

Effects of Controlled Burns on Soil Nutrients and Respiration
Implication for Possible Sandplain Grassland Restoration on Martha's
Vineyard

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ABSTRACT

Fire has significant impacts on soil properties, nutrient content, nutrient cycling, and microbial activity and has been shown in previous studies. However, these effects have not been studied to a large extent on the coastal plains of New England, where fire has been a long-documented disturbance. Fire is important in maintaining areas of sandplain grassland, a globally rare ecosystem. Effects of prescribed burning on sandplain vegetation have been studied (Motzkin 2002), but impacts on soil have not been extensively documented. We studied soils of unburned oak forests and burned oak forest. We found that organic soil in burned areas showed higher pH in organic soil and in mineral soil, lower microbial activity as measured by respiration and net N mineralization, and long-term difference in soil properties that we attributed to fire and use of prescribed burns. Additionally, prescribed burns can be used to restore soils and establish areas of sandplain grasslands because of its effects on soil properties.

Keywords: fire, prescribed burning, soil nutrients, soil respiration, soil properties, sandplain grasslands

INTRODUCTION

Fire is an important dynamic in many ecosystems. Fire and prescribed burns can alter soil properties, nutrient content, nutrient cycling, and microbial activity. Annual and semi-annual prescribed burns have been shown to change the thickness of the organic horizon and increase the bulk density in the A horizon (Phillips 2000). Prescribed burning also increases pH following a fire (Arocena 2003, Ivanauskas 2003), due to the displacement of H⁺ ions by base cations on soil exchange sites (Aber 2001). Most cations increase in abundance following fire due to their concentration in the ash except in some very hot fires where the ash is blown away from winds produced by the fire and lost (Aber 2001). However, Debano (1978) found measurable losses of potassium from burned sites.

Fire has a large impact on biogeochemical cycles. Carbon is both consumed in combustion and volatilized, immediately reducing the amount of organic matter in the upper two soil layers (Debano 1978). Fire releases enough carbon to reduce the carbon to nitrogen ratio of the soil organic layer (Aber 2001). Similarly, nitrogen is also volatilized during the fire (Aber 2001), resulting in measurable N losses from the organic layer (Debano 1978, Jurgensen 1981), but increased mineral soil N content (Choromanska 2001). The extent of C and N losses from the organic horizon are dependent on fire temperature (Caldwell 2002). Nutrients peak in availability one year following a fire (Dumontet 1997) and subsequently decrease to values lower than originally found (Ivanauskas 2003). However, Aber (2001) also observes that a high fire frequency might yield a lower-productivity system in the long run.

Fire also affects other nutrients. It increases the availability of nutrients such as ammonium, nitrate, and base cations in the organic layer of the soils through deposition in ash (Christensen 1973, Dumontet 1997, Choromanska 2001), but has been found to have little effect on the nutrients in the mineral horizon (Franklin 2003). Fire increases availability of ammonium that, when combined with higher soil pH and lower C/N ratios,

should lead to higher rates of nitrification (Christensen 1973, Aber 2001). Forest burning has been shown to lower long-term net nitrogen mineralization (Turner 1997), and also results in lower potentially mineralized N (Choromanska 2001).

One of the sources of carbon loss is from decreased microbial biomass in both the organic soil layer and the mineral soil layer (Choromanska 2001). Dumontet (1997) found that fire has a lingering effect on microbial biomass that results in peak biomass one year after the fire, but biomass decreases to values lower than initial conditions over time.

The dominant disturbance on Martha's Vineyard during the past two centuries has been fire. Fires have been present since at least 8000 years ago but increased in frequency following European settlement (Parshall 2002). Fire typically benefits sandplain grasses and forbs by eliminating competition from woody vegetation, especially shrubs. Fire frequency has been greatly reduced because of improved fire detection and suppression, but this is leading to species changes and subsequent decline of ecosystems like the sandplain grasslands (Motzkin 2002). The most effective burns for grassland restoration and nutrient release occur during the growing season (Dunwiddie 1998), when they are prohibited (Foster 2002).

Sandplain grasslands are a globally rare ecosystem unique to coastal plains of the Northeast (Dunwiddie 1998). Sandplain grasslands are characterized by relatively nutrient-poor soils and frequent disturbances that maintain plant species composition. They contain several species of rare native grasses and wildflowers, provide important wildlife habitat, and face increasing pressure from developing human populations in coastal regions (Motzkin 2002).

Sandplain grasslands on Martha's Vineyard are a priority for restoration. The goal is to create and maintain areas containing a high diversity of native grass and forb species. Restoration groups use several methods establish species composition of sandplain grassland. To thwart shrub encroachment, groups use controlled/prescribed burning and mechanical mowing. Prescribed burns influence species composition (Foster 2002), and increase light to the understory by decreasing canopy cover, shrub cover, and shrub expansion (Dunwiddie 1998). Restoration groups also hope to increase open areas of sandplain grassland created from different land uses, such as former agricultural lands and forested areas. Prescribed understory burns are used in an attempt to create these areas because of its effect on shrub cover and species composition. Other methods include clear-cuts, understory cutting, and grazing (Motzkin 2002).

The effects of controlled burns on soil characteristics may have some implications for sandplain grassland restoration. Even though prescribed burning is commonly used for maintenance of sandplain grasslands, its effects on soil are not well understood within the context of grassland restoration. Whether fire changes soil to resemble those found in well-established sandplain grassland communities, or whether burned areas still resemble forested areas is unknown. We investigated how understory burning and wildfire affected soil properties and nutrients by comparing burned forest areas with unburned forest area. We eventually compared soil properties, nutrients, and respiration of burned areas with different land uses, including sandplain grasslands, tall oak forests, and plowed agricultural land to determine whether prescribed burning in forests changed soil properties to resemble those found in sandplain grasslands.

METHODS

We conducted this study on Martha's Vineyard, an island off the Southern coast of Cape Cod, Massachusetts, USA that was formed by glacial deposits. It is less than 250 km² and has three distinct geomorphologic regions: moraine, outwash overlying moraine, and outwash plain (Foster 2002). Sampling locations are on the Southern part of the island on outwash deposits with coarsely textured soils that are uniform throughout the sites, in areas where fires have occurred, either unintentionally or as a management technique.

Sampling locations were in areas where prescribed burns were identified and characterized with help from The Nature Conservancy. Most sites are located on public land or conservation land that is open to the public. We selected 4 sites with known burn history and similar vegetation types (Table 1). To minimize error from different land histories, growing conditions, and microclimates, we chose both a burn site and a control plot within each grouping of sites. Sites located on Kohlberg property (private land) are KNC, KB03, KBO2, and KB99. Sites located in Smith Woods, part of Manuel Correllus State Forest, are SWC, SW02, and SWJ99. Two additional sites were located at both Manuel Correllus State Forest in Manager's Meadow (SFC, SFMM), and at Long Point (LPC, LPB), owned by the Trustees of Reservations of MA.

