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Effect of Soil Compaction and Biomass Removal on Soil CO_2 Efflux in a Missouri Forest

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Abstract: Forest disturbances associated with harvesting activities can affect soil properties and soil respiration. A soda-lime technique was used to measure soil carbon dioxide (CO_2) efflux rates in clearcut plots of a Missouri oak-hickory (*Quercus* spp. L.—*Carya* spp. Nutt.) forest 4 years after being treated with two levels of forest biomass removal and two levels of compaction, both separate and in combinations, and an uncut control. Respiration rates were measured twice a month from mid-April through October. Soil CO_2 efflux rates were significantly ($p < 0.001$) higher in uncut control plots than in clearcut plots, but differences between biomass removal or soil compaction treatments were not significant. Soil CO_2 efflux rates were positively correlated with soil temperature. The lack of difference between soil CO_2 efflux rates in weed control and no weed control subplots suggests that several more years may be required for regenerating clearcut plots to produce soil respiration rates similar to those in uncut control plots.

Keywords: Soil respiration, soil metabolism, carbon dioxide evolution, soil disturbance, soil temperature

INTRODUCTION

The impacts of disturbance on forest soil productivity depend on their magnitude and persistence. Forest harvesting removes biomass and nutrients

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from the site. The effects of disturbance on soils include topsoil displacement, compaction, porosity loss, and redistribution and incorporation of organic matter. These changes can affect water availability and combine with soil changes to produce many interactive soil processes that influence the growth of vegetation. The competition for water and nutrients between trees and other vegetation is a critical factor in forest management (Nambiar and Sands 1993).

The effects of disturbance can also be evaluated by looking at soil properties. The efflux of CO_2, from the soil, often referred to as soil respiration, can indicate soil condition. Soil respiration is the net effect of combined metabolic activity of roots, free living and symbiotic heterotrophs (i.e., fungi, microorganisms, and macroorganisms), and uptake by plant roots (Singh and Gupta 1977). The flow of carbon as CO_2 comes from several sources including microbial, faunal, and root respiration. Forest floor CO_2 efflux has been measured for a wide variety of forest ecosystems (Raich and Schlesinger 1992). Microbial and root respiration is related to and dependent on the quality of the soil and has been shown to be a function of root biomass (Behera, Joshi, and Pati 1990) and soil temperature and moisture (Hanson et al. 1993; Peterjohn et al. 1994). Soil properties such as temperature, moisture, and nutrient availability and their interactions have both direct and indirect effects on soil respiration (Schlesinger 1977). This study was conducted to determine if soil respiration rates differed among several levels of forest disturbance. To accomplish this, soil CO_2 evolution in plots with two levels of forest biomass removal and two levels of compaction, both separate and in combination, and in an uncut control were measured and compared.

MATERIALS AND METHODS

Study Site

The study was installed in one of a network of Long-Term Soil Productivity studies (LTSP) initiated by the USDA Forest Service (Powers et al. 1990). The Missouri LTSP study was implemented in 1994 to assess the effects of forest management practices on forest productivity in the Central Hardwood Region (Ponder and Mikkelson 1995). The study is in the Ozark Region of southeastern Missouri on the Carr Creek State Forest in Shannon County, on the upper side of two ridges with northeastern aspects. The preharvest forest was occupied by a mature, second-growth, oak-hickory forest type. Site index ranged from 74 to 80 based on *Quercus velutina* Lam. at 50 years (Hahn 1991). Slopes of 20–28% are characteristic of the site. Soils are silt loams that resulted from cherty residuum primarily of the Clarksville series (Loamy skeletal mixed mesic Typic Paleudults) (Gott 1975). Mean annual precipitation and temperature is 112 cm and 13.3°C, respectively. Moisture drains easily through the soil to subsurface channels. The Missouri LTSP study has three levels of biomass removal (bole only, whole tree, and

whole tree plus forest floor) and three levels of compaction (none, medium, and severe). The factorial design was replicated three times.

