

FOREST HARVEST EFFECTS ON SOIL CHEMICAL PROPERTIES
AND NUTRIENT CONCENTRATIONS IN OZARK HIGHLAND SOILS

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AND NUTRIENT CONCENTRATIONS IN OZARK HIGHLAND SOILS

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For the Missouri Ozarks.

For Soil Judging.

For Liz.

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ABSTRACT

Mixed hardwood systems of the Missouri Ozark Forest Ecosystem Project are harvested using clearcutting (CC) and single-tree selection (STS) regeneration methods. This work indicates possible effects of regeneration method on surface soil nutrient pools. Ten years after harvest, soil samples were collected in 10 cm increments from 0- to-30 cm in each treatment (CC, STS, and no-harvest removal sites), in three different nutrient status soils pre-determined by subsoil percent base saturation (BS: low, $\leq 20\%$ BS; medium, 20 – 50 % BS; and high, $\geq 50\%$ BS) using a paired sampling approach (i.e., samples were collected in treated and nearby non-treated locations). Samples were analyzed for pH, extractable base cation concentrations, total organic carbon (TOC), total nitrogen (TN) content, and stabile and labile nitrogen pools (SN and LN, respectively) via extractions and mineralization (PMN). Statistical analyses were performed on concentration difference values of paired samples (i.e., treated – untreated concentrations). Results indicate that Ca, TOC, TN, SN, LN and PMS concentration difference values are consistently smaller in STS and greater in CC than their paired controls, especially in high nutrient status soils and the surface 10 cm ($\alpha=0.10$). Disparity in soil nutrients is attributed to differences in slash distribution within the treatments.

CHAPTER 1: INTRODUCTION, OBJECTIVES AND LITERATURE REVIEW

1.1 Introduction

Forested ecosystems cover approximately one-third of Missouri and these lands are ecologically and monetarily significant to the State. The majority of forested lands in Missouri are located in the Ozark Highlands and soils of this region are marginally productive or unproductive for traditional agriculture (e.g., row crop agriculture or grazing). Thus, these lands are managed as forests to provide timber, particularly oak species. Due to the wide spread use of silviculture on Missouri's public and private lands, forest management research is actively conducted by university, state and federal scientists. Research on the effects of forest management and harvest primarily focuses on vegetation and wildlife metrics. Interestingly, the soil, a primary factor in plant growth, has been understudied in these ecosystems. Given the long rotation of forests and low initial soil nutrient levels, changes in soil nutrient levels due to harvest have been minimal or unobserved. However, the potential increased demand for forest products, especially biofuels may lead to shortened rotations with greater biomass removals. This necessitates quantifying all ecological effects of harvest management. Given the range of forest harvest and ecosystems studied to date, the effect of harvest in the Missouri Ozarks is difficult to project with great certainty. The Missouri Department of Conservation's (MDC) long-term Missouri Ozark Forest Ecosystem Project (MOFEP) provides an ideal

opportunity to study possible harvest effects on soil properties. The large spatial variability of soil properties and differing management practices implemented at MOFEP permit targeting specific combinations of soil and forest management techniques. For example, soils at MOFEP can be categorized into different nutrient status (low, medium and high) and these soils can be found in MOFEP sites treated with even-aged (EAM), uneven-aged (UAM), and no harvest management (NHM). More specifically, clearcutting and single-tree removal regeneration methods can be compared to non-harvested areas.

The effects of harvest removals on soil nutrients have been observed elsewhere when whole trees are harvested (WTH) and less so in sawlog or stem only harvests (SOH). Percentages of different canopy retention and age differ after harvest at MOFEP, but all harvests are SOH. However, few studies at MOFEP have incorporated a soil nutrient status component into their study design. Such studies are necessary to more fully understand the effect of forest regeneration methods on soils with differing initial nutrient status. Failure to perform investigations of this nature may result in implementation of unsustainable forestry practices in the Ozark Highlands, and elsewhere, that could adversely impact forest health.

1.2 Objectives and Hypotheses

Primary Research Objective

To elucidate the impact of forest regeneration methods on Missouri Ozark Highland soil nutrient concentrations, pools and chemical properties ten years post-harvest.

Specific Research Objectives

1. To ascertain the influence of forest regeneration methods (EAM clearcuts, UAM single-tree selections and NHM no harvest areas) on soil extractable base cation concentrations and pH in low, medium, and high nutrient status soils.
2. To determine the influence of forest harvest on stable and labile soil nitrogen (N) pools in low, medium and high nutrient status soils.

Specific Research Hypotheses

1. Smaller concentrations of base cations and lower pH will be observed in harvested soils compared to unharvested soils. The difference between harvested and unharvested locations will be greatest in high nutrient status soils; moderate and low nutrient status soils will show little to no differences in base nutrient amounts between harvested and unharvested locations. Additionally, differences between harvested and unharvested soils will be more evident in clearcuts than single-tree selections due to the greater concentration of timber removal in a clearcut.

2. No pattern of N difference between harvested and unharvested locations will be observed as a function of forest regeneration methods in high and moderate nutrient status soils. Low nutrient status soils will have smaller N concentrations in soils within clearcuts than unharvested soils, but little to no differences between single-tree selections and unharvested locations.

1.3 Literature Review

1.3.1 Missouri Ozark Forest Ecosystem Project (MOFEP)

The Missouri Ozark Forest Ecosystem Project is a long-term experiment established to investigate forest management influence on a host of ecosystem components (Sheriff, 2002). Mixed hardwood systems at MOFEP are managed according to MDC's *Forest Land Management Guidelines* (MDC, 1986). Nine study sites of approximately 400 hectares each are assigned one of three treatments, EAM, UAM, and NHM and all treatments were replicated in three blocks. Ten to twelve percent of each site was harvested with the prescribed technique in 1996; final regeneration cuts were clearcuts within EAM sites and single tree and small group removals in UAM sites. The sites may also be thinned as necessary between harvests which occur approximately every ten to fifteen years. The NHM sites do not undergo any timber removals (Brookshire et al., 1997). Prior to the initial harvest, five years of pretreatment data were collected for ecological parameters, such as overstory and ground flora and wildlife (Brookshire and Shifley, 1997; Shifley and Brookshire, 2000). Soil mapping of the sites was performed and soil characterization data were collected (Kabrick et al., 2000; Meinert et al., 1997),

but a comprehensive analysis of soil nutrients and chemical properties was not undertaken.

Soils at MOFEP and elsewhere in the Ozark Highlands are highly variable and dominated by weathered Ultisols and Alfisols, and a summary of geological and soil characteristics of soils in this region as described by Hammer (1997), Meinert et al. (1997) and Kabrick et al. (2000) is provided below. Bedrock materials consist of layers of sandstone and dolomite with varying amounts of chert (Fig 1.1). The most common parent material is hillslope sediments formed due to extensive weathering of the bedrock and landscape. Some loess parent material can be found accumulated on stable summits. Alluvium is also found in lower landscape positions and drainages. Soils formed in residuum are typically found overlying more resistant strata or dominating lower sections of soil profiles in depositional landscape positions (e.g., hillslope sediments over residuum). Alfisols and Ultisols are the most common taxonomic soil orders and soil base saturation is typically low except where dolomite outcrops are common. Soil drainage classification ranges from moderately well-drained to excessively well-drained. Depth to bedrock in these soils varies from shallow to very deep, although the presence of fragipans can limit effective plant rooting depth. Cumulatively, the aforementioned soil properties, steep slopes, and a large volume of coarse fragments suit the native oak, hickory and some pine vegetation, but few other economically valuable tree species prosper.

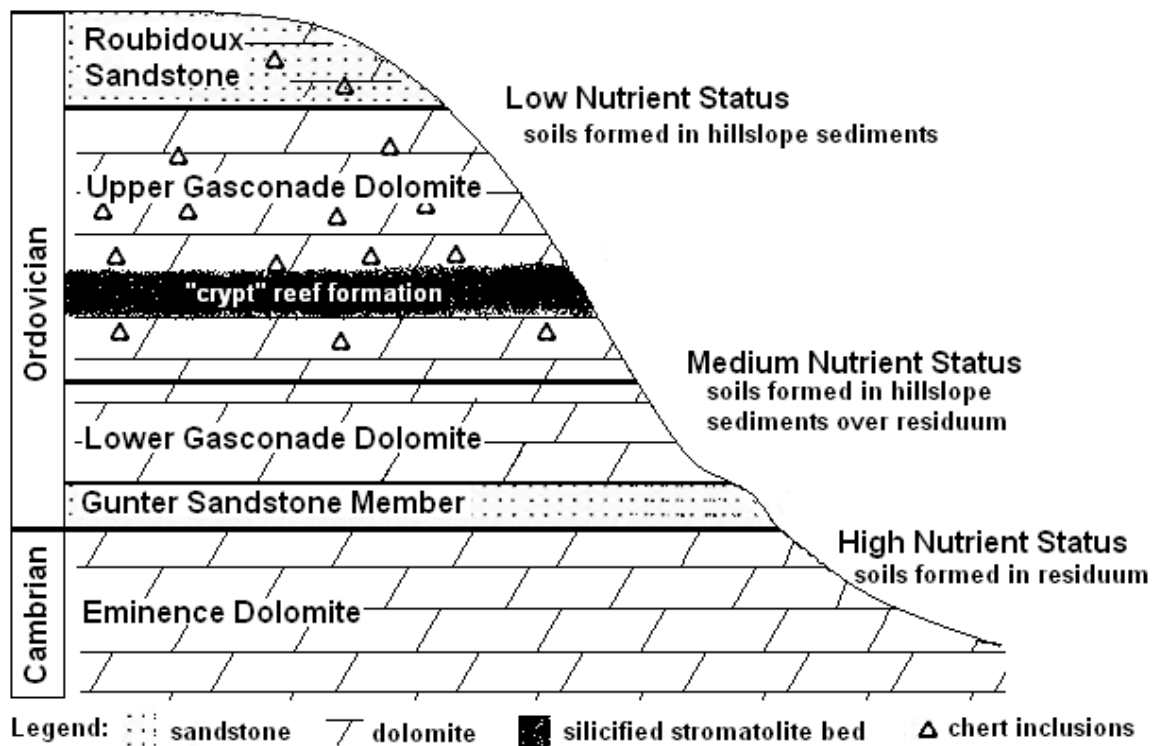


Figure 1.1. Representative landform profile diagram of bedrock geology and soil nutrient status occurrence at the Missouri Ozark Forest Ecosystem Project. Adapted using information from Meinert et al. (1997) and Orndorff et al. (2001).

The few soil nutrient studies conducted at MOFEP have revolved around microbial activity and sulfur (S) and carbon (C) pools. The impact of EAM on C, S, nitrogen (N), potassium (K), and magnesium (Mg) transformations was determined by Spratt (2002). Two years following clearcutting, soil surface S decreased while subsoil S increased. Soil C, N and K also decreased in clearcut sites while direct harvest effects on Mg concentration were difficult to elucidate. During a study of soil C pools by Li et al. (2007), it was observed that soil C in mineral horizons in UAM stands increased by 14% compared to NHM stands six years after harvest. Additionally, an increase in total N was observed in EAM sites compared to NHM and UAM sites eight years post treatment. However, it is unknown what specific harvest method occurred in each treated stand. This thesis research expands upon these previous studies by focusing on the specific regeneration method used, different pools of N in the soil as well as base cation concentrations, organic carbon, and pH across different treatments and soil types.

1.3.2 Forest Management Techniques and Harvest Practices

The timber in Ozark forest stands is a valuable economic resource for Missouri residents and businesses, and the most cost-effective method of timber removal and oak regeneration is clearcutting (Johnson et al., 2002). Currently, MDC includes clearcutting as a management tool to achieve stands of the same- or closely-aged trees (MDC, 1986). This EAM technique is designed to provide whole site harvests every 80-100 years in the Ozarks. The disturbance from clearcuts is concentrated but uniform across a whole stand, allowing ample sunlight for shade-intolerant species to regenerate (Johnson et al., 2002). Immediately following clearcutting, the large amount of slash left is available for

degradation. Given the widespread area and cutting of almost all vegetation in a clearcut, slash deposition is fairly contiguous.

In contrast, UAM does not strive for a single cohort of similar aged trees within a stand but rather a set distribution of age and size trees; single-tree or group selection is conducted to achieve this distribution. Uneven-aged management requires multiple entries into a stand over a full rotation compared to relatively few entries for EAM. After one rotation, UAM trees may be less likely to be injured as many trees selected for removal are smaller (Bruhn et al., 2002). However, UAM injured trees are more likely to remain and accumulate in the landscape while clearcuts remove a majority of injured trees. Within UAM sites, single tree and small group removals may be more dispersed throughout a stand during any single entry. Subsequently, site disturbance and slash distribution will be non-uniform. Under both forest management practices, pioneer plants and stump sprouts initiate vegetation reestablishment once established vegetation has been removed. However, differences in canopy cover between EAM and UAM treatments can cause species distribution to shift over time (Jensen and Kabrick, 2008).

These management techniques can have a variety of impacts on forest soil properties. The intensive removal of timber via clearcutting requires more concentrated use of heavy equipment and greater direct physical disturbance of the soil. Physical disturbances, as well as the removal of tree biomass from the ecosystem, can alter soil nutrient cycling and nutrient pool sizes (Fisher et al., 2000; Kimmins, 1997). A net loss of nutrients from the ecosystem occurs as large amounts of biomass are removed, and soil erosion may decrease soil nutrient pools in the harvested area (Federer et al., 1989; Holmes and Zak,

1999; Kimmins, 1997). The opening of the canopy and biomass removal increases exposure of soil to the sun and other elements, altering the microclimate of the sites. A flush of nutrients may be released from slash into soil solution and lost from the soil via leaching due to a lack of established vegetation utilizing nutrients (Belleau et al., 2006). The quantification of forest harvest effects on nutrient cycling is crucial to ensuring Missouri forest management is sustainable.