We collected four soil samples from each sampling site, two from the organic layer and two from the mineral soil. Organic soil was collected by removing a 10cm by 10cm square from the organic soil and removing mineral soil from the underside. Mineral soil was collected by using a stainless steel coring device after removing the organic layer of soil. Mineral soil was sampled to a depth of 15 cm.

We also measured soil horizon thickness of the organic horizon, A horizon, E horizon, and B1 horizon (if present) after digging a soil pit, and then used a Munsell soil color chart to characterize the soil color.

Our laboratory analysis consisted of tests to measure bulk density, pH, soil respiration, cations, soil nitrogen and carbon stocks, nitrogen mineralization, nutrients, and potential nitrification.

We calculated Bulk density using the weights of oven-dried soil and the dimensions of the brownie or soil corer. Soil moisture content was measured by determining the change in weight between fresh soil and oven-dried soil. Soils were dried at approximately 50 C for 5 days.

We measured soil pH of a slurry using an Accumet pH/conductivity meter. The slurry consisted of 50 mL water and either 5 g of organic soil or 10 g of mineral soil.

To measure soil respiration, we placed approximately 2 cm of soils in jelly jars and recorded weights. We watered soils every three days to maintain soil moisture. Soils equilibrated for 5 days, at which point we measured respiration using a Licor 6200 infrared gas analyzer for a period of 3 minutes. We calculated respiration based on the CO₂ flux, found from the slope of CO₂ concentration (ppm s⁻¹) according to methods in the SES lab handout weeks 5&6, 2003. If CO₂ flux was non-linear either at the beginning of the measurement or the end, we used the linear portion of the curve to obtain an estimate of the flux.

We measured the concentration of base cations (calcium, magnesium, potassium, and sodium) on wet soil using the protocol described by Dean (2002) following methods outlined by Fernandez & Robarge (1986). We added 100 mL of ammonium chloride to the equivalent of 5 g of dry soil, shook for 1 hour, and filtered using vacuum filtration and Whatman GF/F filters. 12 drops of concentrated HCl were added to approximately 60 mL of sample to prevent microbial growth. To 10 mL of sample, we added 1 mL of 1% lanthanum chloride, mixed, and analyzed on an atomic absorption spectrometer (Perkin-Elmer 2380) to obtain Ca^{2+} , Mg^{2+} , K^+ , and Na^+ concentrations.

We determined soil carbon and nitrogen stocks using a Perkin-Elmer 2400 elemental analyzer on approximately 10 g of organic soil and 20-30 g of mineral soil. We used bulk density to determine soil carbon and nitrogen stocks.

We calculated net nitrogen mineralization from measurements of nitrate and ammonium in soils before and following a 15-day incubation period at 31 C. Soil nutrient extractions were done using 50 mL of 1 M potassium chloride (KCl). Samples were shaken for one hour at 150 rpm, filtered using gravity filtration and then using GF/F filters, and frozen until analysis. Nitrate samples were analyzed using the Lachat. Ammonium samples were analyzed on a spectrophotometer following reactions with phenol, nitropusside solution, and hypochlorite oxidizing solution. Absorbance was measured using a UV-1600 spectrophotometer at a wavelength of 640.0 nm. Samples were diluted with 1 M KCl when necessary.

Potential nitrification was done based on methods of Belser & Mays (1980) and Schmidt & Belser (1982). We added 30mL of ammonium phosphate to the fresh soil equivalent of 5g of dry weight and placed solution in 60mL centrifuge tubes. Samples shook in tubes at 150rpm at room temperature for 2, 6, 12, and 24 hours. Before filtering, samples were centrifuged in tubes for 5 minutes, gravity filtered with Fischer Q8 coarse paper filters, and then pressure filtered using a Whatman GF/F filter. Samples were frozen until we analyzed them for NO_3^- on the Lachat analyzer used for nitrate samples. To obtain potential nitrification rates, we plotted all time points for each sample and took the slope of the linear portion of the curve.

Data analysis

For regressions analysis, standardized data was plotted (percent change from the values in the control plot). Significance was found between sites at 95% confidence level.

For the ANOVA test and the analysis of principle components, data was averaged to find a mean value for each burn site. ANOVA were conducted comparing the difference between land-use (burned and control sites), and also difference between sites. ANOVAs were conducted at the 95% confidence level using the Bonferroni mean. The same averaged data values were used in the analysis of principle components.

RESULTS

Soil pH was significantly higher ($p=0.0205$) in burned sites relative to control sites in organic soils (Figure 2a). Soil pH was higher in burned mineral soils except SF (Figure 2b).

Total base cations were lower in organic soils of burned sites than control sites (Figure 3a). Total base cations showed no consistent trends in the mineral soil (Figure 3b). Potassium and sodium concentrations were lower in organic soils at burned sites than control sites (Figures 4a, 5a). Potassium was also lower in mineral soils at burned sites (Figure 4b), while sodium showed no consistent trends (Figure 5b). Total base cation concentrations were much lower in mineral soil than organic soil (2.87-28.28 mEq in organic, 0.08-0.92 mEq in mineral soil). Calcium was the most abundant base cation in organic soil (Figure 6a), but much less abundant in mineral soil (Figure 6b). Significant site differences of Ca^{2+} concentrations in the organic soil were measured between K^+ and SW (a), and SF (b). Magnesium was less abundant than calcium in the organic soil (Figure 7a), and present in trace amounts in mineral soils (Figure 7b). Additionally, SFMM had very high base cation concentrations in the mineral soil.

Carbon and nitrogen stocks in the organic soils were lower in the two years following burns at Kohlberg and SW (Figure 8a, 9a). C and N stocks were higher in burned plots than control plots at LP (burn age=1 yr) and the two burns that occurred 4 years before measurements (KB99, SWJ99). Significant site differences were found between Kohlberg, SW, LP (a), and SF (b). Mineral carbon stocks did not exhibit any consistent trends between burned and control sites (Figure 8b). However, mineral nitrogen stocks were generally lower in burned sites than control sites, with the exception of LP (Figure 9b). The C:N ratio of organic soil was generally higher in burned plots, but not significantly (Figure 10a). However, the C:N ratio in the mineral soil generally was higher in burned sites (Figure 10b). Mineral soil had a higher C:N ratio than the organic soil.

Organic soil respiration was significantly lower ($p=0.0124$) in all burned sites than in control sites (Figure 11a), but did not show any consistent trends in burned mineral soil (Figure 11b). Respiration in the organic soil was much higher than in the mineral soil.

