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**FIRE FREQUENCY, NUTRIENT CONCENTRATIONS AND
DISTRIBUTIONS, AND $\delta^{13}\text{C}$ OF SOIL ORGANIC MATTER AND
PLANTS IN A SOUTHEASTERN ARIZONA GRASSLAND**

by

Thomas Howard Biggs

A Dissertation Submitted to the Faculty of the

DEPARTMENT OF GEOSCIENCES

In Partial Fulfillment of the Requirements
For the Degree of

DOCTOR OF PHILOSOPHY

In the Graduate College

UNIVERSITY OF ARIZONA

1997

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entitled Fire Frequency, Nutrient Concentrations and Distributions,
and $\delta^{13}C$ of Soil Organic Matter and Plants in a Southeastern
Arizona Grassland

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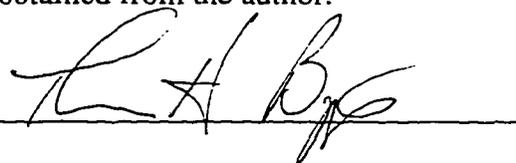
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A handwritten signature in cursive script, appearing to read "R. A. By", is written over a horizontal line.

ACKNOWLEDGMENTS

This project could not have reached a successful conclusion without the support and assistance of my Committee Chairman, Jay Quade, and Bob Webb of the U.S. Geological Survey. I greatly appreciate the many hours they devoted to the study over the past three years.

This study was funded by the Southwestern Borderlands Ecosystems Management Program of the U.S.D.A. Forest Service, Rocky Mountain Forest and Range Experiment Station; Jerry Gottfried and Carl Edminster of the Forest Service were very supportive of the research and reviewed the two manuscripts. Partial funding was supplied by the U.S. Geological Survey, Chris Cochran of the Natural Resources Conservation Service, Tucson, provided surficial soils information and the fire history records for the study area, and Sheridan Stone of the Wildlife Office, Fort Huachuca Military Reservation, facilitated with access to the study sites on the military reservation and arranged for personnel and equipment to dig the back hoe trenches. Tina Hayden and Laska Rohovit, of the Department of Soil, Water and Environmental Science, University of Arizona, assisted with soil and plant analyses. Jan Bowers, Peter Griffiths, Betsy Pierson, Ray Turner, and Doug Wellington, all from the U.S. Geological Survey, helped with the plant biomass harvesting, and Donna Opocensky and Peter Griffiths of the U.S. Geological Survey helped with laboratory analyses. In addition, species lists of the 3 sites were made by Jan Bowers. Much of the laboratory work, including CO₂ extractions, was done at the Desert Laboratory, Tucson. Dr. Dave Dettman, of the Department of Geosciences, University of Arizona, assisted with the mass spectrometer analyses. Guy McPherson, of the Department of Renewable Natural Resources, University of Arizona, and Sean Connin, of the Desert Laboratory, Tucson, provided excellent critical reviews of the two manuscripts.

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ABSTRACT

Over the past century, woody plants and shrubs have increased in abundance at the expense of grasslands in many semiarid regions. The availability and concentrations of nutrients influence the relative success of plants, but the effects of fire frequency on soil nutrients is unknown for semiarid grasslands. On the gunnery ranges of Fort Huachuca in southeastern Arizona, study sites were established to examine the effects of fire frequency on soil biogeochemistry, plant biochemistry, and $\delta^{13}\text{C}$ values in soil organic matter (SOM). The sites were on homogeneous granitic alluvium where wildfire frequency history is known from 1973 to present and no cattle grazing has occurred in recent decades. Subplots represent fire frequencies of no burns, 3 fires per decade, and 5 fires per decade. The "no burn" plot has abundant C_3 *Prosopis velentina* (mesquite) trees, whereas the burned plots are open C_4 -dominated grasslands with scattered mesquite trees. *Prosopis* trees have altered SOM pools by the concentration of plant nutrients and the addition of isotopically light shrub litter. Frequent fires have altered the basic geochemistry and nutrient availabilities of the soil, and the changes appear to be significant enough to affect plant growth. Soil pH increases with burning frequency, and TOC, total nitrogen, and plant-available phosphorus show significant increases on the infrequently burned plot. Burning is advantageous for preservation or restoration of grasslands, as total living grass biomass is greater on the two burned plots. Root biomass is significantly lower on the "frequently burned" plot. Concentrations of the key nutrients nitrogen and phosphorus are reduced in plants on the burned sites compared to plants on the unburned site. Fires help re-distribute nutrients but evidence of nutrient concentrations and $\delta^{13}\text{C}$ values are retained in SOM for many decades. Estimates of bulk carbon turnover rates range from 112 to 504 years. Evidence for modern C_3 shrub expansion is found in the shift of SOM $\delta^{13}\text{C}$ values from values characteristic of C_4

grasses to C₃ shrubs in surface soil layers. $\delta^{13}\text{CSOM}$ values indicate that the Holocene and Late Pleistocene were dominated by C₄ grasslands, and the pre-Late Pleistocene vegetation was a C₄-grass savanna with abundant C₃ plants.

CHAPTER 1

INTRODUCTION TO THE DISSERTATION

Grasslands are characterized by the dominance of graminoids and the general absence of trees, whereas savannas, systems characterized by scattered trees with open canopies, support a continuous grass understory and can be considered as a special element within grassland (Tieszen and Detling, 1983). Throughout the southwestern United States and other semiarid areas of the world, woody plants and shrubs have increased in abundance at the expense of grasslands (Archer, 1994; Bahre, 1991; Hastings and Turner, 1965; Herbel, 1985). The rates and mechanisms of this ecosystem shift are much debated, with the encroachment attributed to over-grazing and its attendant soil loss (Bahre, 1977), fire suppression (Grover and Musick, 1990), climate change (Hastings and Turner, 1965; Neilson, 1986), or combinations of these and additional factors (Archer, 1989; Cox et al., 1993; Wright and Bailey, 1980). Fire suppression, which began in the early 1900's, combined with livestock grazing has given shrubs and trees a competitive advantage over grasses (Griffiths, 1910). Likewise, there is considerable debate as to whether the influx of woody vegetation into areas that were historically grasslands represents grassland degradation (Schlesinger et al., 1990) or ecosystem rejuvenation (Holden, 1996).

The effects of fire frequency on the vegetation composition of desert grasslands is relatively well known (McPherson, 1995). The availability and amount of key soil nutrients influence the relative success of plants, but the effects of fire frequency on soil nutrients are unknown. This investigation was conducted at Fort Huachuca Military Reservation in southeastern Arizona where wildfire frequency history is known from 1973 to present (Fig. 1), detailed soils mapping has been done, and no significant cattle grazing has occurred in recent decades. The area was selected for detailed study because

Figure 1. Composite fire history map for the south gunnery ranges on the Fort Huachuca Military Reservation, 1973-1995. Grid #1 is the 'Unburned' study site, Grid #2 is the 'Moderately Burned' study site, and Grid #3 is the 'Frequently Burned' study site. (C. Cochrane, unpublished data)



sites representing fire frequencies of no burns, infrequent burns, and frequent burns are in close proximity on a single geomorphic surface with relatively homogeneous soil properties.

The initial objective of the study was to determine how the spatial distributions and concentrations of plant nutrients in soil organic matter (SOM) differ on the three sites with different fire histories. The primary hypothesis to be tested is that the availability and spatial distribution of soil total organic carbon (TOC), plant-available phosphorus (PO_4^{3-}), plant-available nitrogen (NO_3^-), and other soil properties may be affected by fire. Unburned areas will have plant-available nutrients in greater concentrations than burned areas and soils in areas burned relatively infrequently will have more macronutrients than frequently burned areas.

The study also examined the relationships between nutrient distributions and concentrations, modern vegetation on the three sites, and the carbon isotopic ($\delta^{13}\text{C}$) values of the SOM. *Prosopis velutina* (mesquite), the largest C_3 plants in the study area, are common on the unburned site, but uncommon on the two burned sites which are mostly covered by C_4 grasses. *Prosopis* trees should affect the distribution of nutrients and $\delta^{13}\text{C}$ values in the surficial SOM. The nutrient concentrations and $\delta^{13}\text{C}$ values can be used in combination to examine the hypothesis that C_4 grasses are being displaced by C_3 woody plants on the grasslands of southeastern Arizona. The combination of $\delta^{13}\text{C}$ values and TOC may also be used to estimate the turnover rates of carbon in SOM.

The third objective of the study was to determine the possible effects of fire frequency on plants by measuring and comparing surface and subsurface biomass on the three sites and determining the concentrations of key macronutrients and micronutrients in the plant material. It is hypothesized that the effects of fire frequency will be reflected in total biomass, variations in the types of biomass from site to site, and biochemistry of plant material harvested from the three study sites.

The fourth objective of the study was to determine the subsurface distribution of nutrients and $\delta^{13}\text{C}$ values in older soil horizons. Evidence for plant community changes should be preserved in the $\delta^{13}\text{C}$ values of buried soil horizons.

The following appendices constitute the bulk of this dissertation. APPENDIX A consists of a manuscript entitled "Fire frequency and spatial variability of soil biogeochemistry and plant biochemistry in a southeastern Arizona desert grassland" (I am the lead author). In this report, the soil geochemistry of surface and subsurface samples, seasonal variations of SOM nutrient concentrations, soil respiration results for several sampling seasons, and the plant biochemistry analyses are all described. The ramifications of the results for ecosystem management are also discussed. The manuscript has been prepared for submittal for publication consideration in the journal *Plant and Soil*.

APPENDIX B consists of a manuscript entitled "Fire, nutrient concentrations, and $\delta^{13}\text{C}$ of soil organic matter in a southeastern Arizona desert grassland" (I am the lead author). This paper presents the $\delta^{13}\text{C}$ values from surface and subsurface SOM collected from the three burn sites, as well as $\delta^{13}\text{C}$ values of respired CO_2 collected on the sites. The $\delta^{13}\text{C}_{\text{SOM}}$ results are discussed relative to the present vegetation patterns and the spatial distributions and concentrations of nutrients on the three sites. Carbon turnover rates are estimated for C_3 to C_4 change and for C_4 to C_3 change. Paleoecological interpretations are made for Holocene and Pleistocene epochs. The manuscript has been prepared for submittal for consideration for publication in journal *Geoderma*.

APPENDIX C is entitled "Nutrient and $\delta^{13}\text{C}$ data for surface and subsurface soil samples" and consists of data compiled during the study of total organic carbon, plant-available nitrogen, plant-available phosphorus, and $\delta^{13}\text{C}$ values for all surface and subsurface soil samples for the three sites.

CHAPTER 2

PRESENT STUDY

The methods, results and conclusions of this study are presented in the documents appended to this dissertation. The following is a summary of the most important aspects of these documents.

Isolating the effects of climate, fire suppression, or over-grazing is difficult but necessary to determine the appropriate management practices for grasslands. The study area at Fort Huachuca provided a good natural laboratory for retrospective studies useful in defining the magnitude of fire effects on nutrient concentrations. Efforts to slow or reverse the conversion of grassland to savanna may be thwarted by changes in the distribution and availability of soil nutrients (Schlesinger et al., 1990), which are strongly affected by fire (Wright and Bailey, 1980). Little is known of the effect of fire frequency on nutrient distribution and availability in desert grasslands. Studies in other ecosystems (Adams et al., 1994; Keith, 1991; Kutiel and Shaviv, 1989; Weinhold and Klemmedson, 1992) indicate considerable quantities of macronutrients are volatilized, lost in aerosols, and removed in run-off (Wright and Bailey, 1980).

The productivity of semiarid regions is determined by the availability of water and the ability of the soil to meet plant nutrient requirements. The primary plant nutrients are the essential mineral elements in soil materials required for optimum plant growth. To be productive, a soil must have an adequate supply of all the essential nutrients in forms that plants can use, as plant growth will be limited by a deficient available supply of any one element. Of the ten essential plant nutrients, the available supplies of nitrogen, phosphorus, and potassium are more likely to be insufficient for maximum plant growth (Day and Ludecke, 1993). This investigation analyzed for plant-available forms of nitrogen (NO_3^-) and phosphorus (PO_4^{3-}), as well as total organic carbon (TOC), in the

soil organic matter (SOM) for all surface and subsurface samples collected from the three study sites. Total nitrogen, bulk density, cation-exchange capacity (CEC), soil pH, and potassium and other soluble salts were analyzed in smaller subsets of soil samples. Plant tissues were analyzed for total nitrogen, carbon, phosphorus, and soluble salts.

Nutrient availability is typically low in the desert grasslands. Nutrients become available due to the transformation of organic material into chemical forms that can be utilized by plants. This mineralization occurs through the activities of soil microbes and depends on adequate moisture as well as favorable temperatures. In the grasslands of southeastern Arizona, rainfall occurs as winter precipitation (December to March) and as summer monsoons (July to September). To address the possible seasonal variations of nutrient levels, this study collected subsets of soil samples from each of the study sites during the fall and spring after the initial Spring 1995 sampling period. Soil respiration was also measured during five seasons between June 1995 and November 1996 to determine CO₂ flux rates and microbial activities on the three study sites.

The results of this study indicate that (1) fire frequency has altered the basic geochemistry and nutrient availabilities of the soil, (2) significant differences can be measured in SOM and plant tissues that can be directly related to the frequency of fires, and (3) burning is advantageous for preservation or restoration of grasslands, but too much burning can be detrimental to the ecosystem. Soil pH increased with burning frequency, and CEC, a key component of soil fertility, was 50% greater on the two burned sites compared to unburned Site 1. Amounts of NO₃⁻ decreased with increasing fire frequency, whereas total nitrogen, TOC and PO₄⁻³ were higher on the moderately burned site and lower on the frequently burned site compared to the unburned site. Fire frequency apparently decreased the spatial variability of NO₃⁻, TOC and PO₄⁻³ on the study sites at Fort Huachuca.

One management strategy has been to slow or reverse the conversion of grassland to savanna. Fire is commonly suggested as a management tool for the suppression of velvet mesquite (*Prosopis velutina*) and some other shrubs in the desert grassland (Cave and Patten, 1984; Humphrey, 1949). *Prosopis* significantly alter nutrient cycling in desert grasslands because the trees accumulate TOC and nitrogen (N) in the soil beneath canopies (Tiedemann and Klemmedson, 1973). Distribution plots of TOC and plant-available N, and P on the unburned Site 1 confirm these nutrients are sequestered beneath mature *Prosopis* trees. Similar nutrient plots for Sites 2 and 3 indicate fires redistribute nutrients and increases their concentrations in soils not under mesquite canopies. Rapid conversion of savannas to grasslands may require frequent fires because only a small percentage of mature *Prosopis* trees and as few as two-thirds of the immature *Prosopis* shrubs are killed in single fires (Cable, 1973; Wright et al., 1976). Burning may not be able to prevent encroachment of undesirable shrubs into grasslands, but merely slow down the process (Cable, 1967; Schwartz et al., 1996).

A critical aspect of nutrient cycling is the source of the organic matter which enters the decomposer system directly from litterfall. To help determine carbon cycling, or turnover rates, this study measured the total organic carbon content and the $\delta^{13}\text{C}$ values (which provide a natural label between plants with different photosynthetic processes) of SOM for all surface and subsurface soil samples. Repeat aerial photography was utilized to estimate the timing of vegetation changes on the three sites. From these data, the minimum turnover time of C₄-derived carbon (from grasses) beneath large *Prosopis* trees was estimated to be ~ 112 to 270 years, whereas the complete turnover of original C₃-carbon (from *Prosopis* ?) under grasslands was estimated to take a minimum of 135 to 504 years.

Most managers realize that maximization of production cannot come at the expense of the grassland's ability to regenerate after grazing/fire/disturbance. To

determine the effect of fire on biomass, plant biomass was harvested from fifteen 1 m² quadrates on each of the three study sites. The biomass was sorted into functional groups and the differences between the three sites determined. This snapshot of productivity indicated total living grass biomass was greater on the two burned plots, but variances were not significantly different for shrubs, herbaceous dicots, and litter between plots. Total living non-*Prosopis* biomass was greater on the two burned plots than on the unburned plot. Concentrations of nitrogen and phosphorus were lower in plant tissues from the two burned sites compared to similar material from the unburned site, but the amount of carbon in the plant tissue was higher on the two burned sites compared to the unburned site.

Another mechanism reducing nutrient uptake is a direct reduction of root growth resulting from the loss of above-ground carbon due to overgrazing or fire. If plants are unable to transport sufficient food to roots, root growth and nutrient uptake will either cease or slow. The mean biomass of shallow roots was lower in the two burned sites compared to the unburned site, but these differences may be related to presence of *Prosopis*. The moderately burned site had higher root biomass than open (non-canopy) positions on the unburned site.

$\delta^{13}\text{C}$ values of surficial SOM confirms that grass cover has declined over the past 100 years on the south gunnery ranges at Fort Huachuca, although isolated trees probably were not uncommon on the historic grasslands. Evidence in the surface soil layers for a modern C₃ shrub expansion is reflected in the substantial shift of SOM $\delta^{13}\text{C}$ values from C₄ grasses to C₃ shrublands. $\delta^{13}\text{C}$ values from buried horizons indicate the Holocene and Pleistocene were dominated by C₄ grasslands, and the pre-Late Pleistocene vegetation was a C₄-savanna with abundant C₃ plants very similar to the modern unburned site.

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APPENDIX A

PERMISSIONS

NOTE: The following manuscript is being prepared for submission for publication in the journal *Plant and Soil*, but has not been published at the time of compilation of this dissertation.

APPENDIX A
FIRE FREQUENCY AND SPATIAL VARIABILITY OF SOIL
BIOGEOCHEMISTRY AND PLANT BIOCHEMISTRY IN A SOUTHEASTERN
ARIZONA DESERT GRASSLAND

Abstract

Over the past century, woody plants and shrubs have increased in abundance at the expense of grasslands in many semiarid regions. Current strategies for ecosystem management are based on a slowing or outright reversal of this trend, with prescribed burning a key tool. The availabilities of nutrients influence the relative success of plants, but the effects of fire frequency on soil nutrients are unknown for desert grasslands. On the gunnery ranges of Fort Huachuca in southeastern Arizona, study sites were established to examine the effects of fire frequency on soil organic matter (SOM), biogeochemistry, and plant biochemistry on one geomorphic surface. The sites were on homogeneous granitic alluvium where wildfire frequency history is known from 1973 to present, detailed soils mapping has been done, and no cattle grazing has occurred in recent decades. The sites represent fire frequencies of no burns, 3 fires per decade, and 5 fires per decade. The "no burn" plot has abundant mature *Prosopis velutina* (mesquite) trees, whereas the burned plots are open desert grassland with widely scattered mesquite trees. *Prosopis* trees appear to have altered SOM pools by the concentration of key nutrients. Burning is advantageous for preservation or restoration of grasslands, as results indicate total living grass and small shrub biomass was greater and the biomass of *Prosopis* was much less on the two burned plots compared to the "no burn" plot. Basic soil geochemistry and nutrient distributions were different among the three sites, and the changes appear to be significant enough to affect plant growth. Root biomass was

significantly lower on the "frequently burned" plot. In plants on the burned sites, concentrations of key nutrients such as nitrogen and phosphorus were significantly reduced, whereas carbon content was increased, compared to plants on the unburned site. Fires help re-distribute nutrients but evidence of nutrient concentrations is retained in SOM for many decades. A fire frequency not exceeding 2 fires/decade may be advantageous if the goal of restoration is to maximize production of grasses and minimize *Prosopis* without depleting soil macronutrient supplies.

Introduction

Throughout the southwestern United States, vegetation in what historically was desert grassland has changed to a savanna of trees and shrubs with scattered perennial grasses (Bahre, 1991; Bahre, 1995; Brown, 1950; Buffington and Herbel, 1965; Cable and Martin, 1973; Cox et al., 1993; Hastings and Turner, 1965; Hennessy et al., 1983; Humphrey, 1953; Humphrey, 1958; Humphrey, 1963; Humphrey and Mehrhoff, 1958; McPherson, 1993). Regional desertification, a process perceived as an ecosystem shift from a more forage-productive semidesert grassland to a less forage-productive desert shrubland, is of concern in the semiarid areas of other parts of the United States (Archer, 1989; Archer et al., 1988; Branscomb, 1958; Dick-Peddie, 1993; Dzurec et al., 1985; Grover and Musick, 1990; Heady, 1973; Hennessy et al., 1983; Herbel, 1985) and in other countries (Acocks, 1988; Bond et al., 1994).

Encroachment of woody plants into grasslands has been attributed to over-grazing and its attendant soil loss (Bahre, 1977; Brown and Lowe, 1980), climate change (Hastings and Turner, 1965; Neilson, 1986), suppression of wildfires (Grover and Musick, 1990), or combinations of these and additional factors (Cox et al., 1993; Wright and Bailey, 1980). Grasslands established under past climatic conditions may be less robust in present climate regimes and may be more vulnerable to woody plant

encroachment (Neilson, 1986). It has also been argued that woody plants have always been present in the grasslands, not restricted to only riparian areas (Bahre, 1991). Depending on the context, the influx of woody species has been viewed as an invasive degradation or an ecological boon for arid lands (Holden, 1996). Although competition for soil resources between grasses and *Prosopis* may be minimal early in the life cycle of *Prosopis*, grasses are ineffective in excluding *Prosopis* except where there are large accumulations of litter (Brown and Archer, 1989). The roots of *Prosopis* may compete with grasses by quickly extracting shallow soil water, much as shrubs reportedly do (Archer, 1994; Cable, 1969). Development of shrub canopy reduces the amount of light reaching the ground and alters local microclimate, with much of the reduction of grasses resulting from herbivory activities beneath the sheltering closed canopies (Hobbs and Mooney, 1986).

Knowledge of the rate and spatial distribution of the encroachment process would improve management techniques of the grasslands environment. For many years, one management strategy for desert grasslands has been to slow or reverse the conversion of grassland to savanna. These strategies may be thwarted by changes in the distribution and availability of soil nutrients (Schlesinger et al., 1990), which are strongly affected by fire (Wright and Bailey, 1980). Prehistoric wildfires, whether aboriginal- or lightning-set, are thought to have played a large role in the suppression of trees and shrubs in southeastern Arizona leading to the association of wildfire with grasslands (Humphrey, 1958; Humphrey, 1963; Humphrey, 1974; Humphrey and Mehrhoff, 1958). Fire suppression, which began in the early 1900s, may have combined with livestock grazing to give shrubs and trees a competitive advantage over grasses (Griffiths, 1910), although it is not apparent from historical records that frequent fires occurred in the southeastern Arizona grasslands between 1859 and 1890 (Bahre, 1985).

The effect of fire frequency on the species composition of desert grassland is relatively well known (McPherson, 1995). Fire is commonly suggested as a management tool for the suppression of velvet mesquite (*Prosopis velutina*) and some other shrubs in the desert grassland (Cave and Patten, 1984; Humphrey, 1949; Wright, 1973; Wright, 1980). Repetitive burning in desert grasslands is beneficial if suppression of *Prosopis* and restoration of grass cover is the management objective (Robinett, 1994). The presence of *Prosopis* alters soils in many ways (Virginia, 1986; Virginia and Jarrell, 1983) and affects establishment and growth of other species, particularly grasses (Bush and van Auken, 1991; Van Auken and Bush, 1989) and other shrubs (Archer, 1994). Rapid conversion of savannas to grassland may require frequent fires because only a small percentage of mature *Prosopis* trees and as few as two-thirds of the shrubby immature individuals are killed in single fires (Cable, 1961; Cable, 1967; Cable, 1973; Reynolds and Bohning, 1956; White, 1969; Wright et al., 1976). *Prosopis* is tolerant of fire, but recurring fires keep them small in stature and inhibit seed production (Wright et al., 1976). Fire destroys *Prosopis* seeds at the surface but does not affect the subsurface seed bank (Cox et al., 1993); these seeds may germinate in the years following the fire. In addition, other undesirable shrubs quickly reinvade (Cable, 1967). Seeds of grassland species in general do not disperse far and do not persist in the soil, making re-invasion by grassland species unlikely (Hobbs and Mooney, 1986).

Seasonality of fires is extremely important because fires in summer are hotter and have greater effects on C₃ plants such as *Prosopis* and other shrubs than winter fires (Britton and Wright, 1971; Cable, 1965; McPherson, 1995). This is because in grasslands, species with C₄ and C₃ photosynthetic pathways co-exist and phenological development is often offset in such a manner that C₃ species (woody plants and many herbaceous dicots) initiate spring regrowth and are most active physiologically and developmentally earlier in the growing season than C₄ grasses. As temperatures increase

and C₄ plants become physiologically more active, the activity of the C₃ plants decline (Tieszen and Detling, 1983). In grasslands, frequent spring fires reduce the number of grass, forb, and woody species, remove the litter layer, and, given sufficient moisture, cause elevated decomposition rates, which enhances soil fertility, and hence, the productivity of highly competitive C₄ grasses (Hulbert, 1984; Knapp and Seastedt, 1986). Fires in cool seasons may be effective against C₃ plants if sufficient fuel loading is available (Martin, 1983).

The prehistoric interval between wildfires in the desert grassland has been estimated at 2-3 yrs (Bahre, 1991; Humphrey, 1958) and 10-20 yrs (Leopold, 1924; Wright, 1980); a more recent estimate suggests fires every 7-10 yrs (McPherson, 1995). Studies on dry sclerophyll communities in Australia (Cary and Morrison, 1995; Morrison et al., 1995) show that fires every 5-8 yrs can dramatically reduce the abundance of fire-sensitive species, especially shrubs that dominate the community biomass during fire-free intervals. Recent studies in tallgrass prairie ecosystems of northeastern Kansas found a significant monotonic decline in plant species richness with increasing fire frequency because species intolerant of fire become locally extinct (Collins et al., 1995). Robinett (1994) concluded that intervals of 10-20 yrs between fires does not appear to diminish resource values or productivity of desert grasslands, and Bock et. al (1986) concluded that an interval of no less than 5 yrs between fires may benefit wildlife populations.

Effects of fire on soil biogeochemistry

In addition to retarding establishment and growth of trees and shrubs, frequent fires presumably would deplete soil nutrients by volatilization and erosion, but little is known of the effect of fire frequency on nutrient cycling in desert grasslands. Nutrient availability to plants is determined by the ability of soil to supply nutrients to plant roots and the ability of the plant to absorb and utilize the nutrients. Soil pH is an important

factor in determining the solubilities of N, P, and K in the soil for plant uptake and plant growth (Fageria, 1992). Seasonality of fire, as well as maximum surface temperatures, strongly affect changes in soil nutrients (McPherson, 1995; Sharrow and Wright, 1977; Wells et al., 1979). Studies in other regions indicate equivocal effects of fire -- but typically losses -- on soil nitrogen (N) and phosphorus (P) and, to a lesser extent carbon (C) (Adams et al., 1994; Blank et al., 1994; DeBano et al., 1979; Keith, 1991; Kutiel and Shaviv, 1989; Raison, 1979; Weinhold and Klemmedson, 1992). Considerable quantities of macronutrients are volatilized, lost in aerosols, and removed in surface runoff (DeBano and Conrad, 1978; Wright and Bailey, 1980); soil erosion is greatly increased after fires (Wells, 1985). Many of these changes result from loss of shading, which can increase soil temperatures for 1-2 yrs after the fire.

Most studies have concentrated on the effects of fire on soil nitrogen (Wells et al., 1979). Nitrogen is the most important nutrient for crop production and its deficiency occurs almost everywhere (Fageria, 1992), because nitrogen is extremely mobile and leaves ecosystems through more avenues and in greater quantities than most other nutrients (Crews, 1993). The N cycle is an open system in grassland ecosystems (Woodmansee and Duncan, 1980) and fire is expected to remove significant amounts of NO_3^- . Although N_2 -fixing bacteria colonize the rhizosphere of desert grasses (Bruening and Bollen, 1979), *Prosopis* is the major N fixer (Bailey, 1976) and probably the largest source of N in semiarid savannas (West and Klemmedson, 1978). In the soils of desert grasslands, nitrate (NO_3^-) is the most abundant available form of nitrogen, with ammonia (NH_4^+) present only in very small amounts (Day and Ludecke, 1993). Nitrate comprises about 25% of the total soil nitrogen pool (Rundel et al., 1982), with the rest being organic-N that must be mineralized before plants can use it. Hot fires over dry soils volatilize accumulated organic matter in the upper few centimeters of the soil, reducing soil N (DeBano et al., 1979; Raison, 1979). Non-symbiotic N fixation may also increase

(Jorgensen and Wells, 1971). After a low-intensity fire, rates of nitrogen mineralization in the soil increased (Sharrow and Wright, 1977), and N was 2-5 times higher in surface soil for about 6 months (Keith, 1991). Frequent burning over many years may significantly reduce soil N (Ojima, 1994). Keith (1991) documented a 50% reduction in N mineralization over 2 yrs of a 3-yr fire cycle in an Australian eucalypt forest. Nitrogen stresses stimulate root growth at the expense of shoot growth, as the roots become sinks for carbohydrates produced by photosynthesis (Fageria, 1992).

A weak correlation between two variables may belie a more important relationship that is masked by indirect interactions. Fires may have the direct effect of increasing short-term N availability, but simultaneously promoting species conservative in their use of N and producing recalcitrant litter (Clark, 1990). C₄ grasses require less N than C₃ plants for photosynthesis, so the C₄ grasses are less limited under nitrogen-deficient conditions (Tieszen and Detling, 1983) if the available N is not tied up. By initiating growth earlier in the season, C₃ plants such as *Prosopis* may be able to capitalize upon a relatively abundant supply of available mineral nitrogen in the spring. Growth of C₄ grasses, although beginning later after some of this available N had been depleted by C₃ plants, would not be as N-limited as might be expected because of lower N requirements (Tieszen and Detling, 1983).

Soil organic phosphorus is part of the dynamic P cycle that includes the immobilization, mineralization, and redistribution of P in soil which depends on physical-chemical properties as much as microbial, mycorrhizal, or plant uptake (Stewart and Tiessen, 1987). Bio-available phosphorus is critical to plant biomass production because it controls the accumulation and availability of nitrogen and carbon in ecosystems (Crews, 1993; Eisele et al., 1989). Phosphorus is available to plants in the form of phosphate ions (PO_4^{3-}) through the slow dissolution of primary P minerals or as biomass P (Stewart and Tiessen, 1987). P is less mobile than N in soils and it is not lost from the

root zone by leaching (Day and Ludecke, 1993). Fire results in additions of available P in ash which may stimulate microbial nitrogen fixation (Eisele et al., 1989; Ojima, 1994).

Soil organic matter (SOM) is a major component of biochemical cycles of the major nutrient elements and the quantity and quality of SOM both reflects and controls primary productivity (Fageria, 1992). SOM is derived from a number of sources, including plant roots, root exudates, soil organisms, organic substances washed into the soil from vegetation, and, most importantly, plant litter. Organic material consists predominantly of carbon, hydrogen, oxygen, and nitrogen, with carbon providing the framework for organic structures (Ellis and Mellor, 1995). Organic matter is amorphous, varies widely in composition, and a portion of it is in constant flux as microorganisms break it down as a source of energy (Barber, 1995). In arid and semiarid regions, organic matter is concentrated primarily in the upper soil layers where most of the root systems are concentrated (Klemmedson, 1989).

Although not a plant nutrient, total organic carbon (TOC) provides a measure of production in an ecosystem. C is an essential element that is derived from CO₂ in the atmosphere during photosynthesis. In forage plants, more than 90% of yield, or total dry matter, produced by the individual plants originates during photosynthesis and is stored as carbohydrates; components of yield are plants per area, shoots per plant, and yield per shoot (Fageria, 1992). However, there is no direct relation between the amount of plant matter and litter produced on a soil and the amount of organic matter in the soil (Stevenson, 1986).

Prosopis significantly alters nutrient cycling in desert grassland because the tree accumulates TOC, P, N, and sulfur (S) in the soil beneath its canopy (Tiedemann and Klemmedson, 1973a, 1973b), similar to the "islands of fertility" concept described for grassland areas invaded by shrubs (Virginia and Jarrell, 1983). Mechanical removal of *Prosopis* reduces the availability of most macronutrients except total P and S (Tiedemann

and Klemmedson, 1986), leading to decreased plant growth (Klemmedson and Tiedemann, 1986). The effects of *Prosopis* removal by fire on bio-available N and P, as well as other geochemical attributes, are unknown.

Objectives and hypotheses

Retrospective studies are useful in defining the magnitude of the fire effects on nutrient concentrations. Fire frequency and land use on Fort Huachuca in southeastern Arizona (Fig. 1) has been well-documented since 1973 (Robinett, 1993). The initial objective of this study was to examine sites with different fire histories on one geomorphic surface for differences in the spatial distribution of nutrient concentrations. To accomplish this objective, the concentrations and distributions of soil TOC, NO_3^- , and PO_4^{-3} , as well as other soil properties, were measured in areas of known fire frequency and relatively homogeneous soil properties. The primary hypothesis to be tested is that the availability and spatial distribution of soil TOC, NO_3^- , and PO_4^{-3} and other properties may be affected by fire. Unburned areas will have plant-available nutrients in greater concentrations than burned areas and, furthermore, soils in areas burned relatively infrequently will have more macronutrients than frequently burned areas.

A second objective was to determine the impact of *Prosopis* on the nutrient concentrations and distributions in the SOM in the desert grasslands by comparison of open areas with under-canopy soil samples on the three sites.

The third objective of this project was to determine the possible effects of fire frequency on plants by measuring surface and subsurface biomass on the three sites and determining the concentrations of key macronutrients and micronutrients in the plant material. It is hypothesized that the effects of fire frequency on plant growth in the desert grasslands will be reflected in biomass and in the nutrient concentrations of plant biochemistry.

The fourth objective was to identify seasonal variations of soil nutrient characteristics, including soil respiration rates in terms of total flux of carbon dioxide per unit area, on the soil plots with different fire histories to ascertain if the seasonality of fires will impact nutrient cycling patterns. Most grasslands with mixtures of C₃ and C₄ plants should follow a bimodal growth pattern marked by seasonal variations, both in productivity and nutrient status (Sims and Singh, 1978b; Tieszen and Detling, 1983). Therefore, soil nutrient contents presumably are seasonally variant.

Study Area

Research was conducted at a study area located southeast of an unnamed stream which drains Woodcutters' Canyon on the south gunnery ranges of Fort Huachuca Military Reservation (N.31°30'45", W.110°19'30"), southeastern Arizona (Fig.1). Currently the gunnery ranges are covered by a mixture of C₄ grasses and C₃ shrubs and trees typical of the lower elevations of the Huachuca Mountains (Bowers and McLaughlin, 1996), and are characterized as savannas of scattered trees with open canopies and a continuous grass understory. Vegetation on the gunnery ranges has been mapped as "desert plains grassland" (Whitfield and Beutner, 1938) and "semidesert grassland" (Brown and Lowe, 1980); in New Mexico, this distinctive biome is referred to as "desert grassland" (Dick-Peddie, 1993). In the mid-1800's, the area now used as firing ranges consisted of C₄-dominated grasslands, with mesquite largely relegated to riparian areas (Humphrey and Mehrhoff, 1958). Detailed fire history of the site is known from 1973 to 1995 (C. Cochrane, unpublished data) and livestock have been excluded from the military reservation since the late 1940's. The elevation of the study area is 1,490 m and mean annual precipitation is approximately 500 mm, with about 70% falling in the July-October period.

The study area is on a single geomorphic surface, a Holocene alluvial fan comprised of granitic material deposited on the east flank of the Huachuca Mountains. The fan has a uniform slope of about 5 percent on the study area. It is covered by a sandy loam, classified as an Aridic Haplustalf (USDA, 1994a) in the Gardencan-Lanque complex (USDA, 1994b), that has a remarkably homogeneous and fine-grained character for a rangeland soil. We used a grid-style experimental design composed of three study sites established on the gunnery ranges where a road junction created fire breaks that allowed sites of relatively homogeneous geomorphic and physical character but different fire frequency to be in close proximity (Fig. 2). Site 1 has not been burned since 1973, and the year of the most recent fire is unknown. Site 1 is dominated by mature *Prosopis velutina* (velvet mesquite). Site 2, which has a moderate fire frequency of 2 fires/decade, burned in July, 1983 and more recently burned in January 1991 (Table 1). Site 2 is covered by native grasses, forbs, and small shrubs with widely scattered *Prosopis* trees. Site 3, which has a high fire frequency of 4 fires/decade, burned in February 1981 and most recently burned in February 1989 (Table 1). The plant cover of Site 3 is dominated by native grasses, small shrubs, and shrubby *Prosopis*.

Prosopis, the subshrub *Eriogonum wrightii*, the perennial bunchgrass *Eragrostis intermedia*, and several herbaceous dicots, particularly *Heterotheca subaxillaris* and *Descurania pinnata*, are common on all 3 study sites. Shrubs that are considered indicator species of overgrazing in desert grasslands, such as *Isocoma tenuisecta*, are not present. *Leptochloa dubia* and *Sporobolus cryptandrus*, 2 native perennial bunch grasses, are abundant on the unburned site but are not present in the burned areas; similarly, *Jatropha macrorhiza*, a herbaceous perennial, the shrubs *Mimosa biuncifera* and *Calliandra eriopoda*, and *Bouteloua gracilis* and *B. hirsuta*, native perennial bunch grasses, are common on the burned sites but are rare at the unburned site. The introduced perennial grass *Eragrostis lehmanniana* (Anable et al., 1992; Cox et al., 1988) is present

on the unburned site but is more common on the burned sites, as has been observed elsewhere in southeastern Arizona (Cable, 1967; Robinett, 1994).

Aerial photographs of the south ranges taken in 1935, 1946, 1956, 1970, 1975, 1983, 1984, and 1994, as well as oblique ground photographs taken between 1872 and 1915, were examined to supplement the available fire history. No *Prosopis* is apparent on the study sites in 1935 photographs, but several can be seen in 1946 aerial photographs. All three study sites appear irregularly disturbed in the 1946 photographs, probably as a result of tank and artillery training exercises during World War II. Successive aerial photographs show amelioration of the disturbances, indicating that all 3 sites have had a similar land-use history since 1946 except for fire frequency. Sites 2 and 3 appear largely treeless in an aerial photograph taken in January 1975. From the condition of these sites in the aerial photographs, fires probably have shaped the vegetation on Sites 2 and 3 for several decades. Widespread woodcutting or other types of landscape disturbance have not occurred recently at these sites (M. Shaughnessey, pers. commun., 1996). No stumps with signs of woodcutting were observed on the sites.

Methods

Sampling methods

In April 1995, we established a 30 m by 30 m grid that encompassed *Prosopis* individuals at each of the 3 study sites. The grid consisted of node points at 3-m intervals (Fig. 1) for a total of 121 sampling points per site. Some of our analyses used all 121 sampling points, whereas other aspects were examined on samples collected from selected nodes within the grid. The area of *Prosopis* canopy cover was estimated by measuring individual canopies in the field, plotting the extents of each on the respective 5 X 5 quadrille ruled maps for each study site, and counting the total number of squares included in the tree outlines.

Soil physical properties and vegetation

Bulk density samples were collected from 10 randomly selected node points from each study site. We used a core sampler (Blake and Hartge, 1986) with a diameter of 30 mm and a length of 70 mm (volume = $1.54 \times 10^{-4} \text{ m}^3$). After oven-drying, the samples were weighed to determine their mass for bulk density calculations. Because the lag gravel on the soil surface appeared to be greater on the frequently burned site than on the other two sites, we determined the gravel content of the bulk density samples by sieving through a 2-mm screen and weighing the retained gravel.

On each study site, we excavated back hoe trenches ranging from 11 to 18 m long and approximately 1.5 m deep. We described the pedons using standard methods (Soil Survey Staff, 1975). We collected <0.063 mm samples for clay mineralogy analysis using semi-quantitative x-ray diffraction (Starkey et al., 1984). This method has an accuracy of $\pm 20\%$.

