Surficial Geology and Fire in Southeastern Arizona Grasslands – Effects on Soil Geochemistry in Semiarid Ecosystems, Fort Huachuca Military Reservation, Arizona

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Abstract

Throughout the southwestern United States, vegetation in what historically was grassland has changed to a mixture of trees and shrubs; exotic grass species and undesirable shrubs have also invaded the grasslands at the expense of native grasses. The availability and amount of soil nutrients influence the relative success of plants, but few studies have examined fire effects on soil characteristics in a temporal, spatial, and species group-specific fashion. Likewise, few studies have tied fire effects and ecological aspects to the underlying geology. Our research investigates the effects of fire events on selected soil characteristics pH, nitrate (NO_3^-), plant-available phosphorus (PO_4^{-3}), and total organic carbon (TOC) on native grass-, exotic grass-, and mixed grass-dominated plots distributed on four different geological surfaces. Treated and control plots were sampled prior to burn treatment and at intervals after the burns. In addition to new geologic mapping of the study areas, results indicate the geologic substrate is the most important variable for explaining pH, NO_3^- and PO_4^{-3} values in the soils. Dominant grass type – native, non-native, or mixed – had little effect on the response of soil geochemistry to fire events: post-burn results indicate vegetation was a significant factor only for TOC. Recovery to pre-burn levels varies with characteristic: there were no significant initial differences between vegetation types, but significant differences in NO_3^-, PO_4^{-3}, and TOC amounts occur as a result of fire events, geological characteristics, and time. The research helps identify the soil response to fire and the recovery times of soil characteristics, further defines which fire frequency is optimal as a management strategy to maximize soil macronutrient contents, and illustrates the important role geology plays in grassland ecosystems.

Keywords: fire, soil geochemistry, geomorphology, phosphorus, nitrogen, organic carbon

INTRODUCTION

Large-scale loss of habitat and reduction of biodiversity have sparked increased conservation and restoration efforts by land managers. Information describing the physical framework of habitats is critical for identifying solutions to these land use and environmental issues. Substrate character may affect the spatial distribution of soil characteristics (Caravaca et al, 1999) and thus the distribution of native and non-native plants in native grasslands, and improved understanding of the geologic characteristics could improve management techniques of the grasslands environment. Management strategies may be thwarted by changes in the distribution and availability of soil nutrients, which are strongly affected by fire (Wright, 1980; Cave and Patton, 1984; Picone, et al, 2003). Prescribed fire has become an important land management tool for restoration of ecosystem structure and function, but the long-term absence of fire events and multiple land use changes may have produced irreversible changes in semiarid grasslands. Although managed burns may not yield the same results as natural fire regimes, ecological benefits are realized as a reduction in the level of uncertainty during decision-making processes related to land use concerns, site utilization, hazard mitigation, and environmental preservation or restoration.

Because the ecological character of semiarid regions is determined by the dominant vegetation, change creates significant alterations in biotic and abiotic conditions (Schlesinger et al., 1990). Such changes may be perceived as degradation of grasslands in the southwestern United States and northern Mexico, including the Fort Huachuca Military Reservation. These semi-arid grasslands have been transformed by fire suppression, overgrazing, and invasive native woody plants and non-native grasses (Cable, 1973; Crawford and Gosz, 1982; Harrison et al, 2003). Fire, whether natural or anthropogenic, is a critical factor in determining species composition in grasslands: fire decreases shrub cover and increases grass cover (White & Loftin, 2000; Brockway et al., 2002) therefore maintaining grassland structure (McPherson, 1995) as well as high-quality grazing habitat.

During the past 100 years, *Prosopis velutina* (velvet mesquite), a native species, has expanded from predominantly riparian settings to more xeric uplands, encroaching upon historical grasslands (McPherson, 1995). Prior to the past century, fires occurring every 5-7 years killed young mesquite trees, limiting recruitment into grassy areas away from washes. One of the effects of this increase in *Prosopis* distribution has been a concentration of plant-available soil nutrients under *Prosopis* canopies on the gunnery ranges at Fort Huachuca (Virginia and Jarrell, 1983; Biggs, 1997; Wilson et al, 2003) and other study areas, thus depriving native grasses of necessary resources. These accumulations may persist after the disappearance of *Prosopis* from an area (Biggs, 1997) and hinder rangeland management efforts to re-establish native grasses. Previous studies have shown that fires may aid in the redistribution of soil nutrients. It is possible the changes in these ecosystems due to fire suppression are irreversible as there may not be the fine fuel load necessary to sustain fire events of the necessary magnitude to return the grasslands to their previous structure (Bahre, 1985; McPherson, 1995).

Exotic grass species and undesirable forbs and shrubs have also invaded the semiarid grasslands at the expense of native grass species (Robinett, 1994; McClaren, 1995). Lehmann's lovegrass (*Eragrostis lehmanniana* Nees), a South African perennial grass, was introduced to provide erosion control and forage for cattle. Since its introduction, Lehmann's lovegrass has extended its range at the expense of numerous native grasses, especially as a result of disturbance events such as frequent wildfires (Anable et al, 1992). Widespread establishment of fire-tolerant non-native grass species is perceived to be detrimental to resource management goals such as maintenance of high-quality wildlife habitat and livestock grazing values. Efforts to restore invaded areas to native flora by using natural processes like fire may return the grasslands to their former species composition. However, few studies have examined fire effects on plant-available soil nutrients in a temporal, spatial, and species-specific fashion.

Desert grasslands are water limited and nutrient regulated, with soil fertility determined by the concentration of essential nutrients. Nutrient availability to plants is determined by the ability of soil to supply nutrients to plant roots. Certain of these essential nutrients originate from the breakdown of minerals in the soil (e.g. phosphorus), whereas others are extracted from the atmosphere (e.g. nitrogen). The substrate of the grassland study area is composed of a series of alluvial fans of different ages that were shed from the Huachuca Mountains (Pearthree, 2004; Demsey and Pearthree, 1994; Huckleberry, 1996). Alluvial units of different lithologic composition and age should impart different nutrient and geochemical dynamics to the soils produced on them. This aspect of grassland ecosystems has not yet been adequately addressed in the desert Southwest.

Soil pH is an important factor in determining the solubilities of these plant nutrients. The nitrogen (N) cycle is an open system in grassland ecosystems: nitrogen is extremely mobile and leaves the ecosystem through more avenues and in greater quantities than most other nutrients. The ammonia form (NH^{-4}) is especially volatile in desert grasslands; nitrate, the plant-available form (NO_3^-), is perhaps more important to determine ecosystem vitality. Soil organic phosphorus (in the form of phosphate, PO_4^{-3}) is part of the dynamic phosphorus (P) cycle that includes the immobilization, mineralization, and redistribution of P in soil. Bio-available phosphorus is critical to plant biomass production because it controls the accumulation and availability of nitrogen and carbon in ecosystems (Stewart and Tiessen, 1987). Total organic carbon (TOC), although not a plant nutrient, provides a measure of productivity in an ecosystem.

To study the effects of fire management upon *Prosopis*, native and exotic grasses, and soil nutrient cycling, factors such as climate and land-use history should be held as constant as possible. Study areas that meet the qualifications for this kind of analysis were established on the Fort Huachuca Military Reservation in southeastern Arizona by professors Guy McPherson and Bob Steidl of the School of Renewable Natural Resources, University of Arizona, as part of a study of fire effects on biodiversity within grasslands and *Prosopis* savannas. Their studies focused on birds, small mammals, invertebrates, and plant communities (Geiger & McPherson, 2004). As a complement to their studies, we utilized the established study plots to examine the role of surficial geology and soil geochemistry in the responses of these ecosystems to fire. In addition to new surficial geologic mapping of the study areas, the research established nutrient levels on unburned grasslands and, after the scheduled controlled burns, determined the response times of soil characteristics on the burned grasslands.

Our investigation involved three phases (see Methods section, below, for details). Phase 1 involved the collection of soil samples from the established McPherson group control sites (n = 9) (Figure 1) and designated June treatment study sites (n = 9) in early to mid-June, 2001. These samples were collected, dried and prepared for analysis. They were analyzed for pH, TOC, plant-available phosphorus, and plant-available nitrogen (NO_3^-). Phase 2 took advantage of the controlled burns in June, 2001 on the established study sites (n = 9) by re-sampling the treated plots immediately after the controlled burns, approximately six weeks after the burn treatments, again after six months, and a final collection one year after the controlled burn. The unburned control sites were also re-sampled one year after the initial sampling phase. All soil samples were analyzed for soil characteristics noted above. The third phase involved the geologic mapping of the nine areas of Fort Huachuca covered by the study (Plates 1, 2 and 3). Pearthree (2004) mapped the surficial geology of the Huachuca City 7.5-minute quadrangle to the north of Fort Huachuca; Demsey and Pearthree (1994) mapped the surficial geology of the Sierra Vista area east and north of the Fort boundaries and Huckleberry (1996) mapped a small area within the Fort, but the geology of the base itself and the proposed study sites has not been mapped in any detail.

METHODS

The study site is located on the eastern flank of the Huachuca Mountains along the upper San Pedro River Basin. The climate is semiarid with temperatures ranging from a mean maximum of 25^{o}C to a mean minimum of 10^{o}C. Precipitation distribution is bimodal, with about 60% of the rainfall occurring during the summer monsoon period (July – September) and about 25% during the winter months.

The McPherson/Steidl field experiment is a large-scale randomized block design with a full-factorial treatment structure with existing vegetation community as a blocking factor (native grass dominated, introduced lovegrass dominated, and mixed native and non-native plots) and burn season as the treatment effect (spring fire, summer fire, no fire). The three types of grasslands thus represent a continuum of invasion by non-native species. In the summer of 1999, 18 sets (blocks) of sites, 6 within each of these 3 types of grassland communities, were delineated within the Fort Huachuca Military Reservation (Figure 1, Plates 1, 2 and 3). Within each block, three 1-ha plots were established. Each of the 3 plots within a block will receive one of the three fire treatments. Nine of the blocks were burned in 2001 and the remaining nine blocks were burned in 2002, for a total of 3 replicates per community type (n = 3) per treatment (n = 3) in a given year (n =2). The corners of the 54 plots were marked with metal fence posts and the GPS coordinates (Appendix B) recorded to ensure the plots could be relocated.

Surficial geologic mapping of areas encompassing the burn sites allowed us to put the sites in their appropriate geomorphic context. Because of the lack of detailed geology available for Fort Huachuca, the geological conditions were not considered during site selection by the McPherson/Steidl group. All of the sites are located on alluvial substrate, but field reconnaissance and comparison with nearby areas that are mapped (Pearthree, 2004; Demsey and Pearthree, 1994) indicated sites selected represent a wide range of surface ages and soil characteristics. Standard surficial geologic mapping techniques were used to produce the geologic maps of the sites and interpret the geomorphology of the study sites to provide the first-order information layer that can be combined with soil geochemistry, vegetation distribution patterns, and other aspects of the overall study.

We mapped the surficial geology of three tracts on Fort Huachuca that encompass all of the burned blocks (Figure 1; Plates 1-3). The geomorphology and surficial geology of the study sites were determined through interpretation of aerial photographs and fieldwork. Color aerial photography (scale 1:24,000) flown in September and October 1987, obtained from the Wildlife Office at Fort Huachuca, was used to distinguish geomorphic surfaces of different ages and landform type using criteria such as topographic position, degree of surface degradation, degree of stream dissection, soil development and characteristics, and surface coloration (Bull, 1991). In addition, we drew upon mapping and soils analyses conducted by the Natural Resources Conservation Service (NRCS, 2003). The largest tract is a ~ 6 square mile area in the southeastern part of Fort Huachuca. This tract encompasses 6 of the study blocks and is contiguous with previous geologic mapping in Garden Canyon (Huckleberry, 1996) and adjacent to the Fort (Demsey and Pearthree, 1994). The other two mapped areas in the northern and western parts of the Fort cover the remaining 3 study blocks. These areas are proximal to the Huachuca City geologic map (Pearthree, 2004). Each of these tracts contains a variety of surficial geologic units ranging from modern active channels to middle to early Pleistocene alluvial fan remnants to indurated, tilted Tertiary alluvial basin-fill deposits. These map units and distinguishing characteristics were field checked and correlations were made between the different areas of the ranges. The mapping was transferred to a digital orthophotoquad base from 1996, compiled in a GIS format, and the final line work was generated from the digital data. The geomorphology, sedimentology, and soil development associated with each surficial geologic map unit is discussed below.

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 can be utilized by the plant through the root system (Raison, 1979). Therefore, this study focused on the plant-available soil nutrients for nitrogen (NO_3^-) and phosphorus (PO_4^{-3}), as well as soil pH and total organic carbon (TOC), instead of total element concentrations to determine the effects of fire. Our soil geochemical study utilized a 30m x 30m grid internal to each of the 1-ha plots established by the McPherson/Steidl team scheduled for 2001 no burn (n = 9) and summer (June) burn treatments (n = 9). Corner and center posts were marked with 36” long flagged rebar and the GPS coordinates recorded. For Phase 1, a set of 25 to 28 random surface soil samples (0 – 5 cm depth) were collected within each control and treated (burned) sub-grid, with the locations marked with fire-resistant aluminum tags, prior to the scheduled June burn treatment (total samples collected prior

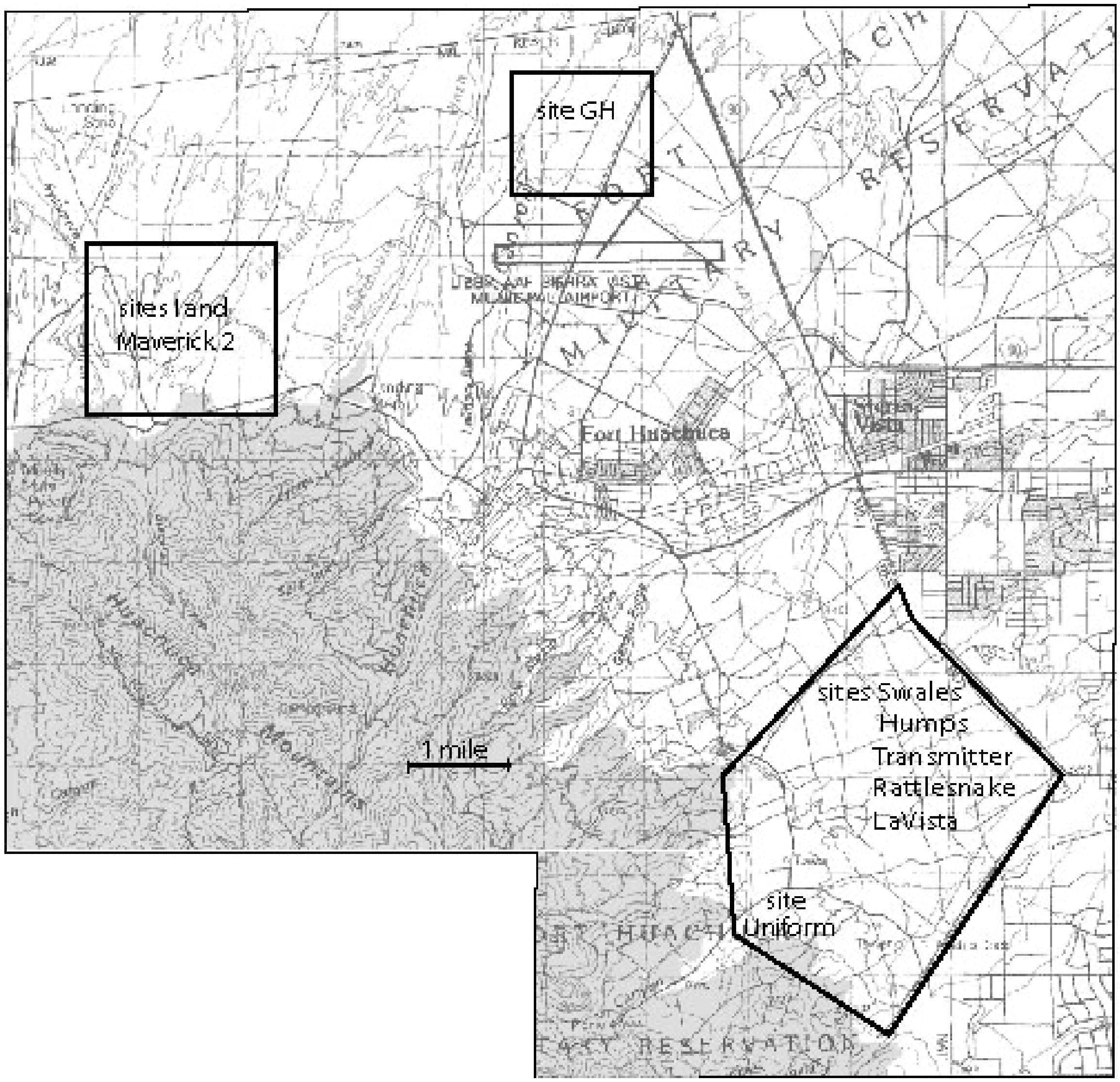


Figure 1. General locations of burned plots and areas of new surficial geologic mapping. Geologic mapping within the bold lines is shown in Plates 1, 2 and 3 at the back of this report.

to burn event ≥ 480). All samples were sifted through a 2-mm sieve in the field. Immediately after the burn event, a second (Phase 2) set of surface soil samples was collected at the established grid points on the nine burned sub-grids (n = 9). Sampling was repeated on the burned grids approximately six weeks, six months, and one year after the burn treatment to determine nutrient response and recovery. Care was taken to avoid sampling the exact spot at each grid point each time, but samples were collected within a 12-inch (25 cm) radius of the metal tag. The unburned control (no burn) grids were re-sampled one year after the initial collection.