Net nitrogen mineralization was lower in the organic soils of burned sites than control sites (Figure 12a), with the exception of LP. Higher net N min in mineral soils was measured in burned sites than control sites at Kohlberg, SF, and LP (Figure 12b). Mineral soil net N mineralization was lower than rates in the organic layer.

Large amounts of net nitrification occurred in SFC (figure 13a), but levels of net nitrification were $< 0.5 \text{ g N m}^2 \text{ day}^{-1}$ at all other sites. Net nitrification was higher in the organic soil than mineral soil for SFC (Figure 13b). SFC was the only site with measurable amounts of nitrate in the mineral soil (Figure 14b), and had the second highest ammonium concentrations (Figure 15b).

Potential nitrification showed no clear patterns in the organic soil (Figure 16a). However, it was generally lower in mineral soils of burned sites than control sites (Figure 16b). Potential nitrification was higher in mineral soils than organic soils. Potential nitrification in mineral soils showed a weak inverse trend with potential nitrification in the organic layer.

Linear Regressions using burn age

pH increased following a burn and decreased over time after burning (Figure 17) in both organic and mineral soil. In organic soil, both C and N stocks decreased initially following fire and increased over time (Figure 18), ending at with larger stocks than the

control plots. The change in organic soil N stock over time was statistically significant ($p=0.008$). Respiration in organic soil decreased following a fire and continued to get lower (Figure 19). Respiration increased in mineral soil over time after burn (Figure 19). Net N min increased initially in both mineral and organic soil and decreased over time (Figure 20), but still ends at higher values than it began. Total base cations decreased in organic soil (Figure 21a) and increased in mineral soil following burning (Figure 21b).

Analysis of Principle Components

Analysis of principle components showed that burned oak organic soils more are similar to organic soils found in sandplain grasslands. Sandplain grassland sites are more similar to burned oak soils than unburned oak soils (Figures 22a). PC1 and PC2 explain a cumulative 57.4% of variance. Major components of PC 1 are depth and total base cations. Major components of PC2 are nitrate concentrations, C:N ratios, and potential nitrification. Mineral soils in burned forests closely resembled unburned forests using this analysis (Figure 22b). 61.4% of variance of data in mineral soil is explained by PC1 and PC2. Major components of PC1 are pH, potential nitrification, and respiration. Major components of PC2 are bulk density and calcium concentration.

DISCUSSION

Burned sites show several important differences in soil properties from unburned sites. These can be attributed to a few key differences namely burn intensity, microbial activity, and burn age. Burn intensity varied between sites, as did microbial activity, and the number of years since the last burn. These factors exerted noticeable impacts on several assays.

Burn intensity has an effect on pH and cation concentrations in soils on Martha's Vineyard. We measured higher pH in burned sites than unburned sites, which is expected because of higher base cation concentrations in ash that displace H^+ ions on soil exchange sites (Aber 2001). However, we measured lower base cation concentrations in organic soils at most sites due to lower concentrations of potassium and sodium. Live tree material, like twigs and trunks, contains high amounts of cations (Debano 1978). We suspected these prescribed burns were not intense enough to consume live material because we did not see increased base cations except in the mineral soil of the most intense burn, SFMM.

We expected to see larger and more consistent decreases in organic soil carbon and nitrogen stocks than we did due to prescribed burns (Dumontet 1978, Jurgensen 1981). Mineral soil nitrogen stocks were generally lower in burned sites than unburned sites, opposite to findings by Choromanska (2001). Burn intensity and temperature were probably not high enough to remove enough carbon to significantly change C:N ratio in the organic layer (Caldwell 2002). The higher C:N ratio that we measured in the mineral soil can be attributed to the lower N stocks in the mineral soil. Additionally, there is no explanation for the significant differences in C stocks that were observed between SF and the other sites.

Sites with burned soils showed much less microbial activity in the organic horizon, as indicated by significantly lower soil respiration (Choromanska 2001, Dumontet 1997). However, microbes are not limited by labile C or N (Litton 2003), even

though there are corresponding low C and N stocks in burned organic soils. Soils studied did not exhibit a peak microbial biomass as measured by respiration one year following fire, as found by Dumontet (1997) in a Mediterranean pine forest.

Microbes also control N mineralization, which is related to total content of organic nitrogen in the soil (Marion 1998, McCarty 1995) and linked to carbon availability (Schlesinger 1997). We measured lower C and N stocks in organic soils that had lower net N mineralization and respiration, indicating less microbial activity.

Rates of potential nitrification were much higher than actual nitrification values, which were very small. This indicates that nitrification at these sites is limited by ammonium. Ammonium concentrations increase following a burn, but this does not significantly affect net nitrification rates because potential nitrification is lower at burned sites than control sites as also found by Christensen (1973). This could be because of the insignificant decreases in C:N ratios (Aber 2001), or because microbial respiration and subsequent activity is lower in burned sites than control sites, indicating lower microbial populations and consequently fewer nitrifying bacteria.

There are some site differences in net nitrification, even within the paired sites. Organic soil at SFC had high concentrations of NO_3 and NH_4 , high potential nitrification, net nitrification, and net N mineralization for no obvious reason. The mineral soil had a high N stock and nitrification, and high nitrate concentrations. SFMM is located approximately 200 m from SFC, and while SFMM exhibited high net N mineralization and base cation concentrations, it exhibited none of the other high rates. Patchy nitrification as seen in SF has been previously documented (Goodale 2001).

Burn age also influenced soil properties. Soil pH decreased with the age of burn because acid deposition leached the base cations from the soil, leading to a lower soil pH once again.

Increases of carbon and nitrogen stock over time indicate that burning may lead to higher plant productivity following fire, enhancing C and N stocks in the organic soil. Litton (2003) found C and N stocks did not influence microbial biomass, and therefore respiration in organic soil was lower than control respiration despite increases in C and N stocks. Microbial populations in organic soil do not recover from the burn within 6 years. Dumontet (1997) found long-term differences in microbial activity that they attributed to fire.

Burn age and total base cations had an interesting dynamic. Total base cations were lower than control sites in the organic soil and continued to decline relative to the controls with increased burn age. However, the concentration of total base cations increased relative to control sites in the mineral soil of older burn sites. This indicates that cations are leached from the organic soil, leading to lower concentrations with burn age, and carried into the mineral soil, where they are sometimes held, leading to an increase in total base cation concentration. This also explains why decreased pH is observed in the organic soil of older burn sites.

