Effects of Fire Interval Restoration on Carbon and Nitrogen in Sedimentary- and Volcanic-Derived Soils of the Mogollon Rim, Arizona

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Abstract—*Prescribed fire was returned into over-stocked ponderosa pine stands on the Mogollon Rim of Arizona for the purpose of restoring fire into the ecosystem and removing fuel buildups. Prescribed fires have been ignited at intervals of 1, 2, 4, 6, 8, and 10 years to determine the best fire return interval for Southwestern ponderosa pine ecosystems. Two sites were treated: one on volcanic-derived soils, and the other on sedimentary-derived soils near Flagstaff, Arizona, starting in 1976 and 1977 respectively. Samples from upper 5 cm of the A horizons were analyzed for total carbon and nitrogen using an elemental analyzer. Soil carbon and nitrogen levels were highly variable and exhibited an increasing, but inconsistent, concentration trend related to burn interval. High spatial variability measured within treatments is probably due to micro-site differences (location of samples in the open, under large old-growth trees, in small-diameter thickets, in pole-sized stands, next to downed logs, etc.). Stratification of samples by micro-site differences could possibly reduce the within-plot variability but add considerable complexity to the sampling design.*

Introduction

The pre-European settlement ponderosa pine forests of the Mogollon Rim consisted of open stands of uneven-aged trees with a significant grass-forb understory. Light surface-fires occurred on an average interval of 2 to 12 years in Arizona and New Mexico (Weaver 1951, Cooper 1960, Dietrich 1980). These fires consumed forest floor material, burned most of the young regeneration, and promoted growth of a dense, grassy understory. Catastrophic crown fires were rare due to the lack of ladder fuels and the clumpy, widely spaced ponderosa pine canopy (Dieterich 1980, Sackett 1980). Fine fuels reduction from heavy sheep and cattle grazing and then modern forest fire suppression resulted in the development of dense, overstocked stands.

Forest floor fuel loads that were 0.4-4.5 Mg/ha prior to 1870 have since increased by one to nearly two orders of magnitude. Average loadings of naturally fallen fuels were 49 Mg/ha two decades ago with some stands accumulating up to 112 Mg/ha (Sackett 1979, Sackett et al. 1996). Annual accumulations since then have been in the range of 1.3 to 7.8 Mg/ha/yr. Tree densities that were once <130 stems/ha have increased dramatically, especially in dense thickets with more than 2,750 stems/ha (Sackett 1980, Covington and Sackett 1986). Stand basal areas that were <11.5 m^2/ha prior to removal of fire from ponderosa pine stands on the Mogollon Rim have since increased by a three- or four-fold factor (Marlin Johnson, personal communication). Ponderosa pine stands reached a critical ecological point in 1991. Fuel loads had so increased that by the end of the 20th century wildfires

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consumed four times the area that they did in the period from 1910 to 1990 (Neary et al. 1999).

Carbon and Nitrogen in Ponderosa Pine Ecosystems

Fires can greatly alter nutrient cycles of forest ecosystems depending on fire severity, fire frequency, vegetation, and climate (Neary et al. 1996). Responses of total C and N are variable and depend on the site conditions and fire characteristics. In most soils, the majority of the N pool is contained in the soil organic matter (OM). Mineral forms of N are usually lower but respond to fire. For example, Grove et al. (1986) found no change in organic C in the surface 0-1.2 in (0-3 cm) of soil immediately following burning; however, percent total N increased. Knoepp and Swank (1993) found no consistent response in total N in the upper soil layer, but increases in ammonium N (NH_4-N) concentrations and N mineralization occurred on areas where a burning treatment followed felling.

As would be expected, frequency of burning affects C accumulations. A study was carried out on tropical savanna sites in Africa having both clay and sandy soils that were burned repeatedly every 1, 3, or 5 years (Bird et al. 2000). While the clay sites had greater total C than did the sandy soils, they responded similarly to burning. All unburned sites had 40-50 percent greater C than burned sites. Low frequency burning (every 5 years) resulted in an increase in soil C of about 10 percent compared to the mean of all burned areas. High frequency burning (every year) decreased C about 10 percent. In another study, Wells et al. (1979) reported the results of a 20-year burning study in a pine plantation in South Carolina. They found that periodic burning over a 20-year period removed 27 percent of the forest floor. Annual burning conducted in the summer removed 29 percent of the forest floor as compared to a 54 percent loss resulting from winter burning. The total OM content of the surface soil (0-5 cm) increased in all cases but there was no effect on the 5-10 cm soil layer. Interestingly, when they summed the OM in the forest floor and in the surface 0-10 cm of soil they found that these low-severity periodic burns sites had not reduced, but only redistributed the OM.

