	1.8
PHSTS	21.6	7.7	11.8	3.1
Uncut	21.5	6.7	20.3	7.0

CC = clearcut; PSW = pine shelterwood; PHSW = pine-hardwood shelterwood; PSTS = pine single-tree selection; PHSTS = pine-hardwood single-tree selection; UC = unharvested control.

used for the study. Each stand was initially subdivided into quarters to facilitate establishment of 12 randomly located, permanent subplots that were used for sampling vegetation. These quarters were oriented perpendicular to the dominant slope within the stand. In stands receiving a uniform manual site-preparation treatment, subplots in one of the four quarters were randomly selected. In stands receiving different site-preparation treatments, forest floor sampling was restricted to the quarter assigned to the manual site-preparation treatment. This assured that the site preparation would be the same in all areas used for forest floor sampling. Subplots in the chosen quarter represented the lower, middle, or upper topographic positions. In total, 72 subplots were sampled from these 24 stands. Pre-harvest and post-harvest conifer and hardwood basal areas in the selected subplots (Guldin and others 1994) are presented in table 1.

Field Sampling

Sampling was conducted during February and March of 1993 prior to harvesting and again in 1997 approximately 3.5 years after harvesting. Five sampling locations were systematically located 11.4 m from each subplot center. Sampling locations were relocated if abnormal conditions occurred, such as large surface rocks, woody debris more than 7.6 cm in diameter, or previous manmade disturbances (e.g. old roads, etc.). Thus, samples and results reflect forest floor conditions from undisturbed areas that were not dominated by rocks or woody materials. Less than 5 percent of the sample locations had to be relocated due to these criteria.

The forest floor, excluding woody debris greater than 7.5 cm in diameter, was collected within a 0.1-m^2 square frame at each of five sampling locations. Two layers or stages of decomposition were recognized: (1) a litter L layer, which included the uppermost, relatively undecomposed material that was mostly deposited in the autumn pulse of litterfall and (2) a fermentation F layer consisting of partially decomposed, older material located between the soil surface and the L layer. The L and F layers are also frequently referred to as the O_i and O_e horizons, respectively. The color, texture, and level of fragmentation of foliage (especially the hardwoods) were used to define the boundary between the L and F layers. The boundary between the bottom of the F layer and the soil surface was also based on decomposition stage. The F layer contains fragments of vegetation that could be identified. By contrast, the soil surface was either mineral soil or dark, amorphous organic matter, representing the humus H layer or the O_a horizon. A well defined H layer rarely exists in the forest floors of southern forests because of rapid decomposition rates and incorporation of organic matter within the soil by fauna (Switzer and others 1979). Thus, any H layer material present was not included within the forest floor sample.

Laboratory Procedures and Analysis

Forest floor samples were dried to a constant weight at 75 °C and weighed. Each L layer sample was separated into woody and foliar components. The woody component (WD) included branches, bark, small stems, and reproductive material (e.g., pine cones). The foliar component of each sample was separated into pine (PF) and hardwood foliage (HF) and weighed. Thus, the L layer was represented by PF, HF, and WD in 1993. As a result of the prolific increase in herbaceous plants in the harvested areas, a miscellaneous class of L layer was added in 1997. All forest floor woody material from the clearcuts was classified as F layer due to its highly degraded form 3 years after harvesting and the lack of any current year inputs of woody material.

The forest floor material for a given component was composited for each subplot and ground to pass a 20-mesh sieve. Loss on ignition was determined by heating samples at 500 °C for 4 hours. This is a frequently used approximation of organic matter and is commonly expressed as a percent of total weight. Forest floor concentrations of P, K, Ca, Mg, Mn, S, and Fe were determined by inductance coupled plasma analysis after nitric/perchloric digestion (University of Arkansas, Soil Test Laboratory, 1990a). Total N concentrations were determined using a Tecator Kjeltec Model 1030 Auto Analyzer after sulfuric acid/hydrogen peroxide digestion (University of Arkansas, Soil Test Laboratory, 1990b).