Implications for grassland restoration

Fire changes the properties of organic soils in oak forests to resemble the organic soil found in sandplain grasslands. Organic soils from burned oak forests are more similar to soils of sandplain grasses than unburned oak soils are (Figure 23a). Depth of the organic soil, sum of base cations, C:N ratio, potential nitrification, nitrate

concentration, and net nitrogen mineralization exert the largest influence on the similarity of the soils and are the factors that fire changes to cause forest sites to resemble the sandplain grass sites. Therefore, in order for conservation groups to create new areas of sandplain grasslands, burning will help to change forest soils to resemble those found in the sandplain areas.

Mineral soils are similar between sandplain grasslands, burned forests, and unburned forests (Figure 23b), indicating that fire does not impact the mineral soil significantly, agreeing with findings by Franklin (2003). Additionally, this analysis reveals that the impacts of current land-use on mineral soils are very small. Also, it does confirm that decades of difference in vegetation have not significantly changed soils from their common parent material.

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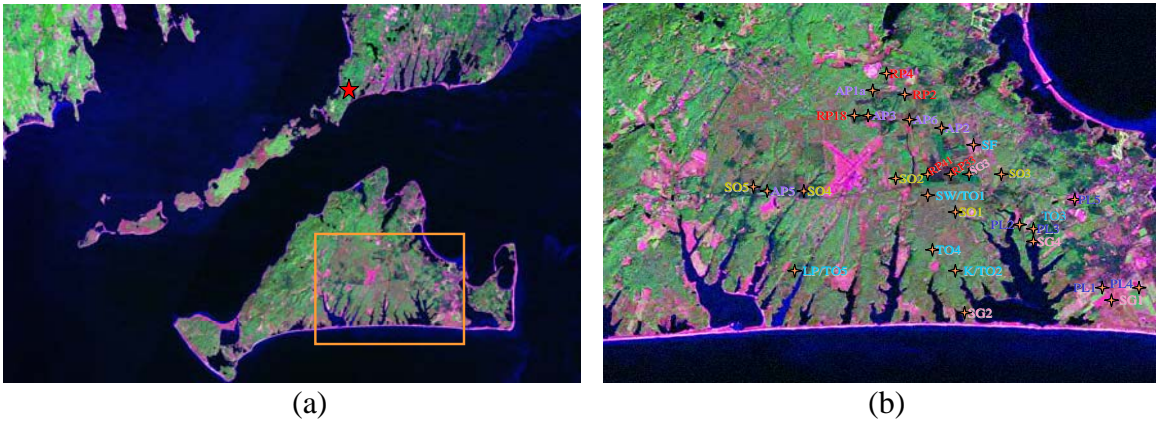


Figure 1. Aerial photo of Martha's Vineyard (a). Box represents area shown in (b), with sampling sites marked.

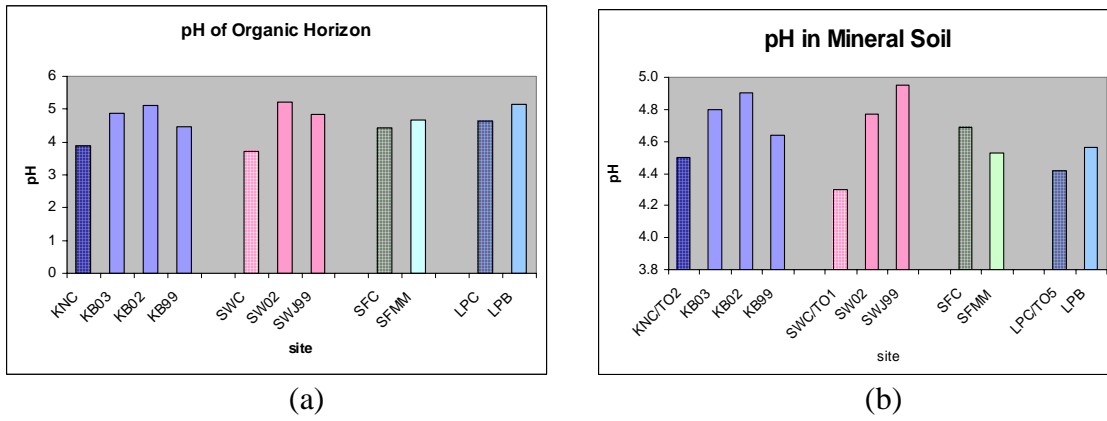


Figure 2. Comparison of pH values in organic soil (a) and mineral soil (b).

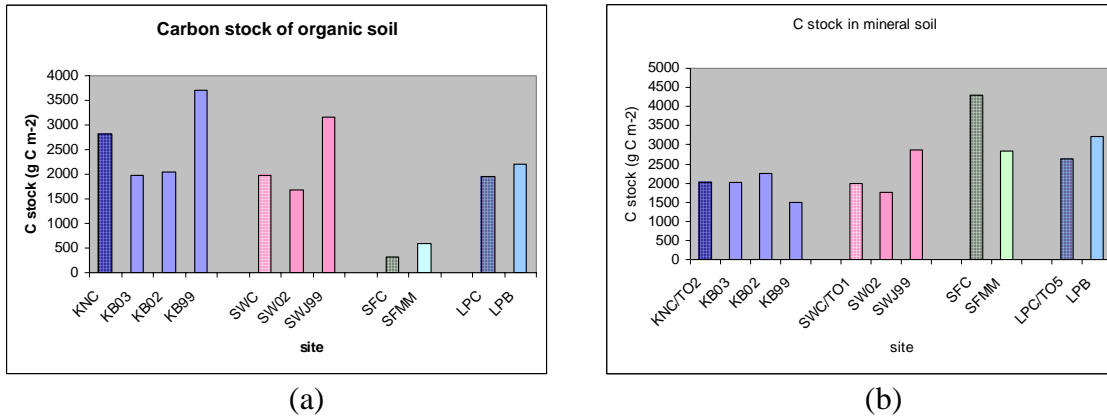
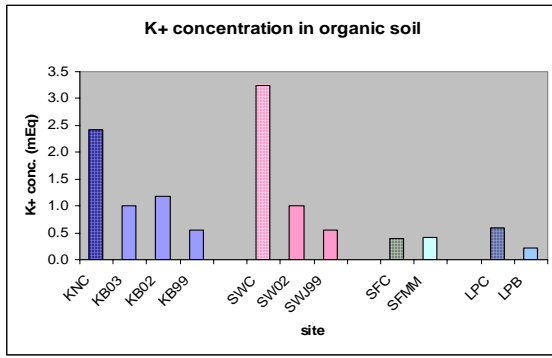
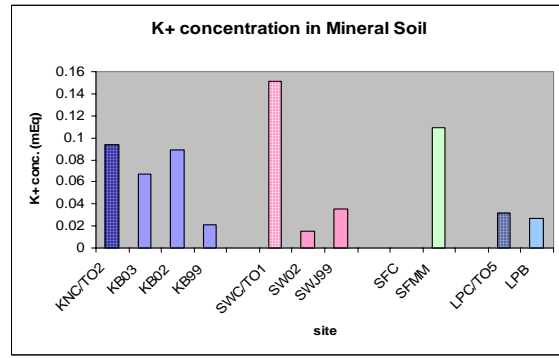


Figure 3. Total base cation concentration in organic soil (a) and mineral soil (b).