The similarity of plant species composition on all 3 sites was calculated using Otsuka's index of similarity (Simpson, 1980),

$$I = n_t / (n_a n_b)^{0.5}, \quad (3)$$

where n_t = total number of species and n_a and n_b are the total species on each site.

Plant biomass

Two methods were used to calculate plant biomass in late September-early October 1995 after a relatively dry summer growing season. For *Prosopis*, the volume of wood >38 mm diameter was estimated using the visual-segmentation technique (Born and Chojnacky, 1985) and coefficients developed for *Prosopis* in southern Arizona (Chojnacky, 1988). To convert from volume to dry-weight biomass, an average wood density of 650 kg/m^3 was determined from 3 samples of dried wood collected from Site

2. Biomass of leaves and the remaining wood <38 mm was estimated by collecting 12 sample branches in 2 size classifications. We then counted branches in the 2 size classes on all the trees and estimated biomass.

Above-ground small woody and herbaceous species were harvested from 1-m² quadrates on 15 randomly selected nodes from each study site. The clipped biomass was sorted into the functional groups of "forbs" (herbaceous dicots), perennial grasses, shrubs, cactus, *Prosopis* seedlings, and litter. Plant parts were dried at ambient laboratory temperatures for 3 months prior to weighing. The biomass of shallow roots was measured using a soil corer, with 3 cores from a depth of 0-70 mm taken in each of the 1-m² quadrates that was harvested. The cores were oven-dried at 65°C for 48 hrs and weighed to calculate bulk density. After dispersion in water, the organic material was collected by a flotation method, oven dried at 65°C for several days, and weighed.

Plant analyses

The dried and sorted plant material was ground through a coarse Wiley mill and a 10 g split of each sample was taken. These splits were dried for several days at 65°C, then ground through a 40-mesh sieve using a Wiley mill. A section of *Prosopis* trunk, taken from the tree removed during trenching on Site 1, was dried for several months at ambient laboratory temperatures, then sawed into four pieces and the sawdust collected and dried for several days at 65°C. Total carbon and nitrogen for each sample was measured by high temperature combustion using a Carlo Erba 1500 Nitrogen, Carbon, Sulfur Analyzer (Artiola, 1990). To determine total phosphorus, calcium, magnesium, sodium, and potassium, plant material was processed by acid digestion in a hydrogen peroxide + nitric acid solution (EPA Method 3051). Total calcium, magnesium, sodium, and potassium were measured using a Leeman Labs ICP Emission Spectrometer (EPA

Method 6010). Total phosphorus was measured using a Hitachi U-2000 Spectrophotometer.

Soil chemistry

Almost all nutrients absorbed by plants are in an inorganic form. Organic forms of nutrients in the soil solution are mineralized to inorganic forms before they are supplied to the plant through the root system (Barber, 1995). Therefore, although total nitrogen was measured for a subset of samples, this study focused on the plant-available soil nutrients instead of the total element concentrations.

Surface samples were collected in late April - early May 1995 at each of the 3-m grid nodes for a total of 121 surface samples on each plot (Fig. 1). Of these, 111 were scooped from the upper 50 mm and a subsample of 10 were extracted using a core sampler. Samples from Site 1 were described as "open" and "canopy" to reflect their position with respect to large *Prosopis*; too few *Prosopis* were present on Sites 2 and 3 to segregate samples. Subsurface samples were collected on 3-m horizontal spacing from one wall of each pit; samples were spaced over a 0.05 m depth range at 0.1 m depth intervals in the Holocene soil and at 0.20 m depth spacings from the Pleistocene soil. The number of subsurface samples was not the same on all three sites. All surface and subsurface soil samples were oven-dried at 65° C for several days, then sifted through a 2-mm sieve. The soil samples were split into subsamples for the various chemical analyses.

Soil pH was determined using a glass electrode pH meter and standard methods (McLean, 1982). After displacement using 1N NH₄OAC (Thomas, 1982), the exchangeable cations of Na⁺, K⁺, Ca⁺⁺, and Mg⁺⁺ were measured using atomic absorption. The cation exchange complex (CEC) values were measured using a 3-step cation displacement method (Rhoades, 1982). Because the soil does not contain

significant CaCO_3 , special methods normally used for desert grassland soils were not required. Sodium acetate (NaOAC) was added to the sample to saturate the exchange sites, followed by NH_4OAC to displace Na^+ . The concentration of Na^+ was then measured by atomic absorption.

Plant-available phosphorus (PO_4^{-3}) was extracted using the Olsen bicarbonate method (Olsen and Sommers, 1982) and analyzed using a Hitachi U-2000 Spectrophotometer. Subsets of all surface and subsurface soil samples were pretreated with H_3PO_4 and ball milled to create uniform samples. Total organic carbon (TOC) and total nitrogen (NH_4^+ and NO_3^-) were measured on the pretreated samples by high temperature combustion (Nelson and Sommers, 1982) using a Carlo Erba 1500 Nitrogen, Carbon, Sulfur Analyzer. NO_3^- nitrogen was measured by ion chromatography (Keeney and Nelson, 1982) using a Dionex Model 2320i Ion Chromatograph. Repeated measurement of a soil standard and periodic duplication of samples yielded a precision of 0.01% for carbon, nitrogen and phosphorus.

Soil nutrient contents presumably show seasonal variations, but we partially evaluated this assumption. A set of 23-25 random surface samples was collected from each site in early October 1995; the same subset was re-sampled in late April - early May 1996. For each seasonal sample NO_3^- and PO_4^{-3} were measured using the techniques described above. The values we obtained were then compared with values for samples collected in May-June 1995. TOC was assumed seasonally invariant because of its slow turnover rate and not measured.

Soil-respired CO_2

Soil-respired CO_2 was measured using standard techniques (Anderson, 1982). A dish containing 20 ml of 1N NaOH was placed beneath an inverted 19-liter bucket at

selected grid nodes on each site. The NaOH solution was recovered after 24–48 hours and treated with SrCl₂ or BaCl₂ to precipitate SrCO₃ or BaCO₃. Control blanks of sealed NaOH solution were also saved for each sample set. Respiration samples were collected in June 1995, September 1995, February 1996, and November 1996.

Statistical analyses

A combination of ANOVA, parametric, nonparametric, and spatial statistics were used to determine differences among the 3 study sites. We analyzed grouped data (e.g., PO₄⁻³ concentrations from the 3 sites) using a 1-way ANOVA and Bartlett's test of significance for homogeneous variances (Wilkinson, 1989). Welch's test (Milliken and Johnson, 1984) was used to test the hypothesis of similarity among the group of sites. Differences among the means were evaluated using Dunnett's T3 multiple comparison procedure (Dunnett, 1980). For isolated data comparisons, the data was analyzed using nonparametric statistics, such as the Wilcoxon and Kruskal-Wallis tests (Conover, 1980), and t-tests where the assumption of normality could not be rejected. A level of significance of P ≤ 0.05 was used to reject the null hypothesis of no differences among the groups or specific compared means and variances. All analyses were made with SYSTAT software (Wilkinson, 1989) and MCP (post hoc Multiple Comparison, Analysis of Variance) software (R. King, U.S. Forest Service, written commun., 1996).

To evaluate differences in the spatial distribution of TOC, NO₃⁻, and PO₄⁻³, semivariograms were calculated (Deutsch and Journel, 1992; Warrick et al., 1986) for the 121 node points on each study site. The semi-variance, g , is calculated from each point u using

$$g(h) = 0.5 (Z(u+h) - Z(u))^2, \quad (1)$$

where h = distance between nodes and Z is the concentration of the macronutrient at u . h was not considered a function of direction (isotropic assumption). Each site generated

6,824 values of g . The semi-variances were plotted by distance between grid nodes. The spatial distribution of semi-variance was modeled using a spherical model, for which g is modeled as

$$g(h) = g(0) + c [1.5 h/a - 0.5 (h/a)^3], \quad (2)$$

where $g(0)$ = the nugget, c = the sill, and a = the range (Deutsch and Journel, 1992). The spherical model was fit by eye to the paired-data semi-variances. MGAP software (Rockware, 1991) was used to calculate the semivariograms and spherical models.

Results

Homogeneity of soil physical properties and vegetation

Soil properties were similar among the sites. Bulk density, which was normally distributed, did not differ ($p \leq 0.05$) among the plots ($x = 1,400 \text{ kg/m}^3$; Table 2). Visual examination indicated that lag gravel on the soil surface was greater on Site 3, which was verified by the core samples. The mean gravel contents of surface soils on Sites 2 and 3 were 6.3 and 7.6% higher, respectively, than for Site 1 (Table 2). We interpret this difference to be the result of increased surface runoff and erosion from the burned sites compared with the unburned site, although the high gravel content could reflect a facies change in deposition on the alluvial fan.

All 3 back hoe trenches had similar pedons (Fig. 3), indicating a high degree of similarity among the 3 sites. The upper 0.50-0.60 m of soil developed in the Holocene, with characteristics typical of such soils in the Fort Huachuca area (Demsey and Pearthree, 1994). This soil consists of an A horizon with little alteration and a Bt2 horizon with modest clay illuvation consistent with an early Holocene age. Clay particles in this soil were mostly illite (40%) with poorly crystallized kaolinite (20%) and quartz (15%). The A-horizon was variable between the three sites. On unburned Site 1, A1 and A2 horizons were recognized (Fig. 3A) and total combined thickness ranged between 20

and 40 cm. On moderately burned Site 2, the A-horizon ranged between 30 and 40 cm in total thickness and were separated into A1, A2, and A3 horizons (Fig. 3B). In contrast, the A-horizon on frequently burned Site 3 (Fig. 3C) was represented only by a thin veneer about 6 cm thick, possibly reflecting the increased erosion of unprotected topsoil after frequent fires. The Holocene B-horizons have similar soil characteristics on the three sites (designated Bt1 in Figs. 3A, 3B, and 3C), but vary in thickness: the Bt1 undulated between 15 to 40 cm thick on Site 1, it gradually increased in thickness from 5 cm on the west to 25 cm on the east on Site 2, and it was a consistent 30 cm thick blanket on Site 3. The variations in horizon thicknesses appear to be unrelated to surface vegetation distributions.

The pedons show a buried soil under all 3 sites that strongly affected growth of deep-rooted species such as *Prosopis* (Fig. 3). This buried soil, consisting of a clay loam, is interpreted to be of Pleistocene age and is the fine-grained equivalent of a rocky soil that is common in the vicinity of Fort Huachuca (Demsey and Pearthree, 1994). The contact between the Holocene soil and the underlying Pleistocene paleosol was sharp and planar beneath all three sample sites (Figs. 3A, 3B, and 3C). Most *Prosopis* roots spread laterally along the top of the thick clay horizons; a few roots penetrated into the Pleistocene soil along prominent cracks. Clay particles in the buried soil were mostly montmorillonite (60%) with illite (15%) and kaolinite (10%). The buried Pleistocene soil stratigraphy was divided into 2 units, designated 2 and 3, based on the color, the amount of clay, and other soil features. No absolute ages have been determined for the Pleistocene units of the study area. The horizons of the 2 strata developed on an irregular 3 surface and were beveled before the deposition of the overlying Holocene units. Thicknesses and occurrences of individual 2-horizons were quite variable in each trench and also varied from trench to trench. In trenches on Sites 2 and 3, discontinuous 2A horizons were present that ranged up to 32 cms thick (Fig. 3). In trench 2, two 2Bt

horizons were present, whereas only one 2Bt horizon was recognized in trenches 1 and 3. A maximum of 10 cm of 2Bt thickness was preserved in two discontinuous lenses below the Holocene-Pleistocene contact in trench 1, whereas the 2Bt in trench 3 varied from 5 cm to 40 cm thick from north to south. Below the 2Bt horizons in trench 1 and 3 were very clay-rich horizons designated 3Bt1 and 3Bt2. The 3Bt1 horizon was mottled orange and gray-brown and contained abundant clay skins, whereas 3Bt2 was almost gleyed in appearance and clay skins were less evident. The contact between these two horizons was undulatory in trench 1, but more planar in trench 3. These units were not reached in trench 2.

Geochemistry of the surface soil

A. pH, CEC, and exchangeable cations. Soil pH did not differ between the unburned and moderately burned sites, but pH was higher on the frequently burned Site 3 (Table 3). In addition, the variance of soil pH on Site 3 was significantly lower than on the unburned site. Although seasonal variations were apparent in measurements taken in the fall of 1995 and the spring of 1996, the proportional differences in soil pH between the sites remained constant. Soil CEC was about 40% higher in the burned sites (Table 3), but the variance of CEC was not significantly different among the 3 sites.

Of the 4 exchangeable cations, only Ca^{++} was lower in burned sites (Table 3). The variability of Na^+ , K^+ , and Ca^{++} was markedly different among the 3 sites and was lower in the burned sites; Mg^{++} was not significantly different among the sites. The concentrations of exchangeable ions were not significantly different between the two burn treatments (Table 3).

B. TOC, N, NO_3^- , and PO_4^{-3} . The concentrations of soil macronutrients were considerably different among the 3 sites. In comparison to Site 1, TOC was significantly higher on the moderately burned Site 2 and lower on the frequently burned Site 3 (Table

3). Likewise, the concentration of PO_4^{-3} was 60% higher on Site 2 but 28% lower on Site 3. NO_3^- did not differ between Sites 1 and 2, but mean NO_3^- was 57% less on Site 3 than on Site 1. The variability of all 3 macronutrients decreased with frequent burning (Table 4).

On Site 1, TOC, NO_3^- , and PO_4^{-3} were more abundant under *Prosopis* canopy than in the open areas between trees (Table 4). The macronutrient concentrations among the open node points of Site 1 were compared with Sites 2 and 3 to determine the net effect of fire on patches that could support herbaceous species, particularly grasses. For both TOC and PO_4^{-3} , the mean concentrations in the soils of moderately burned Site 2 were higher than in the open nodes of Site 1, and the concentrations in Sites 1 and 3 were similar (Table 4). The NO_3^- concentration in Site 2 was significantly higher in comparison to open nodes on Sites 1 and 3.

Total N was low on all three sites and the variances were not significantly different (Table 4). The means for Sites 1 and 2 were equivalent, with the mean for Site 3 slightly lower than the other two. Comparison of total N and NO_3^- for 10 nodes on each of the 3 sites (30 total paired samples) indicated no direct correlation between the total nitrogen present in the SOM and the amount of nitrate available in the SOM.

C. Spatial distribution of macronutrients. Frequent fires apparently decreased the spatial variability of TOC, NO_3^- , and PO_4^{-3} on the study sites at Fort Huachuca. Contour plots of the nutrient topography showed significant peaks in all three macronutrients clustered around standing *Prosopis* trees on the unburned site and the single *Prosopis* on the infrequently burned site (Figs. 4, 5 and 6). Coincident nutrient peaks were also present on both Site 2 and Site 3 (Figs. 4, 5 and 6) that are unrelated to either *Prosopis* or clusters of other C_3 plants. These features on the burned sites suggest

that nutrient peaks remained from *Prosopis* individuals that had burned or been removed before 1975.

The semivariograms for soil TOC, NO_3^- , and PO_4^{3-} for the 3 sites (Fig. 7) indicate striking differences in the spatial variability of macronutrients. The spatial variability of NO_3^- decreased by more than 2 orders of magnitude with increasing fire frequency (Fig. 7b). The semivariogram for NO_3^- for the unburned Site 1 was nonstandard (negative sill and range, see Warrick et al. 1986), which reflected the spacing of mature *Prosopis*; the maxima in semi-variance roughly corresponded to 1.5 times the spacing between trees, or the distance of maximum spatial variability (Figs. 5 and 7b).

The spatial variability of soil TOC increased in the moderately burned site compared to Site 1, but decreased slightly with frequent burning (Fig. 7a). The spatial variability of PO_4^{3-} decreased slightly with moderate burning, but the variance was about 80% lower on the frequently burned plot (Fig. 7c).

D. Seasonal variation of macronutrients. The concentrations of NO_3^- showed considerable seasonal fluctuations and significant statistical variations in the three seasons that were sampled (Table 5). October 1995 amounts on respective sites were 3 to 7 times larger than the concentration in the spring of that year. Differences between samples from the spring of 1995 and the spring of 1996 were relatively small on Sites 2 and 3, but very significant on unburned Site 1. Because *Prosopis* is the largest single source of N-fixation, most of the high concentrations were on canopy sites. Therefore, the NO_3^- increase was highest on the unburned Site 1, but the burned sites also have low numbers of presumed N-fixing species such as *Mimosa* and *Calliandra*. Although there were on average 1-3 mg/kg variations in PO_4^{3-} concentrations from season to season on the respective sites (Table 5), the site to site ratios remained constant for each season reflecting the low mobility and turnover rates of phosphorus in the grasslands ecosystem.

Subsurface nutrients

The concentrations of TOC and macronutrients at depth was considerably different among the 3 study sites (Figs. 8, 9, and 10). In the Holocene soil, the removal of PO_4^{-3} by mesquite is suggested by low concentrations proximal canopies (Fig. 10). Overall PO_4^{-3} was significantly higher on Site 2 than on Sites 1 and 3 (Table 6, Fig. 10). Concentrations of NO_3^- were not significantly different between the unburned and moderately burned sites, but NO_3^- declined significantly in the frequently burned site (Fig. 9). Concentrations of TOC were very similar in the Holocene intervals of the three sites.

The Pleistocene soil, which few plant roots penetrate because of its dense clay, has a basic pH (7-8), in contrast to the acidic Holocene soil. In general, TOC and macronutrient concentrations were greater in the Holocene soils than in the lower Pleistocene soil (Figs. 8-10). In particular, PO_4^{-3} has been stripped from the Pleistocene soils on Site 1 and values on Site 3 were very low, whereas concentrations beneath Site 2 are similar to the concentrations in the Holocene intervals (Fig. 10). TOC levels decreased with depth, although, not surprisingly, the buried 2A horizons of Sites 2 and 3 had higher TOC amounts than the other Pleistocene horizons (Fig. 8). Concentrations of NO_3^- were mostly below detection limits in trenches 2 and 3.

Plant biomass

The species composition was similar among the study sites, although the abundances of several species changed considerably. A total of 64 species were observed on the geomorphic surface; 50 species were present on unburned Site 1, whereas Sites 2 and 3 had 37 and 39 species, respectively (J.E. Bowers, unpublished data). The values of Otsuka's I were 0.697, 0.679, and 0.632 for comparisons of Sites 1- 2, Sites 1-3, and Sites

2-3, respectively, which indicates a high and consistent degree of similarity among the study areas.

A. Mesquite Trees. Prosopis appeared on the 3 study sites between 1935 and 1946. Actual ages of mesquite are difficult to determine, especially for multi-stemmed trees. A 1975 aerial photograph showed the current pattern of *Prosopis* on Site 1, and Site 3 apparently had been burned shortly before that photograph was taken. By comparing 1975 and 1994 aerial photographs, we found that the burned sites lost several established *Prosopis* individuals, probably as a result of fires between 1981 and 1991, resulting in a more open appearance.

The canopy of *Prosopis* covered 34% of the unburned Site 1, about 3% of the moderately burned Site 2, and <1% of the frequently burned Site 3. *Prosopis* comprised nearly 98% of the living biomass and more than 85% of the total biomass on Site 1 (Table 7). Much of the litter on Site 1 was also derived from mesquite. The amount of *Prosopis* biomass on Site 1 was an order of magnitude larger than on Site 2 and 60 times larger than on Site 3; *Prosopis* formed almost 43% of the total biomass on Site 2 and 12% on Site 3 (Table 7).

B. Grasses, Forbs, and Shrubs. The biomass of grasses was 350 and 300% higher on the moderately and frequently burned sites, respectively, compared to the unburned site (Table 7). Although the moderately burned site had the greatest biomass of grasses by weight, this amount was only slightly greater than on the frequently burned site. However, grasses contributed 41% of the living material on Site 3 and only about 17% on Site 2. The variability of grass biomass was significantly higher on the burned sites. The biomass of forbs was equivalent on the three sites, although forbs comprised a higher percentage of the living and total biomass on the burned sites than on the unburned site (Table 7).

The biomass of shrubs increased with burning (Table 7). Shrub biomass was 12 times greater on the moderately burned site than on the unburned site. Shrubs made up almost 17% of the living biomass on the two burned sites, but was a minor constituent of the unburned site. The most common shrub, *Eriogonum wrightii*, is a palatable native species commonly found in desert grassland. *E. wrightii* was distributed throughout Site 2, and was observed to line the outer canopy edges of many of the *Prosopis* trees on Site 1. The variabilities of grass and shrub biomass were both higher on the burned areas compared to the unburned site.

C. Litter and total above-ground biomass. Biomass harvesting was done in early October after maximum growing season for C₄ grasses, so the recent litter component should have been at maximum (Sims et al., 1978). The amount of litter was not significantly different among the 3 sites, despite the fact that the mean biomass of litter on Site 1 was about twice the mean values for Sites 2 and 3 (Table 7). The variability of litter biomass was an order of magnitude higher on Site 1 because of the large amount of litter under *Prosopis* trees. Litter contributed 12.5% of the total biomass on the unburned Site 1 (Table 7); in contrast, litter contributed 29% and 54% of the total biomass on Sites 2 and 3, respectively. The total above-ground biomass on unburned Site 1 was 4.5 times greater than infrequently burned Site 2, and almost 9 times greater than frequently burned Site 3, due to the presence of *Prosopis* trees (Table 7).

D. Biomass of shallow roots. The mean biomass of shallow roots at 0-70 mm depth was lower in the burned sites (Table 7). The variability of root biomass was heterogeneous among the 3 sites. On the unburned Site 1, shallow-root biomass was 2.9 times higher under *Prosopis* canopy, which indicates that differences in shallow-root biomass on the burned sites may be related to differences in the density of *Prosopis*.

Plant biochemistry

A. *Prosopis*. A limited number of *Prosopis* samples from trees on the unburned site were analyzed for total carbon, key nutrients, and soluble salts (Table 8a). There was a wide variation in measured amounts between plant tissue systems for particular components. For example, leaves and roots contained more than 3 times as much nitrogen as did seed pods and wood. There was also a wide range for some components within the same plant system. Calcium content of mesquite twigs ranged from 35,600 to 54,500 ppm and potassium in twigs varied from 1,060 to 3,060 ppm. Carbon content did not vary much between tissue systems, although carbon-to-nitrogen ratios ranged from 21.4 to 76.5 due to nitrogen concentration differences. These results were similar to analyses on specimens of *Prosopis juliflora* from the Santa Rita Experimental Range (Klemmedson and Smith, 1972).

One twig from a small shrubby *Prosopis* on frequently burned Site 3 was also analyzed (Table 8a), which showed marked differences from similar *Prosopis* twigs from unburned Site 1.

B. *Grasses, Forbs, and Shrubs*. For grasses, forbs, and shrubs, the amount of carbon in the plant tissues was higher on the two burned sites compared to the unburned site, although there was little difference between the two burned sites (Table 8b). Grasses and shrubs on the burned sites had 5 to 10% more carbon than their counterparts on the unburned site. Analysis of variance indicated significant differences between Site 1 and Site 2, and between Site 1 and Site 3. Conversely, concentrations of nitrogen (Table 8c) and phosphorus (Table 8d) in the plant tissues of the two burned sites were lower than samples from the unburned site. Nitrogen variances were significantly lower on Site 2 and Site 3 compared to Site 1. Nitrogen concentrations in grasses were 32 to 37% lower on the burned sites versus the unburned site, whereas the nitrogen levels in forbs and shrubs ranged between 21 and 25% lower compared to Site 1 plants. Nitrogen

concentrations were also about 5% lower in Site 3 plants compared to plants from Site 2. Phosphorus concentrations in plant tissues from the two burned sites were 13 to 35% lower than those from the unburned site (Table 8d). Grasses and forbs on frequently burned Site 3 were 13% and 9% lower in phosphorus than samples from infrequently burned Site 2, but shrubs on Site 3 were 10% higher in phosphorus than shrubs on Site 2. Variances for phosphorus were equal for the three sites. Carbon-to-nitrogen ratios were lower on the unburned site compared to the two burned sites for grasses, forbs and shrubs (Table 8e). Sites 2 and 3 had similar ratios.

Concentrations of the exchangeable cations varied with plant group as well as site (Table 8f). Calcium concentrations in grasses were greatest on the unburned site and decreased with increasing burn frequency. In the forbs, calcium amounts were equivalent on Sites 1 and 2 (except for beneath *Prosopis* canopies), both of which were higher than Site 3 forbs. The shrubs on Site 2 and Site 3 were a little higher in calcium than the shrubs on Site 1. Concentrations of magnesium in grasses were about 20% higher on unburned Site 1 compared to the two burned sites. Shrubs and forbs had similar magnesium concentrations on all three sites, although there was considerable variation between open and canopy areas of the unburned site. Potassium concentrations for grasses, forbs, and shrubs on the unburned site were very high compared to plants from the two burned sites, and concentrations of potassium decreased with increased burn frequency. Sodium concentrations were usually below detection limits for these plant groups.

C. Litter. The amount of carbon and the carbon-to-nitrogen ratios of litter were lowest on the unburned site. The carbon content of litter on the infrequently burned site was more than 11% greater than the unburned site, whereas the frequently burned site had an 8% increase in carbon content compared to the unburned site (Table 8b). The mean

C:N on Site 2 was 33% higher than Site 1, and Site 3 was 41% higher than Site 1 (Table 8e).

As with the living plants, the concentrations of nitrogen and phosphorus in the litter decreased with increasing fire frequency. The means between Sites 1 and 2 and between Sites 1 and 3 differed, as did the variances between the sites (Tables 8c and 8d). Calcium and potassium concentrations in the litter decreased with burning, although the differences between the infrequently burned site and frequently burned site were not notable. Magnesium also decreased with burning, although the mean for the frequently burned site was greater than that of the infrequently burned site (Table 8f).

D. Subsurface biomass. The carbon content of roots did not vary much between the three burn sites (Table 8b). Mean C:N ratios were higher on both burned sites than on the unburned site, reflecting the significant decrease in nitrogen concentration in roots from the two burned sites (Tables 8c and 8e). The variances for nitrogen concentrations differed between all three sites. The means for phosphorus concentrations were equivalent on Sites 1 and 2, but Site 3 was significantly lower; variances between the three sites were different (Table 8d).

Soil respiration

Soil air normally contains elevated CO₂ levels due to root and microbial respiration, although the concentration fluctuates due to temperature, soil moisture, root growth, microbial activity, pH, and gaseous exchange with the atmosphere (Sheppard et al., 1994). The effects of fire frequency on root densities and microbial activities may also be revealed by changes in rates of CO₂ evolution at the soil-atmosphere boundary. Soil-respired CO₂ was collected five times from June 1995 to November 1996 (Table 9). Results indicated significant seasonal fluctuations on all three sites, with the highest respiration rates occurring in late summer after the seasonal monsoon rains and the lowest

rates in the late fall and winter. On unburned Site 1, there was very little difference between open areas and canopy areas for any particular sampling season. There was very little difference in respiration rates between the unburned site and the two burned sites during the warm seasons, although the rates on frequently burned Site 3 were slightly higher than the other two for the June and September measurements. There was a significant decrease in the respiration rates on Sites 2 and 3 during the colder seasons of November and February compared to the unburned site.

Discussion and Implications

On a single geomorphic surface near Woodcutter's Canyon at Fort Huachuca, fire events of moderate and high frequency appear to have suppressed the biomass of *Prosopis* compared to an adjacent unburned area. During extensive use as live-ammunition military training facilities since before the turn of the century, the grassland gunnery ranges at Fort Huachuca must have been burned frequently, although fire records for the ranges were not maintained prior to 1973. Historic photographs suggest mesquite trees were concentrated in riparian areas before World War II, a conclusion that seems to be supported by 1935 aerial photography. By 1946, *Prosopis* trees had become established on portions of the interdrainage alluvial fan surface and, from later aerial photographs, their numbers appear to have increased in some areas in subsequent years.

The occurrence and frequency of fires in the desert grasslands appears to be reflected in the distributions of key nutrient concentrations in soil organic matter and plant biochemistry. A comparison of SOM concentrations of TOC, plant-available N, and plant-available P show changes in quantities and spatial distributions as a result of fire frequency between the three study sites. Soil pH increases with higher fire frequency. Cation exchange capacity, a measure of soil fertility, is about 50% greater on

the burned sites, but Na^+ , K^+ , and Ca^{++} decrease in burned sites. The soil carbon pools on the three study sites were consistently low, ranging from a maximum of 1.29% beneath the *Prosopis* canopies to 0.87% on the frequently burned site and 0.88% on intercanopy areas of the unburned site (Table 4). The biomass of grasses and other shrubs was higher on the burned sites than in the nearby unburned area. One shrub species that increased, *Eriogonum wrightii*, is native and not an invader symptomatic of disturbance or desertification. The changes in biomass distribution observed at Fort Huachuca are in accord with changes observed elsewhere in southeastern Arizona (Humphrey, 1963; Humphrey, 1974; Humphrey and Mehrhoff, 1958; McPherson, 1995).

One effect of fire appears to be the redistribution of macronutrients from under *Prosopis* to the remainder of the landscape. Fires result in the deposition of large amounts of N and P onto the soil surface, where the nutrients are highly susceptible to erosion and leaching losses (Weinhold and Klemmedson, 1992). Our results clearly reflect this, as soil PO_4^{-3} and NO_3^- increased with moderate fire frequency, but decreased with increasing fire frequency. Differences between infrequently burned Site 2 and frequently burned Site 3 do not reflect losses during the most recent burning episode, as Site 2 burned more recently than Site 3 (Table 1). Mean TOC increased slightly with moderate burning, and the increased spatial variability of TOC is in joint response to the increase in grass and shrub biomass and the slow cycling rates of soil C. The "islands of fertility", evident beneath the *Prosopis* trees on the unburned site (Figs 4, 5, and 6), seem to have been reduced by the redistribution of nutrients by fire events on the two burned sites, although residual concentrations remain. Even on Site 3, where frequent fires may have augmented nutrient cycling, pockets of macronutrients persist in the SOM.

For any element which is incorporated into biomass, the biogeochemical cycle of that element in a given ecosystem will be coupled to that of any other element similarly incorporated (Williams, 1987). Nitrogen, which exists in the soil primarily in an

immobilized state as a component of plant, animal, and microbial residues, will continue to be recycled by the soil organisms until the carbon content decreases to a level where the C/N ratio falls below about 30:1 (Day and Ludecke, 1993). Larger C:N ratios indicate that N availability for decomposers is not as favorable as when C:N ratios are small (Schimel et al., 1985). The C:N ratios of the soils on all three sites at Fort Huachuca (Table 4) are well above that value, indicating nitrogen is not a limiting factor.

Lajtha and Bloomer (1988) and Lajtha and Schlesinger (1988) report that CaCO_3 , not soil organic material, controls P retention in southern New Mexico. Because soils at the Fort Huachuca sites are low in CaCO_3 , those results do not appear to be relevant to this study. Results here agree with Stewart and Tiessen (1987), who found phosphorus concentrations to be closely tied to SOM. The amounts of P and TOC were highest on the infrequently burned Site 2, whereas the lowest concentrations of both were on the frequently burned Site 3 (Table 4). Phosphorus, unlike nitrogen, is not as subject to leaching from the soil (Day and Ludecke, 1993) and plays a critical role in N fixation (Crews, 1993; Eisele et al., 1989).

The highest coincident amounts of TOC, N and P accumulated in the soils beneath the mesquite canopies, but these concentrations decreased rapidly with distance from the center of the canopies (Figs. 4, 5, and 6). A similar spatial pattern for N was reported in other mesquite stands (Tiedemann and Klemmedson, 1973a). Spatial heterogeneity of SOM and nutrient pools at scales related to sizes of individual plants have also been reported in the shortgrass steppe of north-central Colorado (Hook et al., 1991). Conversely, McPherson et al. (1993) found no change in concentrations of TOC and total N, but noted the nutrients should increase because of the large amount of litter under the trees.

Over time, the tendency of *Prosopis* to sequester N and P reduces the amount available in the soils of adjacent areas (Virginia, 1986). Concentrations of TOC, NO_3^- ,

and PO_4^{-3} in SOM of Site 1 open areas (i.e., nodes not under *Prosopis* canopies) were less than concentrations in soils beneath *Prosopis* (Table 4) and the spatial variability of macronutrients is generally higher in unburned areas. This was also reflected in the increased availability of nitrogen to grasses, roots, and forbs growing under *Prosopis* (Table 8c), although increases at Fort Huachuca were not as high as reported by other studies (Tiedemann and Klemmedson, 1973b). On the other hand, phosphorus concentrations in plants harvested from canopy locations were lower than plants from open positions, even though PO_4^{-3} was higher in SOM (Table 8d).

A comparison of SOM macronutrient concentrations revealed that canopy interspace areas of unburned Site 1 had lower amounts of soil TOC, NO_3^- , and PO_4^{-3} than the moderately burned Site 2 (Table 4); SOM N and P concentrations of open areas on the unburned site were more than 40% lower than concentrations of available N and P in soils of the infrequently burned site. Nutrient concentrations on frequently burned Site 3 were similar to the unburned open areas.

Results of soil macronutrient distributions at Fort Huachuca show similar patterns to those in Chihuahuan Desert grasslands of New Mexico (Schlesinger et al., 1996), although the distance scale may be much longer because of the size differences between mature *Prosopis* in desert grassland and shrubs in desert scrub. Changes in macronutrient variability may be difficult to reverse in some severely disturbed grasslands (Schlesinger et al., 1990) where fuel loading is too low to carry fires. In areas with higher biomass of fine fuels, fire provides an impetus for accelerated restoration. The remnant peaks in the nutrient topography of Sites 2 and 3 show that macronutrients do not immediately respond to the change in vegetation; instead, the reduction in the high levels of macronutrients is controlled by relatively slow cycling rates. Barnes and Archer (1996) also conclude that the nutrient topography created by *Prosopis glandulosa* persists for decades after removal of the trees. As suggested by the variograms (Fig. 7), turnover rate

of NO_3^- , which has been shown to react quickly to burning (DeBano et al., 1979; Raison, 1979), must be considerably faster than TOC and PO_4^{3-} .

Plants with the greatest growth rates are those which allocate the highest proportion of their photosynthetically fixed carbon to the synthesis of additional photosynthetic tissues, with biomass yield more dependent upon rate of leaf tissue production than on the carbon balance per unit of biomass (Tieszen and Detling, 1983). At Fort Huachuca, the amounts of carbon were higher in plant tissues on the two burned sites (Table 4b), whereas the plant tissue concentrations of both nitrogen (Table 8c) and phosphorus (Table 8d) were lower on the burned sites. Also, the biomass of grasses was 187% greater, the biomass of non-*Prosopis* shrubs was 843% greater, and the total biomass was 143% greater on infrequently burned Site 2 compared to the open areas of unburned Site 1 (Table 7). The highest grass and shrub biomass may thus be related to the SOM macronutrient concentrations, which are highest on Site 2 where the fire frequency is moderate. Reduced total biomass on the frequently burned site apparently reflects the lower concentrations of SOM macronutrients. However, grass and shrub biomass are much greater on the frequently burned Site 3 compared to open areas on the unburned site. Therefore, frequent burning, which may be required to quickly reduce and suppress *Prosopis* (Cable, 1961), appears to reduce soil nutrient concentrations when compared to less frequent fires, but creates soil fertility more favorable for grasses and other forage plants with lower N requirements.

On the other hand, root growth is generally favored over shoot growth in mineral-deficient soil, presumably because a smaller proportion of current photosynthate can be utilized for shoot growth in nutrient-deficient plants (Fageria, 1992). The amounts of grass and shrub biomass increased on both burned sites (Table 7) relative to the total unburned site and the open areas of the unburned site. Concurrently, root biomass was similar on the unburned and infrequently burned sites; root biomass was lower on the

frequently burned site and the open areas of the unburned site (Table 7). Therefore, soil nutrient concentrations, although low, appear to be adequate to support plant populations on all three burn scenarios, but production of grasses and other forage plants is greatest on the infrequently burned site.

In a study of ten North American grasslands, peak live biomass was reported to range from 84 to 336 g/m² and showed linear increases related to growing season precipitation (Sims and Singh, 1978a). Mean total shoot standing crop for these ungrazed grasslands averaged 245 g/m² and varied from 36 g/m² on desert grassland at Jornada, N.M. to almost 700 g/m² in tallgrass prairie (Sims et al., 1978). In comparison, living biomass on the infrequently burned Site 2 was measured to be 860 g/m² (Table 7) after a relatively dry growing season, whereas frequently burned Site 3 (290 g/m²) was slightly above the grassland average and unburned Site 1 open areas were about 50% below the average. Strangely, shallow root biomass on all three study sites was an order of magnitude lower compared to other semiarid ecosystems (Klemmedson, 1989; Sims et al., 1978). However, the amounts of surface litter accumulated on the two burned sites and the intercanopy areas of the unburned site were equivalent to more temperate mixed grass prairie ecosystems (Sims et al., 1978) and double the amounts reported for Sonoran Desert grasslands (Klemmedson, 1989). Litter accumulations under *Prosopis* canopies in this study were about 30% higher than reported accumulations beneath *Prosopis* in Sonoran and Chihuahuan Desert locations (Klemmedson, 1989).

In the Holocene soil horizons, close proximity of *Prosopis* was evident on Site 1: concentrations of PO₄⁻³ in the soil beneath the removed tree were low compared to profiles under canopy margin and open areas, whereas NO₃⁻ and TOC were typically higher. The impact of the single-stem *Prosopis* on Site 2 was reflected in higher NO₃⁻ concentrations, but was not as evident for PO₄⁻³. On frequently burned Site 3, concentrations of NO₃⁻ and PO₄⁻³ were consistently much lower in the Holocene

horizons compared to the other two sites, probably reflecting the loss of these nutrients due to frequent fires. Burn frequency and *Prosopis* proximity seemed to affect subsurface TOC concentrations much less than NO_3^- and PO_4^{3-} (Table 6, Fig. 8), although these similarities may reflect a combination of increased litter on Site 1 and the amount of charcoal residue on the burned sites.

In the Pleistocene soils, the low amounts of plant-available phosphorus on Site 1 (Fig. 10) suggest that cycling of P may be controlled by long-lived *Prosopis*, as the deeper soil horizons have been stripped of P in the vicinity of mature trees. On the burned sites, the removal of *Prosopis* and the deposition of ash may have increased P by translocation downward in the soil column. The lower concentrations under Site 3 compared to Site 2 reflect increased amounts of P lost due to volatilization in more frequent fires. Decreases in plant-available N and P may also be due to higher pH levels, which decreases solubilities of the nutrients (Barber, 1995), the increase in clay component, and decline in soil organic matter (Stewart and Tiessen, 1987). As P is lost from soil, its forms change systematically with time from primary minerals in young sites, to organic P in older sites (< 150,000 yrs.), and then on to insoluble or physically protected, biologically unavailable Fe- and Al-bound P in the oldest sites (Vitousek et al., 1997).

Analyses of SOM and plant material from each of the study sites indicate that fires and *Prosopis* have affected the nutrient availabilities in the grasslands. The effects of *Prosopis* have been well-documented in the literature and reconfirmed in this study. In a comparison of open areas not under mesquite canopies, the only variable that was significant and linearly related to nutrient concentrations and biomass differences was fire frequency. For open grassland positions, it appears that the biomass differences at Fort Huachuca reflect changes in soil geochemistry and nutrient availability due to differences in fire history.

Collins et al. (1995) reported plant species richness was highest at an intermediate time period following disturbance and was consistently lowest on frequently burned sites with lower fire intensity. The study at Fort Huachuca confirms those results in terms of biomass on sites of different fire histories. On a more fundamental level, this study suggests that productivity can be controlled by fire frequency through the redistribution of key nutrients in the soil.

