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EFFECTS OF PRESCRIBED FIRE INTERVALS ON CARBON AND NITROGEN IN FOREST SOILS OF THE MOGOLLON RIM, ARIZONA

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1. 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 (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 lack of ladder fuels, and the clumpy, widely spaced ponderosa pine canopy (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 the 49 to 112 Mg/ha range (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, with denser thickets of 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 consumed four times the area that they did in the period from 1910 to 1990 (Neary et al. 1999).

1.1 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, DeBano et al. 1998). Responses of total carbon (C) and nitrogen (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 low in forest soils. But total N changes in response to prescribed fire are variable (Grove et al. 1986, Knoepp and Swank 1993, Covington and Sackett 1986).

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 which were burned repeatedly every 1-, 3-, or 5-years (Bird et al. 2000). Low frequency burning (every 5-years) resulted in an increase in soil C of about 10% compared to the mean of all burned areas. High frequency burning (every year) decreased C about 10%. 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 increased the total organic matter (OM) content of the surface soil (0-5 cm) but had 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.

1.2 Nitrogen in Ponderosa Pine Ecosystems

Prescribed fire has long been viewed as an important tool for restoring ponderosa pine stands in the Southwest (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 Spring and Limestone Flats), to restore overstocked ponderosa pine stands by introducing

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prescribed fire at 1-, 2-, 4-, 6-, 8-, and 10-year intervals. Since ponderosa pine growth is often limited by low 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 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 parent material. Almost all N found in the vegetation, water, and soil of wildland ecosystems 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 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 starts at 200° C and is 100% at 500° C. 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% of 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% 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% 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. A study by Monleon et al. (1997) of ponderosa pine understory burns showed that only the surface soils, 0 to 5cm, had any significant response. Sites burned at a 4-month interval increased total C and inorganic N following burning. Fires at a 5-year interval resulted in a decrease in total soil C and N, and a decrease in the C/N ratio. Total soil C and N did not change with a 12-year interval.

1.3 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). 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 increases in available N in the soil following fire are 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 was studied in the burning interval study established by Sackett (1980) is N. Covington and Sackett (1986) examined N levels in the upper 5 cm of mineral soil at the Chimney Spring study. They found that mineral forms of N (NH_4-N and NO_3-N) made up less than 2% of the total N pool. Burning at 1- and 2-year intervals significantly increased only NH_4-N levels. 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 two-year burning interval at the Chimney Spring 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.

2. METHODS

2.1 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. The 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, 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 Spring

The Chimney Spring 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 stony clay loam textured fine montmorillonitic, frigid, Typic Argiborolls derived from basalt and cinders. Stand structure and fuels were described by Sackett (1980). The original ponderosa pine stand was virtually undisturbed from 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 (d.b.h greater than 28 cm, 133 stems/ha). The basal area was 33.0 m^2/ha in trees larger than 10 cm d.b.h. 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, Coconin National Forest, about 2 km northwest of Clint's Well, Arizona. Soils are very fine sandy loam textured, fine montmorillonitic Typic Cryoboralfs. These soils developed from weathered sandstone with limestone inclusions. Stand structure and fuels were 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 (d.b.h greater than 28 cm, 82 stems/ha). The basal area was 22.5 m^2/ha in trees greater than 10 cm d.b.h. The original fuel load of dead surface and ground fuels was 34.9 Mg/ha.

2.2 Soil Sampling

The soils at both the Chimney Spring and Limestone Flats sites were sampled in late December, 2002. The initial sampling location was located randomly 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 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. The samples were air dried in the laboratory, ground to a size of < 2 mm, and sub-sampled for analysis. Sub samples were oven dried further at about 30^o C.

2.3 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, 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.

2.4 Statistical Analysis

Data were analyzed using the SAS univariate ANOVA under the GLM Procedure (SAS 2000). The ANOVA was robust enough to be useful without data transformation. Tukey's Studentized Range test was used for means separation of C and N values ($p = 0.05$).

3. RESULTS AND DISCUSSION

3.1 Carbon

Total C levels in the Limestone Flats and Chimney Spring soil A horizons exhibit two trends (Figure 1). The first is that soil C is significantly higher at Chimney Spring (intervals 0, 2, 6, 8, and 10; Table 1). 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 Spring 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 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 Spring that Covington and Sackett (1986) identified as "sawtimber" (old growth). Soil classification also explains the difference between the carbon in the LimestoneFlats 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.