All soil samples were oven-dried at 65° C immediately after collection. Samples were sieved, ball-milled, split into subsamples and acid treated for geochemical analysis to determine pH, plant-available phosphorus (PO_4^{-3}), total soil nitrate (NO_3^-), total soil organic matter (SOM) values. Soil pH was determined using a glass electrode pH meter and standard methods (McLean, 1982). Plant-available phosphorus (PO_4^{-3}) was extracted using the Olsen bicarbonate method (Olsen and Sommers, 1982) and analysed using a Hitachi U-2000 Spectrophotometer. Total organic carbon (TOC) and plant-available nitrogen (NO_3^-) were measured on pretreated samples by high temperature combustion (Nelson and Sommers, 1982) using a Carlo Erba 1500 Nitrogen, Carbon, Sulfur Analyzer; NO_3^- was measured by ion chromatography (Keeney and Nelson, 1982) using a Dionex Model 2320i Ion Chromatography. Lab work was conducted at the Soil, Water, and Environmental Science Lab at the University of Arizona by University of Virginia and University of Arizona student assistants. A total of approximately 1780 samples were processed for this study (Appendix A), and repeated measurement of a soil standard and periodic duplication of samples yielded a precision of 0.01% for carbon, nitrogen and phosphorus.

GEOLOGIC AND GEOGRAPHIC SETTING

The Fort Huachuca Military Reservation is built on the northeastern piedmont of the Huachuca Mountains, on the western margin of the San Pedro Valley in Cochise County, southeastern Arizona. The mountains trend northwestward from the US-Mexico border approximately 30 km (20 mi) to their terminus just west of Fort Huachuca. The mountains range from about 1550 m (5000 ft) to 3000 m (9500 ft) in elevation. The northern Huachuca Mountains at Fort Huachuca are composed primarily of Precambrian granite, Paleozoic sedimentary rocks, Mesozoic volcanic rocks, and Mesozoic sedimentary rocks (Hayes and Raup, 1968). Streams draining the eastern side of the range have deposited alluvial fans and terraces on the piedmont extending from the mountain front to the San Pedro River (Wohl and Pearthree, 1991). The Bobocomari River, a major tributary of the San Pedro just north of Fort Huachuca, forms the base level for streams flowing from the northern end of the Huachuca Mountains. The Bobocomari has incised at least 30 meters into late Cenozoic basin-fill deposits since the early to middle Quaternary in response to downcutting by the San Pedro River to the east (Pearthree, 2004). Therefore, the geomorphology of the study areas is dominated by the incision of the San Pedro and Bobocomari rivers and their tributaries: alluvial fan remnants and terraces ranging in age from Holocene to early Pleistocene record former positions of these tributary channels (Figure 2).

The Fort Huachuca area lies within the Mexican Highland subprovince of the southern Basin and Range province. Extensional deformation resulted in range-bounding normal faulting along which the Huachuca Mountains were uplifted relative to the San Pedro basin to the east. Major tectonism ceased in this region about 5 million years ago (Ma) (Menges and Pearthree, 1989). Evidence of continued, sporadic faulting in the area includes fault scarps that cut middle Pleistocene alluvium on the eastern piedmont of the Huachuca Mountains (Demsey and Pearthree, 1994). During and subsequent to the

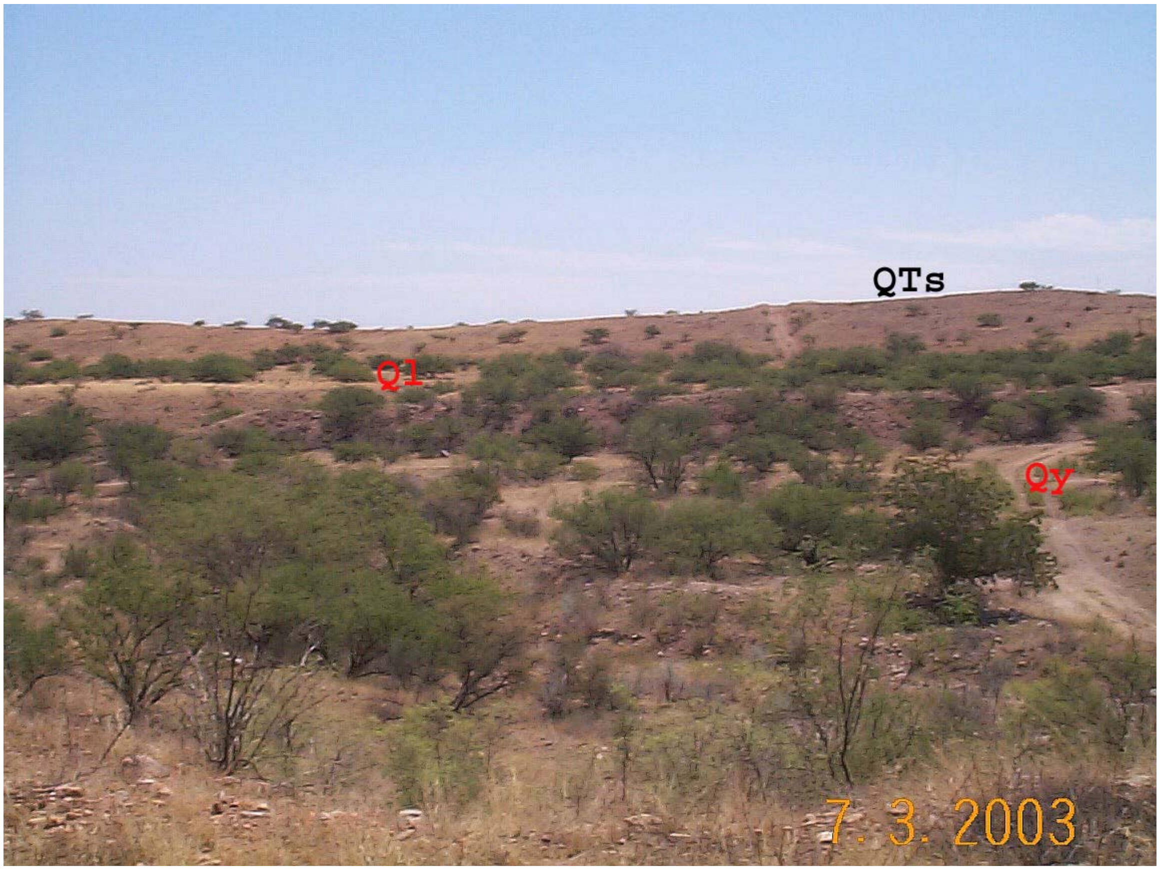


Figure 2: Slaughterhouse Wash is one of the major tributaries of the Bobocomari River on the west range at Fort Huachuca and incision has been very pronounced along its course. In this view, looking east from the west side of the wash, the active channel (Qyc) and floodplain (Qy) are apparent; the terrace formed by late Pleistocene deposits (Ql) is just beyond the active channel. The ridge in the distance is eroded early Pleistocene to Tertiary (QTs) fan material.

normal faulting, the San Pedro basin continued to be filled by sediments shed from the bordering Huachuca Mountains (Menges and McFadden, 1981). Following a period of landscape stability and diminished sedimentation in latest Pliocene (~2 Ma), widespread progradation of coarse-grained alluvial fans began in the early Pleistocene (~1.6 Ma) and continued until the onset of basin-wide incision caused by downcutting of the San Pedro River in late Pleistocene (Lindsay et al, 1990).

The Huachuca Mountains have continued to shed alluvium into the San Pedro basin during the Quaternary (Wohl and Pearthree, 1991), with major depositional pulses probably triggered by regional climatic changes (Bull, 1991). As a result, most of the piedmont is covered by alluvium that was deposited 10s to 100s of thousands of years ago (Demsey and Pearthree, 1994). The upper San Pedro River Valley began to downcut dramatically approximately 0.6 Ma: the downcutting of the river lowered the base level for the valley and caused dissection of the earlier alluvial fans and bajadas (Huckleberry, 1996). The present-day Huachuca piedmont is characterized by discontinuous, ephemeral washes and relatively narrow areas of active alluvial fan deposition. Deposits formed during the Holocene to present are restricted to stream valleys incised in the older deposits and limited alluvial fan accumulations near the mountain front.

CHARACTERISTICS OF SURFICIAL GEOLOGIC UNITS

Alluvial surfaces represent periods of active deposition during run-off or debris flow events. An active surface may become isolated due to lateral shifts of active channels or vertical incision by active channels. The criteria used to differentiate and map alluvial surfaces may also be used to estimate relative age of the depositional surface, as the surface marks the end of significant deposition (Demsey and Pearthree, 1994). Features such as relative topographic height, surface morphology and soil development are key geomorphic indicators of alluvial surface age (Gile et al, 1981). The compositions of the clastic materials that comprise the fan systems may also vary in space and time, as erosion removes certain bedrock units and exhumes others in the mountain source areas.

Analysis of aerial photography in semiarid regions results in maps of Tertiary and Quaternary geology and geomorphology. Mapping consisted of delineation of surficial geologic units deposited by streams, washes, debris flows or sheet-flow events on portions of the eastern piedmont of the Huachuca Mountains. Such maps may also delineate flood plain hazards in the study areas and indicate where water has flowed in the past. Alluvial deposits are identified by age based on their relative topographic positions, surface characteristics, subsequent erosion and incision, and soil-profile characteristics. Alluvial surfaces of similar age have a characteristic appearance because they have undergone similar post-depositional modifications. Distinct differences between younger and older surfaces may be roughly estimated based on these surface characteristics, especially the extent of soil development (Bull, 1991; Gile et al, 1991). Old surfaces that have been isolated from deposition or reworking for hundreds of thousands of years are characterized by strongly developed soils with thick clay- and/or calcium carbonate-rich horizons. The surfaces are gradually modified over thousands of years to produce a more rounded, often dissected fan surface topography. Younger fan surfaces often retain characteristics of the original depositional topography, show minimal soil development, and are basically undissected.

Soil profiles develop gradually once active flow and deposition of new cover materials have ceased (Figure 3). The nature of profile development is strongly influenced by the climate during a particular geologic time span. Soils develop by a combination of *in situ* chemical weathering of the alluvial deposits and inputs of eolian materials such as clay, silt, and calcium carbonate (Gile et al, 1981). Soils that developed during wetter periods are characterized by clay accumulation and reddening (iron accumulation), whereas soils formed during periods of diminished rainfall exhibit pronounced calcium carbonate build-up (caliche) (Machette, 1985).

FIRE AND SEMIARID GRASSLANDS

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

Figure 3: Soil pit dug on the middle Pleistocene (Qm) surface just east of Site Swales reveals the three dimensional aspects of the alluvial surface. Zones of abundant boulders and cobbles represent high energy channels whereas finer grained portions were deposited in slack water or interfluve areas. Subsequent pedogenic carbonate is evident approximately a meter below the present surface, and clay development is quite pronounced.

element within the grassland ecosystem (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 grass species (Archer, 1994; Bahre, 1995). The rates and mechanisms of this ecosystem shift are much debated, with the encroachment attributed to over-grazing and its attendant soil loss, fire suppression, climate change, or some combination of these and other factors (Grover and Musick, 1990; Hastings and Turner, 1965; Cox et al., 1993; Wright and Bailey, 1980). The question of whether the influx of woody vegetation into grasslands represents ecosystem degradation (Schlesinger et al., 1990) or ecosystem rejuvenation (Holden, 1996) is also unresolved.

Another important change to the grasslands of Arizona and other parts of the Southwest has been the introduction and subsequent spread of South African Lehmann lovegrass (*Eragrostis lehmanniana* Nees.). Fire-tolerant invasive grass species like lovegrass have begun to dominate significant areas of the grasslands in large part due to disturbance events (Anable, et al, 1992). The widespread establishment of non-native grass species is perceived to be detrimental to resource management goals such as maintenance of quality wildlife habitat and livestock grazing values.

Fire in grasslands consumes much of the litter and aboveground standing foliage but rarely kills the buds and meristematic growth regions protected in root crowns or below-ground rhizomes (Grover & Musick, 1990). The seedlings of many shrubs and other woody plants are sensitive to fire: some will not re-sprout if their tops are killed and others are vulnerable to fire mortality until reaching a certain degree of maturity. Recurring fires thus suppress fire-intolerant species such as mesquite. Seasonality of fires may also be a major factor in the success of non-native grass species (Brockway, et al, 2002) and the suppression of unwanted shrub or tree species (Robinette, 1994; McPherson, 1995).

In addition to retarding establishment and growth of trees and shrubs and enhancing the spread of exotic grasses, frequent fires presumably would deplete soil nutrients by volatilization and erosion. Seasonality of fire, as well as maximum surface temperatures, strongly affects changes in soil nutrients (Sharrow and Wright, 1977; Brockway et al, 2002). Studies indicate losses of soil nitrogen and phosphorus, and to a lesser extent carbon, by volatilization, by aerosol losses, and by removal in surface runoff due to increased soil erosion (Debano and Conrad, 1978; Raison, 1979; Wright and Bailey, 1980).

RESULTS

SITE GEOLOGY AND ALLUVIAL HISTORY

Primary mapping was done using color aerial photography provided by the Fort Huachuca Wildlife Office, with extensive field checking. In this study, surficial units are subdivided into three primary categories based on estimated age, **Qy** (young, Holocene to modern), **Q** (Pleistocene), and **T** (Tertiary undifferentiated). Subdivisions of these age categories were mapped (Plates 1, 2 and 3) where feasible, although no independent data for evaluating the numerical ages of the deposits were obtained in this study. **Qy** deposits are subdivided into **Qy** and **Qyc** in order of decreasing relative age. Quaternary (**Q**) deposits are divided into broad age categories of ‘late’ (**Ql**), ‘middle’ (**Qm**), and ‘early’ or ‘old’ (**Qo**). Surfaces that appeared more eroded or degraded were identified by ‘**d**’ (e.g., **Omd**) to differentiate them from more planar surfaces. Tertiary (**Ts**) units were not differentiated. A combined map unit (e.g., **Qly**, **Qmo**, **QTs**) is used if the relationship is not clear. The age estimates of the units at Fort Huachuca are based on comparisons with similar soil-profile development in other studies of similar physical and climatic setting in southern New Mexico (Machette, 1985) and correlations with depositional units described in earlier studies in the San Pedro Valley (Pearthree, 2004; Shipman and Ferguson, 2003; Youberg, et al, 2004; Huckleberry, 1996; and Demsey & Pearthree, 1994). Map units range from areas of very recent deposition in active channels to very old tectonically deformed relict alluvial fan deposits that are several millions of years old.

All three of the map areas for this study are well away from the base of the Huachuca Mountains and alluvial fans are the predominant landform in the study areas (Figure 1). Alluvium is sediment carried and deposited primarily by running water. An alluvial fan is a conical deposit that is produced by a combination of gravity settling and stream flow that typically diminishes downstream on the fan. As a stream, as well as a more catastrophic debris flow, exits a highland source area, it will lose its ability to transport sediment due to reduced discharge and a change from a confined channel to an unconfined channel. Deposition will shift both laterally on the fan surface (as the sediment-ladened flow seeks the path of least resistance) and up and down the alluvial slope according to the amount of discharge. Overall grain size diminishes from fan apex to the distal margins of the fan, although some surprisingly coarse deposits may be carried well out from the mountain front by major storm events. The downslope deposition may also be affected by channel entrenchment, which can extend the confined reach of the channel and result in coarse materials carried to the distal portions of the fan.

Alluvial deposits are also formed as terraces along stream channels and may be continuous or discontinuous along the margins of the channel. The terrace may represent an abandoned floodplain of a stream that has continued to downcut due to base level decline, or it may be an area of greater past deposition on the active floodplain that is only inundated during infrequent high water events. Whether isolation occurs due to lateral shifts of the active channel or down-cutting of that active channel, the age of the alluvial unit is determined by when deposition ceased on it upper surface.

The Tertiary units consist of very old, deeply eroded and dissected, indurated alluvial fan deposits. The deposits are dominated by polylithic gravels ranging from boulders to pebbles in a carbonate-rich sandy matrix. Where the deposits are well-exposed in dry washes on the west range, they are tectonically tilted, with a dip of 13^{o} to 27^{o} to the west-southwest (unit **Ts**, Figure 4); on the crests of ridges, determination of the structure is not as obvious (unit **QTs**). Both QTs and Ts surfaces are gray to white on aerial photographs. Soil cover is usually very thin on these surfaces.

The apparent depositional pattern during the Quaternary is one of decreasing competence and transport capacity of streams draining the Huachuca Mountains, as well as progressive channel incision and dissection of the piedmont as a result of downcutting by the San Pedro River. The early Pleistocene was a period of progradation of coarse-grained alluvial fans over the Huachuca piedmont. Material deposited during this period forms much of the upper St. David Formation in the Benson – St. David area to the north (Lindsay and others, 1990). The coarse gravelly deposits of unit **Qo** of the study areas may correspond to this early Pleistocene period of alluvial fan progradation (Figure 5).