Nitrogen in Ponderosa Pine Ecosystems

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 fuel loads while promoting a healthy, fire-resistant, and productive forest. Sackett (1980) established a set of studies near Flagstaff, Arizona (Chimney Springs and Limestone Flats), to restore overstocked ponderosa pine stands by introducing prescribed fire at 1-, 2-, 4-, 6-, 8-, and 10-year intervals. Since ponderosa pine growth is often limited by low nitrogen (N) availability, a major concern with frequent prescribed fire is the effect on soil N pools (Powers 1980).

Nitrogen is considered the most limiting nutrient in wildland ecosystems and as such it requires special consideration when fire is managed, 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 parent material. Almost all N found in the vegetation, water, and soil of wildland systems has to be added to the system from the atmosphere. The cycling of N involves a series of interrelated complex chemical and biological processes.

Nitrogen pools can be severely disturbed by soil heating during the combustion process. Volatilization is the chemically driven process most responsible

Table 1—Soil nitrogen loss with increasing temperature (adapted from DeBano et al. 1998).

Stage	Soil temperature (° C)	Soil N loss (%)
1	<200	None
2	200-300	25-50
3	300-400	50-75
4	400-500	75-100
5	>500	100

for N losses during fire. There is a gradual increase in N loss by volatilization as temperature increases (Knight 1966, White et al. 1973). The amount of N loss at different temperatures follows the heating sequence shown in table 1. As a general rule the amount of total N that is volatilized during combustion is directly proportional to the amount of OM destroyed (Raison et al. 1985a). It has been estimated that almost 99 percent of the volatilized N is converted to N_2 gas (DeBell and Ralston 1970). At lower temperatures N_2 can be produced during OM decomposition without the volatilization of N compounds (Grier 1975). The N that is not completely volatilized either remains as part of the unconsumed fuels or it is converted to highly available ammonium nitrogen (NH_4-N) that remains in the soil (DeBano et al. 1979, Covington and Sackett 1986, DeBano 1991).

Estimates of the total N losses during prescribed fire must be based on both fire behavior and total fuel consumption because irregular burning patterns are common. As a result, combustion is not complete at all locations on the landscape (DeBano et al. 1998). For example, total N loss was studied during a prescribed burn in southern California (DeBano and Conrad 1978). In this study, only 10 percent of the total N contained in the plant, litter, and upper soil layers was lost. The greatest loss of N occurred in aboveground fuels and litter on the soil surface. In another study of N loss during a prescribed fire over dry and moist soils, about two-thirds of the total N was lost during burns over dry soils compared to only 25 percent when the litter and soil were moist (DeBano et al. 1979). Although these losses were relatively small, it must be remembered that even small losses can adversely affect the long-term productivity of N-deficient ecosystems.

Monleon et al. (1997) conducted understory burns on ponderosa pine sites burned 4 months, 5 years, and 12 years previously. The surface soils, 0 to 5 cm, showed the only significant response. The 4-month burned sites had increased total C and inorganic N following burning, and an increased C / N ratio. Burning the 5-year-old sites resulted in a decrease in total soil C and N, and a decrease in the C / N ratio. Total soil C and N in the surface soils did not respond to burning on the 12-year-old site.

Nitrogen Losses — An Enigma

It has been conclusively established by numerous studies that total N is decreased as a result of combustion (DeBano et al. 1998). The amount of N lost is generally proportional to the amount of OM combusted during the fire. The temperatures at which N is lost are discussed above. In contrast, available N is usually increased as a result of fire, particularly NH_4-N (Christensen 1973, DeBano et al. 1979, Carballas et al. 1993). This increased N availability enhances post-fire plant growth, and gives the impression that more total N is present after fire. Increased fertility, however, is misleading and short-lived. Temporary increase in available soil N following fire is usually rapidly utilized by plants and microorganisms in the first few years after burning.