Experimental Design

For the present experiment, four treatments were used from the original nine in the LTSP study, and an uncut control treatment was added to give an indication of the extreme treatment impacts. Treatments were two levels of biomass removal [removal of merchantable boles only (FF) and the removal of the whole tree plus forest floor (NFF)], two levels of soil compaction [no soil compaction (NSC) and severe compaction (SC)], and their combinations. Each treatment was replicated three times for a total of 12 plots plus 3 uncut control plots. The uncut plots were adjacent to treatment plots. Treatment plots are divided into subplots; in one-half, herbicides were used to control weeds (U $-$) and in the other half, weeds were free to grow (U $+$). Plots are approximately 0.4 ha in size. In each treated plot, six respiration chambers were installed to measure the CO_2 evolution, and they were positioned equally across the middle of the plot (three chambers per subplot). In addition, three respiration chambers were spaced equally across the middle of each of the three uncut control plots.

Soil CO_2 Measurements

Measurements of soil CO_2 evolution began in April and continued until October. Soil respiration was sampled approximately every 14 days. Because of the remote location of the site, the static chamber and soda lime techniques were used to measure cumulative soil CO_2 efflux (Edwards 1982; Bowden et al. 1993; Schlentner and van Cleve 1984).

The chambers were made of 30-cm lengths of PVC pipe. Each chamber had a diameter of 25.4 cm for a total soil surface area of 490.6 cm^2. Rough edges were filed smooth to prevent tears in plastic covers placed over containers. The bottom edge of the chamber was inserted into the soil to a depth of 5 cm, not disturbing roots but making good contact with the soil. To anchor each chamber, two pieces of metal electrical conduit measuring approximately 13 mm in diameter and 50 cm long were driven approximately 35 cm deep into the ground adjacent to the exterior of the chamber on opposite sides several inches just below the top of the chamber. Lengths of conduit used to anchor chambers were attached with screws, which were sealed over with silicon. Chambers were installed 3 weeks prior to sampling and remained throughout the sampling period. Vegetation within chambers was clipped and discarded. Protective cages of wire mesh with 2.5-cm openings were placed over chambers to prevent rodent damage.

Granular soda lime, 6–12 mesh size, was used as an absorbent for CO_2. Approximately 30 g of soda lime were placed in glass petri dishes that had

diameters of 9 cm and heights of 1.5 cm. The petri dishes covered 12.6% of the floor within the chamber, exceeding Edwards's (1982) suggestion of a 5% minimum of the surface area of the chamber. Soda lime was oven dried for 24 h at 100°C, weighed to the nearest 0.001 g, placed in petri dishes, covered with petri dish lids, and sealed in zip-lock plastic bags. The petri dishes were taken to plots, uncovered, and placed in the chambers. A beaker containing 25 mL of water was also placed in each chamber to ensure adequate moisture for CO_2 adsorption. The tops of the chambers were covered with plastic that was held in place with two large rubber bands. The soda lime was allowed to accumulate. Time of exposure for the first chamber was about 2 h earlier than for the last chamber because of setup time. Exposure time for each trial began at approximately the same time of the day. After approximately 24 h, the petri dishes were collected in the order of exposure, covered, labeled, sealed in zip-lock plastic bags, and transported to the laboratory. The dishes of soda lime were oven dried at 100°C for 24 h and weighed. Two blank samples per plot were exposed to account for absorption of CO_2 during handling.

The CO_2 absorption onto the soda lime was determined by the difference in sample weights and multiplied by 1.69 g to account for the loss of chemical water during the drying process (Grogan 1998). The weight of CO_2 from the blank was subtracted from the sample weight.

Soil temperature was also measured at the time of CO_2 sampling. A soil thermometer was inserted into the soil to a depth of 5 cm inside the chamber at the time of soda lime placement and removal to measure temperature. The two temperature values were averaged to help account for any heating of soil due to chamber closure. Soil temperature-moisture resistance cells (Soiltest®), which had been installed at 10, 20, and 30 cm deep 1 year earlier, were used to measure the mean soil temperature and soil moisture resistance over the 0- to 30-cm depth. Although not done for data in this study, moisture percentage can be determined by relating resistance readings (ohms) to a calibration curve (resistance vs. moisture %).

Repeated measures analysis of variance (with sampling periods as the repeated factor) (SAS 1989) was used to assess treatment effects on soil respiration. The effect of weed control in clear-cut plots was treated as a split plot design, with organic matter removal and compaction treatments as main plots and weed control as subplots in a separate analysis of variance. Tests indicating significant differences in mean values among treatments were followed by a Tukey test for multiple means comparisons. Pearson correlation analysis was performed on CO_2 evolution, soil temperature, and soil moisture resistance.