The highest preserved surfaces of Qmo on the west range and Qo on the south range at Fort Huachuca may represent the early Pleistocene period of aggregation mapped by

Figure 4: The oldest alluvial deposits in the study area are poorly sorted polymictic conglomerates (top) of Miocene to Pliocene age (Ts/QTs). These basin fill deposits were tilted by tectonic activity as the San Pedro Basin continued to down-drop along normal faults and buried by younger, undeformed deposits such as the Qmo beds west of Site I (bottom).

Demsey and Pearthree (1994) and further supports the conclusion that dissection began in the upper San Pedro Valley during early Pleistocene while sediment continued to accumulate farther north near Benson and St. David.

Figure 5: Distal view of Site LaVista (dark green polygon) on Qo surface, six weeks after burn treatment. The alluvial fan is dominated by carbonate rock debris from the Huachuca Mountains (background).

The upper piedmont of the Huachucas experienced several major pulses of aggradation through the middle Pleistocene, as indicated by coarse alluvial fan deposits at different topographic elevations (units **Qmo**, **Qm**). The coarse gravelly clay-rich orange Qmo and Qm surfaces are extensive across the study areas, indicating at least two major periods of aggradation (Figure 6). The topographic differences between the two surfaces also indicate a period of net erosion occurred between the two sediment pulses. Locally, Quaternary and Holocene erosion has cut down into underlying Tertiary deposits.

An extended period of net erosion evidently followed the deposition of the middle Pleistocene fans. Late Pleistocene alluvial fan deposits (**Ql**) are typically not as coarse-grained as the earlier fans, nor are they as extensive (Figure 7). Most of the late Pleistocene deposits formed as inset terraces along drainages that dissected the middle Pleistocene fans. The finer grain sizes compared with the Qm, Qmo, and Qo deposits indicate the fluvial systems were less able to transport coarse bedload away from the

Figure 6: Bouldery clay-rich early middle Pleistocene (Qmo) alluvial material forms the surface of Site I on the west range at Fort Huachuca. This site has mixed native and exotic grasses, as well as abundant agave.

Figure 7: Late Pleistocene (Ql) coarse fan deposits in Slaughterhouse Wash west of Site GH.

mountains. These deposits represent periods of aggradation superimposed on the long-term downcutting of the piedmont by the decline of the San Pedro base level.

Alluvial surfaces of Pleistocene and older age have been removed from fluvial activity for more than 10,000 years. The majority of these surfaces stand several meters to several tens of meters above the active drainages. Therefore, these surfaces generally do not receive significant flow or deposition from active channels, but they may experience sheet flow runoff during intense rainfall events. There is also some potential for lateral bank erosion during large flow events that could undercut some of these higher surfaces.

The extent of Holocene deposits (**Qy**) on the Huachuca piedmont is limited to narrow belts along active channels and adjacent low discontinuous terraces, small alluvial fans emanating from small drainages near the base of the mountains, and thin veneers of fine-grained sediment deposited on older fan surfaces during episodes of sheet-flow runoff. These young alluvial surfaces may be flood prone in the study areas.

Study sites were located on four different surfaces (Plates 1, 2 and 3). One plot (site Uniform) is on a Holocene (Qy) fan (Figure 8) composed of brown (10YR colors)

Figure 8: Site Uniform is a native grass dominated site on a Holocene (Qy) fan at the mouth of Gardner Canyon. The sediments are brown, coarse-grained, very sandy and micaceous, and show little soil development.

coarse micaceous loamy sand with only incipient soil development, covered with lush native grasses. Four plots are located on early-middle Pleistocene (Qm, Qmo or Qmd) fan surfaces (sites GH, I, Rattlesnake and Transmitter) (Figure 9). These surfaces have

Figure 9 (top): Site GH is a Lehmanns lovegrass covered Qmo surface. Note the abundant boulders and cobbles in the reddish orange clay-rich soil. Site Transmitter (bottom) is a Lehmanns lovegrass dominated plot on the south gunnery ranges. As this post-burn photo illustrates, the site is on a reddish orange early middle to middle Pleistocene surface (Qmo). Although it is clay-rich, boulders and cobbles are not as abundant on this surface compared to other Qmo or Qmd surfaces, perhaps because it was more distal to the alluvial source, or it formed as a slackwater area of the channel, or a combination of both factors.

reddish orange (5 to 2.5YR colors) typically very bouldery clay-rich soils; vegetation on three of the sites is dominated by Lehmanns, although site I has mixed grasses with abundant agave. Two sites (Humps and LaVista) are on early Pleistocene (Qo) surfaces and both sites are dominated by native grasses. The surfaces are degraded with abundant boulders coated with carbonate (caliche); soils are brown (10YR colors) clay loams with abundant carbonate chips (Figure 10). Two sites (Maverick 2 and Swales) are on 'veneered' fan surfaces (Qy/Qm) characterized by bouldery orange (7.5YR) clay-rich soil with a thin, often patchy cover of brown sandy loam soil deposited by Holocene events and subsequently partially removed by sheet flow erosion (Figure 11). Both of these sites have mixed grasses as the dominant vegetation cover.

Figure 10: The burn treatment removed the native grass cover from this site, revealing the bouldery make-up of the Qo fan material. Pedogenic carbonate is common on the rock clasts and as chips in the soil. Most of the clasts are limestones from the Huachuca Mountains.

SOIL GEOCHEMISTRY

The complete tables of geochemical results are provided in Appendix A of this report. The nine study sites were compared graphically and statistically to determine overall trends in the data and determine the roles of geologic substrate and vegetation types in the effects of burn events on key soil characteristics.

Figure 11: A thin remnant of brown fine-grained Holocene material remains beneath small mesquite trees near the Swales site. The site name was derived from the gently rolling terrain on the surface: most of the surface is reddish orange bouldery Qm with the higher areas still covered by fine grained brown Holocene deposits.

The effects of vegetation types and geological substrates on the soil response to prescribed fire are discussed in separate sections in this report because only a limited set of vegetation types: geological substrates combinations are available in the field sites. This prevented a full factorial analysis on vegetation, geology and vegetation-geology interaction effects. However, by building separate models incorporating either the vegetation or the geology factors, we could compare the model performance to explain soil nutrient dynamics and select the one that has better fit to the data.

Two information criteria are commonly used for model selection in ecology: Akaike Information Criteria (AIC) and Bayesian Information Criteria (BIC). We will utilize AIC and BIC to compare four statistical models: 1) null model with no information on vegetation types or geological substrates (*Null model*); 2) vegetation model with information only on vegetation types (*Vegetation model*); 3) geology model with information only on geological substrates (*Geology model*); and 4) a combination model of vegetation type and geological substrate (*Full model*) with only four combination types: early Pleistocene + native vegetation, early-middle Pleistocene + exotic vegetation, Holocene + native vegetation, “Veneered surfaces” + mixed vegetation). The model with the smallest AIC and BIC values is the best model that explains the most variation in soil nutrients with the least parameters.

The AIC and BIC criteria agreed with each other on all comparisons. For long-term soil nutrient response to prescribed fire, the *Geology model* is the best model in explaining soil pH, NO_3^-, and PO_4^{-3}, whereas the *Vegetation model* is the best model in explaining TOC (Table I). This is not surprising given that TOC should be highly correlated with biomass burning. Interestingly, for temporal changes in soil characteristics after prescribed fire, the *Full model* is the best for explaining pH, NO_3^- and PO_4^{-3}, whereas the *Null model* is the best model for explaining TOC (Table II).

The opposite results exhibited for long-term response and temporal dynamics suggests that temporal dynamics of soil nutrients, except TOC, are more difficult to describe than long-term response. Therefore, including information on both vegetation types and geological substrates will generate the best model. Among the four soil characteristics examined, TOC behaves most differently from others. The fact that the *Null model* is the best model to explain TOC dynamics suggests that other important environmental factors might not be included in the candidate models.

Table I: Selection of models on long-term soil nutrient response to prescribed fire

Variables	Criteria	Null	Geology	Vegetation	Full	Best model
pH	AIC	-677	-1298	-1209	-1209	Geology
	BIC	-665	-1285	-1196	-1196	
NO_3^-	AIC	3957	3920	3946	3946	Geology
	BIC	3969	3932	3958	3958	
TOC	AIC	-4256	-4264	-4289	-4289	Vegetation
	BIC	-4244	-4252	-4276	-4276	
PO_4^{-3}	AIC	2216	1925	2093	2093	Geology
	BIC	2228	1938	2105	2105	

Table II: Selection of models on soil nutrient temporal dynamics following prescribed fire

Variables	Criteria	Null	Geology	Vegetation	Full	Best model
pH	AIC	-1501	-1872	-1886	-1912	Full
	BIC	-1448	-1819	-1833	-1859	
NO_3^-	AIC	6082	5997	6045	5982	Full
	BIC	6135	6050	6098	6035	
TOC	AIC	-6613	-6530	-6542	-6550	Null
	BIC	-6560	-6477	-6489	-6497	
PO_4^{-3}	AIC	2871	2611	2816	2475	Full
	BIC	2924	2664	2869	2528	

The effects of vegetation types and geological substrates on the soil nutrient response to prescribed fire are discussed separately because only a limited set of vegetation types/ geological substrates combinations are available in the field sites. However, by building separate statistical models incorporating either the vegetation or the geology factors, we could compare the model performance in explaining soil nutrient dynamics. Results indicate **Geology** is the most important variable for explaining soil pH, NO_3^-, and PO_4^{-3}, whereas **Vegetation** is most important in explaining TOC.

Effects of Dominant Plants

Sites were separated into the three dominant vegetation groups and pre-burn values for each property were set to zero to provide a clearer picture of the data trends. Repeated ANOVA and pair comparison tests (at significance level $\alpha = 0.05$) were done. The bottom-line results: dominant plants do not affect temporal response of soil geochemistry to burn events except for pH ($F_{2,432}^{pH} = 4.68$, P = 0.001; $F_{2,432}^{nitrate} = 1.85$, P = 0.16; $F_{2,432}^{TOC} = 2.23$, P = 0.11; $F_{2,432}^{phosphate} = 2.46$, P = 0.09). Burn plots with exotic plants became more acid one year after the burn comparing to control plots, but burn plots and control plots with native and mixed plants do not differ in pH trends after the burn (Fig. 12a). After one year pH was slightly lower on virtually all sites, even on sites with high pedogenic carbonate in the soils. Although there was some fluctuation of values during the year (probably an effect of monsoonal rains), levels of PO_4^{-3} on all burn plots, except for those with mixed plants, decreased only slightly or remained the same level one year after the burn, whereas control plots had decreased significantly over the same period (Fig. 2d). Nitrate behaved in a similar fashion, in that on all burn plots except those with mixed plants, NO_3^- increased one year after the burn comparing to control plots (Fig. 12b), indicating that volatilization was not a significant factor. The combination of nitrate and PO_4^{-3} behavior suggests ash was not removed from the study plots. Although not statistically significant, TOC seemed to be lower on burn plots comparing to control plots with native and mixed plants, and higher on burn plots with exotic plants (Fig. 12c).

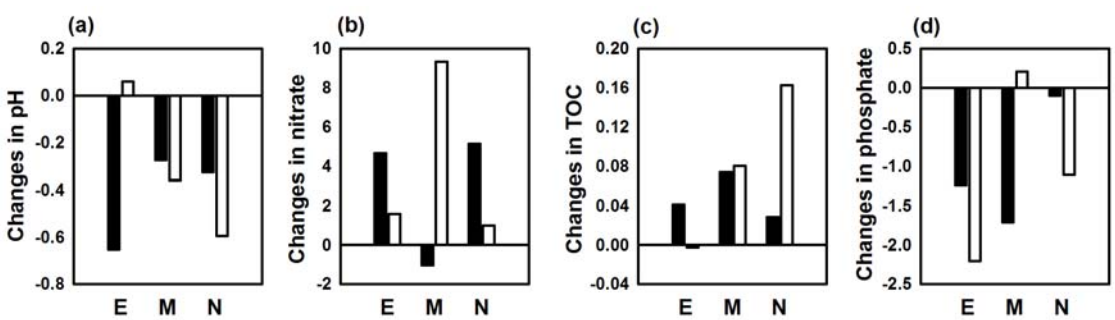


Figure 12. Soil geochemistry response to a burn event on sites with three different types of dominant plants. On each panel, black bars denote burn plots, while white bare denote control plots. Y-axis is the changes in pH (a) at the end of one-year period after the burn event from pre-burn values. Similarly, changes in nitrate is shown in (b), changes in TOC shown in (c), and changes in phosphate shown in (d). On X-axis, “E” is exotic plants, “M” is mixed plants, and “N” is native plants.

Responses of soil characteristics to prescribed fire: the importance of vegetation

In addition to the summary graphs above, changes in each characteristic over time are illustrated (Figures 13A-13D), and a second series of graphs was created in order to distinguish trends in the data within each vegetation category (Figures 14A-14F). The second set of graphs contains the control site data so any trends could be compared to a baseline. A final set of graphs plotted characteristics against one another as shown in Debano and Conrad (1978) (see Appendix A), but we determined there were no trends in characteristic comparisons, so this approach will not be discussed further.

Figure 13A: pH changes through time

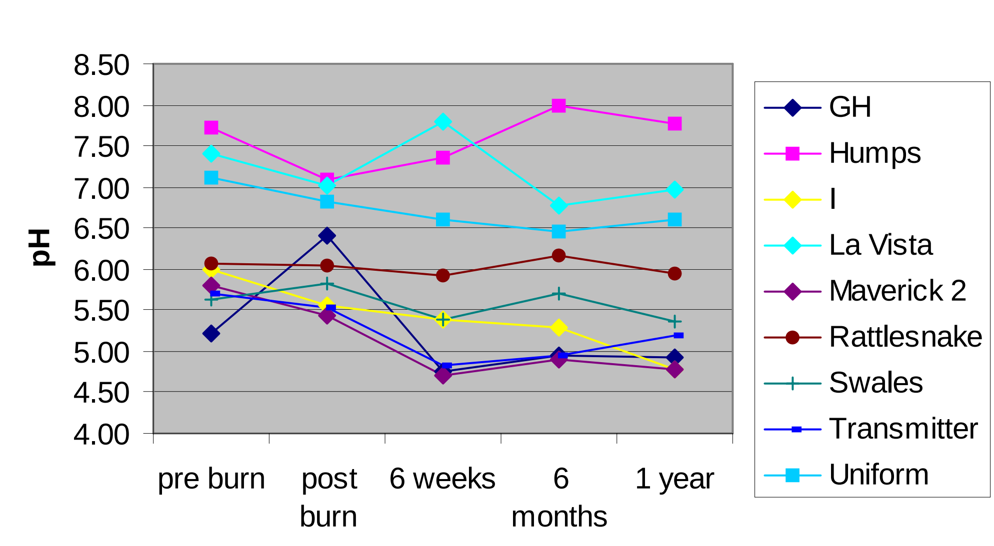
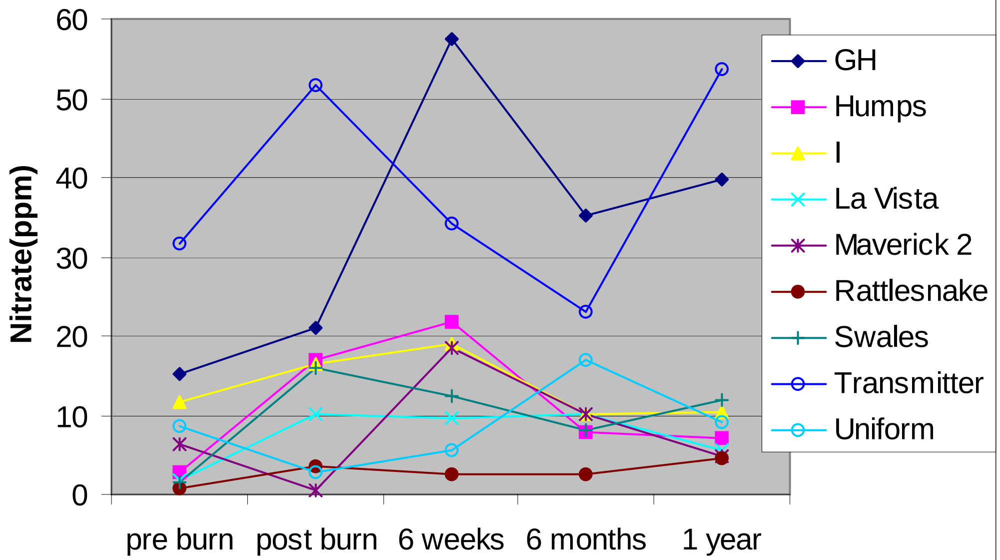


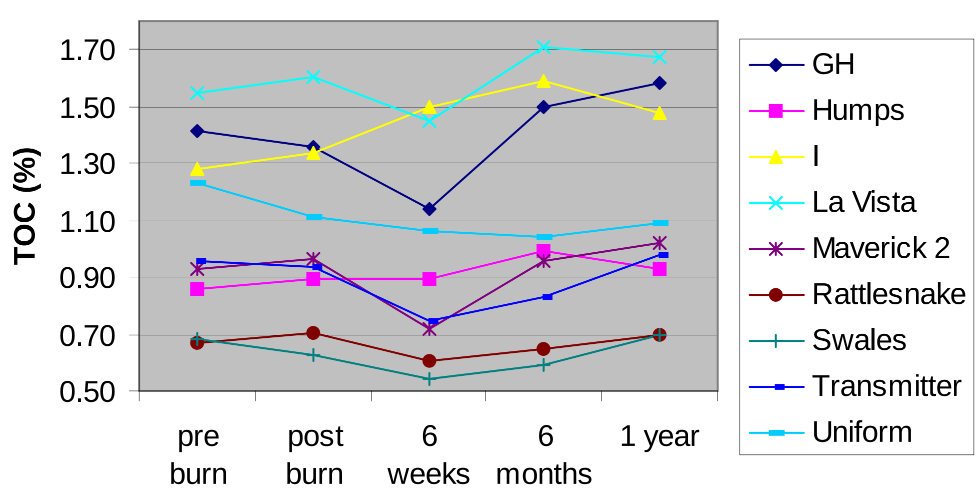
Figure 13B: Nitrate changes through time



Average pH values varied from site to site and the trends over time are shown in Figure 13A. Immediately after the burn event, an overall decrease (increased acidity) was apparent on seven of the nine sites, which follows the expected trend. The majority of sites continued to show an increase in acidity six weeks after the burn, but by six months more than half of the sites were slightly more alkaline. This trend probably reflects renewed biological activity after the monsoon rains of late summer/early fall. Average nitrate values (Figure 13B) increased on nearly all sites immediately after the burn event, but there were no consistent trends in remaining sampling sets. The summer monsoon rains may provide an explanation for such variation in nitrate concentrations. Christenson (1973) reported samples taken after rainfall contained a higher nitrate concentration than those taken prior to rain; conversely, Singh et al (1991) noted a decrease in inorganic nitrogen during the rainy season because increased plant growth uptake any available nitrogen. These contrasting results could suggest something other than vegetation controls the activity of nitrogen in the grasslands.

