PRESCRIBED FIRE IMPACTS ON SOIL CARBON AND NITROGEN

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Prior to European settlement of the Mogollon Rim, ponderosa pine forests consisted of open stands of uneven-aged trees with a significant grassy understory (Sackett 1979). Light surface fires occurred on an average interval of 2–12 years in Arizona and New Mexico (Weaver 1951; Cooper 1960; Dieterich 1980). These fires consumed part of the forest floor litter, burned most of the young trees, and promoted growth of a dense, grassy understory. Crown fires were rare due to lack of ladder fuels and the widely spaced ponderosa pine canopy (Dieterich 1980:44–48; Sackett 1980). Grass fuels reduction from heavy sheep and cattle grazing in the late nineteenth century, and then forest fire suppression during much of the twentieth century, have resulted in the development of dense, overstocked stands.

Forest floor fuels most likely were less than 4 Mg/ha prior to 1870, but have since increased 10 to 100 fold (Sackett 1979; Sackett et al. 1996). Annual accumulations now are in the range of 1.3 to 7.8 Mg/ha/yr. Tree densities that were once < 130 stems/ha have increased to more than 2750 stems/ha in the densest stands (Sackett 1980; Covington and Sackett 1986). Stand basal areas have also experienced a 3- or 4-fold increase (Marlin Johnson, personal communication). Ponderosa pine stands reached a critical ecological point in the 1990s; fuel loads had built up so much that by the end of the twentieth century, wildfires burned four times the area that they did in the period from 1910 to 1990 (Neary et al. 1999).

Fires can greatly alter nutrient cycles of forest ecosystems depending on fire severity, fire frequency, vegetation, and climate (Neary et al. 1996: 107–117). Responses of total carbon (C) and nitrogen (N) are variable and depend on the site conditions and fire characteristics (DeBano et al. 1998). In most soils, the majority of the N pool is contained in the soil organic matter (OM). As would be expected, frequency of burning affects C accumulations. Prescribed fire has long been viewed as an important tool for restoring ponderosa pine stands in the Southwest (Sackett 1980; Sackett et al. 1996). The purpose of prescribed fire is to reduce forest fuels while promoting a healthy, fire-resistant, and productive forest. Sackett (1980) established a set of studies near Flagstaff, Arizona (Chimney Spring and Limestone Flats) to restore overstocked ponderosa pine stands by introducing prescribed fire at intervals of 1, 2, 4, 6, 8, and 10 years. Because ponderosa pine growth is often limited by low N availability, a major concern with frequent prescribed fire is the effect on this soil element (Powers 1980).

Nitrogen is considered the most limiting nutrient in forests. Thus it requires special consideration when managing fire, particularly in N-deficient ecosystems (Maars et al. 1983). Nitrogen is unique because it is the only soil nutrient that is not supplied to the soil by chemical weathering of rocks and sediments. Almost all N found in the vegetation, water, and soil of forests has been added from the atmosphere. The cycling of N involves a series of interrelated complex chemical and biological processes that can be disrupted by fire (DeBano et al. 1998).

Nitrogen in the soil can be severely disturbed by heating during the combustion process; volatilization is the process most responsible for N losses during fire. There is a gradual increase in N loss by volatilization as temperature increases (Knight 1966). Usually the amount of total N that is volatilized during prescribed fires is directly proportional to the amount of OM destroyed (Raison et al. 1985). Most of the volatilized N is converted to N_2 gas (DeBell and Ralston 1970). The N that is not completely volatilized either remains as part of the unconsumed fuels or is converted to ammonium nitrogen (NH_4-N) that remains in the soil (DeBano et al. 1979; Covington and Sackett 1986; DeBano et al. 1998).

Monleon et al. (1997) studied understory burns on ponderosa pine sites burned at different inter-

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vals. They found that only surface soils, 0–5 cm, showed any significant response to fire. Covington and Sackett (1986) previously examined N concentrations in the upper 5 cm of mineral soil at the Chimney Spring burning interval study (Sackett 1980). They found that mineral forms of N (NH_4-N and nitrate nitrogen, NO_3-N) made up less than 2 percent of the total N pool. Burning at 1 and 2 yr intervals significantly increased only NH_4-N levels in the soil. Total soil N in the upper 5 cm was not affected by prescribed fire interval. A later study (Wright and Hart 1997) assessed the affects of the 2 yr burning interval at the Chimney Spring site. It inferred that repeated burning at 2 yr intervals might have detrimental long-term effects on N cycling, as well as depletion of the forest floor and surface mineral soil C and N pools.

