The Effects of Fire Events on Soil Geochemistry in Semi-Arid Grasslands

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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. Our research investigates the effects of fire events on selected soil characteristics (pH,* NO_3^-, PO_4^{-3}, *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, post-burn results indicate geology is the most important variable for soil pH,* NO_3^-, *and* PO_4^{-3}. *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 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 role geology plays in grassland ecosystems.*

Introduction

Information describing the physical framework in semiarid grasslands is critical for identifying solutions to land use and environmental issues. Desert grasslands are water limited but nutrient regulated: soil fertility is determined by the concentration of essential nutrients in soils, and nutrient availability to plants is determined by the ability of soil to supply those nutrients to plant roots. These nutrients include phosphorus in the bio-available form phosphate (PO_4^{-3}) and nitrogen in the nitrate form (NO_3^-). Phosphorus is critical to plant biomass production because it controls the accumulation and availability of nitrogen and carbon in ecosystems. Nitrogen can be fixed by plants from the atmosphere, but the amount of phosphorus is limited by the geologic substrate. Soil pH is an important factor in determining the solubilities of plant nutrients. Total organic carbon (TOC) is a measure of productivity in the grasslands. Management strategies may be thwarted by changes in the distribution and availability of soil nutrients, which are strongly affected by fire (Wright, 1980).

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). One 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), which has begun to dominate significant areas of the grasslands in large part due to disturbance events (Anable et al. 1992). The likely decrease in wildlife diversity in Lehmann-dominated areas, the less palatable character compared to native grasses, and the increase in fire frequencies (Anable et al. 1992) accompanying the increased dominance of non-native grass species are perceived to be detrimental to resource management goals such as maintenance of quality wildlife habitat and livestock grazing values.

Soil character may affect the levels and spatial distribution of nutrient concentrations which in turn may determine the competitiveness of native over non-native plants in semiarid grasslands. Improved understanding of the substrate could improve management techniques of the grasslands environment. The objectives of this project were to map the alluvial geology, determine the physical soil properties of the study sites, and examine the effects of a burn event on selected soil characteristics.

Study Sites and Methods

The study area is located on the Fort Huachuca Military Reservation along the eastern flank of the Huachuca Mountains in the upper San Pedro River Basin in southeast Arizona. The three types of grasslands—native grass-dominated, non-native lovegrass-dominated, and mixed native and non-native grasses—represent a continuum of invasion by non-native species. Paired 1-hectare treated and control plots were created on 18 sites distributed over the reservation, with nine of the sites burned in 2001 and nine in 2002. Within each plot, a 30-meter by 30-meter subplot was defined, and from each subplot 25-30 randomly distributed soil samples were taken from the treated and control sites. Sampling was repeated on the burned plots immediately after, 6 weeks after, 6 months after, and 1-year after the burn treatment. Control sites were sampled a second time one year after the burn. Analyses for key soil characteristics (pH, NO_3^-, PO_4^{-3}, and TOC) were done. The geology was determined through interpretation of aerial photographs and field work to produce geologic maps and descriptions of study site geomorphology.

Results

Geology of the sites

The study sites (figure 1) are underlain by alluvial fans composed of rock material transported from the adjacent Huachuca Mountains. Study sites were located on four different age surfaces. Relative topographic height, surface morphology,