As expected, average total organic carbon values of the study site soils were low, averaging less than 1.5% on all but one site (Figure 13C). TOC also shows marked variability: immediately after the burn, some of the sites had slightly higher TOC levels, but the others were slightly lower. “Lushness” of pre-burn vegetation – which might have been expected to cause greater amounts of ash deposition – did not seem to matter: Site Uniform (see Figure 8) had a dense cover of native grasses and Site Transmitter a dense cover of lovegrass, yet the average TOC on both sites was lower than the pre-burn values. On the other hand, both Site Humps (native grass dominated) and Site I (mixed grasses) were very rocky with considerable amounts of bare ground between clumps of grasses, yet both sites had higher average post-burn TOC levels than pre-burn. The onset of monsoon rains six weeks after the burn is reflected in reduced average TOC values on most sites, but TOC did increase on most sites after six months and one year, and all sites

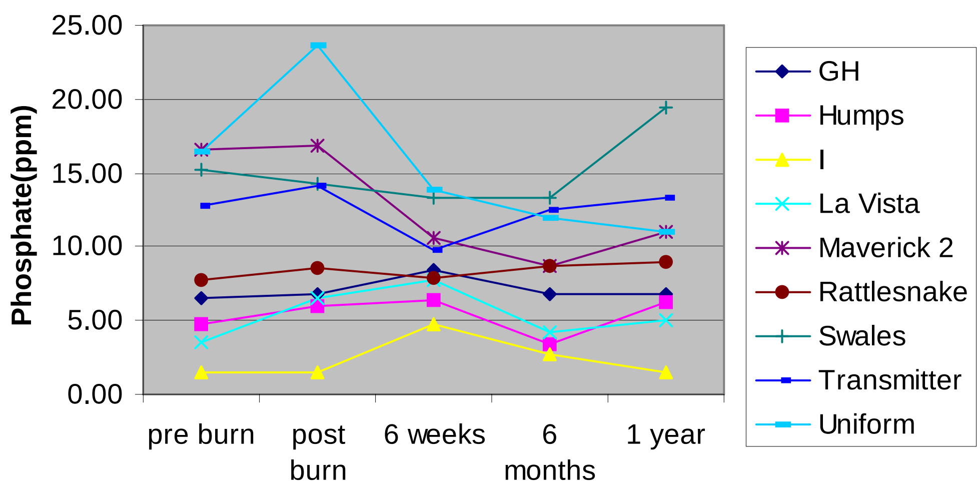
Figure 13C: TOC changes through time



except Site Uniform had higher carbon amounts after one year than before they were burned. This is probably due to plant growth and biological activity rather than ash deposition.

Phosphate (Figure 13D) concentrations increased on eight of the nine sites immediately after the burn event, but there were no consistent trends after six weeks, although three sites had sharp drop-offs that were perhaps the result of runoff. One year after the burn, most of the sites had modest gains in phosphate concentrations over pre-burn levels, although a third of the sites had not recovered to pre-burn levels.

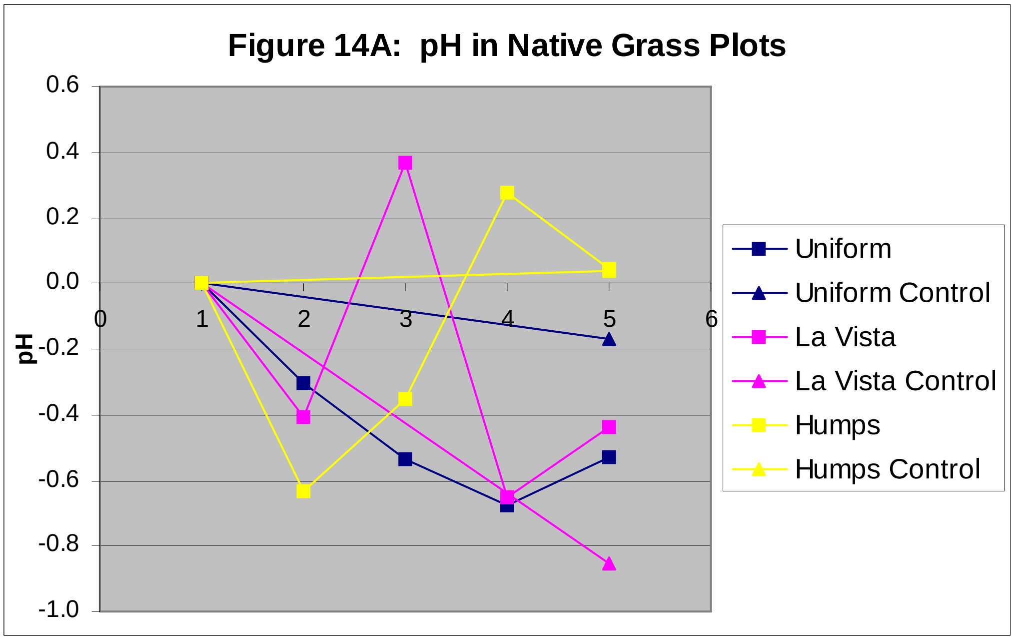
Figure 13D: Phosphate changes through time



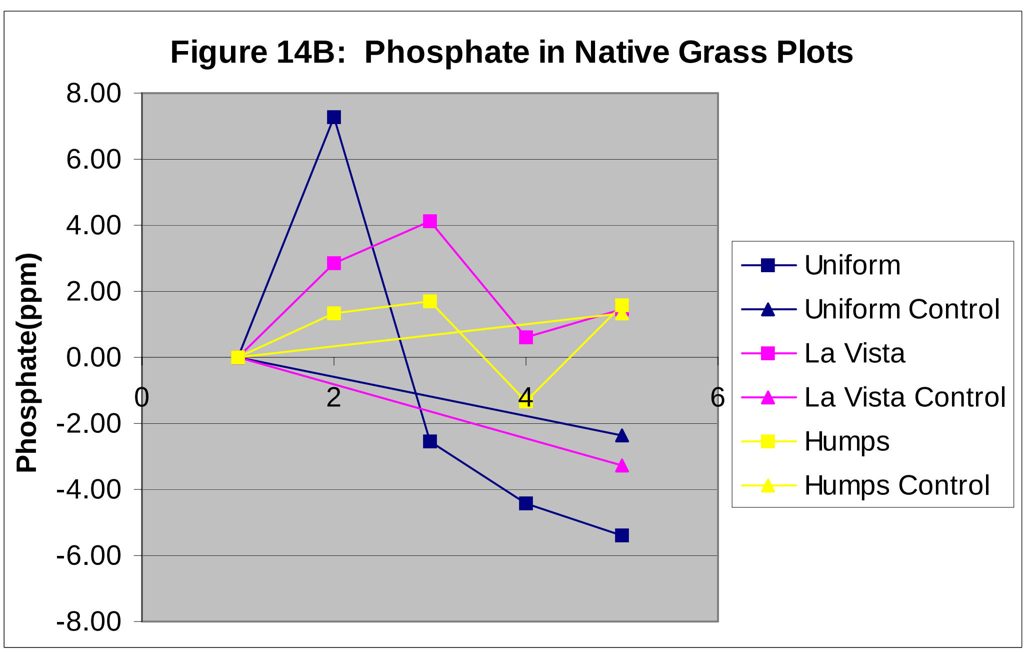
Comparison of the nine sites shows some general patterns of response to burns and recovery of the soil characteristics, but there are large inconsistencies in these gross trends. Therefore, the results were plotted according to dominant vegetation type on the sites, so only three sites were plotted per graph. However, the magnitude of changes were so varied that these graphs were difficult to interpret. To better clarify the data trends, the pre-burn nutrient concentrations were set to zero and the initial characteristic value was subtracted from all subsequent values in order to place them all on the same scale. Only those figures that show important trends are shown in the text; all other graphs can be found in Appendix A.

Native grass sites show a drop in pH value immediately after the burn as shown in Figure 14A. This increase in acidity supports the hypothesis that the pH would decrease immediately after the burn. After the initial drop in pH there is no other trend in common with all three sites. This figure also includes the control plots in order to show recovery of the sites. Site Humps is the only site to have a similar pH one year after treatment as the control plot. Site Uniform is much more acidic than its control plot whereas site La

Vista is more basic than its control because the control plot shows a dramatic decrease in pH.



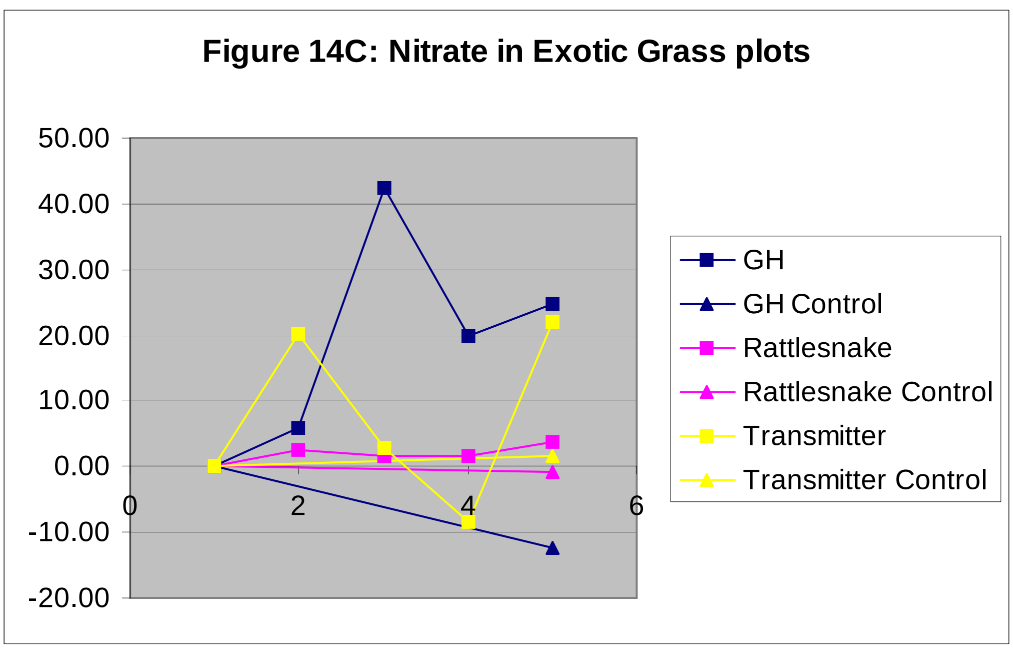
Another strong correlation between native grass plots is shown in phosphate concentrations. Figure 14B shows the zeroed plot of phosphate concentrations. This graph supports another hypothesis: phosphate concentrations will increase immediately after the burn treatment due to ash deposition (Debano and Conrad, 1978; Snyman, 2003). Site Uniform shows the largest increase in phosphate concentration, but with time



the concentration decreases. The decreases in phosphate concentration are most likely due to plant utilization during growth during the rainy season as well as the erosion of the soil particles to which phosphate has adsorbed.

The second vegetation category is the exotic Lehmann's lovegrass dominated plots. The pH values of lovegrass dominated sites decreased six weeks after treatment, although all three sites show an increase in pH after six months. These changes in pH could be due to the release of more acidifying agents from the ash into the soil with the onset of the summer monsoon season and then an uptake of some of these agents either through plants or microorganisms during growth.

Both nitrate (Figure 14C) and phosphate (Figure 14D) concentrations increased in lovegrass sites immediately after the burn. This supports the hypothesis that phosphate concentrations would increase immediately after the burn treatment, but it contradicts the hypothesis that nitrate would be removed from the system through volatilization during the burn treatment. These increases in phosphate and nitrate are due to nutrient redistribution through ash deposition as well as increased nitrification potential in the soil as a result of increased soil temperatures (Sharrow and Wright, 1977; Woodmansee and Wallach, 1981). An alternative explanation for the increase in nitrate is that the fires did not reach high enough temperatures to volatilize the nitrate so it was still contained in the ash (Klemmedson et al., 1962). Six weeks after the burn nitrate concentrations continued to be above the pre-burn levels. After six months nitrate concentrations remained above pre-burn levels for sites GH and Rattlesnake, whereas nitrate concentrations on site Transmitter had fallen below the original concentrations. One-year after the burn treatment, nitrate concentrations rebounded to above the pre-burn levels. This is due to the burn treatment as the control plots show either a decrease in nitrate concentrations or a minimal increase compared to the nitrate concentration increases on treated plots.



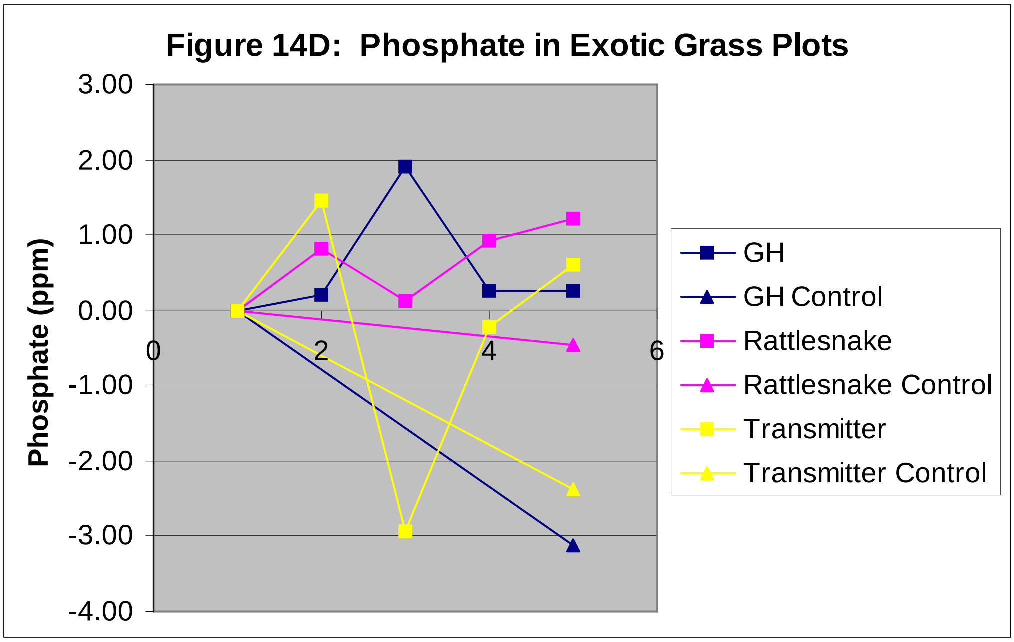
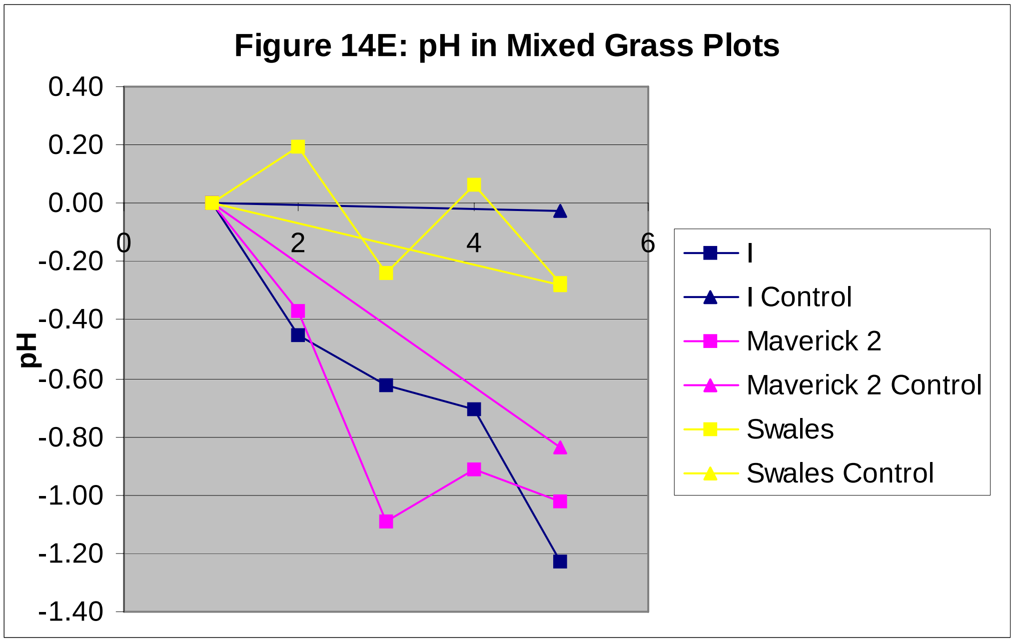
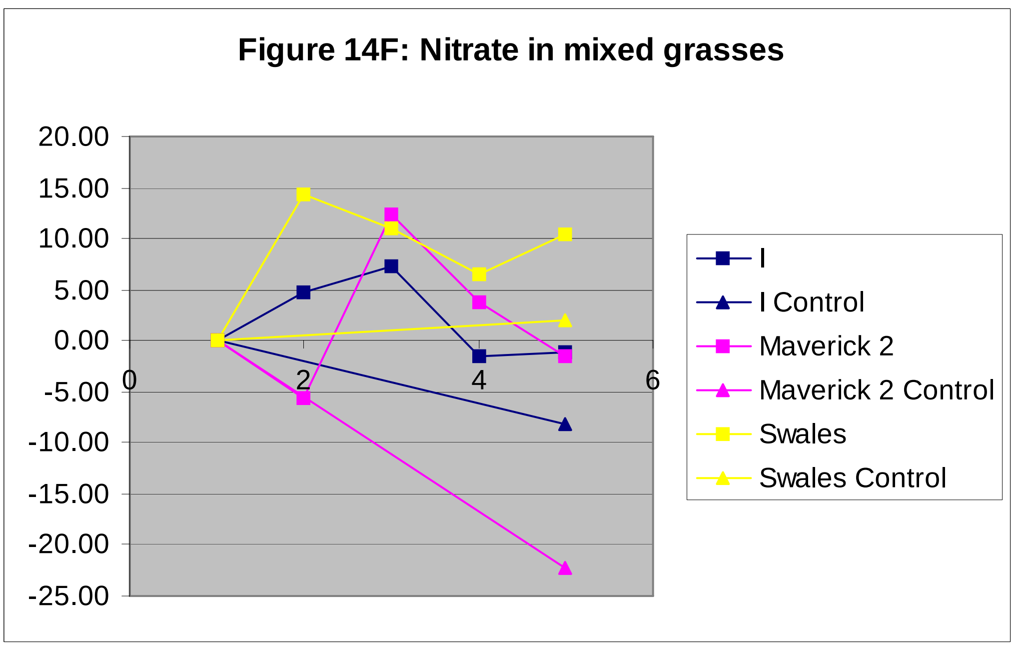


