FOREST SOIL RESPONSE TO FUEL REDUCTION TREATMENTS IN THE SOUTHERN APPALACHIAN MOUNTAINS

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Abstract—The National Fire and Fire Surrogate Study (FFS) was established to monitor the impacts of fuel reduction treatments (prescribed fire-only, mechanical fuel reduction-only, and a combination of prescribed fire and mechanical fuel reduction) on a host of ecosystem properties at 13 sites across the United States. Treatment impacts were monitored on the Southern Appalachian Mountain FFS site for three to four years following treatment. Control and treatment means for forest floor C:N ratio, soil extractable calcium, and the Ca:Al molar ratio differed one to two years posttreatment. These differences were not noted three to four years posttreatment, but differences were noted for soil extractable iron and soil pH. Results from this analysis suggest that these treatments were applied under the appropriate conditions and guidelines to conserve forest soil resources.

INTRODUCTION

In 2002, 7.2 million acres of forested land burned in seven of the western United States, accounting for the deaths of 23 firefighters and damage to 852 structures. The fire suppression efforts that year cost more than $1 billion (USDA Forest Service Position Paper 2003). In response to rising concerns over wildfire hazard and a desire to restore forest structure and function that may have been altered by close to a century of fire exclusion, the National Fire and Fire Surrogate Study was begun in 1999 to gather a more broad understanding of the effects of fuel reduction treatments on ecosystem properties. This research stretches across 13 study sites around the country and at each site, some use of prescribed fire and harvesting, alone and in combination, is being conducted. Soil resources are one of the many ecosystem components of interest.

Various reports have been published regarding the effects of prescribed fire, harvesting, and a combination of the two on soil resources. The range of fire-induced changes to soil properties and processes is quite varied, depending largely on fire intensity, temperature, vegetation type and amount, soil moisture, and other factors (Wells and others 1979). Increases, decreases, and nonsignificant changes to soil biological, chemical, and physical properties have been documented extensively on a site-by-site basis based upon these factors in response to fire. As a whole, prescribed fires have been found to cause minimal changes to soil resources (Johnson and Curtis 2001, Van Lear 1985). The nature of fire intensity in the southern United States is particularly dominated by understory (Coastal Plain, Piedmont) and mixed fires (Southern Appalachians) that do not consume large quantities of organic matter or expose large amounts of mineral soil (Stanturf and others 2002).These effects should be considered on a site-by-site basis, however.

Harvesting elicits a response similar to burning based upon the extent, method, and timing of harvesting. Soil physical properties tend to be the most sensitive properties with regard to harvesting. Soil bulk density has been found to increase in several studies following harvesting, largely due to the use of mechanized equipment. Other considerations should be given to the amount of material removed during harvesting and the amount of residual materials that are left to decompose after harvesting. Zhou and others (1998) found that residues left in place after harvesting had little influence on the potential N mineralization rates in the soil, but Merino and others (1998) found that the removal of logging residues reduced N mineralization following both whole-tree harvesting and stem-only harvesting of pine forests in Spain.

Burning alone and harvesting alone are desirable to some degree for the reduction of fuels. However, the heavy fuel-loading present in many stands throughout the U.S. calls for a combination of treatments, such as both thinning and burning (Stanturf and others 2002). Many studies have evaluated the effects of prescribed fire and harvesting individually, but not as many have examined the effects of a combination treatment, particularly for the longer term. Much like the two treatments individually, several studies show mixed results for the combination of thinning and burning on N. Knoepp and Swank (1993) suggested that total N and soil NO_3^--N availability were not affected by the felling and burning of pine-hardwood stands in the Southern Appalachian Mountains. They also concluded that an initial pulse of soil NH_4^+-N was seen in as little as 48 hours after treatment and remained elevated up to one year posttreatment. Little leaching losses and movement of N were found as well. Clipping and burning of material was noted by Wells and others (1979) to cause increased N mineralization as well. In this paper, we summarize the response of soil resources for the Southern Appalachian Mountain FFS site for four years posttreatment.