Statistical Design and Methods

To evaluate whether different regeneration cutting methods altered forest floor characteristics, a randomized complete block analysis of variance was used to evaluate differences among study treatments. Ecoregions, as described by Baker (1994), were used as the blocking factor. Dependent variables used for the analysis were either individual post-harvest measurements or differences between pre-harvest and post-harvest measurements (1993-1997). The differences in pre- and post-harvest measurements were used to evaluate if changes in various forest floor components after harvesting were similar or differed among treatments. If differences among treatments were significant (α=0.05), Dunnet's multiple range test (Dunnet 1964) was used to compare the magnitude of changes of the harvested treatments to any changes in the uncut controls. Significant differences between a given harvesting treatment and the uncut treatment indicated changes in a forest floor component or nutrients were of greater magnitude than could be attributed to normal annual variation or inconsistencies in forest floor sampling techniques.

Table 2—Mean mass, organic matter content, and loss on ignition of the total forest floor, L layer, and F layer for each treatment in 1993 and 1997

	CC		PSW		PHSW		PSTS		PHSTS		UC	
Layer	1993	1997	1993	1997	1993	1997	1993	1997	1993	1997	1993	1997
						Mass ($Mg\ ha^{-1}$)						
Total	22.4	21.1	25.1	22.6	24.9	21.8	26.2	21.4	28.2	19.5	24.0	20.5
L	4.4	1.3	5.7	2.5	5.5	2.8	6.0	1.8	5.1	2.4	5.5	2.9
F	18.0	19.8	19.5	20.1	19.3	19.0	20.1	19.7	23.1	17.1	18.5	17.6
						Organic matter content ($Mg\ ha^{-1}$)						
Total	17.8	15.0	19.3	18.3	19.8	17.9	19.9	17.3	19.1	16.6	19.0	17.8
L	4.3	1.1	5.4	2.4	5.3	2.6	5.8	1.7	5.0	2.3	5.3	2.8
F	13.6	13.9	13.8	16.0	14.4	15.2	14.1	15.6	14.2	14.4	13.7	15.0
						Percent loss on ignition						
Total	80.1	71.1*[a]	77.7	81.5	79.2	81.6	76.6	81.8	69.0	85.2	79.1	86.4
L	96.4	90.9*	95.5	96.0	96.0	95.0	96.2	95.6	96.2	96.1	96.0	96.8
F	76.0	69.7*	72.8	79.7	74.6	79.3	70.5	80.6	62.9	83.8	73.2	84.7

L = litter layer; F = fermentation layer; CC = clearcut; PSW = pine shelterwood; PHSW = pine-hardwood shelterwood; PSTS = pine single-tree selection; PHSTS = pine-hardwood single-tree selection; UC = unharvested control.
[a] Changes between preharvest (1993) and postharvest (1997) for a given forest floor attribute and regeneration cutting method denoted by * significantly differ ($\alpha = 0.05$) from those observed in the uncut control.

RESULTS AND DISCUSSION

Mass and Organic Matter

Mass of all forest floor components and organic matter content of the L layer were generally lower, while the loss on ignition of the total forest floor and F layer was greater in 1997 than in 1993 (table 2). These changes were relatively consistent among all treatments including the uncut stands. This variation in mass and loss on ignition appears to be related to a subtle difference in sampling methodologies used in 1993 compared to 1997. A greater portion of the forest floor was designated as the F layer and potentially less of the H layer/mineral soil interface was included with the F layer in 1997 than in 1993. Thus loss on ignition and organic matter contents were greater in the F layer, while organic matter content and mass were lower in the L layer in 1997 than in 1993.

These changes in sampling methods were caused by the manner in which the crews collected and delineated samples in 1993 and 1997. Although one original member of the 1993 crew helped to train the 1997 crew, differences in collection methods were still evident. Assuming annual fluctuations in the amount or composition of forest floor are relatively minor in uncut stands, any changes in these parameters observed in the uncut stands between 1993 and 1997 most likely represent differences in sampling methodologies. Thus, any changes in forest floor characteristics within the harvested stands greater or less than those in the uncut control should represent actual differences related to silvicultural practices and harvesting, rather than sampling methodology.