Figure 14D shows similar increases in phosphate concentrations immediately after the burn and one-year after the burn. Adams et al. (1994) attribute the increase in phosphorus concentrations to an increase in mineralization of organic phosphorus. Giovanni et al. (1990) also saw an increase in phosphorus mineralization as a result of soil heating. One year after the burn treatment phosphate concentrations were much higher than the control plot concentrations. These elevated concentrations are due to the burn treatment as the control plots show a sharp decrease in phosphate concentration at the end of the sampling period.

The final vegetation category studied is mixed grass plots, which contain both the native grasses and the exotic grasses, but are dominated by neither. Within these plots, there are few obvious trends in the data. The most apparent trends are in pH and nitrate concentrations. As illustrated in Figure 14E, mixed grass plots decreased in pH after six weeks, which is probably due to the mobilization of acidifying agents from the ash during the summer monsoons. These sites also show a second decrease in pH one year after the burn. These plots also had decreased nitrate concentrations after six months (Figure 14F). This could be due to plant usage during growth or erosion of ash during the monsoon rains. Emmerich (1999) suggested that the primary reason for loss of nutrients, including nitrogen, after fire is through sediment loss. Figure 14F also shows that higher nitrate concentrations were present one year after the burn treatment.

Any long-term increase in the amount of nitrate or phosphate in treated plots is significant for management of the ecosystem. Eight of the nine treated plots show increased nitrate concentrations over the control plots one-year after the burn. Seven of the nine treated plots show a similar increase in phosphate at the one-year sampling. These increases are important because productivity in semi-arid grasslands is considered nutrient-limited (Bennett et al., 2003; Marion et al., 1991). Miles (1958) determined that





the amount of nitrogen in the system regulates the availability of phosphorus. Therefore any increase in nitrogen potentially leads to an increase in the amount of phosphorus in the system. It should follow that if burn treatments can increase the amount of plant-available nitrogen and phosphorus, then the productivity of the ecosystem will increase. Further study of the length of time that these nutrients stay elevated above the untreated plots will give land managers significant insights into the frequency of grassland burns needed to improve the soil for grassland growth.

For statistical analysis, long-term responses and temporal changes were studied. We used this approach because the control plots were sampled on a long-term scale (one year) and could not be compared statistically to the temporal data collected on the treated plots. Four sets of comparisons were examined: between control plots and burn plots using long-term data, between vegetation types using long-term data, between time intervals using temporal data, and between vegetation types using temporal data. Long-term responses of soil characteristics and nutrients to prescribed fire were tested with a repeated ANOVA design (SAS v8.2 proc mixed) where control plots and burn plots were monitored immediately before the prescribed fire, as well as one year after the fire. Following the repeated ANOVA, pairs of control plots and burn plots are compared for native, mixed and exotic vegetation, respectively. These three pair comparisons revealed how vegetation type may have affected the way soil characteristics responded to prescribed fire. All tests are performed at the significance level of $\alpha=0.05$.

The full repeated ANOVA model contains seven different effects: (1) *Vegetation effect* tests whether or not different vegetation types have different levels of soil nutrients, regardless of fire treatment and temporal variation; (2) *Burn effect* tests whether or not burn plots and control plots have different levels of soil nutrients, averaged across pre-burn and post-burn periods; (3) *Time effect* tests whether or not soil nutrients change during the one year period; (4) *Vegetation X Burn effect* tests whether or not the differences between burn plots and control plots vary depending on vegetation types; (5) *Vegetation X Time effect* tests whether or not the differences in soil nutrients before and after fire vary depending on vegetation types; (6) *Burn X Time effect* tests whether or not the differences in soil nutrients before and after fire vary depending on fire treatment; and (7) *Vegetation X Burn X Time effect* tests whether or not the differences in soil nutrients before and after fire varied depending on fire treatment and vegetation types. We will focus our discussion on the two most interesting effects, *Vegetation effect* and *Burn X Time effect*.

Prescribed fire has an effect on pH, NO_3^-, PO_4^{-3}, but not on TOC during the one-year period (Table III: see *Burn × Time effect*). Based on pair comparisons between burn plots and control plots for different vegetation types, we can further describe soil nutrient responses to fire given the vegetation type. Soil pH values at sites with different vegetation types respond to fire differently such that only sites with mixed vegetation showed a significant decrease in pH after fire but not the sites with exotic or native vegetation (Figure 15). The increase in NO_3^- after fire is significant on sites with native vegetation, but not exotic or mixed vegetation sites (Figure 16). Soil TOC increased after fire on sites with exotic vegetation, but not on sites with mixed or native vegetation (Figure 17). Soil PO_4^{-3} showed a general decreasing trend throughout the one-year period on control plots. However, prescribed fire appears to supplement PO_4^{-3} in soil on burn plots on sites with exotic and mixed vegetation, but not on sites with native vegetation (Figure 18).

In addition to fire effect, the type of dominant vegetation has an overall effect on soil pH, TOC and PO_4^{-3} values, but not on NO_3^- values (Table III: *Vegetation effect*).

Table III. Long-term soil nutrient response to prescribed fire

Effect	pH	NO_3^-	TOC	PO_4^{-3}
Vegetation	***	NS	***	***
Burn	NS	NS	NS	*
Time	**	NS	***	NS
Vegetation X Burn	***	***	*	***
Vegetation X Time	***	NS	NS	NS
Burn X Time	*	***	NS	*
Vegetation X Burn X Time	*	NS	NS	NS

NS: non-significance; * =p<0.05; ** = p<0.01; *** = p<0.001

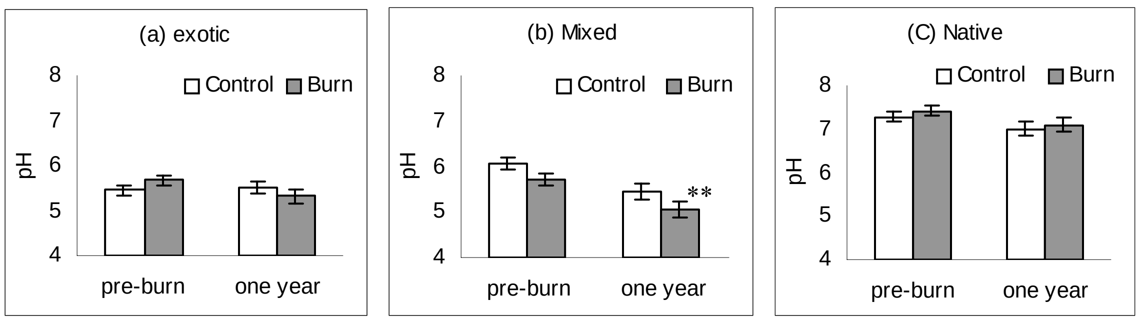


Figure 15: Soil pH response to prescribed fire for exotic, mixed and native vegetation
* =p<0.05; ** = p<0.01; *** = p<0.001

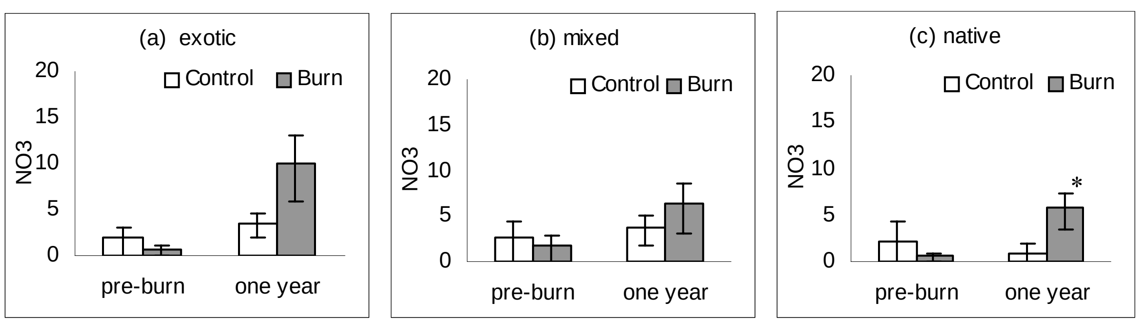


Figure 16: Soil NO_3^- response to prescribed fire for exotic, mixed and native vegetation
* =p<0.05; ** = p<0.01; *** = p<0.001

Sites with native vegetation have higher pH and TOC values than sites with either exotic or mixed vegetation (Figure 14 and Figure 16). PO_4^{-3} values, on the other hand, are highly dynamic such that they differ among all three vegetation types with native vegetation sites having the lowest PO_4^{-3} values and mixed vegetation sites having the highest PO_4^{-3} values (Figure 18).

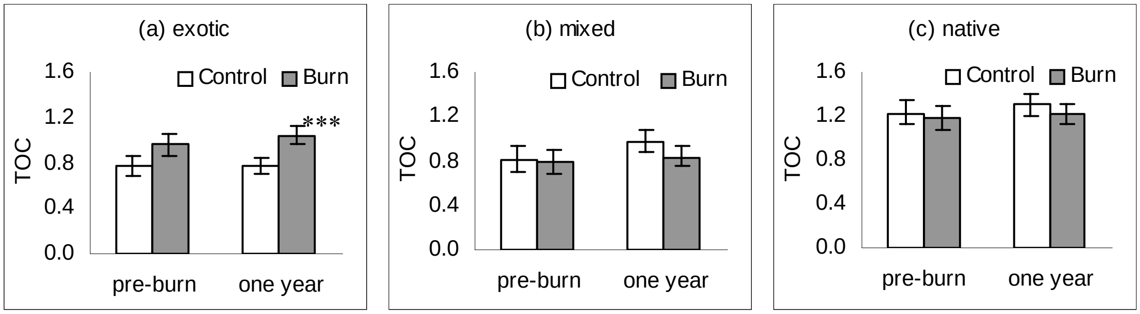


Figure 17: Soil TOC response to prescribed fire for exotic, mixed and native vegetation
* =p<0.05; ** = p<0.01; *** = p<0.001

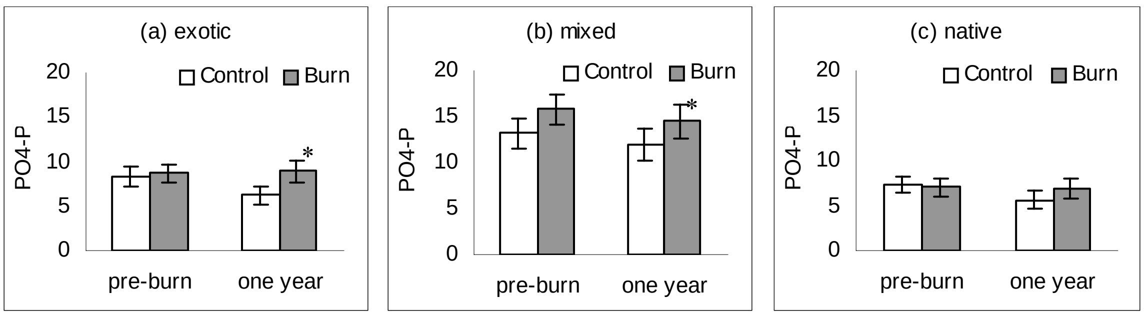


Figure 18: Soil PO_4^{-3} response to prescribed fire for exotic, mixed and native vegetation
* =p<0.05; ** = p<0.01; *** = p<0.001

Temporal changes in soil characteristics after prescribed burning

Temporal changes in soil nutrients on burn plots were monitored at five time intervals: pre-burn, 1 week after fire, 6 weeks after fire, 26 weeks (6 months) after fire, and 52 weeks (one year) after fire. Pre-burn levels are compared with nutrient levels at successive time periods to reveal the temporal patterns of soil nutrient recoveries after fire. We specifically tested the effect of dominate vegetation on the temporal changes of soil characteristics after the burn event with a repeated ANOVA design (SAS v8.2 proc mixed). Following repeated ANOVA, we compared soil nutrients in each successive period with pre-burn period for each of the vegetation types, namely, pre-burn versus week 1, pre-burn versus week 6, pre-burn versus week 26 and pre-burn versus week 52. These pair comparisons can be used to estimate the time period(s) needed for soil characteristics to recover from fire for a given vegetation type. Because multiple non-independent comparisons were done simultaneously, the significance level was adjusted with Bonferroni method to control the experiment-wise error rate at α=0.05.

Soil pH, NO_3^-, TOC and PO_4^{-3} changed significantly over time after the fire treatment (Table IV: *Time effect*). With the exception of TOC, the temporal changes after fire differed among vegetation types (Table IV: *Vegetation* × *Time effect*). In addition, vegetation types had an overall effect on soil pH and TOC levels throughout the monitoring period (Table IV: *Vegetation effect*).

Table IV: Temporal changes in soil nutrients after prescribed fire

Effect	pH	NO_3^-	TOC	PO_4^{-3}
Vegetation	***	NS	**	NS
Time	***	***	***	***
Vegetation X Time	***	***	NS	***

NS: non-significance; * =p<0.05; ** = p<0.01; *** = p<0.001

The pair comparisons showed that:

1) pH values on sites with native vegetation were consistently higher than on sites with mixed or exotic vegetation. Prescribed fire had a stronger negative effect on pH levels at sites dominated by mixed and exotic vegetation compared to sites with native vegetation. Examination of the native vegetation sites showed soil pH levels decreased immediately after burning, but recovered to pre-burn levels six weeks after burning; soil pH values decreased slightly again after six months and remained lower than pre-burn levels through the end of the one-year monitoring period. This secondary decline is probably due to seasonal events other than the prescribed fire. On mixed and exotic vegetation sites, soil pH values began to decrease at week 6 and did not recover to pre-burn levels at any successive time period before the end of the one-year period (Figure 19A). The difference between native vegetation sites and the exotic and mixed sites suggests that native vegetation has some buffering effect that enables soil pH values to more rapidly recover from fire.

2) NO_3^- values showed an increasing trend throughout the one-year period. There are no differences in NO_3^- values among vegetation types. However, the temporal patterns in NO_3^- changes differed among vegetation types: sites with exotic vegetation appeared to peak first (one week after the burn), followed by native vegetation (six weeks) and mixed vegetation (six months). At the end of the one-year period, the amount of NO_3^- increase was higher at sites with exotic vegetation than sites with either mixed or native vegetation (Figure 19B). This suggests that exotic vegetation is most sensitive to NO_3^- increase.

3) TOC values responded similarly to pH values in that they are consistently higher at sites with native vegetation than sites with mixed or exotic vegetation. TOC levels decreased slightly after six weeks but recovered to pre-burn level by the end of the one-year period. This temporal pattern is similar for native, mixed and exotic vegetation (Figure 19C). TOC response to prescribed fire was generally minor and was least affected by vegetation types, compared to the other soil characteristics studied here.