The purpose of this study was to determine the levels of total N and C in the upper 5 cm of the mineral soil at the Chimney Spring and Limestone Flats research sites 16 years after the Covington and Sackett (1986) study. Another objective of this study was to find whether additional sampling might be necessary to determine if soil C and N were related to burning frequency.

METHODS

The original study sites established in 1976 and 1977 were designed to determine the best burning interval necessary to provide continuous fire hazard reduction; the studies are described in greater detail by Sackett (1980), Covington and Sackett (1986), and Sackett et al. (1996). Sites were selected on basaltic-derived soils at Chimney Spring, Fort Valley Experimental Forest, north of Flagstaff, Arizona, and limestone-derived soils at Limestone Flats, Long Valley Experimental Forest, near Clint's Well, Arizona. Each study site has 21 plots of 1.0 ha each. There are three replications of unburned (25+ years since a previous fire) and 1, 2, 4, 6, 8, and 10 yr prescribed fire treatments. All of the burn rotation treatments, except for the 10 yr rotation and controls, were burned the previous October (2001).

The soils at both the Chimney Spring and Limestone Flats sites were sampled in late December of 2002. The initial sampling spot was located randomly within the central 400 m^2 of each plot. The next two samples were located 5 m from the first sample, selected by a randomization process, in two of the cardinal directions from the first sample. The locations were not stratified by stand structure or other site feature, as was done in the study by Covington and Sackett (1986).

About 500 g was collected from the 0–5 cm depth of the mineral soil at three locations in each plot. This amounted to nine samples for each treatment (three replications) at each of the two sites. The samples were air dried in the laboratory, ground to a size of < 2 mm, and subsampled for analysis. Sub samples were oven dried further at about 30° C.

Soil total C and N were analyzed on a ThermoQuest Flash EA1112 C-N analyzer. The computer-controlled instrument oxidizes samples at 1500° C, and determines C and N content by integration of gas chromatograph output of CO_2 and NO_2. Standards and blanks were analyzed along with the field samples to provide quality control.

The data presented here were not analyzed statistically. Only means, maximums, and minimums are presented.

RESULTS AND DISCUSSION

Carbon

For most of the burning intervals, Chimney Spring sites were higher in soil C (Figure 1). Total C levels in the Limestone Flats and Chimney Spring soil A horizons were very similar where no prescribed burning was done and in plots burned at a 4 yr interval. Concentrations at the two sites were similar between treatments, ranging from an average of 2.84 and 2.87 percent in the unburned control plots to 4.83 to 5.81 percent in the 8 yr burn interval plots (Table 1). The initial forest floor fuel loadings at the start of the study were very similar at both locations (34.0 to 34.9 Mg/ha; Sackett 1980). However, the Chimney Spring site had twice as many pole-sized and larger diameter trees (Sackett 1980). Covington and Sackett (1986) reported higher levels of N (hence C) under old-growth stands; the unstratified nature of the sampling in this study may have picked up more of these sites. Soil could also explain some of the difference between the C in the Limestone Flats and Chimney Spring soils. The latter were classified as Argiborolls belonging to the Mollisol soil order, indicating that they have naturally higher organic matter contents than the Cryoboralfs (Alfisol soil order) found at Limestone Flats.

Soil C data appear to show increasing amounts of C in the soil with prescribed fire up to a burn interval of 8 yr (Figure 1). The increasing amounts of C resulting from burning would most likely correlate with the additional accumulations of fuels due to the greater length of time between treatments. Monleon et al. (1997) studied understory fires on ponderosa pine sites that burned at

Table 1. Soil carbon and nitrogen percentages at 0–5 cm depth at the Limestone Flats and Chimney Spring sites, by prescribed fire interval.

	Soil Carbon			Soil Nitrogen		
Fire Interval	Min	Max	Mean[1]	Min	Max	Mean[1]
Limestone Flats						
1	2.22	4.79	3.31	0.16	0.25	0.20
2	1.27	8.57	2.87	0.07	0.38	0.18
4	2.01	6.10	4.29	0.13	0.31	0.27
6	1.96	4.70	3.19	0.11	0.26	0.19
8	1.80	9.68	4.83	0.15	0.43	0.30
10	1.60	9.34	3.46	0.10	0.55	0.23
25+[2]	1.43	3.95	2.84	0.12	0.23	0.18
Chimney Spring						
1	2.02	9.03	4.74	0.13	0.53	0.28
2	1.78	9.72	3.55	0.18	0.50	0.25
4	1.74	8.04	4.30	0.10	0.52	0.33
6	2.47	9.96	4.69	0.18	0.42	0.27
8	2.25	12.24	5.81	0.17	0.55	0.36
10	3.23	8.13	5.48	0.15	0.45	0.34
25+[2]	1.43	3.95	2.84	0.12	0.23	0.18