The consequences of N losses during fire on ecosystem productivity depend on the proportion of total N lost for a given ecosystem (DeBano et al. 1998). In N-limited ecosystems even small losses of N by volatilization can impact long-term productivity. Consequently, a key ecosystem parameter that has been studied in the ponderosa pine restoration study established by Sackett (1980) is N.

Covington and Sackett (1986, 1992) examined N concentrations in the upper 5 cm of mineral soil at the Chimney Springs burning interval study (Sackett 1980). They found that mineral forms of N (NH_4-N and NO_3-N) made up <2% of the total N pool. Burning at 1- and 2-year 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 effects of the two-year burning interval at the Chimney Springs site. It inferred that repeated burning at two-year intervals may have detrimental long-term effects on N cycling, along with depletion of the forest floor and surface mineral soil C and N pools.

Methods

Study Sites

The original study sites established in 1976 and 1977 were designed to determine the optimum-burning interval necessary to provide continuous fire hazard reduction. These studies are described in greater detail by Sackett (1980), Covington and Sackett (1986), and Sackett et al. (1996). Sites were selected on volcanic soils at Chimney Springs, Fort Valley Experimental Forest, north of Flagstaff, Arizona, and sedimentary soils at Limestone Flats, Long Valley Experimental Forest, near Clint's Well, Arizona. Twenty-one 1.0 ha plots make up each study site. There are three replications of unburned (control), and 1-, 2-, 4-, 6-, 8-, and 10-year prescribed fire treatments. All of the burn rotation treatments, except for the 10-year rotation and controls, were burned the previous October (2001).

Chimney Springs

The Chimney Springs study is located in the Fort Valley Experimental Forest, Rocky Mountain Research Station, Coconino National Forest about 3 km northwest of Flagstaff, Arizona. Soils are Brolliar stony clay loam, a fine, smectic, frigid Typic Argiboroll derived from basalt and cinders (Meurisse 1971). Stand structure and fuels are described by Sackett (1980). The original ponderosa pine stand was virtually undisturbed by wildfire since 1876 but was grazed in the late 19th century and placed under fire control. At the initiation of the study, the ponderosa pine stand consisted of reproduction (976 stems / ha), saplings (2,752 stems / ha), pole-sized trees (771 stems / ha), and old growth (dbh >28 cm, 133 stems / ha). The basal area was 33.0 m^2 / ha in trees >10 cm dbh. The original fuel load of dead surface and ground fuels was 34.0 Mg / ha.

Limestone Flats

The Limestone Flats study is located in the Long Valley Experimental Forest, Rocky Mountain Research Station, Coconino National Forest, about

2 km northwest of Clint's Well, Arizona. Soils are very fine sandy loam textured, fine, smectic, Typic Cryoboralfs. These soils developed from weathered sandstone with limestone inclusions. Stand structure and fuels are described by Sackett (1980). The original ponderosa pine stand was treated with a sanitation cutting in the mid 1960s to remove trees attacked by insects and disease. It was also grazed in the late 19th century, and placed under fire control, but grazing had been eliminated many years prior to 1976. The ponderosa pine stand consisted of reproduction (1,373 stems / ha), saplings (2,881 stems / ha), pole-sized trees (388 stems / ha), and old growth (dbh >28 cm, 82 stems / ha). The basal area was 22.5 m^2 / ha in trees >10 cm dbh. The original fuel load of dead surface and ground fuels was 34.9 Mg / ha.

Soil Sampling

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

Approximately 500 g was collected from the 0-5 cm depth of the mineral soil. The samples were air dried in the laboratory, sieved to a size of <2 mm, and sub-sampled for analysis. Sub samples were ground to a 40 mesh particle size then oven dried at 40^o C.

Carbon and Nitrogen Analysis

Soil total C and N were analyzed on a Thermo-Quest Flash EA1112 C-N analyzer. The computer-controlled instrument oxidizes samples at 1,500^o C, separates CO_2 and NO_2, by gas chromatography on a packed column, and determines C and N content with a thermal conductivity detector. Analysis was performed using a standard protocol for this instrument, which includes blanks, certified soil standards, and quality control samples during operations.