Harvesting did not appear to significantly change total forest floor, L layer, or F layer mass or organic matter content. Differences between 1993 and 1997 values in the harvested stands were similar to those observed in the uncut stands (table 2). However, clearcutting significantly reduced loss on ignition of the L layer and F layer. Due to the alteration in sampling procedures, loss on ignition in 1997 was greater or approximately equal to 1993 values in the uncut control. Differences in pre- and post-harvest loss on ignition were reduced in the shelterwood and clearcut regeneration treatments. In the case of the clearcut, 1993 values were significantly greater than the 1997 values. Harvesting often churns and mixes mineral soil with the forest floor (Mroz and others 1985; Alban and Perala 1990; Liechty and others 1992). Thus, part of this decrease in loss on ignition could be attributed to mixing of mineral soil with forest floor as a result of harvesting and associated disturbances.

The changes in loss on ignition could also be related to the changes in composition of the forest floor. Figure 1 and table 3 indicate that composition of the L layer was altered by the harvesting treatments. The amount of litter classified as miscellaneous was greatest in the treatments that had the highest amount of tree removal (CC, PSW, and PHSW). This increase in the miscellaneous L layer component occurred with the rapid occupation of harvested sites by herbaceous plants. The clearcut had the largest amount of herbaceous vegetation and the lowest amounts of PF in the L layer. This modification to litter inputs appeared to have altered the character and physical attributes of the forest floor in the stands that received the greatest amount of tree removal. Loss on ignition of miscellaneous material was lower than HF, which was lower than PF (table 3). Evidently, the reduction in the loss of ignition in the clearcut was caused by: (1) the reduction in PF, (2) the increase in