4) PO_4^{-3} values increased immediately after the burn, but decreased to pre-burn levels after one year at sites with native vegetation. However, sites with exotic or mixed vegetation did not show any significant temporal fluctuations in PO_4^{-3}. There was no overall difference in PO_4^{-3} among vegetation types throughout the one-year period (Figure 19D). The result suggests that PO_4^{-3} levels are most sensitive to prescribed fire at sites with native vegetation.

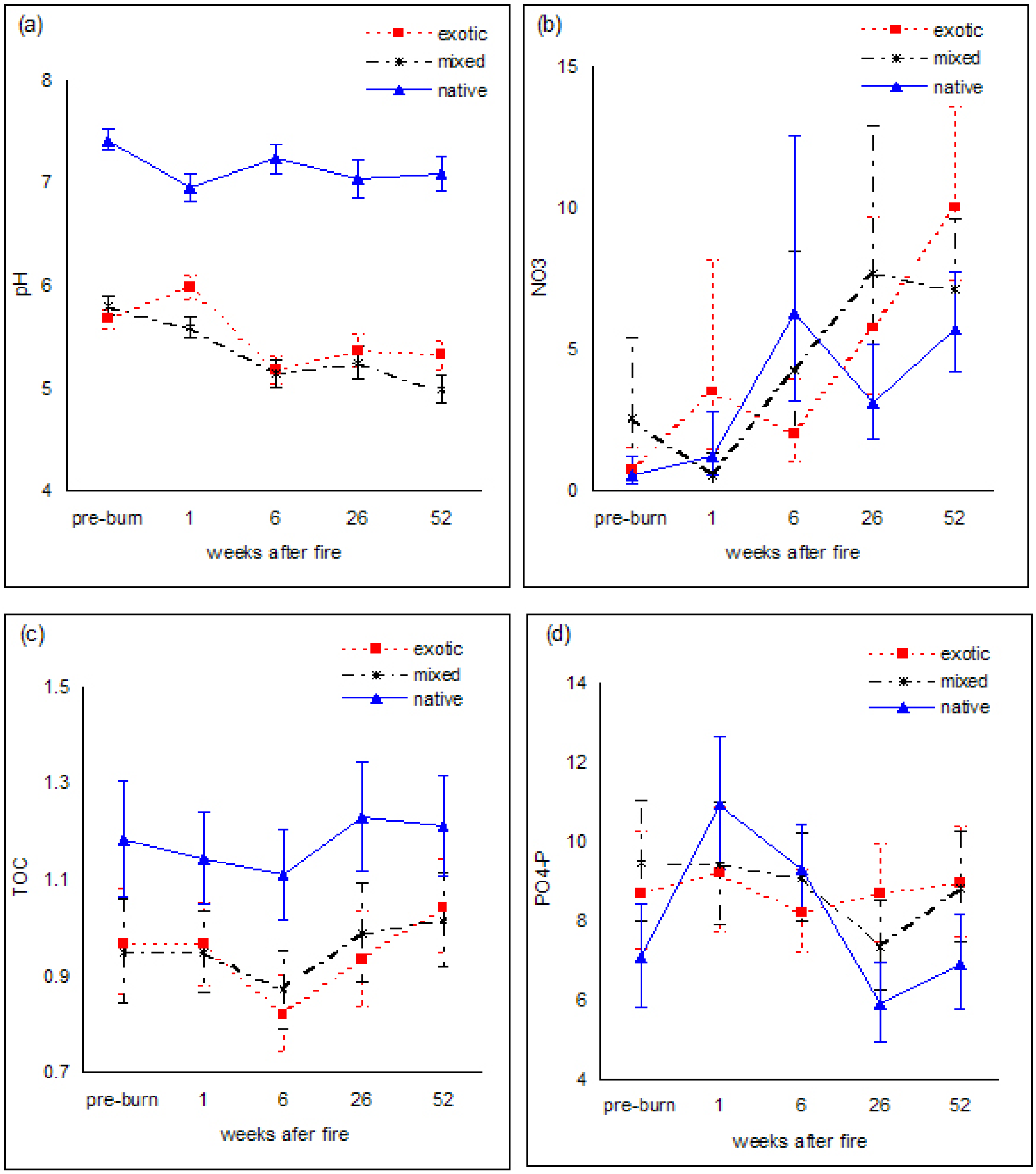


Figure 19: Temporal changes in soil nutrients after prescribed fire for native, mixed and exotic vegetation types. 95% confidence intervals are plotted around the means.

The main conclusions apparent in this research suggest plant-available nitrate and phosphate increase after burn treatment due to ash deposition. Nitrate concentrations remained elevated above pre-burn levels at least one year after the burn event. Phosphate concentrations on treated plots were higher than phosphate concentrations on control plots one year after the burn treatment. Further investigations to determine how much longer these controlling nutrients remain elevated could allow determination of the frequency of burns necessary to be beneficial to the fertility of the grasslands ecosystem.

Effects of Geology

Because the original design of the controlled burns project was concerned with dominant vegetation, we did not have equal numbers of plots for each vegetation/ substrate combination. However, with repeated ANOVA and pair comparison tests (at significance level $\alpha = 0.05$) done based on four geological substrate type, we found that except for TOC, the temporal changes in soil geochemistry after the burn differed among the geological substrates ($F_{3,430}^{pH} = 5.27$, P = 0.001; $F_{3,430}^{nitrate} = 6.38$, P < 0.001; $F_{3,430}^{TOC} = 1.59$, P = 0.19; $F_{3,430}^{phosphate} = 6.47$, P < 0.001). Specifically, soil became more acid one year after the burn on early-middle Pleistocene and Holocene substrates, but not other substrates (Fig. 20a). Nitrates increased on burn plots comparing to control plots at early Pleistocene sites, but not at other sites (Fig. 20b). Phosphate decreased slightly or remained at the pre-burn concentration on burn plots comparing to control plots at all sites except for early-middle Pleistocene, which showed a significant decrease in PO_4^{-3} on burn plots (Fig. 20d). All types of dominant plants/geological substrates combined, fire has an effect on pH, NO_3^-, and PO_4^{-3} but not on TOC during the one-year time period. In addition, dominant plants/geological substrates have an overall effect on all four characteristics studied, regardless of burn treatments and background temporal variations.

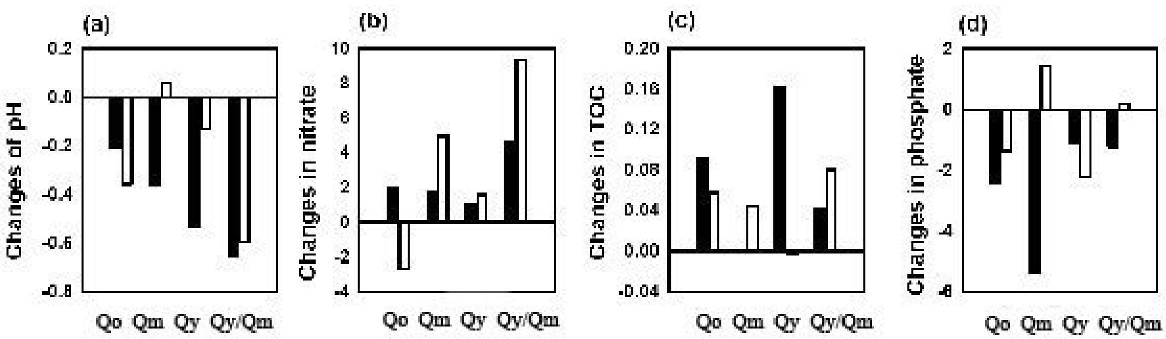


Fig. 20. Soil geochemistry response to a burn event on sites with four different types of geological substrates. On each panel, black bars denote burn plots, while white bare denote control plots. Y-axis is the changes in pH (a) at the end of one-year period after the burn event from pre-burn values. Similarly, changes in nitrate is shown in (b), changes in TOC shown in (c), and changes in phosphate shown in (d). On X-axis, “Qo” is early Pleistocene, “Qm” is early-middle Pleistocene, “Qy” is Holocene, and “Qy/Qm” is late Pleistocene veneered surface.

Responses of soil characteristics to prescribed fire: the importance of Geology

As illustrated in Figure 13A (above), average pH values varied markedly between the sites. This is a reflection, in part, of the geologic substrate as well as the dominant vegetation. Both of the sites located on Qo surfaces – which are high in pedogenic carbonate – have the most alkaline soils. The lone Qy surface also had soils that averaged just below neutral: as much of the alluvial material that covers that site originated from carbonate bedrock in the Huachuca Mountains carried out of Garden Canyon and it is too young for soil processes to have altered it, this result is not surprising. The four Qmo or Qm surfaces and two veneered surfaces, with the clay-rich soils, were more acid. Results for TOC, PO_4^{-3} and NO_3^- indicate the importance of substrate were not as clear.

To see beyond the average sample values, long-term responses of soil characteristics to prescribed fire were tested with a repeated ANOVA design (SAS v8.2 proc mixed) where control plots and burn plots were monitored immediately before the prescribed fire, as well as one year after the fire. Following the repeated ANOVA, pairs of control plots and burn plots were compared for early Pleistocene (Qo), early-middle Pleistocene (Qm), Holocene (Qy) and “Veneered” (Qy/Qm) surfaces, respectively. These four pair comparisons revealed how geological substrates may have affected the way soil nutrients respond to prescribed fire. All tests are performed at the significance level of α=0.05.

The full repeated ANOVA model contains seven different effects: (1) *Geology effect* tests whether or not different geological substrates have different levels of soil nutrients, regardless of fire treatment and temporal variation; (2) *Burn effect* tests whether or not burn plots and control plots have different levels of soil nutrients, based on the values averaged across pre-burn and post-burn periods; (3) *Time effect* tests whether or not soil nutrients change during the one year period; (4) *Geology X Burn effect* tests whether or not the differences between burn plots and control plots vary depending on geological substrates; (5) *Geology X Time effect* tests whether or not the differences in soil nutrients before and after fire vary depending on geological substrates; (6) *Burn X Time effect* tests whether or not the differences in soil nutrients before and after fire vary depending on fire treatment; (7) *Geology X Burn X Time effect* tests whether or not the differences in soil characteristics before and after fire vary depending on fire treatment and geological substrates. We will focus our discussion on two most interesting effects, *Geology effect and Burn X Time effect*.

Prescribed fire had an effect on pH, NO_3^-, PO_4^{-3}, but not on TOC during the one-year period (Table V: see *Burn × Time effect*). Based on pair comparisons between burn plots and control plots for different geological substrates, we could further describe soil

Table V: Long-term soil response to prescribed burning

Effect	pH	NO_3^-	TOC	PO_4^{-3}
Geology	***	*	***	***
Burn	NS	NS	NS	**
Time	***	***	*	***
Geology X Burn	***	*	**	*
Geology X Time	***	NS	NS	**
Burn X Time	*	***	NS	*
Geology X Burn* X Time	*	**	NS	**

NS: non-significance; * =p<0.05; ** = p<0.01; *** = p<0.001

responses to fire given the geological substrates. Soil pH values decreased after prescribed fire on Qy and Qy/Qm surfaces but not on Qo or Qm plots (Figure 21). NO_3^- levels increased after fire at sites on early Pleistocene substrates but not on other

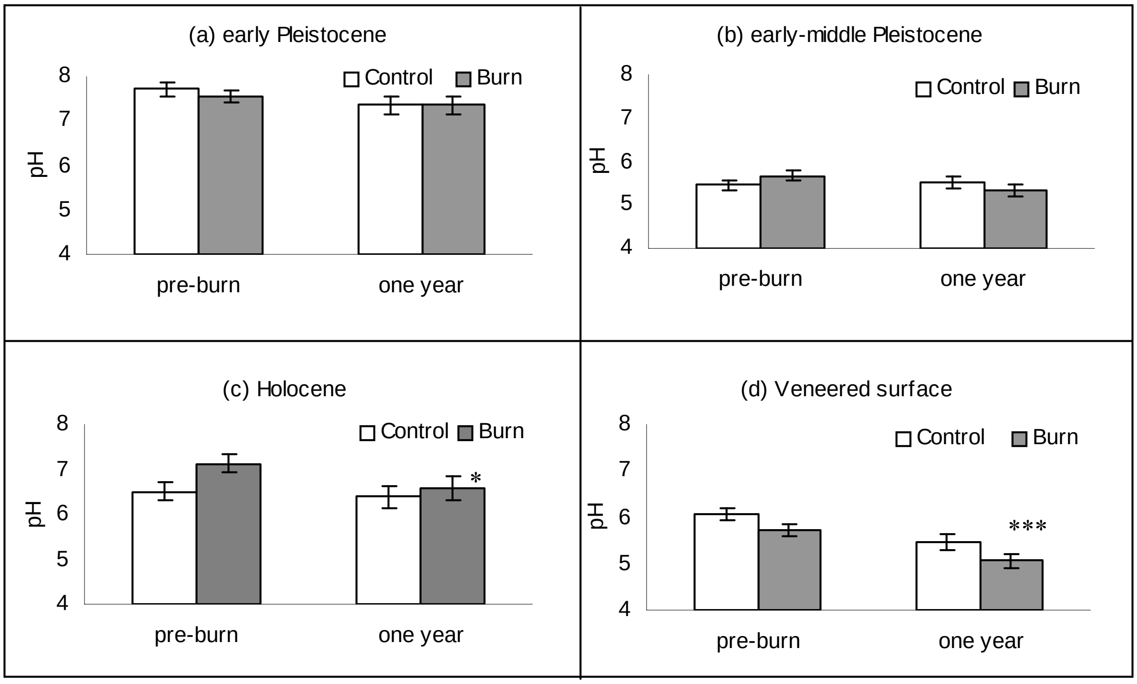


Figure 21: Comparisons of soil pH response to prescribed fire among geological substrates NS: non-significance; * =p<0.05; ** = p<0.01; *** = p<0.001

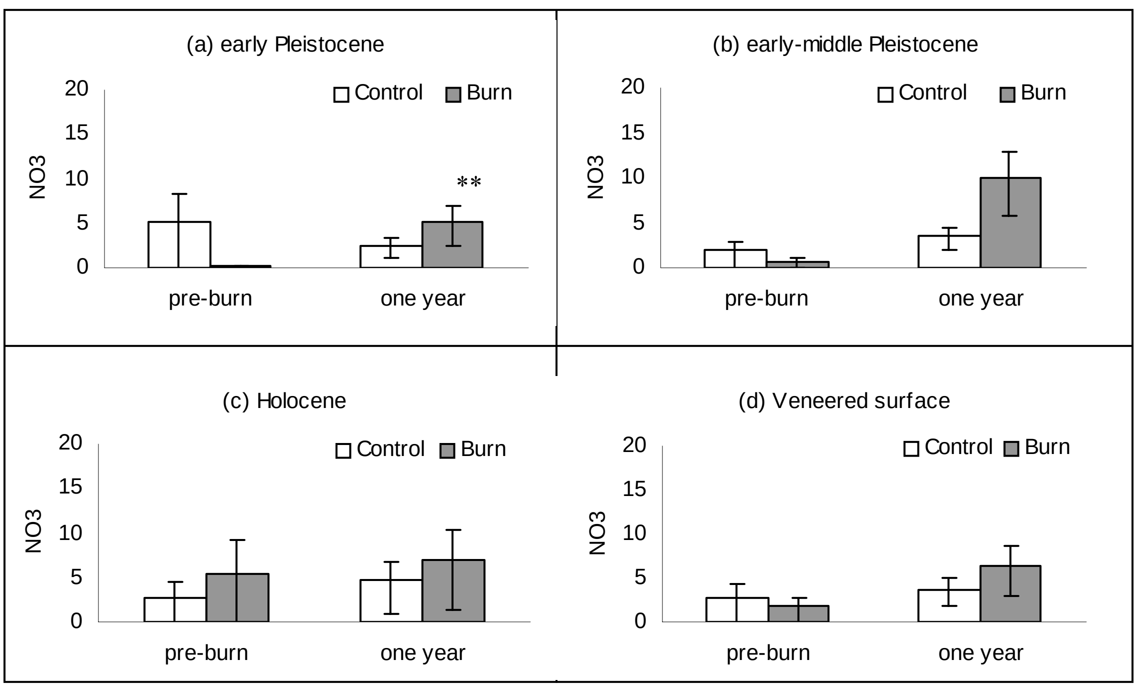


Figure 22: Comparisons of soil NO_3^- response to fire among geological substrates
NS: non-significance; * =p<0.05; ** = p<0.01; *** = p<0.001

geological substrates (Figure 22). TOC levels increased after fire at sites on early-middle Pleistocene but not on other geological substrates (Figure 23). PO_4^{-3} levels decreased after fire at sites on all geological substrates except for early Pleistocene (Figure 24).