[1]Means calculated from 9 samples (3 in each of 3 replications).
[2]Plots not burned since the beginning of the study.

intervals up to 12 yr. They found that significant responses to fire occurred only in the surface soils (0–5 cm), and that there were no differences between unburned sites and sites burned at a 12 yr interval. These data reflect the variability in soil C produced by a random sampling approach. Noticeable differences in soil color, indicating higher and lower levels of soil C, were noted during the sampling of the 0–5 cm mineral soil depth. Maximum soil C percentages varied by a factor of two between burning intervals and were two to six times greater than minimum levels (Table 1). With one exception (Limestone Flats 2 yr interval), it appears that the prescribed fires reintroduced into the two sites have increased soil C.

Sackett et al. (1996) concluded that the best burning interval was 4 years for reducing fuel loads. The C trend indicates that the best interval for increasing soil C appears to be 8 years, at both sites included in this study. A complete statistical analysis needs to be done to verify this trend and the differences between burned and unburned plots.

Nitrogen

Total N levels followed the same trends as total soil C (Figure 2). Total N concentrations were mostly higher across the range of burning. Concentrations increased from an average of 0.18–0.19 percent in the unburned control plots to 0.30–0.36 percent in the 8 yr burn interval (Table 1). Soil total N is usually correlated with total C because most of the A horizon soil N pool is tied up in organic matter (Figure 3; see also Maars et al. 1983). Covington and Sackett (1986) reported that less than 2 percent of the soil N measured in their mid 1980s sampling was mineralized N. The data from this sampling do not support Wright and Hart's (1997) hypothesis that burning at 2 yr intervals at Chimney Spring may have detrimental long-term effects on N cycling. At the Limestone Flats site, soils collected from the 2 and 6 yr burn intervals were virtually the same as the unburned control. The soil N pool at either site does not provide a readily available source of N to plants and microorganisms because of the slow decomposition rates in these semi-arid ecosystems (DeBano et al. 1998). This limitation, rather than any declines in the total soil N pool, may account for the N enigma (potential loss of total N but stimulation of plant growth) that DeBano et al. (1998) have discussed.

Prescribed fire appears to increase soil N, but the response was not as great at Limestone Flats as at Chimney Spring. Like soil C, the highest levels of soil total N were measured in the 8 yr interval plots. The variability in soil N seen in the 2 and 6 yr burn interval plots (Table 1) is due to the same factors that affected soil C.