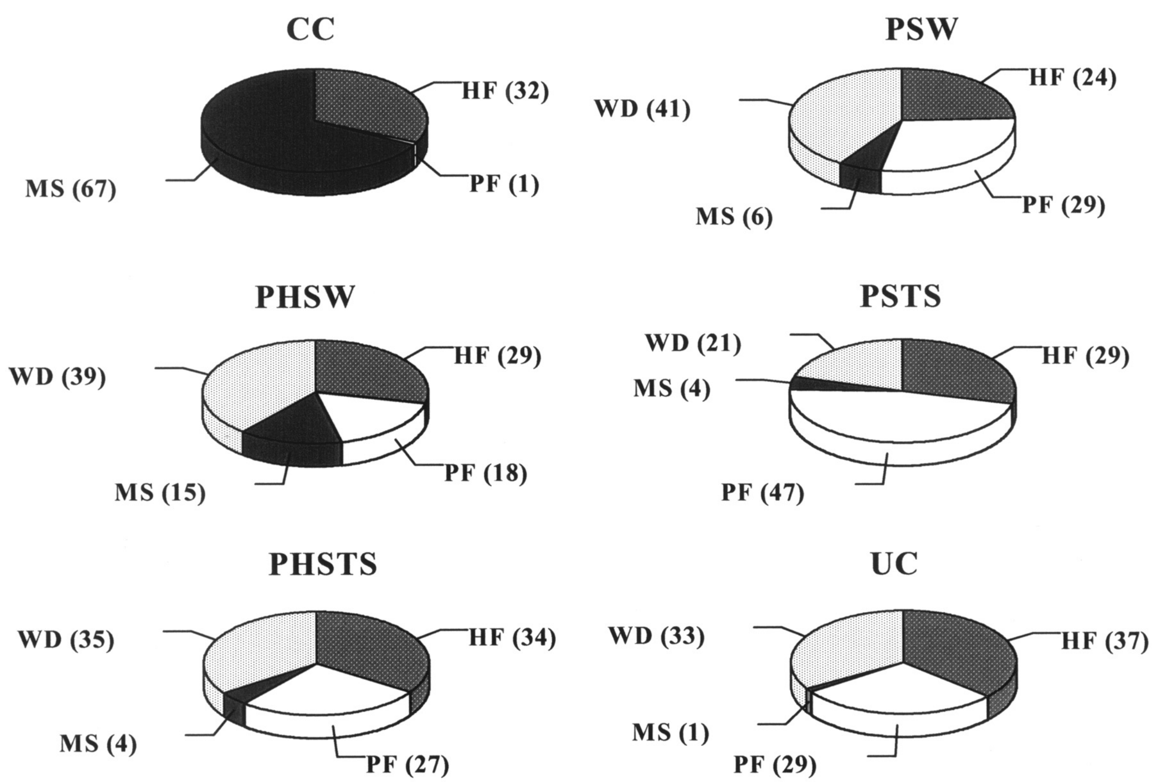

Figure 1—Proportion of mass (percent) in L layer hardwood foliage (HF), pine foliage (PF), woody (WD), and miscellaneous (MS) components by reproduction cutting method in 1997; CC = clearcut, PHSW = pine-hardwood shelterwood, PHSTS = pine-hardwood single-tree selection, PSW = pine shelterwood, PSTS = pine single-tree selection, UC = unharvested control.

Table 3—Mean mass and loss on ignition for the L layer hardwood foliage, pine foliage, and miscellaneous components in 1997

Component	CC	PSW	PHSW	PSTS	PHSTS	UC
			Mass (*Mg ha*$^{-1}$)			
HF	0.41*[a]	0.60*	0.81	0.51*	0.81	1.06
PF	0.01*	0.70	0.50*	0.82	0.63	0.83
MS	0.85*	0.15	0.42	0.07	0.10	0.04
			Percent loss on ignition			
HF	95.0	94.5	93.4	94.2	94.5	94.2
PF	96.4	96.6	96.5	96.1	96.5	96.1
MS	89.8*	94.2	92.2	93.4	94.6	94.3

CC = clearcut; PSW = pine shelterwood; PHSW = pine-hardwood shelterwood; PSTS = pine single-tree selection; PHSTS = pine-hardwood single-tree selection; UC = unharvested control; HF = hardwood foliage; PF = pine foliage; MS = miscellaneous components.

[a] Treatments for a given with an * are significantly (α = 0.05) different than the uncut control.

miscellaneous material which has the lowest loss on ignition, and (3) the mixing of mineral soil and forest floor.

The increased amount of herbaceous vegetation also appeared to reduce potential changes in forest floor mass attributed to the removal and harvesting of trees within the clearcut treatments (table 3). In the clearcut during 1997 approximately 62 percent of the L layer mass or 0.85 Mg ha^{-1} was classified as miscellaneous. Without the input of this material to the forest floor and ultimately to the soil, organic pools would likely have been significantly lower with this regeneration method.

A change in forest floor composition was also noted for the pine only treatments (PSW and PSTS). In each of these two treatments, hardwood removal significantly lowered the amount of HF in the L layer (table 3). However, these changes in composition did not appear to significantly alter loss on ignition of the forest floor or the L layer.

Nutrient Concentration

Harvesting treatments also altered the chemical composition of the forest floor. Most conspicuous was a decrease in N, P, and S concentrations of the overall forest floor and the F layer within the clearcut stands (table 4). N, P, and S concentrations in the F layer and the forest floor of the uncut controls in 1997 were higher or similar to concentrations

Table 4—Mean preharvest (1993) and postharvest (1997) total forest floor, L layer, and F layer nutrient concentrations for each regeneration cutting method

