Total Carbon and Nitrogen in Mineral Soil After 26 Years of Prescribed Fire: Long Valley and Fort Valley Experimental Forests

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Abstract—*Prescribed fire was introduced to high density ponderosa pine stands at Fort Valley and Long Valley Experimental Forests in 1976. This paper reports on mineral soil total carbon (C) and nitrogen (N) at Long Valley. Total soil C and N levels were highly variable and exhibited an increasing, but inconsistent, concentration trend related to burn interval. Total N ranged from 0.1 to 0.45%. Randomly collected soil sample C ranged from 2.2 to 5.7%, but stratified sampling indicated a greater total C range from 1.7 to 11.5%. Random sampling allows scaling up to stand and landscape level but stratified sampling does not. The latter provides an index of C and N variability due to stand conditions (old growth, pole-sized stands, and ponderosa pine thickets), clearings devoid of trees, or heavy woody debris accumulations.*

Introduction

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). Grass biomass reduction from intensive sheep and cattle grazing in the late 19th century, a large ponderosa pine (*Pinus ponderosa*) regeneration pulse in the early 20th century, and then forest fire suppression during much of the 20th century 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 ten to one hundred fold (Sackett 1979, Sackett and others 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 2,750 stems/ha in the densest stands (Covington and Sackett 1986, Sackett 1980).

Fires can greatly alter nutrient cycles of forest ecosystems depending on fire severity, fire frequency, vegetation, and climate (Neary and others 1996). Responses of total carbon (C) and nitrogen (N) are variable and depend on the site conditions and fire characteristics (DeBano and others 1998). Sackett (1980) established a set of studies near Flagstaff, Arizona (Chimney Spring, Fort Valley Experimental Forest (EF), and Limestone Flats, Long Valley EF), to restore overstocked ponderosa pine stands by introducing prescribed fire at 1-, 2-, 4-, 6-, 8-, and 10-year intervals. Covington and Sackett (1986) previously examined N concentrations in the upper 5 cm of mineral soil at the Chimney Spring burning interval study. They found that mineral forms of N (NH_4-N and nitrate nitrogen, 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 Spring site. Neary and others (2002, 2003) reported on the initial analysis of C and N levels in both Chimney Springs and Limestone Flats soils.

The purpose of the study reported here 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 determine if additional sampling might be necessary to determine if soil C and N were related to burning frequency. The focus of this paper is on the general results from both sites with a special focus on Limestone Flats results.

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. The studies are described in greater detail by Sackett (1980), Covington and Sackett (1986), and Sackett and others (1996). 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.

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 smectitic, frigid, Typic Argiborolls derived from basalt and cinders. Stand structure and fuels were described by Sackett (1980).

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 smectitic Typic Cryoboralfs. These soils developed from weathered sandstone with limestone inclusions. Sackett (1980) described the original stand structure and fuels, and prior land management.

Sampling

The soils at both the Chimney Spring and Limestone Flats sites were first 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 km from the first sample, selected by a randomization process, on two of the cardinal directions from the first sample. About 0.5 kg was collected from the 0-5 cm depth of the mineral soil. The samples were air dried in the laboratory, sieved to < 2 mm, then sub-sampled and ground to pass a 100 mesh sieve (0.149 mm), and sub-sampled again for analysis. Sub samples were oven dried further at about 30° C.

The second sampling of Limestone Flats occurred in 2004. Ten random soil samples were collected using a Cartesian Coordinate System. This system is based on randomly selected grid coordinates, referenced to the plot center (Burt and Barber 1996). Bearings and distances are calculated from the plot center to locate the sampling points on the virtual grid system. For the systematic sampling, three replicate soil samples spaced 1 m from a sampling center were collected from the center of representative old growth areas, pole-size stands, dense thickets, clearings, and coarse woody debris piles. Samples were processed the same as in the 2003 sampling.

Analytical

Soil total C and N were analyzed on a Thermo-Quest Flash EA1112 C-N analyzer. The computer-controlled instrument

Table 1. Studentized Tukey's test for C and N by treatment, Limestone Flats and Chimney Springs, Arizona, burning interval restoration studies, 2002 sampling.

Element	Burning Interval (years)	Mean (%)	Tukey's Test (p = 0.05)	Samples - n
Carbon	0	3.035	A	18
	1	3.282	AB	18
	2	3.432	AB	18
	4	4.294	AB	18
	6	3.942	AB	18
	8	5.634	B	18
	10	4.472	AB	18
Nitrogen	0	0.200	A	18
	1	0.199	AB	18
	2	0.227	AB	18
	4	0.298	AB	18
	6	0.228	AB	18
	8	0.352	B	18
	10	0.281	AB	18

oxidizes samples at 1,200° C, and determines C and N content by thermal conductivity following separation by a gas chromatographic column measuring CO_2 and NO. Quality controls were analyzed along with replicate samples every 10th sample, then regresses using a calibration curve developed from known standards and blanks.