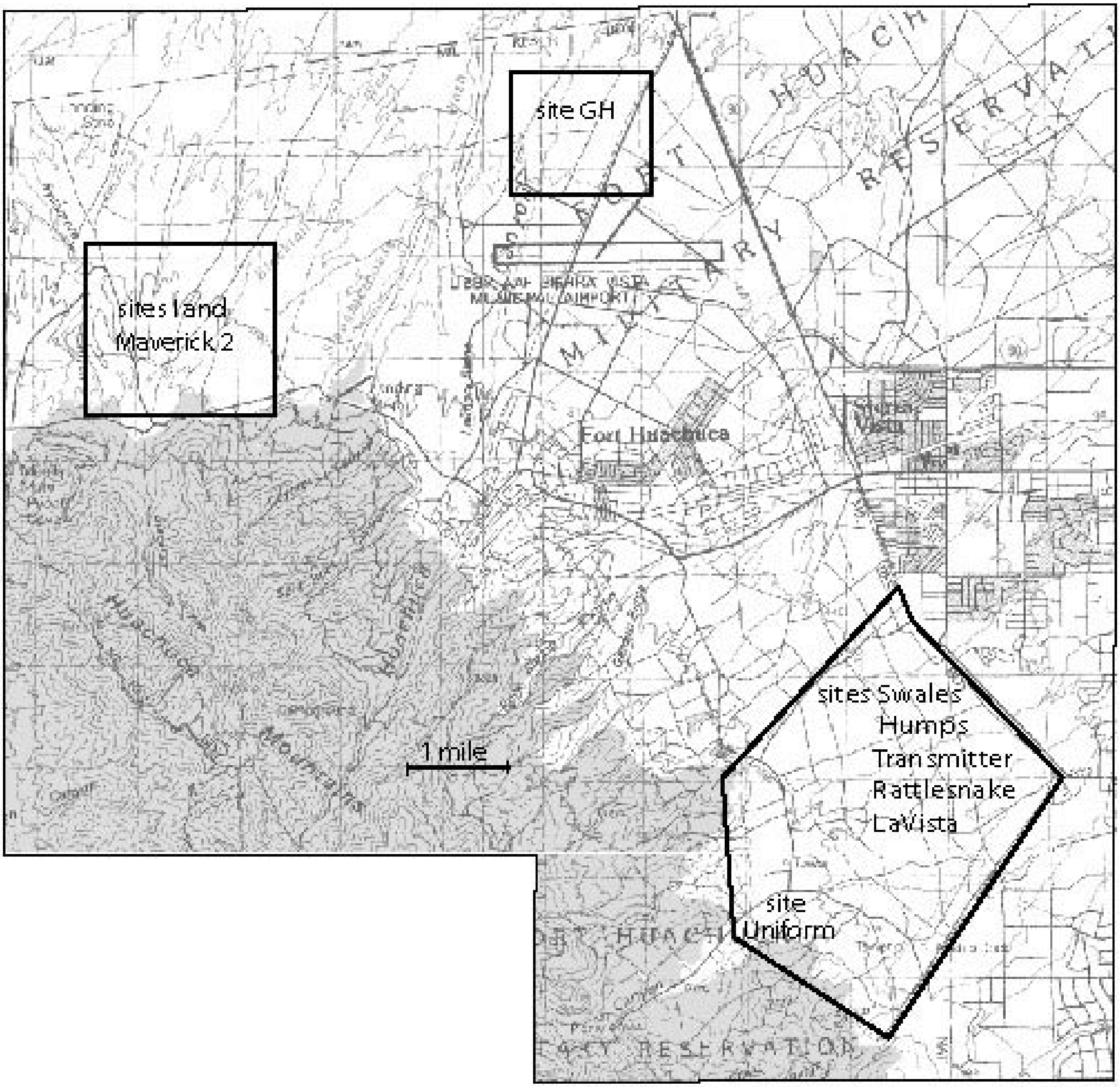

Figure 1—Locations of burned plots and proposed surficial geologic map areas. Proposed surficial geologic map areas are outlined by bold lines and incorporate all of the burned plots. The diamond-shaped map area in the southeastern part of Ft. Huachuca will be contiguous with existing surficial geologic mapping in Garden Canyon (Huckleberry 1996) and off of the base (Demsey and Pearthree 1994).

and soil development are key indicators of alluvial surface age. Older fan surfaces have more rounded, often dissected topography, and have strongly developed soils with thick clay and/or calcium carbonate-rich horizons. Younger fan surfaces often retain features of the original depositional topography and have weak soil development.

The age estimates of the alluvial units at Fort Huachuca are based on comparisons with similar depositional units described in earlier studies in the San Pedro Valley (Pearthree 2004; Demsey and Pearthree 1994; Huckleberry 1996). One plot (site Uniform) is on a Holocene (**H**) fan composed of brown (10YR colors) coarse micaceous loamy sand with only incipient soil development, and covered with lush native grasses. Four plots are located on early-middle Pleistocene (**emP**) fan surfaces (sites GH, I, Rattlesnake, and Transmitter). These surfaces have reddish orange (5 to 2.5YR colors) very bouldery clay-rich soils; vegetation on three of the sites is dominated by Lehmanns; site I has mixed grasses with abundant agave. Two sites (Humps and LaVista) are on early Pleistocene (**eP**) surfaces and both 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. Two sites (Maverick 2 and Swales) are on “veneered” late Pleistocene fan surfaces (**Vs**) 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.

Soil Geochemistry

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 α = 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 (figure 2a). 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 (figure 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 (figure 2b), 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 compared to control plots with native and mixed plants, and higher on burn plots with exotic plants (figure 2c).