METHODS

Study Area

The Southern Appalachian Mountain study site of the FFS resides on the Green River Game Land in Polk County, North

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Carolina. The Game Land covers 5,841 ha and is managed by the North Carolina Wildlife Resources Commission. Stands are a mixture of oaks, pines, and hickories based on topographic location (Waldrop 2001). Some of the oak species include northern red (*Quercus rubra*), chestnut (*Q. prinus*), white (*Q. alba*), and black (*Q. velutina*). Mountain-laurel (*Kalmia latifolia*) and great rhododendron (*Rhododendron maximum*) are the predominant shrub species. Soils within the Evard soil series (fine, loamy, Typic Hapludults) and Cliffield soil series (loamy-skeletal, mixed, subactive, mesic Typic Hapludults) are characteristic of the area. These well-drained soils are found in mountain uplands (Soil Survey Staff 2005).

Experimental Design and Treatment Descriptions

The treatments proposed by the FFS are prescribed burn-only, mechanical cutting-only, a combination of cutting and burning, and a control. A randomized complete block design was used for this study. Each replicate was a contiguous block of land which helped control any variability among sites. Each treatment area was at least 13 ha in size and basal area ranged from 21 to 31 m2/ha before treatment installation (unpublished data). Stand age ranged from 80 to 120 years (Waldrop 2001). This study site had not been cut in at least 10 years prior to treatment and had not been burned in the previous 5 years.

Cutting operations were conducted from December 2001 to March 2002. This treatment was conducted by chainsaw crews that were contracted to cut all trees greater than 1.8 m tall and less than 10.2 cm diameter breast height (d.b.h.). All shrubs were additionally cut and piles of these materials were kept at less than 1.3 m high. The burning for the burn-only and mechanical and burn treatments of replication 3 was conducted on March 12, 2003. These fires were ignited using strip-headfires and spot fires that produced average flame lengths of one to two m or less. The average flame temperature measured by heat tiles 1 m above ground was 120 ^{o}C. Flames of up to 5 m with temperatures up to 788 ^{o}C were measured in localized areas as influenced by topographic position and the intersection of flaming fronts (Tomcho 2004). Average flame lengths for these fires were also 1 to 2 m or less and average flame temperature was around 93 ^{o}C.

Soil Sampling

Soil sampling took place within ten 20 by 50 m plots that were randomly assigned within each of the replicates for all treatments. These plots were also designated for vegetation measurement for another component of the FFS study. For the determination of O horizon C and N, samples were taken from six 10 by 10 m subplots. These samples were oven-dried at 76 ^{o}C for 16-24 hours. Six samples at these locations were also collected to evaluate the levels of mineral soil C, N, extractable elements (Al, B, Ca, Cu, Fe, Mg, Mn, P, K, Soluble S, Na, Zn) and pH to the 10 cm soil depth. These samples were oven-dried at 76 ^{o}C for 16-24 hours. Samples were taken 1 to 2 m outside each of the 10 by 10 m subplots to the 10 cm soil depth to determine soil bulk density at each plot using a Model H Oakfield soil probe for the pretreatment and first posttreatment period. Collection of the pretreatment soils data began in June 2001. In like fashion, samples were collected in 2003 to assess the response for the first posttreatment period. To determine the second posttreatment responses, sampling was conducted in the summer of 2005. Bulk density samples were not obtained in 2005 due to a delay in sampling for some of the areas in 2003.

Soil Processing and Laboratory Analysis

Six O horizon samples for each plot were ground using a Wiley mill with a 2 mm sieve. 20 mL from each of the 6 ground samples were then mixed together in a 120 mL vial to comprise one sample for each plot. The same procedure used for processing the O horizon samples was used to prepare the samples needed to determine mineral soil C, N, extractable elements, and pH levels, except grinding of the mineral soil samples was conducted using a Sawyer mill. Bulk density samples were sorted for rocks and roots before and after drying, as needed. The ovendry weight was then divided by the volume of the soil sample to obtain estimates of bulk density in g/cm^3.