1.3.3 Effect of Forest Harvest on Soil Nutrients and pH

As noted previously, forest harvest can have an effect on nutrients in an ecosystem due to biomass removal, erosion and leaching. Whole tree harvest involves the greatest biomass removal from the forest. Unlike SOH, the whole tree is removed leaving little to no logging slash on-site and a decreased pool of nutrients to maintain site fertility. Johnson and Todd (1998) noted a direct relationship between soil nutrients and forest harvest. They observed that a mixed oak forest yielded greater soil exchangeable base cation concentrations in SOH compared to WTH; soil Ca increases were closely related to the estimated Ca released from slash during a 15-year period following harvest. These increases in nutrient concentrations were not only observable in the soil but in foliar tissues as well. The contribution of slash to soil nutrient pools can also be observed in the short-term as well, especially in the forest floor. Two years after SOH, Belleau et al. (2006) observed increases in total Ca, K, Mg, and pH increased in the forest floor soil horizons, but no change in the mineral soil. With more time for nutrients to cycle, these increases may also be seen in the mineral soil.

While WTH may result in lower soil nutrient concentrations compared to SOH, initial or control nutrient levels may not be greatly affected. In a study of harvest effects compared to preharvest data and a no-harvest reference watershed in Maine, McLaughlin and Phillips (2006) noted that bulk soil Ca, Mg, and K concentrations did not decrease up to 17 years after WTH compared to a reference watershed. Calcium increased significantly in the harvested watershed over both preharvest and reference watersheds. Interestingly, Mg concentrations decreased in both harvested and reference watersheds when compared to preharvest conditions, indicating loss of Mg from the soil is significant regardless of harvest.

In the southern Appalachians, Knoepp and Swank (1997a) found that long-term soil base cation concentrations in surface soils increased for three years after SOH, and Mg and K remained high 17 years post-treatment, relative to pretreatment conditions. In contrast to McLaughlin and Phillips (2006), no significant changes were observed in the reference watershed over the course of the study. These results, unique to each study, indicate the inherent variability in forest composition, soils, and regeneration method across the U.S. which make direct comparisons between ecosystems difficult and highlight the need for region specific studies to fully evaluate harvest impacts.

Observed increases in soil base cation concentrations (e.g., McLaughlin and Phillips, 2006) are unexpected as Ca depletion is thought to be a significant issue for sustaining soil productivity in the southeastern United States (Federer et al., 1989; Huntington et al., 2000), particularly after WTH in Ca-poor parent materials. Federer et al. (1989) estimated losses in soil and biomass base cations over 120 years in forests across the

eastern U.S. Depending on harvest intensity and site characteristics, total soil and biomass pools of K and Mg may be reduced by as much as 2-10%, while Ca pools could decrease from 20-60%. Huntington et al. (2000) estimated 80 years of Ca losses via tree uptake and soil leaching would result in soil Ca levels that would substantially affect timber quality. However, these depletions have not been observed in bulk soil. Federer et al. (1989) also suggested distinctive increases in an element such as Ca after WTH could be due to harvest effects that result in increasing mineral weathering. In regions such as the Missouri Ozarks where soil and parent material weathering is already extensive, the ability of soil and bedrock formations to continually supply base cations may be limited.

While changes in bulk forest floor and mineral soil nutrient pools after harvest can affect site quality, measurements of soil solution reflect changes in nutrient flux and can yield a different pattern of harvest effects. Mahendrappa et al. (2006) attributed changes in surface organic materials to changes in soil solution chemistry after harvest events. Solution pH decreased after SOH relative to WTH. Changes in pH were attributed to proton release as organic matter was mineralized and ammonium (NH_4^+) converted to nitrate (NO_3^-). While both harvest methods increase mineralization in the soil, SOH provides slash which then decomposed unlike WTH where the whole tree is removed and minimal slash remains. Four years after harvest, similar soil pH values across varying intensity removals were attributed to similar slash distributions in each treatment (Jerabkova et al., 2006). Dahlgren and Driscoll (1994) observed increased base cation concentrations in soil solution collected from WTH sites relative to soil solution from a

reference watershed. Increases in base cation concentrations were attributed to enhanced leaching from the forest floor.

Soil solution pH at depths of 25 and 50 cm was also greater in the regenerating watershed relative to the reference and pre-harvest watersheds in the McLaughlin and Phillips (2006) study, though H^+ concentration did not differ significantly. Since pH is the inverse \log_{10} of the H^+ activity, as pH increases the H^+ concentration should decrease by an order of magnitude and deviations between the two are difficult to reconcile. In this case, it was attributed to slash not available for mineralization to contribute H^+ after WTH. However, soil solution Ca, Mg, K concentrations were lower after WTH compared to preharvest levels and the regenerating watershed (McLaughlin and Phillips, 2006). In particular, at 50 cm, Ca concentrations increased immediately following harvest but returned to preharvest levels two years later and decreased linearly 10-20 years post-harvest. Mg behaved in a similar fashion. Reference watershed Ca concentrations at 50 cm fluctuated slightly during the first 10 years and doubled by year 20. The different behavior of soil base cations Ca and Mg may be due to the tighter cycling of smaller pools post-harvest removal, thus limiting the amount of base cations available for leaching.

1.3.4 Effect of Forest Harvest on Soil Nitrogen Pools and Carbon

Of particular interest is the effect harvesting has on soil nitrogen (N), because N is often the most limiting nutrient in many terrestrial ecosystems (Vitousek and Howarth, 1991). Nitrogen is present in the environment in a variety of forms ranging from N_2 (g) to complex organic molecules and plant available ionic species (e.g., NH_4^+ and NO_3^-).

During the mineralization process, organic N is transformed by N mineralizing bacteria to NH_4^+ . In aerobic soils, NH_4^+ is rapidly converted to NO_3^- through the nitrification process. Ammonium ions can be retained in the soil by negatively-charged clay particles and organic matter, while NO_3^- has a high tendency to be lost via leaching. Organic N forms are considered relatively stable and they are slowly transferred to labile and plant available inorganic N pools. Labile pools are the most susceptible to any type of ecosystem disturbance, but they can be replenished from more stable pools (Westerhof et al., 1998).

In order to simplify results, some studies focus on total nutrient amounts as opposed to individual pools. Though easier to measure, total nutrient amounts tend to be dominated by stable forms and may not show significant change after a single harvest event or other disturbance. Seventeen years after WTH in central Maine, no depletion was observed in soil total C or N when compared to a reference watershed (McLaughlin and Phillips, 2006). Southern Appalachian mixed hardwoods showed no significant differences in total C and N at a depth of 10-30 cm over 15 years post-WTH (Knoepp and Swank, 1997b). In the 0-10 cm soil samples, slight decreases were observed in total C and N at a depth during the first and third years after harvest. However, 15 years post-treatment, total N regained pre-treatment concentrations in the 0-10 cm depth while total C remained slightly lower (Knoepp and Swank, 1997b). More significant differences were observed in SOH where total C and N increased after harvest, presumably due to slash deposition, before returning to pre-harvest levels 5 years later.

One measure of N transfer from stable to labile pools involves soil organic matter mineralization studies. Mineralization is typically measured using a contained soil sample incubated in the laboratory (aerobic and anaerobic incubation procedures) or buried in the field (buried bag technique) and the amount of inorganic N released through time is measured (Bradley and Parsons, 2007; Nadelhoffer, 1990; Stark, 2000; Vitousek and Matson, 1985; Weaver, 1994). The resulting mineralized N yield is dependent upon initial amounts of N, climatic or incubation conditions and the sustained requirement of N by vegetation. For example, *in situ* N mineralization was found to be significantly greater in an Andisol with higher initial N content than an Entisol with lower initial N (Scott et al., 1998). However, the lesser amount of N mineralized in the Entisol was proportionately greater than that of the Andisol, relative to the initial total N concentration. These results suggest that while total N mineralization may be greater when total N is large, N may have a shorter residence time in the stable organic pool when the total N pool is small (i.e., the kinetics of N mineralization is greater when total N pool is smaller).

Nitrogen mineralization in the soil is also affected by disturbances such as timber harvest. Shortly after a traditional clearcut, Holmes and Zak (1999) observed significantly increased N mineralization and nitrification from *in situ* buried bag incubations conducted in a northern hardwood forest. This suggests mineralization will increase in response to a clearcut. However, in a central hardwoods chronosequence, Idol et al. (2003) revealed that N mineralization was lowest immediately after clearcut harvest and mineralization increased to maximum values in an 80-100 year old mature site. It

was suggested the highly weathered Alfisols studied may be experiencing limiting nutrients besides N; harvesting may cause a decrease in another limiting nutrient affecting N cycling rates in different age stands. These contrasting results highlight the need for region specific studies to fully evaluate harvest impacts.

Different degrees of harvest intensity add to the variation in harvest effects on soil N pools. While concentrations of N are higher in foliage than litter and lowest in slash, the relative amounts of each pool are greater with decreasing N concentration (Fisher et al., 2000). The removal of low N slash may still deplete soil N pools. Aerobic laboratory incubations of forest floor samples collected four years after coastal western hemlock clearcut and shelterwood harvests yielded greater NH_4^+ mineralization in clearcuts relative to old growth stands; shelterwood sites had intermediate mineralization rates (Bradley and Parsons, 2007). Increasing N mineralization with increased harvest intensity is likely the result of greater slash left on site which can undergo decomposition. In loblolly pine plantations, WTH significantly decreased net N mineralization in field and laboratory incubations when compared SOH (Vitousek and Matson, 1985). The large amount of slash from large branches and smaller limbs left on site in SOH provides a nutrient source unavailable in WTH.

By combining the effects of slash left on site with harvest removal and soil nutrient status, total management effects on nutrient cycling can be determined. Potential N mineralization determined in laboratory soil sample incubations correlated positively with higher nutrient status soils and increased slash amounts relative to low nutrient status soils and little-to-no slash left on blue gum (*Eucalyptus globules*) plantation sites

one to six years after clearcut harvest (O'Connell et al., 2004). This indicates that the practice of leaving slash on-site may contribute to total and labile N pools, particularly after net N loss due to biomass removal on low fertility sites.

While N transfer between nutrient pools is an important measure of nutrient cycling, the size of the pools is critical to site quality. Mahendrappa et al. (2006) observed greater NO_3^- soil solution concentrations in the first two years following SOH and WTH of white spruce (*Picea glauca*), and NO_3^- concentrations were greater in the SOH area than WTH. The authors hypothesized that this resulted from slash mineralization and subsequent conversion of NH_4^+ to NO_3^- . Jerabkova et al. (2006) observed that NH_4^+ concentrations in soil extractions collected from variable retention harvest stands were greater than NO_3^- concentrations regardless of the percentage harvest occurring in boreal forests. These ions are immediately available to plants and also susceptible to loss or retention in the soil. Soluble organic N (SON) amounts, however, did show a decrease with increasing biomass removal (Jerabkova et al., 2006). Soluble organic nitrogen consists of materials that may be utilized by plants but are most likely to be mineralized into ionic forms, and are susceptible to leaching (Chen et al., 2005). The decrease in SON could indicate a loss of organic N not yet reflected in the inorganic pool or simply shorter residence time in SON forms. Nevertheless, the correlation of treatment with one N pool and not another reflects the complexity of N cycling processes in forest soils.

1.4 Summary of Literature Review and Relationship to Current Study at MOFEP

Given the broad range of forested ecosystems and study results, it can be difficult to discern a distinct pattern of soil nutrient changes applicable to Missouri Ozarks forests. Mixed oak and hardwood forests concentrations of base cations have increased in SOH compared to WTH (Johnson and Todd, 1998) and preharvest conditions (Knoepp and Swank, 1997a). However, base cations, especially Ca, are projected to reach timber quality limiting levels in the southeastern U.S. (Federer et al., 1989; Huntington et al., 2000). Southern Missouri's highly weathered soils and bedrock are unlikely to continue supplying soil base cations with forest removal and a lowering of pH values can also be expected.

Dahlgren and Driscoll (1994) evaluated soil solution along an elevational/vegetational gradient; they observed that harvest disturbance had a greater effect in shallow soils at high elevations such that vegetation recovery after harvest was delayed. While low nutrient soils at MOFEP are typically higher in the landscape, they are generally not shallow to bedrock and increased soil depth may minimize overall mineral nutrient losses observed in surface horizons due to harvest.

A comparison of harvest effect on north- and south-facing slopes revealed nutrient concentrations fluctuating on the exposed slope and decreasing on the protected slope (Knoepp and Swank, 1997b). Even though efforts were made to keep aspect consistent, MOFEP high nutrient status soils typically have variable depth to bedrock and are lower in the landscape and more protected. Increased moisture content in protected landscape positions could increase losses due to leaching compared to soils at greater elevation and

exposure which dry more rapidly. Given the tight cycling of base cations, losses from the bulk soil are unlikely to be seen in low nutrient status soils in MOFEP, but the surplus of base cations in high nutrient status soils may experience depletion ten years after harvest, especially in clearcuts where the biomass removal is concentrated.

When ascertaining any effect of harvest on soil N cycles, Scott et al. (1998) concluded that proportional losses of N may be greater in low nutrient soil than higher nutrient soils due to the sensitivity of the N cycle in low nutrient soils to C removals by harvest. Since C and N distribution in the soil profile is concentrated in surface horizons, the depth of MOFEP low nutrient soils may not mitigate N losses by cycling throughout the profile. Labile N is susceptible to losses and removal from the soil by plant uptake. Stable pools may slowly contribute to the labile pool but if inputs are limited both stable and labile fractions may be depleted over time. Additionally, the lower landscape positions of medium and high nutrient status soils increases the accumulation of organic litter and N containing leachates from clearcuts higher in the landscape. Thus, is it unlikely that medium and high nutrient status soils will experience any effects on N pools due to harvest.