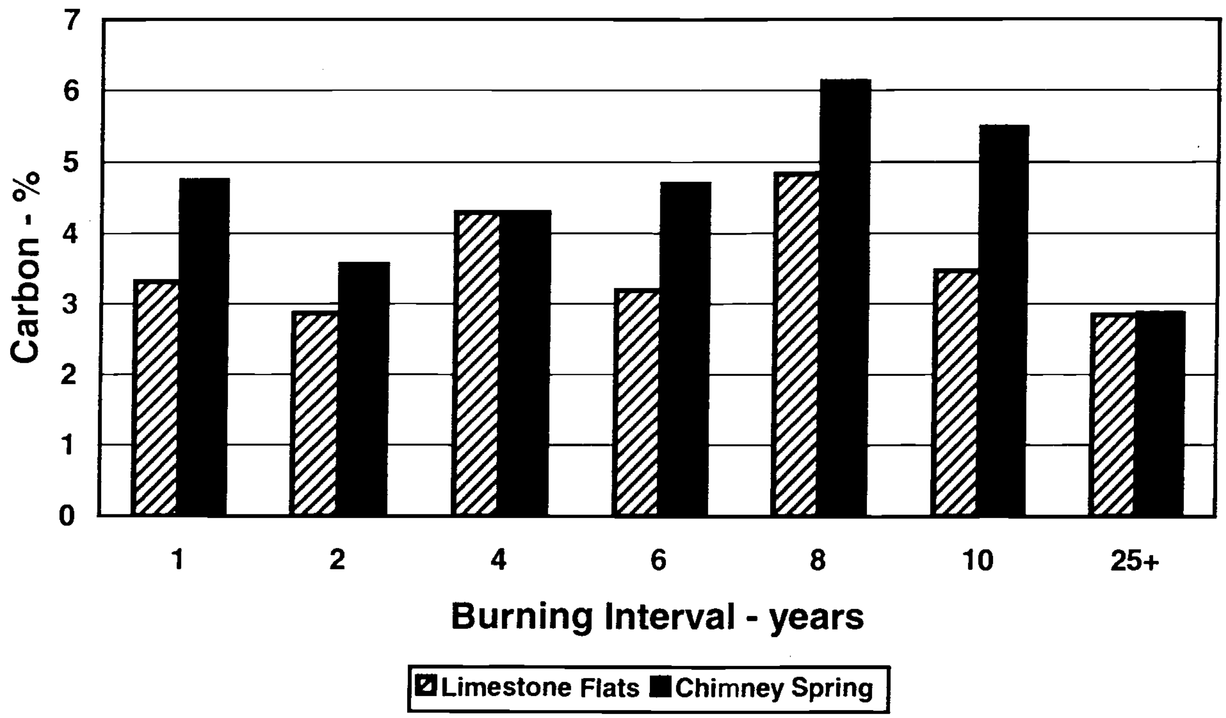

Figure 1. Limestone Flats and Chimney Spring, Arizona, burning interval study soil carbon, December of 2001.

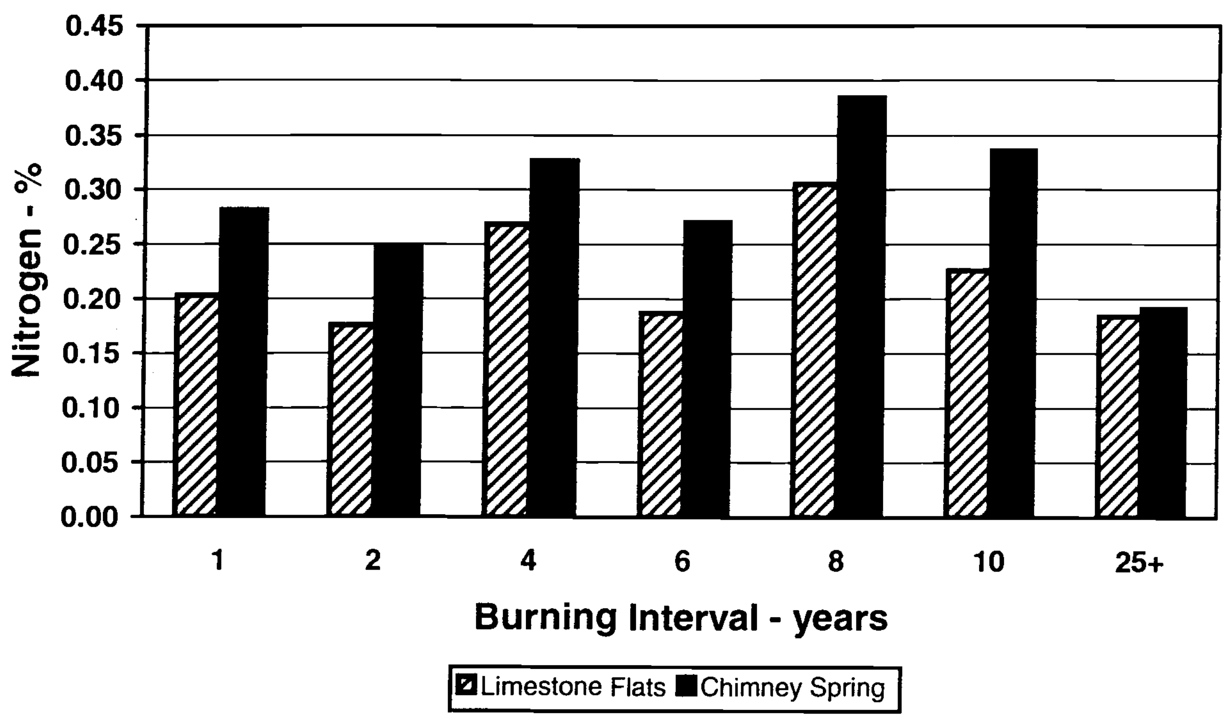

Figure 2. Limestone Flats and Chimney Spring, Arizona, burning interval study soil nitrogen, December of 2001.