All pretreatment and first posttreatment results were conducted by Brookside Analytical Laboratories in New Knoxville, Ohio. O horizon and mineral soil C and N and soil pH were all completed by the U.S. Forest Service Forestry Sciences Laboratory in Athens, Georgia for the second posttreatment results. Analysis for the second posttreatment soil extractable elements was again contracted to Brookside Laboratories. Regardless of the laboratory used, C and N for the forest floor and mineral soil were determined by the combustion of samples and subsequent measurements conducted by the Perkin-Elmer 2400 Series II CHNS/O Analyzer. The additional element concentrations were determined using Mehlich III methodology and subsequent analysis for each element of interest by ICP-Optical Emission Spectrometry. Soil pH was determined using a 1:1 soil to water solution.

The Ca:Al molar ratio was calculated for each sampling period for both locations. This ratio has been suggested to be a useful tool in determining potential nutrient imbalances. Cronan and Grigal (1995) suggest that there is an increased risk of critical impacts on tree growth and nutrition as this ratio is found to be less than 1.0. Molar weights for both Ca and Al were needed to derive this ratio. The equation for this ratio is as follows:

$$\frac{[(\text{mg Ca/kg soil})/\ (40.01\ \text{g Ca/M Ca})]}{[(\text{mg Al/kg soil})/\ (26.98\ \text{g Al/M Al})]}$$

Statistical Analyses

To obtain an accurate assessment of the effects of fuel reduction on the soils of this area, several statistical procedures were conducted using SAS (SAS Institute 2002). An analysis of variance (ANOVA) was conducted using the pretreatment data to determine if differences in soil properties existed before treatment installation based on the treatment designations. An analysis of covariance (ANOCOVA) was conducted for both locations to determine the first posttreatment response of the variables, with pretreatment data serving as a covariate. In cases where the covariate proved to be non-significant, it was removed from the analysis and an ANOVA was performed. The second posttreatment period results were also evaluated using ANOCOVA with pretreatment values serving as the covariate. In cases where the covariate was nonsignificant, it was removed and ANOVA was used to compare treatment effects. All comparisons were made at the 0.05 level of significance.

RESULTS AND DISCUSSION

Forest Floor Carbon and Nitrogen

The pretreatment covariate was significantly related to the values obtained for first posttreatment O horizon C and for the C:N ratio, but not for O horizon N. The ANOCOVA means for C and the ANOVA means for N suggest that there were nonsignificant differences among the means of the treatments, but the ANOCOVA mean for the C:N ratio on the mechanical and burn treatment was significantly lower than the means of the other treatments (table 1).

In similar fashion to the first posttreatment results, the pretreatment covariate was not significantly related to the second posttreatment results for O horizon N. No significant differences were detected among the ANOCOVA means for C and for the C:N ratio. The ANOVA means for N also suggested nonsignificant differences. It appears that the overall organic quality of the forest floor has been conserved.

The means of the treatments did not differ from one another when measured for the second posttreatment period. This follows the findings of Wells and others (1971), Knoepp and Swank (1993), and Johnson and Curtis (2001), and suggests that these treatments cause little change to forest floor dynamics. These natural systems are relatively efficient at replenishing the amount of material consumed or displaced by these treatments (Van Lear 1985).

Table 1—Treatment means for soil variables noted to possess significant differences among the treatments during either the first or second post-treatment periods for the Southern Appalachian National Fire and Fire Surrogate study. Means are shown plus or minus the standard error without correction for unequal sample sizes. Significant differences among the means are noted by different letters following means within a row ($\alpha = 0.05$)