1.4 References

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CHAPTER 2: EVALUATION OF FOREST HARVEST MANAGEMENT ON SOIL EXCHANGEABLE BASE CATIONS, PH, TOTAL ORGANIC CARBON AND TOTAL NITROGEN IN THE OZARK HIGHLANDS

2.1 Abstract

The Missouri Ozark Forest Ecosystem Project (MOFEP) is a long-term experiment established to investigate forest management influence on a host of ecosystem components. Mixed hardwood systems at MOFEP are managed with even-aged (EAM), uneven-aged (UAM), and no harvest (NHM) management, and soils at MOFEP are dominated by highly weathered Ultisols and Alfisols. This study seeks to elucidate the effect of harvest practices on surface soil nutrient pools present at MOFEP. Three soils were selected based on relative nutrient status as indicated by subsoil percent base saturation (BS): low, $\leq 20\%$ BS; medium, $20 - 50\%$ BS; and high, $\geq 50\%$ BS. In 2007, ten years after harvest, samples were collected in 10 cm increments from 0 to 30 cm in each treatment and soil using a paired sampling approach (i.e., samples were collected in treated and nearby non-treated locations). Treatments sampled were EAM clear cuts, UAM single-tree selections and NHM sites. Samples were analyzed for a variety of soil chemical properties including pH, extractable base cation concentrations (Ca, Mg, K), and total organic carbon (TOC) and total nitrogen (TN) content. The data indicate that exchangeable Ca, TOC and TN are significantly different ($\alpha=0.10$) between EAM and

UAM sites. Concentrations are consistently smaller in soils under single-tree selection sites relative to clearcut sites, when both are compared to non-harvested controls, particularly at the 0 – 10 cm depth. However, these differences are not always significant. Disparity between the treated soils is attributed to differences in slash distribution within the treatments.

2.2 Introduction

When utilizing forest resources, different regeneration methods are often implemented to achieve particular management goals. Many studies have noted harvest impacts on vegetation and wildlife communities; however, fewer studies have focused on harvest effects on site quality and sustainability. Depletion of soil nutrient pools, in particular soil base cations (Federer et al., 1989; Huntington et al., 2000) and total N (Vitousek and Matson, 1985), with increased nutrient removals via timber harvest is increasingly becoming a concern (Adams et al., 2000; Ballard, 2000; Chatterjee et al., 2008; Johnson et al., 2008; Johnson et al., 1988; Thiffault et al., 2008). Soil has a significant influence on site quality but timber harvest effects on soil resources, particularly in the Ozark Highlands, have not been thoroughly investigated. Additionally, the extensive weathering of Missouri Ozarks soils may limit the ability of the soil and bedrock formations to continually supply base cations ameliorating harvest removals.

Soils of the Missouri Ozark Highlands are dominated by highly weathered Ultisols and Alfisols (Hammer, 1997; Meinert et al., 1997). Bedrock deposition dating back to Ordovician and even pre-Cambrian periods (Fig. 1.2) have weathered into soil materials with low base cation content and low cation exchange capacity (CEC) (Hammer, 1997;

Kabrick et al., 2000; Meinert et al., 1997). Soils in the study region are formed primarily in gravelly hillslope sediments, hillslope sediments over residuum, or residuum. Drainages are deeply incised, waterways frequently flow below the surface (Orndorff et al., 2001), and occasional large floodplain and terrace landscapes of alluvial deposits are used for pasture. Soil nutrient status is variable and a significant proportion of forest nutrients are contained in the wood of trees (Kabrick et al., 2009). Calcium (Ca) is of particular interest as the bole of a tree contains a large amount of calcium that is removed with harvest. Thus, Ca depletion is a concern in soils containing small quantities of total Ca (Federer et al., 1989; Huntington et al., 2000; Kabrick et al., 2009). The net loss of nutrients from the forest system due to harvest and limited capacity for replenishment via mineral weathering may reduce soil nutrient content over time, thereby adversely affecting site productivity.

Soil base cations in the solid phase and soil solution can exhibit varying response to harvest. Whole-tree harvest (WTH) can increase soil solution base cation concentrations compared to a reference watershed (Dahlgren and Driscoll, 1994), and stem only harvest (SOH) can induce even greater base cation concentrations in soil solution (Johnson and Todd, 1998). These effects have been attributed to increased mineralization and leaching of forest floor layers and abundant slash left on site. As organic materials decompose, organic acids are produced, H^+ is released via conversion of NH_4^+ to NO_3^- , and base cation substitution occurs on exchange sites which, in concert, lowers soil solution pH (Mahendrappa et al., 2006). However, decreases in bulk soil pH are not always observed (Jerabkova et al., 2006).

Soil chemistry changes are frequently observed in the first years following harvest, particularly increases from nutrient flushing or the *assart* effect (Belleau et al., 2006; Kimmins, 1997; Knoepp and Swank, 1997a; McLaughlin and Phillips, 2006). Others have observed long-term alterations to soil properties including soil carbon and nitrogen (Johnson and Todd, 1998; Knoepp and Swank, 1997a; Knoepp and Swank, 1997b; McLaughlin and Phillips, 2006). Contrasting results from above mentioned studies in different regions and climates, forest and soil types, management and regeneration methods highlight the need for region specific studies to fully evaluate harvest impacts. Therefore, the objective of this study was to determine how the forest harvest practices utilized by land managers in Missouri influence soil nutrient contents.

2.3 Materials and Methods

2.3.1 Site Selection and Description

The Missouri Ozark Forest Ecosystem Project is a long-term experiment in the Missouri Ozark Highlands designed to study the effects of the Missouri Department of Conservation (MDC) forest management practices on many ecosystem attributes (Brookshire et al., 1997). Study sites consist of nine sites each approximately 400 ha in size that have been assigned one of three treatments, EAM, UAM and NHM. Ten-to-twelve percent of each site was harvested with the prescribed technique in 1996 as dictated by the MDC's *Forest Land Management Guidelines* (MDC, 1986).

Three soil groups of high, medium and low nutrient status were selected for study. Nutrient status was determined by percent base saturation (BS) of CEC for the soil map unit at the diagnostic subsoil depth for taxonomic classification (USDA-NRCS, 1999)

and underlying bedrock strata (Table 2.1). These criteria were chosen because the base saturation of the soils in this region is largely dependent upon the underlying geologic formation and depth to bedrock (Kabrick et al., 2000; Meinert et al., 1997). Additionally, it was hypothesized that nutrient cycling would result in translocation of base cations from deeper depths, thereby increasing base cation concentrations in surface horizons as well.

In each of the nine sites, locations of select soil map units with desired treatments and characteristics were chosen for consistency of slope class and exposure, and soil/site characteristics were verified in the field prior to sampling. Treatment areas for soil sampling purposes were EAM clearcuts and UAM single-tree selections; NHM sites were also sampled to serve as controls. All locations sampled were found on the backslope landscape position. However, locations varied in position on the backslope (i.e., from lower to upper backslope positions). Slope of the sampling locations ranged from 10 to 60%, but over nine-tenths were positioned on slopes of 20 to 50%. The majority of field locations sampled (39 out of 54) had a northeast or east orientation. However, due to the pattern of harvest removals and soil occurrence, eleven locations had a southeastern orientation, two were due south and two faced southwest. Particular treatments or soil types were not favored in any aspect class and the paired sampling technique used should account for any small discrepancies due to differences in aspect.

Table 2.1. Soil, landform, and geological information used to locate and identify MOFEP soils with target nutrient status[†].

Target Soil Nutrient Status	Subsoil BS [‡] at diagnostic depth	Soil Map Units	Common Soil Series	Landform	Underlying Bed Rock Formation	Parent Material	Common Soil Classification
	--- (%) ---						
High	> 50	74, 81	Arkana, Bardley	Backslopes, Shoulders	Gasconade, Eminence	Hillslope sediments over residuum	Very-fine, mixed, active, mesic Mollic Hapludalfs (Arkana)
Medium	20-50	82	Alred	Backslopes, Benches, Shoulders	Gasconade, Eminence	Hillslope sediments over residuum	Loamy-skeletal over clayey, siliceous, semiactive, mesic Typic Paleudalfs (Alred)
Low	<20	63, 80	Bender, Clarksville	Backslopes, Shoulders, Summits	Roubidoux, Gasconade	Hillslope sediments	Loamy-skeletal, siliceous, semiactive, mesic Typic Paleudults (Clarksville)

[†] Information obtained from Kabrick et al. (2000) and Meinert et al. (1997).

[‡] BS, soil base saturation.

2.3.2 *Soil Sampling*

All soil sampling was conducted during the second week of July in 2007. At each of the three soil types within a site, field replicate subsamples (1 kg per depth) were collected from three shallow, hand-dug pits in 10 cm increments from 0-30 cm within a clearcut (EAM harvest) or surrounding a stump (UAM harvest) and in paired non-harvested reference areas within the EAM or UAM site. One-half of each soil sample collected was placed in polyethylene bags, sealed, and stored at 4°C. The remaining sample was placed in polypropylene storage tubs and air-dried upon return to the laboratory. Organic matter on the surface (O horizons) was also sampled and placed in paper bags, air dried upon return to the laboratory, ground and stored in plastic bags at 4°C.

In cases where the soil map unit being sampled extended from the harvested area into a non-harvested area, sampling of the non-harvest paired samples was conducted at least one mature tree height from the harvest/non-harvested interface (Fig. 2.1). When the soil map unit being sampled was contained in a harvested section of forest, the nearest representative, non-harvested soil map unit with comparable landscape position, slope, and aspect was sampled. The paired sampling procedure was also employed on the control (NHM) sites for purposes of consistency. Identification of each location in control sites as “harvested” or “non-harvested” was randomly assigned. This paired sampling approach was utilized to minimize differences in spatial variability between the treated and untreated controls due to the relatively large geographic separation between several of the sites. Such a technique lends itself to investigating significant differences

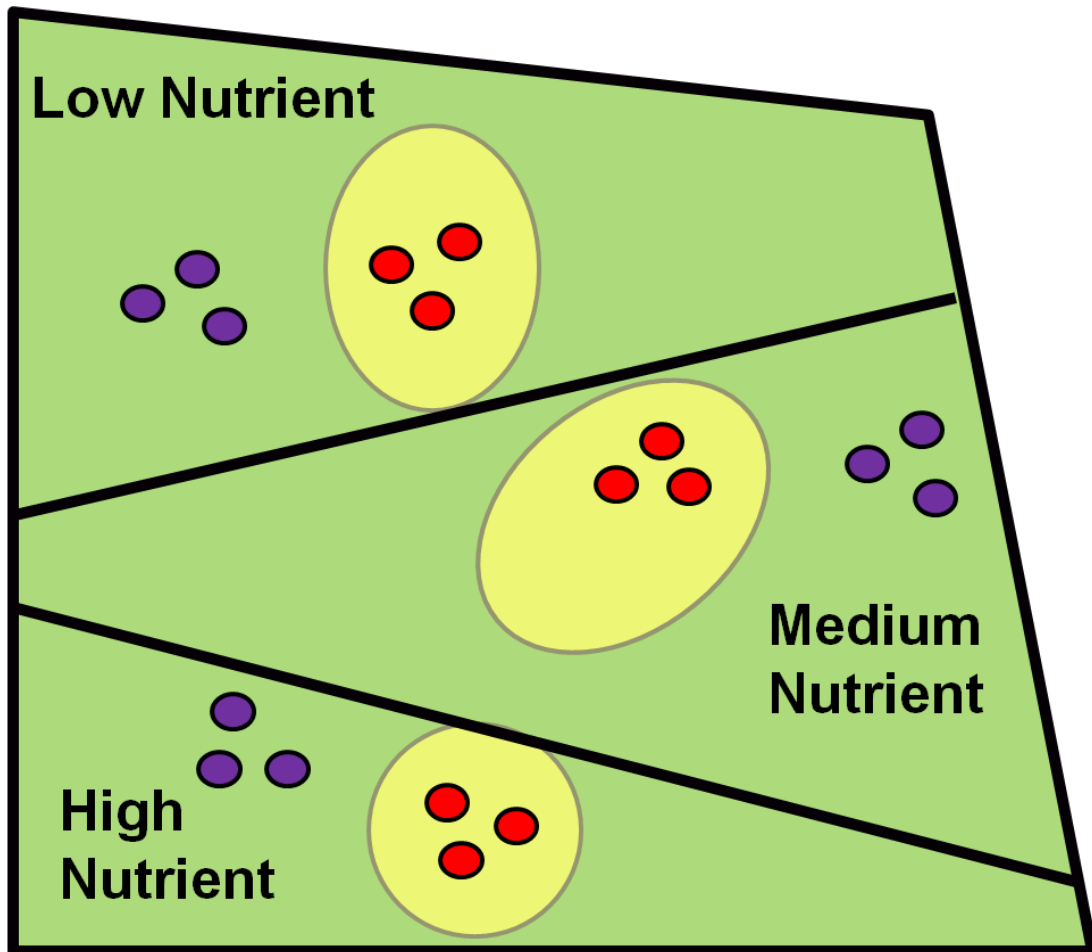


Figure 2.1. Idealized diagram of MOFEP site sampling stratification by soil nutrient status and paired sampling design. The site is divided into three soil nutrient status areas and within each soil a harvested location and non-harvested reference location is identified outside of the treated area.

between harvest treatments and soils by statistically analyzing difference values (treated minus control) obtained between the pairs. One pair of harvested and non-harvested soils was not present for sampling because no high nutrient status soil was clearcut at MOFEP Site 9 (EAM). Two non-harvested locations were sampled and analyzed, but the data from these samples were not used in the statistical analyses to minimize imbalance in the design.

2.3.3 *Sample Characterization and Experimental Protocols*

After air-drying, soil samples were ground, passed through a 2 mm mesh sieve, and sent to the Missouri Soil Characterization Laboratory (Columbia, MO) for analyses detailed in the USDA-NRCS *Soil Survey Laboratory Methods Manual* (Burt, 2004). Particle size analysis was determined using pipette analysis with standard pretreatments and dispersion (method 3A1a1a). Soil CEC and extractable cations, (Ca, Mg, K and Na) were determined using 1 M ammonium acetate ($\text{CH}_3\text{COONH}_4$) extraction, steam distillation, HCl titration and atomic absorption spectrophotometry (CEC-7, method 4B1a1a1a1a1). These effective CEC values were used for statistical analysis and to calculate percent base saturation (BS). Cation exchange capacity was also determined by the summation of extractable bases plus the BaCl_2 -triethanolamine released extractable acidity (EA) (CEC-8.2, method 4B2a1a1a1). Extractable Al of low pH samples was determined using 1 M KCl extraction and inductively coupled plasma - atomic emission spectrophotometry (ICP-AES, method 4B3a1a1a1). Soil pH was measured in 1:1 soil-to-water ratio and 1:2 soil-to-0.01 M CaCl_2 salt solution (methods 8C1a and 8C1e, respectively). Total organic carbon (TOC) was determined by dry combustion method

4H2a, modified to 927 °C. Samples were dried at 40°C for 24 hours for consistency with other nitrogen procedures, finely ground and analyzed for total nitrogen (TN) using dry combustion (method 4H2a2a1).