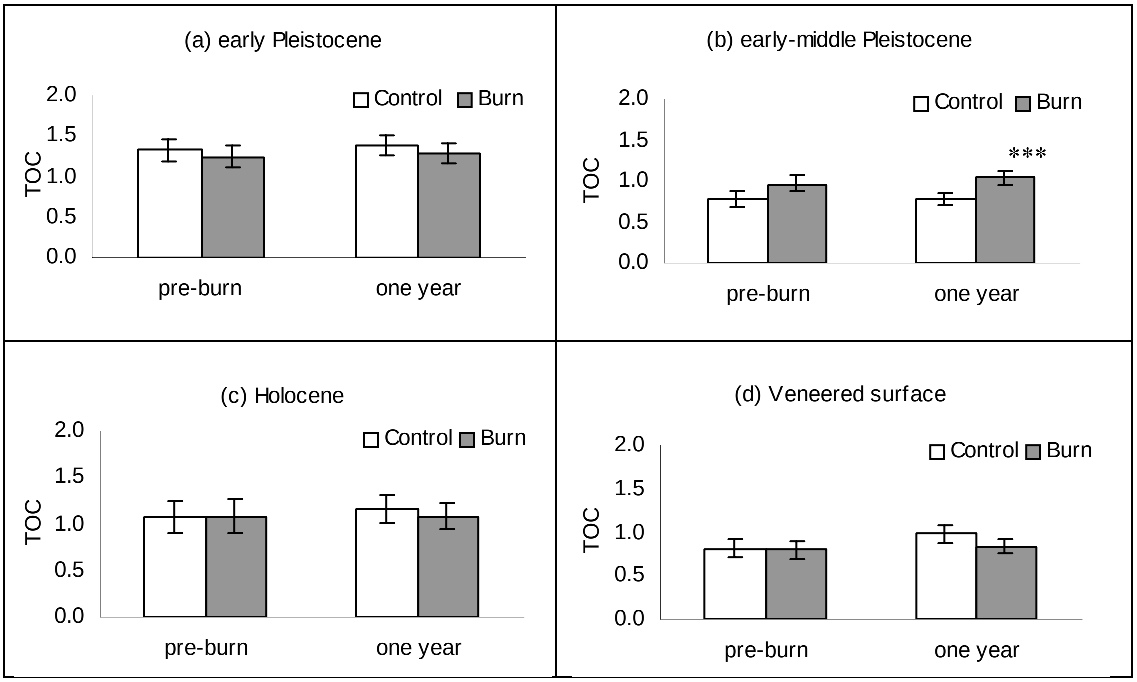


Figure 23: Comparison of soil TOC response to fire among geological substrates
NS: non-significance; * =p<0.05; ** = p<0.01; *** = p<0.001

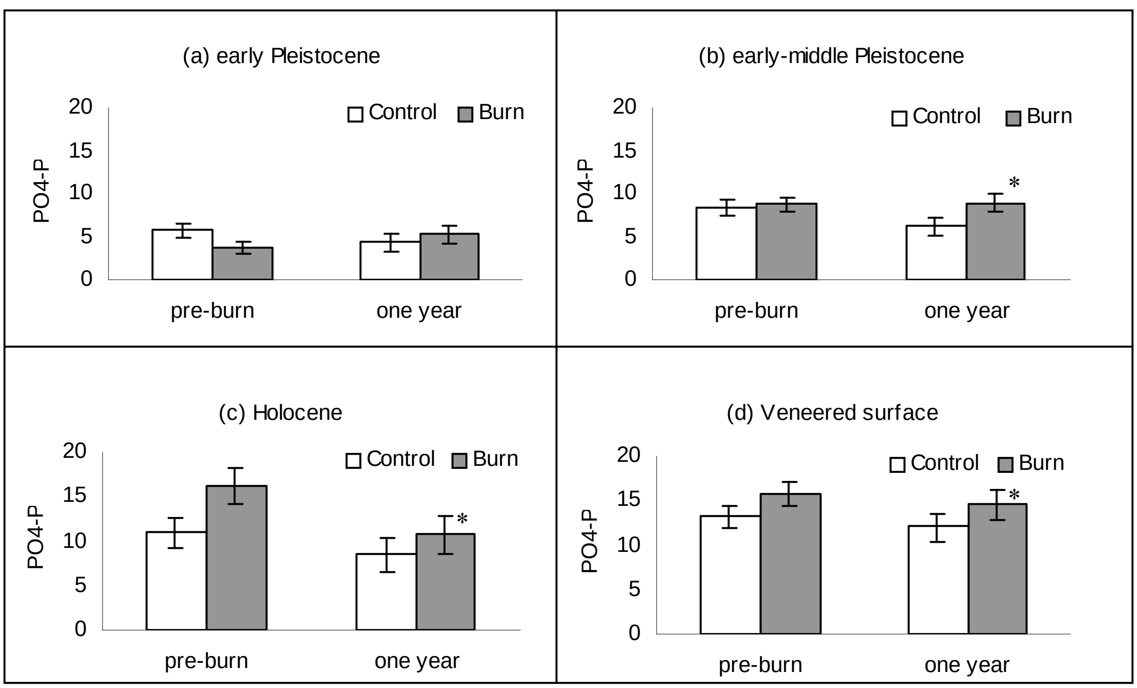


Figure 24: Comparison of soil PO_4^{-3} response to burning among geological substrates
NS: non-significance; * =p<0.05; ** = p<0.01; *** = p<0.001

In addition to fire effect, geological substrates have an overall effect on soil pH, NO_3^-, TOC, and PO_4^{-3} (Table V: *Geology effect*). Early Pleistocene (Qo) sites have the highest overall soil pH and TOC levels, followed by Holocene (Qy), whereas early-middle Pleistocene (Qm) and "Veneered" (Qy/Qm) surfaces have lowest pH and TOC levels (Figure 21 and Figure 23). NO_3^- levels are similar across geological substrates except a slightly higher level on pre-burn Holocene compared to the other surfaces (Figure 22). PO_4^{-3} levels are highest on "Veneered" surfaces after one year, followed by Holocene, early-middle Pleistocene and lowest on early Pleistocene (Figure 24).

Temporal changes in soil characteristics after prescribed fire

Temporal changes in soil characteristics on burn plots were monitored at five time intervals: pre-burn, 1 week after fire, 6 weeks after fire, 26 weeks (6 months) after fire, and 52 weeks (one year) after fire. Pre-burn values were compared with nutrient levels at successive time periods to reveal the temporal patterns for recovery of soil characteristics after fire. We specifically tested the effect of geological substrates on the temporal changes of soil nutrients after fire with a repeated ANOVA design (SAS v8.2 proc mixed). Following repeated ANOVA, we compared soil nutrients in each successive period with pre-burn period for each of the geological substrates, namely, pre-burn versus week one, pre-burn versus week six, pre-burn versus six months and pre-burn versus one year. These pair comparisons can be used to estimate the time period needed for soil nutrients to recover from fire for a given geological substrate. Because multiple non-independent comparisons are done simultaneously, the significance level is adjusted with Bonferroni method to control the experiment-wise error rate at α=0.05.

Soil pH, NO_3^-, TOC and PO_4^{-3} changed significantly over time after the fire (Table VI: *Time effect*). With the exception of TOC, the temporal changes after fire differed among geological substrates (Table VI: *Geology × Time effect*). In addition, geological substrates had an overall effect on soil pH, TOC and PO_4^{-3} levels throughout the monitoring period (Table VI: *Geology effect*).

Table VI: Temporal changes in soils after prescribed fire

Effect	pH	NO_3^-	TOC	PO_4^{-3}
Geology	***	NS	***	***
Time	***	***	***	***
Geology X Time	***	***	NS	***

NS: non-significance; * =p<0.05; ** = p<0.01; *** = p<0.001

In order to trace detailed temporal response of soil geochemistry to the burn event at any given substrate and vegetation type combination, we compare data from the burn plots taken at five time intervals during the one-year period (Fig. 25), and we found:

1) Soil pH levels were lower one week after fire treatment on early Pleistocene sites, recovered to pre-burn levels by week 6, and remained slightly lower than pre-burn levels

at the end of the one-year period. Soil pH levels dropped by week 6 at sites on Early-middle Pleistocene, Holocene and “Veneered” surfaces, and remained below original values at all successive time periods (Figure 25a).

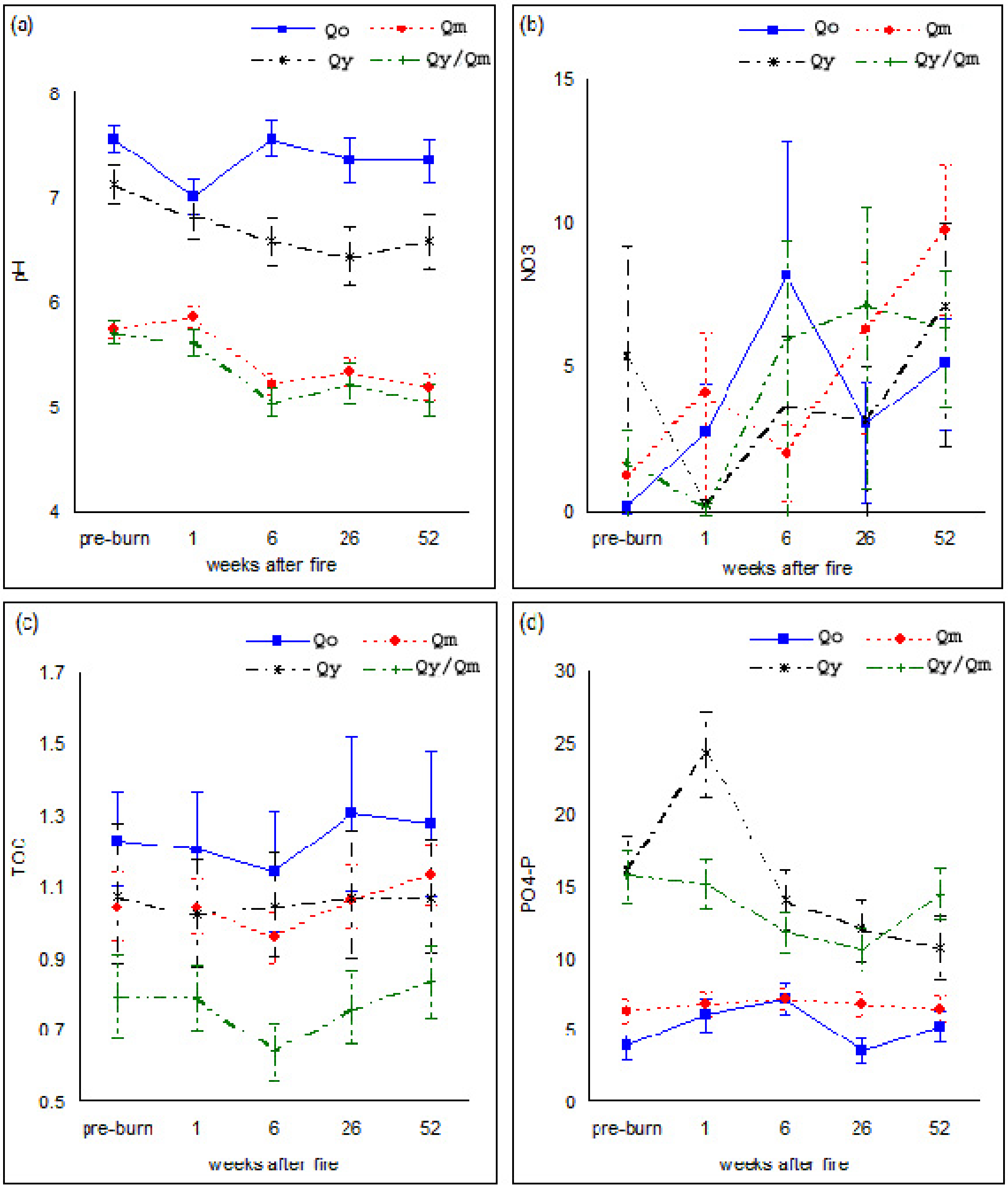


Figure 25: Temporal changes in soil pH (a), NO_3^-(b), TOC(c) and PO_4^{-3}(d) after prescribed fire. Week 0 is the pre-burn value, and week 1, week 6, week 26 and week 52 are values taken at each time period after the burn. Filled circles denote “early Pleistocene substrate with native plants”; open circles denote “early-middle Pleistocene substrate with exotic plants”; filled triangles denote “early-middle Pleistocene substrate with mixed plants”; open triangles denote “Holocene substrate with native plants”; filled squares denote “late Pleistocene veneered surface substrate with mixed plants”. These are the five unique combinations of geological substrate+vegetation type at the study site.

2) NO_3^- levels at sites on early Pleistocene and early-middle Pleistocene surfaces increased immediately after fire treatment and stayed consistently higher than pre-burn levels throughout the one-year period. However, Holocene and "Veneered" surfaces did not show a significant change in NO_3^- over time compared to pre-burn levels (Figure 25b).

3) TOC levels showed a slight decrease six weeks after the burn event, but overall there was no significant temporal change in TOC after fire. This lack of temporal pattern was consistent across all geological substrates (Figure 25c).

4) PO_4^{-3} levels decreased immediately after fire on early Pleistocene surfaces but recovered to pre-burn levels by week 26. A similar pattern was seen on "Veneered" surfaces where PO_4^{-3} levels decreased by week 6 and recovered to pre-burn levels by week 52. On the Holocene surface, PO_4^{-3} levels increased immediately after burning, then dropped at week 6 and remained at lower-than-pre-burn levels throughout the one-year period. Lastly, early-middle Pleistocene sites did not show any significant temporal changes in PO_4^{-3} levels. At any given time period, PO_4^{-3} levels were consistently higher at sites on Holocene and "Veneered" surfaces (Figure 25d).

CONCLUSIONS

Any long-term increase in the amount of nitrate or phosphate in treated plots is significant for management of the ecosystem. Eight of the nine treated plots showed increased nitrate concentrations over the control plots one-year after the burn. Seven of the nine treated plots showed a similar increase in phosphate at the one-year sampling. The increases in nitrate and phosphate are important because productivity in semi-arid grasslands is considered nutrient-limited.

The surficial geology of the study sites was the main control on soil characteristics and response to burn events. This study also examined soil characteristics with regard to the dominant vegetation present on the sample plots. Dominant grass vegetation – native, non-native, or mixed – had little effect on the response of soil geochemistry to fire events. The concentration of plant-available nitrate and phosphate did increase after the burn treatment due to ash deposition. Nitrate concentrations remained elevated above pre-burn levels one year after the burn. In addition, phosphate concentrations on treated plots were higher than phosphate concentrations on control plots one year after the burn. Debano and Conrad (1978) found a significant loss of nitrogen in hot chaparral fires, whereas another study (Emmerich, 1999) in grassland fires reported an absence of significant nutrient loss immediately after a burn event and concluded soil was the major control on nutrient loss. Results of this study suggest the intensity of the fires was not hot enough to volatilize these nutrients, and the nature of the geological substrate and degree of soil development does play a significant role in nutrient response. Dominant grass vegetation – native, non-native, or mixed – had little effect on the response of soil geochemistry to fire events.

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Appendix A: Geochemical data for all sites: available on accompanying CD

Appendix B: GPS data for all sites: available on accompanying CD

PLATES

Map Explanation for Plates 1, 2, and 3

Plates 1, 2 and 3 depict the surficial geology of part of Fort Huachuca in Cochise County, southeastern Arizona. This surficial geology was mapped primarily using 1:24,000-scale 1987 color aerial photographs obtained from the U.S. Forest Service and Fort Huachuca. The physical characteristics of Quaternary alluvial surfaces (channels, alluvial fans, floodplains, stream terraces) evident on aerial photographs and in the field were used to differentiate their associated deposits by age. In addition, we drew upon the mapping and soils analyses conducted by the Natural Resources Conservation Service (NRCS, 2003). Original mapping was done on aerial photos. This mapping was transferred to a digital orthophoto base from 1996. Mapping was compiled in a GIS format and the final linework was generated from the digital data. Surficial deposits of the map area were then correlated with similar deposits in this region in order to roughly estimate their ages.

The physical characteristics of Quaternary alluvial surfaces (channels, floodplains, stream terraces, and alluvial fans) were used to differentiate their associated deposits by age. Alluvial surfaces of similar age have a distinctive appearance and soil characteristics because they have undergone similar post-depositional modifications. They are different from both younger and older surfaces. Terraces and alluvial fans that are less than a few thousand years old still retain clear evidence of the original depositional topography, such as of bars of gravel deposits, swales (trough-like depressions) where low flows passed between bars, and distributary channel networks, which are characteristic of active alluvial fans. Young alluvial surfaces have little rock varnish on surface clasts and have little soil development, and typically they are minimally dissected. Old fan and terrace surfaces, in contrast, have been isolated from substantial fluvial deposition or reworking for hundreds of thousands of years. These surfaces are characterized by strongly developed soils with clay-rich argillic horizons, well-developed tributary stream networks that are entrenched a few meters to tens of meters below the fan surface, and in some cases cemented calcium-carbonate horizons.

Surface and soil characteristics were used to correlate alluvial deposits and to estimate their ages. The ages of alluvial surfaces in the southwestern United States may be roughly estimated based on these surface characteristics, especially soil development (Gile and others, 1981). Surface pits and exposures along cut banks were used to assess soil characteristics associated with deposits of different ages and from different sources. Soils and surfaces documented in the map area were generally correlated with soils and surfaces described in Quaternary mapping studies of adjacent areas conducted by Menges and McFadden (1981), Demsey and Pearthree (1994), Shipman and Ferguson (2003), Pearthree (2004), and Youberg and others (2004). These correlations were also used to roughly estimate the ages of surficial deposits in the map area.