	CC		PSW		PHSW		PSTS		PHSTS		UC	
Layer	1993	1997	1993	1997	1993	1997	1993	1997	1993	1997	1993	1997
	percent											
	N											
Total	0.97	0.89*[a]	0.90	0.92	0.91	0.97	0.89	0.92	0.91	1.00	0.89	1.01
L	0.68	1.01*	0.68	0.76	0.68	0.88	0.69	0.80	0.70	0.82	0.68	0.78
F	1.04	0.87*	0.98	0.95	0.98	0.98	0.95	0.93	0.96	1.01	0.95	1.05
	P											
Total	0.059	0.049*	0.055	0.049	0.057	0.050	0.052	0.048	0.055	0.052	0.052	0.052
L	0.047	0.052	0.044	0.037	0.047	0.041	0.047	0.038	0.046	0.041	0.043	0.037
F	0.061	0.049*	0.059	0.052	0.060	0.051	0.054	0.049	0.057	0.054	0.055	0.055
	K											
Total	0.09	0.06	0.10	0.06	0.09	0.06	0.08	0.06	0.09	0.06	0.07	0.06
L	0.07	0.06	0.07	0.08	0.08	0.10	0.07	0.09	0.07	0.09	0.06	0.10
F	0.10	0.06	0.11	0.06	0.10	0.06	0.09	0.06	0.10	0.06	0.08	0.06
	Ca											
Total	0.73	0.70	0.88	0.81	0.87	0.89	0.82	0.84	0.79	0.83	0.79	0.81
L	0.85	0.74	1.13	0.75	1.08	0.96	1.08	0.74	1.00	0.82	1.00	0.89
F	0.70	0.69	0.79	0.83	0.80	0.87	0.75	0.85	0.75	0.84	0.72	0.80
	Mg											
Total	0.098	0.080	0.105	0.076*	0.103	0.083	0.093	0.070*	0.123	0.093*	0.101	0.080
L	0.112	0.097	0.118	0.080*	0.122	0.101	0.118	0.087*	0.114	0.095	0.097	0.095
F	0.095	0.079	0.101	0.075*	0.098	0.081	0.086	0.068	0.125	0.093*	0.082	0.076
	S											
Total	0.10	0.08*	0.08	0.08	0.09	0.08	0.09	0.08	0.09	0.08	0.09	0.09
L	0.05	0.09	0.08	0.07	0.08	0.07	0.08	0.07	0.08	0.07	0.07	0.07
F	0.10	0.08*	0.09	0.08	0.10	0.08	0.09	0.08	0.09	0.08	0.09	0.09
	Mn											
Total	0.10	0.05*	0.14	0.09*	0.12	0.10*	0.14	0.09*	0.12	0.08*	0.12	0.14
L	0.08	0.05	0.12	0.07*	0.11	0.08	0.12	0.08*	0.09	0.07	0.11	0.11
F	0.10	0.04*	0.15	0.10*	0.13	0.11	0.14	0.09*	0.13	0.08*	0.13	0.14
	Fe											
Total	0.39	0.45	0.50	0.33	0.37	0.32	0.33	0.24	0.53	0.21	0.38	0.15
L	0.02	0.12	0.04	0.02	0.02	0.08	0.02	0.02	0.02	0.01	0.02	0.01
F	0.48	0.48	0.63	0.37	0.47	0.38	0.42	0.26	0.65	0.24	0.05	0.17

L = litter layer; F = fermentation layer; CC = clearcut; PSW = pine shelterwood; PHSW = pine-hardwood shelterwood; PSTS = pine single-tree selection; PHSTS = pine-hardwood single-tree selection; UC = unharvested control.

[a] Changes between preharvest (1993) and postharvest (1997) forest floor concentrations for a given regeneration cutting method denoted by * significantly differ ($\alpha = 0.05$) from those observed in the uncut control.

measured in 1993. In contrast concentrations of these three nutrients in the forest floor of the clearcuts generally decreased after harvesting (table 4). Decreases in concentrations of these nutrients appeared to be strongly related to the observed decreases in loss of ignition. N, P, and S are important elements in organic constituents, such as proteins, amino acids, etc. Mixing of mineral soil, which has N, P, and S concentrations, with the forest floor would significantly reduce the concentrations of these elements in addition to lowering loss on ignition. However, mixing of mineral soil with forest floor did not significantly lower base concentrations due to the greater similarity of concentrations of bases in these two materials.

Although loss on ignition decreased after harvesting in both the L layer and the F layer, concentrations of N, P, and S in the L layer generally increased after clearcutting. Average concentration of N, P, and S in the clearcut stands were respectively 0.68, 0.047, and 0.08 percent prior to harvesting in 1993 and 1.01, 0.052, and 0.09 percent after harvesting in 1997 (table 4). Increases of N were significantly greater than those found in the uncut stands (table 4). These increases in concentration were related to the decrease of PF and the corresponding increase of HF and miscellaneous material in the L layer within the clearcuts (figure 1 and table 5). Concentrations of N, P, and S were 36 to 50 percent greater in HF and miscellaneous material than in PF (table 5). Thus while mixing of mineral soil and forest floor tended to decrease N, P, and S in the F layer, the reduction of PF increased the concentrations of these nutrients in the L layer. The reduction in N, P, and S levels in the F layer was apparently great enough to decrease the overall concentrations of these elements in the forest floor as a whole.