2.3.4 *Data Analysis.*

All experimental data was entered into a Microsoft Access 2007 database (MOFEP Solid Soil Chemistry.accdb) with calculations performed in both Access and MS Excel 2007. The accuracy of identifying field locations with the soils of interest was evaluated via statistical analyses of all non-harvested samples in SAS Enterprise Guide software, Version 4.2 of the SAS System for Windows XP (Copyright © 2006-2008 SAS Institute Inc., Cary, NC, USA), using the Mixed procedure. A split-plot analysis of variance model was utilized with the split occurring by soil nutrient status (Table 2.2). Harvest effects were determined using difference values of sampling pairs. Difference values for each pair of samples were calculated by first averaging field subsample replicates by depth class. Each average value from a non-harvested location was then subtracted from a paired average value in a harvested location. The resulting difference value was positive if the harvested location had a greater average than the paired non-harvested location, and the difference value was negative if the opposite occurred. Statistical analyses were performed on difference values using the Mixed procedure in SAS Enterprise Guide software. A spatially-repeated split-plot analysis of variance model was utilized with the split occurring by soil nutrient status and each depth class was considered a spatially repeated sampling (Table 2.3). Depth was treated as a covariant as two adjacent depths should have more in common than more distant depths (e.g., 0-10 cm

Table 2.2. Split-plot design analysis of variance table for determination of soil nutrient status (SNS) assignment efficacy of soils from unharvested locations. Main effect SNS and error due to possible interactions with fixed effects: depth, replicate (Rep), and assigned MOFEP treatment (i.e., EAM, UAM, or NHM).

Source	Degrees of Freedom
SNS	2
Depth	2
Rep	2
Treatment	2
SNS*Depth	4
SNS*Rep	4
SNS*Treatment	4
Depth*Rep	4
Depth*Treatment	4
Rep*Treatment	4
SNS*Depth*Rep	8
SNS*Depth*Treatment	8
SNS*Rep*Treatment	8
Depth*Rep*Treatment	8
SNS*Depth*Rep*Treatment	16

Table 2.3. Split-plot design analysis of variance table with harvest treatment main effect, each site split by soil nutrient status (SNS), each sampling repeated by depth.

Source	Degrees of Freedom
Treatment	2
SNS	2
Treatment*SNS	4
Depth	2
Treatment*Depth	4
SNS*Depth	4
Treatment*SNS*Depth	8

samples should be more like 10-20 cm samples than 20-30 cm samples). Significance ($\alpha = 0.1, 0.05, 0.01$ and 0.001) between mean values was determined using Tukey-Kramer adjusted values due to sample imbalance.

2.4 Results and Discussion

2.4.1 Physical Characteristics and Control Soil Properties

Soils were typically covered with one to two cm of Oi horizon and coarse woody debris, along with chert and some sandstone gravel. Coarse fragments within the profile ranged from < 10 to > 80 percent of soil volume, and coarse fragments were dominated by chert gravel although some sandstone gravel and cobbles were present. The dominant soil color hue was 10YR, but some 7.5YR and 5YR hues were found lower in the profile. High value and chroma were observed throughout subsurface materials and soil color chroma of two or less was only observed in surface horizons, indicating well-drained conditions. Typical profiles were comprised of A horizons underlain by eluvial (E) and/or transition horizons (AB and BE were most common), and B horizons exhibiting illuvial clay accumulation. Soil structure ranged from strong to weak granular and subangular blocky, and some angular blocky structure was observed in higher clay content subsoil horizons.

Over one-half of the samples analyzed had a soil texture class of silt loam, and soils with loam, clay and sandy loam textures comprised an additional 35% of samples. In all soils studied, soil particle size became increasingly finer with depth (i.e., clay content increased). Low nutrient status soils had the least variability in soil texture class with all samples found to be in loam texture classes and an overwhelming 80 percent silt loam

textures. Medium nutrient status soils followed a similar pattern; 70% of sample textures were silt loam, but a few subsoil samples consisted of clay and clay loam textures. High nutrient status soils contained the greatest soil texture class variability and no clear texture was predominant. Larger particle sizes decreased with increasing depth, 0-10 cm samples favoring loam, 20-30 cm samples with more clay and clay loam textures, and samples collected from 10-20 cm consisted of soil textures ranging from loam to clay loam.

In this study, we used pre-existing soil characterization data collected by Kabrick et al. (2000) to identify soil map units with varying base saturation at the diagnostic subsoil depth used for soil taxonomic classification. It was anticipated that forest nutrient cycling processes would result in translocation of nutrient from deeper depths to surface soil horizons resulting in a range of base saturations in surface as well as subsoil horizons. Analysis of data from all non-harvested locations (i.e., NHM and paired control samples) revealed that this *a priori* assignment of soil nutrient status worked well for identifying high nutrient status soils. Average base saturation \pm standard error (SE) of high nutrient status soils was 69 ± 4 % of soil CEC (Table 2.4). Thus, average base saturation of high nutrient status classes of soils met criteria initially established for separating the different soil classes (Table 2.1). However, *a priori* assignment of medium and low nutrient status soils was less than satisfactory. Mean base saturation of medium and low nutrient status soils were $22 \pm 4\%$ and $20 \pm 4\%$, respectively, and these values were not statistically different. Base saturation of medium nutrient status soils met initially established criteria for defining this nutrient status class of soil (i.e., mean base

Table 2.4. Average soil chemical properties for no harvest management (NHM) and non-harvested, paired control soil samples associated with different nutrient status soils.

Soil Nutrient Status	BS [†]	Ca [‡]	Mg [‡]	K [‡]	CEC [§]	EA [§]	pH _s [¶]	(H ⁺) _{salt} [#]	TOC ^{††}	TN ^{‡‡}
	(%)	----- (cmol _c kg ⁻¹ soil) -----							-- (g kg ⁻¹ soil) --	
High	69 a ^{§§}	12 a	6.9 a	0.35 a	24 a	5.7 a	5.9 a	8 x 10 ⁻⁶ a	21 a	1.6 a
Medium	22 b	1 b	0.6 b	0.21 b	9 b	6.9 b	4.6 b	3.4 x 10 ⁻⁵ b	13 b	0.9 b
Low	20 b	1 b	0.5 b	0.20 b	9 b	7.2 b	4.6 b	3.4 x 10 ⁻⁵ b	14 b	0.9 b
Significance Level ^{¶¶}	***	**	**		**		**	**	*	*

[†] BS, percent base saturation by weight.

[‡] Exchangeable concentrations of Ca, Mg and K.

[§] CEC, cation exchange capacity determined by the sum of exchangeable base cations and extractable acidity (EA).

[¶] pH_s, soil pH measured in 0.01 M CaCl₂ soil slurry.

[#] (H⁺)_{salt}, activity of hydrogen ions calculated from pH_s.

^{††} TOC, total organic carbon.

^{‡‡} TN, total nitrogen.

^{§§} Letters indicate significant differences between values within a column as determined using the Tukey-Kremer adjusted test of means.

^{¶¶} Asterisks under each column indicate significance levels: no asterisk, $\alpha=0.1$; *, $\alpha=0.05$; **, $\alpha=0.01$; and ***, $\alpha=0.001$.

saturation between 20-50%); whereas, mean base saturation of low nutrient class soils was slightly greater than the initially established criteria.

Trends in the data similar to base saturation between different soil nutrient categories are also evident for exchangeable bases, CEC, TOC and TN (Table 2.4). Inverse trends are observed for EA and hydrogen ion activity, resulting, subsequently, in lower pH values for medium and low nutrient status soils. When data were further investigated by depth within each nutrient status class (Table 2.5), BS, Ca, K, TOC, TN and EA were all greater in the surface 10 cm than 10-20 and 20-30 cm depths in medium and low nutrient status soils; Ca, K, EA, TOC and TN were also greater in the surface 10 cm than 10-20 and 20-30 cm depths of high nutrient status soils. High nutrient status soils exhibited similar CEC with depth and BS and Mg concentration increased with depth in these soils.

Greater nutrient concentrations in the surface 10 cm of non-harvested soils suggest nutrient cycling across all soils are influenced by surface deposition of materials rather than cycling throughout the soil profile. Only high nutrient soil map units exhibit BS clearly indicative of the underlying parent material, particularly since BS and Mg increase with depth (Table 2.5). The slightly lower concentrations in 0-10 cm BS and Mg compared to 10-20 and 20-30 cm samples suggest the cycling of these two soil properties in high nutrient soils are controlled by losses at the surface, likely plant uptake and leaching, and replenishment from lower in the soil profile. In contrast in high nutrient status soil, soil chemical properties and nutrient pools lower in the profile do not appear to contribute to other surface soil properties and nutrients (e.g. Ca, K, EA, TOC, TN), and low and medium nutrient status soil chemical properties overall. Rather,

Table 2.5. Average soil chemical properties for no harvest management (NHM) and non-harvested, paired control soil samples associated with different nutrient status soils and each depth class.

Depth (cm)	BS [†] (%)	Ca [‡] -----	Mg [‡] (cmol _c kg ⁻¹ soil)	K [‡] -----	CEC [§]	EA [§]	pH _s [¶]	(H ⁺) _{salt} [#]	TOC ^{††} -- (g kg ⁻¹ soil) --	TN ^{‡‡}
<u>High Nutrient Status Soil</u>										
0-10	65 a ^{§§}	13 a	5.9 a	0.40 a	25 a	6.3 a	5.9 a	8 x 10 ⁻⁶ a	32 a	2.3 a
10-20	67 ab	11 b	6.7 b	0.33 b	23 b	5.3 b	6.0 a	7 x 10 ⁻⁶ a	17 b	1.4 b
20-30	73 b	11 b	8.3 c	0.33 b	25 a	5.5 b	6.0 a	9 x 10 ⁻⁶ a	12 c	1.2 b
Significance Level ^{¶¶}		*		*					*	***
<u>Medium Nutrient Status Soil</u>										
0-10	27 a	2 a	0.8 a	0.28 a	12 a	8.5 a	4.8 a	2.2 x 10 ⁻⁵ a	22 a	1.4 a
10-20	17 b	1 b	0.4 a	0.19 b	8 b	6.6 b	4.5 b	3.6 x 10 ⁻⁵ b	11 b	0.8 b
20-30	19 b	1 b	0.5 a	0.17 b	7 b	5.6 b	4.4 b	4.3 x 10 ⁻⁵ b	6 c	0.5 c
Significance Level	**			**	**	**	*	*	*	
<u>Low Nutrient Status Soil</u>										
0-10	25 a	2 a	0.7 a	0.24 a	13 a	9.3 a	4.9 a	1.9 x 10 ⁻⁵ a	25 a	1.5 a
10-20	17 b	1 b	0.4 a	0.19 b	8 b	6.8 b	4.6 b	3.0 x 10 ⁻⁵ b	11 b	0.8 b
20-30	17 b	1 b	0.4 a	0.17 b	7 b	5.5 c	4.5 b	4.0 x 10 ⁻⁵ c	6 c	0.5 c
Significance Level	**				**	*	*	*	*	*

[†] BS, percent base saturation by weight.

[‡] Exchangeable concentrations of Ca, Mg and K.

[§] CEC, cation exchange capacity determined by the sum of exchangeable base cations and extractable acidity (EA).

[¶] pH_s, soil pH measured in 0.01 M CaCl₂ soil slurry.

[#] (H⁺)_{salt}, activity of hydrogen ions calculated from pH_s.

^{††} TOC, total organic carbon.

^{‡‡} TN, total nitrogen.

^{§§} Letters indicate significant differences between values within a column as determined using the Tukey-Kramer adjusted test of means.

^{¶¶} Asterisks under each column indicate significance levels: no asterisk, $\alpha=0.1$; *, $\alpha=0.05$; **, $\alpha=0.01$; and ***, $\alpha=0.001$.

surface deposition appears to control nutrient cycling in low and medium nutrient status soils, causing surface chemical properties and nutrients to be similar. Given these control soil results, low and medium soils and most high nutrient status soil properties are likely to be influenced by harvest practices that greatly alter surface deposition processes; only BS and Mg in high nutrient status soils may be exempt from harvest changes unless losses are increased. Type 3 Test of Fixed Effects in unharvested soils are reported in Table 2.6.

2.4.2 *Effect of Harvest on Soil Properties.*

Very few soil chemical properties were found to be affected by harvest treatment (Type 3 Tests of Fixed Effect in Table 2.7). Hydrogen ion activity ($(H^+)_{\text{salt}}$) calculated from pH_{salt} values showed no statistical differences between treatments, soil types or depth (Fig. 2.2, $p > 0.1$), similar to results from Jerabkova et al. (2006). Extractable acidity showed a similar lack of differences (Fig. 2.3). Although the surface samples produced a statistically significant positive difference value for EA in no harvest sites relative to the negative value in single-tree selection soils ($p = 0.016$), this directionality is an experimental artifact (Fig. 2.3). In order to replicate the paired sampling used in harvested sites, each location in NHM pairs was randomly assigned as a treated or control location because no harvest actually occurred in these sites. Ideally, the difference values from no harvest pairs would be very close to zero. Therefore, any substantial deviation from zero is indicative of soil property variability. Since each pair assignment had a 50% chance of yielding a positive or negative result, no interpretation can be made on the direction of the no harvest difference value. In fact, changing the sign on the no harvest

Table 2.6. Type 3 Tests of Fixed Effects, evaluating soil nutrient status (SNS)

identification in unharvested locations, including depth, replicate identification (Rep) and MOFEP treatment. Tukey-Kramer adjusted p-values of soil properties and nutrient concentrations from split-plot statistical design.