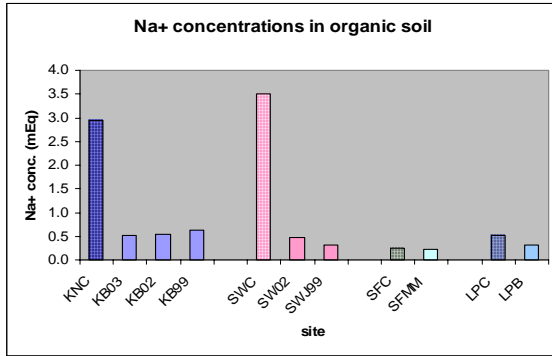


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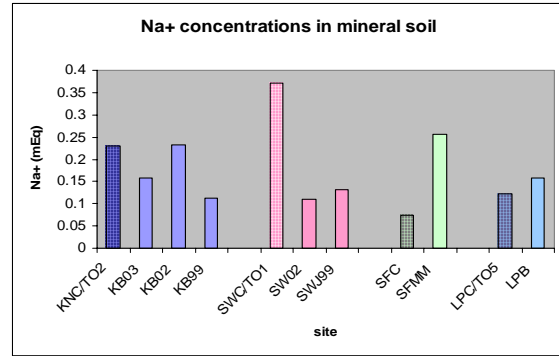


(b)

Figure 4. Potassium (K⁺) concentrations in organic soil (a) and mineral soil (b).

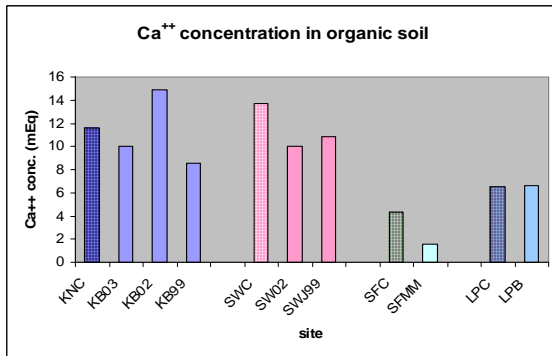


(a)

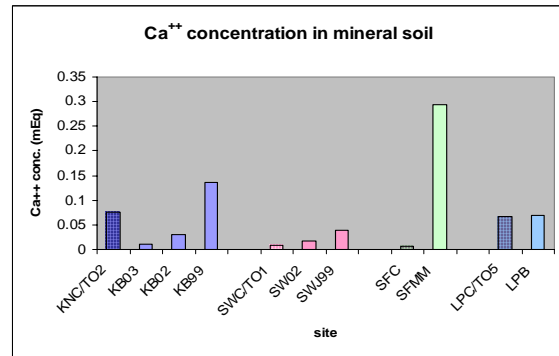


(b)

Figure 5. Sodium (Na⁺) concentrations in organic soil (a) and mineral soil (b).

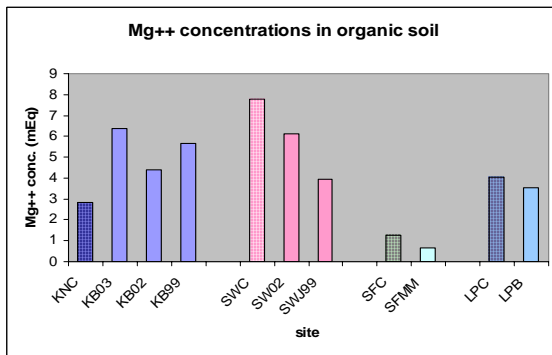


(a)

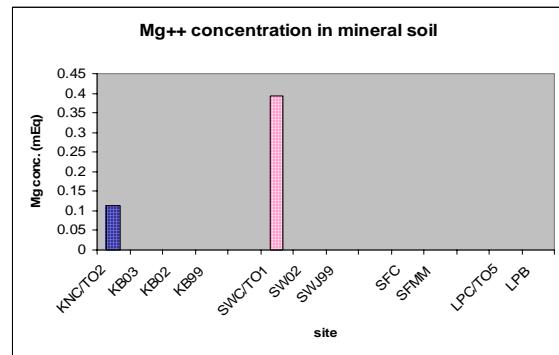


(b)

Figure 6. Calcium (Ca⁺⁺) concentrations in organic soil (a) and mineral soil (b).

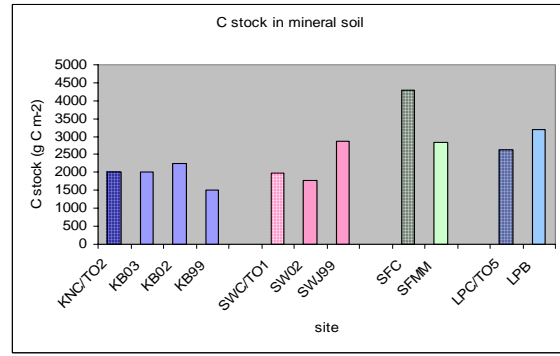
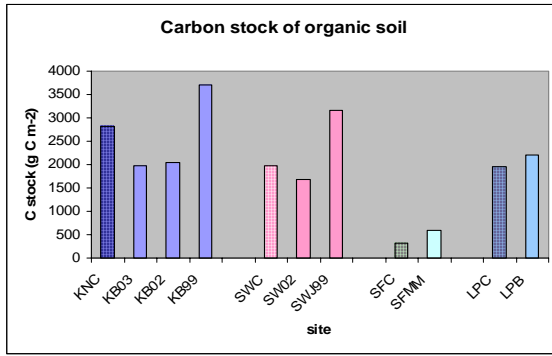


(a)



(b)

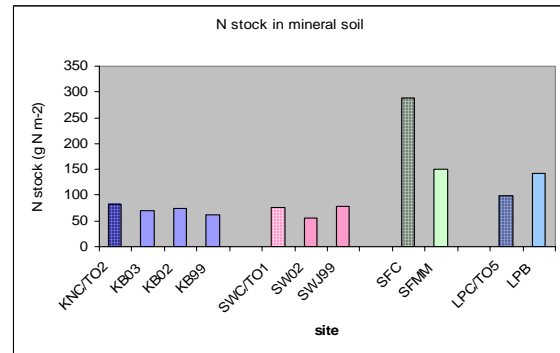
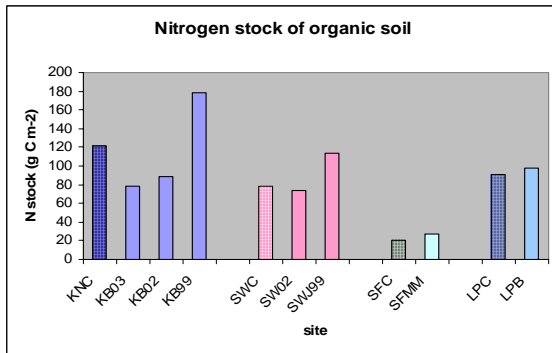
Figure 7. Magnesium (Mg⁺⁺) concentrations in organic soil (a) and mineral soil (b).