	Treatment			
Variable	Control	Burn	Cutting	Cut and Burn
O Horizon C:N				
Pre (p = 0.9062)	36.13a ± 0.76	36.92a ± 0.52	36.35a ± 0.81	37.40a ± 0.79
First (p = 0.0472)	32.10a ± 0.95	31.38a ± 0.82	31.13a ± 0.77	27.49b ± 1.17
Second (p = 0.2171)	25.05a ± 0.56	24.35a ± 0.50	26.53a ± 0.57	24.91a ± 0.54
Calcium (mg Ca/kg soil)				
Pre (p = 0.1557)	319.21a ± 41.73	315.62a ± 37.82	203.55a ± 34.41	215.01a ± 25.40
First (p = 0.0270)	155.83a ± 19.33	123.19ab ± 11.67	100.50b ± 5.96	106.74b ± 7.10
Second (p = 0.4150)*	135.47a ± 23.09	178.97a ± 26.93	135.27a ± 14.26	184.93a ± 31.05
Iron (mg Fe/kg soil)				
Pre (p = 0.0011)	111.01b ± 5.74	105.70b ± 4.19	164.23a ± 8.08	150.28a ± 9.75
First (p = 0.0875)	140.69a ± 7.43	133.44a ± 4.40	121.20a ± 6.96	108.77a ± 3.93
Second (p = 0.0143)	113.36a ± 5.06	105.20a ± 4.00	103.83a ± 4.28	93.38b ± 3.29
Molar Ca:Al				
Pre (p = 0.1041)	0.17a ± 0.02	0.17a ± 0.02	0.10a ± 0.02	0.11a ± 0.01
First (p = 0.0058)	0.11a ± 0.013	0.08b ± 0.008	0.07b ± 0.004	0.07b ± 0.006
Second (p = 0.4781)*	0.07a ± 0.01	0.10a ± 0.01	0.07a ± 0.01	0.10a ± 0.02
Soil pH				
Pre	Not available	Not available	Not available	Not available
First (p = 0.7598)	4.53a ± 0.04	4.60a ± 0.04	4.58a ± 0.04	4.61a ± 0.03
Second (p = 0.0457)	4.72a ± 0.04	4.66ab ± 0.03	4.60b ± 0.03	4.65ab ± 0.03

*=non-significant covariate

Mineral Soil Carbon and Nitrogen
The pretreatment covariate was significantly related to the first posttreatment levels for each of these variables and the ANOCOVA means lead to the assumption of nonsignificant differences among the treatment means. The pretreatment covariate was also significant for the second posttreatment results and the ANOCOVA means suggest non-significant differences among the means of the treatments. The organic fraction of the mineral soil was not significantly altered by these treatments.

Extractable Elements
The pretreatment covariate was significant for all of the first posttreatment results except Na. Significant differences were found among the first posttreatment means for Ca, which appeared to be significantly lower on the mechanical-only and mechanical and burn treatments than the control (table 1). Subsequent differences in the Ca:Al molar ratio were detected as a result of the treatments (table 1).

The pretreatment covariates were not significantly related to the second posttreatment values for B, Ca, Na, and the Ca:Al molar ratio. Significant differences among treatment means were only detected for Fe, which was significantly lower on the mechanical and burn treatment than any of the other treatments (table 1).

When fuels are reduced by harvesting or burning, the reduction of material containing high concentrations of a particular element should be expected to result in declines of that element for some period of time (Wells and others 1971). However, this was not the case for all of these extractable elements with these treatments. The nonsignificant covariates for B and Na suggest the dynamic nature of these elements at any given period of time. The values present for these variables during the pretreatment period were not related to the values present during the second posttreatment period and it appears that additional factors, such as precipitation, decomposition, and organism activity, could play a role in this result.

There is no obvious explanation for the differences in Fe among treatments for the second posttreatment period other than the inherent variability for Fe in any given soil. The Ca:Al molar ratios at each time period for both locations appear to fall well below 1.0, which was suggested to be a critical threshold (Cronan and Grigal 1995). Given that this ratio was lower than 1.0 before treatment and continued to be below that value after the treatments, it appears that these practices do not increase any risk for toxicity or stress that is not already present due to inherent soil properties.

Soil pH
Soil pH was not measured prior to treatment. ANOVA means for soil pH during the first posttreatment period suggest that there were non-significant differences among the means of the treatments (table 1). The first posttreatment values served as the covariate for the second posttreatment results and they were significantly related to these values. Significant differences among the means of the treatments were detected, suggesting that soil pH was significantly higher on the control treatment than the mechanical-only treatment (table 1). This may be due to the fact that mountain-laurel and rhododendron stems were left on the ground and are slow to decompose. The total difference between values for the control and mechanical-only treatments is 0.12, which should not adversely affect regeneration or forest health.

Soil Bulk Density
The pretreatment values were significantly related to the values obtained for the first posttreatment period. Using ANOCOVA means, there were no significant differences among the means of the treatments. Soil bulk density was not measured for the second posttreatment period. Chainsaw-felling of shrubs and understory trees, with and without prescribed burning, caused no significant soil compaction.