Statistical Analysis

Data were analyzed using the SAS univariate ANOVA under the GLM Procedure (SAS 2000) and Tukey's Studentized Range test for means separation of C and N values ($p = 0.05$). The plot design is 6 treatments (burn intervals 1, 2, 4, 6, 8, 10 years) and a control (unburned) times 3 replicates of each treatment and control.

Results and Discussion

Carbon

Total soil C levels in the Limestone Flats and Chimney Springs 0-5 cm horizon exhibit two trends (figure 1). The first is that soil C is significantly higher at Chimney Springs (table 2). The initial forest floor fuel loading (34.0 Mg / ha) was actually lower than the Limestone Flats loading (34.9 Mg / ha). At the start of the study in 1976, the Chimney Springs site had a higher basal area and nearly double the density of pole and old growth trees (Sackett 1980). Covington and Sackett's (1986) stratified sampling indicated higher levels of

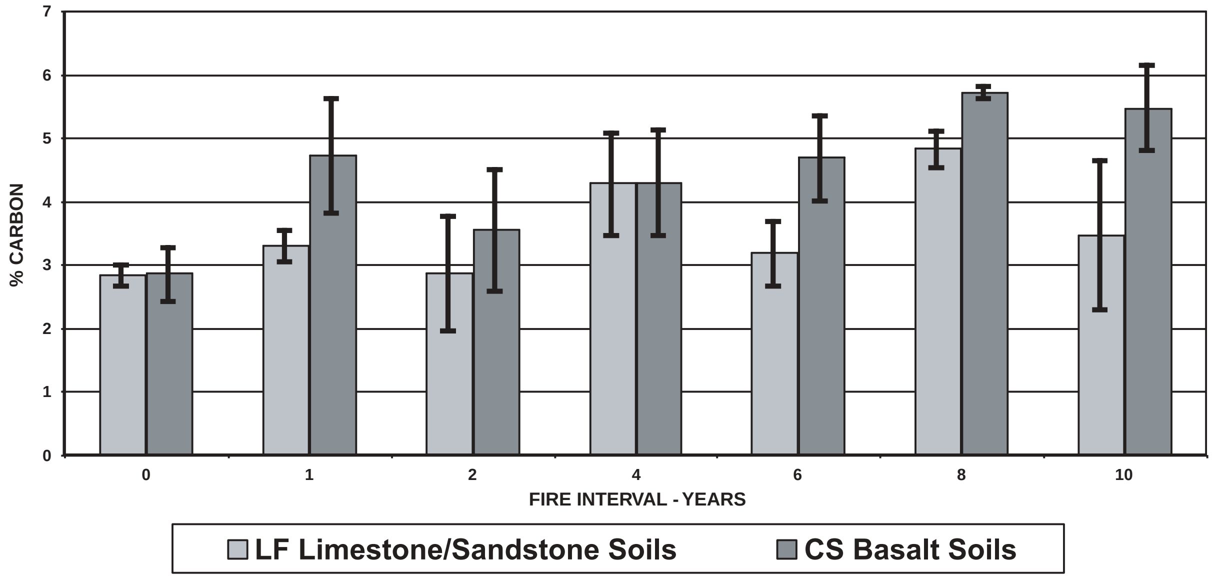

Figure 1—Effect of fire interval on soil total carbon (mean and standard error), Limestone Flats and Chimney Springs burning interval study, Arizona.

Table 2—Studentized Tukey's test for C and N by location, Limestone Flats and Chimney Springs, Arizona, burning interval restoration studies.

Element	Location	Mean (%)	Tukey's test (p = 0.05)	N
Carbon	Limestone Flats	3.543	A	21
	Chimney Springs	4.478	B	21
Nitrogen	Limestone Flats	0.221	A	21
	Chimney Springs	0.287	B	21

N (hence C) in old-growth stands. The random nature of the sampling in this study may have picked up more of the sites at Chimney Springs that Covington and Sackett (1986) identified as "sawtimber" (old growth). Soil classification also explains the difference between the carbon in the Limestone Flats and Chimney Springs 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.