RESULTS AND DISCUSSION

Mean CO_2 efflux rates were significantly ($p < 0.001$) higher in uncut control plots than in treated plots (Table 1). Mean CO_2 efflux for monthly

Table 1. Means for soil surface CO_2 efflux, soil temperature at depths of 5 cm and 0–30 cm, and soil moisture resistance at 0–30 cm over the measurement period following treatments consisting of forest floor present (FF), forest floor absent (NFF), no soil compaction (NSC), soil compaction (SC), with understory present (U +), understory absent (U −), and uncut control in a Missouri Ozark forest

Treatment	Efflux(mg CO_2 m^{-2} h^{-1})	Temperature (C)[a]			Moisture resistance(ohms)
Forest floor		T_1 (5 cm)	T_2 (5 cm)	0–30 cm	0–30 cm
FF	572.39 ± 229.3**a**[b]	25.14 ± 5.3**a**	25.71 ± 5.5**a**	18.29 ± 5.9**a**	23.84 ± 41.4**a**
NFF	582.14 ± 223.5**a**	25.06 ± 5.6**a**	25.70 ± 5.8**a**	17.97 ± 4.9**a**	25.73 ± 43.7**a**
Soil compaction					
NSC	574.71 ± 224.2**a**	24.97 ± 5.6**a**	25.57 ± 5.6**a**	17.77 ± 6.1**a**	24.55 ± 40.3**a**
SC	579.78 ± 230.7**a**	25.23 ± 5.3**a**	25.84 ± 5.6**a**	18.49 ± 4.8**a**	25.02 ± 40.7**a**
Understory					
U −	583.13 ± 225.4**a**	26.15 ± 5.7**a**	26.80 ± 5.8**a**	16.32 ± 7.4**a**	23.37 ± 40.0**a**
U +	571.56 ± 227.8**a**	24.03 ± 5.1**b**	24.51 ± 5.3**ab**	19.22 ± 2.8**b**	26.31 ± 45.3**a**
Uncut	701.43 ± 235.0**b**	20.53 ± 4.1**b**	20.83 ± 4.2**b**	17.38 ± 2.6**a**	25.66 ± 27.8**a**

[a] T_1 and T_2 are temperatures at the beginning and ending of the 24-h sampling period, respectively.

[b] Values in a column for a variable followed by the same letter are not significantly different at the 0.05 level according to Tukey's test.

measurements from April to October was 701 and 577 mg CO_2 m^{-2} h^{-1}, respectively, for uncut and clear-cut treatments. Mean CO_2 efflux rates did not differ significantly between biomass removal and compaction treatments, nor were there differences for CO_2 measurements between weed control treatments (Table 1). But mean CO_2 efflux rates did vary monthly (Figure 1A). Harvesting activities undoubtedly affected soil respiration rates in this study. Several studies, however, indicate that the responses of soil respiration to harvesting can be variable and somewhat ecosystem dependent (Toland and Zak 1994). For example, soil CO_2 efflux rates were similar in intact and clear-cut plots of a mixed deciduous forest in Tennessee (Edwards and Ross-Todd 1983). Harvest intensity in a southern bottomland forest had no significant treatment effect on soil CO_2 evolution (Messina et al. 1997). But soil respiration decreased by 50% in a *Pinus densiflora* forest after it was clear-cut (Ewel, Cropper, and Gholz 1987). Three years after cutting and burning treatments in an eastern Ontario *Populus tremuloides* forest, estimated soil CO_2 efflux rates were similar between plots in the immature aspen and plots in an intact stand (Weber 1990). Mean CO_2 efflux was reduced by nearly 50% in pits compared with control microsites in an experimental blowdown in a central Massachusetts forest (Millikin and Bowden 1996). However,