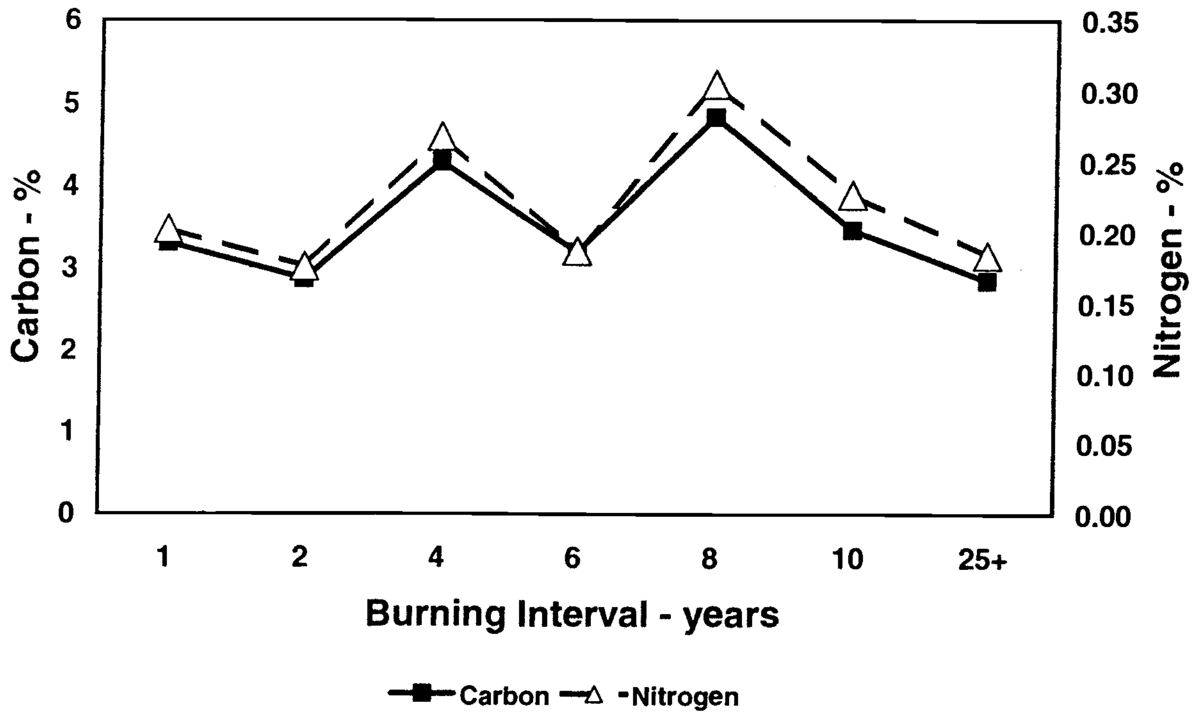

Figure 3. Carbon and nitrogen correlation by burning interval.