Source	----- p-values -----									
	BS [†]	Ca [‡]	Mg [‡]	K [‡]	CEC [§]	EA [§]	pH _s [¶]	(H ⁺) _{salt} [#]	TOC ^{††}	TN ^{‡‡}
SNS	0.001	0.013	0.010	0.121	0.014	0.063	0.008	0.007	0.050	0.058
Depth	0.046	0.022	0.094	0.010	0.006	0.003	0.056	0.018	<0.001	0.001
Rep	0.297	0.369	0.291	0.759	0.350	0.695	0.349	0.686	0.431	0.646
Treatment	0.425	0.255	0.381	0.364	0.256	0.870	0.217	0.412	0.332	0.287
SNS*Depth	0.007	0.986	0.007	0.798	0.032	0.038	0.062	0.039	0.379	0.296
SNS*Rep	0.062	0.296	0.219	0.177	0.423	0.489	0.136	0.259	0.410	0.538
SNS*Treatment	0.489	0.225	0.336	0.263	0.180	0.316	0.291	0.800	0.066	0.182
Depth*Rep	0.744	0.981	0.621	0.527	0.849	0.976	0.989	0.925	0.964	0.899
Depth*Treatment	0.367	0.775	0.773	0.871	0.742	0.781	0.500	0.681	0.987	0.749
Rep*Treatment	0.615	0.074	0.192	0.480	0.145	0.750	0.454	0.873	0.122	0.347
SNS*Depth*Rep	0.709	0.991	0.878	0.629	0.960	0.954	0.766	0.380	0.947	0.991
SNS*Depth*Treatment	0.934	0.876	0.950	0.329	0.550	0.328	0.686	0.736	0.387	0.442
SNS*Rep*Treatment	0.101	0.044	0.174	0.994	0.207	0.084	0.070	0.453	0.887	0.652
Depth*Rep*Treatment	0.968	0.974	0.998	0.914	0.981	0.974	0.957	0.988	0.960	0.956
SNS*Depth*Rep *Treatment	0.958	0.994	1.000	0.930	1.000	0.374	0.945	0.917	0.954	0.988

[†] BS, percent base saturation by weight.

[‡] Exchangeable concentrations of Ca, Mg and K.

[§] CEC, cation exchange capacity determined by the sum of exchangeable base cations and extractable acidity (EA).

[¶] pH_s, soil pH measured in 0.01 M CaCl₂ soil slurry.

[#] (H⁺)_{salt}, activity of hydrogen ions calculated from pH_s.

^{††} TOC, total organic carbon.

^{‡‡} TN, total nitrogen.

Table 2.7. Type 3 Tests of Fixed Effects for differences in soil chemical properties and nutrients. Tukey-Kramer adjusted p-values of soil properties and nutrient concentrations from split-plot spatially repeated statistical design with harvest treatment main effect, each site split by soil nutrient status (SNS), each sampling repeated by depth.

----- p-values -----									
Source	BS [†]	Ca [‡]	Mg [‡]	K [‡]	EA [§]	pH _s [¶]	(H ⁺) _{salt} [#]	TOC ^{††}	TN ^{‡‡}
Treatment	0.408	0.169	0.177	0.181	0.190	0.160	0.202	0.049	0.059
SNS	0.289	0.241	0.302	0.279	0.712	0.379	0.904	0.048	0.068
Treatment *SNS	0.214	0.156	0.072	0.332	0.598	0.261	0.428	0.021	0.035
Depth	0.027	0.196	0.998	0.441	0.752	0.050	0.905	0.130	0.029
Treatment *Depth	0.004	<0.001	0.057	0.147	0.031	0.003	0.531	0.024	0.001
SNS*Depth	0.505	0.206	0.895	0.137	0.684	0.563	0.098	0.702	0.586
Treatment *SNS*Depth	0.079	0.268	0.167	0.176	0.876	0.009	0.073	0.284	0.032

[†] BS, percent base saturation.

[‡] Exchangeable concentrations of Ca, Mg and K.

[§] EA, extractable acidity.

[¶] pH_s, soil pH measured in 0.01 M CaCl₂ soil slurry.

[#] (H⁺)_{salt}, activity of hydrogen ions calculated from pH_s.

^{††} TOC, total organic carbon.

^{‡‡} TN, total nitrogen.

Figure 2.2. Comparison of mean difference values for H^+ activity in 0.01 M $CaCl_2$ soil slurry by soil nutrient status, depth and treatment using the Tukey-Kramer adjusted values test of means. No comparisons were found to be significantly different from one another. Error bars represent one standard error.

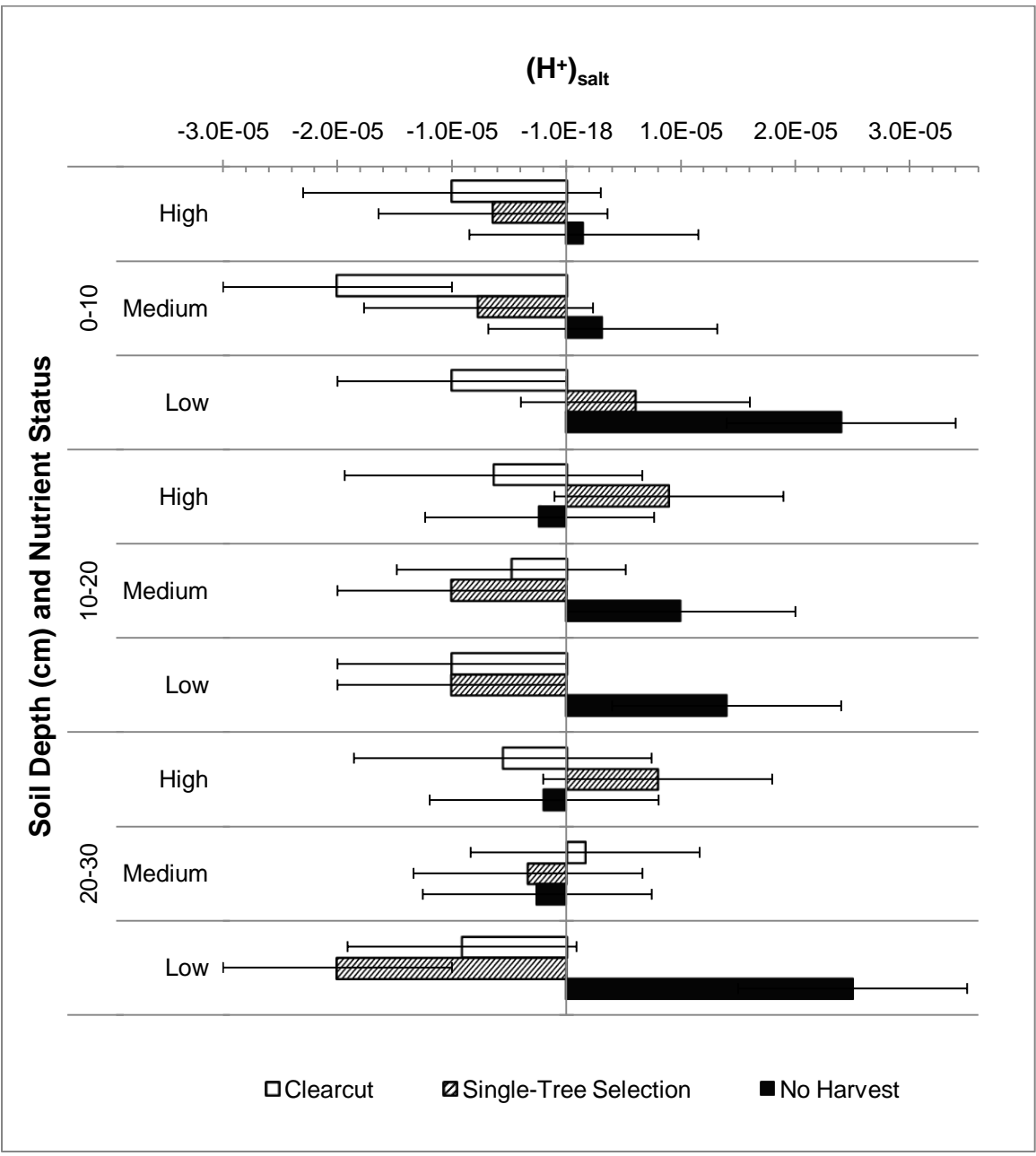
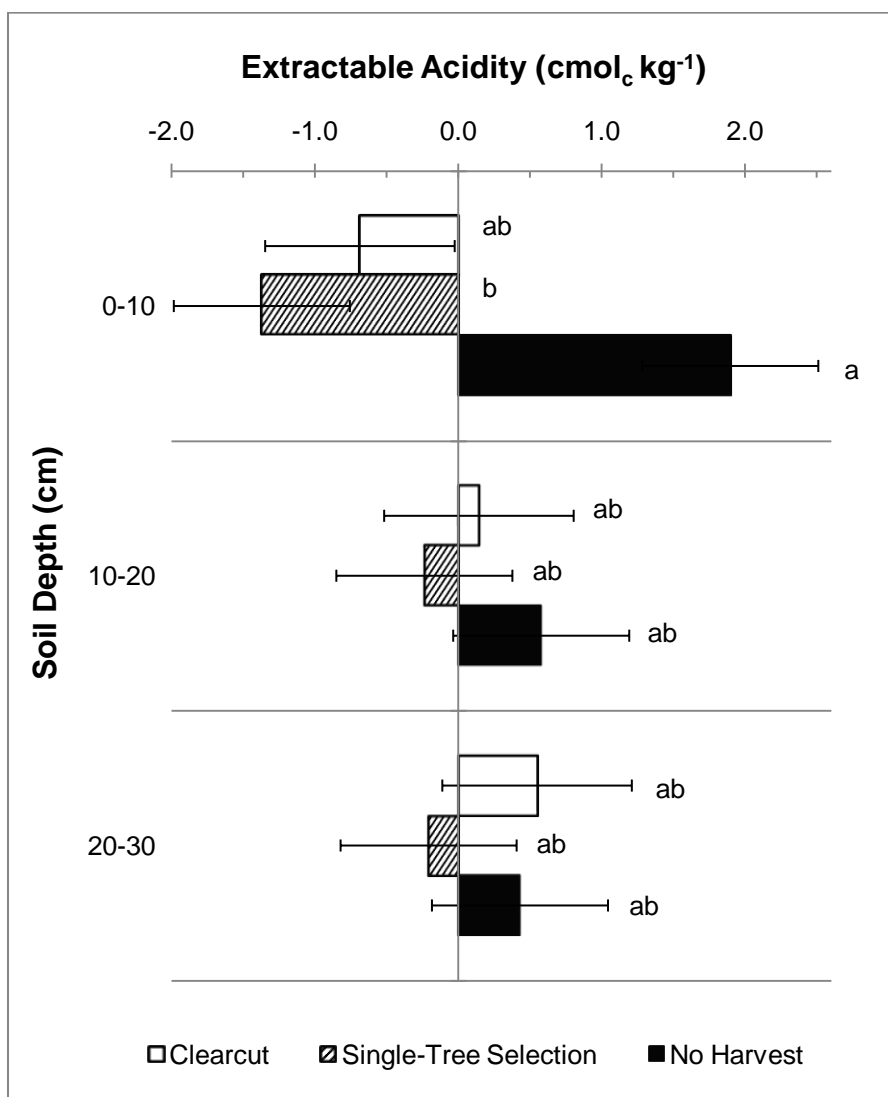


Figure 2.3. Comparison of extractable acidity mean difference values by soil depth and harvest treatment using the Tukey-Kramer adjusted values test of means ($\alpha = 0.05$). Significant differences between all values in figure are represented by the presence of different letters. Error bars represent one standard error.



difference values for EA (0-10 cm depth) and statistically reanalyzing the data resulted in no statistical difference between EA values amongst the treatments ($p > 0.1$).

While BS difference values were not significantly different between treatments ($p > 0.1$), clearcut sites did show differences in BS as a function of soil depth (Fig. 2.4a). The 0-10 cm depth showed greater difference values than either the 10-20 cm ($p = 0.005$) or 20-30 cm pairs ($p = 0.013$). Similar data analyses for the single-tree selection and no harvest sites indicated no significant difference in BS as a function of depth ($p > 0.1$).

Exchangeable Ca difference values mirrored BS results; significant differences were observed between soils in clearcuts as a function of depth (Fig. 2.4b). Therefore, the data appear to indicate that clearcutting increases soil BS, especially exchangeable Ca, at the surface to a greater extent than at deeper depths. This is likely the result of increased mineralization from clearcut slash residues boosting the Ca concentration of low nutrient status soils immediately after harvest. However, it is interesting that no increases in $(H^+)_{\text{salt}}$, as might be expected, were observed. It is possible $(H^+)_{\text{salt}}$ did in fact increase post-harvest but the effect is no longer observable 10 years later, or the buffering capacity of these soils might mitigate fluctuations in $(H^+)_{\text{salt}}$.

A unique difference between treatments was observed in the 0-10 cm samples across all soil types. Soils in clearcuts had increased values of exchangeable Ca that were significantly greater (Fig. 2.5a, $p = 0.034$) than negative difference values of soils at single-tree selections. However, exchangeable Ca difference values from clearcut and single-tree selection sites were not significantly different from no harvest sites ($p > 0.1$).

Figure 2.4. Comparison of (a) percent base saturation and (b) exchangeable Ca mean difference values by soil depth in clearcut harvest treatment using the Tukey-Kramer adjusted values test of means ($\alpha = 0.05$ and 0.01 , respectively). Significant differences between values are represented by the presence of different letters. Error bars represent one standard error. Note: the direction of the difference values is positive, indicating soil values in clearcuts are greater than their non-harvested pairs.