Regeneration treatments that retained pine and excluded hardwoods also altered the forest floor nutrient levels. Decreases in forest floor concentrations of Mg and Mn in the PSW and PSTS treatments after harvesting were significantly greater than decreases observed in the uncut stands (table 4). Tree removal at any level was found to decrease the concentrations of these nutrients in the forest floor. However, changes were always greatest in the PSW and PSTS treatments. Concentrations of bases, such as Mg and Mn, were consistently higher in hardwood compared to PF (table 5). Exclusion of HF with an accompanying dominance of PF ultimately decreased levels of Mg and Mn in the forest floor. This alteration of chemistry of the forest floor was most evident in the L layer but changes in concentrations in the F layer and the total forest floor were also evident. Changes in concentrations of Mg and Mn of the F layer in the PHSTS were also significant. Calcium levels were reduced in PSW and PSTS treatments, but reductions in concentrations after harvesting were not significantly greater than those found in the uncut stands (table 4). The prolific growth of herbaceous vegetation did not appear to have a significant impact on base concentrations of the forest floor. Average concentrations of Ca, Mg, and Mn in the miscellaneous L layer component were similar to concentration of these elements in PF (table 5).

Reductions in forest floor bases, such as Mg and Mn, could not solely be attributed to the increased dominance of PF in the forest floor. Concentrations of these elements in HF and PF were also reduced after harvesting (table 6). A reduction of Mg in HF was evident within all harvesting treatments. Declining levels of Mg in PF were significantly greater than reductions observed in the uncut controls within the PSW and PSTS treatments only. Declining levels of Mn were also evident in HF and PF collected from the harvested treatments. Reductions were only significantly greater than differences in uncut control for the clearcut and PSTS treatments.

The diminished levels of Mg and Mn in the hardwood and pine component of the L layer may potentially be attributed to two specific changes related to harvesting. First, harvesting can result in accelerated soil leaching of NO_3^- (Vitousek 1981; Van Lear and others 1990) and cations (Kimmins 1996). Accelerated leaching of Mg and Mn may have reduced the availability of these two cations in soil and thus uptake of these nutrients by the residual trees. Reduction in uptake can lower levels of nutrients in foliage when original available nutrients in soil are at or below levels required by the residual stand. Harvesting can also change the composition of HF in the forest floor. For example, removal of undesirable species in favor of more desirable species in the PHSW and PHSTS treatments could have altered HF composition. Treatments that retain minimal residual densities dramatically increased the light environment within the stands. These conditions favored growth and establishment of early successional, shade intolerant hardwoods as well as shrubs and other herbaceous vegetation. Early successional hardwood species that respond to the disturbances often have foliage physiology and nutrient levels much different than later successional, shade tolerant species (Hinesley and others 1991; Kozlowski and others 1991).

Table 5—Mean nutrient concentration in L layer hardwood foliage, pine foliage, and miscellaneous components from all treatments in 1997

Component	N	P	K	Ca	Mg	S	Mn	Fe
	- - - - - - - -	- - - - - - - -	- - - - - -	- - - *percent*	- - - - - -	- - - - - -	- - - - - -	- - - - - -
HF	1.06	0.049	0.07	1.16	0.13	0.09	0.12	0.03
PF	0.75	0.042	0.09	0.46	0.09	0.06	0.08	0.01
MS	1.12	0.057	0.09	0.67	0.08	0.09	0.06	0.09

HF = hardwood foliage; PF = pine foliage; MS = miscellaneous components.