(a)

(b)

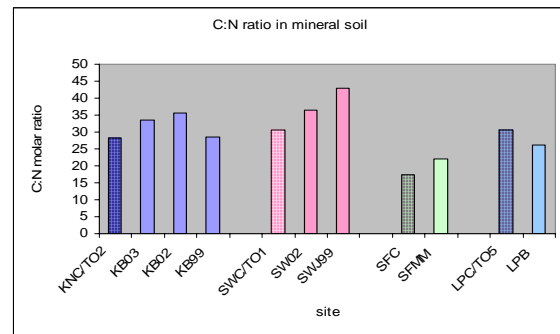
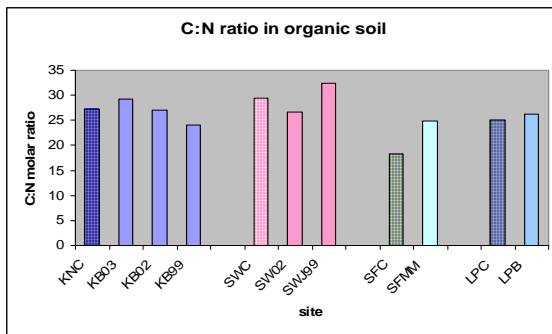
Figure 8. Carbon stock in organic soil (a) and mineral soil (b).



(a)

(b)

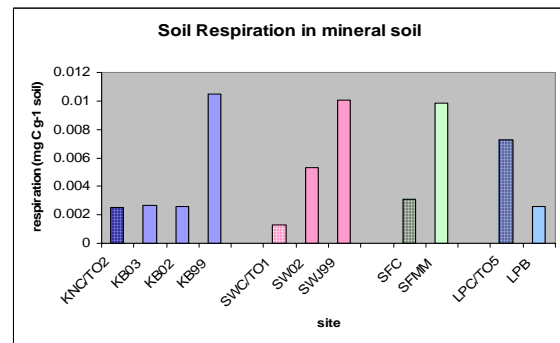
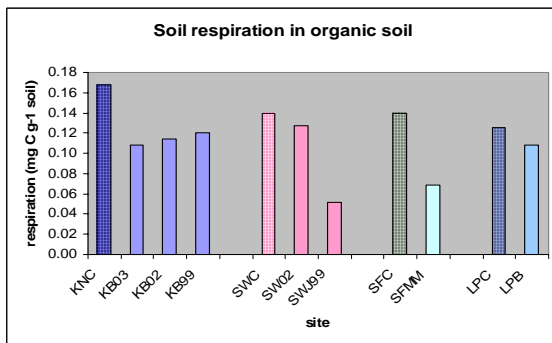
Figure 9. Nitrogen stock in organic soil (a) and mineral soil (b).



(a)

(b)

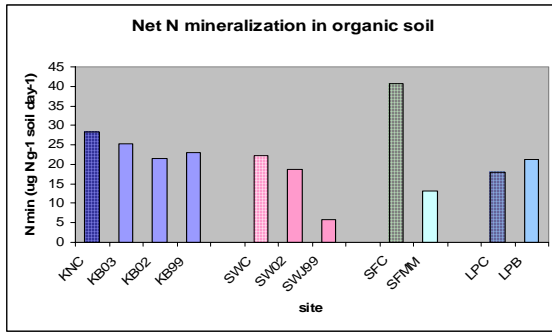
Figure 10. Carbon to Nitrogen molar ratio in organic soil (a) and mineral soil (b).



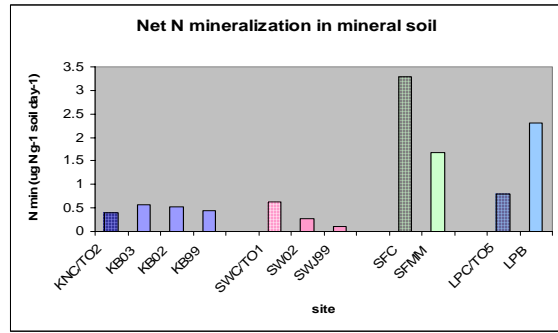
(a)

(b)

Figure 11. Soil respiration rates in organic soil (a) and mineral soil (b).

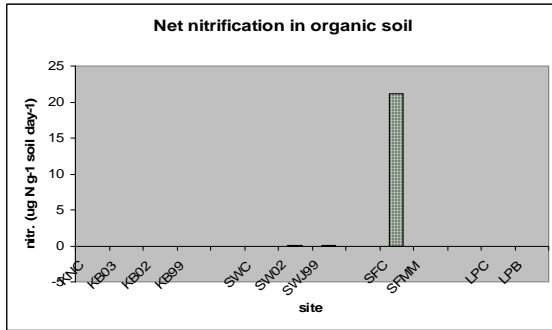


(a)

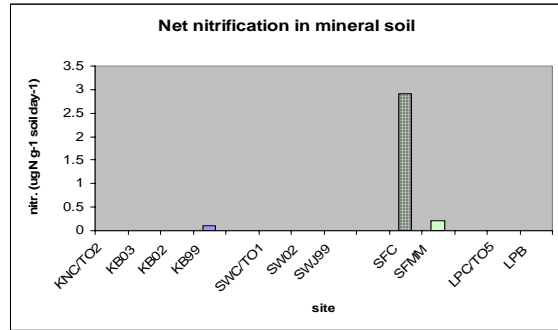


(b)

Figure 12. Net nitrogen mineralization rates in organic soil (a) and mineral soil (b).