The second trend in the soil C data appears to be that burning at the 8-year interval produced statistically significant higher soil C levels than the controls and that burning in general increases total C in the mineral soil (table 3). The C concentration in the soil increased from 2.856% in the control to 5.277% in the 8-year burning interval. However, only the control and 8-year interval are statistically different. These data reflect more of the variability in soil C detected in this random sampling approach than any burning interval trend. It is evident 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. That interval produced the intermediate C level in the 0-5 cm depth of the mineral soil.

Nitrogen

Total soil N levels followed a similar trend as total soil C (figure 2). Total soil N concentrations were mostly higher across the range of burning

Table 3—Studentized Tukey's test for C and N by treatment, Limestone Flats and Chimney Springss, Arizona, burning interval restoration studies.

Element	Burning interval (years)	Mean (%)	Tukey's test (p = 0.05)	N
Carbon	0	2.856	A	6
	2	3.210	AB	6
	6	3.942	AB	6
	1	4.024	AB	6
	4	4.294	AB	6
	10	4.476	AB	6
	8	5.277	B	6
Nitrogen	0	0.188	A	6
	2	0.212	A	6
	6	0.228	AB	6
	1	0.242	AB	6
	10	0.281	AB	6
	4	0.298	AB	6
	8	0.330	B	6

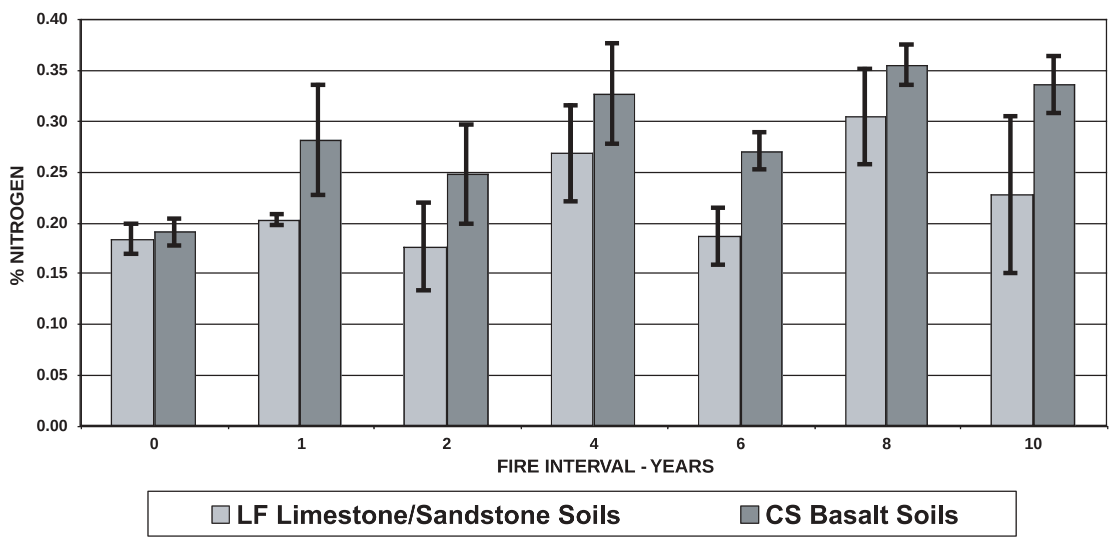

Figure 2—Effect of fire interval on soil total nitrogen (mean and standard error), Limestone Flats (LF) and Chimney Springs (CS) burning interval study, Arizona.

intervals. Concentrations increased from an average of 0.188% in the control plots to 0.330% in the 8-year burning interval (table 3). Soil N at Chimney Springs with Typic Argiboroll soils was significantly different from Limestone Flats with Cryoboralf soils (table 2). Significant differences in total N concentrations where found between control and 2-year burning interval and the 8-year burning interval plot (table 3).