On the basis of these retrospective data from this single geomorphic surface, we agree with Robinett (1994) that the interval between fires in the desert grassland should be greater than 5 yrs to avoid significant losses of macronutrients. Initially, fires only a few years apart may be required to reduce the density of *Prosopis*, after which fire frequency should be reduced. An upper limit to the interval between fires may be determined by recovery or invasion rates of *Prosopis* and invasive shrubs (Cable, 1967). Our results indicate only long-term net effects; the effects of individual fires may be considerably different. The season and amount of fuel present controls the intensity of fires, and fuel loading should be evaluated before prescribed burning if eradication of *Prosopis* is the desired management objective.

Acknowledgments

This study was funded by the Southwestern Borderlands Ecosystems Management Program of the U.S.D.A. Forest Service, Rocky Mountain Forest and Range Experiment Station, with partial funding supplied by the U.S. Geological Survey. Jerry Gottfried and Carl Edminster of the Forest Service were very supportive of the research, Chris Cochrane of the Natural Resources Conservation Service, Tucson, provided surficial soils information, fire history data, and access to some of the early aerial photography, and Sheridan Stone of the Wildlife Office, Fort Huachuca, facilitated with access to the military reservation and arranged for personnel and equipment to dig the back hoe

trenches. Tina Hayden and Laska Rohovit, of the Department of Soil, Water and Environmental Science, University of Arizona, assisted with soil and plant analyses. Jan Bowers, Peter Griffiths, Betsy Pierson, Ray Turner, and Doug Wellington, all from the U.S. Geological Survey, helped with the plant biomass harvesting, and Donna Opocensky and Peter Griffiths of the U.S. Geological Survey helped with laboratory analyses. In addition, species lists of the 3 sites were made by Bowers.

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Figure A1: Location map of the Fort Huachuca area, showing the locations of the Woodcutters' Canyon area and the three study sites.

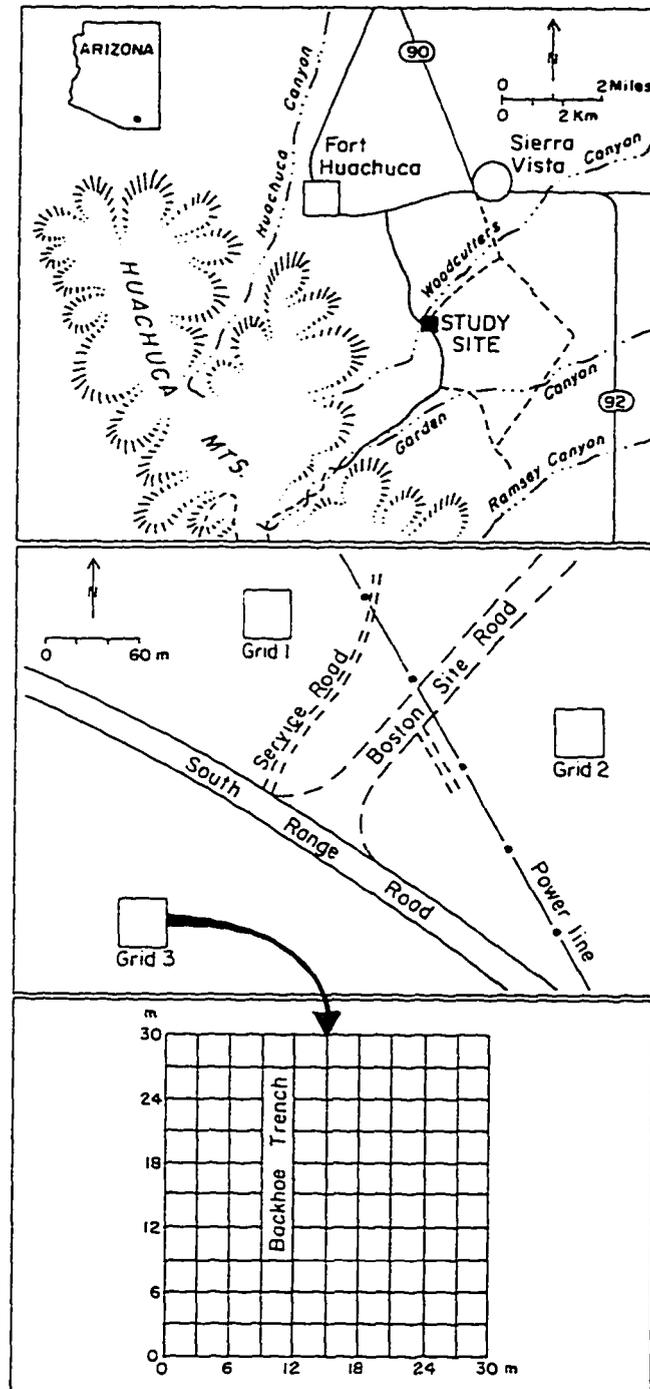


Figure A2: Overview photograph of the Woodcutters' Canyon study sites. Site 1, unburned. Site 2, 3 fires/decade. Site 3, 5 fires/decade.



Figure A3: Diagrams showing the soil profiles exposed in trenches on the three study sites. A. Site 1, unburned. B. Site 2, moderately burned site, 3 fires/decade. C. Site 3, frequently burned, 5 fires/decade.

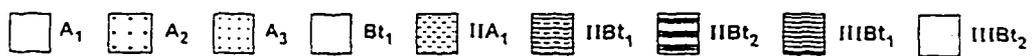
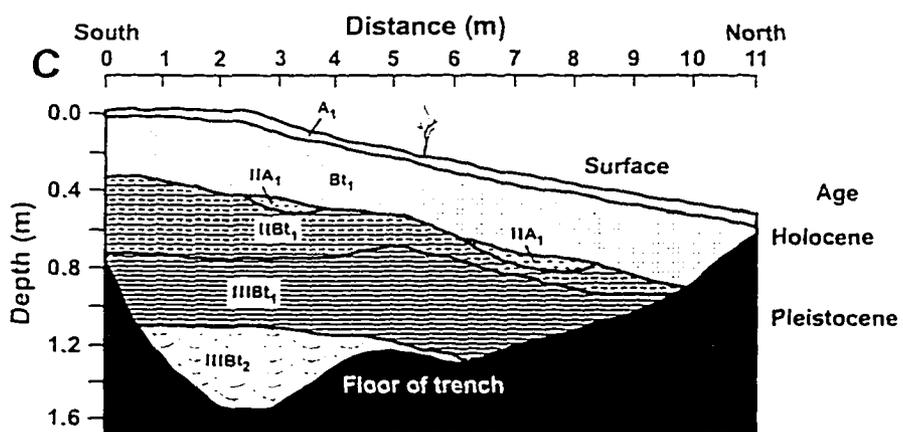
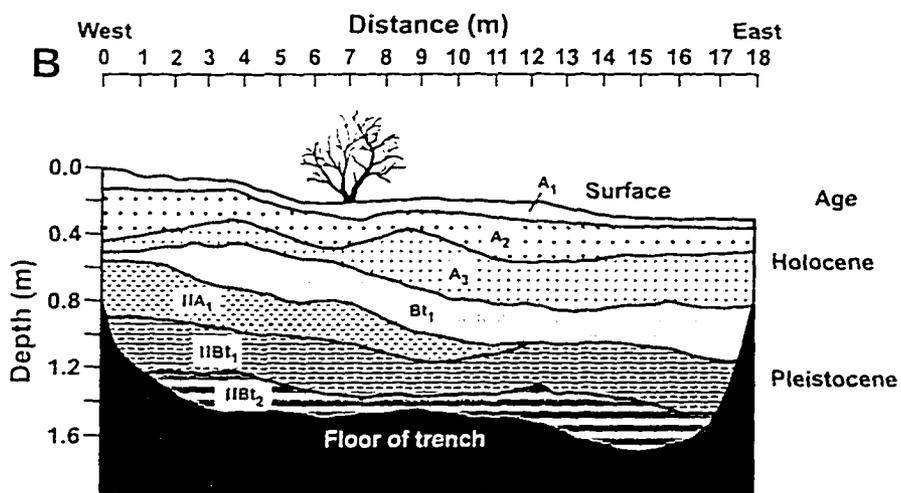
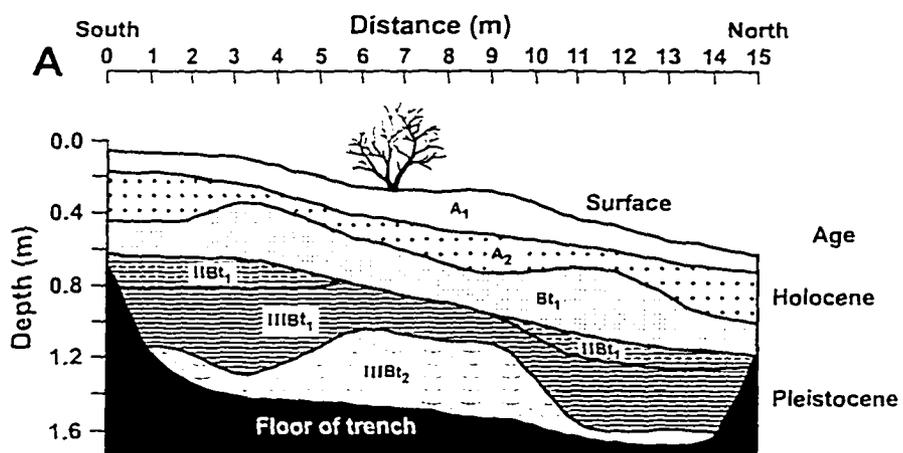
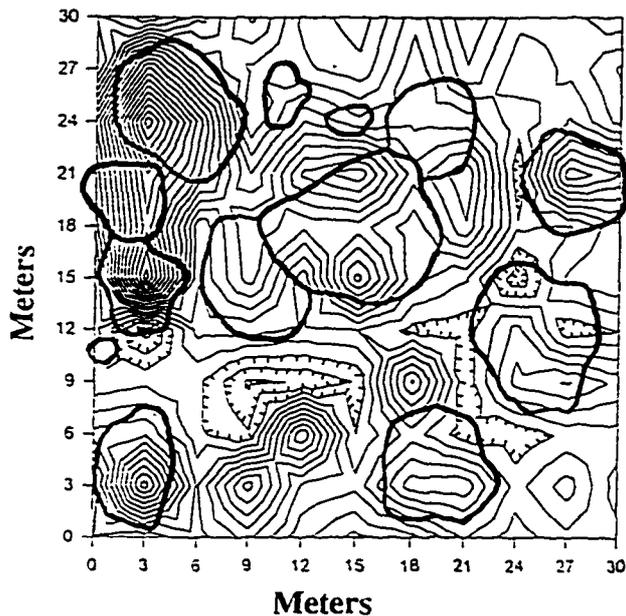
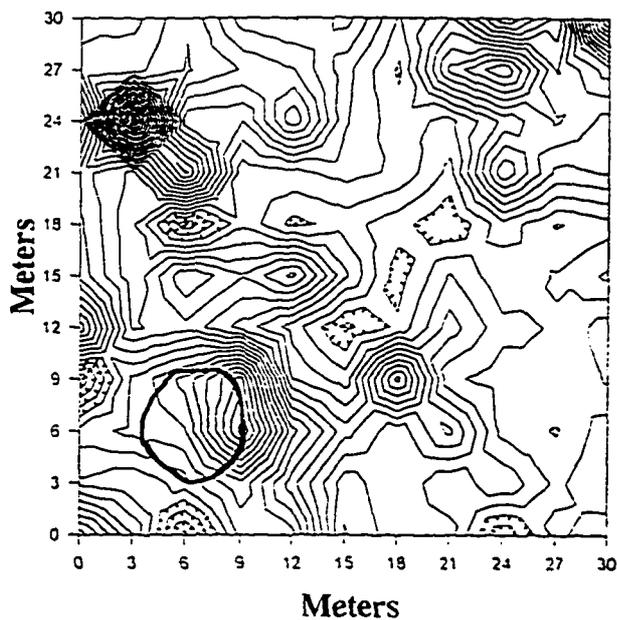


Figure A4: Contour plots of total organic carbon (TOC) on the three study sites at Woodcutters' Canyon. Grid 1, unburned site. Grid 2, moderately burned site, 3 fires/decade. Grid 3, frequently burned, 5 fires/decade. Contour interval 0.10 % TOC.

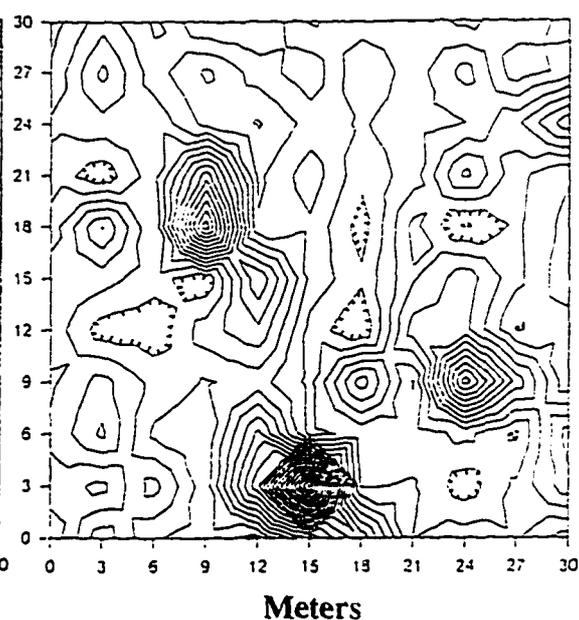
**Site 1: Total Organic Carbon
Unburned Plot**



**Site 2: Total Organic Carbon
Infrequently Burned Plot**



**Site 3: Total Organic Carbon
Frequently Burned Plot**

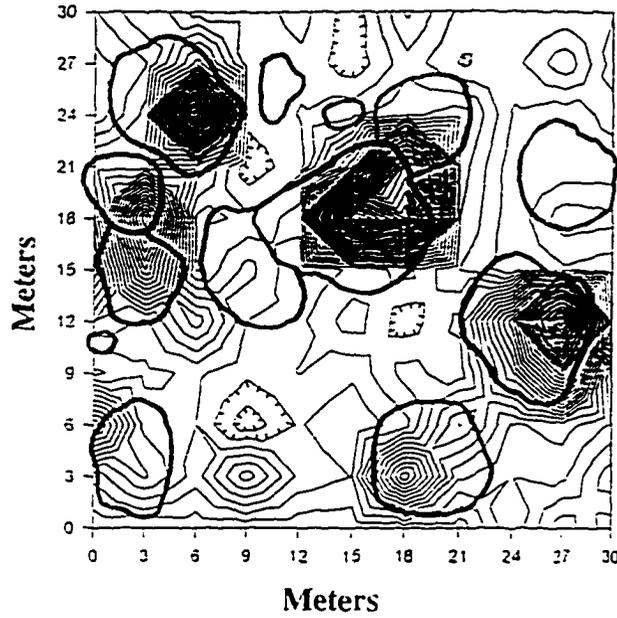


**Mesquite canopy area
(Spring, 1995)**

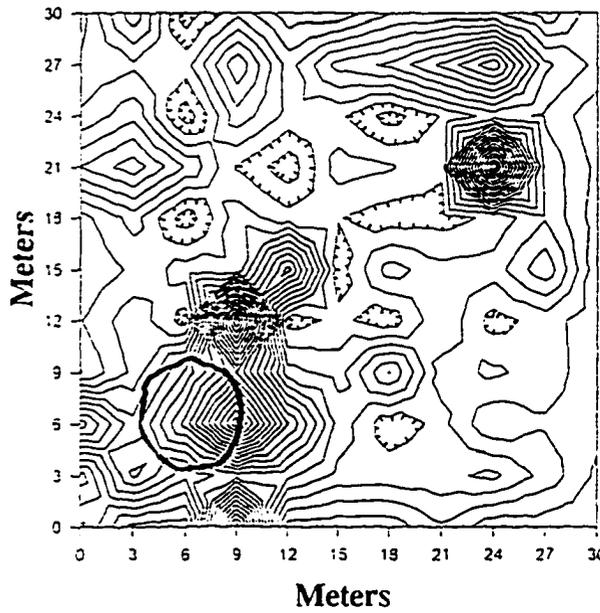
— Contour interval: 0.10% TOC

Figure A5: Contour plots of soluble nitrate (NO_3^-) on the three study sites at Woodcutters' Canyon. Grid 1, unburned site. Grid 2, moderately burned site, 3 fires/decade. Grid 3, frequently burned, 5 fires/decade. Contour interval 1 ppm NO_3^- .

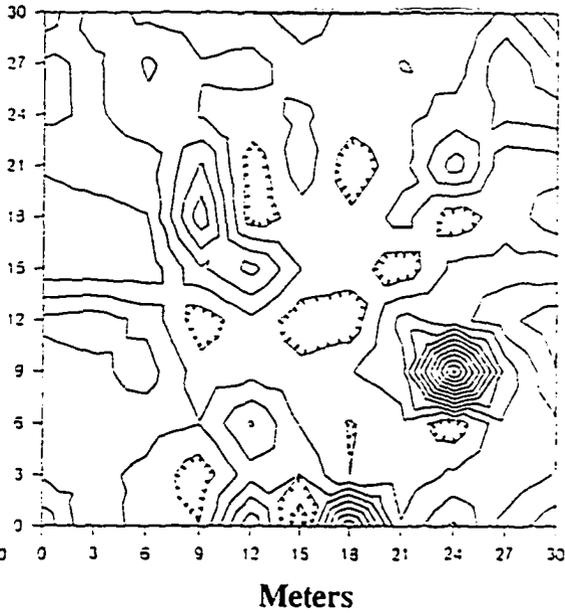
**Site 1: Plant-available Nitrogen
Unburned Plot**



**Site 2: Plant-available Nitrogen
Infrequently Burned Plot**



**Site 3: Plant-available Nitrogen
Frequently Burned Plot**

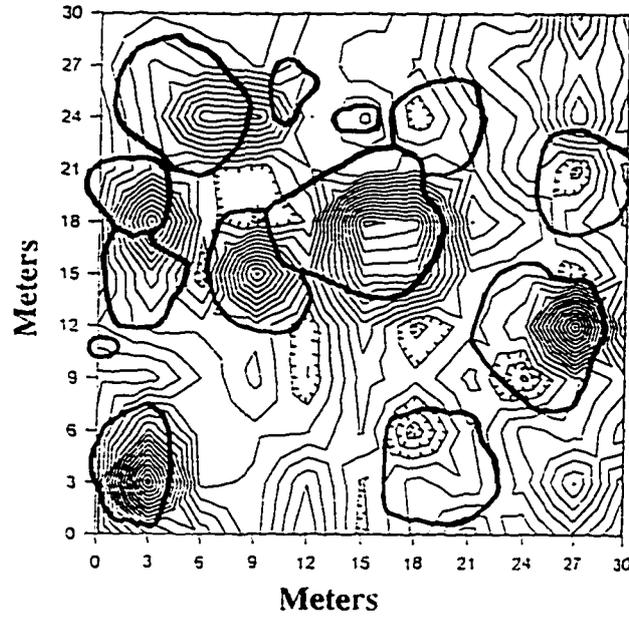


Mesquite canopy area
(Spring, 1995)

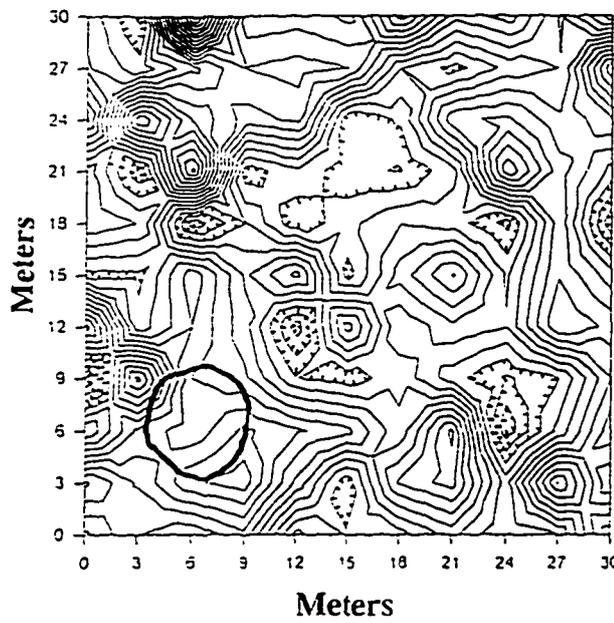
— Contour interval: 1 ppm NO₃⁻

Figure A6: Contour plots of plant-available phosphorus (PO_4^{-3}) on the three study sites at Woodcutters' Canyon. Grid 1, unburned site. Grid 2, moderately burned site, 3 fires/decade. Grid 3, frequently burned, 5 fires/decade. Contour interval 2 mg/kg PO_4^{-3} .

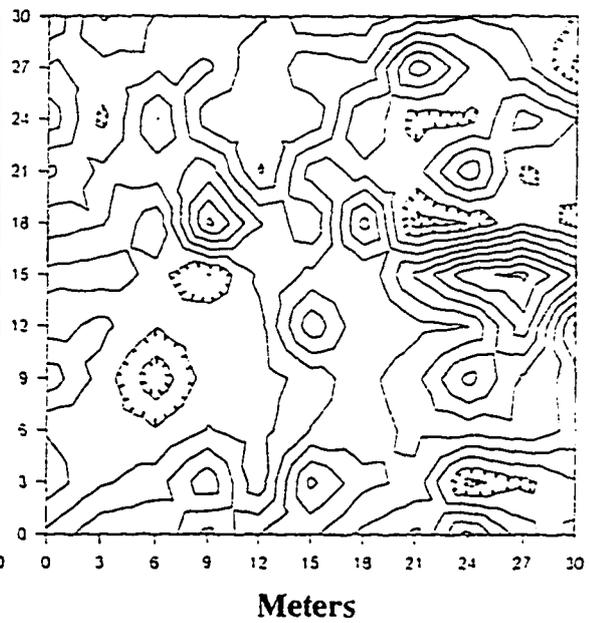
**Site 1: Plant-available Phosphorus
Unburned Plot**



**Site 2: Plant-available Phosphorus
Infrequently Burned Plot**



**Site 3: Plant-available Phosphorus
Frequently Burned Plot**



Mesquite canopy area
(Spring, 1995)

— Contour interval: 2 mg/kg PO₄⁻³

Figure A7: Semivariograms of soil organic matter components on the three study sites at Woodcutters' Canyon. A. Total organic carbon (TOC). B. Soluble nitrate (NO_3^-). C. Plant-available phosphorus (PO_4^{3-}).

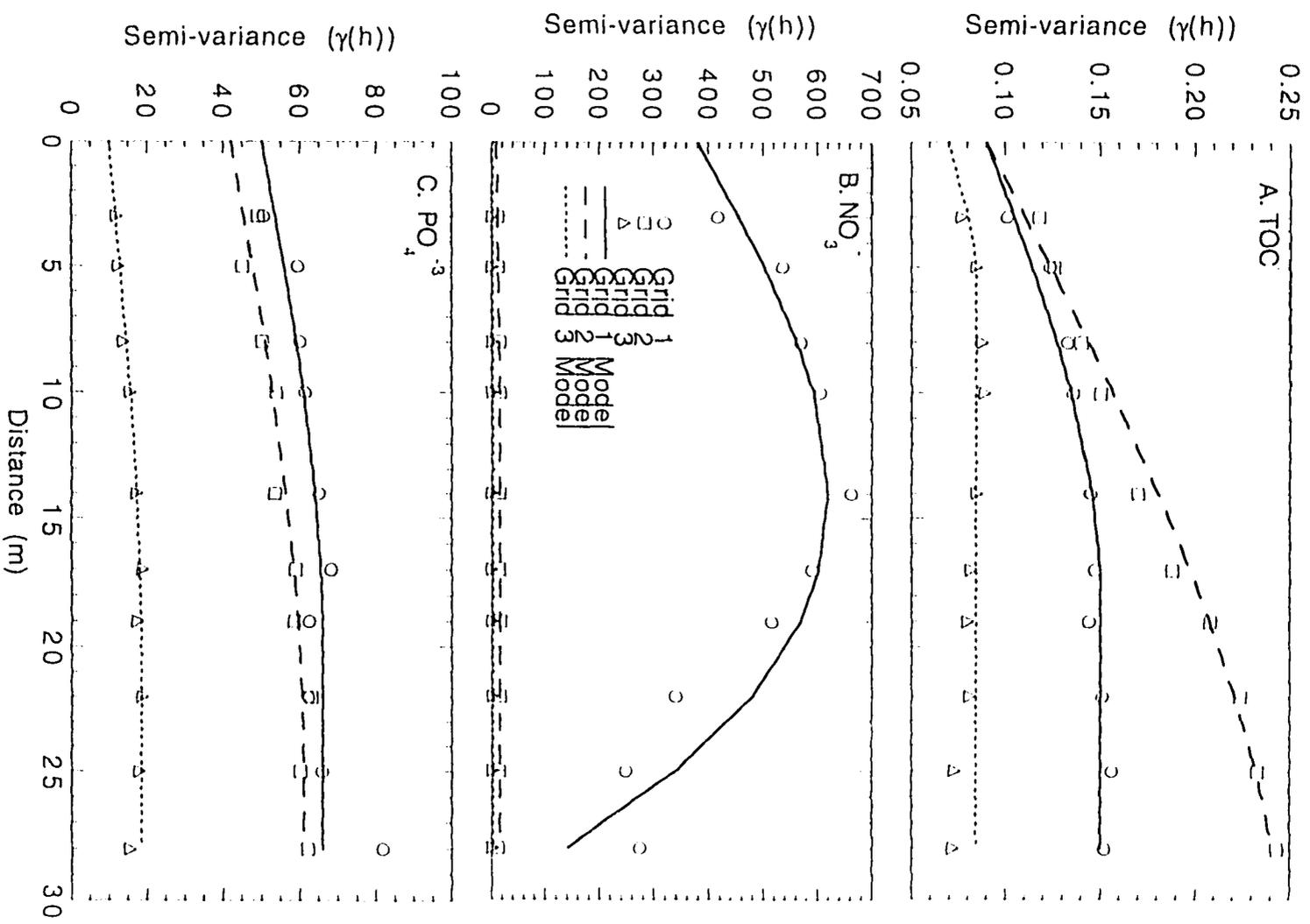


Figure A8: Diagrams showing total organic carbon (TOC) distribution in the soil profiles exposed in trenches on the three study sites. A. Site 1, unburned. B. Site 2, moderately burned site, 3 fires/decade. C. Site 3, frequently burned, 5 fires/decade. Surface extent of *Prosopis* canopy indicated. Values are % TOC.

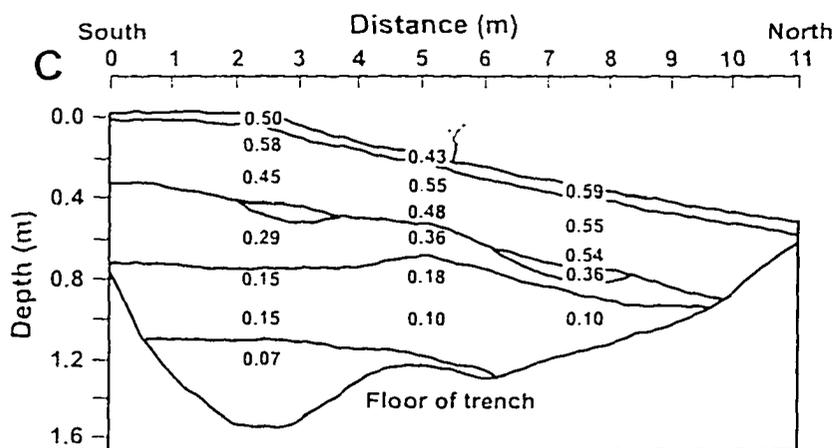
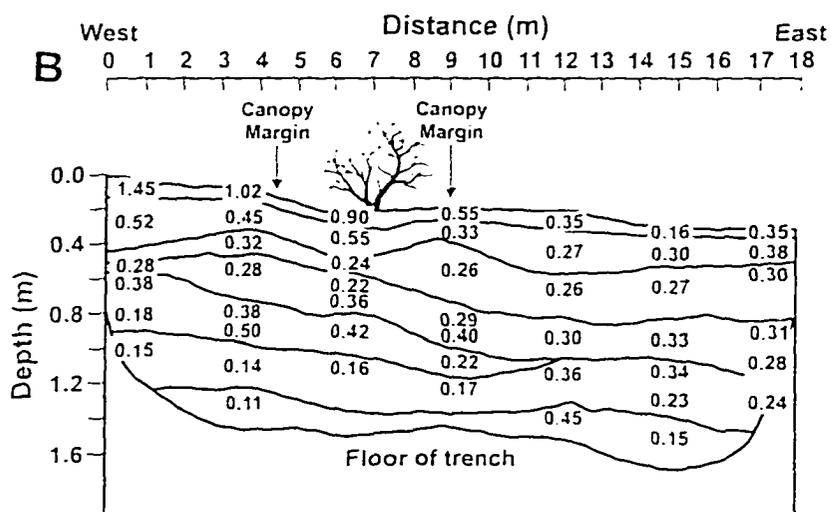
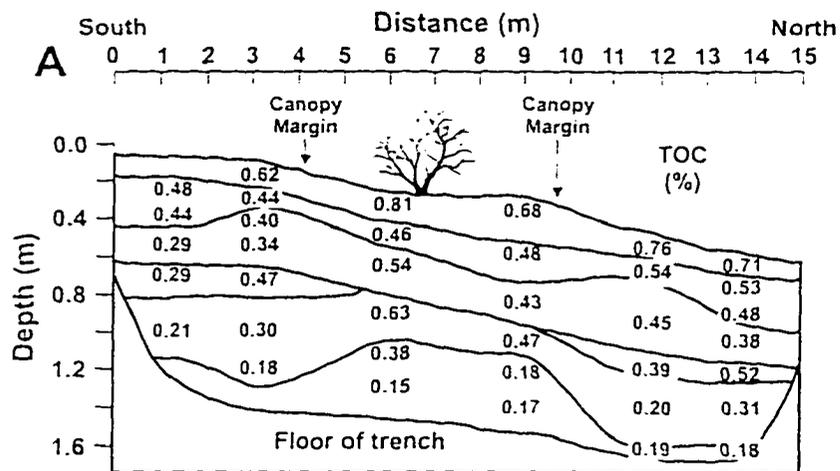


Figure A9: Diagrams showing soluble nitrate (NO_3^-) distribution in the soil profiles exposed in trenches on the three study sites. A. Site 1, unburned. B. Site 2, moderately burned site, 3 fires/decade. C. Site 3, frequently burned, 5 fires/decade. Surface extent of *Prosopis* canopy indicated. Values in ppm NO_3^- .

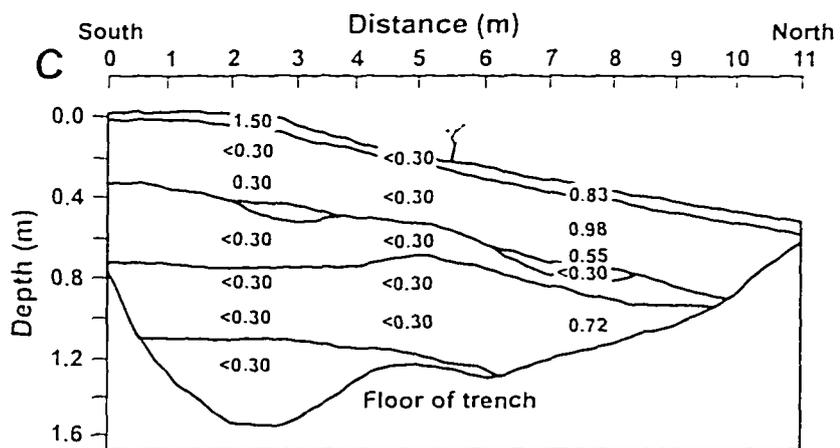
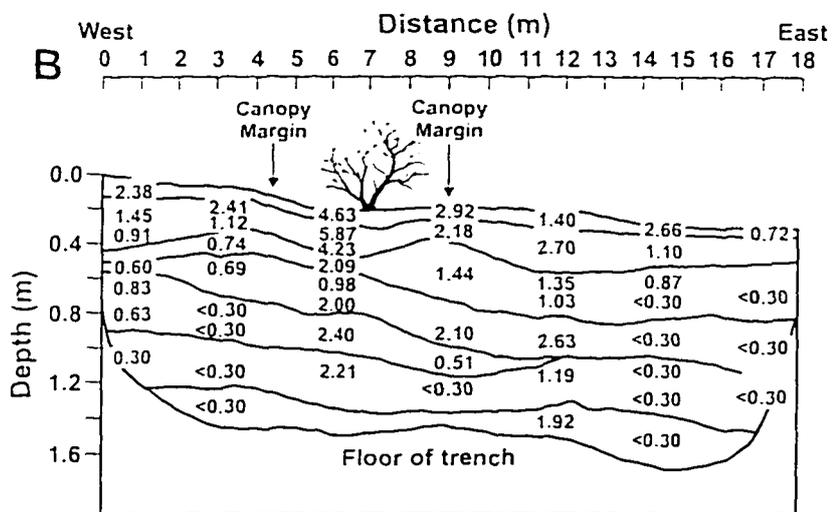
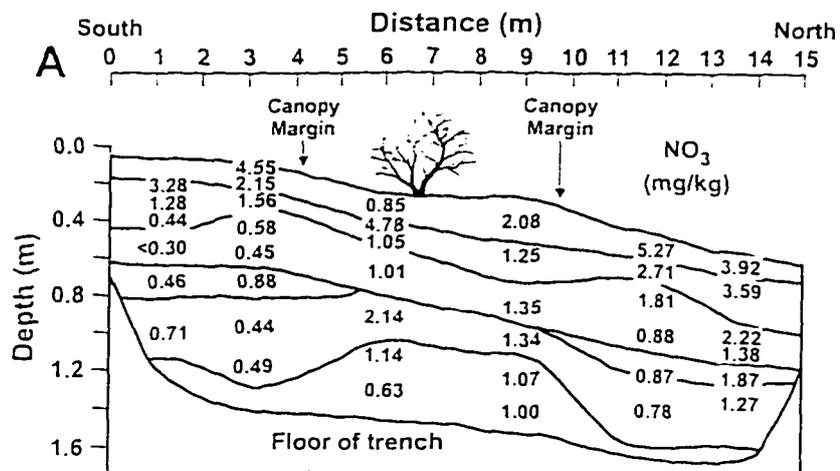


Figure A10: Diagrams showing plant-available phosphorus (PO_4^{-3}) distribution in the soil profiles exposed in trenches on the three study sites. A. Site 1, unburned. B. Site 2, moderately burned site, 3 fires/decade. C. Site 3, frequently burned, 5 fires/decade. Surface extent of *Prosopis* canopy indicated. Values in mg/kg PO_4^{-3} .

Table A1. Fire histories of the 3 study sites at Fort Huachuca, southeastern Arizona.

	SITE 1	SITE 2	SITE 3
		FIRE HISTORY	
Dates of fires after 1973	none	7/83, 5/84, 1/91	2/81, 7/83, 5/86, 2/88, 2/89
Fire frequency, 1981-1995 (number/decade)	0	3	5
Average interval (yrs) between fires, 1981-1995	∞	5	3

Table A2. Soil physical properties of 3 study sites with different burn histories at Fort Huachuca, southeastern Arizona.

		SITE 1	SITE 2	SITE 3
Bulk density (kg/m ³)	x	1,350	1,390	1,460
	SD	122	90	131
Gravel content (%)	x	11.5 ^a	17.8	19.1
	SD	3.1 ^b	1.8	8.7

Notes: All statistics are based on n=10. The null hypothesis is that means and variances are equal, and we only report rejections of the null hypothesis at $p \leq 0.05$.

^a The means for Sites 1 and 2 are significantly different.

^b The variances among the sites are significantly different.

Table A3. Soil pH, cation-exchange capacity, and major cations in 3 sites with different fire histories at Fort Huachuca, southeastern Arizona.

			Site 1	Site 2	Site 3
fires/decade			0	3	5
pH	(spring 1995)	x^a	5.57 ^e	5.75 ^f	6.24
		SD	0.55 ^g	0.27	0.29
pH	(fall 1995)	x^h	5.17 ^{d,e}	5.62	6.19
		SD	0.34	0.39	0.18
pH	(spring 1996)	x^i	5.69 ^e	5.87 ^f	6.45
		SD	0.60 ^g	0.44	0.31
CEC	(meq/100g)	x^b	6.49 ^{d,e}	9.16	9.04
		SD	2.05 ^g	3.32	2.63
Na ⁺	(μg/g)	x^c	1.99	1.50	1.27
		SD	2.57 ^g	0.68	0.39
K ⁺	(μg/g)	x^c	14.00 ^d	7.21	9.02
		SD	11.9 ^g	2.94	3.14
Ca ⁺⁺	(μg/g)	x^c	8.43 ^{d,e}	5.99 ^f	4.30
		SD	4.27 ^g	1.57	0.91
Mg ⁺⁺	(μg/g)	x^c	1.66	1.74	1.42
		SD	0.47	0.51	0.28

Table A3. Soil pH, cation-exchange capacity, and major cations in 3 sites with different fire histories at Fort Huachuca, southeastern Arizona (continued).

Notes: The null hypothesis is that means and variances are equal, and we only report rejections of the null hypothesis at $p \leq 0.05$.

a $n = 20$.

b $n = 15$.

c $n = 9$.

d The means for Sites 1 and 2 are significantly different.

e The means for Sites 1 and 3 are significantly different.

f The means for Sites 2 and 3 are significantly different.

g The variances among the sites are significantly different.

h $n = 5$ for Sites 1 and 3; $n = 4$ for Site 2.

i $n = 7$

Table A4. Soil TOC, total nitrogen, C:N, NO_3^- , C:NO_3^- , and PO_4^{-3} in soil organic matter on 3 sites with different fire histories at Fort Huachuca, southeastern Arizona.

			SITE 1	SITE 2	SITE 3		
fires/decade			0	3	5		
			SITE 1	SITE 2	SITE 3		
			All nodes	Open	Canopy	Open	Open
TOC	(%)	x^a	1.01 ^{c,d}	0.88 ^{x,i}	1.29	1.18 ^e	0.87
		SD	0.37 ^f	0.23 ^h	0.47	0.44	0.28
N	(%)	x^b	0.102	na	na	0.105	0.086
		SD	0.023	na	na	0.025	0.016
C:N	(%)	x^b	11.07 ^{d,e}	10.79 ^x	11.49	11.06 ^e	10.38
		SD	0.93 ^f	1.01 ^h	0.69	0.88	0.66
NO_3^-	(mg/kg)	x^a	4.86 ^d	2.05 ^x	17.38	3.71 ^e	2.04
		SD	9.59 ^f	1.89 ^h	36.65	3.77	1.62
PO_4^{-3}	(mg/kg)	x^a	15.50 ^{c,d}	14.16 ^{x,i,j}	18.44	24.87 ^e	11.10
		SD	8.11 ^f	6.41 ^h	10.45	7.52	4.07

Table A4. Soil TOC, total nitrogen, C:N, NO_3^- , C:NO_3^- , and PO_4^{3-} in soil organic matter on 3 sites with different fire histories at Fort Huachuca, southeastern Arizona (continued).

Notes: The null hypothesis is that means and variances are equal, and we only report rejections of the null hypothesis at $p \leq 0.05$. na -- not applicable, insufficient data to test differences.

^a $n = 121$ (all samples, all sites); for Site 1, $n = 83$ (open), $n = 38$ (canopy).

^b $n = 10$ (all sites); for Site 1, $n = 6$ (open), $n = 4$ (canopy)

^c The means for all nodes on Sites 1 and 2 are significantly different.