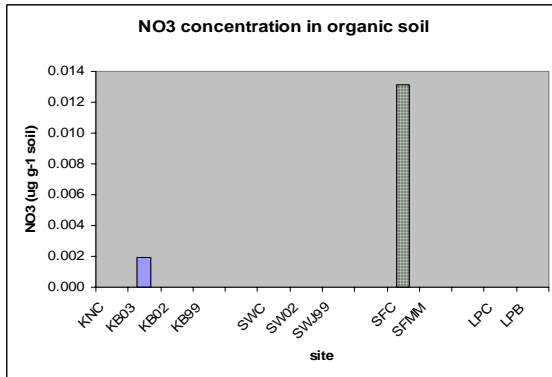


(a)

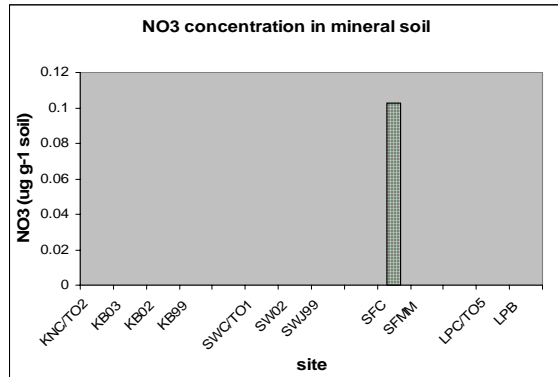


(b)

Figure 13. Net nitrification in organic soil (a) and mineral soil (b).

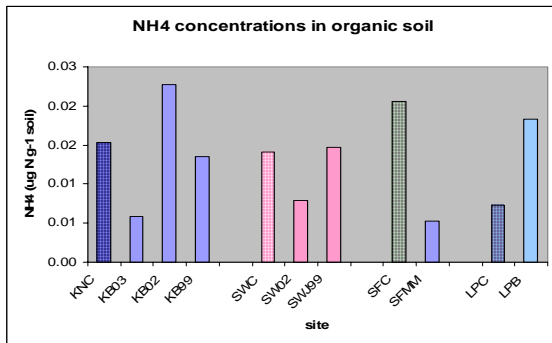


(a)

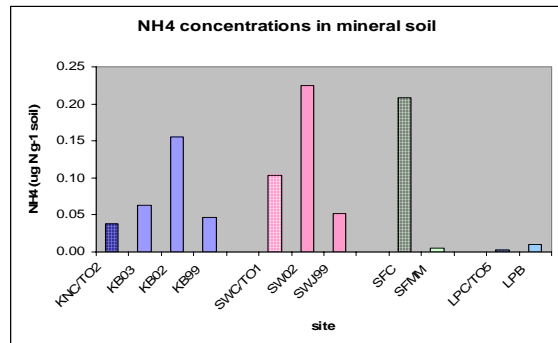


(b)

Figure 14. Nitrate concentrations in organic soil (a) and mineral soil (b).

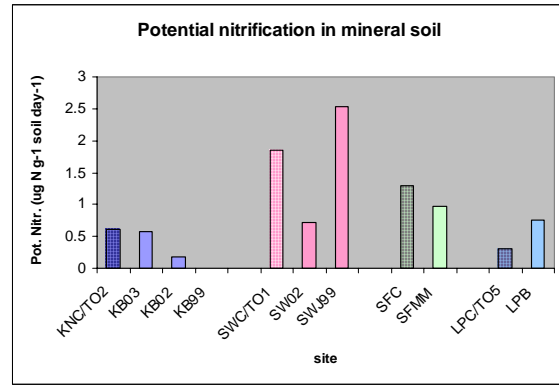
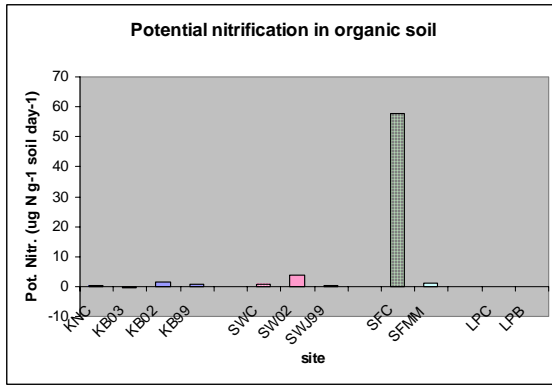


(a)



(b)

Figure 15. Ammonium concentrations in organic soil (a) and mineral soil (b).



(a)

(b)

Figure 16. Potential nitrification in organic soil (a) and mineral soil (b).

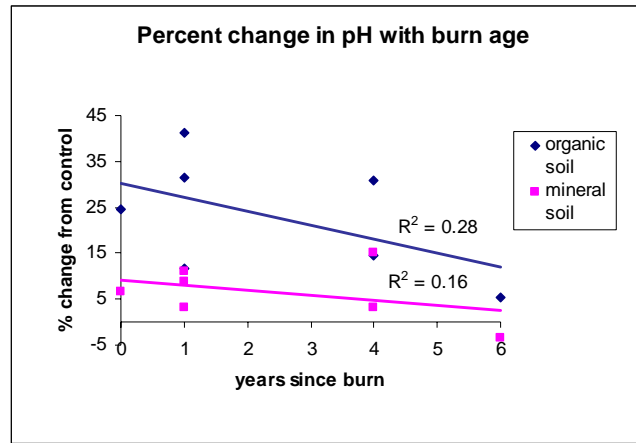


Figure 17. Percent change in pH values with increasing burn age in organic and mineral soil.

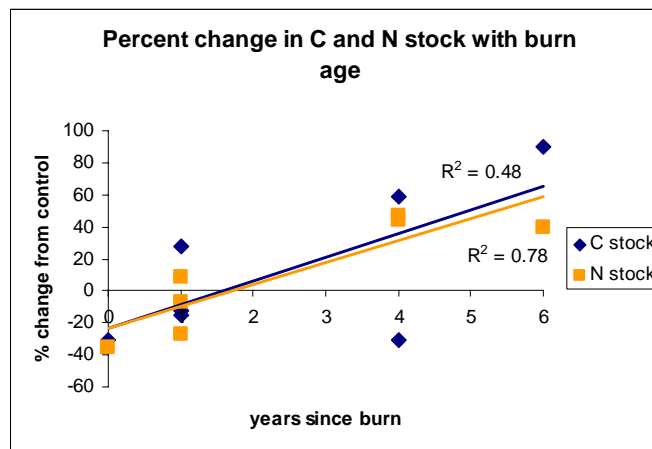


Figure 18. Percent change in Carbon and Nitrogen stocks with increasing burn age in organic soil.

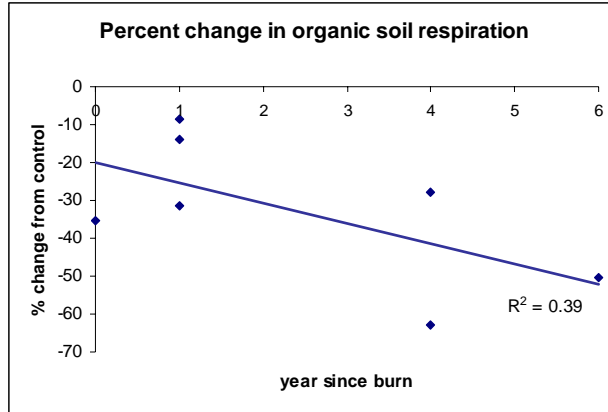


Figure 19. Percent change in microbial respiration values with increasing burn age in organic soil.