Statistical Analysis

Data were analyzed using the SAS univariate ANOVA under the GLM Procedure (SAS 2000). The Station statistician determined that the ANOVA was robust enough to be useful without data transformation (R.M. King, personal communication). Tukey's Studentized Range test was used for means separation of C and N values (p = 0.05).

Results

2002 Sampling

Soil total C and total N are strongly correlated (Neary and others 2002, 2003). Organic matter in the soil is a major source of N, and organic and cation exchange sites adsorb the mineral forms of N.

Total C levels in the Limestone Flats and Chimney Spring mineral soil (0-15 cm) in the 2002 sampling exhibited two trends (Figure 1; Neary and others 2002, 2003). The first is that soil C was higher in the Chimney Spring volcanic soils. Soil classification explains part 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. The second trend in the soil C data appeared to be one of increasing amounts up to burn interval 8 years, which would indicate the influence of the fire. The

C concentration in the soil increased from 3.04% in the control (no burning) to 5.63% in the 8-year interval (Table 1). However, only the control and 8-year interval were statistically different. These data reflect more of the variability in soil C detected in the 2002 random sampling approach than any burning interval trend.

Total N levels followed the same trends as total soil C. Total N concentrations were mostly higher across the range of burning intervals. Concentrations increased from an average of 0.20% in the unburned control plots to 0.35% in the 8-year burn interval. The data from the 2002 sampling (Neary and others 2003) did not support Wright and Hart's (1997) hypothesis that burning at 2-year intervals can have detrimental long-term effects on N cycling, along with depletion of the forest floor and surface mineral soil C and N pools.

The lack of a 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 2.22% to 4.79%, a span of 2.57%. The unburned control samples had a range from 1.43% to 3.95%, a very similar span of 2.52%. The 8-year burning interval plots at Chimney Spring had the highest variability. Soil total C ranged from 2.25% to 12.24%, a span of 9.99%. The unburned control plot samples at Chimney Spring had a range from 1.78% to 6.66%, a span (4.88%) nearly double that of the Limestone Flats control. A full discussion of within plot variability, found to be greater at Chimney Springs than at Limestone Flats, can be found in Neary and others (2003).

2003 Sampling

The random soil sampling in 2003 using a larger number of samples and a Cartesian Coordinate sampling design detected a similar pattern to the mineral soil N measured in the 2002 sampling (Figure 2). Soil total N increased from 0.13% in the 1-year burns to a peak of 0.25% in the 8-year burns. Concentrations in the 2003 sampling at the Long Valley
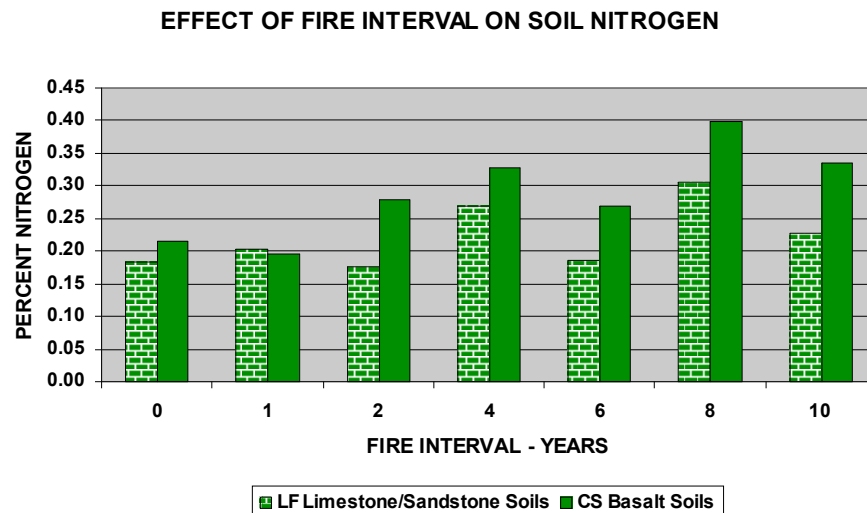
EFFECT OF FIRE INTERVAL ON SOIL NITROGEN

Figure 1. Effect of prescribed fire interval on soil total nitrogen, Limestone Flats (LF) and Chimney Springs (CS) burning interval study, 2002, Coconino National Forest, Arizona (Neary and others 2003).