The second trend in the soil C data appears to be one of increasing amounts up to burn interval 8-years which would indicate the influence of the fire. It would be expected that the 10-year rotation would continue this trend if it had been burned. The increasing amounts of C resulting from the fire would most likely correlate with the additional accumulations of fuels due to the length of time between treatments. The C concentration in the soil increased from 3.035% in the control (no burning) to 5.634% in the 8-year 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.

3.2 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 intervals (the 1-year interval was the only exception). Concentrations increased from an average of 0.200% in the unburned control plots to 0.352% in the 8-year burn interval. Soil N in the 2-year through 10-year plots at Chimney Spring with Typic Argiboroll soils was significantly different from those at Limestone Flats with Cryoboralf soils (Table 2). As with total soil C, the only significantly different total N concentrations were between the control and the 8-year burning-interval plots.

Soil total N is highly correlated with total C since most of the A horizon soil N pool is tied up in organic matter. Covington and Sackett (1986) reported that less than 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 do not support 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 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.

3.3 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. The 1-year burning interval plot samples for total C at Limestone Flats ranged from 2.218% to 4.788%, a span of 2.570%. The unburned control samples had a range from 1.432% to 3.954%, a very similar span of 2.522%. In some instances, soil total C values from plots burned every year for over 20 years were lower than those from the unburned controls. For the most part, the within-plot total C variability was less than 2–fold.

The 8-year burning interval plots at Chimney Spring had the highest variability. Soil total C ranged from 2.253 to 12.241%, a span of 9.988%. The unburned control plot samples at Chimney Spring had a range from 1.781 to 6.657%, a span (4.876%) nearly double that of the Limestone Flats control. Within plot variability was much higher than at Limestone Flats. Samples 1 through 3 ranged from 12.241 to 2.674%, a nearly 5-fold difference.

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. Covington and Sackett (1986) stratified their sampling at Chimney Spring 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 adding 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.

4. SUMMARY AND CONCLUSIONS

The effects of restoration of burning intervals in ponderosa pine stands on total C and N concentrations in the A horizon of two different soil types was examined. The burning intervals (0-, 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 and N levels in soils of the unburned plots and the 8-year burning interval, there were no differences between burning intervals. This study determined that burning increased mineral soil C and N, but did not support Wright and Hart's (1997) contention that the most frequent 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 (less than 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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Figure 1. Effect of fire interval on soil total carbon, Limestone Flats and Chimney Springs burning interval study, Arizona.