^d The means for all nodes on Sites 1 and 3 are significantly different.

^e The means for all nodes on Sites 2 and 3 are significantly different.

^f The variances among the sites are significantly different.

^x The means for open and canopy for Site 1 are significantly different.

^h The variances for open and canopy for Site 1 are significantly different.

ⁱ The means for open areas on Site 1 and Site 2 are significantly different.

^j The means for open areas on Site 1 and Site 3 are significantly different.

Table A5. Seasonal changes in soil organic matter concentrations of NO_3^- and PO_4^{3-} in 3 sites with different fire histories at Fort Huachuca, southeastern Arizona.

		Site 1	Site 2	Site 3
fires/decade		0	3	5
APRIL - MAY 1995				
NO_3^- (mg/kg)	x	4.36 ^{b*}	3.89 ^{b*}	2.52 ^{d*}
	SD	6.41 [#]	4.36 [#]	2.49 [#]
PO_4^{3-} (mg/kg)	x	21.56 ^c	27.89 ^b	14.25 ^d
	SD	10.56	11.73	5.52
SEPTEMBER - OCTOBER 1995				
NO_3^- (mg/kg)	x	36.73 ^c	12.84 ^a	7.30 ^b
	SD	45.20	24.73	12.48
PO_4^{3-} (mg/kg)	x	19.73 ^c	24.75 ^a	12.28 ^b
	SD	8.85	8.85	4.25
EARLY MAY 1996				
NO_3^- (mg/kg)	x	65.01 ^c	6.04 ^b	9.38 ^d
	SD	86.02	6.31	18.74
PO_4^{3-} (mg/kg)	x	19.08 ^c	25.75 ^b	14.10 ^d
	SD	7.15	13.26	5.88

Notes: The null hypothesis is that means and variances are equal, and we only report rejections of the null hypothesis at $p \leq 0.05$.

^a $n = 22$, ^b $n = 23$, ^c $n = 24$, ^d $n = 25$.

* The means for the three sample sets are significantly different.

The variances for the three sample sets are significantly different.

Table A6. Comparison of TOC, NO_3^- , and PO_4^{3-} in the subsurface Holocene soil (see Fig. 3) in 3 sites with different fire histories at Fort Huachuca, southeastern Arizona.

			Site 1	Site 2	Site 3
fires/decade			0	3	5
TOC	(%)	x^a	0.50	0.40 ^c	0.54
		SD	0.13 ^d	0.25	0.07
NO_3^-	(mg/kg)	x^a	1.80 ^b	1.60 ^c	0.64
		SD	1.37 ^d	1.36	0.45
PO_4^{3-}	(mg/kg)	x^a	1.39 ^b	6.80 ^c	1.99
		SD	1.67 ^d	9.67	3.81

Notes: The null hypothesis is that means and variances are equal, and we only report rejections of the null hypothesis at $p \leq 0.05$.

^a Site 1, $n=32$; Site 2, $n=38$, and Site 3, $n=13$.

^b The means for Sites 1 and 2 are significantly different.

^c The means for Sites 2 and 3 are significantly different.

^e The means for Sites 1 and 3 are significantly different.

^d The variances among the sites are significantly different.

Table A7. Above- and below-ground biomass on 3 sites with different fire histories at Fort Huachuca, southeastern Arizona.

		Site 1				Site 2		Site 3	
Organic material		Biomass (kg/m ²)	% of Biomass	Open node* Biomass (kg/m ²)	% of Biomass	Biomass (kg/m ²)	% of Biomass	Biomass (kg/m ²)	% of Biomass
<i>Prosopis</i> ^a	Wood >38 mm	3.10				0.36		0	
	Biomass <38 mm	1.65				0.16		0.078	
	Total	4.75	85.4	0	0	0.52	42.6	0.078	12.2
Grasses ^b	x	0.0406 ^{c,d}	0.7	0.0495	11.6	0.142	11.7	0.120	18.8
	SD	0.0259 ^f		0.0229		0.123		0.0481	
Forbs ^b	x	0.0578	1.0	0.0628	13.5	0.0531	4.4	0.0454	7.1
	SD	0.0287		0.0308		0.0341		0.0199	
Shrubs ^b	x	0.0122 ^c	0.2	0.0017	0.4	0.145 ^e	11.9	0.0479	7.5
	SD	0.0286 ^f		0.0037		0.141		0.0866	
Shallow roots ^g	x	0.0014		0.0009	0.008	0.00105		0.00068	
	SD	0.00151 ^f		0.0008		0.00171		0.00034	
LIVING BIOMASS ^b		4.86 ^{c,d}	87.3	0.114	25.5	0.86 ^e	70.6	0.29	45.6

Table A7. (Continued)

		Site 1				Site 2		Site 3	
		Biomass (kg/m ²)	% of Biomass	Open node* Biomass (kg/m ²)	% of Biomass	Biomass (kg/m ²)	% of Biomass	Biomass (kg/m ²)	% of Biomass
Organic material									
Dead and Litter ^b	x	0.696	12.5	0.387	74.5	0.354	29.0	0.347	54.2
	SD	1.22		0.203		0.126		0.209	
TOTAL ^b		5.56		0.502		1.22		0.64	

Notes: The null hypothesis is that means and variances are equal; we only report rejections of the null hypothesis at $p \leq 0.05$.

^a See text for explanation of *Prosopis* biomass estimation. Differences among the sites cannot be tested statistically but are obviously different (Fig. 2). Totals may not equal 100% due to rounding.

^b $n = 15$.

^c The means for Sites 1 and 2 are significantly different.

^d The means for Sites 1 and 3 are significantly different.

^e The means for Sites 2 and 3 are significantly different.

^f The variances among the sites are significantly different.

^g $n = 45$.

* $n = 11$

Table A8a. Plant biochemistry of *Prosopis* tissue systems on sites with different fire histories, Fort Huachuca, southeastern Arizona

SITE 1 (UNBURNED)

Mesquite Tissue system	n =	Carbon %	Nitrogen ppm	C:N	Phosphorus ppm	Calcium ppm	Magnesium ppm	Potassium ppm
wood	1	47.2	6,200	76.5	62.1			
twigs	3	41.8	15,200	27.4	739	43,200	799	1,950
leaves	3	48.1	22,500	21.4	771			
seed pods	1	48.8	6,400	76.3	2,160			
roots	2	49.2	22,100	22.3	290			

SITE 3 (FREQUENTLY BURNED)

Mesquite Tissue system	n =	Carbon %	Nitrogen ppm	C:N	Phosphorus ppm	Calcium ppm	Magnesium ppm	Potassium ppm
twigs ^a	1	47.1	21,400	22.0	967	19,900	1,340	5,320

Table A8b. Total percent carbon content of plant tissues and soil organic matter on sites with different fire histories, Fort Huachuca, southeastern Arizona.

CARBON CONTENT (%)					
	Site 1: Unburned plot			Site 2: Infrequently burned plot	Site 3: Frequently burned plot
	All Points	Canopy Pts.	Open Pts.		
SOIL	0.90*	1.28 ^b	0.76 ^d	0.99*	0.82*
SD	0.34	0.46	0.12	0.27	0.15
GRASSES	40.7 ^a	42.3 ^c	40.4 ^f	44.6*	43.7*
SD	3.00		3.08	1.05	2.58
ROOTS	23.3*	25.3 ^b	22.5 ^d	23.1*	22.9*
SD	5.26	2.67	5.86	4.81	4.36
FORBS	38.3*	37.8 ^b	38.5 ^d	45.1*	44.7 ^h
SD	2.43	2.34	2.56	0.67	1.17
SHRUBS	45.3 ^g	45.1 ^c	45.8 ^e	49.1 ^a	47.6*
SD	0.6			0.66	0.65
LITTER	38.1*	40.8 ^b	37.2 ^d	43.1*	41.5*
SD	2.95	1.73	2.75	2.00	1.94

* n=15, ^h n=14, ^a n=12, ^d n=11, ^f n=10, ^l n=8, ^b n=4, ^g n=3, ^c n=2, ^e n=1

Table A8c. Total nitrogen composition of plant tissues and soil organic matter on sites with different fire histories, Fort Huachuca, southeastern Arizona.

	TOTAL NITROGEN (ppm)				
	All Points	Unburned plot		Infrequently Burned Plot	Frequently Burned Plot
		Canopy Points	Open Points		
SOIL	11.34*	38.15 ^b	1.59 ^d	2.35*	1.85*
SD	32.1	59.1	1.5	2.1	1.3
GRASSES	13,875 ^a	16,200 ^c	13,410 ^f	9,500 *	8,807 *
SD	1989		1832	1291	796
ROOTS	14,100 *	18,125 ^b	12,636 ^d	11,493 *	10,920 *
SD	3971	3269	3167	2371	3042
FORBS	21,620 *	27,125 ^b	19,618 ^d	16,487 *	16,500 ^h
SD	4778	3620	3390	3621	2987
SHRUBS	15,500 ^g	14,300 ^c	17,900 ^e	12,300 ^d	11,613 *
SD	2081			1552	2046
LITTER	14,940 *	19,950 ^b	13,118 ^d	11,367 *	9,647 *
SD	5834	7346	4215	2036	2500

* n=15, ^h n=14, ^a n=12, ^d n=11, ^f n=10, ⁱ n=8, ^b n=4, ^g n=3, ^c n=2, ^e n=1

Table A8d. Total phosphorus (P) content of plant tissues and phosphorus (as PO_4^{-3}) in soil organic matter on sites with different fire histories, Fort Huachuca, southeastern Arizona.

	PHOSPHORUS (mg/kg)				
	All Points	Site 1 Unburned Plot		Site 2 Infrequently Burned Plot	Site 3 Frequently Burned Plot
		Canopy Points	Open Points		
SOIL	16.39 *	25.53 ^b	13.06 ^d	22.75 *	10.34 *
SD	8.8	10.1	5.7	6.0	3.0
GRASSES	1771 ^a	1565 ^c	1812 ^f	1311 *	1143 *
SD	364		387	288	291
ROOTS	1035 *	1197 ^b	977 ^d	1037 *	837 *
SD	264	369	206	231	166
FORBS	2489 *	2383 ^b	2527 ^d	2165 *	1976 ^h
SD	603	432	669	476	375
SHRUBS	1633 ^g	1675 ^c	1550 ^e	1010 ^a	1116 *
SD	171			209	270
LITTER	1038 *	1049 ^b	1034 ^d	774 *	655 *
SD	372	536	327	137	124

* n=15, ^h n=14, ^a n=12, ^d n=11, ^f n=10, ⁱ n=8, ^b n=4, ^g n=3, ^c n=2, ^e n=1

Table A8e. Carbon : nitrogen ratios of plant tissues on sites with different fire histories, Fort Huachuca, southeastern Arizona.

	CARBON: NITROGEN				
	All Points	Site 1 Unburned Plot		Site 2 Infrequently Burned Plot	Site 3 Frequently Burned Plot
		Canopy Pts.	Open Pts.		
GRASSES	29.3 ^d	26.1 ^c	30.1 ^f	46.9*	49.6*
SD	4.97		5.11	6.7	5.9
ROOTS	16.5*	13.9 ^b	17.8 ^d	20.1*	20.9*
SD	2.2	1.1	1.6	4.0	3.9
FORBS	17.7*	14.0 ^b	19.6 ^d	27.4*	27.1 ^h
SD	4.5	2.5	4.0	7.7	4.8
SHRUBS	29.2 ^g	31.5 ^c	25.6 ^e	39.9 ^a	41.0*
SD	3.5			5.0	6.9
LITTER	25.5*	20.4 ^b	28.4 ^d	38.0*	43.0*
SD	10.2	10.9	9.7	9.0	10.5

* n=15, ^h n=14, ^a n=12, ^d n=11, ^f n=10, ⁱ n=8, ^b n=4, ^g n=3, ^c n=2, ^e n=1

Table A8f. Soluble salts in plant tissue systems on sites with differing fire histories at Fort Huachuca, southeastern Arizona.

SITE 1: UNBURNED PLOT: All Quadrates

Soluble salt	Grasses ^f (ppm)	Roots ^h (ppm)	Shrubs ^c (ppm)	Forbs ^h (ppm)	Litter ^h (ppm)
Calcium	4,100	12,000	7,300	16,300	23,100
Magnesium	1,100	1,100	1,700	2,500	1,500
Sodium	78	327	<95	<75	170
Potassium	12,200	2,300	18,000	47,100	3,000

SITE 1: UNBURNED PLOT: Open Quadrates

Soluble salt	Grasses ^d	Roots ^d	Shrubs ^a	Forbs ^d	Litter ^d
Calcium	4,100	10,000	8,100	17,600	13,200
Magnesium	1,000	1,200	1,400	1,500	1,600
Sodium	88	329	<80	<70	173
Potassium	12,000	2,500	30,400	28,100	2,700

SITE 1: UNBURNED PLOT: Canopy Quadrates

Soluble salt	Grasses ^b	Roots ^d	Shrubs ^b	Forbs ^d	Litter ^d
Calcium	4,300	14,000	6,900	15,000	33,000
Magnesium	1,200	900	1,900	3,500	1,300
Sodium	60	326	103	83	<160
Potassium	12,500	2,200	11,800	66,200	3,300

Table A8f. Continued

SITE 2: INFREQUENTLY BURNED PLOT

Soluble salt	Grasses ^g	Roots ^g	Shrubs ^g	Forbs ^g	Litter ^g
Calcium	3,300	10,800	8,200	17,700	7,100
Magnesium	800	3,200	1,700	2,600	1,100
Sodium	<110	359	<110	<110	<110
Potassium	8,500	5,000	5,800	25,800	2,600

SITE 3: FREQUENTLY BURNED PLOT

Soluble salt	Grasses ^g	Roots ^g	Shrubs ^e	Forbs ^f	Litter ^g
Calcium	2,800	11,200	7,800	13,800	6,700
Magnesium	800	2,600	1,700	3,000	1,300
Sodium	<110	324	<110	<110	<150
Potassium	6,300	5,500	4,700	21,300	2,400

a n = 1

e n = 5

b n = 2

f n = 6

c n = 3

g n = 7

d n = 4

h n = 8

Table A9. Average soil respiration rates for several seasons on sites with differing fire histories at Fort Huachuca, southeastern Arizona.

SOIL RESPIRATION RATES (mmoles/m²/hr)					
	June	September	October	February	November
	1995	1995	1995	1996	1996
<u>SITE 1: UNBURNED PLOT</u>					
--- All samples	2.41 ^d	2.96 ^d	2.68 ^d	1.42 ^d	1.67 ^f
SD	0.36	0.29	0.28	0.12	0.20
--- Open points	2.54 ^c	3.10 ^c	2.63 ^c	1.44 ^c	1.72 ^e
SD	0.24	0.35	0.33	0.14	0.09
--- Canopy points	2.25 ^a	3.07 ^a	2.86 ^a	1.46 ^a	1.58 ^c
SD	--	--	--	--	0.32
<u>SITE 2: INFREQUENTLY BURNED PLOT</u>					
	2.40 ^b	3.04 ^b	2.70 ^b	1.13 ^b	1.35 ^f
SD	0.19	0.10	0.20	0.13	0.14
<u>SITE 3: FREQUENTLY BURNED PLOT</u>					
	2.62 ^b	3.23 ^b	2.37 ^b	1.21 ^b	1.20 ^f
SD	0.72	0.05	0.27	0.14	0.07

a_n = 2; b_n = 3; c_n = 4; d_n = 6; e_n = 7; f_n = 11

APPENDIX B
PERMISSIONS

NOTE: The following manuscript is being prepared for submission for publication in the journal *Geoderma*, but has not been published at the time of compilation of this dissertation.

APPENDIX B
**FIRE, NUTRIENT CONCENTRATIONS, AND $\delta^{13}\text{C}$ OF SOIL ORGANIC
MATTER IN A SOUTHEASTERN ARIZONA DESERT GRASSLAND**

Abstract

Over the past century, C₃ woody plants and shrubs have increased in abundance at the expense of C₄ grasses in many semiarid regions. Wildfire suppression may be one of the principal causes of this encroachment. On the gunnery ranges of Fort Huachuca in southeastern Arizona, study sites were established on homogeneous granitic alluvium to investigate the effects of fire frequency on nutrient distributions and $\delta^{13}\text{C}$ values in soil organic matter (SOM). *Prosopis* (mesquite) trees have altered SOM pools by the concentration of plant nutrients and the addition of isotopically light shrub litter. These soil carbon changes do not extend beyond canopy margins. $\delta^{13}\text{C}$ values reflect current vegetation, soil faunal inputs, and seasonal variations, with little lateral mixing of CO₂. Elevated TOC and plant nutrient (N, P) concentrations and depleted $\delta^{13}\text{C}$ values in surficial SOM are associated with C₃ *Prosopis* on an unburned plot, which enables recognition of former *Prosopis*-occupied sites on plots with variable burn histories. Fire helps re-distribute nutrients but evidence of elevated nutrient concentrations probably associated with former *Prosopis* is retained in SOM for many decades. Surface SOM $\delta^{13}\text{C}$ values indicate the estimated minimum turnover time of C₄-derived carbon beneath large mature *Prosopis* is ~ 112 to 270 years. In contrast, complete turnover of original C₃ carbon to C₄ carbon under grasslands is estimated to take a minimum of 135 to 504 years. Our study confirms that grass cover has declined over the past 100 years, although isolated C₃ trees or shrubs probably were not uncommon on the historic C₄-dominated grasslands. We find evidence in surface soil layers for a modern C₃ shrub expansion

reflected in the substantial shift of SOM $\delta^{13}\text{C}$ values from C₄ grasses to C₃ shrublands. There is also evidence for plant community changes in buried soil horizons, as $\delta^{13}\text{C}$ values indicate the Holocene and Late Pleistocene were dominated by C₄ grasslands, and the pre-late Pleistocene vegetation was a C₄-grass savanna with abundant C₃ plants.

Introduction

Regional desertification is of wide concern in the semiarid areas of the southwestern United States and other dry areas of the world. The process is perceived as a general shift from a more-forage-productive semidesert grassland to a less-forage-productive desert shrubland ecosystem. Prior to the significant Anglo migration to the Southwest in the late 1800's, the valleys supported more grass cover than at present, with most shrubs and trees restricted to riparian locations (Hastings and Turner, 1965). The rates and mechanisms involved with this change are controversial. It has also been argued that woody plants have always been present in the grasslands (Bahre, 1991). Encroachment of woody plants into grasslands of southeastern Arizona and other semiarid grassland ecosystems was caused by overgrazing and attendant soil erosion (Bahre, 1977), fire suppression (Grover and Musick, 1990), climate change (Hastings and Turner, 1965; Neilson, 1986), or combinations of these and additional factors (Cox et al., 1993; Wright and Bailey, 1980). Knowledge of the rate and spatial distribution of the encroachment process would improve management techniques in grasslands. A combination of stable carbon isotope and plant nutrient evidence is examined in this study to determine the effects of wildfire frequency on plant community dynamics in a grassland site in southeastern Arizona.

Carbon isotopes in plants

The carbon isotopic composition of plants reflect the climate and the environment in which they grow and is, therefore, a powerful tool in paleoecological reconstruction. Approximately 99% of all carbon in nature is the ^{12}C isotope, with most of the remaining 1% being ^{13}C . The differences in the ratios between the two stable isotopes, expressed as $\delta^{13}\text{C}$ in parts per thousand (‰), are small:

$$\delta^{13}\text{C} \text{ (in ‰)} = ([R_{\text{sample}}/R_{\text{standard}}] - 1) \times 1000 \quad \text{and } R = {}^{13}\text{C}/{}^{12}\text{C}.$$

The $\delta^{13}\text{C}$ value is a function of how a plant initially processes carbon dioxide during photosynthesis and is determined by differences in fractionation at the diffusion, dissolution and carboxylation steps of photosynthesis (Farquhar et al., 1989). Terrestrial plants possess substantially more negative (or ^{13}C -depleted) $\delta^{13}\text{C}$ values than ambient atmospheric CO_2 (currently about -7.7‰).

Most trees, shrubs, and cool season grasses utilize the C_3 photosynthetic pathway (Calvin Cycle). C_3 plants average about $-27 \pm 6\text{‰}$ in $\delta^{13}\text{C}$ worldwide, with variations caused by shifts in the balance between diffusive supply through the plant stomates and enzymatic demand in individual plant species (Lajtha and Marshall, 1994). The variation can also reflect the mean annual precipitation of a region which, in turn, affects the water-use efficiency and life expectancy of the plants (Ehleringer, 1989; Schuster et al., 1992). Most desert grasses and other plants adapted to hot, dry climates employ the more water-efficient Hatch-Slack photosynthetic pathway (C_4). C_4 plants do not show much variation in the enzymatic versus diffusive balance and $\delta^{13}\text{C}$ values cluster about $-13 \pm 2\text{‰}$ (Lajtha and Marshall, 1994). In drier, hotter regions, C_4 grasses constitute a high proportion of the vegetation (Knapp, 1993). Most desert succulents utilize a third photosynthetic pathway, Crassulacean acid metabolism (or CAM), but these plants are a very minor component in the study area.

There is some variation of $\delta^{13}\text{C}$ values between leaves, stems, and other tissue systems within a given plant species (Benner et al., 1987; Leavitt and Long, 1986; Stout and Rafter, 1978), perhaps due to microhabitat variations or altitude (Ehleringer and Cooper, 1988; Lajtha and Marshall, 1994), seasonality (Flanagan et al., 1996; Smedley et al., 1991), canopy effects (Robinson and Scrimgeour, 1995; Tieszen and Boutton, 1989), variations in precipitation and atmospheric CO_2 concentrations (Feng and Epstein, 1995), or combinations of these factors (Mole et al., 1994). These within-group differences are small relative to between-pathway differences (Tieszen and Archer, 1990).

Carbon isotopes in soils

Soil organic matter (SOM) is an integrated mix of plant litter, roots, and microbial biomass in the soil. The $\delta^{13}\text{C}$ value of soil organic matter reflects the relative proportion of C_3 to C_4 plant material present (Ludlow et al., 1976; Martin et al., 1990). On this basis, natural ^{13}C abundance in SOM has been used as a proxy to estimate the turnover rates of SOM when the original vegetation was replaced by plants with a different photosynthetic pathway (Martin et al., 1990). It has also been utilized as a tracer of paleoecological vegetation changes in many parts of the world, including Africa (Bond et al., 1994; Schwartz et al., 1996; Schwartz et al., 1986), India (Mariotti and Peterschmitt, 1994), South America (Guillet et al., 1988; Volkoff and Cerri, 1987), Central America (Johnson and Wedin, 1997), and western North America (Dzurec et al., 1985; McPherson et al., 1993; Steuter et al., 1990). The technique has also been used to plot vegetation shifts and ecological changes in Holocene soils (Ambrose and Sikes, 1991; Martinelli et al., 1996; Pessenda et al., 1996).

The decay continuum from plant litter to soil organic matter is complex. The transformation of plant residues into SOM does not move at the same rate in all carbon

forms (Stevenson, 1986) and appears to involve small but reproducible fractionation effects (Nadelhoffer and Fry, 1988). The $\delta^{13}\text{C}$ value of plant litter also does not remain constant, as biochemical fractions with differing isotopic ratios decay at different rates. Plant lipid is consistently 5 - 10‰ more depleted in ^{13}C values than whole plant material, but most lipids decompose rapidly (< one year) under aerobic conditions in well-drained soils (Park and Epstein, 1960). Plant lignin, which is depleted in ^{13}C , is more resistant to decomposition than plant cellulose, which is enriched in ^{13}C (Melillo et al., 1989). No standard methods have been established to separate the multiple pools of C that make up SOM. Recent studies have recognized that plant residues can be divided into two distinct categories of soil organic matter according to their mean residence time: a light fraction turns over in less than a few decades, and a heavy fraction that turns over in more than a few hundred years (Hsieh, 1997). This two-component model for SOM dynamics is also discernible by ^{14}C radiocarbon methods (Connin et al., 1997; Harrison, 1996) as “active soil carbon” with turnover rates of 25 years and “passive soil carbon” which has turnover rates on the order of hundreds to thousands of years. It is still not clear what properties of SOM determine what material makes up each category. $\delta^{13}\text{C}$ values differ for each soil fraction, with the coarser fractions containing less carbon and always lower in ^{13}C than the clay-rich fraction (Balesdent et al., 1988; Gregorich et al., 1995; Martin et al., 1990). It may be that physical protection by the clay minerals rather than chemical differences distinguish the two categories (Hsieh, 1997).

There are important implications of the bimodal distribution of SOM components. In both natural and disturbed soils, 50 to 90% of the carbon in the upper soil horizons (~20 cm) resides in fast-cycling pools with turnover times of 7 to 65 years (Trumbore et al., 1996). At deeper depths of a soil, the preserved SOM is dominated by the stable, slow-cycling pools with turnover times of hundreds to thousands of years (Balesdent et al., 1988; Hsieh, 1997; Wang et al., 1997). Organic matter tends to migrate

downward as it decays, so the relative amount of old carbon is greater in deeper horizons compared to the topsoil, even as the total amount of carbon decreases with depth (O'Brien and Stout, 1978). Humic substances, which dominate grassland ecosystems, tend to be firmly bound to clays and do not become as easily involved with new biological processes, thus enhancing their preservation. Therefore, the residue-derived humus in the deeper soil horizons is less subject to changes in $\delta^{13}\text{C}$ due to biomass production or decomposition. The hypothesis that illuviation of ^{13}C -enriched carbon to deep soil layers could have a different $\delta^{13}\text{C}$ than inputs at the surface has also been considered but rejected (Dzurec et al., 1985; Nadelhoffer and Fry, 1988).

Soil systems will tend toward a steady state that reflects the accumulated plant residues, possible localized variations in decomposition intensity, and landscape-scale perturbations (Nadelhoffer and Fry, 1988; van Kessel et al., 1994) if the environment and land management remain constant over long periods (Anderson and Domsch, 1989). Therefore, although SOM does undergo additional changes with depth and time, the carbon isotope alterations are not large enough to mask the $\sim 14\%$ difference between C_3 and C_4 plants.

A common perturbation of natural grassland ecosystems is fire. Burning produces a high number of carbonized particles which in favorable conditions can be preserved in soil layers. Charcoal remaining on the soil surface just after a fire is immediately exposed to erosion-fragmentation processes, but is largely unaffected by microbial decomposition. Charcoal fragments, as with other large particles found on the soil surface, are buried through bioturbation and sedimentation processes. The original fuel components can still be distinguished on the basis of charcoal particle morphology after millions of years (Sander and Gee, 1990). Decomposition of plant litter is affected by close proximity of charcoal but the direction of these effects is unpredictable (Zackrisson et al., 1996).

In addition to soil organic matter, significant quantities of carbon are present in the soil as "soil CO₂", which is the gas occupying pore space in a soil, and "soil-respired CO₂", which represents the flux of CO₂ through a soil (Cerling et al., 1991). Respired CO₂ is produced by a combination of organic matter degradation (bacterial respiration) and root respiration, and has been observed to be isotopically more like the dissolved, short-lived labile organic carbon than bulk SOM (Amundson et al., 1997; Bacon and Keller, 1997; Connin et al., 1997). Isotopic variations occur due to seasonal variations in plant metabolism resulting from moisture availability (Flanagan et al., 1996; Smedley et al., 1991). The $\delta^{13}\text{C}$ of respired CO₂ has also been utilized to determine turnover rates of soil C (Schonwitzer et al., 1986; Trumbore et al., 1996).

Objectives

The present study is an extension of our investigations of the effects of wildfire frequency on the nutrient distributions of the grasslands in southeastern Arizona (Biggs et al., 1996; Biggs et al., 1997). The initial objective of this study was to determine how $\delta^{13}\text{C}$ values and concentrations of plant nutrients in the soil organic matter differ on three study plots with different burn histories. Total organic carbon (TOC), plant-available nitrogen (NO₃⁻), plant-available phosphorus (PO₄⁻³), and carbon isotopic abundances were measured on the three sites. The study assesses local variations in carbon isotopic values and nutrient concentrations in SOM which may be related to present vegetation. As the $\delta^{13}\text{C}$ value of soil organic matter is long lived, a corollary objective was to identify the possible effects wildfire might have on the distribution of $\delta^{13}\text{C}$ values of the surface SOM.

A second objective was to examine the hypothesis that C₄ grasses are being displaced by C₃ woody plants on the grasslands of southeastern Arizona. Vegetation shifts from C₄ to C₃ plants provide a natural label of SOM in an environment, but the

turnover rates of C, N, and P are not known. The study will ascertain whether nutrient concentrations and carbon isotopic values can be used in combination as a tool to recognize vegetation changes on the surface. If woody plants have been in long-term residence, then the combination of nutrient concentrations and carbon isotopic values may reflect a C₃ overprint. The reverse may also be true.

A third objective was to determine the spatial distribution of the SOM $\delta^{13}\text{C}$ values compared to the canopy area of individual C₃ trees and examine the SOM $\delta^{13}\text{C}$ and nutrient patterns of trees with varying ages. This will be done by determining the spatial and temporal variations in soil-respired CO₂ and then comparing the isotopic patterns of surficial SOM and soil-respired CO₂ on an unburned, C₃-dominated study area with patterns retained in SOM and soil-respired CO₂ on burned sites. If this can be satisfactorily illustrated, the method could be used to tie the $\delta^{13}\text{C}$ isotopic pattern to paleo-horizon distributions of vegetation during the Holocene and Pleistocene.

Study Area

Research was conducted at a study area designated Woodcutters' Canyon Site on the south gunnery ranges of Fort Huachuca Military Reservation, southeastern Arizona (N.31°30'45", W.110°19'30"). Currently the gunnery ranges are covered by a mixture of C₄ grasses and C₃ shrubs and trees typical of the lower elevations of the Huachuca Mountains (Bowers and McLaughlin, 1996). *Prosopis velutina* (velvet mesquite) is the principal C₃ tree species in the study area. The ranges are actually savannas within the mapped range of historic desert grassland (Brown and Lowe, 1980). In the mid-1800s, the area now used as firing ranges consisted of C₄-dominated grasslands, with mesquite mostly relegated to riparian areas (Humphrey and Mehrhoff, 1958). Detailed fire history of the site is known from 1973 to 1995 (C. Cochrane, unpublished data) and livestock

have been excluded from the military reservation since the late 1940's. The elevation of the study area is 1,490 m and mean annual precipitation is approximately 500 mm, with about 70% falling in the July-October period.

Three study sites were established on the gunnery ranges where a road junction created fire breaks that allowed sites of identical geomorphic and pedogenic character but different fire frequencies to be in close proximity (Fig. 1). Site 1 has not been burned since 1973, and the year of the most recent fire is unknown. Site 1 is dominated by mature *Prosopis*. Site 2, which has a moderate fire frequency, burned three times between July 1983 and January 1991 (Table 1). Site 2 is covered by native grasses, forbs, and small shrubs with widely scattered *Prosopis* trees. Site 3, which has a high fire frequency, burned five times between February 1981 and February 1989 (Table 1). The vegetation on Site 3 is dominated by native grasses, small shrubs, and small *Prosopis* shrubs.

Aerial photographs of the south ranges taken in 1935, 1946, 1956, 1970, 1975, 1983, 1984, and 1994, as well as oblique ground photographs taken between 1872 and 1915, were examined to supplement the available fire history. No *Prosopis* trees are apparent on the study sites in 1935, but several can be seen in 1946 aerial photographs. All three study sites appear irregularly disturbed in the 1946 photographs, probably as a result of tank and artillery training exercises during World War II. Successive aerial photographs show amelioration of the disturbances, indicating that all 3 sites have a similar land-use history since 1946 except for fire frequency. Sites 2 and 3 appear largely treeless in an aerial photograph taken in January 1975. From the condition of these sites in the aerial photographs, fires probably have shaped the vegetation on Sites 2 and 3 for several decades.

The study area is on a Holocene alluvial fan comprised of granitic material deposited on the east flank of the Huachuca Mountains. The fan has a uniform slope of

about 5 % on the study area. It is covered by a sandy loam, classified as an Aridic Haplustalfs (USDA, 1994a) in the Gardencan-Lanque complex (USDA, 1994b), that has a remarkably homogeneous and fine-grained character for a rangeland soil. The A-horizons are variable between the three sites. On unburned Site 1, A1 and A2 horizons are recognized (Fig. 2A) and total combined thickness ranges between 20 and 40 cm. On moderately burned Site 2, the A-horizons range between 30 and 40 cm in total thickness and are separated into A1, A2, and A3 horizons (Fig. 2B). In contrast, the A-horizon on frequently burned Site 3 (Fig. 2C) is represented only by a thin veneer about 6 cm thick, probably reflecting the increased erosion of unprotected topsoil after frequent fires. The Holocene B-horizons have similar soil characteristics on the three sites (designated Bt1 in Figs. 2A, 2B, and 2C), but vary in thickness: the Bt1 undulated between 15 to 40 cm thick on Site 1, it gradually increased in thickness from 5 cm on the west to 25 cm on the east on Site 2, and it was a consistent 30 cm blanket on Site 3. Clay illuviation was not pronounced in the Holocene soils. The variations in horizon thicknesses appear to be unrelated to surface vegetation distributions.

The contact between the Holocene soil and the underlying Pleistocene paleosol was quite sharp and planar beneath all three sample sites (Figs. 2A, 2B, and 2C). The Pleistocene soil stratigraphy was divided into two units (prefixed 2 and 3) based on the color, the percentage of clay, and other soil features. No absolute ages have been determined for the Pleistocene units of the study area. The horizons within unit 2 developed on an irregular surface of unit 3 and were beveled prior to the deposition of the overlying Holocene units. Thicknesses and occurrences of individual horizons in unit 2 were quite variable in each trench and also varied from trench to trench. In trench 2, two 2Bt horizons were present, whereas only one 2Bt horizon was recognized in trenches 1 and 3. Only a maximum of 10 cm of 2Bt thickness was preserved in two discontinuous lenses below the Holocene-Pleistocene contact in trench 1; the 2Bt in trench 3 varied

from 40 cm to 5 cm thick from south to north. Below the 2Bt horizons in trench 1 and 3 were very clay-rich horizons designated 3Bt1 and 3Bt2. These units were not reached in trench 2.

Methods

A 30 m by 30 m grid that encompassed *Prosopis* individuals was established on each of the study sites. Node points were established at 3-m intervals for a total of 121 sampling points per grid. A complete set of surface samples from all grid points was scooped from the upper 50 mm at each node point from each study site in late April - early May 1995. A set of 23-25 random surface samples was collected from each site in early October 1995; the same subset was re-sampled in early May 1996. A trench approximately 1.5 m deep was excavated on each site and the soil profiles were described using standard methods (Fig. 2). A complete set of subsurface soil samples was collected from the three trenches in June 1995. Samples were collected at 10-cm depth intervals in the Holocene soil and at 20-cm depth spacings from the Pleistocene horizons. All surface and subsurface samples were oven-dried at 65° C for several days, then sifted through a 2-mm sieve prior to separation into subsamples. Although these soils do not contain carbonate (non- effervescent with pH between 5.0 and 6.8), subsets of all surface and subsurface samples were pretreated with H₃PO₄ and homogenized by ball milling. Total organic carbon (TOC) and plant-available nitrogen (N, as NO₃⁻) were measured on the pretreated samples, and phosphorus (P, as PO₄⁻³) was measured on untreated samples for all soil samples (Biggs et al., 1997). Bulk density, soil pH, cation exchange complex (CEC), exchangeable cations of Na⁺, K⁺, Ca⁺⁺ and Mg⁺⁺, total N, and total P were determined for a subset of samples from each grid. A combination of ANOVA, parametric, nonparametric, and spatial statistics were used to determine differences among the three study sites (Biggs et al., 1997).

Plant biomass samples were collected in late September-early October 1995 after a relatively dry summer growing season. Above-ground small woody and herbaceous material harvested from 1 m² quadrates on 15 randomly selected nodes from each study site were sorted into the general groups of perennial grasses, shrubs, forbs, cacti, *Prosopis*, and undifferentiated litter. For larger *Prosopis*, the volume of wood >38 mm diameter was estimated using the visual-segmentation technique (Born and Chojnacky, 1985) and coefficients developed for *Prosopis* in southern Arizona (Chojnacky, 1988). To convert from volume to dry-weight biomass, a wood density of 650 kg/m³ from 3 samples of dried wood collected from Site 2 was used. Biomass of leaves and the remaining wood <38 mm was estimated by collecting and weighing 12 sample branches in 2 size classifications. The branches in the 2 size classes on all the trees were then counted and the total estimated biomass for the trees summed. Subsurface biomass was sampled using a soil corer; 3 cores from a depth of 0-70 mm were taken in each of the 1 m² quadrates and the organic material was collected by flotation, dried and weighed.

Soil-respired CO₂ was measured using standard techniques (Anderson, 1982). A dish containing 20 ml of 1N NaOH was placed beneath an inverted 19-liter bucket at selected grid nodes on each site. The NaOH solution was recovered after 24-48 hours and treated with SrCl₂ or BaCl₂ to precipitate SrCO₃ or BaCO₃. Control blanks of sealed NaOH solution were also saved for each sample set. Respiration samples were collected in June 1995, September 1995, February 1996, and November 1996.

Carbon isotopic ratios of plant and soil organic matter samples were measured on the CO₂ obtained by combustion under vacuum at 900° C in the presence of cupric oxide and silver foil. Carbon isotopic ratios of SrCO₃ or BaCO₃ were determined from the CO₂ produced by dissolution in 100% phosphoric acid at 50° C. The CO₂ gas was then purified under vacuum using a -70° C ethanol bath/liquid nitrogen extraction line and analyzed on a gas-ratio mass spectrometer (Finnegan MAT-Delta S) at the University of

Arizona. Isotopic results for carbon ($\delta^{13}\text{C}$) are presented as per mil (‰) deviation of the sample CO_2 from the Peedee belemnite (PDB) standard.

Analytical precision, determined as the standard deviation obtained on 57 replications of laboratory reference USGS-24 graphite, is $< 0.16\text{‰}$. For samples of soil organic matter, sample heterogeneity will determine precision. For this reason, SOM isotopic values were also verified using multiple combustions of samples (approximately one repeat for every fifteen samples analyzed). The isotopic values of carbonates produced from soil respiration were verified using duplicate samples and comparison with 6 replications ($\text{SD} < 0.12\text{‰}$) of our Carrara Marble CO-1 internal laboratory standard.

Results

Surface soils and vegetation dynamics

On the grasslands at Fort Huachuca, velvet mesquite (*Prosopis velutina*) is the largest woody C_3 species. With normal winter season rains, these shrubs typically flower in the spring or summer and seeds germinate the following winter or spring (Tieszen and Detling, 1983). The average $\delta^{13}\text{C}$ value for representative samples of *Prosopis* on the Fort Huachuca grasslands was determined to be -25.5‰ ($n=2$, $\text{SD}=0.18$) and average values for representatives of the plant groups forbs and shrubs were -26.4‰ ($n=4$, $\text{SD}=0.62$) and -27.5‰ ($n=6$, $\text{SD}=1.50$) respectively. The primary native C_4 grasses are grammas (*Bouteloua* sp. and *Eragrostis intermedia*), which complete flowering, seed maturation, dispersal, and early establishment coincident with late summer and fall rains and remain dormant through the winter (Tieszen and Detling, 1983). Samples of C_4 grasses had an average $\delta^{13}\text{C}$ value of -14.3‰ ($N=5$, $\text{SD}=0.38$) on the study sites.