Table 6—Concentrations of Mg and Mn in L layer hardwood and pine foliage components

	CC		PSW		PHSW		PSTS		PHSTS		UC	
Component	1993	1997	1993	1997	1993	1997	1993	1997	1993	1997	1993	1997
	percent											
	Mg											
HF	0.16	0.11*[a]	0.18	0.14*[a]	0.14	0.09*[a]	0.17	0.12*[a]	0.18	0.14*[a]	0.15	0.14
PF	—[b]	—[b]	0.12	0.08*[a]	0.12	0.09	0.12	0.08*[a]	0.12	0.10	0.10	0.09
	Mn											
HF	0.14	0.06*[a]	0.19	0.12	0.19	0.12	0.20	0.11*[a]	0.17	0.11	0.21	0.18
PF	—[b]	—[b]	0.10	0.08	0.09	0.07	0.09	0.07	0.08	0.07	0.10	0.10

L = litter layer; HF = hardwood foliage; PF = pine foliage.
[a] Absolute differences between concentrations for pre- and post-harvest sampling (1993 and 1997) denoted with * are significantly greater than differences for uncut control ($\alpha = 0.05$).
[b] There was not sufficient pine foliage for chemical analysis in the clearcut stands.

The study design did not let us directly determine which of these factors were responsible for the changes in foliar chemistry. Since reductions in PF Mg also occurred after harvesting and shortleaf pine was the dominate species prior to and after harvesting, it seems likely that changes in concentrations of Mg were at least in part due to changes in availability of Mg in the soil. However, greater reductions in concentrations occurred in HF and a greater number of treatments showed significant reductions in concentrations of Mg and Mn in HF than PF. These responses would also support the hypothesis that a change in hardwood species composition has altered HF chemistry within the L layer. It is likely that both nutrient availability and species composition has changed in the harvested stands during the study.

Reductions in nutrient concentrations other than Mg were not significant. N concentrations of PF in the PSW treatment and HF concentrations of Fe in the clearcut stands significantly increased after harvesting. Increases in concentrations of these elements within the other treatments were not significantly greater than in the uncut stands. Thus increases in N and Fe were considered anomalies.

Nutrient Content

Similar to mass, nutrient contents of the forest floor were generally lower in all treatments in 1997 compared to 1993 (table 7). Decreased nutrient contents were related to the differences in sampling methodology and potentially natural changes in annual fluxes of litter. The lack of any significant reductions in nutrient content within the forest floor appears to be related to a high variation in forest floor mass among plots, treatments, and sampling periods rather than the lack of a significant change in nutrient concentrations (table 4). Significant reductions of Mg and Mn in the F layer of the PHSTS treatment and Mn in the F layer of the PSW were evident. However, substantial decreases in mass of the F layer along with changes in concentrations were responsible for changes within the PHSTS treatment. Reductions in the Mn contents of the PSW treatment reflect changes in concentrations rather than mass.

Reductions in contents of N, P, Ca, Mg, S, and Mn between pre- and post-harvested periods were consistently greater in the harvested than those in the uncut stands. Even if results of the PHSTS treatment are disregarded, reductions in amounts of these elements were as much as 3-7 times greater in the harvested stands than in the uncut control. Elements which showed the greatest reductions in concentrations, such as Mn, usually had the greatest reductions in contents (tables 4 and 7). Changes in contents of the L and F layers were variable and for the most part decreased. However, Ca content of the F layer and the Fe content of the L layer in one or more of the harvested treatments increased. It seems likely from our results that nutrient contents in the forest floor decreased after harvesting but these decreases were not substantial enough to be statistically significant.

Given the high variability within forest floor mass and contents, we cannot accurately estimate the amount of loss associated with a given harvesting treatment. To better determine the significance of these losses, differences in contents between pre- and post-harvest periods were adjusted for observed differences in the uncut control by subtracting average uncut control differences. These adjusted values were then expressed as a percent of the original 1993 content for a given treatment. The PHSTS treatment had the greatest reduction in forest floor mass (18.5 percent) and generally the greatest reductions in nutrient content. Reductions in Mn were substantial for all harvesting treatments. If the PSTS treatment is disregarded, reductions in other nutrients were generally less than 20 percent of original pre-harvest contents. Mg and K also consistently showed relatively high reductions in all or the majority of treatments. There appeared to be no specific trends in nutrient content reductions related to intensity of tree removal as indicated by target residual densities. The clearcut stands that had the greatest amount of tree removal often showed the lowest nutrient content reduction.