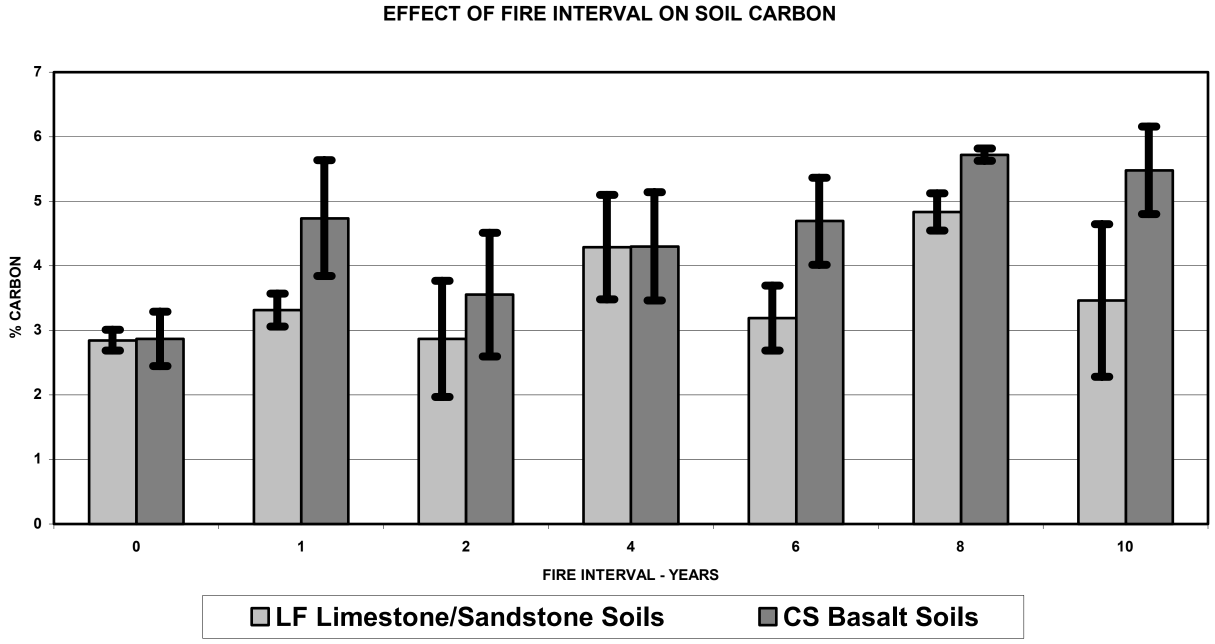

Figure 2. Effect of fire interval on soil total nitrogen, Limestone Flats and Chimney Springs burning interval study, Arizona.

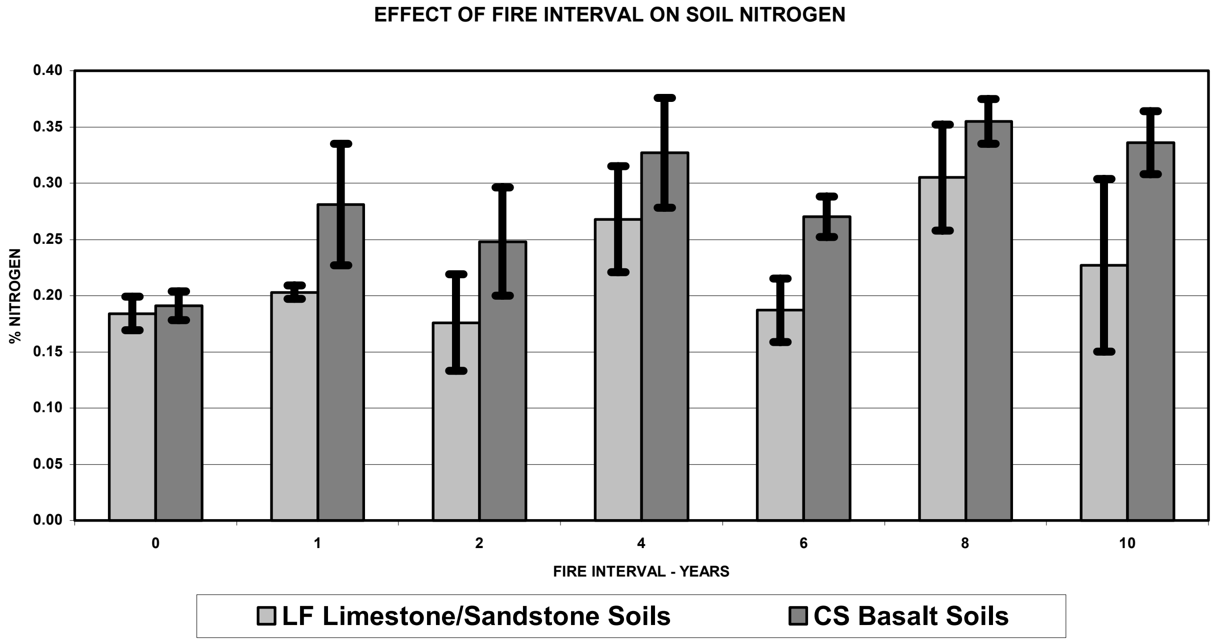

Table 1--Summary statistics for GLM ANOVA

Dependent Variable	Source	DF	Type III SS	Mean Square	F Value	Pr>F
Carbon	Location	1	27.5849	27.5849	5.96	0.0162
	Treatment	6	69.7275	11.6212	2.51	0.0256
	L x T	6	15.6632	2.6105	0.56	0.7580
Nitrogen	Location	1	0.1362	0.1362	11.11	0.0012
	Treatment	6	0.2763	0.0461	3.76	0.0019
	L x T	6	0.0277	0.0046	0.38	0.8923

Table 2--Studentized Tukey's test for C and N by treatment, Limestone Flats and Chimney Springs, 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