The distribution of soil organic matter $\delta^{13}\text{C}$ values on the three study plots is closely tied to the predominant vegetation on each site. Unburned Site 1, which has 34 %

of its total area covered by *Prosopis* canopies, has a total above-ground biomass of 5.6 kg/m², of which 85.4% is living *Prosopis* and 12.5% is undifferentiated litter (mostly *Prosopis*) (Biggs et al., 1997). C₃ shrubs and forbs total 1.3% and C₄ grasses comprise less than 1.0% of total biomass weight. Site 1 SOM has an average $\delta^{13}\text{C}$ value of -19.5‰, with an average for 83 open (i.e., sample points not under canopy coverage) node points of -18.7‰ and for 38 canopy points -21.0‰. The most depleted SOM $\delta^{13}\text{C}$ value on Site 1 is -23.6‰, which is 1.5 - 2.0‰ enriched in ¹³C compared to *Prosopis* from the site; the most enriched SOM $\delta^{13}\text{C}$ value is -16.5‰, which is 2.2‰ depleted compared to C₄ grasses. Moderately burned Site 2 contained one single-stemmed *Prosopis* that accounted for 42.6% of the 1.2 kg/m² total biomass of the site, although its canopy covered only 3% of the sample grid area. Shrubs and forbs total 16%, C₄ grasses comprise 11.7%, and undifferentiated litter make up the rest of the total biomass weight. The site has an average $\delta^{13}\text{C}$ value of -18.0‰ for SOM, indicating it is dominated by C₄ grasses. Frequently burned Site 3 has an average SOM $\delta^{13}\text{C}$ value of -17.2‰ reflecting the C₄ grass dominance on the site. Total above ground biomass on Site 3 is 0.6 kg/m², of which 19% is C₄ grasses and 54.2% undifferentiated litter, much of which is grass litter. The site contains less than 1% mesquite canopy and about 12% of biomass as *Prosopis* shrubs (see Biggs et al., 1997, for biomass details).

Regression analyses indicate no linear relationship between SOM $\delta^{13}\text{C}$ and TOC, PO₄⁻³ and NO₃⁻ concentrations in SOM on any of the study sites (Figs. 3A, B, C). Therefore, a pattern recognition approach is used to interpret the significance of the data. Nutrient distributions and $\delta^{13}\text{C}$ values appeared to be characterized by three-way interactions of photosynthetic pathway (i.e. C₄ vs. C₃ species), sampling location (open vs. canopy), and wildfire frequency. The contour maps of the distribution of SOM $\delta^{13}\text{C}$ values (Figs. 4, 5, and 6) mimic the patterns for both nitrate (NO₃⁻) and soil phosphate

(PO_4^{-3}), although NO_3^- is more vulnerable to removal by leaching and surface runoff (Day and Ludecke, 1993). As *Prosopis* is known to accumulate these nutrients (Tiedemann and Klemmedson, 1973), the relationship is not surprising. Surface concentrations of TOC in the soils of the study sites are consistently low, rarely above 2%. In most cases, the higher concentrations follow the presence of *Prosopis*, but there are a few TOC peaks apparently unrelated to C₃ vegetation.

On the unburned site, the pattern of surface SOM $\delta^{13}\text{C}$ depletion follows the distribution patterns of TOC, PO_4^{-3} and NO_3^- concentrations; all of these patterns are strongly related to the *Prosopis* canopies (Fig. 4). The $\delta^{13}\text{C}$ values and higher nutrient concentrations also correspond to the relative ages of the individual trees. SOM beneath *Prosopis* individuals with multiple stems had $\delta^{13}\text{C}$ values 1 to 3‰ more negative than single-stemmed trees. The highest concentrations of PO_4^{-3} and NO_3^- are also beneath the multi-stemmed *Prosopis* (e.g. grid points 18N-15E, 12N-27E). The concentrations of TOC are often only slightly greater beneath the largest *Prosopis* compared to smaller shrubby trees and even some of the open areas. Some TOC peaks (e.g. 3N-9E, 6N-12E, 9N-18E) are in open locations not associated with PO_4^{-3} , NO_3^- , or C₃ vegetation. The spatial signal of $\delta^{13}\text{C}$ values extends to approximately the margin of the canopy in SOM. The lateral extent of the isotopic signal is also enhanced with apparent tree age, as the depletion pattern does not extend the entire canopy beneath the smaller younger (?) trees. The impact of the C₃ *Prosopis* may also be apparent in the open portions of Site 1, for the mean SOM $\delta^{13}\text{C}$ value beneath open grid points with grass cover is 1.5‰ (or 9%) more negative than the average value on frequently burned Site 3. This is probably a reflection of the impact of several decades of eolian *Prosopis* litter mixing with C₄ material and near-surface *Prosopis* roots.

There are similar, although less pronounced, zones of SOM $\delta^{13}\text{C}$ depletion on Site 2 (Fig. 5). Most of these are associated with nutrient peaks interpreted to represent the positions of *Prosopis* individuals burned or removed in previous decades (Biggs et al., 1996; Biggs et al., 1997). Grid points 15N-12E, 24N-3E, and 27N-24E are interpreted as possible former *Prosopis* sites. Other zones with depleted SOM $\delta^{13}\text{C}$ signals but no corresponding nutrient concentrations could indicate small C_3 shrubs or perhaps the presence of mesquite roots (e.g. 3N-3E). Interestingly, the large single-stemmed *Prosopis* on Site 2 (subsequently removed during trenching) did not produce a strong $\delta^{13}\text{C}$ depletion value in SOM, nor high nitrate and TOC values typical for *Prosopis* directly beneath the canopy (although PO_4^{3-} concentration was greater). This might imply the *Prosopis* individual was a recent arrival on Site 2. However, just to the east of the canopy margin there is a depleted SOM $\delta^{13}\text{C}$ zone (Fig. 5, grid points 6N-9E, 9N-9E, 12N-9E) which does correspond to higher nutrient concentrations; this suggests the prevailing west wind helps concentrate plant litter beyond the canopy of the modern tree on very open sites. Similarly, the area around point 21N-24E has high nutrient concentrations but a fairly enriched SOM $\delta^{13}\text{C}$ signature, which suggests it may be a downwind relict of the *Prosopis* interpreted at site 27N-24E. Similar effects were not evident on Site 1, which is more protected from the wind by a small knoll to the west as well as the greater density of mature trees, nor on Site 3, which has no large *Prosopis* to generate significant litter.

The SOM $\delta^{13}\text{C}$ variations are more subdued on frequently burned Site 3 (Fig. 6), reflecting the dominance of C_4 grasses on the site. One pronounced area of depletion (9N-24/27E, 12N-24E) corresponds to higher concentrations of TOC, PO_4^{3-} and NO_3^- and is interpreted as a former *Prosopis* site. Another depleted $\delta^{13}\text{C}$ value coincident with high nutrient values in SOM at 21N-24E may also represent an old *Prosopis* site. The

zone of $\delta^{13}\text{C}$ depletion at 24N-30E appears to correspond to a small, modern *Prosopis* shrub, although nutrient concentrations are hardly above the values from adjacent open sites. The small nutrient peak at 3N-15E -- especially indicated by high NO_3^- -- is probably associated with a small *Prosopis* shrub (estimated age 6 years, as it appears to post-date the most recent burn event) at grid point 0N-15E. There are elevated nutrient concentrations (e.g. 18N-9E) with no complementary depleted SOM $\delta^{13}\text{C}$ value, no adjacent zones of depletion, and no modern C₃ shrubs present. The cause of these features is uncertain.

A subset of ten random surface soil samples was collected from each of the 3 study sites one year after the original sampling was done (Table 2). On Site 1, the SOM beneath *Prosopis* canopy sites yielded $\delta^{13}\text{C}$ values 0.8‰ more depleted (n=5) in 1996 compared to 1995, whereas the values on open sites were nearly identical to results from 1995 (average change 0.09‰, n=5). On Site 2, the average difference was -0.66‰ (n=10) and on Site 3 the average change was -0.25‰ (n=10). The changes probably reflect increased activity of C₃ plants following the slightly wetter winter of 1996. Overall, the results suggest annual fluctuations are not very large.

Soil respiration

Soil-respired CO_2 was collected at four times from June 1995 to November 1996 (Table 3). With two areas of exception, $\delta^{13}\text{C}$ values of CO_2 were consistently more depleted than SOM values for each individual grid point regardless of Site or time of year. On all three sites there were seasonal $\delta^{13}\text{C}$ differences which probably reflected the activity levels of the dominant plants and soil fauna at the sampling point. In general, the canopy points on Site 1 are the most depleted; the open points on Site 1 are more depleted than samples collected from Site 2 and Site 3 grasslands, probably reflecting the

respiration of shallow roots from adjacent mesquite or other shrubs. CO₂ from Site 3 grasslands are 0.5‰ enriched in ¹³C compared to Site 2.

On Site 1, the CO₂ collectors were placed as a transect through a single-stemmed *Prosopis* (Fig. 4, 3N-18E) so that 2 samples were beneath the canopy and 2 samples were on open points on opposite sides of the canopy. There is a robust C₄ community beneath the open canopy of the tree, which is reflected in the SOM δ¹³C value. As with the SOM signal, the spatial signal of δ¹³CO₂ extends to approximately the edge of the *Prosopis* canopy. The δ¹³C value of the soil-respired CO₂ shows a consistent enrichment outside the canopy margin compared to beneath the canopy (Fig. 7A) for each sampling period.

On Sites 2 and 3, three collectors per grid were placed on random points. δ¹³CO₂ values were generally depleted in September after the seasonal monsoon rains and were enriched during the mid-winter period when plants are dormant, although not all sample points followed that pattern (Table 3). June and November δ¹³CO₂ values were typically intermediate between the late summer and winter values.

The soil respiration sampling in November 1996 was expanded (n=11 per Site) to examine certain nutrient concentrations and/or SOM δ¹³C features in addition to the original series (Table 3). On Site 1, a set of three collectors (Fig. 3, points 24/30N-6E) sampled another large *Prosopis* tree, 2 collectors were placed on open sites away from *Prosopis* influence, and 6 collectors re-sampled the previous *Prosopis* transect (Fig. 7A). As with the other canopy transect, there was consistent enrichment of the δ¹³CO₂ value away from the canopy center of the second tree (Fig. 7B). These results indicate the δ¹³CO₂ signal is directly related to the distance from the *Prosopis* trunk.

On Site 2 the eight additional collectors were placed to test SOM nutrient and/or δ¹³C features (Fig. 5, Table 3). It was not possible to sample a transect through a *Prosopis* site, as the only tree on Site 2 was removed during trenching and much of the

original canopy area was covered by pit tailings. One collector was positioned on the east edge of the former canopy (6N-9E) and it recorded the most depleted $\delta^{13}\text{CO}_2$ value on the site; two other collectors just outside the southern margin of the original canopy (3N-3E, 3N-6E) were slightly enriched compared to the 6N-9E value. All three were similar to values measured outside the canopies on Site 1 (Table 3). Two transects were sampled through a SOM nutrient/ $\delta^{13}\text{C}$ feature centered at 24N-3E, a point interpreted to represent a former *Prosopis* site. Results for $\delta^{13}\text{CO}_2$ were not as clear as they were for SOM $\delta^{13}\text{C}$: the $\delta^{13}\text{CO}_2$ signals at 3 m and 6 m showed little variation (Fig. 8A). The $\delta^{13}\text{CO}_2$ value at the center of the peak was slightly enriched compared to the SOM $\delta^{13}\text{C}$ measurement.

The eight additional collectors on Site 3 were placed on the site according to nutrient concentrations (as SOM $\delta^{13}\text{C}$ results were not available) (Table 3). A zone of high nutrient concentrations centered around 9N-24E (Fig. 6) is interpreted as a former *Prosopis* site and subsequent SOM $\delta^{13}\text{C}$ results support that conclusion. A four-point, west to east, transect across this zone showed the $\delta^{13}\text{CO}_2$ values are enriched 3 m away from the nutrient peak by approximately 1‰. The sample point at the center of the feature as well as the two points 3 m to either side are all enriched compared to the SOM $\delta^{13}\text{C}$ values, indicating the present dominance of C_4 grasses.

Subsurface

$\delta^{13}\text{C}$ values of SOM from the trench walls of all three study sites reveal significant differences between the $\delta^{13}\text{C}$ composition of the subsurface SOM and the current community vegetation (Figs. 9A, 9B, and 9C). There are marked vertical variations in the $\delta^{13}\text{C}$ value distributions in the soil profiles and these are consistent across all three sites. On all sites, the Holocene soil horizons show a rapid downward enrichment in $\delta^{13}\text{C}$ values in the initial 10 cm (to values of -14 to -16‰). In the underlying Pleistocene horizons, the $\delta^{13}\text{C}$ results in the II-horizons are enriched at the top

but show some depletion toward the base, especially in trench 2 where the greatest 2Bt thicknesses occur. The lower Pleistocene III-horizons are generally more depleted than the overlying Pleistocene units and show an abrupt shift back to more depleted values that are remarkably similar to the $\delta^{13}\text{C}$ results from surface horizons of mixed C_3 trees and C_4 grasses.

There appears to be no relationship between SOM $\delta^{13}\text{C}$ and concentrations of TOC, PO_4^{3-} and NO_3^- in the subsurface profiles. On sites 1 and 2, representative canopy and open positions on the trench walls show no affinity between nutrient concentrations and SOM $\delta^{13}\text{C}$ with changing depth, except at the surface (Figs. 10 and 11). Similarly, two vertical profiles in trench 3 also show no correlations with depth (Fig. 12).

Discussion

This is the first landscape-style study to incorporate nutrient concentrations and the $\delta^{13}\text{C}$ values of soil organic matter for reconstruction of vegetation changes on the surface and in underlying soil horizons. The $\delta^{13}\text{C}$ signal in soil organic matter provides a potential record of vegetation changes in the surface soils and in subsurface horizons. The combination of high TOC, PO_4^{3-} , and NO_3^- accumulations with depleted $\delta^{13}\text{C}$ values in surficial SOM is evidence of C_3 plants present or recently present on a particular site. It is apparent that *Prosopis* plants have produced substantial changes in soil nutrient concentrations and SOM $\delta^{13}\text{C}$ values in less than 60 years. The spatial extent of the combined signal may be a function of the size of the plant and the length of time it has occupied the site. Evidence suggests that C_4 plant biomass was greater prehistorically and that SOM pools are in a state of transition.

Surface soil organic matter

The SOM $\delta^{13}\text{C}$ values of surface soils beneath C_3 and C_4 vegetation at Fort Huachuca indicate a shift from anticipated values similar to variations documented elsewhere. Several mechanisms have been described to explain these shifts. Previous studies have demonstrated that the carbon isotope composition of detritus from a C_4 salt-marsh grass (*Spartina alterniflora*) decreases by 2 - 6‰ during biogeochemical breakdown. This alteration was inferred to occur as polysaccharides were preferentially removed, leaving a lignin-derived carbon with lower ^{13}C (Benner et al., 1987). Other studies in C_3 forests found no evidence for selective preservation of ^{13}C -depleted litter components and reported a slight enrichment (1 - 2.5‰) during the litter decomposition to SOM phase at increasing depths (Gregorich et al., 1995; Nadelhoffer and Fry, 1988; O'Brien and Stout, 1978). This shift has been ascribed to a decrease of ~1.5‰ in the $\delta^{13}\text{C}$ value of atmospheric CO_2 during the last 150 years as a consequence of burning mostly -25‰ fossil fuels (Marino and McElroy, 1991), diagenetic isotope fractionation during decomposition (Nadelhoffer and Fry, 1988; O'Brien and Stout, 1978) or microbial respiration or fermentation leading to an enrichment of microbial products compared to plant material (Balesdent et al., 1993; Macko and Estep, 1984).

A recent study of isotopic values beneath both C_4 and C_3 grass populations (Wedin et al., 1995) found no selective preservation of ^{13}C -depleted lignin and determined that the observed shifts in isotopic values were caused by the incorporation of new carbon from SOM into litter by fungal or microbial decomposers. Isotopic contamination due to fungal/microbial activity resulted in a shift of 0.5 to 3.0‰ from the original plant material. However, in C_4 plant matter, this shift resulted in a depletion of ^{13}C in SOM, whereas in C_3 plant matter the shift was in the direction of ^{13}C enrichment. The shift was seen in both bulk tissue and lignin fractions of the plants. There is no fixed constant for the ratio of microbial biomass carbon to soil organic carbon, with a range of

0.27% to more than 7% reported in the literature (Anderson and Domsch, 1989). This new external C represents from 12 to 19% of the total bulk tissue litter C at 70% mass loss. It indicates the fidelity with which $\delta^{13}\text{C}$ values are transferred from plant tissues to SOM is high under aerobic conditions (Wedin et al., 1995).

In this study, results on the three surface plots showed shifts in $\delta^{13}\text{C}$ values of SOM slightly greater than anticipated for C₃ or C₄ monocultures. According to Wedin, et al. (1995), microbial effects will shift the $\delta^{13}\text{C}$ of C₄-derived soil carbon by approximately -2‰, producing a $\delta^{13}\text{C}$ of SOM beneath grasses of ~ -16‰. Although the most enriched surface SOM $\delta^{13}\text{C}$ value found on Site 3, which had the largest percentage of C₄ grasses, was -14.8‰ (Fig. 6, points 30N-18E and 30N-24E), the average $\delta^{13}\text{C}$ value was -17.1‰. The most enriched value on Site 2, also heavily populated with C₄ grasses, was -15.7‰ (Fig. 5, point 21N-0E), but the average Site 2 $\delta^{13}\text{C}$ value was -18.0‰. Conversely, the SOM $\delta^{13}\text{C}$ value produced by microbial effects beneath C₃ *Prosopis* should be ~-23.5‰. The most depleted SOM $\delta^{13}\text{C}$ value found in the study was -23.6‰ under a dense C₃ *Prosopis* canopy on Site 1 (Fig. 4, point 21N-18E). The 38 canopy grid points on Site 1 had an average $\delta^{13}\text{C}$ value of -21.0‰ and the average for the 83 open points was -18.7‰. Therefore, the heterogeneity of the plant communities on the three sites results in a blended signal that causes a slightly greater SOM $\delta^{13}\text{C}$ shift than would be expected under monocultures of C₃ or C₄ plants, but the overall results are also consistent with the incorporation of new carbon from microbial decomposers into SOM during the diagenetic degradation of plant litter (Wedin et al., 1995).

The $\delta^{13}\text{C}$ values of SOM can be used to estimate the proportion of C₃ and C₄ plant biomass from mixed field communities or from competition experiments (Ludlow et al., 1976), using the formula:

$$\text{Percentage of } C_4 \text{ component} = \frac{\delta^{13}C_{SOM} - \delta^{13}C_{100\%C_3}}{\delta^{13}C_{100\%C_4} - \delta^{13}C_{100\%C_3}} * 100$$

By using the average study area $\delta^{13}C$ values of grasses (-14.3‰) for 100% C_4 and of *Prosopis* (-25.5‰) for 100% C_3 end-members, the open areas of Site 1 (avg. -18.7‰) would be expected to have 61% C_4 biomass and overall Site 1 (avg. -19.5‰) is estimated to be 54% C_4 biomass. The -23.6‰ $\delta^{13}C$ value beneath the most dense multi-stemmed mesquite tree (Fig. 4, point 21N-18E) indicates the SOM is 83% C_3 material, which is expected as the litter is composed of a thick layer of mesquite leaves, seeds, and wood. Similarly, the SOM under a large single-stemmed *Prosopis* at point 21N-3E (with $\delta^{13}C$ value -22.8‰), which has very few small plants growing beneath its canopy, represents 75% C_3 material. Beneath the smaller, single-stemmed *Prosopis* trees the SOM $\delta^{13}C$ values indicate a mixture of organic material derived from C_3 and C_4 plants. An example of this is point 3N-3E (Fig. 4), where the SOM $\delta^{13}C$ value is -20.2‰, which indicates about 47% of the soil organic carbon originated from C_4 plants. This is also expected, given the mixed nature of the plant community under the open canopy of the younger trees. This mixed plant community is also reflected in the overall -21‰ average $\delta^{13}C$ value of SOM for the 38 canopy sites, which indicates about 60% of the vegetation is C_3 plants. On Site 2, C_4 plants account for 73% of the vegetation. On Site 3, approximately 85% of the plant biomass is C_4 grasses. These estimates probably reflect the gross biomass compositions more accurately than estimates using biomass weight percentages, in part because they incorporate temporal variability not accounted for by one-time sampling.

The rate of new carbon mixing with the preexisting SOM pool can be examined using shifts in the $\delta^{13}C$ values. To quantify SOM turnover following *Prosopis* invasion

at Fort Huachuca, the timing of *Prosopis* establishment needs to be determined. From the aerial photography, it is known that all three sites were C₄-dominated with no *Prosopis* in 1935, but some *Prosopis* were present in 1946. Therefore, the age of the oldest mesquite can not be greater than about 60 years. One method used to estimate organic matter turnover rates ("medium-term") from the natural abundance of ¹³C was presented by Martin et al. (1990). By using results from Ludlow et al. (1976) to estimate remaining C₄ vegetation, they determined:

$$C_{4\text{carbon lost}} = 100 - \%C_{4\text{remaining}} * \frac{C_2}{C_1}$$

where C₁ is the original C content of the soil and C₂ is the C content after change has occurred. These values are composites of fast-cycling and slow-cycling carbon pools. If it is assumed that the average TOC percentage of the surface 0-5 cm SOM on modern Site 2 (which was 1.2%) approximates that of all sites in 1935 (i.e., C₁), estimates of carbon turnover can be made. On unburned Site 1 at point 21N-18E, about 77% of C₄ carbon has been lost in approximately 60 years, while point 21N-3E has lost 57%; at point 3N-3E approximately 31% of C₄ carbon has turned over since the *Prosopis* first occupied the position, although the elapsed time since the germination of the tree can not be determined.

Using the same approach, the inferred former *Prosopis* locations on the burned sites can be evaluated to estimate how much of the original C₃ material remains in the SOM. On Site 2, points 15N-12E, 24N-3E, and 27N-24E (Fig. 5) are all interpreted as "ghost trees". If the assumption is made that the SOM of these points was once composed of 100% C₃ *Prosopis* material, then about 31%, 30%, and 24% of the original C₃ carbon has been lost from the respective locations. Points 9N-24E and 21N-24E on frequently burned Site 3 (Fig. 6) are also interpreted as former *Prosopis* sites. It is

estimated that these points have lost approximately 12% and 52%, respectively, of original C₃ carbon content. Because it is unlikely that the SOM values were ever 100% C₃ carbon, these estimates represent maximum potential losses. The amount of time that has elapsed since the *Prosopis* trees were removed is ≥ 60 years, as no trees are apparent on 1935 aerial photographs.

Long-term experiments in temperate soils indicate that mineralization of SOM is not a linear process, with mineralization rates high in an initial stage and then decreasing rapidly (Martin et al., 1990). To estimate the exponential turnover rates of C₄ or C₃ carbon for a particular point, the decay equation $A = A_0 e^{-\lambda t}$ can be utilized, with A = measured %TOC₄(or 3) of a point, A₀ = the initial %TOC, t = time, and λ = turnover rate. By using the assumption that t = 60 years, the turnover rate for C₄carbon may be estimated on Site 1. Therefore, the SOM beneath the large multi-stemmed *Prosopis* at point 21N-18E would be 100% C₃ material after 52 more years (112 years total turnover time) and the total turnover time for SOM beneath the large single-stemmed tree at 21N-3E would be 270 years. These estimates represent minimum turnover rates, as the trees could have been established more recently than 60 years. Because the small single-stemmed tree at 3N-3E appears to be much younger than 60 years, an assumption of t = 20 years was used to determine that SOM turnover time would be about 1185 years under it. On the two burned sites, the turnover time from C₃ to C₄ material on inferred former *Prosopis* points ranges from 494 and 503 years (at points 15N-12E and 27N-24E, respectively) on Site 2 to 298 years and 135 years on Site 3 (points 9N-24E and 21N-24E, respectively).

There are several possible explanations for the difference in the turnover rates between the C₄ carbon on Site 1 and the C₃ carbon on Sites 2 and 3. *Prosopis* contributes much more litter to the soil organic matter than grass in a given amount of time (Klemmedson, 1989), which would quickly dilute the C₄ carbon component. The

size of the *Prosopis* and amount of C₄ understory should also influence the turnover rate, as evidenced by the three trees on Site 1. Moreover, rapid turnover of shallow-rooted grasses is characteristic of arid land environments (Whitford et al., 1988). In addition to greater production of organic material, *Prosopis* may concentrate more carbon and fix carbon more tightly than the C₄ grasses, thus slowing the turnover rate after grass invasion. Estimation of turnover rates on the two burned sites may also be affected by the size of the original C₃ trees and the amount of material left in the SOM when the trees were removed. The differences in turnover rates between Sites 2 and 3 also suggest frequent fires may increase turnover rates of surficial SOM. Finally, the results from Sites 2 and 3 may be influenced by the presence of charcoal.

Previous studies have used shifts in SOM $\delta^{13}\text{C}$ values to determine carbon turnover rates. Many of these studies have been done as controlled agricultural experiments, in which C₃ or C₄ species have been introduced on plots previously dominated by the opposite photosynthetic type and the timing of plant conversion was known. Balesdent et al. (1987) estimated 22% of total soil C turned over after 13 years of C₄ corn (*Zea mays*) cultivation in southwestern France; total turnover was estimated to be 36 years. Wedin et al. (1995) reported 12.7% to 22.6% new C in SOM 4 years after of C₄ grass introduction in east-central Minnesota. In subtropical Brazil, 50% of the original C₃ soil carbon was lost in the first 12 years after clearing of forest and planting of sugar cane (Volkoff and Cerri, 1987). And in a tropical savanna, 52-70% (avg. 59%) of soil C in the upper 10 cm turned over in 16 years due to C₃ invasion of C₄ grasslands (Martin et al., 1990).

The range of turnover estimates is due to variations in soil types and textures, geographic setting, variable SOM levels and other factors (Trumbore et al., 1996). For example, Gregorich et al (1995) found the turnover time was strongly linked to soil particle size and location of the material relative to plow depth. Cultivated soil looses

about 25% of its carbon due to reduced inputs of organic matter and increased rates of organic matter oxidation (Harrison, 1996). Studies in the midwestern United States reported that after approximately 100 years of cultivation, the proportion of organic matter of prairie origin was no less than 50% (Balesdent et al., 1988) and theoretical turnover time for slow-cycling carbon is 4,700 years (Harrison, 1996). Calculated turnover times for two midwestern U.S. prairie soils were 853 and 2973 years (Hsieh, 1992). In non-agricultural semiarid systems, it has been calculated that SOM pools under *Prosopis* will equilibrate isotopically with mesquite litter in about 2,500 years (Connin et al., 1997).

Soil-respired $\delta^{13}\text{C}$ values

The $\delta^{13}\text{C}$ values of soil-respired CO_2 are clearly dominated by current vegetation. This is consistent with results from other studies in which soils planted with C_3 or C_4 monocultures showed $\delta^{13}\text{CO}_2$ values very close to the $\delta^{13}\text{C}$ values of plant tissues after seven years of cultivation (Schonwitz et al., 1986). The majority of $\delta^{13}\text{CO}_2$ values on all three study sites (Table 3) were depleted compared to corresponding SOM $\delta^{13}\text{C}$ values. These values indicate that the preferential consumption of organic material by, and respiration activity of, soil microbes, the major contributors (approximately 71%) to the CO_2 flux from the soil (Parker et al., 1983), is even more of a major factor of soil-respired CO_2 than microbial organic material is to total SOM. Summer is the time of maximum litter disappearance, when most annual precipitation occurs and soil temperatures are optimum for maximum microbial activity (Parker et al., 1983). The maximum shifts of $\delta^{13}\text{CO}_2$ values occurred in late summer at Fort Huachuca following the monsoon rains; the shifts in other seasons were not as pronounced. The most depleted $\delta^{13}\text{CO}_2$ values were under *Prosopis* canopies on Site 1 and the most depleted values on Sites 2 and 3 corresponded with locations interpreted as former *Prosopis* sites.

The spatial distribution of $\delta^{13}\text{CO}_2$ values shows enrichment with distance from the base of the tree or tree site, indicating there is little lateral mixing of CO_2 . It is not known when a *Prosopis* occupied the locations on Sites 2 and 3, but results indicate the C_4 grasses now dominate CO_2 at these positions.

$\delta^{13}\text{C}$ values in the subsurface

Carbon concentration is more sensitive than depth in describing soil mixing processes (Ladyman and Harkness, 1980) and there is frequently a sharp change in concentration between litter and the uppermost mineral soil layers. After the plant material has entered the highly resistant soil humus pool, the isotopic signal is relatively independent of depth (Balesdent et al., 1993). This appears especially true for clay-rich B-horizons, where organic matter is biologically stable and not much affected by new organic matter derived from C_3 or C_4 crops on the surface (Balesdent et al., 1988). With age, the $\delta^{13}\text{C}$ value represents the original vegetation, and does not result from downward moving carbon matter, long-term diagenetic effects, or root activity (Ambrose and Sikes, 1991). The observed enrichment of $\delta^{13}\text{C}$ with depth in mineral horizons beneath C_3 vegetation is consistent on all three study sites, and is similar to results reported from other soil types and is largely independent of soil redox status (Balesdent et al., 1993).

Charcoal was not collected nor separately analyzed as part of this study, but significant amounts were apparent in many of the surface soil samples taken from Sites 2 and 3 and the subsurface samples from all three sites. The charcoal is finely disseminated in subsurface horizons and no well-defined layers of charcoal were identified in the soil pits. The effects of fire on the $\delta^{13}\text{C}$ of SOM have not been discussed in the literature. As wildfire is a kinetic event in an open system, burning should preferentially release ^{12}C , leaving the charcoal isotopically enriched. However, published graphs of SOM and

charcoal $\delta^{13}\text{C}$ values from grasslands of Central Brazil clearly reflect the effects of microbial activity on the SOM isotopic value, whereas the charcoal retained the original C_3 isotopic value of the plants (Pessenda et al., 1996). The ^{14}C dates of charcoal and humin from that study did not show significant age differences, verifying that the source for the SOM carbon was identical to that of the charcoal. Therefore, it can be concluded that charcoal resists microbial attack and thus charcoal $\delta^{13}\text{C}$ values are more favorable for recognizing former vegetation than SOM $\delta^{13}\text{C}$ values. Furthermore, as the non-charcoal fraction of SOM decreases with depth and time, the proportion of resistant charcoal increases. This will result in a $\delta^{13}\text{C}$ signal that closely represents the original vegetation. Although the hypothesis needs further evaluation, it appears that the main effect of fire on $\delta^{13}\text{C}$ is that it preserves the original carbon isotopic composition of the plant in charcoal form better than other soil organic fractions. Charcoal is also geologically long lived, with paleo-charcoals recognized in Paleozoic-aged sediments (Sander and Gee, 1990).

Plant communities can be reconstructed for the Holocene and Pleistocene ecosystems from the SOM $\delta^{13}\text{C}$ values. The $\delta^{13}\text{C}$ data for the older Pleistocene (3-horizons, Fig. 9) soil indicate the presence of a mixed-woodland with a predominantly C_4 perennial grass understory (Neilson, 1986). The vegetation pattern was probably intermittent trees with spatial distributions very similar to the modern mosaic on unburned Site 1.

During the development of the 2-horizons (Fig. 9), the ecosystem changed from mixed woodland with grassy understory in the lower portions to grassland dominated in the upper portions of the unit. The 2-soil horizons, interpreted here to represent the Upper Pleistocene, display SOM $\delta^{13}\text{C}$ values mostly between -14‰ and -17‰ , with a few values of less than -20‰ . In the absence of accurate dates for these 2-horizons, they may, in fact, be Holocene in age, for the transition from C_3 shrubland to C_4 grassland

may have occurred during the early Holocene warming trend (Neilson, 1986) or about 8500 yrs BP (Van Devender, 1995).

The surface horizons, interpreted here as Holocene, were clearly true grasslands that were probably maintained by climate patterns that favored summer precipitation (Neilson, 1986) and swept periodically by fires that inhibited expansion of woody plants. The $\delta^{13}\text{C}$ enrichment in the SOM with depth in Holocene soil horizons is systematic on all three burn sites and is similar to changes documented in other regions. The $\delta^{13}\text{C}$ values in Holocene soil horizons in all three trenches range between -14‰ and -16.5‰ , clearly indicative of C_4 -dominated grasslands, with no suggestion of a significant C_3 plant population. Other studies in southeastern Arizona found similar $\delta^{13}\text{C}$ enrichment of SOM at shallow depths beneath *Prosopis juliflora* and *Quercus emoryi*, both C_3 trees, and concluded the trees were recent invaders of C_4 grasslands (McPherson et al., 1993).

Conclusions

The $\delta^{13}\text{C}$ values of SOM are shown to be coincident with the concentrations and spatial distributions of key soil nutrients such as phosphorus and nitrate. The use of SOM $\delta^{13}\text{C}$ values coupled with plant nutrient data provides direct evidence to confirm that *Prosopis* woodland has encroached into grasslands on the south gunnery ranges at Fort Huachuca. Although Martin et al. (1990) reported colonization by trees had modified the SOM $\delta^{13}\text{C}$ values throughout the soil profile, we do not find that to be the case. The isotopic signal of the present vegetation does not persist much below a depth of 5 cm, even beneath the mature *Prosopis* of Site 1. The pronounced shift to more positive soil $\delta^{13}\text{C}$ values below the surface cannot be explained by downward transport of ^{13}C -rich organic matter because the current source of organic carbon is mostly C_3 flora. Values under present mesquite trees are $\delta^{13}\text{C}$ enriched compared to expected C_3 vegetation signals and indicate these trees are recent occupants of former grassland sites.

On the other hand, this study also presents evidence from relict $\delta^{13}\text{C}$ values and remnant nutrient concentrations left in surficial SOM of the two burned sites that C_3 trees formerly existed in grassland areas. These findings support a model for grassland savannas with intermittent tree cover which varied from place to place over the savanna, with individual trees established as earlier ones die (Menaut et al., 1990). In this model, open savannas are unstable and will convert to closed-canopy woodlands in the absence of episodic hot fires to regulate tree density. The presence of 'ghost trees' on the two burned study sites support this model.

The turnover rates for total bulk carbon can be estimated using the $\delta^{13}\text{C}$ values of SOM. These rates are influenced by the amounts of new carbon added to the system. Therefore, C_3 mesquite trees, which typically add more litter material to the SOM than C_4 grasses, obliterate the pre-existing $\delta^{13}\text{C}$ values of grasses more rapidly than grasses can erase the SOM $\delta^{13}\text{C}$ values of earlier C_3 plants. Frequent fires may also increase the turnover rate of carbon in surficial SOM by volatilization of carbon compounds and removal of these compounds due to increased erosion.

The $\delta^{13}\text{C}$ values of respired CO_2 collected from the study sites were consistently more depleted than SOM $\delta^{13}\text{C}$ values from the respective collection points. The $\delta^{13}\text{CO}_2$ values varied seasonally due to root and soil fauna respiration. On transects beneath large trees on the unburned site, the combination of SOM $\delta^{13}\text{C}$ values and $\delta^{13}\text{CO}_2$ values indicative of C_3 plants extend to the margin of the *Prosopis* canopy.

There have been previous landscape-scale studies (van Kessel et al., 1994) that used sampling intervals too coarse to recognize patterns similar to those found in this study. Other attempts to verify ecological changes used agricultural situations where tillage, irrigation, fertilization or other factors were employed, which upset the natural portion of the experiment. Transect-style sampling fails to reveal landscape-scale

distributions of isotopic signals or nutrient concentrations. For example, a transect-style study on a nearby area of the Fort Huachuca military base did not find increased concentrations of carbon or nitrogen under *Prosopis* trees and concluded that the mesquite may have colonized the site so recently that soil nutrient levels have not had time to increase (McPherson et al., 1993). This study found increased nutrient concentrations and depleted SOM $\delta^{13}\text{C}$ values under *Prosopis* shrubs as young as six years and also illustrated the probable eolian effects on SOM in the open savannas.

The distribution of $\delta^{13}\text{C}$ values from SOM of an inferred Pleistocene horizon indicate the area of modern-day Fort Huachuca was a savanna of scattered C₃ trees with an understory of C₄ grasses. During the Holocene, the area was dominated by C₄ grasslands.

Acknowledgments

This study was funded by the Southwestern Borderlands Ecosystems Management Program of the U.S.D.A. Forest Service, Rocky Mountain Forest and Range Experiment Station, with partial funding supplied by the U.S. Geological Survey. Jerry Gottfried and Carl Edminster of the Forest Service were very supportive of the research, Chris Cochrane of the Natural Resources Conservation Service, Tucson, provided surficial soils information and access to some of the early aerial photography, and Sheridan Stone of the Wildlife Office, Fort Huachuca, facilitated with access to the military reservation and arranged for personnel and equipment to dig the back hoe trenches. Much of the laboratory work, including CO₂ extractions, was done at the Desert Laboratory, Tucson. Dr. Dave Dettman, of the Department of Geosciences, University of Arizona, assisted with the mass spectrometer analyses. Tina Hayden and Laska Rohovit, of the Department of Soil, Water and Environmental Science, University of Arizona, assisted with soil analyses. Jan Bowers, Peter Griffiths, Betsy Pierson, Ray Turner, and Doug Wellington, all from the U.S. Geological Survey, helped with the plant biomass harvesting, and Donna Opocensky and Peter Griffiths of the U.S. Geological Survey helped with laboratory analyses. In addition, species lists of the 3 sites were made by Bowers.

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Figure B1: Location map of the Fort Huachuca area, showing the locations of the Woodcutters ' Canyon area and the three study sites.

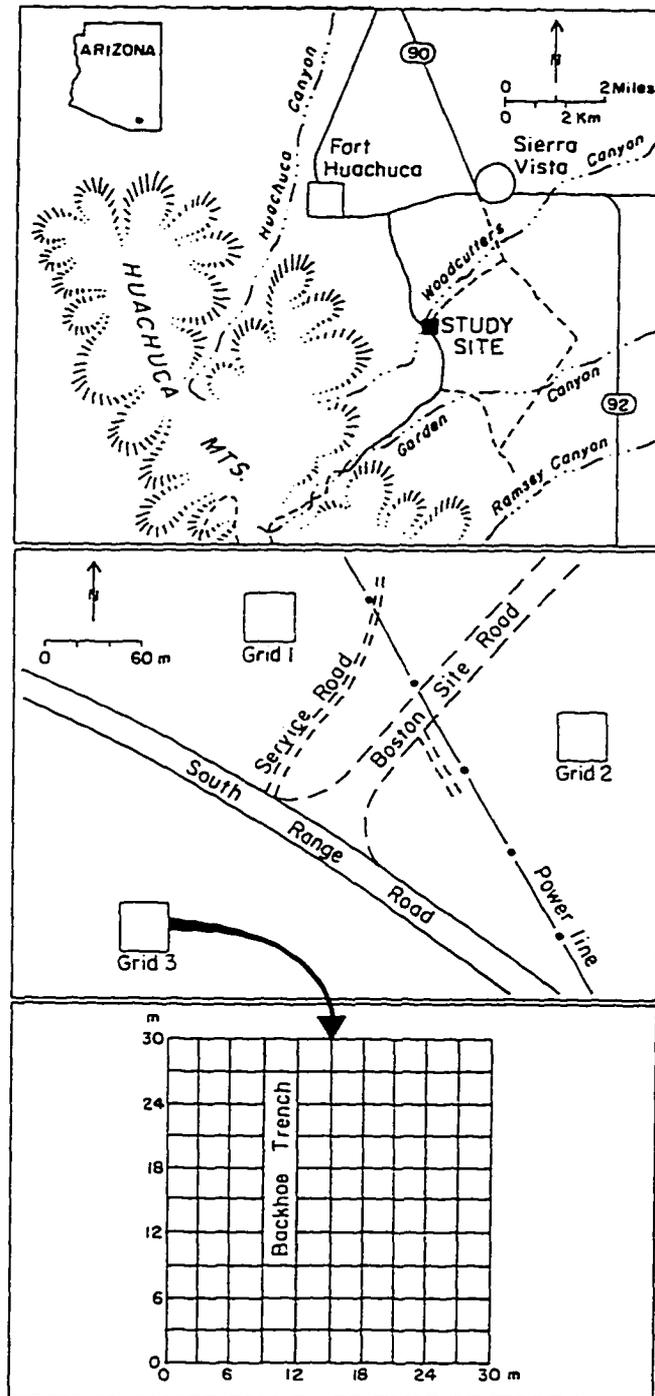


Figure B2: Diagrams showing the soil profiles exposed in trenches on the three study sites. A. Site 1, unburned. B. Site 2, moderately burned site, 3 fires/decade. C. Site 3, frequently burned, 5 fires/decade.