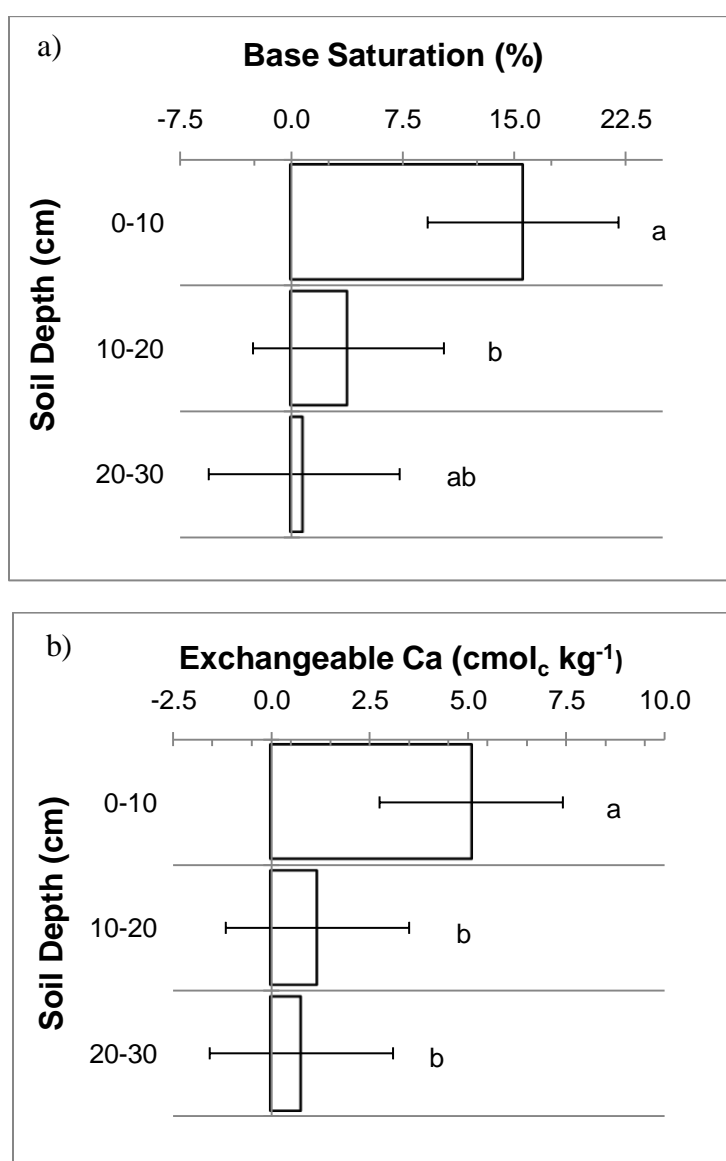
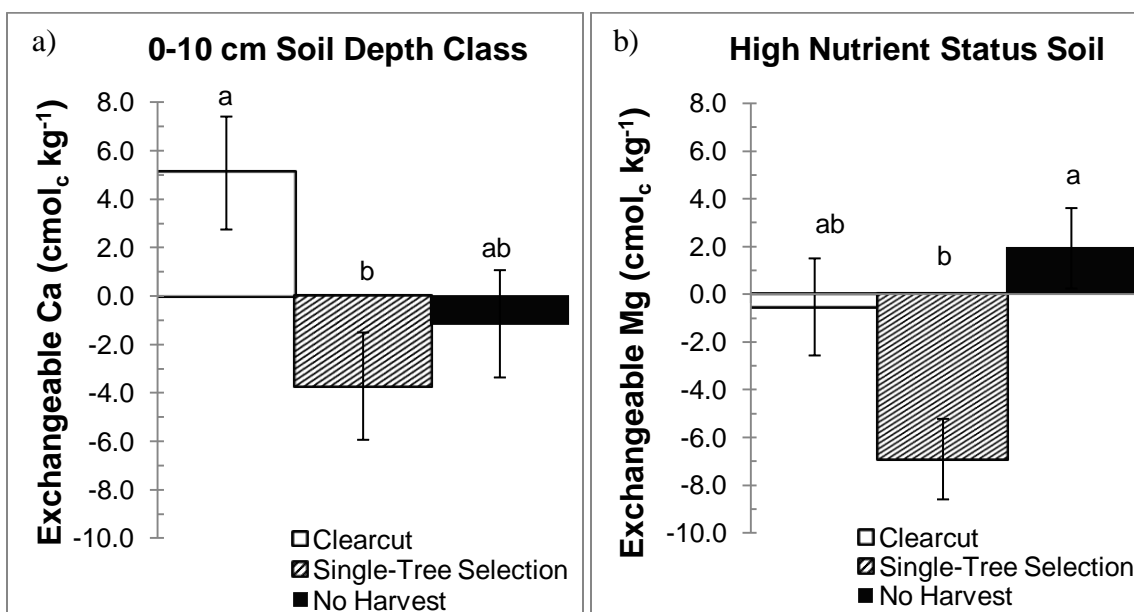


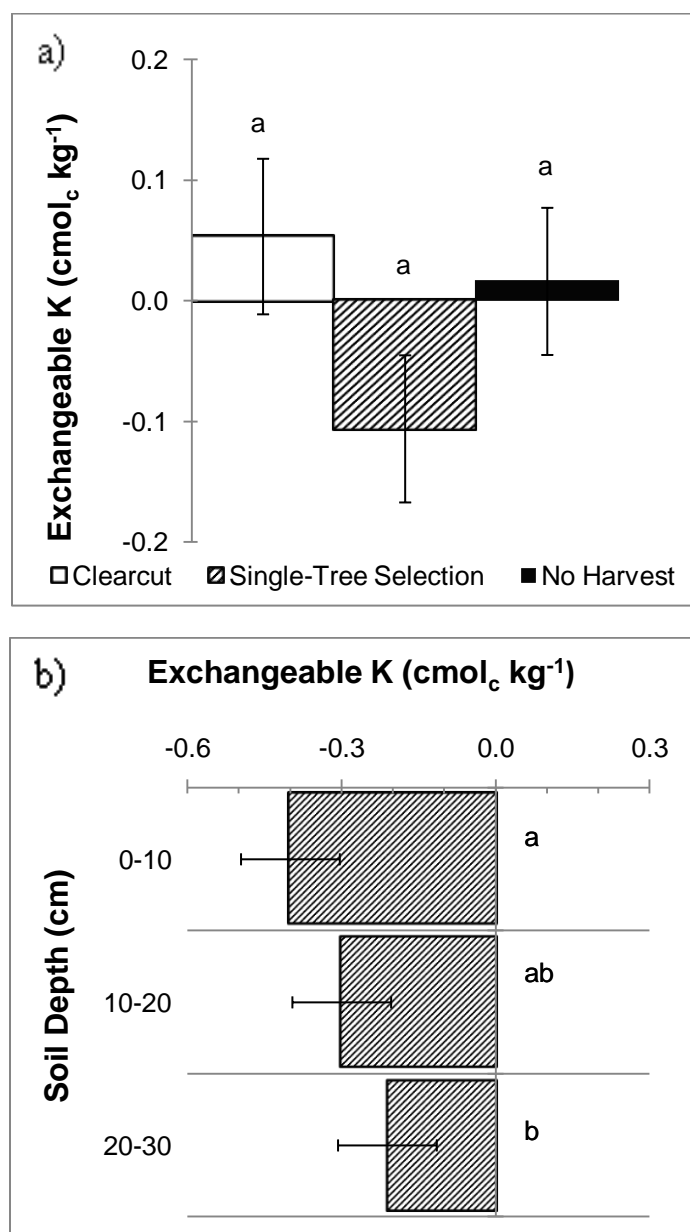
Figure 2.5. Comparison of mean difference values between harvest treatments for (a) exchangeable Ca in the 0-10 cm depth of all soils and (b) exchangeable Mg in high nutrient status soils overall depths as determined by use of the Tukey-Kramer adjusted values test of means (both $\alpha = 0.05$). Significant differences between values are represented by the presence of different letters. Error bars represent one standard error.



Negative difference values for exchangeable Mg concentration in single-tree selection sites were observed in high nutrient status soil (Fig 2.5b). The negative Mg value in single-tree selections was significant from the no harvest values ($p = 0.035$). Similar to EA, when statistical analyses were re-run with the no harvest value directions reversed this significance was lost ($p > 0.1$). Negative difference values were also observed for exchangeable K in single-tree selections (Fig. 2.6a). Though the exchangeable K concentrations were not significantly different across harvest treatment, they did significantly change with depth, becoming smaller in 20-30 cm high nutrient status samples compared to the surface 10 cm (Fig. 2.6b, $p = 0.097$).

These data could indicate that low nutrient status surface soils in clearcuts are enriched in Ca due to the amount of woody slash left on-site; whereas, soils under single-tree selection are depleted of Ca, Mg, and K due to localized slash deposition away from the stump and cation leaching from high nutrient status soils. Presently, the literature focuses on assessing the effects of large harvest disturbances via clearcutting, particularly WTH and SOH and variable retention of up to 50% (Jerabkova et al., 2006). Comparison of harvest effects in soils directly beneath a removed tree appears to be unprecedented. The long term implication of base cation depletion around stumps in UAM single-tree selections remains unknown. It is speculated that future harvest events will result in relatively uniform slash distribution across the entire site at the end of the 100 year rotation. However, the time between harvest and slash deposition for any particular stump could range from 10 to 100 years. It is plausible that the coupled effects of base cation depletion and long time periods between initial tree removal and slash deposition

Figure 2.6. Comparison of exchangeable K mean difference values for (a) harvest treatment and (b) by depth in high nutrient status soil single-tree selections using the Tukey-Kramer adjusted values test of means. Significant differences between values are represented by the presence of different letters ($\alpha = 0.1$). Error bars represent one standard error.