Covington and Sackett (1986) reported that <2% of the soil N measured in their mid 1980s sampling was mineralized N (NH_4-N and NO_3-N). The data from this sampling conflict with Wright and Hart's (1997) hypothesis that burning at 2-year intervals may have detrimental long-term effects on N cycling, along with depletion of the forest floor and surface mineral soil C and N pools. The 2-year burning interval was not significantly different from the control or other burning intervals, only the 8-year burning interval. Wright and Hart (1997) did not investigate the 1-year burning interval, yet our sampling showed it to be at an intermediate level of N in the 0-5 cm horizon. The

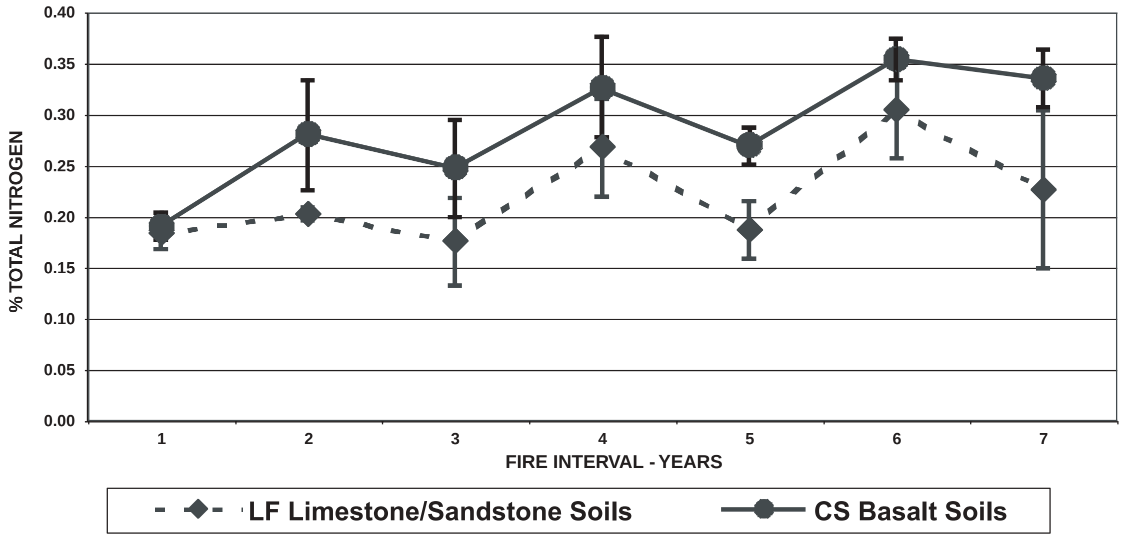

Figure 3—Total nitrogen (mean and standard error) in the A horizon for the Limestone Flats (LF) and Chimney Springs (CS) burning interval study, Arizona.

soil N pool does not provide a readily available source of N to plants and microorganisms because of the slow decomposition rates in these semi-arid ecosystems. This limitation, rather than any declines in the total soil N pool, may account for the N enigma that DeBano et al. (1998) discuss.

Sample Variability

The lack of a strong burning interval response in this study was most likely affected by site variability and the random sampling used. To obtain an understanding of the variability in soil total C and N, individual plot data is quite instructive (figure 4).