Map Unit Descriptions

Qyc – **Modern channel deposits.** Unit Qyc consists primarily of deposits in active channels of the larger tributary drainages, but includes vegetated bars and low terraces. Channel deposits are mapped where they are extensive enough to represent at 1:24,000 scale. Deposits are composed of primarily of sand, pebbles, and cobbles; and small boulders. Locally channels are incised as much as 2 to 3 meters below adjacent Holocene terraces (unit Qy), but in other areas there is no incision. Channels consist of single, relatively large channels and smaller branching channels in areas of channel expansions. Local relief within channels varies from minimal to more than 1 meter between low-flow channels and adjacent gravel bars.

Qy – **Holocene valley bottom alluvium.** Unit Qy consists of young deposits in low terraces and small channels in valley bottoms. Deposits vary widely in particle size, but generally are quite fine, consisting mainly of sand and silt, with minor fine gravel and clay. Small channels generally are incised less than 1 m below adjacent Qy terraces and fans. Channel morphologies generally consist of a single-thread channel or multi-threaded channels. Local relief on Qy deposits generally is minimal, as terrace surfaces typically are planar, but small channels are also common on terraces. Soil development associated with Qy deposits is weak to moderate. Soil clay accumulation is minimal, and calcic horizon development is typically stage I (see Machette, 1985, for description of stages of calcium carbonate accumulation in soils). Terrace and fan surfaces are brown, and on aerial photos they generally appear darker than surrounding areas.

Ql – **Late Pleistocene alluvium.** Unit Ql consists of deposits associated with moderately dissected terraces and small relict alluvial fans. It also includes some deposits on toeslopes of dissected ridges. Active channels are a few meters or less below Ql surfaces. Ql fans and terraces are lower in elevation than adjacent Qi2 and older surfaces, but elevation differences are minimal in some places. Ql deposits generally consist of pebbles, cobbles, and finer-grained sediment. Ql surfaces commonly have loose, open lags of pebbles and cobbles; surface clasts exhibit weak rock varnish; surfaces appear orange on color aerial photos, reflecting slight reddening of surface clasts and the surface soil horizon. Ql soils are moderately strongly developed, with orange to reddish brown clay loam to light clay argillic horizons and stage II calcium carbonate accumulation.

Qm – **Middle Pleistocene alluvium.** Unit Qm consists of moderately dissected relict alluvial fans and terraces with moderate to strong soil development. Qm surfaces are drained by well-developed, moderately to deeply incised tributary channel networks; channels are typically several meters to as much as 10 m below adjacent Qm surfaces. Qm deposits typically consist of sand, pebbles and cobbles. Qm surfaces are characterized by scattered cobble to boulder lags with moderate to strong varnish. Well-preserved, planar Qm surfaces are smooth with scattered pebble and cobble lags; surface color is reddish brown and rock varnish on surface clasts is typically orange or dark brown; surfaces have a distinctive bright red color on color aerial photos, reflecting reddening of the surface soil and surface clasts. Soils typically contain red clay argillic horizons, with obvious clay skins and subangular to angular blocky structure. Underlying soil carbonate development is typically stage II to III, with abundant carbonate to depths of at least 1.5 m in the soil profile, but indurated petrocalcic horizons were not observed.

Qmo – **Middle to early Pleistocene alluvium.** Unit Qmo consists of deposits associated with deeply dissected relict alluvial fans with variable soil development. Qmo surfaces are drained by well-developed, deeply incised tributary channel networks. Surfaces vary from well rounded with few planar remnants of the original deposition surfaces to quite well-preserved, planar fan remnants. Qmo surfaces are typically 5 to 20 meters above adjacent active channels. Qmo deposits are not well-exposed, but probably consist of primarily of pebbles, cobbles, sand and fines. Where Qmo surfaces are fairly well preserved, they are smooth with pebble and cobble lags; rock varnish on surface clasts is typically orange to red. Soil carbonate development is variable, but typically is stage III. Where surfaces are well preserved, soils typically contain dark red, clay loam argillic horizons, with obvious clay skins and subangular blocky structure. More eroded Qmo surfaces are characterized by loose cobble lags with moderate to strong varnish, ridge-and-valley topography, and carbonate litter on the side slopes. On aerial photos, ridge crests on Qmo surfaces typically are dark reddish brown, reflecting reddening of the surface soil and surface clasts, and eroded slopes are gray to white.

Qmd – **eroded slopes formed middle to early Pleistocene alluvium.** Unit Qmd consists of deeply incised and degraded Pleistocene alluvial fan deposits with variably developed soils. Qmd deposits are eroded and dissected by deeply incised channels locally, but their margins may be buried by younger deposits. Depending on local conditions, soils may contain abundant clay, but in other areas most soil has been eroded off of older underlying deposits. Surfaces commonly have an open gravel lag. Qmd surfaces typically are fairly dark and reddish in color on aerial photos.

QTs – **Late Tertiary to early Quaternary basin-fill deposits.** Unit QTs consists primarily of hillslope deposits formed on fine, highly eroded basin-fill deposits. QTs surfaces typically are alternating eroded ridges and valleys, with ridgecrests typically at least 10 above adjacent active channels. Surfaces are drained by deeply incised tributary channel networks and even the highest surfaces atop ridges are rounded. QTs deposits typically are covered by hillslope colluvium and are poorly exposed, but where exposed they consist of tan to reddish sand and gravel. Some beds are moderately indurated, but generally QTs deposits are weakly indurated. On aerial photos, QTs surfaces are generally gray to white, but include some dark reddish brown areas where clay is more abundant.

pCg – **weathered Precambrian granite.**

d – Profoundly disturbed areas, including excavated dikes, ponds, or military facilities that completely obscure the underlying geologic units.

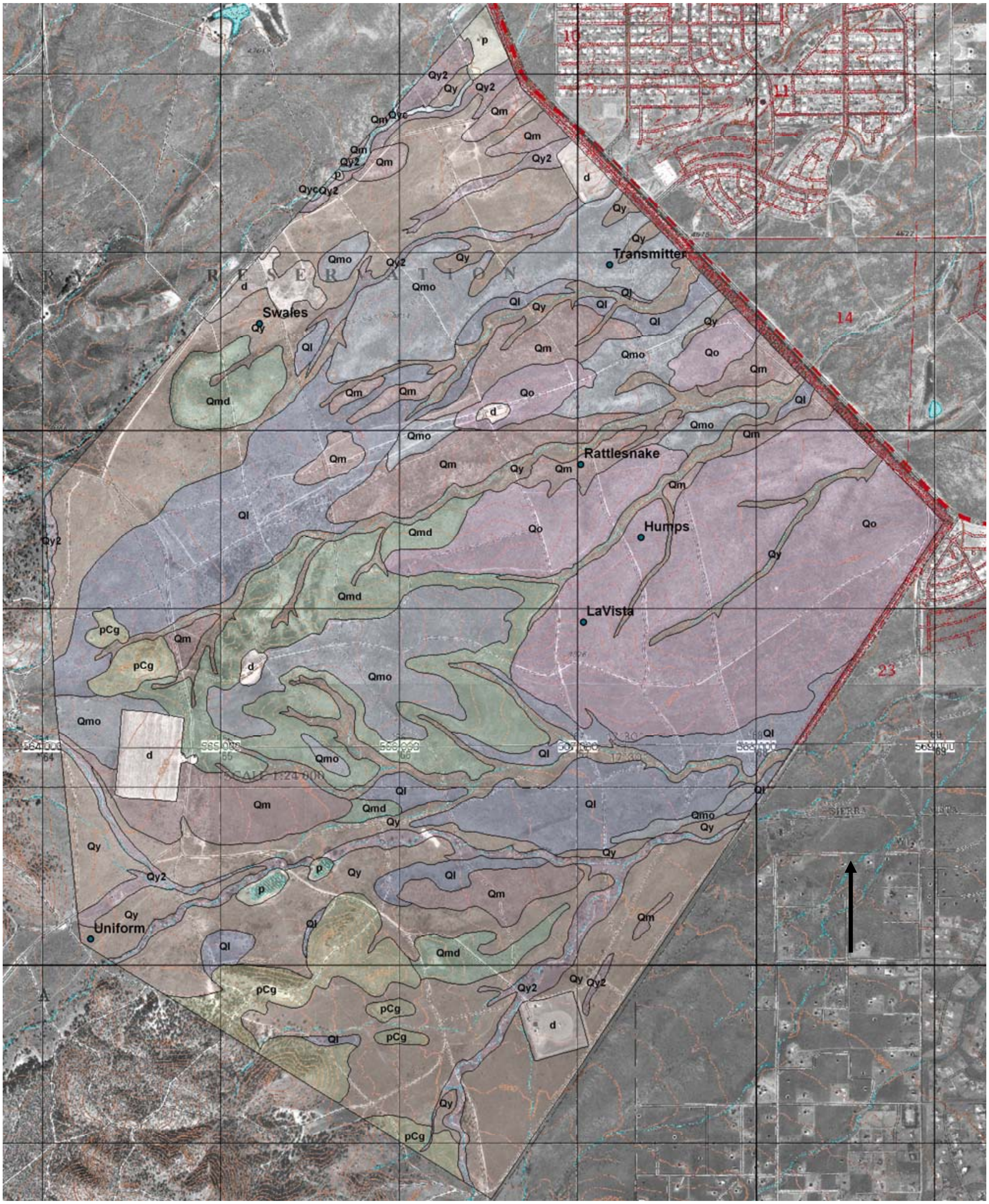

Plate 1. South Range surficial geology and field sites Swales, Transmitter, Rattlesnake, Humps, LaVista, and Uniform. Black squares are 1 km per side; black arrow indicates north. Scale 1:33,000

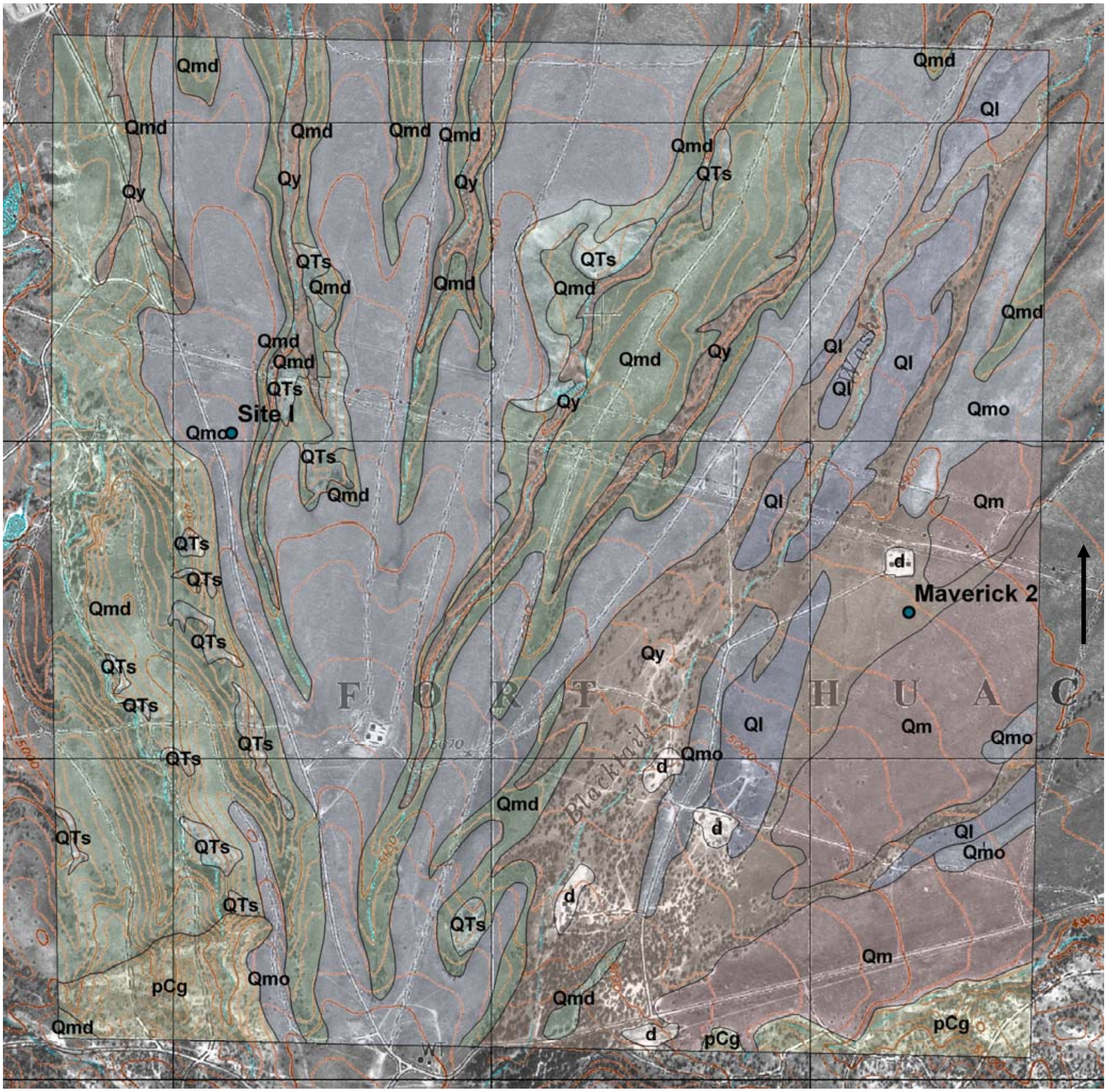

Plate 2. West Range surficial geology and field sites I and Maverick 2. Black squares are 1 km per side; arrow indicates north. Scale 1:20,000.

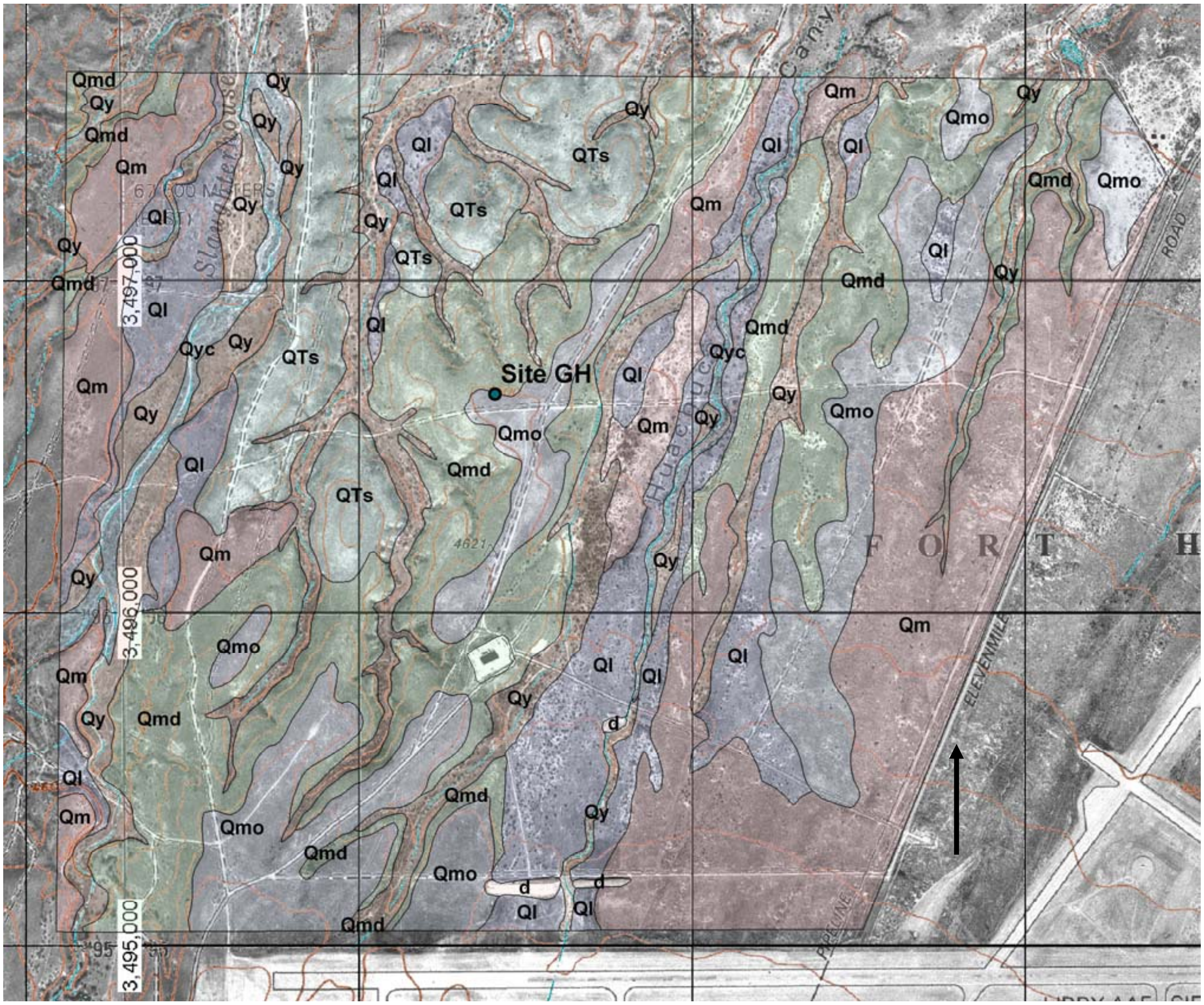

Plate 3. Surficial geology around Site GH. Black squares are 1 km per side; arrow indicates north. Scale 1:20,000.