SOIL N (0- 5cm), PONDEROSA PINE, LIMESTONE FLATS BURNING INTERVAL, RANDOM SAMPLES
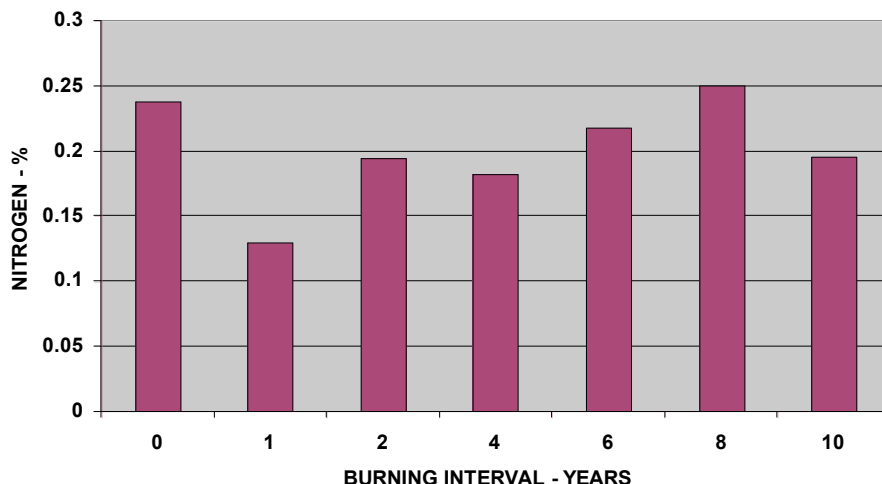

Figure 2. Effect of prescribed fire burning intervals (1, 2, 4, 6, 8, and 10 years; 0 is the control) on surface soil total nitrogen measured in random samples, Limestone Flats, Coconino National Forest, Arizona, 2004.
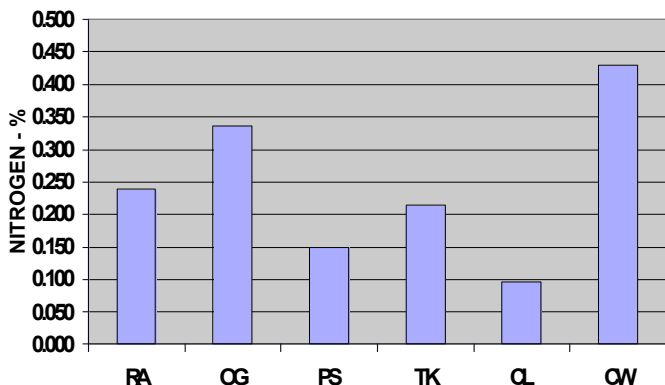

Figure 3. Variability in soil total N.

Limestone Flats site were lower than in 2002. The largest difference between the 2003 and 2002 samplings was that the range in total N was less (0.13 to 0.25%) and the unburned sites had higher levels of soil total N, more similar to the 8-year burning interval than the 1-year interval.

The degree of variability in soil total N (hence soil total C) can be seen in the data comparing random samples to site-specific samples (Figure 3). Soil total N ranged from 0.10% in unburned clearings to 0.43% next to piles of decomposing woody debris. This 4-fold range is twice the range of values between burning intervals (0.13 to 0.25%). This situation complicates interpretation of the sampling data relative to the question of the impact of prescribed fire on soil C and N.

Discussion

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 evident during the 2002 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. The 2003 sampling that compared random to site-specific sampling verified that there is a larger range in variability of soil C and N due to site than due to burning interval. Areas with high amounts of organic matter, such as woody debris piles, old-growth tree bases, and pine thickets, have higher amounts of soil C and N. Whereas clearings with lower amounts of organic matter accumulations, are much lower in C and N concentrations. The range of soil C and N based on site is twice that based on burning interval. This makes it difficult to accept or disprove the hypothesis of Wright and Hart (1997) that the most frequent burning interval could deplete soil N and C pools.

Another factor that was identified in the 2002 sampling (Neary and others 2003) as potentially important 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 and others 1998). Another possibility is that the soil could be high in black C, increasing the total soil content (Wardle and others 2008). The 2003 sampling was not able to identify these areas across the range of burning intervals so "hot spots" were not considered in the analysis. Flagging and marking these locations in subsequent burns could allow this type of analysis in the future.

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 at Fort Valley and Long Valley Experimental Forests 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 and others 1996). Although there were statistically significant differences detected in 2002 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. Although the 2003 sampling measured higher levels of soil total C and N, site variability makes it difficult to assess these results in light of Wright and Hart's (1997) conclusion that the most frequent burning interval could deplete soil N and C pools. Systematic sampling using the Cartesian Coordinate system allowed for relatively rapid sampling, but did not encompass the high variability in C and N shown by the results of the stratified sampling. Additional work is needed at greater level of detail to adequately address the differences between Wright and Hart (1997) and this paper produced by the considerable variability in C and N. Stratification is needed to begin to understand the dynamics of C and N differences in these stands. This also points out the difficulty in assessing the actual C and N content of forest soils in any C accounting or trading system.

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