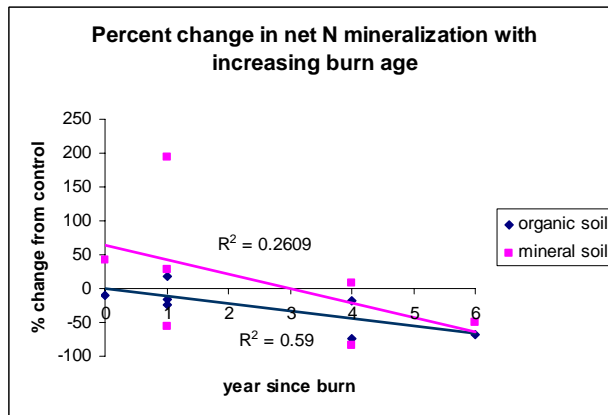
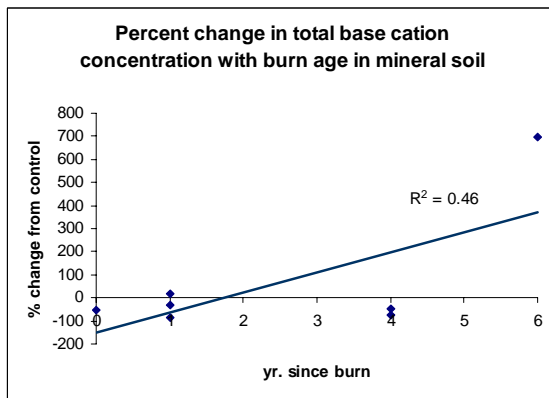
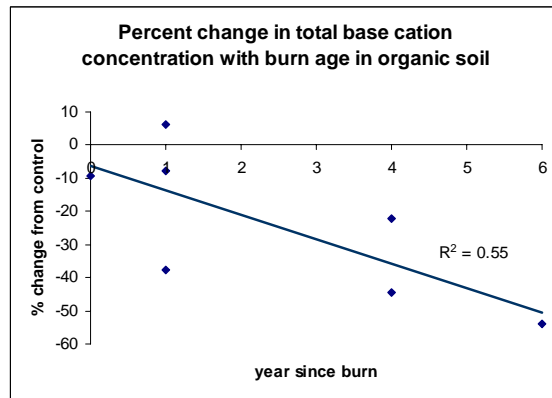


Figure 20. Percent change in net Nitrogen mineralization with increasing burn age.

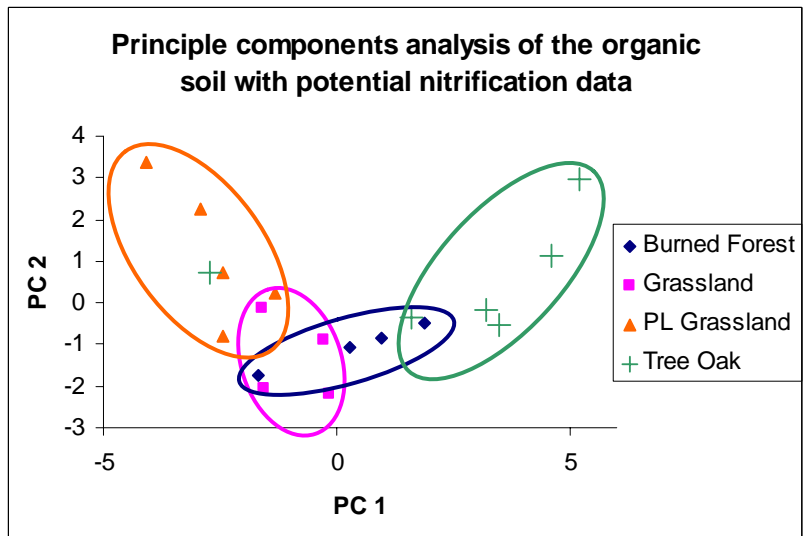


(a)

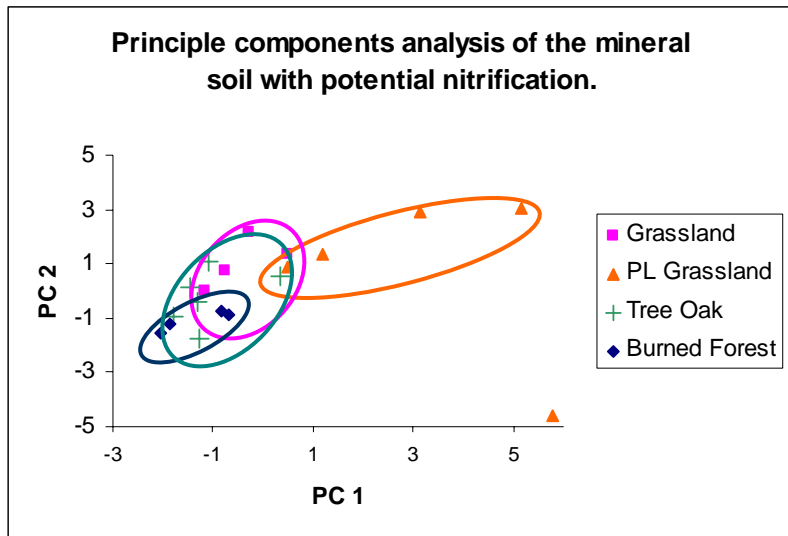


(b)

Figure 21. Percent change in total base cation concentration with increasing burn age in organic soil (a) and mineral soil (b).



(a)



(b)

Figure 22. Principle components of organic soil (a) and mineral soil (b).

Location	Site	Symbol	Burn Year	Intensity	Dominant Vegetation
Kohlberg	Control North	KNC	n/a		tall oak
	Burn 2003	KB2003	2003	avg.	tall oak
	Burn 2002	KB2002	2002	avg.	tall oak
	Burn 1999	KB1999	1999	avg.	tall oak
Smith Woods	Control	SWC	n/a		tall oak
	Fire Path	SW2002	2002	avg.	tall oak
	June Burn	SWJ1999	1999	high	white pine
State Forest	Control	SFC	n/a		scrub oak
	Manager's Meadow	SFMM	1997	high	scrub oak
Long Point	Control	LPC	n/a	avg.	tall oak
	Burn	LPB	2002	avg.	tall oak

Table 1. Site description