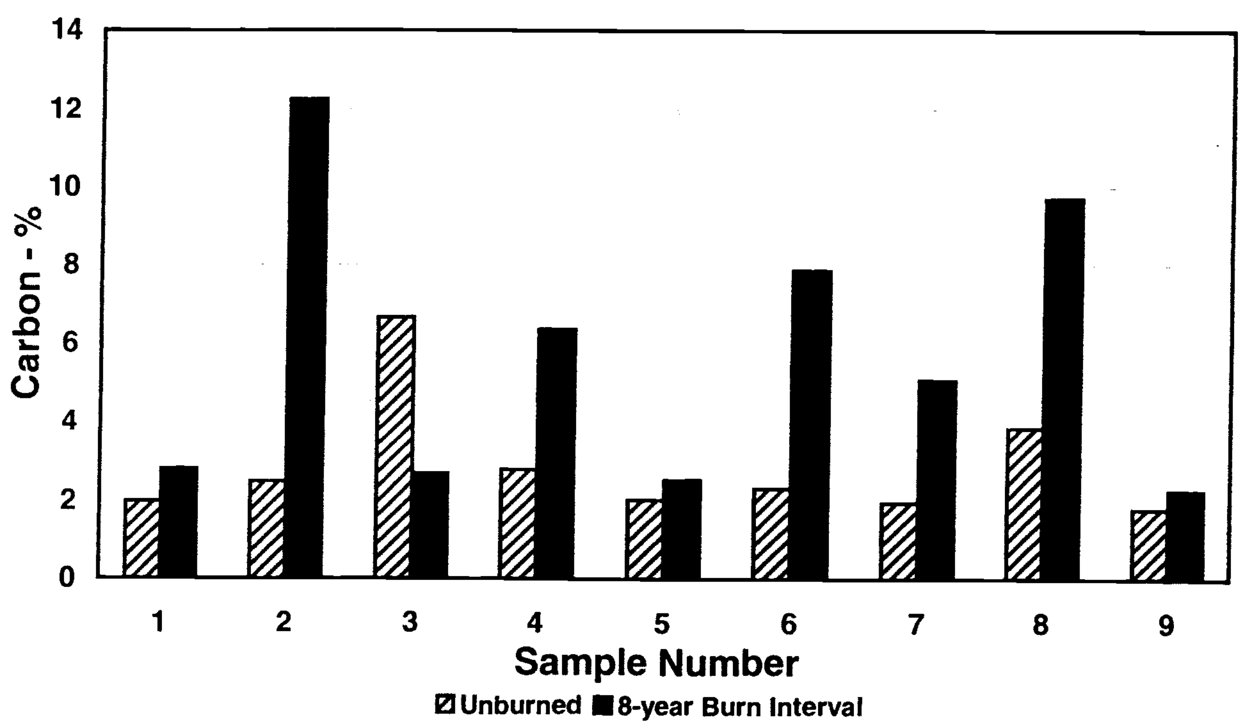

Figure 4. Soil carbon variability, Chimney Spring, Arizona, unburned and 8 yr interval plots, December of 2001.

Sample Variability

The mixed C and N response in this burning interval study was most likely affected by fire and site variability, and the lack of stratification by stand type and condition. Factors that produce such variability include fire temperature and duration, inherent differences in the mineral soil, unequal forest floor fuel loads, stand type (saplings, poles, old growth), understory vegetation, degree of combustion of forest floor fuels, subsampling of field samples, and analytical variability. To obtain an understanding of the variability in soil total C and N at the two sites, individual plot and sample data from the least and most variable plots are quite instructive. Total C values from Chimney Spring 8 yr and control plots are presented in Figure 4. The burning intervals and control samples do not represent any sort of pairing, only an ordering from 1 to 9.

The 8 yr burning interval plots at Chimney Spring had the highest variability. Soil total C ranged from 2.25 to 12.24 percent, a span of 9.99 percent. The unburned control plot samples at Chimney Spring had a range from 1.78 to 6.66 percent, a span (4.88%) over half of the burned plot range.

The total C and N variability observed from the random samples at the Chimney Spring and Limestone Flats sites was probably influenced by a number of factors. It was very evident during the sampling that there were visually apparent differences in the levels of litter accumulations and OM concentrations in the mineral soil under these three different stand types. In addition to stand type (old growth, poles, and sapling thickets), several other factors appeared to be important. Samples collected in the middle of clearings and next to decaying but not completely burned logs had visually apparent differences in color that reflected OM content. Another factor that could be important, but was not readily discernible on the ground, was the presence of "hot spots" where dead and decaying logs were at some point in time completely combusted by the prescribed fires. These logs would create zones of high fire severity that would burn much of the soil OM and drive off most of the surface mineral soil N (DeBano et al. 1998).

Our recommendation to follow up this study is to resample using Covington and Sackett's (1986) stand classification approach (i.e. sawtimber, poles, and saplings), but adding in areas such as clearings, slash, decaying logs, and high-severity burn spots. Although stand type would facilitate scaling up to stand and landscape levels, the other categories would not. Using a composite sample of several cores would also aid in the leveling of variability of the samples. For that reason, unstratified sampling is still of interest. Statistical analysis is still needed to determine sample sizes needed to detect differences between the individual burning intervals.

SUMMARY AND CONCLUSIONS

The effects of introducing prescribed fire at different intervals in ponderosa pine stands on total C and N concentrations in the upper 5 cm of the A horizon of two different soil types were examined. The burning intervals (0, 1, 2, 4, 6, 8, and 10 yr) were established by researchers in 1976 and 1977, and have been maintained thereafter (Sackett 1980; Sackett et al. 1996). This study determined that burning increased mineral soil C and N. It is recommended that the study be repeated with contrasting stratified sampling and higher intensity random sampling approaches. Sampling near the locations used in previous studies would be useful if those locations can be located again.

ACKNOWLEDGMENTS

A special note of thanks is extended to several individuals: Mr. David Brown, Flagstaff High School, for his encouragement of the senior author in her pursuit of knowledge of environmental chemistry, Mr. Dan Cardone for analysis of the soil samples, Dr. Steve Sackett for setting up and maintaining the original study sites, and Mrs. Vicki Neary for assistance with field sampling.

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