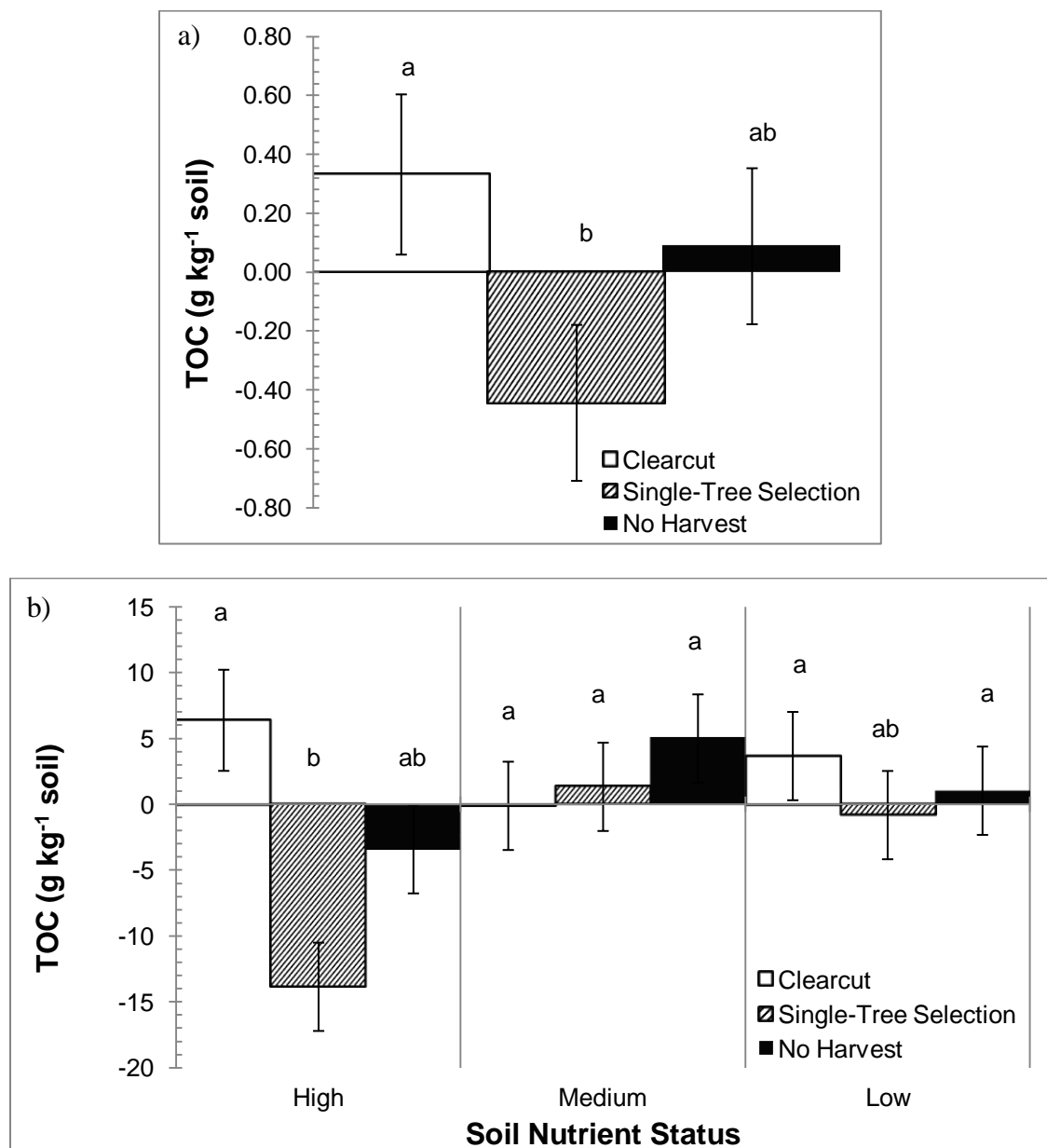


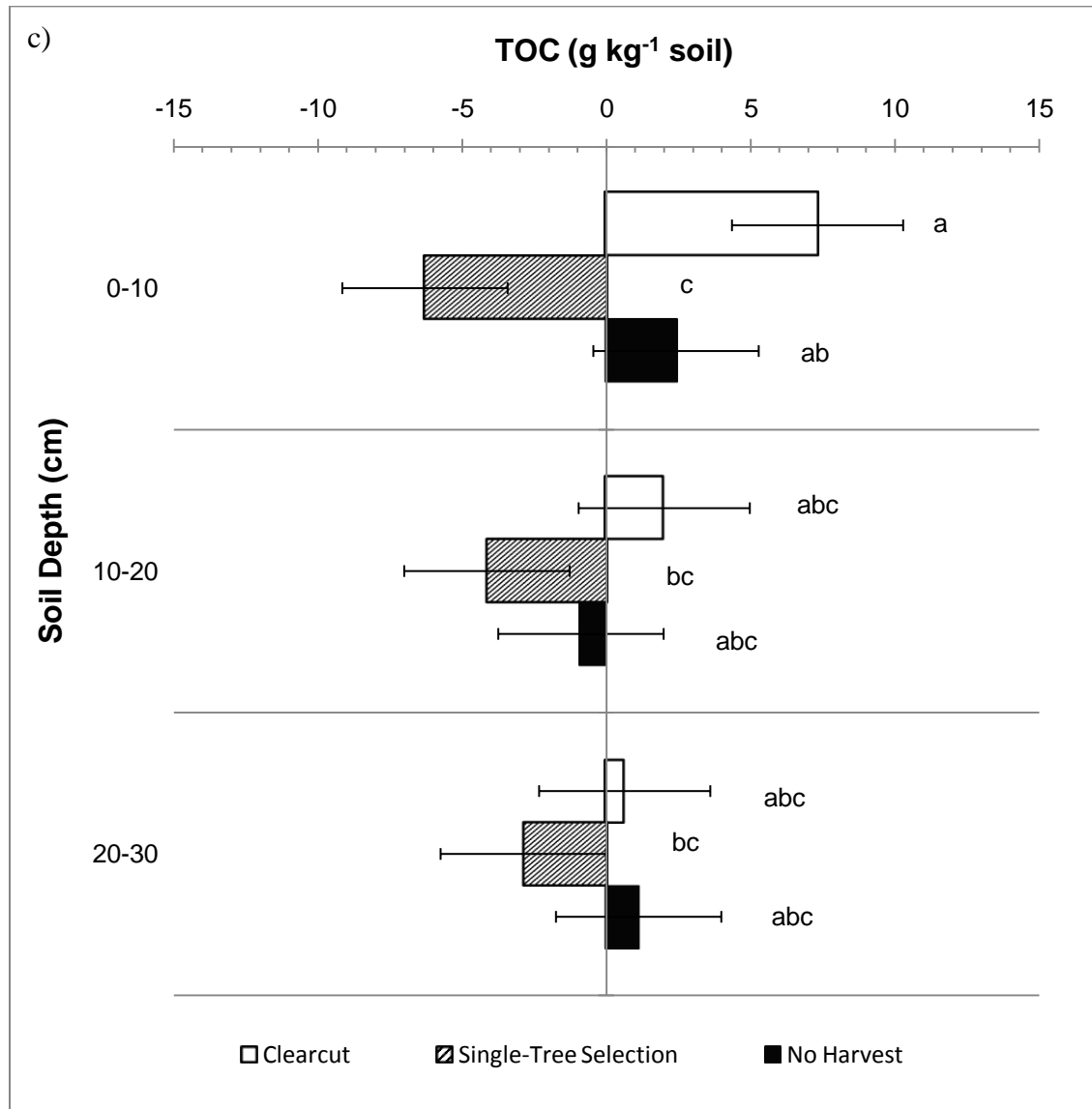
in UAM sites could result in soil conditions that change species composition or adversely affect tree regeneration. The work of Jensen and Kabrick (2008) observed a shift in species composition from relatively shade-intolerant red oaks to relatively shade-tolerant white oaks in UAM and NHM sites at MOFEP, reflecting the limited light availability for regeneration under this management. The threshold of soil base cation depletion in the Missouri Ozarks beyond which species composition is affected is unknown.

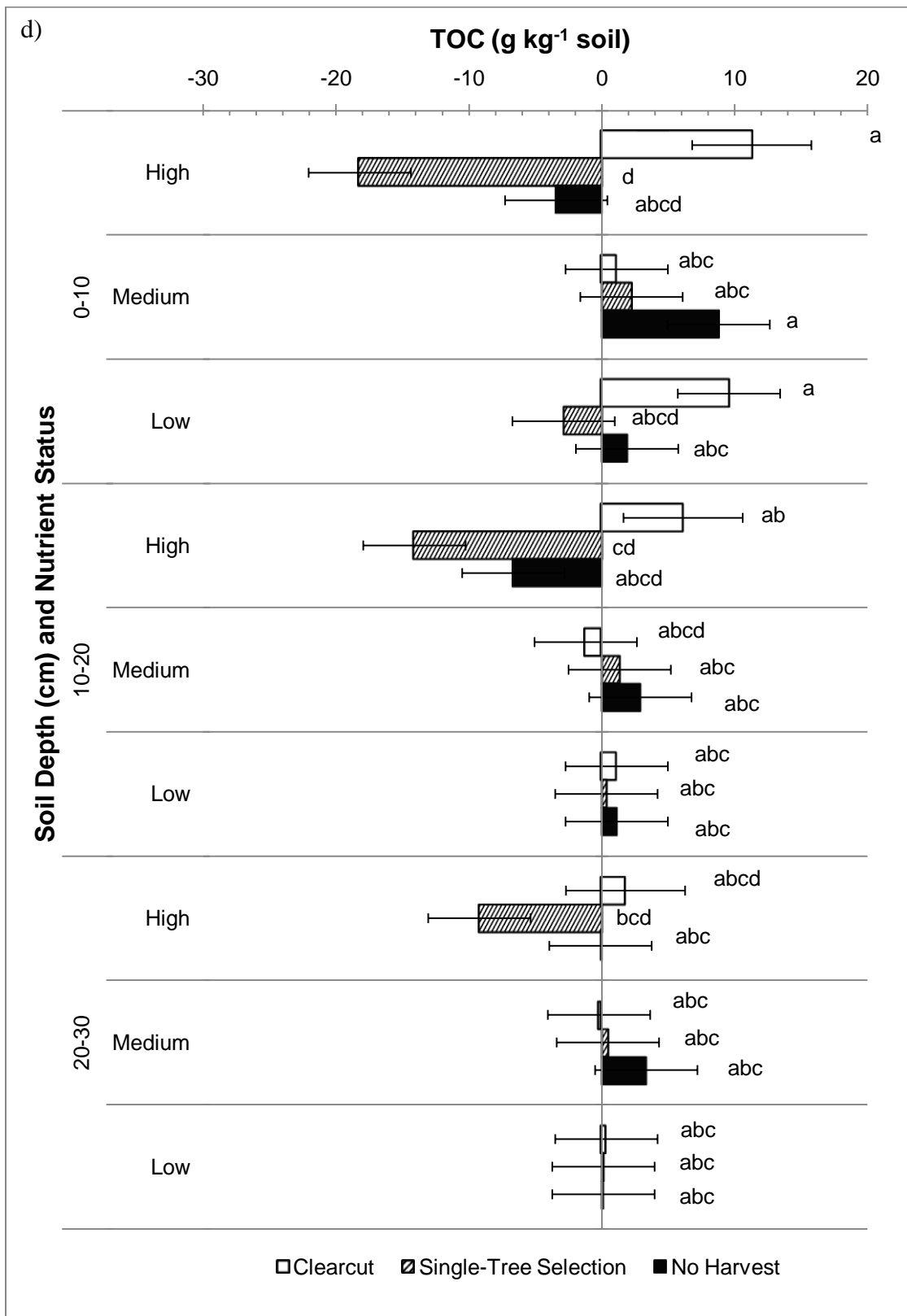
Investigation of organic soil properties provided the greatest number of significant differences between treatments. Significant differences in TOC were observed between positive difference values in clearcut sites and negative values in single-tree selections (Fig. 2.7a, $p = 0.048$). Similar to exchangeable Ca, neither harvest treatment was significantly different from no harvest controls. This same pattern of positive difference values in clearcuts and negative values in single-tree selections was significant (Fig 2.7b, $p = 0.007$) in high nutrient status soils and across all soils from 0-10 cm (Fig. 2.7c, $p < 0.001$). Partitioning difference values by soil nutrient status and depth (Fig. 2.7d), the effect remained significant in high nutrient status soil 0-10 cm depth ($p < 0.001$) and 10-20 cm ($p = 0.048$). However, TOC was not significantly different between clearcuts and single-tree selections at the 20-30 cm depth ($p > 0.1$).

High nutrient status soils and the 0-10 cm depth class generated the largest difference values in treated soils TOC. Previously (see Section 2.4.1, *Control Soil Properties*), TOC in unharvested soils was identified as greatest in the same soils and depths yielding the largest differences with harvest: high nutrient status soils and within each soil at the 0-10 cm depth. This correlation of large control TOC contents and differences in harvested

Figure 2.7. Comparison of total organic carbon (TOC) differences between harvest treatments (a) across all soils and depths, (b) by soil nutrient status, (c) by soil depth, and (d) by soil depth and nutrient status using the Tukey-Kramer adjusted values test of means ($\alpha = 0.05$). Significant differences between all values in each figure are represented by the presence of different letters. Error bars represent one standard error.







soils treatment indicates that soils with larger TOC concentration are affected by harvest whereas soils with lower TOC content are not 10 years later. This could be due to tighter C cycling in soils with lower C content. TOC was observed to increase in clearcuts and decrease around stumps where single trees were removed.

Knoepp and Swank (1997b) observed significant increases in 0-10 cm soil total C following SOH, returning to pre-harvest levels within 5 years of harvest, and a reduction in soil total C during the first and third years after WTH was observed. Soil total C remained slightly below pre-harvest levels up to 15 years later. Increases in soil total C after SOH were attributed to the mineralization of logging slash not present in WTH sites. While both harvests studied by Knoepp and Swank (1997b) lacked any significant long-term differences, the stratification of MOFEP sites by soil nutrient status combined with sampling directly around a single-tree selection is capturing a unique effect of harvest in high nutrient status soils particularly from 0-10 cm but also at lower depths.

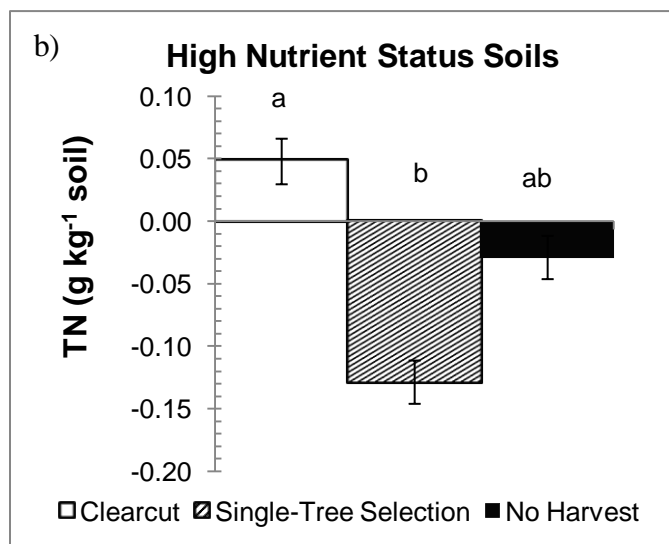
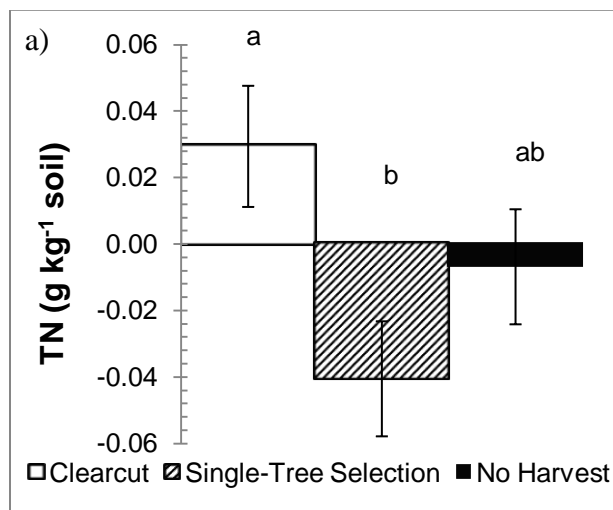
The greater pH in high nutrient status soils and increased soil water content in the lower, more protected landscape positions tend to support larger and more diverse microbial communities in forest soils, especially for soil bacteria (Fisher and Binkley, 2000). This potential community difference between high and low nutrient status soils could cause increased mineralization in high nutrient status soils and increase nutrient losses due to leaching. Even so, clearcutting in high nutrient status soils can mitigate this affect. Spratt (2002) observed increased cellulose mineralization following clearcutting in both high and low landscape positions in MOFEP Site 3.

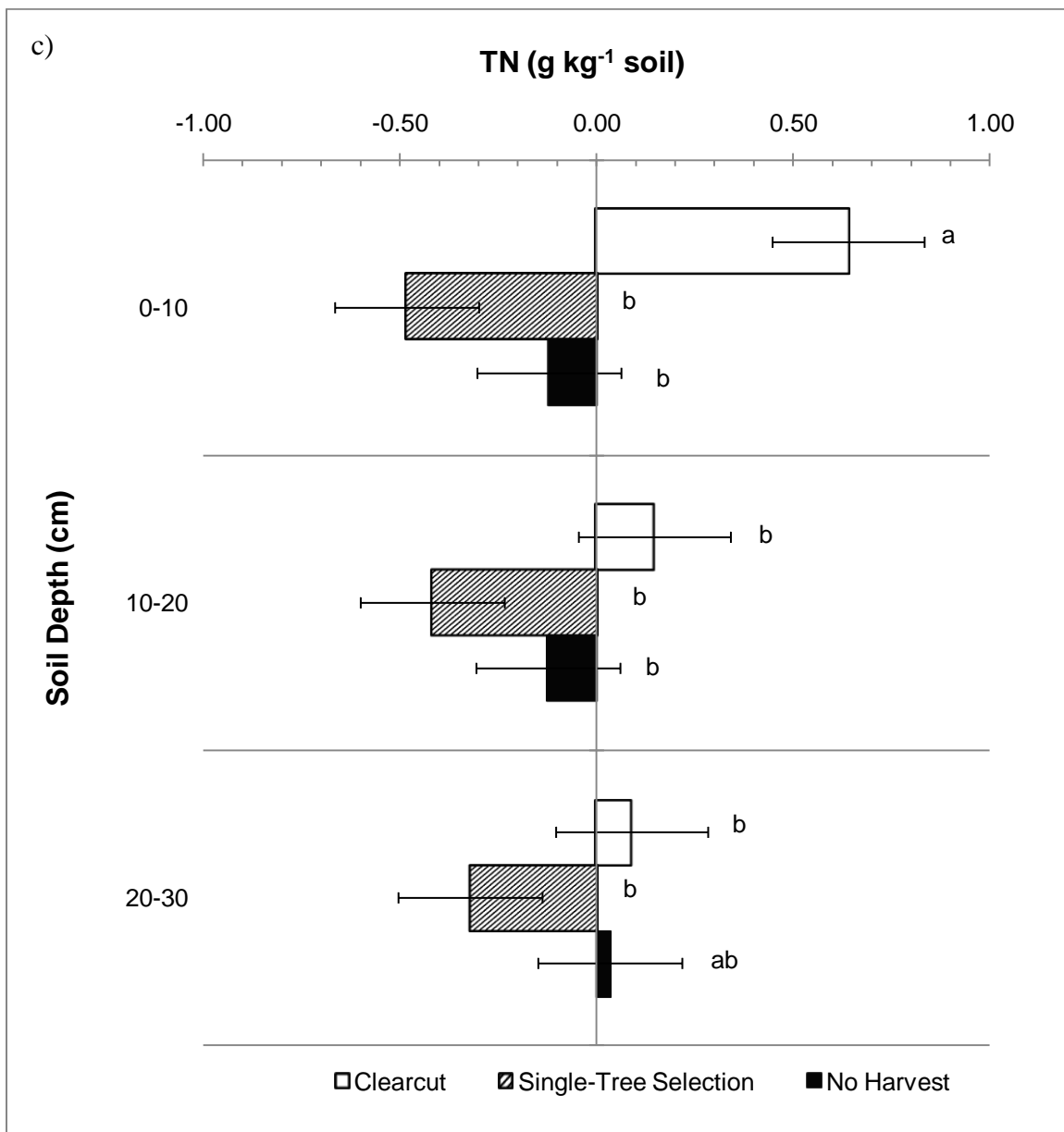
Lignin mineralization also increases in high landscape clearcuts but mineralization in low landscape clearcuts was not significant from controls (Spratt, 2002). Microbial anabolism appeared to decrease significantly after clearcutting in both landscape positions. The large inputs of organic material provide a substrate for mineralization and the high C:N ratio of timber slash redirects nutrient cycling toward microbial immobilization which would increase TOC in the soil, particularly when the inherent microbial community is large and available N will be quickly used (Fisher and Binkley, 2000). Due to the increased capacity of high nutrient soils for mineralization, nutrient loss is possible in single-tree selections lacking slash from the harvested tree.