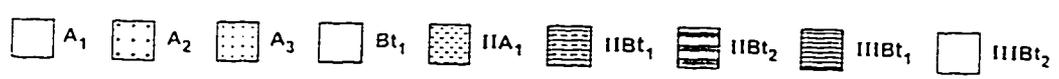
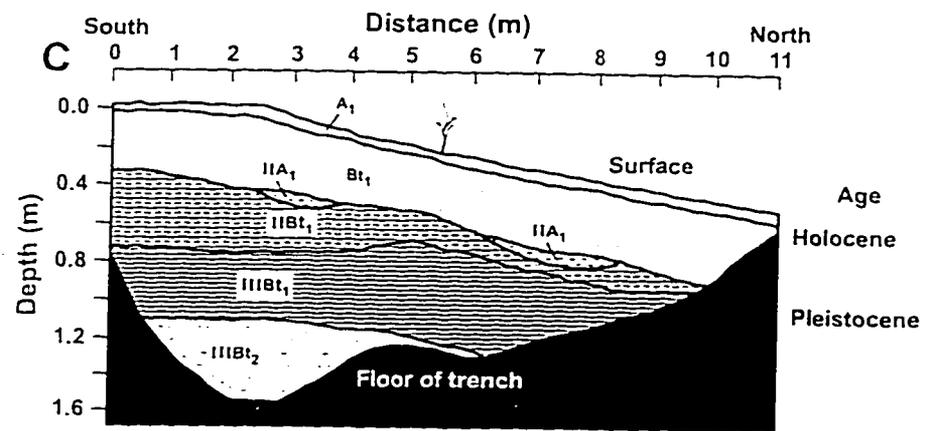
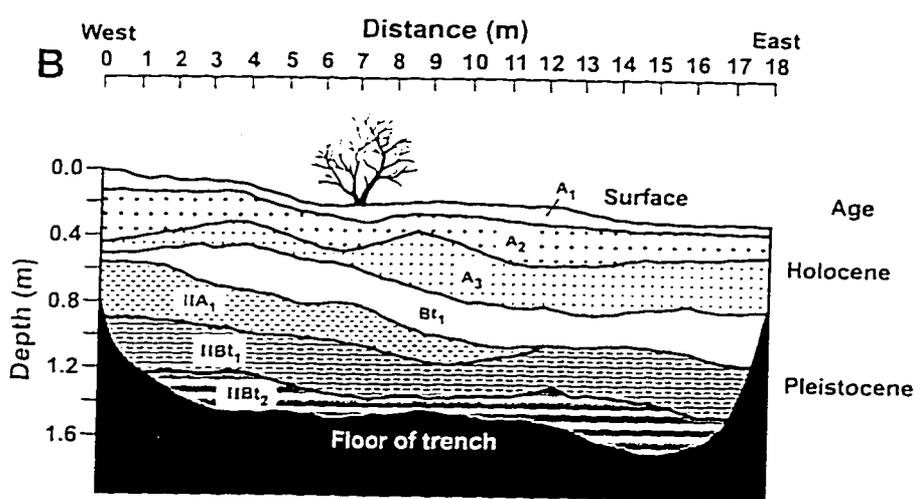
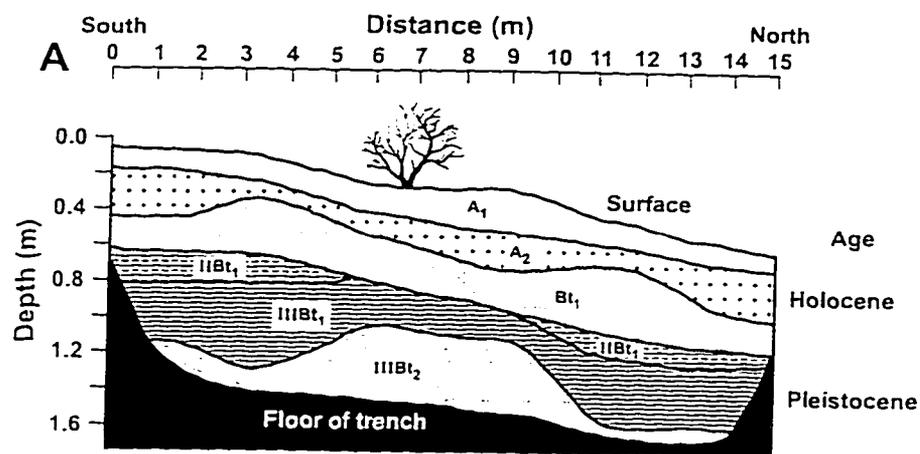


Figure B3: $\delta^{13}\text{C}$ values plotted against total organic carbon (TOC), plant-available phosphorus (PO_4^{3-}), and plant-available nitrogen (NO_3^-) in surface soil organic matter.

- A. Site 1, open vs. canopy sample points on the unburned site: $\delta^{13}\text{C}$ values vs TOC and $\delta^{13}\text{C}$ values vs PO_4^{3-} .
- B. Site 2, infrequently burned site: $\delta^{13}\text{C}$ values vs TOC and $\delta^{13}\text{C}$ values vs NO_3^- .
- C. Site 3, frequently burned site: $\delta^{13}\text{C}$ values vs TOC and $\delta^{13}\text{C}$ values vs NO_3^- .

Figure 3A: Site 1: Open vs Canopy Nodes

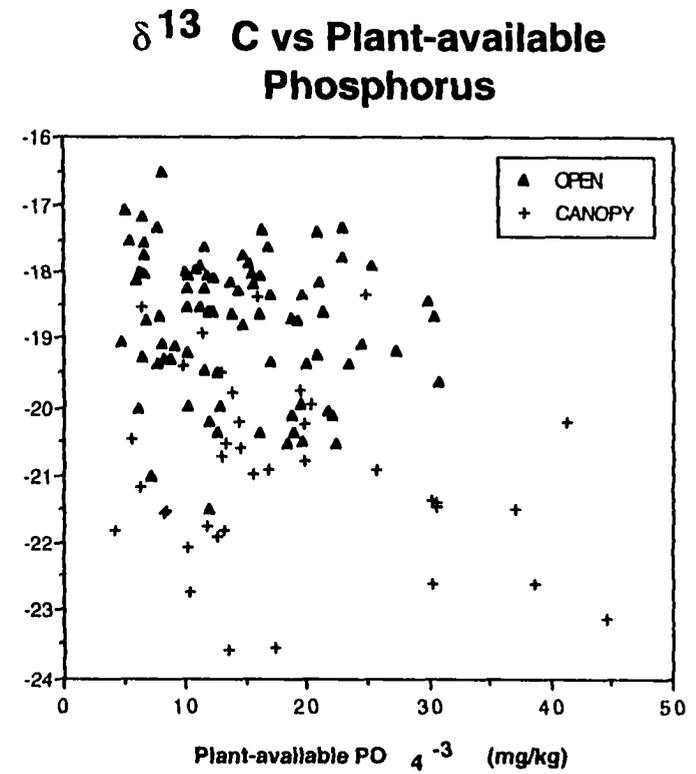
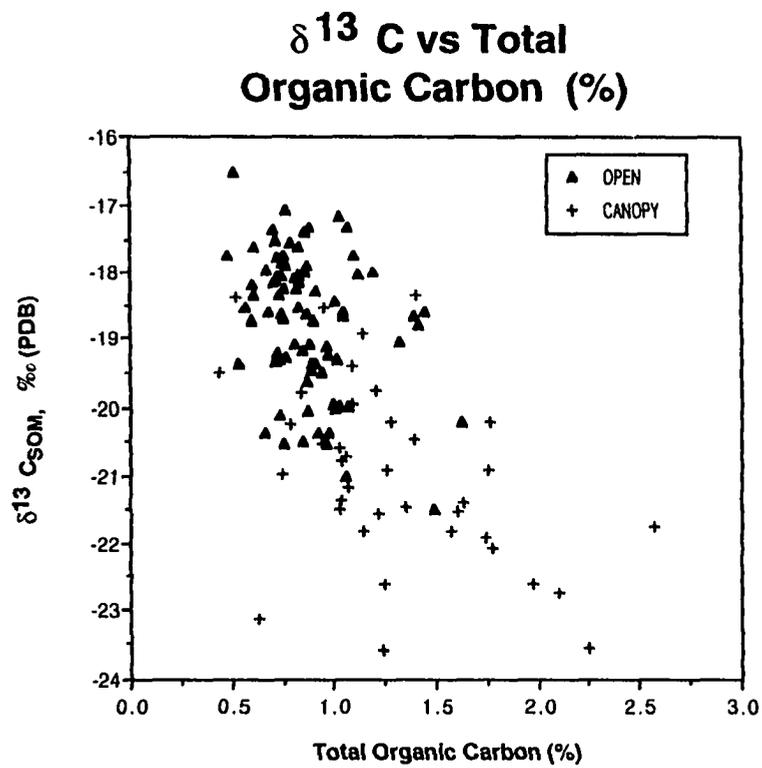


Figure 3B: Site 2: Infrequently Burned Plot

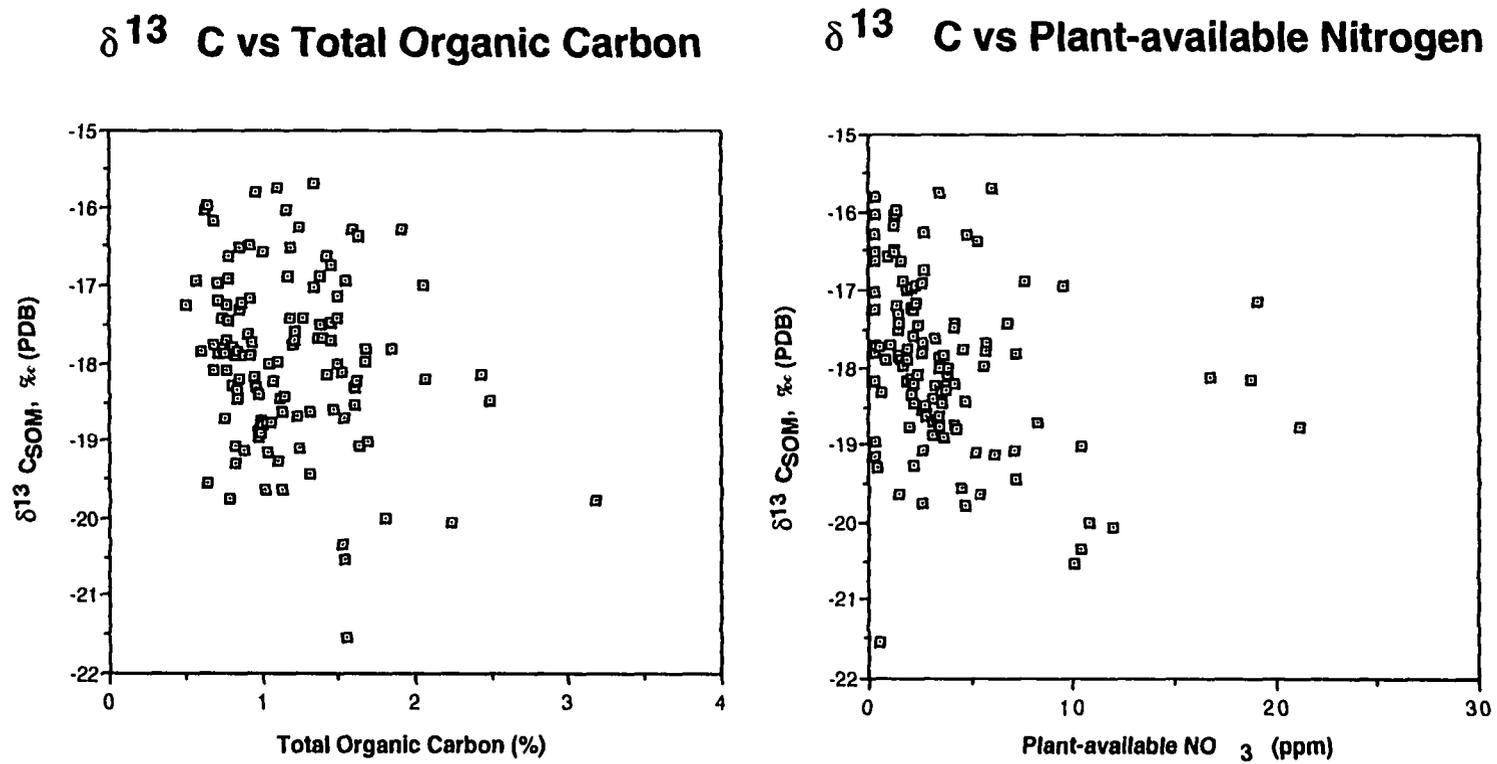


Figure 3C: Site 3: Frequently Burned Plot

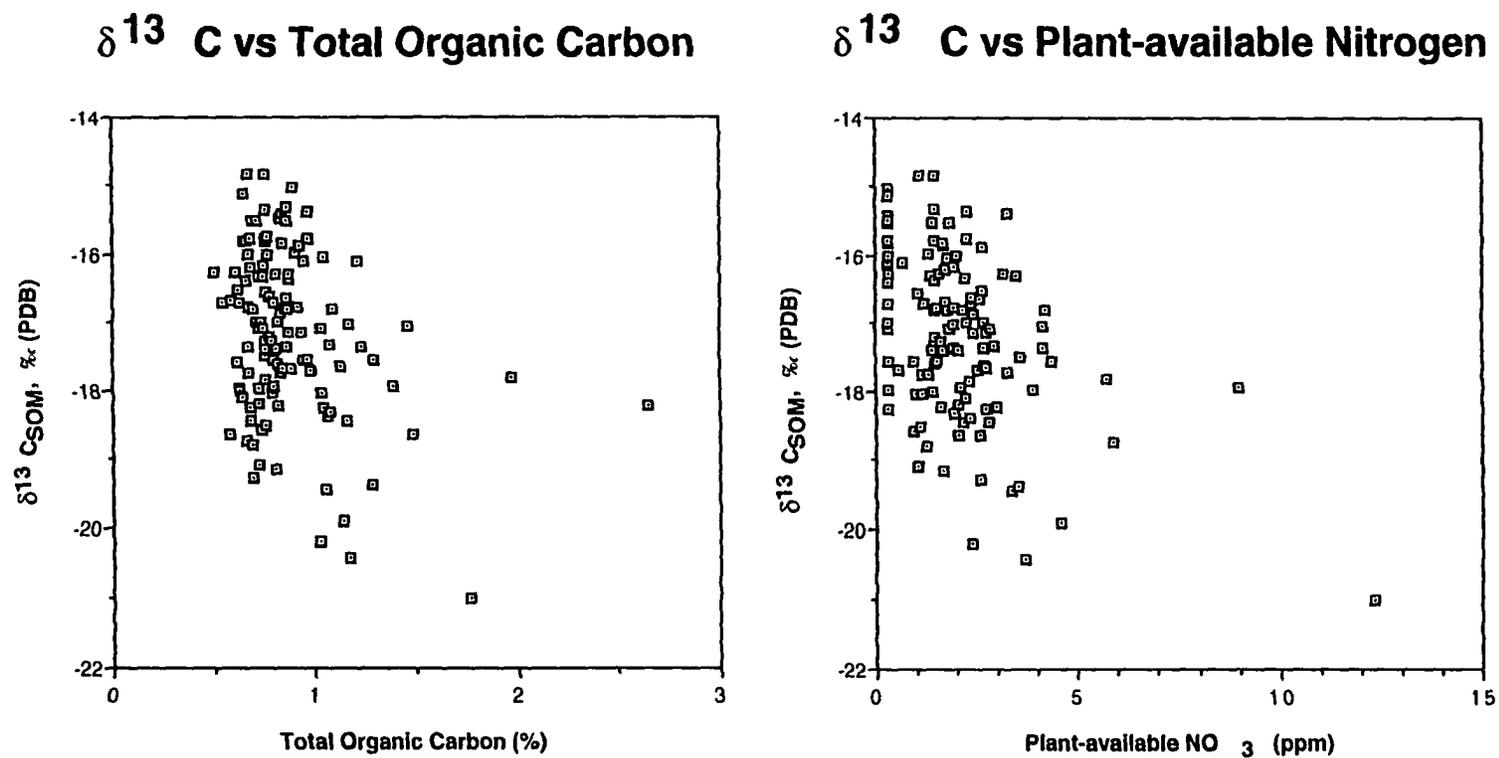
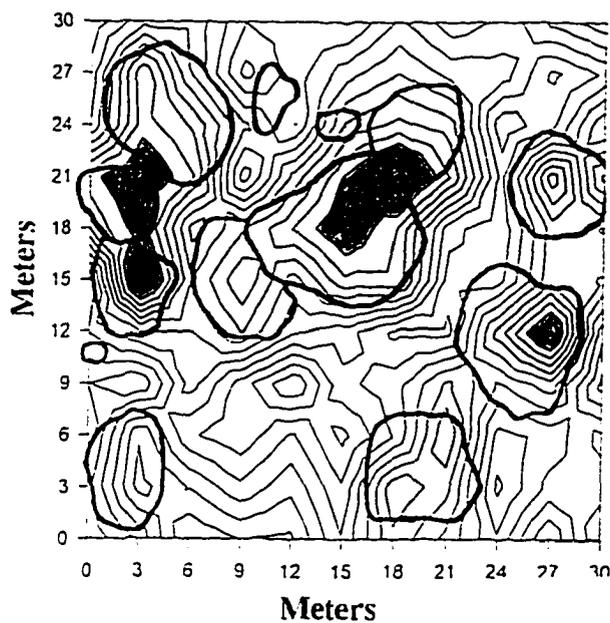


Figure B4: Contour plots of $\delta^{13}\text{C}$, TOC, NO_3^- , and PO_4^{3-} on unburned Site 1.

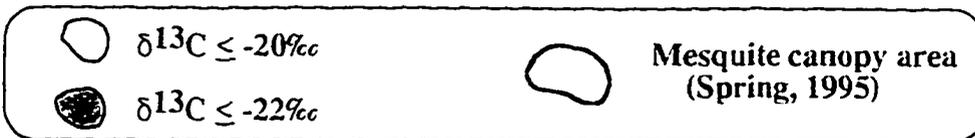
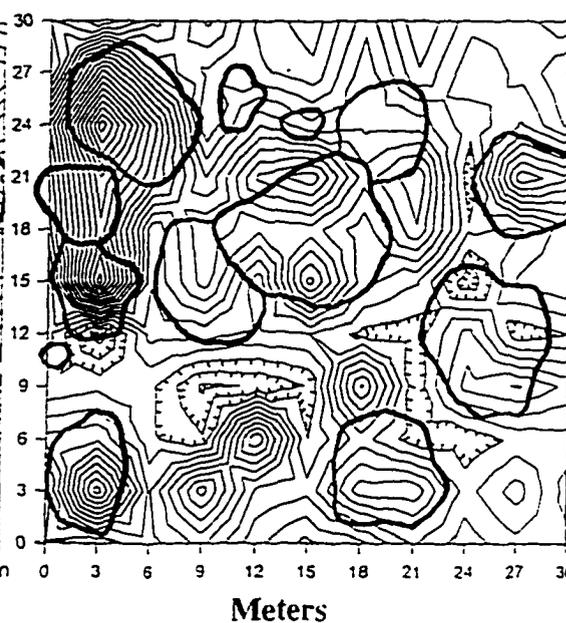
Site 1: $\delta^{13}\text{C}$ on Unburned Site

— Contour interval: $0.50\text{‰ } \delta^{13}\text{C}$



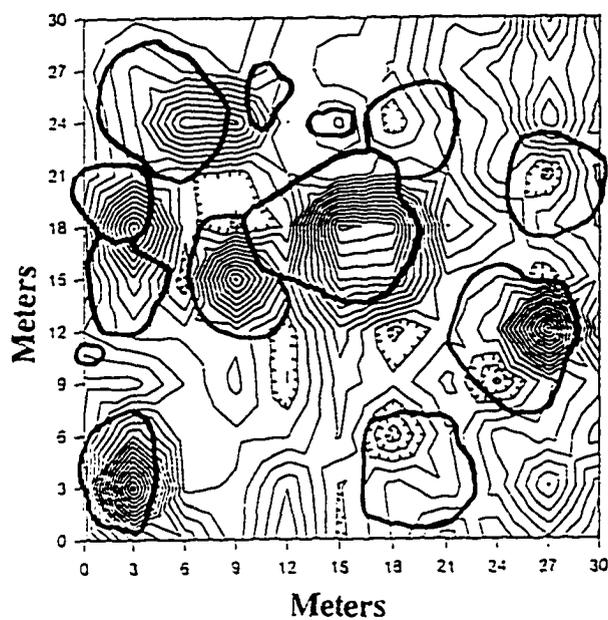
Site 1: Total Organic Carbon

— Contour interval: 0.10 % TOC



Site 1: Plant-available Phosphorus

— Contour interval: 2 mg/kg PO_4^{-3}



Site 1: Plant-available Nitrogen

— Contour interval 1 ppm NO_3^-

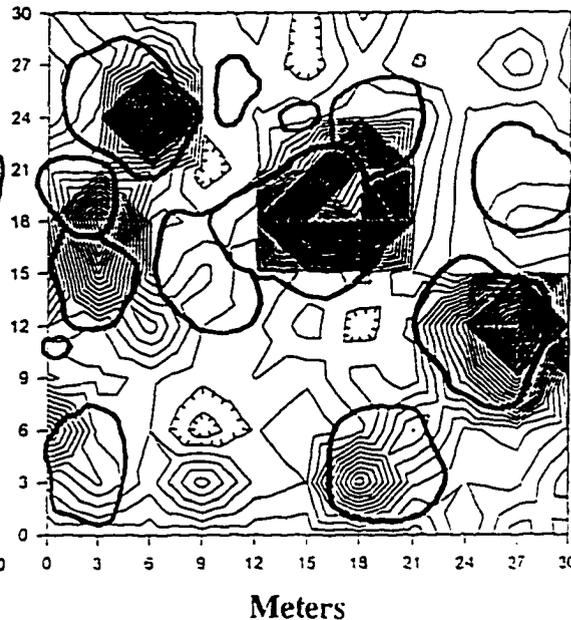
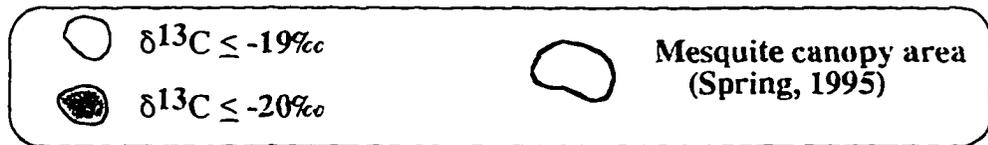
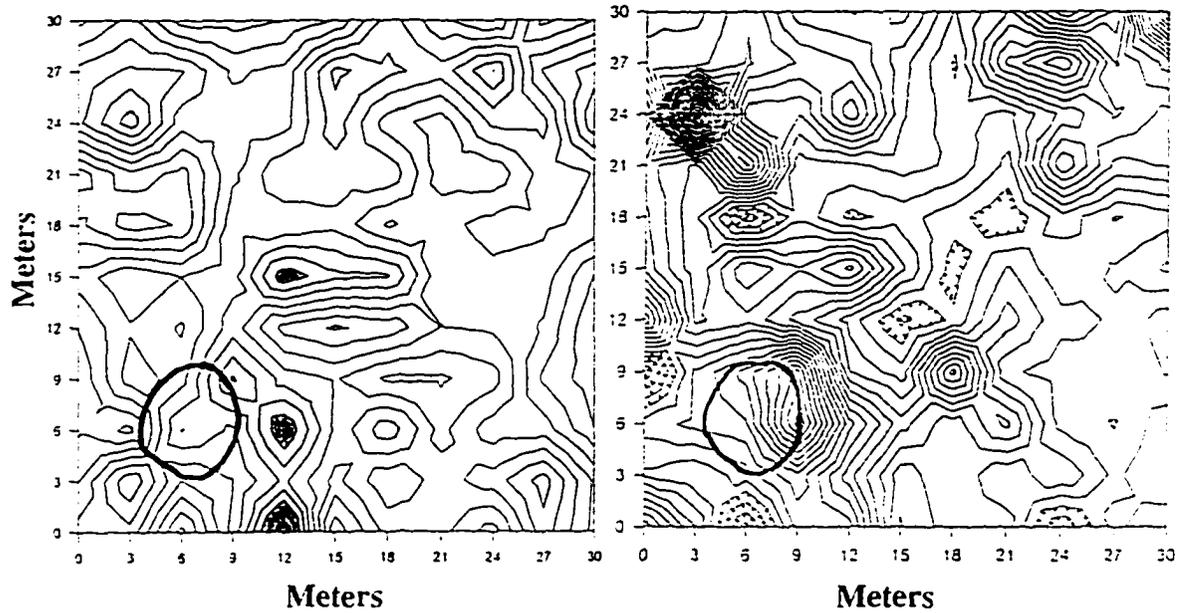


Figure B5: Contour plots of $\delta^{13}\text{C}$, TOC, NO_3^- , and PO_4^{3-} on moderately burned Site 2.

Site 2: $\delta^{13}\text{C}$ Infrequently Burned Site
 — Contour interval: 0.50‰ $\delta^{13}\text{C}$

Site 2: Total Organic Carbon
 — Contour interval: 0.10 % TOC



Site 2: Plant-available Phosphorus
 — Contour interval: 2 mg/kg PO_4^{3-}

Site 2: Plant-available Nitrogen
 — Contour interval 1 ppm NO_3^-

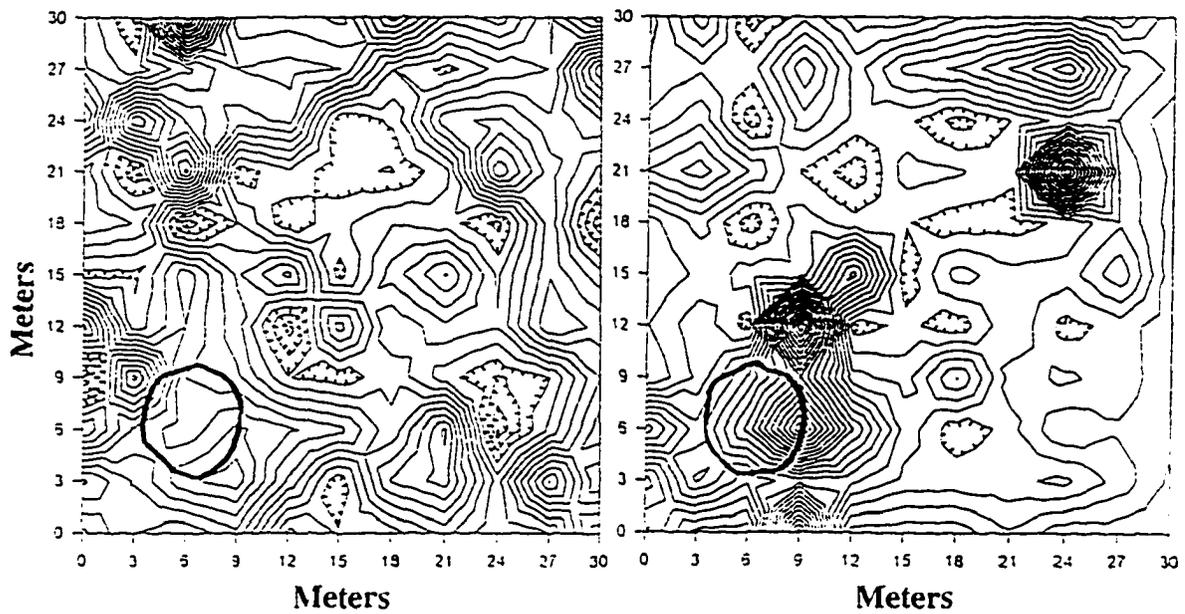


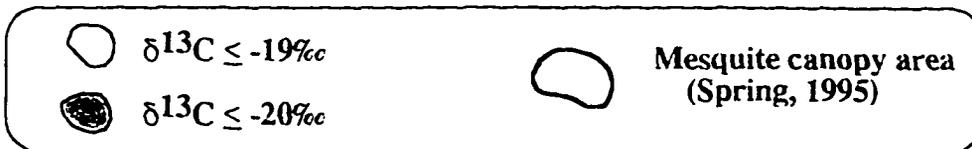
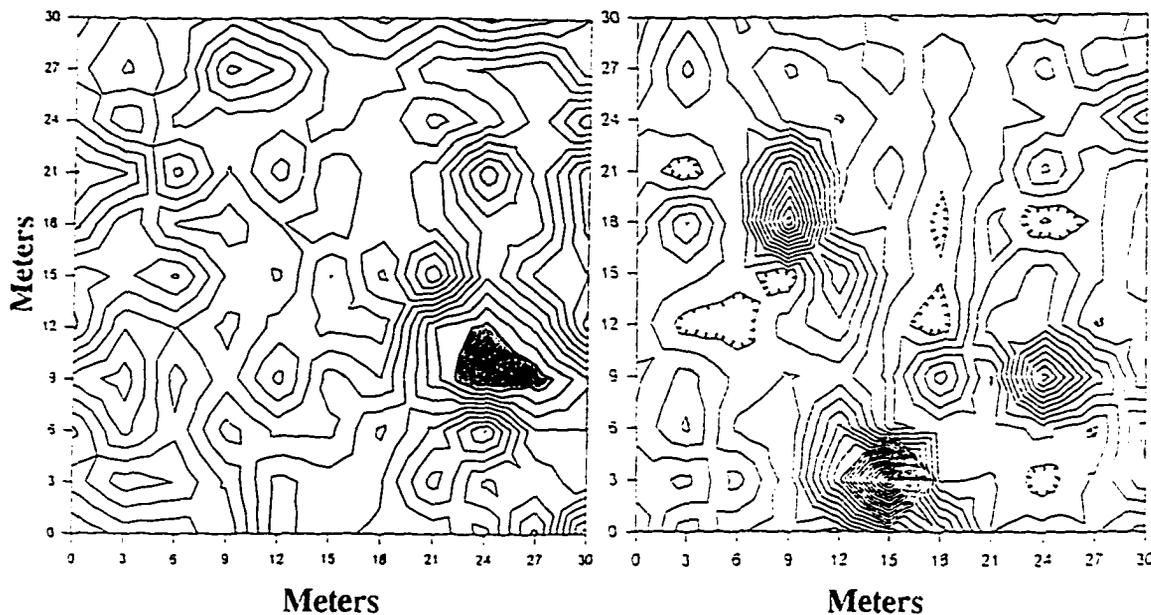
Figure B6: Contour plots of $\delta^{13}\text{C}$, TOC, NO_3^- , and PO_4^{3-} on frequently burned Site 3.

Site 3: $\delta^{13}\text{C}$ Frequently Burned Site

— Contour interval: 0.50‰ $\delta^{13}\text{C}$

Site 3: Total Organic Carbon

— Contour interval: 0.10 % TOC



Site 3: Plant-available Phosphorus

— Contour interval: 2 mg/kg PO_4^{-3}

Site 3: Plant-available Nitrogen

— Contour interval 1 ppm NO_3^-

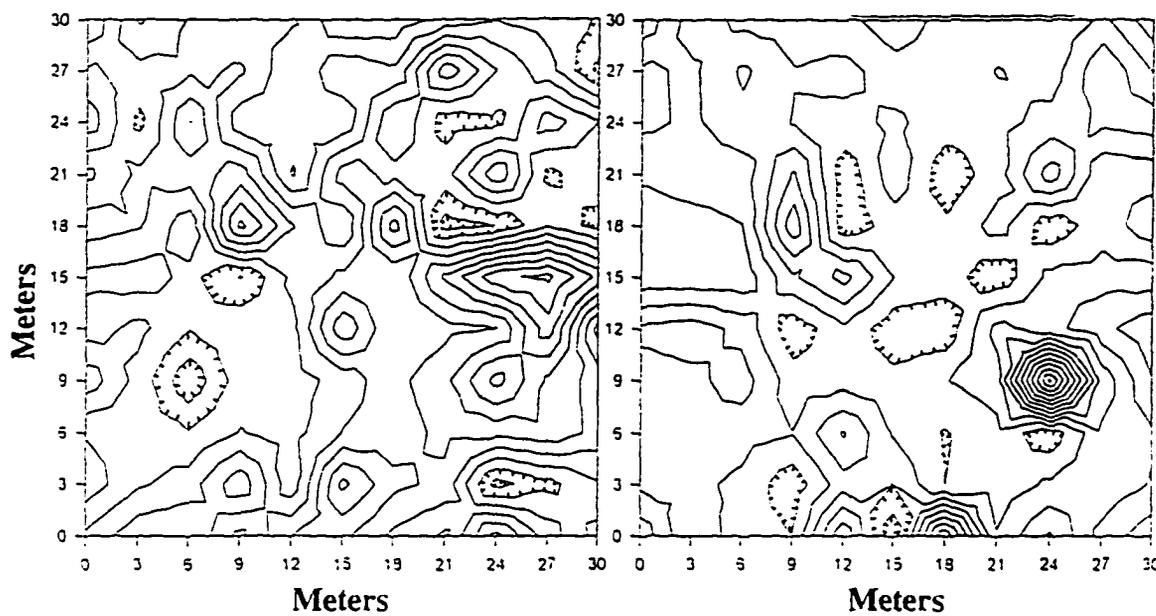
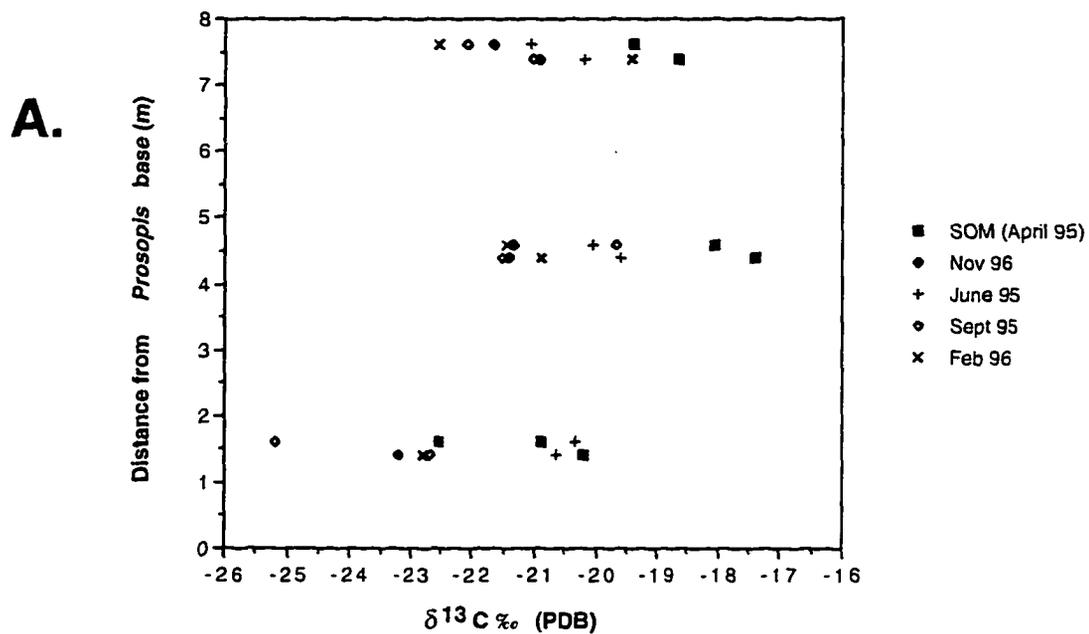


Figure B7: Transects of $\delta^{13}\text{C}$ values of soil organic matter and soil-respired CO_2 through *Prosopis* canopies on unburned Site 1.

- A. *Prosopis* centered near point 3N-18E.
- B. *Prosopis* centered near point 24N-6E.

Figure 7:

Site 1: Unburned Site: Seasonal $\delta^{13}\text{C}_{\text{CO}_2}$
Transect Through *Prosopis* Canopy



Site 1: $\delta^{13}\text{C}_{\text{CO}_2}$ Transect
Through *Prosopis* Canopy

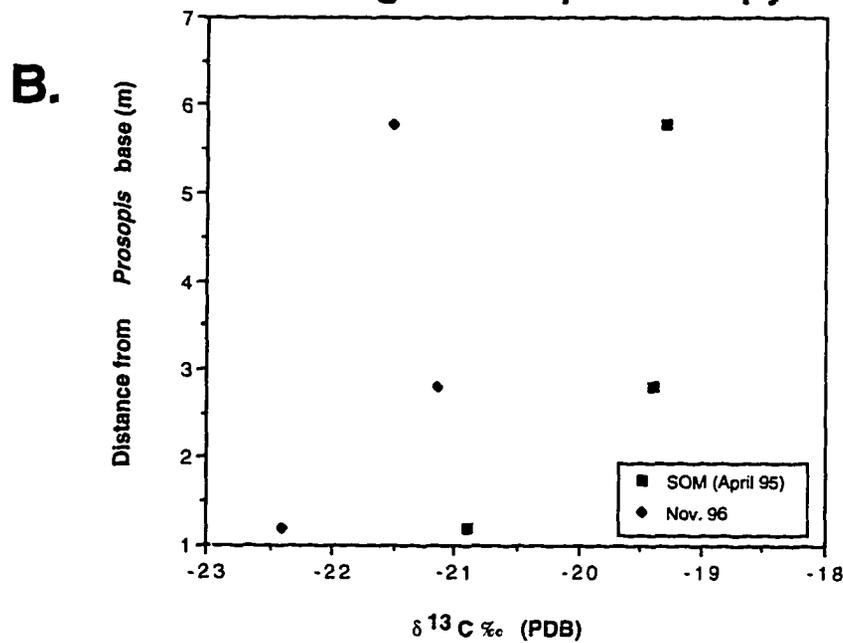
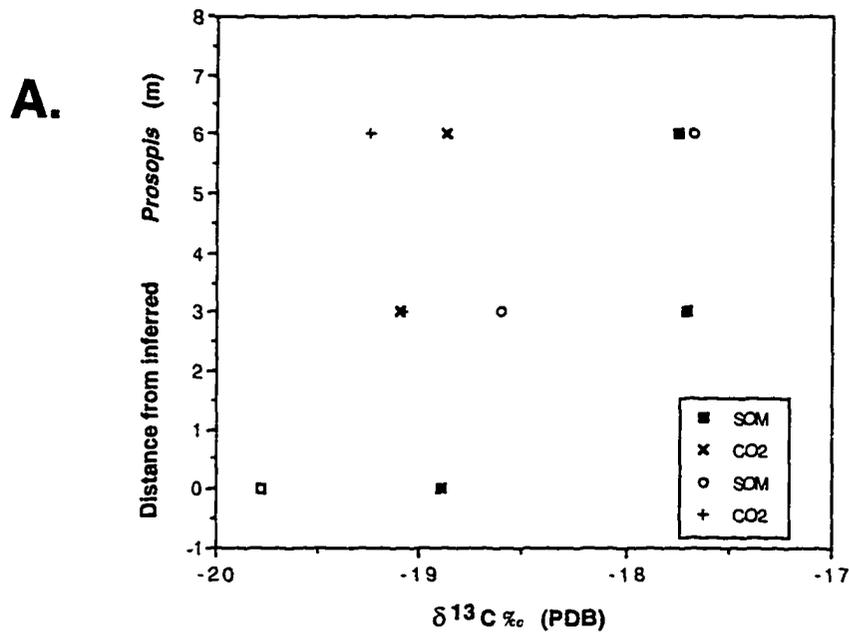


Figure B8: Transects of $\delta^{13}\text{C}$ values of soil organic matter and soil-respired CO_2 through inferred paleo-*Prosopis* trees.