SUMMARY AND CONCLUSIONS
The results suggest that the fuel reduction treatments had little effect on forest soil properties two to four years after treatment. Despite the fact that several differences among treatment means were detected during the first posttreatment period, these differences did not result in subsequent differences for the second posttreatment period. These soils are dynamic and variable, which is evident from the non-significant covariates present for many of the analyses and the high variability for many of the variables. Also, control means did not remain static and constant over time. Many of the variables measured are influenced by organism activity, moisture relations, temperature, and a host of other variables. The results suggest that the planning and implementation of these silvicultural treatments conserved forest soil resources at these sites.

At any location with any management objective in mind, an assessment of soil resources should be considered due to their variable nature. Fuel reduction treatments vary with regard to intensity and severity and any given soil may respond differently as a result of the factors affecting soil heating, organic matter removal or consumption, compaction, and other properties. Each site will respond differently and one definitive statement summarizing the effects of fuel reduction on soils for all sites is not practical or realistic. The goal of this project was to summarize the effects of these particular fuel reduction treatments on the soils of the Southern Appalachian Mountains and the analyses suggest that there were minimal effects noticed as a result of these treatments over a brief period of time.

LITERATURE CITED
Cronan, C.S.; Grigal, D.F. 1995. Use of calcium/aluminum ratios as indicators of stress in forest ecosystems. Journal of Environmental Quality. 24: 209-226.

Johnson, D.W.; Curtis, P.S. 2001. Effects of forest management on soil C and N storage: meta analysis. Forest Ecology and Management. 140: 227-238.

Knoepp, J.D.; Swank, W.T. 1993. Site preparation burning to improve Southern Appalachian pine-hardwood stands: nitrogen responses in soil, soil water, and streams. Canadian Journal of Forest Research. 23: 2263-2270.

Merino, A.; Edeso, J.M.; Gonzalez, M.J. [and others]. 1998. Soil properties in a hilly area following different harvesting management practices. Forest Ecology and Management. 103: 235-246.

SAS Institute, Inc. 2002. SAS user's guide: statistics. Version 9.00. SAS Institute, Inc., Cary, NC.

Stanturf, J.A.; Wade, D.D.; Waldrop, T.A. [and others]. 2002. Background paper: Fire in Southern forest landscapes. In: Wear, D.N.; Greis, J.G. Southern forest resource assessment. Gen. Tech. Rep. SRS-53. U.S. Forest Service, Southern Research Station, Asheville, NC: 607-630.

Tomcho, A.L. Effects of prescribed fire and understory removal on bird communities in a Southern Appalachian forest. M.S. Thesis. Clemson University, Clemson, South Carolina. 72p.

Soil Survey Staff, Natural Resources Conservation Service, USDA. Official Soil Series Descriptions [Online WWW]. Available URL: http://soils.usda.gov/technical/classification/osd/index.html. [Date accessed: 21 December 2005].

U.S. Forest Service. 2003. Position Papers. http://www.fs.fed.us/publications/policy-analysis/fire-and-fuels-position-paper.pdf.

Van Lear, D.H. 1985. Prescribed fire—its history, uses, and effects in southern forest ecosystems. In: Wade, D. (ed.) Prescribed fire and smoke management in the South: conference proceedings. U.S. Forest Service, Southeastern Forest Experiment Station, Asheville, NC: 57-76.

Waldrop, T.A. 2001. A national study of the consequences of fire and fire surrogate treatments-Southern Appalachian Mountains. U.S. Forest Service Study Plan SRS-4101-2008-2.

Wells, C.G.; Campbell, R.E.; DeBano, L.F. [and others]. 1979. Effects of fire on soil: a state-of-knowledge review. Gen. Tech. Rep. WO-7. U.S. Forest Service, Washington Office, Washington, DC. 34 p.

Zhou, M.; Carter, M.C.; Dean T.J. 1998. Response of soil bulk density and mineral nitrogen to harvesting and cultural treatments. In: Waldrop, T.A. (ed.) Proceedings of the ninth biennial southern silvicultural research conference. Gen. Tech. Rep. SRS-20. U.S. Forest Service, Southern Research Station, Asheville, NC: 395-400.