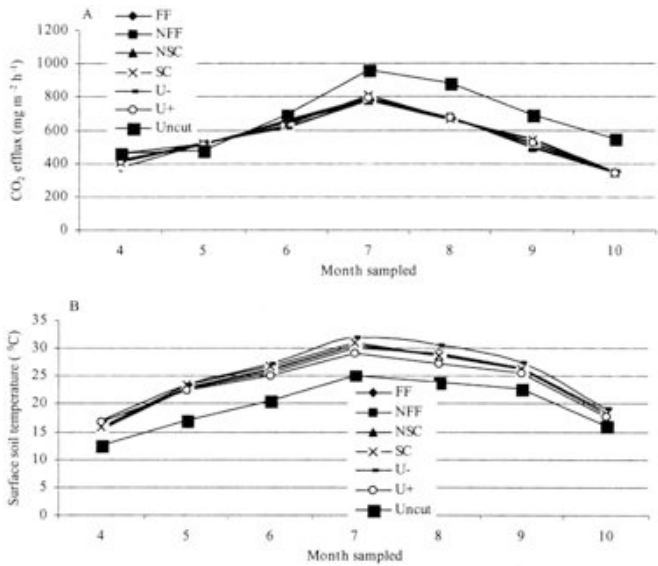

Figure 1. Means for soil CO_2 efflux in graph A and soil temperature at the 5-cm depth in graph B over the measurement period following treatments consisting of forest floor present (FF), forest floor absent (NFF), no soil compaction (NSC), soil compaction (SC), with understory present (U +), understory absent (U −), and uncut control in a Missouri Ozark forest.

CO_2 efflux rates for the mounds created by the blownover trees were not significantly different from CO_2 efflux rates for controls.

In the present study, planted trees and natural regeneration were in their 4th year of growth. It will likely require several more years for root biomass and litter accumulation to be sufficient to generate respiration rates approaching those in the uncut control. The lack of difference in soil respiration rates between compaction treatments suggests that components associated with soil respiration in these soils have not significantly recovered. This is further evidenced by the lack of difference in the rate of CO_2 efflux between plots where weeds were free to grow and those where weeds were eliminated. In addition, some of the differences in soil respiration rates between uncut control plots and organic matter removal treatments can probably be attributed to suspected differences in root biomass and soil C storage. However, these assumptions cannot be substantiated without root biomass and respiration data and long-term measurements.

The difference in the amount of decomposing organic matter in the NFF removal treatment vs. the FF treatments was apparently not sufficient to significantly affect soil respiration. The lack of difference in soil respiration between the two treatments may mean that the minimal removal treatment (FF) drastically lowered CO_2 efflux and that additional biomass removed in the NFF treatment had little effect. Microbial activity can also impact soil respiration (Edwards 1982; Rout and Gupta 1989). Although litter fall was not measured, any additions of C to soil from litter in treated plots of the present study would have been small compared with that in uncut plots. Edwards and Harris (1977) estimated that decaying roots and litter accounted for approximately 64% of the soil CO_2 measured in a mixed deciduous forest in Tennessee. In another study on this site that used these same treatment and uncut plots, microbial C for organic matter removal treatments followed the order: uncut control > FF > NFF; for soil compaction the order was uncut control > NSC > SC (D. Jordan, unpublished data). It appears that most of the differences in soil microbial biomass C can be attributed to the greater annual litter fall in uncut plots than in clear-cut plots. Hence, the higher soil microbial biomass C level in uncut control plots may have contributed significantly to the higher respiration levels in these plots.

Soil respiration was positively related to soil temperature with a correlation coefficient of 30% (Figure 2A). Stronger relationships for soil respiration and soil temperature have been reported (Edwards 1982; Garrett and Cox 1973; Edwards 1975). Garrett and Cox (1973) reported that the highest rate of CO_2 evolution over a 24-h period in an oak-hickory forest in Missouri was 0.90 g m^{-2} h^{-1} at a soil temperature of 23°C. In the present study, the highest mean rate of CO_2 evolution in a 24-h period occurred in July and was about 1 g of CO_2 m^{-2} h^{-1} in the uncut treatment with a soil temperature of 25°C (Figure 1A and B). Soil respiration rates were comparatively low in April and May when soil temperatures were cool, increasing to their highest rates during June to mid-August and declining in September and