Table 7—Preharvest (1993) and postharvest (1997) total forest floor, L layer, and F layer nutrient contents for each regeneration cutting method

	CC		PSW		PHSW		PSTS		PHSTS		UC	
Layer	1993	1997	1993	1997	1993	1997	1993	1997	1993	1997	1993	1997
						kg ha^{-1}						
						N						
Total	216	187	223	206	227	211	230	195	254	197	213	206
L	30	13	38	18	37	25	41	14	36	19	38	22
F	186	174	185	188	190	186	190	181	219	178	175	183
						P						
Total	13.1	10.3	13.7	10.8	14.1	10.8	13.3	10.2	15.2	10.2	12.5	10.7
L	2.1	0.7	2.5	0.8	2.6	1.1	2.6	0.7	2.3	1.0	2.5	1.0
F	10.9	9.7	11.2	10.0	11.6	9.6	10.7	9.5	12.9	9.3	10.0	9.6
						K						
Total	20.5	12.0	26.3	13.3	22.8	14.2	21.0	13.3	26.4	11.9	17.4	12.7
L	3.2	0.8	4.1	1.4	4.3	2.3	4.1	1.4	3.7	1.8	3.3	1.7
F	17.3	11.2	22.2	11.9	18.4	12.0	16.9	11.9	22.7	10.1	14.1	11.0
						Ca						
Total	167	148	215	182	212	196	206	174	221	165	187	162
L	39	9	63	19	62	28	60	13	54	20	58	26
F	129	139	152	163	150	168	146	161	168	145	130	136
						Mg						
Total	22.3	17.2	26.5	16.6	25.5	17.7	23.7	14.7	34.0	17.6*[a]	20.4	15.7
L	5.0	1.1	6.5	1.9	6.7	2.9	6.7	1.5	6.0	2.3	6.0	2.8
F	17.2	16.1	20.0	14.8	18.8	14.7	17.0	13.2	28.1	15.3*	14.8	13.0
						S						
Total	21.8	16.7	21.1	17.3	23.4	16.9	22.7	16.6	25.4	16.3	21.7	18.2
L	3.5	1.2	4.5	1.5	4.4	2.0	4.5	1.2	4.0	1.7	4.2	2.1
F	18.3	15.5	16.6	15.8	19.0	15.0	18.2	15.4	21.4	14.7	17.5	16.1
						Mn						
Total	22.6	9.7	36.5	20.4	30.0	21.7	33.1	19.1	33.1	16.1	28.6	27.4
L	3.9	0.7	6.4	1.6	5.8	2.1	6.6	1.3	4.8	1.7	6.0	3.1
F	18.7	9.0	30.2	18.8*	23.8	19.6	26.4	17.7	28.3	14.5*	22.5	24.3
						Fe						
Total	88	96	134	76	91	68	84	61	152	38*	90	29
L	1	2*	2	1	1	1	2	0	1	0	1	0
F	887	94	132	75	90	68	82	60	151	38	88	29

L = litter layer; F = fermentation layer; CC = clearcut; PSW = pine shelterwood; PHSW = pine-hardwood shelterwood; PSTS = pine single-tree selection; PHSTS = pine-hardwood single-tree selection; UC = unharvested control.
[a] Changes between preharvest (1993) and postharvest (1997) forest floor concentrations for a given regeneration cutting method denoted by * significantly differ ($\alpha = 0.05$) from those observed in the uncut control.

CONCLUSION

Several of the reproduction/cutting methods evaluated in this study were found to alter the characteristics and nutrient compositions of the forest floor. Clearcutting generally was found to increase mixing of forest floor and mineral soil as well as the proliferation of herbaceous vegetation. This resulted in decreasing concentrations of N, P, and S in the forest floor. Regeneration methods that removed the majority of hardwoods tended to decrease levels of Mg and Mn in the forest floor. These decreases were attributed to the increased proportion of PF with lower concentrations of Mg and Mn compared to HF. However, reductions in concentrations of these nutrients were also evident in HF of all of the harvested stands. Reductions in Mn content of the forest floor in the harvested stands were between 22-52 percent but reductions in content of other nutrients were generally less than 20 percent.

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