- A. Inferred paleo-tree on Site 2 at point 24N-3E.
- B. Inferred paleo-tree on Site 3 at point 9N-24E.

Figure B8:

**Site 2: Infrequently Burned Plot:
Transects Through Inferred
Paleo- *Prosopis* "Nutrient Island"**



**Site 3: Frequently Burned Plot: Transect
Through Inferred Paleo- *Prosopis* "Nutrient Island"**

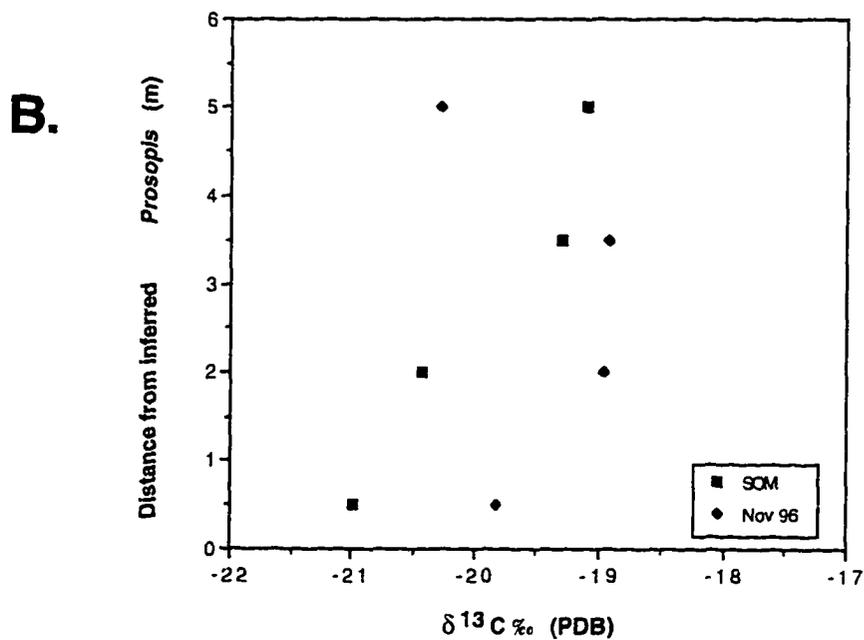


Figure B9: Diagrams showing the subsurface distribution of $\delta^{13}\text{C}$ values on the 3 sites with different fire histories:

- A. Trench on unburned Site 1.
- B. Trench on moderately burned Site 2.
- C. Trench on frequently burned Site 3.

Figure 9A:

Site 1: Profile of $\delta^{13}\text{C}$ in trench on unburned plot

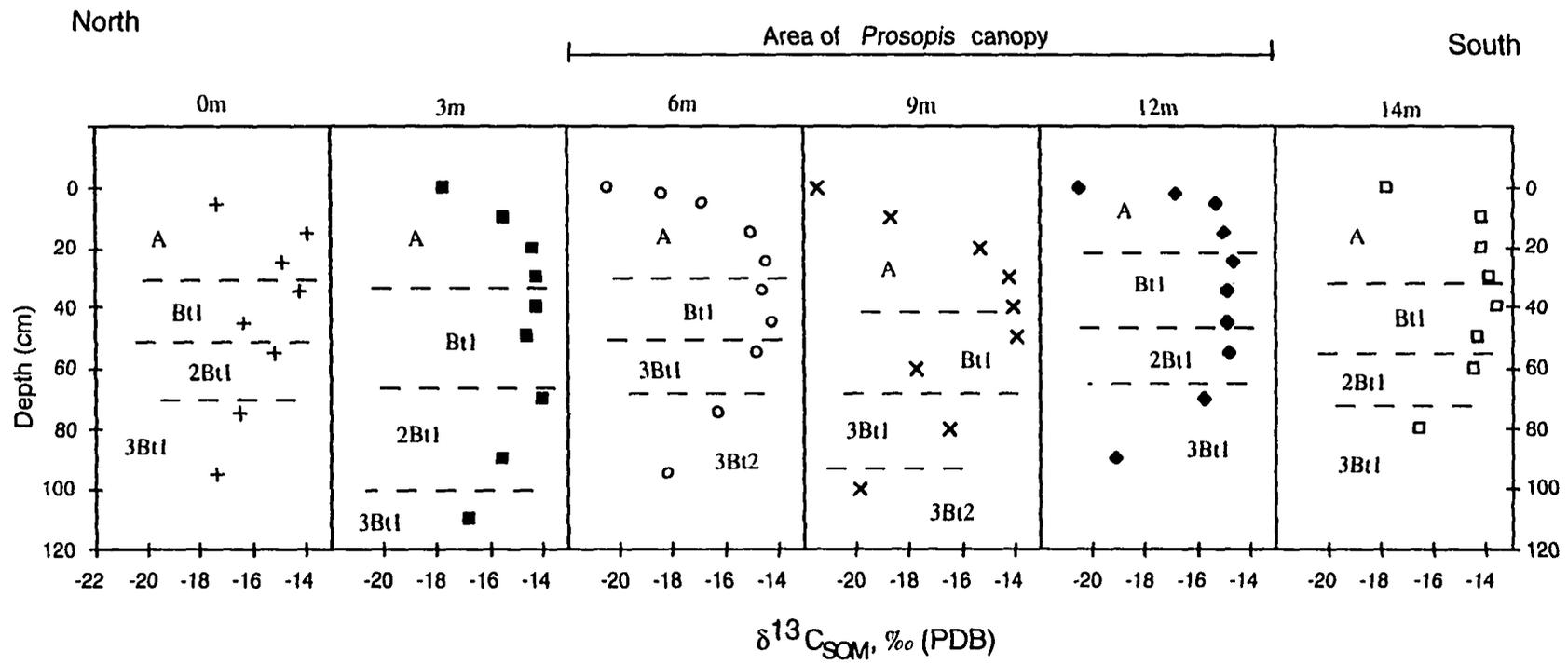


Figure 9B:

Site 2: Profile of $\delta^{13}\text{C}$ in trench on Infrequently burned plot

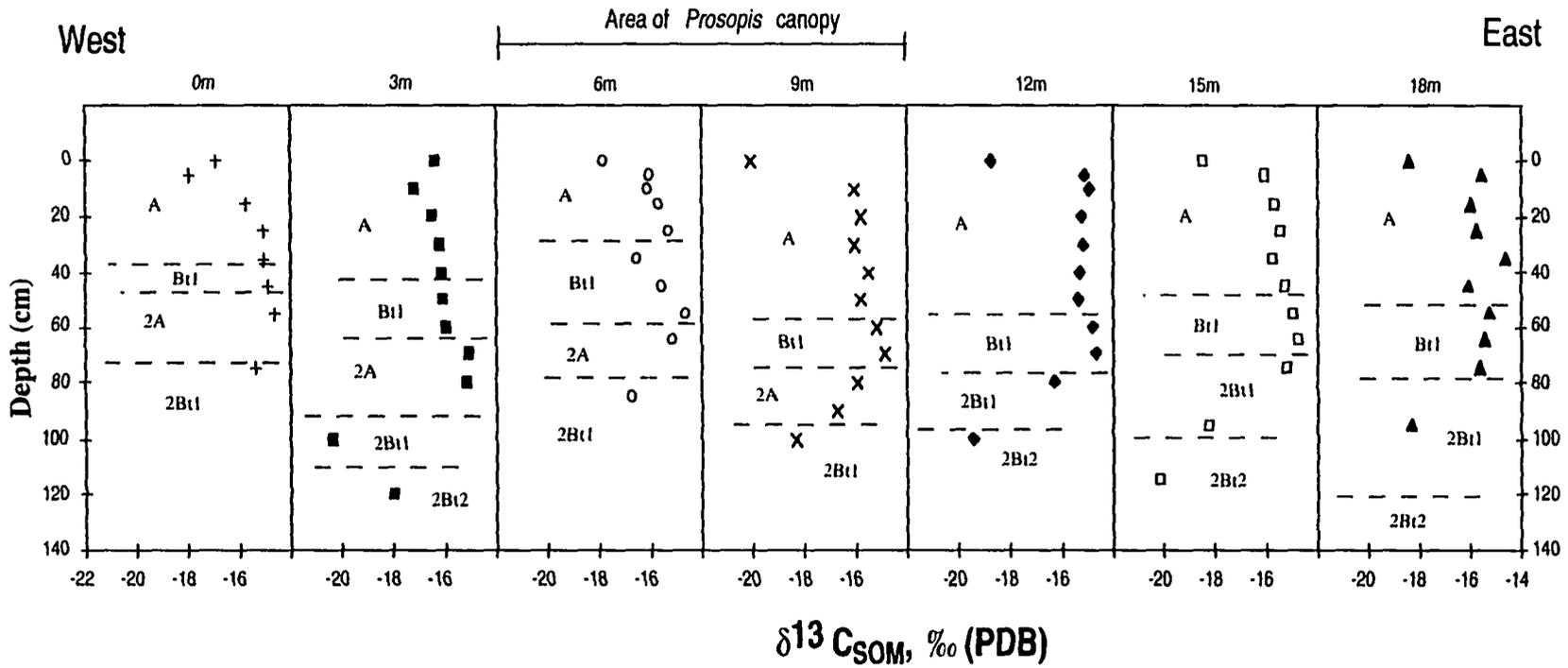


Figure 9C:

Site 3: Profile of $\delta^{13}\text{C}$ in trench on frequently burned plot

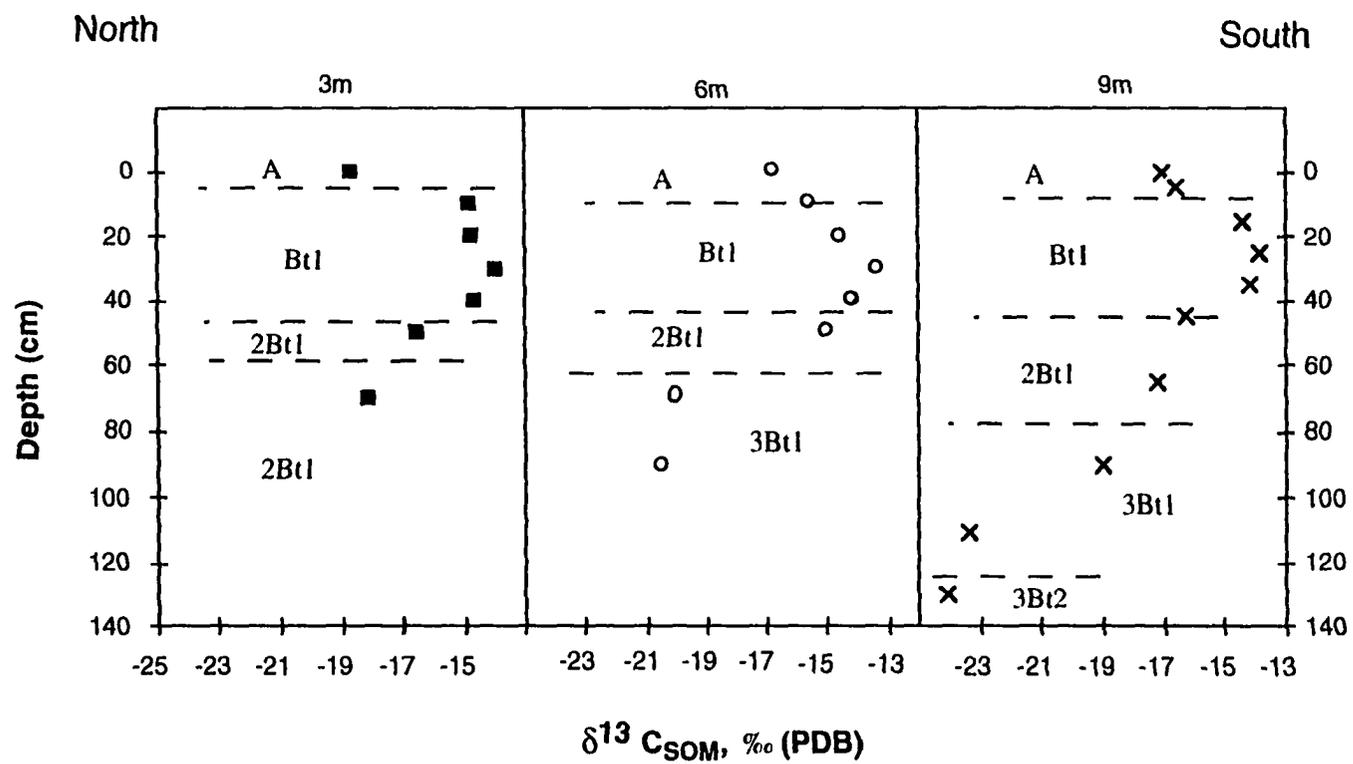
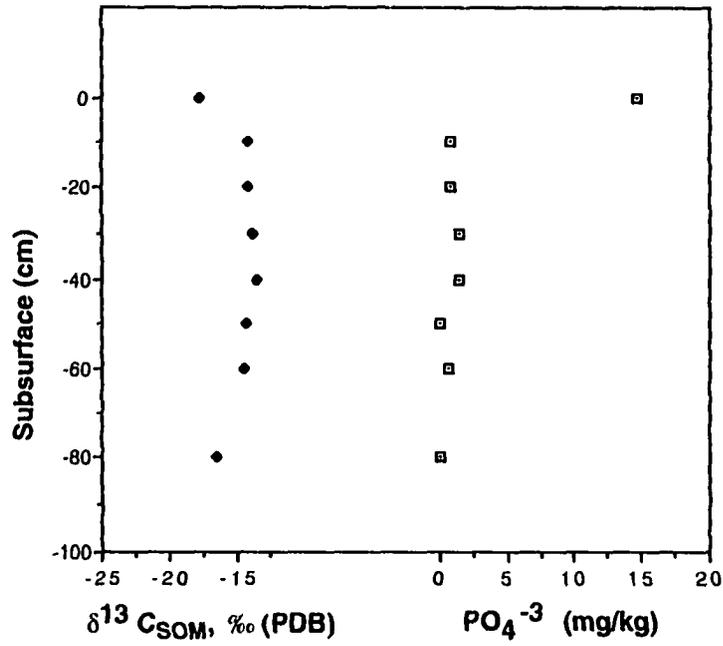


Figure B 10: Diagrams illustrating the relationships between $\delta^{13}\text{C}$ and plant-available phosphorus (PO_4^{3-}), total organic carbon (TOC), and plant-available nitrogen (NO_3^-) in soil profiles beneath (A) open grassland, and (B) *Prosopis* canopy on unburned Site 1.

Figure 10:

A

$\delta^{13}\text{C}$ Values and Plant-Available Phosphorus (PO_4^{-3}) Profiles in Trench 1 at 14 m (Open Site)



B

$\delta^{13}\text{C}$ Values and Plant-Available Phosphorus (PO_4^{-3}) Profiles in Trench 1 at 9 m (Canopy Site)

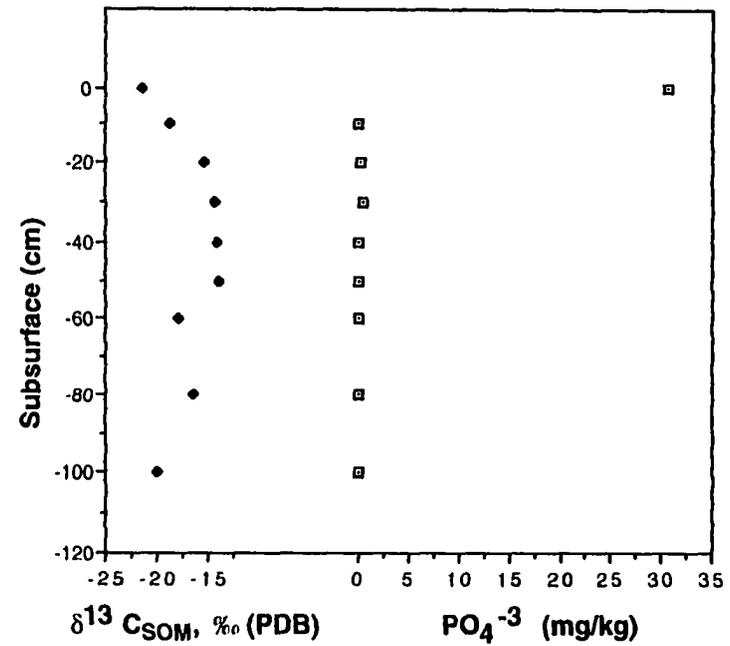
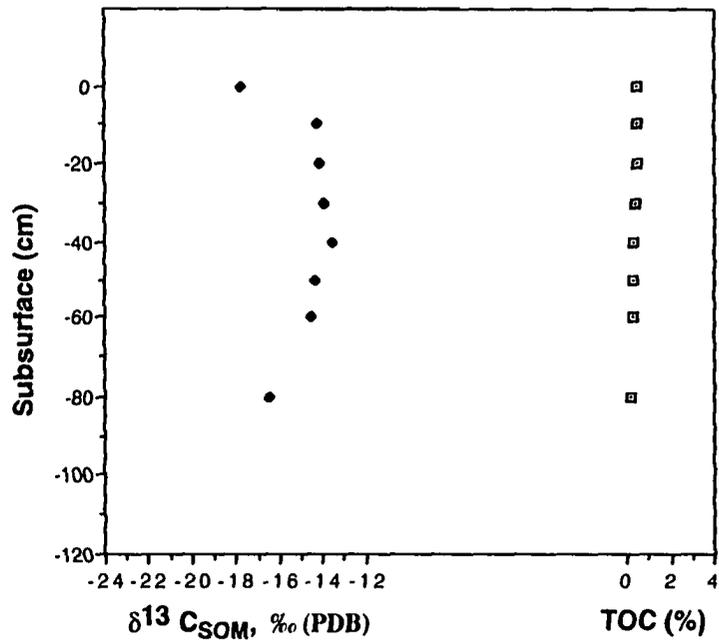


Figure 10, cont.:

A

$\delta^{13}\text{C}$ Values and Total Organic Carbon (TOC) Profiles in Trench 1 at 14 m (Open Site)



B

$\delta^{13}\text{C}$ Values and Total Organic Carbon (TOC) Profiles in Trench 1 at 9 m (Canopy Site)

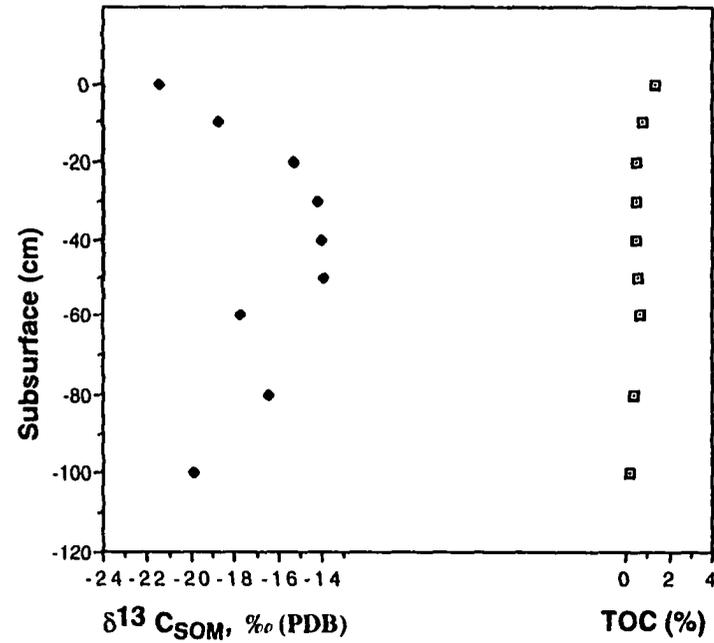
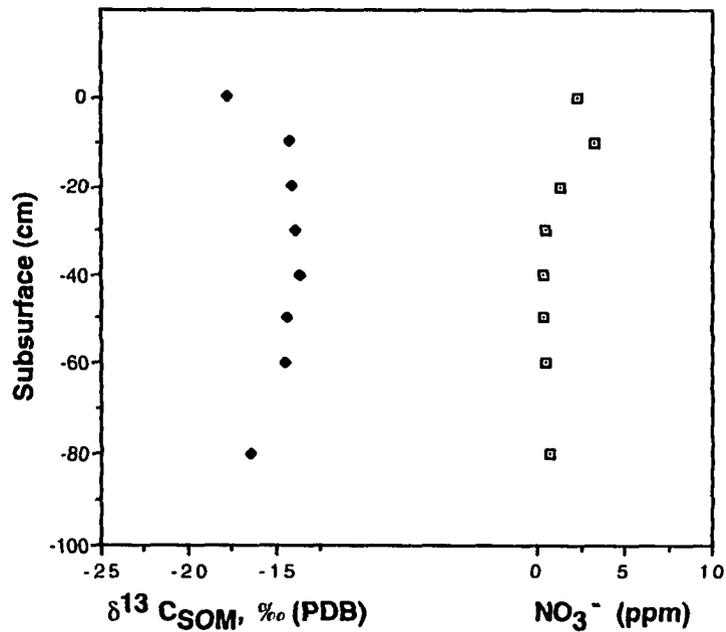


Figure 10, cont.

A

$\delta^{13}\text{C}$ Values and Plant-Available Nitrogen (NO_3^-) Profiles in Trench 1 at 14 m (Open Site)



B

$\delta^{13}\text{C}$ Values and Plant-Available Nitrogen (NO_3^-) Profiles in Trench 1 at 9 m (Canopy Site)

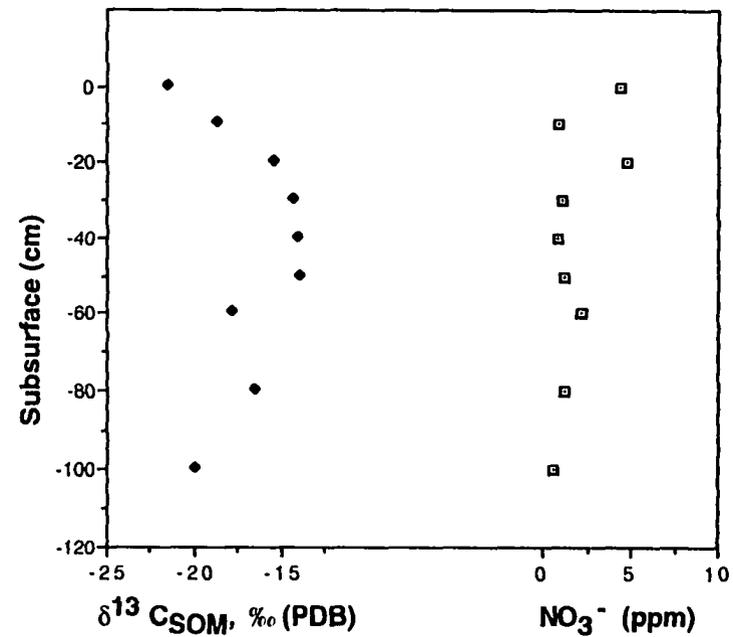
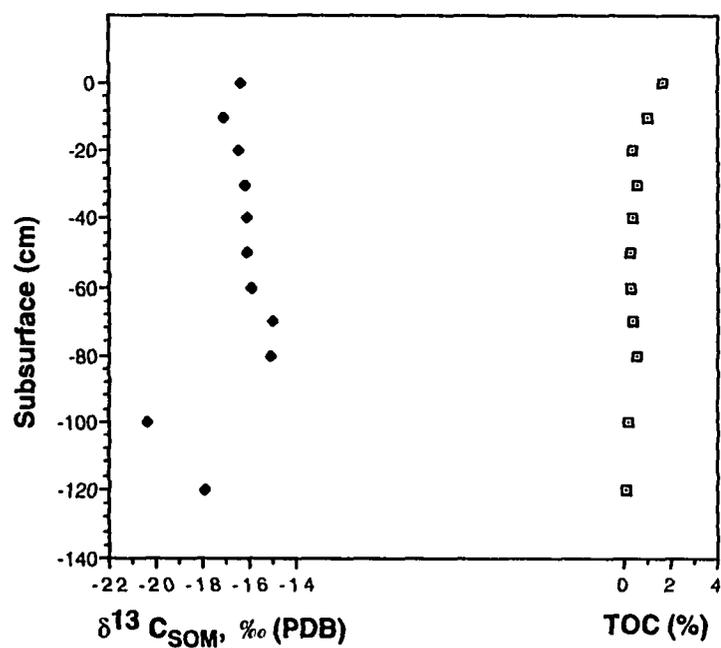


Figure B 11: Diagrams illustrating the relationships between $\delta^{13}\text{C}$ and plant-available phosphorus (PO_4^{3-}), total organic carbon (TOC), and plant-available nitrogen (NO_3^-) in soil profiles beneath (A) open grassland, and (B) *Prosopis* canopy on moderately burned Site 2.

Figure 11:

A

$\delta^{13}\text{C}$ Values and Total Organic Carbon (TOC) Profiles in Trench 2 at 3 m (Open Site)



B

$\delta^{13}\text{C}$ Values and Total Organic Carbon (TOC) Profiles in Trench 2 at 9 m (Canopy Site)

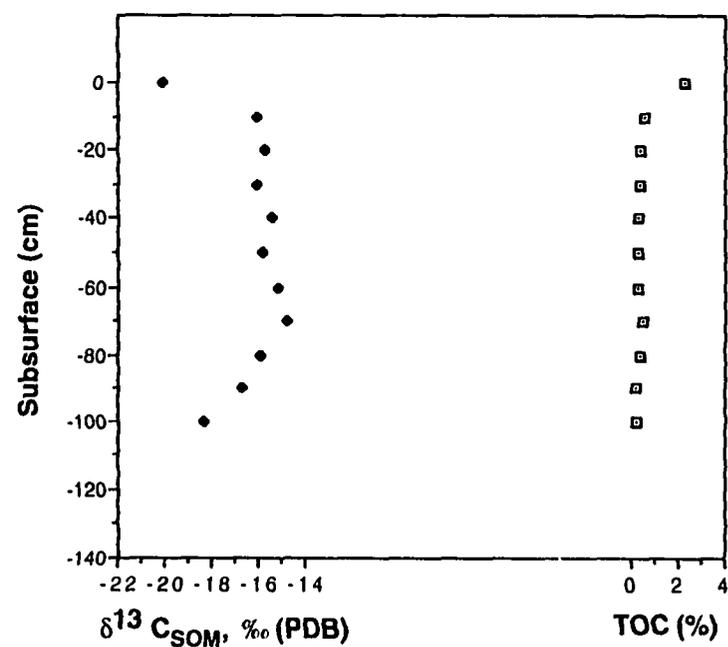


Figure 11, cont.:

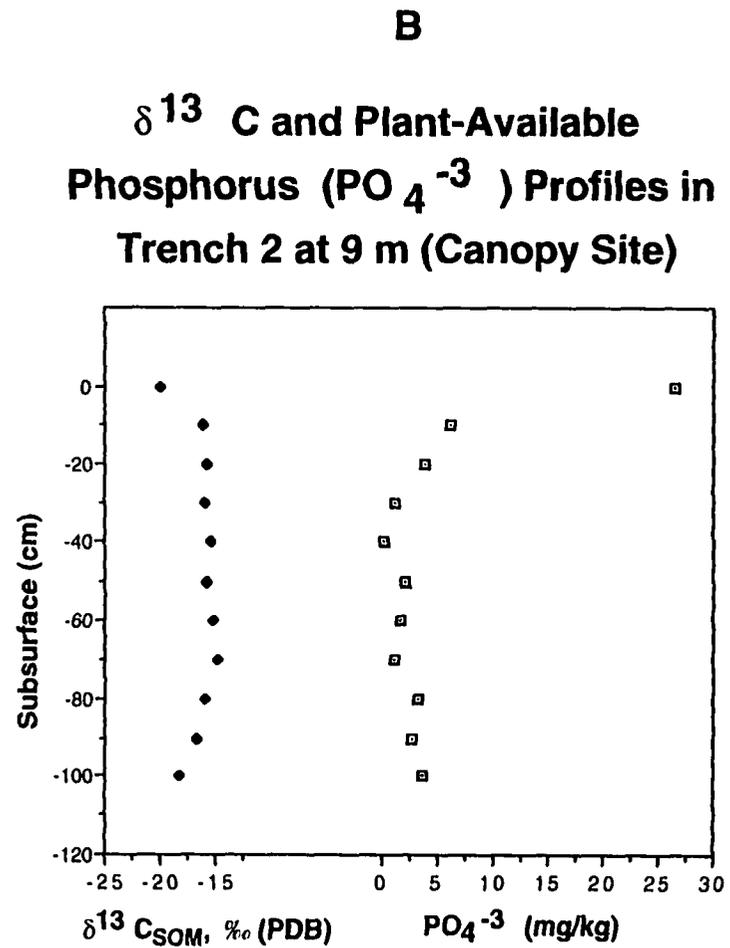
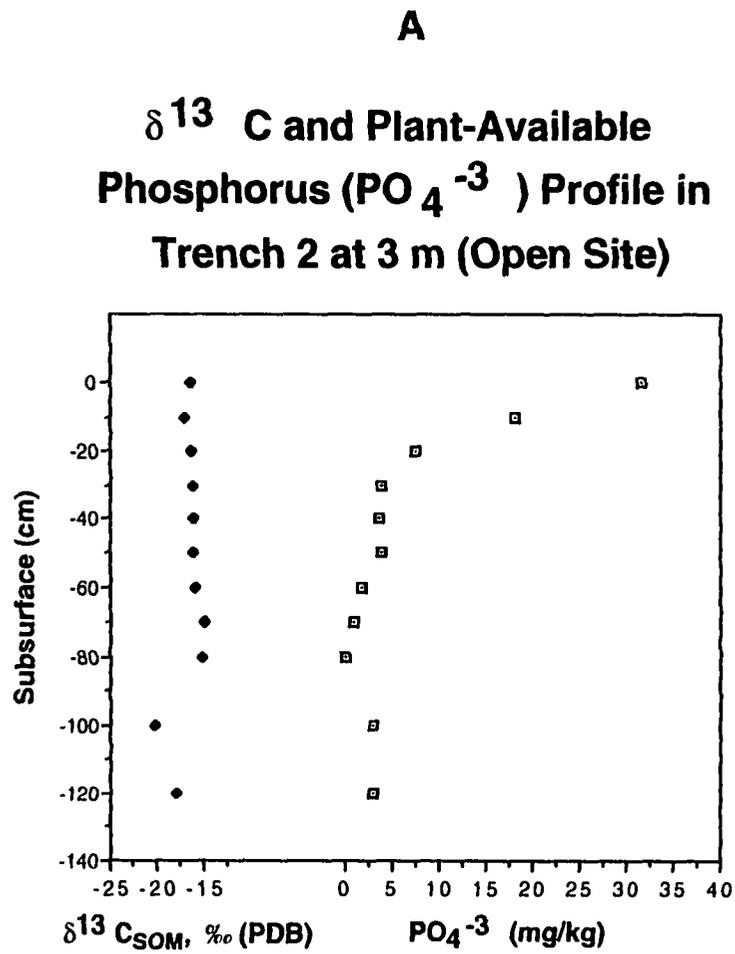
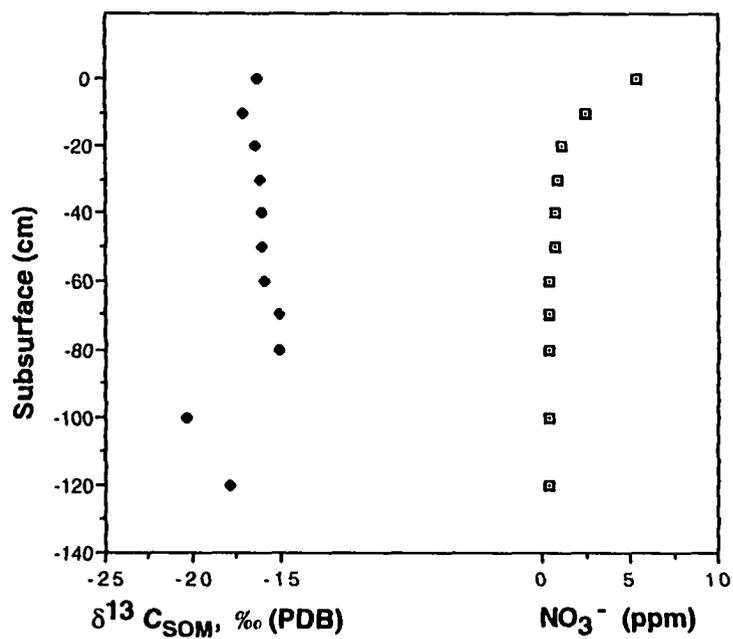


Figure 11, cont.:

A

$\delta^{13}\text{C}$ Values and Plant-Available Nitrogen (NO_3^-) Profiles in Trench 2 at 3 m (Open Site)



B

$\delta^{13}\text{C}$ Values and Plant-Available Nitrogen (NO_3^-) Profiles in Trench 2 at 9 m (Canopy Site)

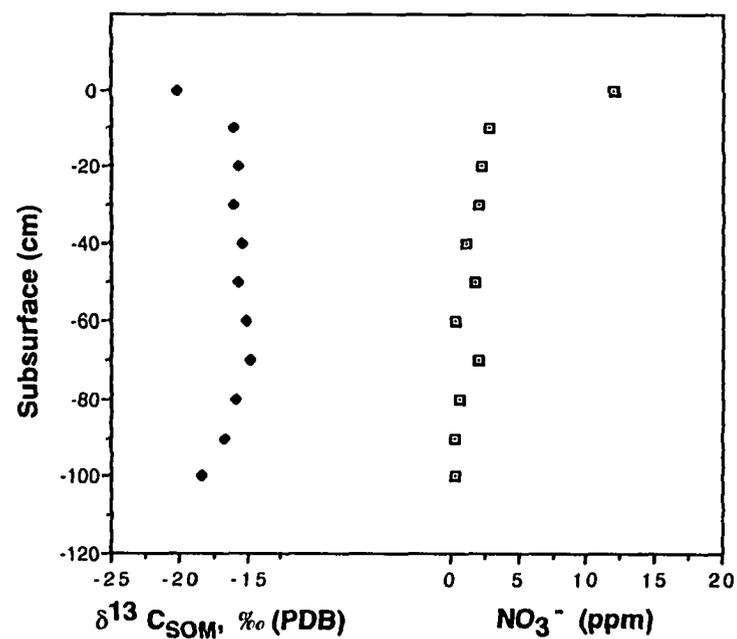


Figure B12: Diagrams illustrating the relationships between $\delta^{13}\text{C}$ and plant-available phosphorus (PO_4^{3-}), total organic carbon (TOC), and plant-available nitrogen (NO_3^-) in soil profiles beneath open grassland on frequently burned Site 3.

Figure 12: $\delta^{13}\text{C}$ Values and Nutrient Profiles in Trench 3 at 9 m.

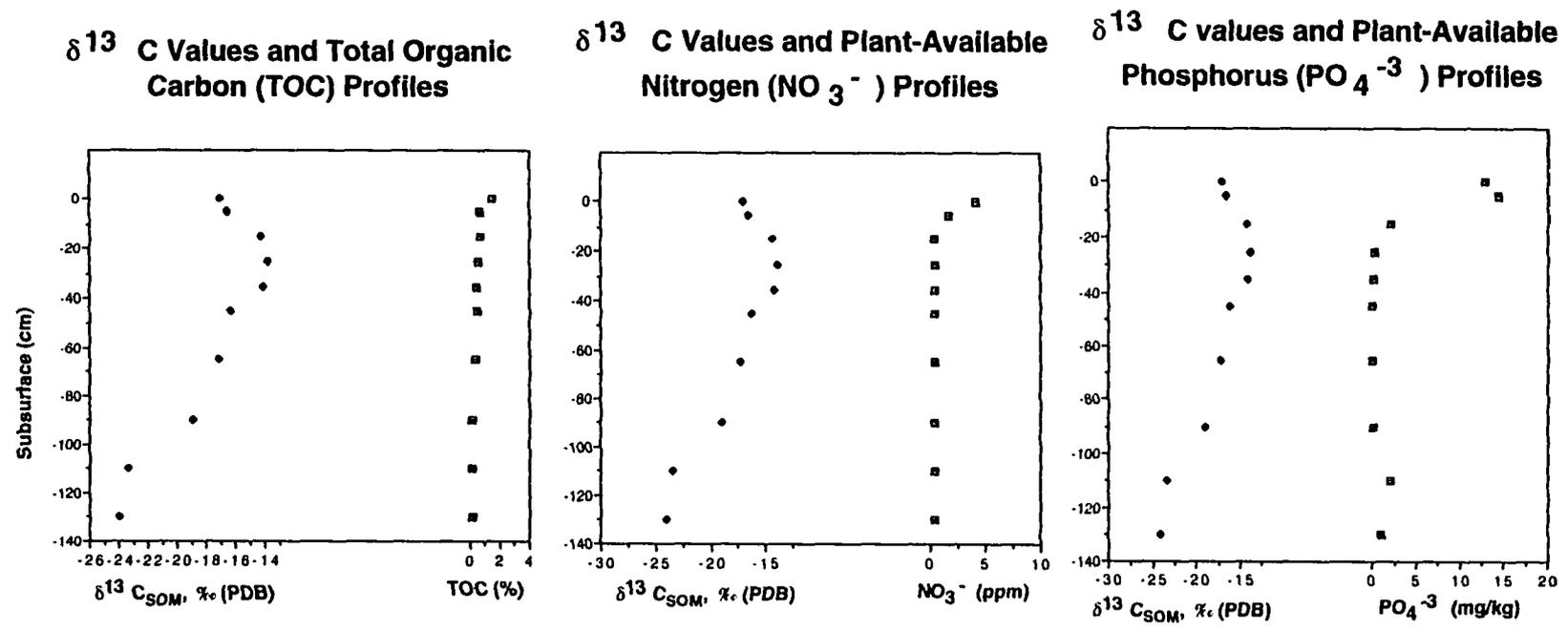


Table B1. Fire histories of the 3 study sites at Fort Huachuca, southeastern Arizona.

	SITE 1	SITE 2	SITE 3
	FIRE HISTORY		
Dates of fires after 1973	none	7/83, 5/84, 1/91	2/81, 7/83, 5/86, 2/88, 2/89
Fire frequency, 1981-1995 (number/decade)	0	3	5
Average interval (yrs) between fires, 1981-1995	∞	5	3

Table B2: Comparison of Spring 1995 soil organic matter $\delta^{13}\text{C}$ values with Spring 1996 soil organic matter $\delta^{13}\text{C}$ values.