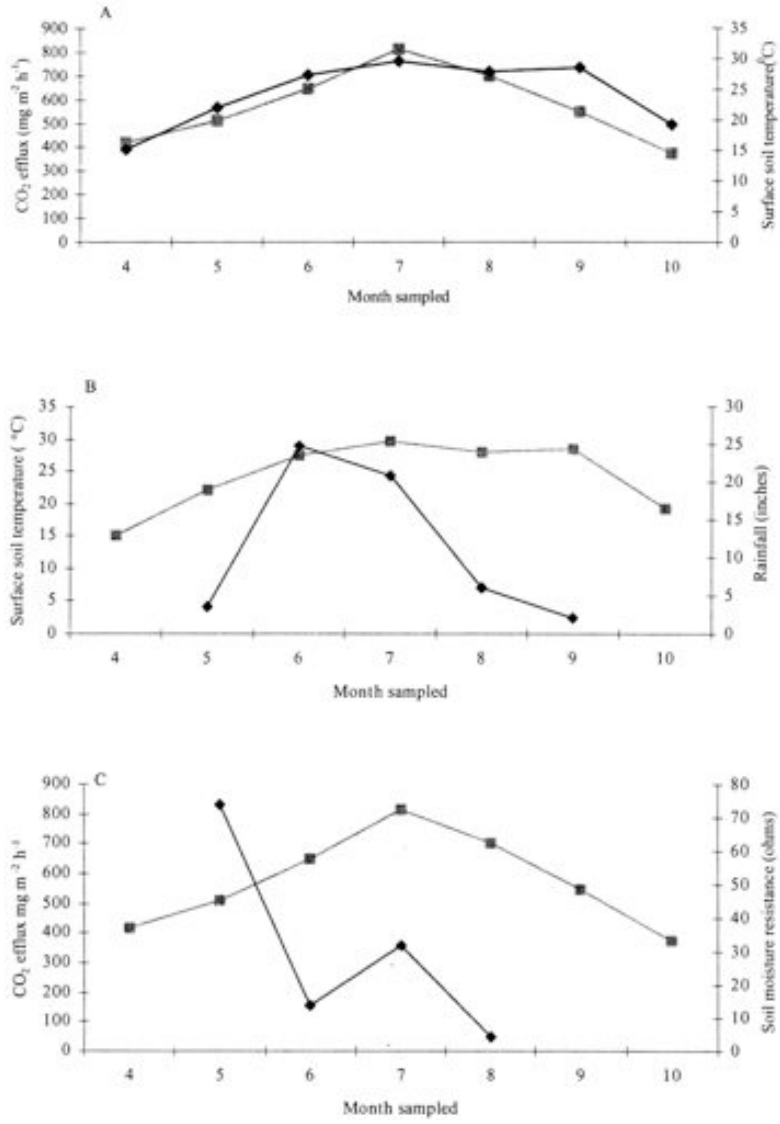

Figure 2. Monthly means for soil CO_2 efflux (■) and soil temperature at the 5-cm depth (◆) in graph A; soil temperature at the 5-cm depth (■) and rainfall (◆) in graph B; and soil CO_2 efflux (■) and soil moisture resistance measurements (◆) in graph C.

October when temperatures were cooling. Soil temperatures were higher in clear-cut plots ranging up to 35°C compared to a maximum of only 25°C in uncut control plots. The weak relationship does not appear to be due to periods of rain that may have depressed soil temperatures during the

sampling period (Figure 2B), nor was the relationship between soil moisture resistance and soil CO_2 efflux significant (Figure 2C).

A review by Singh and Gupta (1977) indicates that the general response of soil respiration to soil temperature or moisture seems to depend on which one is most limiting. Temperature appears to have little effect on respiration when moisture is low, but the effect of temperature increases when moisture is high. At temperatures below 5°C, moisture changes have little effect on soil respiration, but the effect increases at temperatures of 10–20°C. Mathes and Schriefer (1985) found no significant influence of soil moisture conditions (ranging from 4 to 80 MPa soil water suction) on CO_2 efflux. They also concluded that because the biologically active zone of the soil surface is more representative at the 5-cm depth than deeper, demonstrating a significant influence of soil temperature on CO_2 efflux was much more likely than with soil moisture conditions, which are usually recorded much deeper. Bowden et al. (1993) concluded from their work with mixed hardwoods that 80% of the variability in daily soil respiration could be attributed to soil temperature.

CONCLUSIONS

Four years after treatments were applied, soil respiration rates in treated plots are significantly less than the rates in uncut control plots. Aside from differences between uncut control plots and clearcut plots, the general pattern in increases and declines in respiration rates was related to soil temperature. The elements contributing to soil respiration, including roots, litter, and microbial, were not measured. However, the likely higher amount of these elements in the uncut control plots compared with clearcut plots are believed to be responsible for the higher CO_2 efflux rates in those plots. These components, especially roots and litter, in the clearcut plots should grow more abundant as the vegetation develops, thus causing an increase in the rate of CO_2 efflux.

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