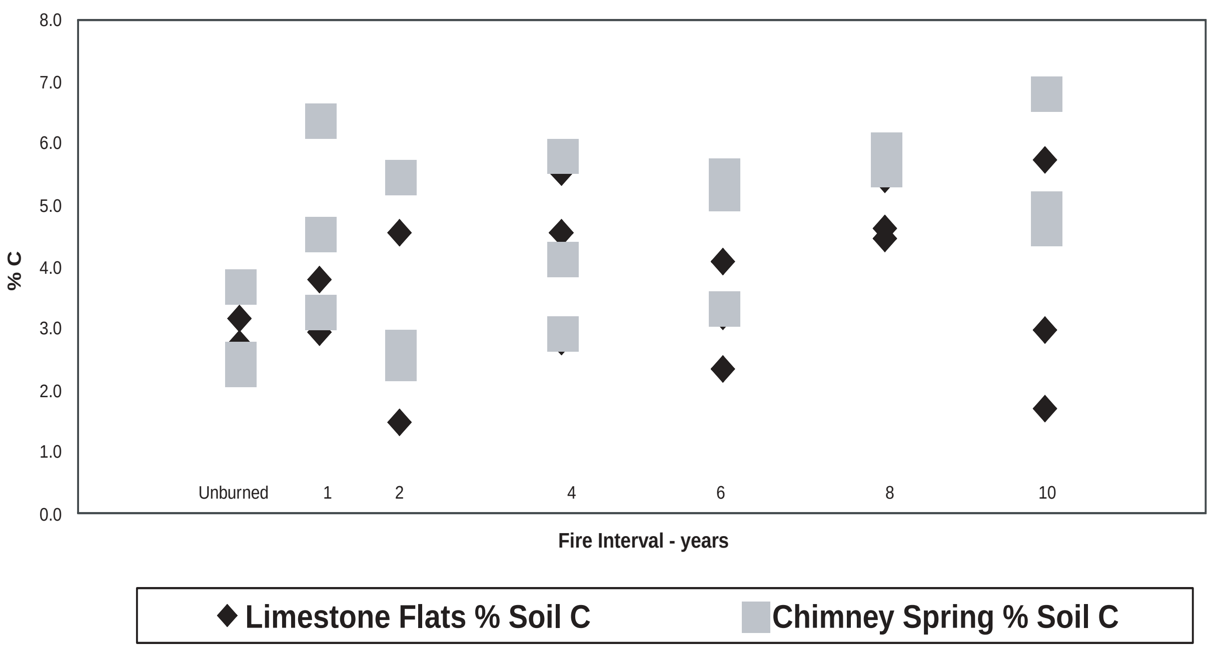

Figure 4—Variability in percent C in mineral soil, Limestone Flats and Chimney Springss burning interval study, Arizona.

The 1-year burning interval plot samples for total C at Limestone Flats ranged from 2.933% to 3.796%, a span of 0.863%. The unburned control samples had a range from 2.630% to 3.160%, a similar span of 0.530%. The 10-year burning interval plots at Limestone Flats had the highest variability. Total soil C in the 0 to 5 cm depth ranged from 1.717% to 5.709%, a span of 3.991%. The unburned control plot samples at Chimney Springs had a range from 2.367% to 3.711%, a span (1.344%) nearly triple that of the Limestone Flats control. Within plot variability was much higher at Chimney Springs than at Limestone Flats (figure 4).

The total C and N variability observed from the random samples at the Chimney Springs and Limestone Flats sites was probably influenced by a number of factors. Covington and Sackett (1986) stratified their sampling at Chimney Springs by stand type (e.g., sawtimber, poles, and saplings). It was very evident during the sampling that there were visually evident differences in the levels of litter accumulations and OM concentrations in the mineral soil under these three different stand types. In addition, 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 discernable on the ground, is 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 as a follow-up to this study is to resample using Covington and Sackett's (1986) stand classification approach (i.e., sawtimber, poles, and saplings), but add in areas such as clearings, decaying logs, and high-severity burn spots. Using a composite sample of several cores would also aid in the leveling of variability of the samples. While the classification does allow easy scaling up to stand and landscape levels, the other categories do not. That is why random sampling is still of interest. Some work is still needed to determine sample sizes needed to detect differences between the individual burning intervals, if such differences exist at all.

Summary and Conclusions

The effects of burning intervals for restoration of ponderosa pine stands on total C and N concentrations in the 0-5 cm horizon of two different soil types was examined. The burning intervals (unburned, 1, 2, 4, 6, 8, and 10 years) were provided by a study established in 1976 and 1977 and have been maintained thereafter (Sackett 1980, Sackett et al. 1996). Although there were statistically significant differences between the total C levels in soils of the unburned plots and the 8-year burning interval, there were no differences between burning intervals. There also was a statistically significant difference between unburned and 2-year burning interval and the 8-year burning interval in total soil N. This study determined that burning increased mineral soil C and N, which conflicted with Wright and Hart's (1997) contention that the 2-year burning interval could deplete soil N and C pools. This study did not examine the mineral fractions of the soil N pool, NH_4-N, and NO_3-N. Although the mineral forms of N are small (<2 % of the total soil N pool), they are very important for plant nutrition and microorganism population functions. It is recommended that the study be repeated contrasting stratified sampling and higher intensity random sampling approaches.

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