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 α = 0.05) done based on four geological substrate types, 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,

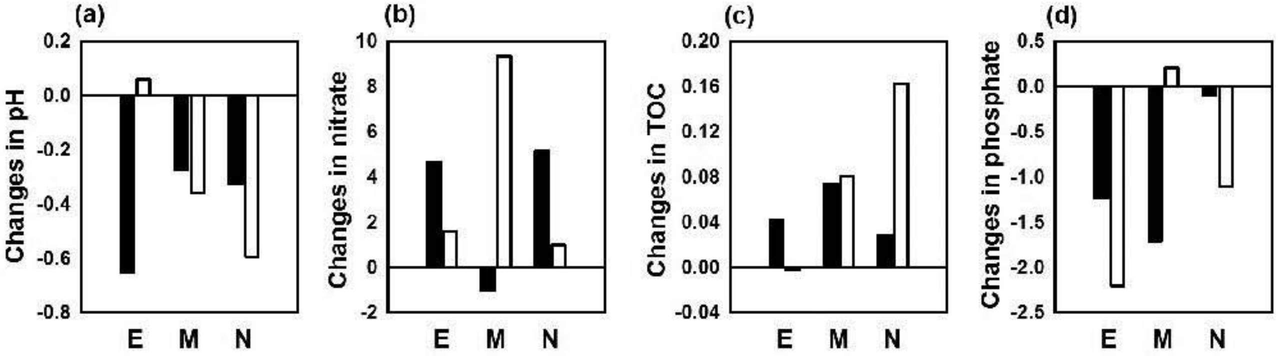

Figure 2—Soil geochemistry response to a burn event on sites with three different types of dominant plants. On each panel, black bars denote burn plots, while white bars denote control plots. Y-axis is the changes in pH (a) at the end of one-year period after the burn event from pre-burn values. Similarly, changes in nitrate are shown in (b), changes in TOC are shown in (c), and changes in phosphate are shown in (d). On X-axis, “E” is exotic plants, “M” is mixed plants, and “N” is native plants.

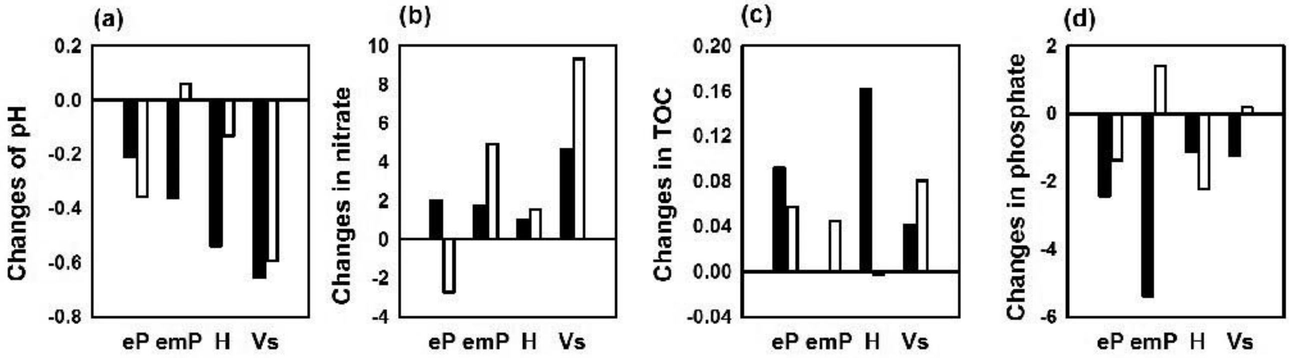

Figure 3—Soil geochemistry response to a burn event on sites with four different types of geological substrates. On each panel, black bars denote burn plots, while white bars denote control plots. Y-axis is the changes in pH (a) at the end of one-year period after the burn event from pre-burn values. Similarly, changes in nitrate are shown in (b), changes in TOC are shown in (c), and changes in phosphate are shown in (d). On X-axis, "eP" is early Pleistocene, "emP" is early-middle Pleistocene, "H" is Holocene, and "Vs" is late Pleistocene veneered surface.

$P < 0.001$; $F^{TOC}_{3,430} = 1.59$, $P = 0.19$; $F^{phosphate}_{3,430} = 6.47$, $P < 0.001$). Specifically, soil became more acid one year after the burn on early-middle Pleistocene and Holocene substrates, but not other substrates (figure 3a). Nitrates increased on burn plots comparing to control plots at early Pleistocene sites, but not at other sites (figure 3b). 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 (figure 3d).

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.

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 (figure 4), and we found:

1. Soil pH values dropped immediately after the burn, and remain more acid than pre-burn values at the end of the one-year period on all sites except early Pleistocene with native plant (eP + N) sites (figure 4a). At early Pleistocene with native plant (eP + N) sites, pH values were recovered more quickly than other sites, and soil did not appear to be more acid than pre-burn values at the end of the one-year period.
2. Soil NO_3^- levels decreased immediately after the burn, but recovered quickly and exceeded pre-burn values at the end of the one-year period for all sites. The trend of increasing NO_3^- levels stabilized by week 26 at early-middle Pleistocene with mixed plant (emP + M) sites and late Pleistocene veneered surfaces with mixed plant (Vs + M) sites, whereas on other sites NO_3^- levels remained increasing at the end (figure 4b).
3. Soil TOC levels dropped one week after the burn on early Pleistocene with native plant (eP + N) sites, early-middle Pleistocene with exotic plant (emP + E) sites, and late Pleistocene veneered surfaces with mixed plant (Vs + M) sites, recovered to pre-burn levels by week 6, and remained close to pre-burn levels at the end of the one-year period. Soil TOC levels increased by week 6 at early-middle Pleistocene with mixed plant (emP + M) sites, and remained slightly higher than pre-burn values at the end of the one-year period (figure 4c).
4. Soil PO_4^{-3} levels increased immediately after the burn, but gradually fell back to pre-burn values or lower on all sites. The pulse release of PO_4^{-3} after the burn is strongest at Holocene with native plant sites (figure 4d).

Discussion and 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 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 soil does play a significant role in nutrient response. The surficial geology of the study sites was the main control on soil characteristics and response to burn events. Dominant grass vegetation—native, non-native, or mixed—had little effect on the response of soil geochemistry to fire events.

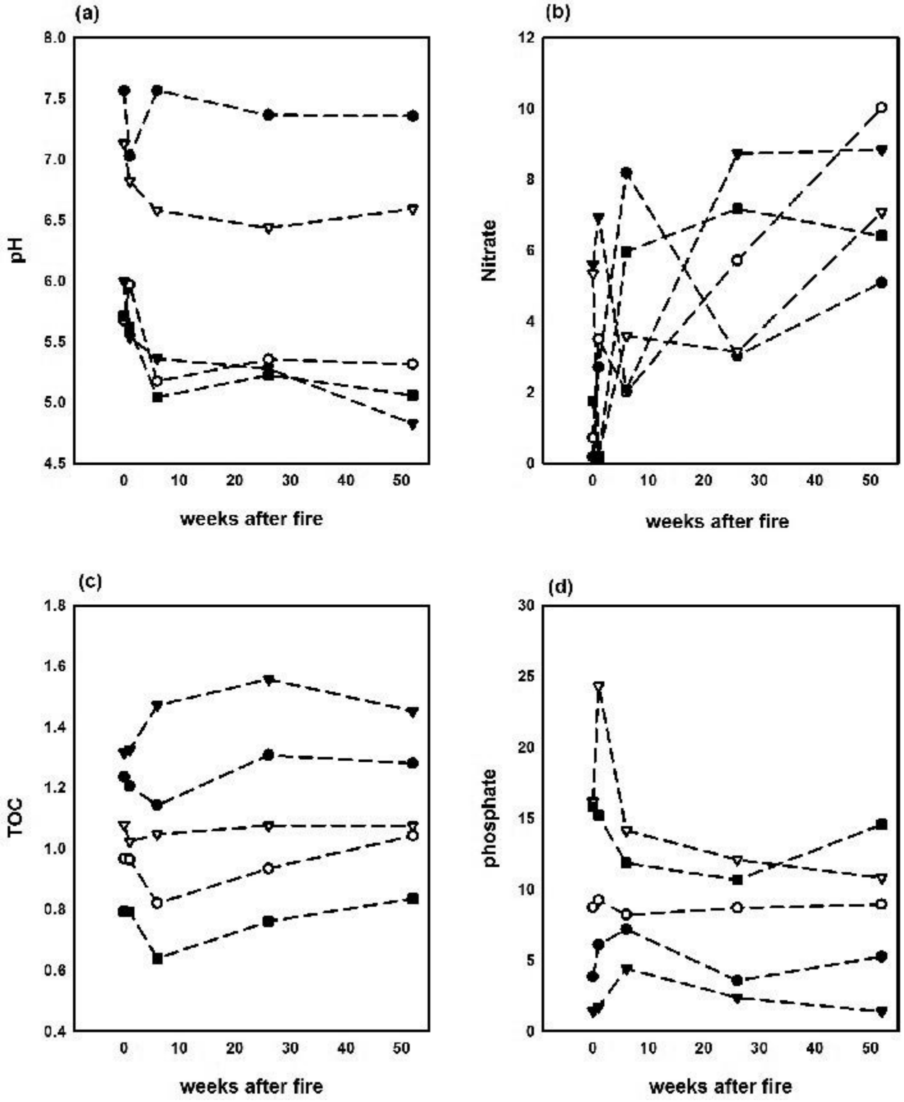

Figure 4—Temporal changes in soil pH (a), NO_3^-(b), TOC(c), and PO_4^{-3}(d) after prescribed fire. Week 0 is the pre-burn value, and week 1, week 6, week 26, and week 52 are values taken at each time period after the burn. Filled circles denote "early Pleistocene substrate with native plants"; open 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.

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