Sample Point	Setting	Spring 1995	Spring 1996	Year-to-year Variation
<u>Site 1</u>				
1-30n-27e	open	-19.6	-20.5	-0.9
1-24n-6e	canopy	-20.9	-23.9	-3.0
1-18n-15e	canopy	-22.6	-23.4	-0.8
1-15n-18e	canopy	-21.4	-21.6	-0.2
1-15n-15e	canopy	-21.4	-23.1	-1.7
1-15n-6e	open/margin	-20.0	-20.5	-0.5
1-9n-24e	canopy/margin	-18.9	-18.4	0.5
1-3n-27e	open	-18.7	-18.0	0.7
1-3n-12e	open	-19.4	-18.8	0.6
1-3n-3e	canopy	-20.2	-19.8	0.4
AVERAGE		-20.3	-20.8	
average $\Delta \delta^{13}\text{C} = -0.5\text{‰}$ (n=10)				
average canopy $\Delta \delta^{13}\text{C} = -0.8\text{‰}$ (n=5)				
average open $\Delta \delta^{13}\text{C} = -0.1\text{‰}$ (n=5)				
<u>Site 2</u>				
2-30n-6e	open	-16.3	-17.3	-1.0
2-27n-21e	open	-18.7	-19.5	-0.8
2-21n-24e	open	-17.1	-18.4	-1.3
2-21n-6e	open	-16.3	-16.5	-0.2
2-15n-3e	open	-18.5	-18.3	-0.2
2-12n-0e	open	-17.0	-17.0	0.0
2-6n-24e	open	-17.7	-18.8	-1.1
2-6n-0e	open	-16.9	-18.8	-1.9
2-0n-30e	open	-17.8	-18.6	-0.8
2-0n-12e	open	-21.5	-21.3	0.2
AVERAGE		-17.8	-18.5	
average $\Delta \delta^{13}\text{C} = -0.7\text{‰}$ (n=10)				
<u>Site 3</u>				
3-30n-18e	open	-14.8	-16.4	-1.6
3-30n-0e	open	-15.8	-16.9	-1.1
3-27n-6e	open	-16.2	-16.8	-0.6
3-21n-18e	open	-16.7	-16.4	-0.3
3-15n-27e	open	-16.9	-18.3	-1.4
3-15n-24e	open	-18.4	-18.3	0.1
3-9n-24e	open	-21.0	-19.0	2.0
3-6n-0e	open	-15.9	-17.3	-1.4
3-3n-15e	open	-18.2	-17.6	0.6
3-0n-0e	open	-18.0	-17.3	0.7
AVERAGE		-17.2	-17.4	
average $\Delta \delta^{13}\text{C} = -0.2$ (n=10)				

TABLE B3: Comparison of $\delta^{13}\text{C}$ Values for SOM and Soil Respired CO_2

Sample Point	Distance from tree	SOM $\delta^{13}\text{C}$	$\delta^{13}\text{CO}_2$ Nov 1996	Difference *	$\delta^{13}\text{CO}_2$ June 1995	$\delta^{13}\text{CO}_2$ Sept 1995	$\delta^{13}\text{CO}_2$ Feb 1996
1-30n-27e	NA	-19.6	-20.3	-0.7			
1-27n-27e	NA	-17.9	-20.2	-2.4			
1-30n-6e	5.8m	-19.3	-21.5	-2.2			
1-27n-6e C	2.8m	-19.4	-21.2	-1.8			
1-24n-6e C	1.2m	-20.9	-22.4	-1.5			
1-3n-27e	7.4m	-18.7	-20.9	-2.2	-20.2	-21.0	-19.4
1-3n-24e	4.4m	-17.4	-21.4	-4.0	-19.6	-21.5	-20.9
1-3n-21e C	1.4m	-20.2	-23.2	-3.0	-20.7	-22.7	-22.8
1-3n-18e C	1.6m	-20.9	-22.6	-1.7	-20.3	-25.2	-22.5
1-3n-15e	4.6m	-18.1	-21.3	-3.3	-20.0	-19.6	-21.5
1-3n-12e	7.6m	-19.4	-21.7	-2.3	-21.1	-22.1	-22.5
AVERAGE		-19.3	-21.5	-2.3			
2-30n-3e	6.0m	-17.7	-19.2	-1.6			
2-27n-9e	NA	-17.4	-19.9	-2.5	-20.5	-20.4	-19.0
2-27n-3e	3.0m	-18.6	-19.1	-0.5			
2-24n-9e	6.0m	-17.8	-18.9	-1.1			
2-24n-6e	3.0m	-17.7	-19.1	-1.4			
2-24n-3e	0.0m	-19.8	-18.9	0.9			
2-15n-21e	NA	-17.6	-18.7	-1.1	-17.7	-16.0	-17.5
2-6n-9e C	NA	-18.1	-20.2	-2.1			
2-3n-30e	NA	-17.9	-19.4	-1.5	-19.5	-20.3	-18.3
2-3n-6e	NA	-17.5	-19.3	-1.8			
2-3n-3e	NA	-19.5	-19.8	-0.3			
AVERAGE		-18.1	-19.3	-1.2			
3-18n-3e	NA	-16.1	-18.4	-2.3			
3-18n-0e	NA	-17.7	-18.0	-0.4			
3-15n-27e	NA	-16.9	-18.6	-1.8	-20.1	-21.4	-18.4
3-15n-9e	NA	-17.1	-18.7	-1.6			
3-9n-30e	5.0m	-19.1	-20.3	-1.2			
3-9n-27e	2.0m	-20.4	-19.0	1.5			
3-9n-24e	0.5m	-21.0	-19.8	1.1			
3-9n-21e	3.5m	-19.3	-18.9	0.4			
3-9n-12e	NA	-15.8	-17.4	-1.6	-18.6	-19.4	-17.9
3-3n-15e	NA	-18.2	-19.0	-0.7			
3-3n-0e	NA	-16.8	-17.8	-1.1	-18.3	-19.4	-19.1
AVERAGE		-18.0	-18.7	-0.7			

C = sampling point beneath *Prosopis* canopy* = Difference between $\delta^{13}\text{C}_{\text{SOM}}$ and $\delta^{13}\text{C}_{\text{CO}_2}$

APPENDIX C**NUTRIENT AND $\delta^{13}\text{C}$ DATA FOR SURFACE AND SUBSURFACE SOIL
SAMPLES FROM THE THREE STUDY SITES AT FORT HUACHUCA,
SOUTHEASTERN ARIZONA**

APPENDIX C

SITE #1 TOTAL ORGANIC CARBON (%)

	0e	3e	6e	9e	12e	15e	18e	21e	24e	27e	30e
30n	0.71	0.53	0.77	1.12	0.76	0.67	0.97	0.6	0.87	0.87	0.98
27n	0.6	1.74	1.09	0.88	0.82	0.73	1.07	0.71	0.98	0.87	0.68
24n	1.32	2.57	1.75	0.81	1.2	1.03	1.07	1.06	0.83	1.01	0.76
21n	1.14	2.1	1.61	1.1	1.63	1.77	1.24	1.49	0.73	1.57	1.41
18n	1.06	1.97	1.02	1.39	1.22	1.25	1.03	1.39	0.81	0.79	0.96
15n	0.86	2.25	1.01	1.35	0.84	1.64	1.04	0.91	0.52	0.92	1
12n	0.83	0.44	0.94	0.94	0.88	0.9	0.77	0.74	1.04	0.63	0.7
9n	0.71	0.77	0.72	0.48	0.51	0.61	1.42	0.73	1.14	1.21	1.07
6n	1.03	1.09	0.72	0.61	1.5	0.7	0.95	0.74	0.72	0.83	0.85
3n	0.75	1.76	0.89	1.45	0.89	0.83	1.26	1.28	0.86	1.05	0.76
0n	0.79	0.74	0.85	1.03	0.73	0.57	0.66	0.91	0.74	0.87	0.83

SITE #2 TOTAL ORGANIC CARBON (%)

	0e	3e	6e	9e	12e	15e	18e	21e	24e	27e	30e
30n	1.38	1.37	1.59	1.24	1.19	1.34	0.99	1.21	0.71	1.03	2.49
27n	1.42	1.47	1.61	1.49	1.4	1.13	0.88	1.54	1.8	1.19	1.45
24n	0.98	3.18	1.22	1.2	1.68	1.11	0.94	0.87	1.13	1.31	1.16
21n	1.34	1.17	1.92	0.93	0.98	1.04	0.98	0.77	1.49	1.07	1.11
18n	1.42	1.11	0.63	0.97	0.77	0.84	0.74	0.6	0.86	0.69	0.76
15n	1.46	1.12	1.49	1.31	1.53	1.02	0.65	0.91	0.72	0.81	0.92
12n	2.06	1.18	1.27	1.06	0.85	0.57	0.72	1.05	0.83	0.79	0.64
9n	1.01	1.62	1.84	2.24	1	0.84	1.64	0.82	0.75	0.79	0.69
6n	1.55	1.63	1.69	2.43	1.54	1.14	0.93	1.23	0.77	0.69	0.86
3n	1.38	1.31	1.45	1.68	1.24	0.84	0.99	0.81	0.99	0.78	0.88
0n	2.07	1.61	0.96	1.52	1.55	0.79	0.95	0.95	0.5	0.82	0.74

SITE #3 TOTAL ORGANIC CARBON (%)

	0e	3e	6e	9e	12e	15e	18e	21e	24e	27e	30e
30n	0.65	0.86	0.68	0.91	0.9	0.69	0.75	0.76	0.67	0.76	0.67
27n	0.72	1.03	0.74	0.58	0.75	0.87	0.61	0.75	0.94	0.63	0.74
24n	0.82	0.86	0.87	0.67	0.59	0.74	0.69	0.76	0.8	0.98	1.28
21n	0.76	0.63	0.86	1.46	0.68	0.86	0.63	0.75	1.13	0.83	0.71
18n	0.84	1.21	0.8	1.97	0.71	0.78	0.55	0.93	0.68	0.82	0.66
15n	0.97	0.94	0.84	0.72	1.29	0.77	0.62	0.89	1.06	0.83	0.62
12n	0.96	0.75	0.73	0.96	1.08	0.66	0.5	1.05	1.02	0.69	0.76
9n	0.88	1.04	0.87	0.79	0.84	0.67	1.16	0.69	1.76	1.16	0.72
6n	0.92	1.12	0.78	0.72	1.23	0.67	0.73	0.75	0.83	0.68	1.15
3n	0.86	0.77	1.04	0.74	1.48	2.64	0.79	0.81	0.64	0.82	1.07
0n	0.72	1.07	0.81	0.75	0.66	1.03	1.38	0.8	0.85	0.81	0.65

SITE #1: PLANT-AVAILABLE PHOSPHORUS (mg/kg)

	0e	3e	6e	9e	12e	15e	18e	21e	24e	27e	30e
30n	5.86	7.66	6.54	6.60	10.22	10.90	9.02	15.64	13.78	30.69	18.80
27n	6.88	12.56	9.76	7.74	11.62	8.22	10.16	16.98	20.88	25.36	21.40
24n	4.66	11.74	25.70	24.48	9.98	14.52	6.28	12.90	16.86	29.98	18.44
21n	4.28	10.24	8.34	6.70	11.94	10.10	13.38	11.82	19.52	13.06	24.86
18n	7.16	30.30	8.74	5.66	8.28	38.62	36.99	7.88	12.20	19.76	22.30
15n	6.30	17.32	6.14	30.66	13.78	30.58	30.18	14.38	15.98	12.54	19.48
12n	10.08	12.90	12.66	13.36	8.08	19.23	11.16	15.22	19.80	44.65	13.68
9n	5.36	5.10	10.10	14.68	7.98	16.98	14.60	18.66	11.42	19.46	22.90
6n	6.48	20.28	10.22	11.48	11.84	16.22	6.54	15.52	22.88	21.02	27.20
3n	6.70	41.27	11.48	12.32	19.96	11.68	16.86	14.26	20.80	30.50	18.78
0n	6.66	16.04	19.60	12.76	22.10	11.22	16.16	23.36	16.16	21.70	15.40

SITE #2: PLANT-AVAILABLE PHOSPHORUS (mg/kg)

	0e	3e	6e	9e	12e	15e	18e	21e	24e	27e	30e
30n	23.30	17.48	53.44	26.48	27.01	25.36	37.14	26.95	29.14	21.84	14.40
27n	24.28	20.82	25.50	30.36	30.90	30.00	20.04	17.16	20.76	22.06	38.04
24n	17.52	41.84	31.70	27.10	28.60	14.12	16.40	27.66	28.36	24.28	28.02
21n	31.02	22.36	42.66	14.74	17.66	14.44	13.84	17.52	35.65	26.84	21.26
18n	31.62	29.90	14.82	20.06	14.40	17.44	19.86	19.00	15.24	27.20	14.14
15n	23.28	23.46	31.32	23.70	28.64	15.18	22.88	28.27	19.66	27.84	22.74
12n	42.97	24.91	29.98	24.68	14.92	29.04	18.06	21.58	20.18	29.96	27.34
9n	25.72	44.75	27.98	26.50	20.06	18.70	21.40	16.86	13.64	15.90	24.06
6n	39.98	31.60	28.58	32.46	30.36	28.70	22.50	32.46	10.42	18.52	27.34
3n	23.58	28.18	33.60	35.22	25.64	16.34	28.24	31.02	19.12	34.18	22.08
0n	30.48	26.02	24.24	27.46	15.42	18.16	18.94	22.74	17.98	19.82	31.47

SITE #3: PLANT-AVAILABLE PHOSPHORUS (mg/kg)

	0e	3e	6e	9e	12e	15e	18e	21e	24e	27e	30e
30n	6.06	12.24	9.80	8.46	8.22	4.12	4.60	6.88	7.86	7.10	5.80
27n	10.22	9.42	9.66	10.22	6.34	9.60	8.36	17.40	11.90	8.66	3.34
24n	13.28	7.44	14.04	6.64	7.30	6.60	13.96	8.86	9.42	15.04	12.00
21n	7.56	10.42	11.02	12.92	5.74	12.98	11.42	11.34	17.57	9.48	11.49
18n	11.10	10.16	6.66	18.60	12.10	8.22	18.86	6.92	8.06	11.72	9.10
15n	7.42	6.90	8.58	5.86	10.48	12.46	12.14	18.48	23.58	24.48	19.44
12n	9.02	10.58	8.12	9.60	9.42	17.58	12.04	13.34	13.94	21.22	9.16
9n	13.24	9.28	4.42	9.04	8.98	10.84	13.34	15.47	20.78	15.66	13.04
6n	8.16	9.16	8.16	10.10	9.20	12.08	12.86	14.61	14.72	15.53	13.30
3n	6.72	9.66	10.96	15.44	8.66	18.55	14.60	13.40	5.20	7.36	9.72
0n	10.44	13.46	13.96	9.42	14.00	14.46	11.54	9.60	16.80	11.18	7.24

SITE #1: SOLUBLE NITRATE (NO₃⁻), ppm

	0e	3e	6e	9e	12e	15e	18e	21e	24e	27e	30e
30n	1.92	4.01	1.52	1.45	2.41	<0.3	4.25	1.61	1.00	1.21	1.04
27n	0.56	1.95	7.41	1.31	1.75	<0.3	2.65	0.86	1.70	3.75	0.49
24n	<0.3	3.40	26.30	1.34	2.07	2.77	3.78	4.47	0.83	<0.3	1.44
21n	4.61	4.62	4.74	<0.3	1.71	9.95	30.20	3.44	<0.3	<0.3	<0.3
18n	2.80	20.00	1.76	2.16	3.53	156,000	126.0	2.97	<0.3	2.64	2.34
15n	<0.3	14.10	1.85	4.38	2.06	3.24	4.40	1.94	<0.3	0.86	<0.3
12n	4.98	3.87	7.61	3.00	2.78	4.57	2.35	4.27	13.70	161.0	1.71
9n	1.79	2.72	3.21	2.26	3.03	2.21	4.39	3.47	9.73	18.70	1.90
6n	12.00	3.67	3.01	<0.3	2.10	1.01	2.60	8.05	3.82	4.50	2.79
3n	2.26	5.20	2.48	6.60	2.77	1.98	12.9	4.21	3.02	3.23	<0.3
0n	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3	3.80	<0.3	2.60

SITE #2: SOLUBLE NITRATE (NO₃⁻), ppm

	0e	3e	6e	9e	12e	15e	18e	21e	24e	27e	30e
30n	1.64	5.74	<0.3	2.73	<0.3	<0.3	1.95	2.17	2.09	<0.3	2.74
27n	2.13	2.82	2.61	6.86	2.57	5.41	6.22	8.26	10.80	4.22	2.72
24n	3.18	4.75	<0.3	4.62	2.66	2.21	0.518	2.10	3.47	2.82	1.26
21n	6.04	7.62	4.87	1.90	<0.3	3.51	3.11	2.20	19.10	3.73	1.72
18n	1.56	3.43	<0.3	3.54	2.37	2.05	1.46	1.50	2.25	3.89	1.47
15n	1.07	2.21	3.50	3.30	10.40	1.49	4.47	3.30	3.48	5.79	1.29
12n	1.93	3.71	1.52	21.20	1.49	2.26	1.35	3.89	1.56	2.44	1.35
9n	0.92	3.24	7.23	12.00	4.34	3.54	7.10	2.58	3.18	2.59	1.28
6n	9.56	5.34	10.40	18.8	10.10	4.68	2.32	3.31	1.09	1.86	1.30
3n	1.45	7.21	4.24	5.65	5.24	3.70	3.62	3.77	4.23	2.64	0.81
0n	4.15	0.68	<0.3	16.8	0.50	<0.3	<0.3	1.86	<0.3	0.37	0.31

SITE #3: SOLUBLE NITRATE (NO₃⁻), ppm

	0e	3e	6e	9e	12e	15e	18e	21e	24e	27e	30e
30n	<0.3	2.55	1.73	1.54	1.32	<0.3	1.45	1.48	1.12	2.23	<0.3
27n	2.18	1.82	3.17	2.05	2.31	1.46	1.56	2.05	1.51	3.89	1.93
24n	2.23	1.81	2.72	1.93	1.71	2.18	1.46	1.70	2.37	3.23	3.54
21n	1.11	1.39	1.46	4.14	<0.3	2.65	<0.3	1.63	4.56	1.18	1.44
18n	0.58	0.69	0.974	5.70	<0.3	1.49	1.21	2.40	<0.3	1.61	<0.3
15n	<0.3	<0.3	<0.3	2.85	4.35	2.00	1.46	<0.3	2.29	2.40	2.61
12n	3.23	3.57	2.70	<0.3	1.76	<0.3	<0.3	3.35	2.35	1.27	<0.3
9n	2.54	2.71	3.47	1.49	1.62	1.31	1.96	2.56	12.30	3.68	1.05
6n	2.61	2.72	2.38	2.02	4.12	1.92	0.92	1.67	<0.3	2.79	2.14
3n	2.16	2.26	1.78	<0.3	2.58	3.01	1.00	1.36	2.19	2.68	1.93
0n	<0.3	2.96	1.42	1.03	5.89	1.17	8.99	2.09	4.17	1.70	<0.3

SITE 1: SOIL ORGANIC MATTER $\delta^{13}\text{C}$ VALUES (‰)

	0e	3e	6e	9e	12e	15e	18e	21e	24e	27e	30e
30n	-18.1	-19.4	-19.3	-18	-18.3	-18	-19.1	-18.2	-18.6	-19.6	-20.4
27n	-18.7	-21.9	-19.4	-17.3	-18.2	-19.3	-20	-19.3	-19.2	-17.9	-18.6
24n	-19.1	-21.8	-20.9	-19.1	-18	-20.6	-21.2	-20.7	-17.6	-18.4	-20.5
21n	-21.8	-22.7	-21.5	-17.7	-20.2	-22.1	-23.6	-21.5	-18.4	-21.8	-18.4
18n	-21	-22.6	-19.3	-20.4	-21.6	-22.6	-21.5	-18.7	-18.1	-20.2	-20.5
15n	-18	-23.6	-20	-21.5	-19.8	-21.4	-21.4	-18.3	-18.4	-20.4	-19.9
12n	-18.6	-19.5	-19.5	-20.5	-19.1	-18.7	-17.9	-17.9	-20.8	-23.1	-18.1
9n	-17.5	-17	-19.2	-17.7	-16.5	-18.4	-18.8	-20.1	-18.9	-19.8	-17.3
6n	-17.2	-19.9	-18.1	-17.6	-18.6	-17.4	-18.5	-21	-17.8	-18.2	-19.2
3n	-17.7	-20.2	-19.5	-18.6	-19.4	-18.1	-20.9	-20.2	-17.4	-18.7	-18.7
0n	-17.5	-18.6	-20.5	-20.0	-20.1	-18.5	-20.4	-19.4	-18.1	-20	-18

SITE 2: SOIL ORGANIC MATTER $\delta^{13}\text{C}$ VALUES (‰)

	0e	3e	6e	9e	12e	15e	18e	21e	24e	27e	30e
30n	-16.9	-17.7	-16.3	-16.3	-16.5	-17	-18.8	-17.6	-17	-19.2	-18.5
27n	-18.2	-18.6	-18.5	-17.4	-17.7	-19.6	-19.1	-18.7	-20	-17.4	-16.7
24n	-18.4	-19.8	-17.7	-17.8	-17.8	-19.3	-17.7	-17.2	-18.6	-18.6	-16
21n	-15.7	-16.9	-16.3	-17.9	-18.9	-18.8	-18.9	-17.3	-17.1	-18.2	-18
18n	-16.6	-15.8	-16.1	-18.3	-18.1	-18.3	-17.4	-17.8	-18.2	-18.1	-17.9
15n	-17.7	-18.5	-18	-18.3	-20.3	-19.6	-19.6	-17.6	-17.9	-17.8	-16.5
12n	-17	ns	-17.4	-18.8	-17.3	-16.9	-17.2	-18	-17.9	-17.4	-16
9n	-16.6	-18.2	-17.8	-20.1	-18.8	-18.4	-19.1	-19.1	-18.7	-16.9	-16.2
6n	-16.9	-16.4	-19	-18.1	-20.5	-18.4	-17.2	-18.7	-17.7	-17.8	-16.5
3n	-17.5	-19.5	-17.5	-18	-19.1	-17.8	-18.9	-18.3	-18.7	-19.7	-17.9
0n	-18.2	-18.3	-15.8	-18.1	-21.5	-16.6	-18.2	-18.2	-17.2	-19.3	-17.8

SITE 3: SOIL ORGANIC MATTER $\delta^{13}\text{C}$ VALUES (‰)

	0e	3e	6e	9e	12e	15e	18e	21e	24e	27e	30e
30n	-15.8	-16.6	-16.2	-16.8	-16	-15.5	-14.8	-15.8	-14.8	-15.3	-16
27n	-16.3	-17.1	-16.2	-18.7	-17.9	-16.4	-16.3	-17.4	-17.6	-18	-16.2
24n	-17	-15.5	-17.1	-16.8	-16.7	-16.3	-16.8	-15.8	-16.7	-17.7	-19.4
21n	-18.5	-18	-15.3	-17	-15.8	-17.4	-16.7	-17.3	-19.9	-17.8	-15.5
18n	-17.7	-16.1	-17.6	-17.8	-17	-17.2	-16.7	-17.1	-18.3	-18.2	-15.8
15n	-15.8	-16.1	-15.4	-17.1	-17.6	-16	-17.6	-15	-18.4	-16.9	-16.5
12n	-15.4	-17.5	-17	-17.7	-16.8	-16.4	-16.2	-19.5	-20.2	-18.8	-15.8
9n	-17.7	-18.3	-16.3	-17.3	-15.8	-17.8	-17	-19.3	-21	-20.4	-19.1
6n	-15.9	-17.7	-16.6	-18.2	-17.4	-17.4	-18.6	-17.4	-15.5	-18.5	-18.5
3n	-16.8	-15.7	-16	-17.1	-18.7	-18.2	-18.1	-16.3	-18.1	-17.6	-18.3
0n	-18	-17.3	-17.4	-16.5	-18.8	-18.1	-18	-17.9	-16.8	-19.2	-15.1

TRENCH ON SITE 1

Horizontal location: 14 meters from North end of trench

Depth from surface	Sample datum	PO ₄ ⁻³	NO ₃ ⁻	TOC	δ ¹³ C
surface	(1-9n-9e closest sample)	14.68	2.26	0.48	-17.746
10 cm	50-55 cm	0.74	3.28	0.48	-14.201
20 cm	40-45 cm	0.8	1.28	0.45	-14.135
30 cm	30-35 cm	1.38	0.44	0.42	-13.904
40 cm	20-25 cm	1.38	<0.3	0.29	-13.571
50 cm	10-15 cm	0	<0.3	0.28	-14.299
(Holocene/Pleistocene contact at + 6 cm)					
60 cm	0- +5 cm	0.64	0.46	0.29	-14.482
	0- (-)5 cm				
	(-)10-15 cm				
80 cm	(-)20-25 cm	0	0.71	0.21	-16.485
	(-)30-35 cm				

Horizontal location: 12 meters from North end of trench

Depth from surface	Sample datum	PO ₄ ⁻³	NO ₃ ⁻	TOC	δ ¹³ C
surface	(1-9n-9e closest sample)	13.36	3	0.94	-20.54
2 cm	60-65 cm	5.34	4.55	0.66	-16.864
5 cm	50-55 cm	1.9	2.15	0.57	-15.282
15 cm	40-45 cm	1.64	1.56	0.44	-15.015
25 cm	30-35 cm	0.7	0.58	0.4	-14.617
35 cm	20-25 cm	1.24	0.46	0.36	-14.831
45 cm	10-15 cm	0.5	0.45	0.32	-14.88
(Holocene/Pleistocene contact at 6 cm)					
55 cm	0- +5 cm	0.1	0.88	0.47	-14.799
	0- (-)5 cm				
	(-)10-15 cm				
70 cm	(-)20-25 cm	0.04	0.44	0.3	-15.775
	(-)30-35 cm				
90 cm	(-)40-45 cm	1.24	0.49	0.18	-19.133
	(-)50-55 cm				

TRENCH ON SITE 1, continued

Horizontal location: 9 meters from North end of trench

Depth from surface	Sample datum	PO ₄ ⁻³	NO ₃ ⁻	TOC	δ ¹³ C
surface	(1-15n-9e closest sample)	30.66	4.38	1.35	-21.45
10 cm	40-45 cm	0	0.85	0.81	-18.688
20 cm	30-35 cm	0.08	4.78	0.47	-15.314
30 cm	20-25 cm	0.34	1.06	0.45	-14.205
40 cm	10-15 cm	0	0.83	0.51	-14.046
50 cm	0- +5 cm (-) 5-0 cm	0	1.18	0.58	-13.909
(Holocene/Pleistocene contact at - 8 cm)					
60 cm	(-)10-15 cm (-)20-25 cm	0	2.14	0.63	-17.764
80 cm	(-)30-35 cm (-)40-45 cm	0	1.14	0.38	-16.451
100 cm	(-)50-55 cm (-)60-65 cm	0	0.63	0.15	-19.875

Horizontal location: 6 meters from North end of trench

Depth from surface	Sample datum	PO ₄ ⁻³	NO ₃ ⁻	TOC	δ ¹³ C
surface	(1-18n-9e closest sample)	5.66	2.16	1.39	-20.45
2 cm	40-45 cm	6.28	2.09	0.71	-18.414
5 cm	30-35 cm	3.92	2.07	0.64	-16.834
15 cm	20-25 cm	1.78	1.27	0.49	-14.995
25 cm	10-15 cm 0- +5 cm	1.86	1.22	0.48	-14.442
35 cm	0- (-)5 cm	1.44	1.2	0.43	-14.584
45 cm	(-)10-15 cm	1.61	1.49	0.42	-14.178
(Holocene/Pleistocene contact at - 18 cm)					
55 cm	(-)20-25 cm (-)30-35 cm	0.64	1.34	0.47	-14.762
75 cm	(-)40-45 cm (-)50-55 cm	0.52	1.07	0.18	-16.223
95 cm	(-)60-65 cm	0.18	1	0.17	-18.164

TRENCH ON SITE 1, continued

Horizontal location: 3 meters from North end of trench

Depth from surface	Sample datum	PO ₄ ⁻³	NO ₃ ⁻	TOC	δ ¹³ C
surface	(1-21n-9e closest sample)	6.7	<0.3	1.1	-17.74
10 cm	20-25 cm	4.16	5.27	0.76	-15.436
20 cm	10-15 cm	0	2.71	0.6	-14.346
30 cm	0- +5 cm	0	1.81	0.47	-14.229
	0- (-)5 cm				
40 cm	(-)10-15 cm	0.46	0.97	0.45	-14.232
50 cm	(-)20-25 cm	0.22	0.78	0.45	-14.603
	(Holocene/Pleistocene contact at - 32 cm)				
	(-)30-35 cm				
70 cm	(-)40-45 cm	0	0.87	0.39	-14.009
	(-)50-55 cm				
90 cm	(-)60-65 cm	0	0.78	0.2	-15.508
	(-)70-75 cm				
110 cm	(-)80-85 cm	0	0.7	0.19	-16.737
	(-)90-95 cm				

Horizontal location: North end of trench

Depth from surface	Sample datum	PO ₄ ⁻³	NO ₃ ⁻	TOC	δ ¹³ C
surface	(no close sample)				
5 cm	10-15 cm	4.02	3.92	0.71	-17.362
15 cm	0- +5 cm	1.12	3.69	0.53	-13.897
	0- (-)5 cm				
25 cm	(-)10-15 cm	0	2.22	0.48	-14.899
35 cm	(-)20-25 cm	0.28	1.62	0.3	-14.175
45 cm	(-)30-35 cm	0	1.23	0.45	-16.333
	(Holocene/Pleistocene contact at -38 cm)				
55 cm	(-)40-45 cm	0	1.87	0.52	-15.145
	(-)50-55 cm				
75 cm	(-)60-65 cm	0	1.27	0.31	-16.461
	(-)70-75 cm				
95 cm	(-)80-85 cm	0	0.74	0.18	-17.384

TRENCH ON SITE 2

Horizontal location: West end of trench

Depth from surface	Sample datum	PO ₄ ⁻³	NO ₃ ⁻	TOC	δ ¹³ C
surface	(2-6n-0e) closest sample)	39.98	9.56	1.55	-16.93
5 cm	60-65 cm	60.8	2.38	1.45	-17.953
15 cm	50-55 cm	10.08	1.46	0.58	-15.745
25 cm	40-45 cm	9.36	0.98	0.45	-15.043
35 cm	30-35 cm	6.19	0.84	0.3	-15.044
40 cm	20-25 cm	3.06	0.6	0.28	
45 cm	10-15 cm	6.94	0.83	0.38	-14.834
(Holocene/Pleistocene contact)					
55 cm	0-(+)5 cm				
	0-(-)5 cm	8.74	0.63	0.18	-14.607
	(-)10-15 cm				
75 cm	(-)20-25 cm	6.4	<0.3	0.15	-15.325
	(-)30-35 cm				

Horizontal location: 3 meters east of west end of trench.

Depth from surface	Sample datum	PO ₄ ⁻³	NO ₃ ⁻	TOC	δ ¹³ C
surface	(2-6n-3e) closest sample	31.6	5.34	1.63	-16.37
10 cm	60-65 cm	18.14	2.41	1.02	-17.13
20 cm	50-55 cm	7.44	1.12	0.38	-16.467
30 cm	40-45 cm	3.96	0.8	0.51	-16.145
40 cm	30-35 cm	3.64	0.68	0.32	-16.067
50 cm	20-25 cm	3.82	0.69	0.26	-16.061
60 cm	10-15 cm	1.9	<0.3	0.29	-15.911
70 cm	0-(+)5 cm	0.92	<0.3	0.38	-15.04
(Holocene/Pleistocene contact at + 2 cm)					
	0-(-)5 cm				
80 cm	(-)10-15 cm	0.02	<0.3	0.5	-15.131
	(-)20-25 cm				
100 cm	(-)30-35 cm	3.06	<0.3	0.14	-20.319
	(-)40-45 cm				
120 cm	(-)50-55 cm	3.06	<0.3	0.11	-17.944
	(-)55-60 cm				

TRENCH ON SITE 2, continued

Horizontal location: 6 meters east of west end of trench.

Depth from surface	Sample datum	PO ₄ ⁻³	NO ₃ ⁻	TOC	δ ¹³ C
surface	(2-9n-6e closest sample)	27.98	7.23	1.84	-17.82
5 cm	60-65 cm	14.58	4.63	0.9	-16.062
10 cm	50-55 cm	8.78	5.87	0.58	-16.071
15 cm	40-45 cm	6.86	4.23	0.53	-15.68
25 cm	30-35 cm	5.44	2.35	0.29	-15.27
35 cm	20-25 cm	5.12	1.83	0.19	-16.533
45 cm	10-15 cm	3.7	0.98	0.22	-15.555
55 cm	0-(+)5 cm	0.1	2	0.36	-14.597
(Holocene/Pleistocene contact at - 4 cm)					
	0-(-)5 cm				
65 cm	(-)10-15 cm	2.02	2.4	0.42	-15.115
	(-)20-25 cm				
85 cm	(-)30-35 cm	4.8	2.21	0.16	-16.747
	(-)40-45 cm				

Horizontal location: 9 meters east of west end of trench.

Depth from surface	Sample datum	PO ₄ ⁻³	NO ₃ ⁻	TOC	δ ¹³ C
surface	(2-9n-9e closest sample)	26.5	12	2.24	-20.09
10 cm	50-55 cm	6.22	2.92	0.55	-16.059
20 cm	40-45 cm	3.86	2.25	0.34	-15.77
30 cm	30-35 cm	1.18	2.1	0.32	-16.055
40 cm	20-25 cm	0.28	1.17	0.27	-15.453
50 cm	10-15 cm	2.02	1.71	0.26	-15.787
60 cm	0-(+)5 cm	1.64	<0.3	0.29	-15.154
	0-(-)5 cm				
70 cm	(-)10-15 cm	1.18	2.1	0.41	-14.837
(Holocene/Pleistocene contact at - 23 cm)					
80 cm	(-)20-25 cm	3.32	0.61	0.38	-15.926
90 cm	(-)30-35 cm	2.66	<0.3	0.22	-16.719
100 cm	(-)40-45 cm	3.7	<0.3	0.17	-18.334
	(-)50-55 cm				

TRENCH ON SITE 2, continued

Horizontal location: 12 meters east of west end of trench.

Depth from surface	Sample datum	PO ₄ ⁻³	NO ₃ ⁻	TOC	δ ¹³ C
surface	(2-9n-12e closest sample)	20.06	4.34	1	-18.79
5 cm	50-55 cm	16.18	1.48	0.35	-15.132
10 cm	40-45 cm	5.8	1.31	0.35	-14.911
20 cm	30-35 cm	7.28	2.7	0.27	-15.252
30 cm	20-25 cm	6.61	1.27	0.27	-15.177
40 cm	10-15 cm	5.66	1.43	0.27	-15.259
50 cm	0-(+)5 cm 0-(-)5 cm	5.2	1.03	0.25	-15.34
60 cm	(-)10-15 cm	6.8	2.73	0.27	-14.789
70 cm	(-)20-25 cm	9.16	2.52	0.34	-14.666
	(Holocene/Pleistocene contact at - 27 cm)				
80 cm	(-)30-35 cm (-)40-45 cm	11.7	1.19	0.36	-16.308
100 cm	(-)50-55 cm (-)55-60 cm	13.7	1.92	0.45	-19.43

Horizontal location: 15 meters east of west end of trench.

Depth from surface	Sample datum	PO ₄ ⁻³	NO ₃ ⁻	TOC	δ ¹³ C
surface	(2-12n-15e closest sample)	29.04	2.26	0.57	-18.45
5 cm	40-45 cm	10.92	2.66	0.16	-16.041
15 cm	30-35 cm	3.12	1.1	0.33	-15.66
25 cm	20-25 cm	1.76	0.95	0.28	-15.402
35 cm	10-15 cm	1.9	0.79	0.26	-15.749
45 cm	0-(+)5 cm 0-(-)5 cm	3.06	<0.3	0.29	-15.227
55 cm	(-)10-15 cm	3	<0.3	0.33	-14.896
65 cm	(-)20-25 cm	4.92	<0.3	0.33	-14.737
	(Holocene/Pleistocene contact at - 29 cm)				
75 cm	(-)30-35 cm (-)40-45 cm	4.02	<0.3	0.34	-15.176
95 cm	(-)50-55 cm (-)55-60 cm	7.88	<0.3	0.23	-18.189
115 cm	(-)70-75 cm	4.74	<0.3	0.16	-20.116

TRENCH ON SITE 2, continued

Horizontal location: East end of trench.

Depth from surface	Sample datum	PO ₄ ⁻³	NO ₃ ⁻	TOC	δ ¹³ C
surface	(2-9n-15e closest sample)	29.04	2.26	0.57	-18.45
5 cm	40-45 cm	1.96	0.77	0.38	-15.569
15 cm	30-35 cm	1	0.67	0.32	-16.033
25 cm	20-25 cm	1.12	<0.3	0.39	-15.768
35 cm	10-15 cm	2.22	<0.3	0.38	-14.639
45 cm	0-(+)5 cm	2.48	<0.3	0.3	-16.063
	0-(-)5 cm				
55 cm	(-)10-15 cm	3.06	<0.3	0.31	-15.241
65 cm	(-)20-25 cm	3.38	<0.3	0.29	-15.463
	(Holocene/Pleistocene contact at - 33 cm)				
75 cm	(-)30-35 cm	5.7	<0.3	0.28	-15.633
	(-)40-45 cm				
95 cm	(-)50-55 cm	9.12	<0.3	0.24	-18.29
	(-)55-60 cm				

TRENCH ON SITE 3

Horizontal location: 9 meters from north end of trench.

Depth from surface	Sample datum	PO ₄ ⁻³	NO ₃ ⁻	TOC	δ ¹³ C
surface	(3-21n-9e closest sample)	12.92	4.14	1.46	-17.040
5 cm	82-86 cm	14.34	1.6	0.6	-16.606
15 cm	70-75 cm	2.12	<0.3	0.67	-14.369
25 cm	60-65 cm	0.36	<0.3	0.59	-13.852
35 cm	50-55 cm	0.16	<0.3	0.42	-14.14
(Holocene/Pleistocene contact at + 47 cm)					
45 cm	40-45 cm	0	0.35	0.47	-16.301
	30-35 cm				
65 cm	20-25 cm	0	<0.3	0.29	-17.215
	10-15 cm				
90 cm	0-5 cm	0.19	<0.3	0.16	-18.961
	(-)10-15 cm				
110 cm	(-)20-25 cm	1.98	<0.3	0.15	-23.394
	(-)30-35 cm				
130 cm	(-)40-45 cm	1.08	<0.3	0.07	-24.048

Horizontal location: 6 meters from north end of trench.

Depth from surface	Sample datum	PO ₄ ⁻³	NO ₃ ⁻	TOC	δ ¹³ C
surface	(3-24n-9e closest sample)	6.64	1.93	0.67	-16.760
10 cm	60-65 cm	2.82	<0.3	0.43	-15.548
20 cm	50-55 cm	1.26	<0.3	0.53	-14.526
30 cm	40-45 cm	0.48	<0.3	0.58	-13.376
40 cm	30-35 cm	0.3	<0.3	0.48	-14.128
(Holocene/Pleistocene contact at + 29 cm)					
50 cm	20-25 cm	0.48	<0.3	0.36	-14.992
	10-15 cm				
70 cm	0-5 cm	0.56	<0.3	0.18	-20.048
	(-)10-15 cm				
90 cm	(-)20-25 cm	0.68	<0.3	0.1	-20.501
	(-)30-35 cm				

TRENCH ON SITE 3, continued

Horizontal location: 3 meters from north end of trench.

Depth from surface	Sample datum	PO ₄ ⁻³	NO ₃ ⁻	TOC	δ ¹³ C
surface	(3-27n-9e) closest sample)	10.22	2.05	0.58	-18.66
10 cm	40-45 cm	1.52	0.83	0.59	-14.842
20 cm	30-35 cm	1.4	1.04	0.53	-14.744
30 cm	20-25 cm	0.88	0.92	0.56	-13.933
40 cm	10-15 cm	0.16	0.55	0.54	-14.692
(Holocene/Pleistocene contact at + 7 cm)					
50 cm	0-5 cm	0	<0.3	0.36	-16.537
70 cm	(-)10-15 cm				
	(-)20-25 cm	0.88	0.72	0.1	-18.122
	(-)30-35 cm				