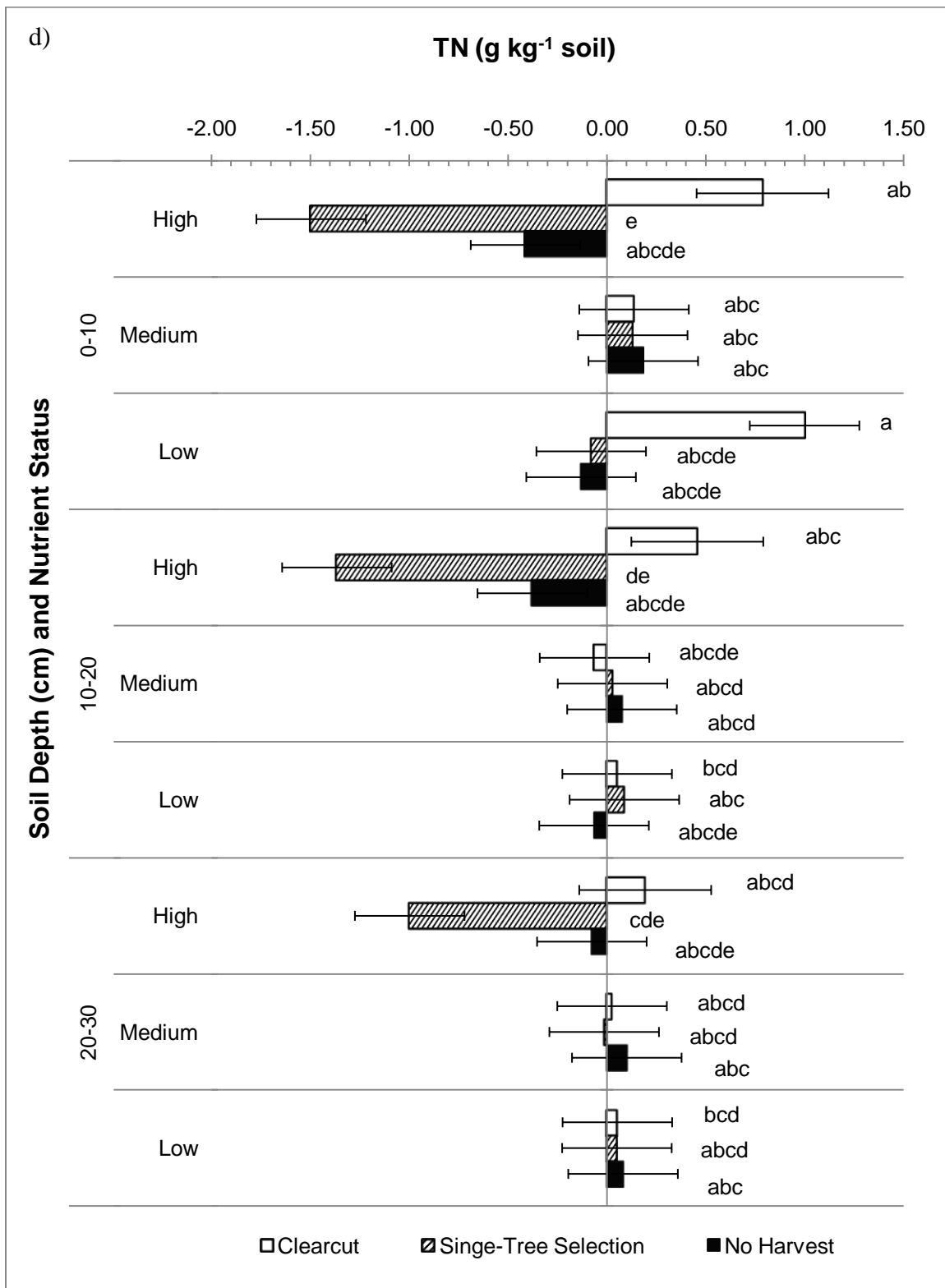
Total N concentrations in the soils studied revealed the same pattern as carbon: positive difference values in clearcut sites which are significantly different from negative values in single-tree selection sites. The difference between harvests was significant over all soils and depths (Fig. 2.8a, $p = 0.052$), in high nutrient status soils (Fig. 2.8b, $p = 0.011$), across all soils from 0-10 cm (Fig. 2.8c, $p < 0.001$), and within high nutrient soils at 0-10 cm (Fig. 2.8b, $p < 0.001$) and 10-20 cm depths (Fig. 2.8d, $p = 0.015$). Knoepp and Swank (1997b) also observed similar response to harvest for soil TN, and they noted that soil TN showed a greater capacity than total C to return to pre-harvest levels 15 years after SOH and WTH. Similar to soil C, Knoepp and Swank (1997b) also attributed increases in N after SOH to mineralization of logging slash not present in WTH.

The opening of the canopy in each harvest increases exposure of soil to the sun, potential for increased temperatures, and preferential deposition of precipitation (Brooks et al., 2003). These factors can enhance mineralization of organic materials, -

Figure 2.8. Comparison of total nitrogen (TN) mean difference values between harvest treatments (a) across all soils, depths and treatments, (b) in high nutrient status soil, (c) across all soils by depth and (d) partitioned by soil depth and nutrient status using the Tukey-Kramer adjusted values test of means ($\alpha = 0.05$). Significant differences between all values in each figure are represented by the presence of different letters. Error bars represent one standard error.







subsequently releasing soil nutrients. Relatively greater concentrations of soil exchangeable Ca, TOC and TN in clearcuts are likely due to the mineralization of slash while relatively smaller concentrations of soil exchangeable Ca, Mg, K, TOC and TN after single-tree selections could be due to increased forest floor mineralization, nutrient leaching, and immobilization by plants (DeLuca and Zouhar, 2000; Holmes and Zak, 1999; Zhu et al., 2003). The harvest slash in single-tree selection sites is unable to replenish soil nutrients at the site of the removal as it is deposited up to a whole tree height away from the residual stump. This difference between harvests may be diminishing over time but remains observable ten years after harvest.

Given the tremendous variability of soil properties at MOFEP, there is no statistical significance differentiating either harvest from no harvest sites. However, the consistent directionality of positive clearcut difference values and negative single-tree selection difference values is difficult to ignore. Further investigations of soil properties prior to and following harvest may further illuminate statistically significant correlations between forest harvest and soil nutrients.

2.5 Conclusions

Few effects of clearcutting and single-tree selections are observed in soil chemical properties, BS and base cation concentrations. More differences between clearcut and single tree harvests were observed in TOC and TN. Ten years after harvest, soil TOC and TN concentrations are greater in clearcut sites and smaller in single-tree selection sites. In the surface 10 cm, exchangeable Ca also was greater in clearcuts and smaller in single-tree selections. While the variability of soil properties is high resulting in no

significant difference between either harvest and no harvest soil properties, the consistent directionality of positive values in soils within clearcuts and negative values in single-tree selections yields statistical significance between the treatments. This pattern of positive values in clearcuts and negative values in single-tree selections was observed for exchangeable K, but was not significant between treatments; negative values in single-tree selections were also observed in the surface 10 cm for extractable acidity and high nutrient status soil exchangeable Mg. Larger TOC, TN Ca and K in clearcuts is likely the direct result of slash deposition during harvest. Single-tree selections translocate the slash deposition away from the location of biomass removal, i.e. the stump, preventing the slash from mitigating nutrient losses directly after timber removals. These altered soil nutrient properties are unlikely to persist over a full 100 year rotation in the Ozarks, but implications for more intensive harvest removal are unknown.

2.6 References

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CHAPTER 3: EVALUATION OF FOREST HARVEST EFFECTS ON STABLE, LABILE, POTENTIALLY MINERALIZABLE AND WATER EXTRACTABLE SOIL NITROGEN POOLS IN THE OZARK HIGHLANDS

3.1 Abstract

The Missouri Ozark Forest Ecosystem Project (MOFEP) is a long-term experiment established to investigate forest management influence on a host of ecosystem components. Mixed hardwood systems at MOFEP are managed with even-aged (EAM), uneven-aged (UAM), and no harvest (NHM) management; all treatments are replicated in three blocks. Soils at MOFEP are dominated by highly weathered Ultisols and Alfisols. However, the effects of timber removal on soil nutrients in the three management systems have not been previously investigated. This study seeks to elucidate the effect of harvest practices on surface soil nitrogen (N) pools in particular soils present at MOFEP. Three soils were selected based on previous measurements of subsoil base saturation (BS) at MOFEP: (1) low, less than 20 % BS; (2) medium, 20 – 50 % BS; and (3) high, greater than 50 % BS. In 2007, ten years after harvest, samples were collected in 10 cm increments from 0 to 30 cm from the three soil types in each harvest treatment using a paired sampling approach (i.e., samples were collected in treated and nearby non-treated locations). Treatments sampled were EAM clear cuts, UAM single-tree selections and NHM sites. Samples were analyzed for total nitrogen (TN) and soil nitrogen pools. Nitrogen pools were investigated by quantifying stable and labile nitrogen (SN and LN,

respectively) via potassium permanganate (KMnO_4) extraction, potentially mineralizable nitrogen (PMN) (84 day aerobic incubation), and water extractable nitrogen (WEN). These pools are increasingly labile from the stable pool remaining after extraction with KMnO_4 , to the more labile pool removed by KMnO_4 , then the pool mineralized by microbes in the incubations, and the most labile N extractable by water. Statistical analyses indicate that soil N pools dominated by complex organic compounds (e.g. TN, SN, LN) were significantly different ($\alpha=0.10$) between clearcut and single-tree selection sites, especially in high nutrient status and the surface 10 cm of soils. Soil N concentrations were consistently smaller in single-tree selection sites and larger in clearcut sites, relative to non-harvested sites. Disparity between the treated soils is attributed to differences in slash distribution within the treatments. Inherently high values of soil N pools, as observed in non-harvested sampling locations, tend to indicate effects of harvest will be evident in the soil 10 years after harvest.

3.2 Introduction

Soil nitrogen (N) is often the most limiting nutrient in many terrestrial ecosystems (Vitousek and Howarth, 1991). While concentrations of N are higher in forest foliage than litter and lowest in logging slash, the relative amounts of each pool are greater with decreasing N concentration (Fisher et al., 2000). The removal of low N slash may still deplete soil N pools. The largest pool of solid phase soil N is contained within complex organic molecules (Kaye et al., 2003), including live root biomass. These forms of N are considered relatively stable and slowly transferred to more labile, inorganic N pools by decomposition and mineralization. During the mineralization process, organic N is

transformed by N mineralizing bacteria to ammonium (NH_4^+) and then nitrate (NO_3^-) through the process of nitrification. While labile pools are the most susceptible to losses, they are replenished from the stable pools (Kaye et al., 2003; Westerhof et al., 1998).

Soil N cycling is measured by monitoring microbial mineralization of organic N in the laboratory (aerobic and anaerobic incubation procedures) or under field conditions (buried bag techniques) (Bradley and Parsons, 2007; Nadelhoffer, 1990; Scott et al., 1998; Stark, 2000; Vitousek and Matson, 1985; Weaver, 1994). Measurement of N mineralization *in situ* provides a measure of mineralizable N under field conditions, and these measurements are strongly influenced by soil properties, timber harvest, and weather or climatic conditions. In contrast, laboratory incubations evaluate mineralization substrate quality. Scott et al. (1998) observed that higher soil C content resulted in higher laboratory measured N mineralization rates in mineral soils but not with materials from the forest floor. This observation could be attributed to differences not only in organic matter content but also the quality of organic substrates undergoing mineralization.

Increased harvest intensity can increase mineralization rates as slash left on-site contribute substrate material (O'Connell et al., 2004). Potential N mineralization determined in laboratory soil sample incubations correlated positively with higher nutrient status soils and increased slash amounts when compared to low nutrient status soils and little-to-no slash left on blue gum (*Eucalyptus globulus*) plantation sites one to six years after clearcut harvest (O'Connell et al., 2004). This indicates that the practice of leaving slash on-site may contribute to the total and labile soil N pools, particularly after

a net N loss due to the harvest biomass removal on a low fertility sites. However, Brais et al. (2002) observed no impact of WTH on soil N mineralization in laboratory incubations; no differences in mineralization were observed between any treatments, suggesting harvest and slash treatments do not affect substrate quality.

Increased harvest intensity also increases mineralization rates as microclimate changes in larger canopy openings and conditions become more conducive to mineralization (Bradley and Parsons, 2007). Clearcut timber harvest increased *in situ* N mineralization in maple-dominated hardwood forests (Holmes and Zak, 1999), but was lowest immediately after clearcut harvest in a central hardwoods chronosequence (Idol et al., 2003). Variable and contrasting results between studies highlight the need for region specific studies as a means to fully evaluate local harvest impacts.

Labile pools of soil N can be measured through monitoring soil solution or solid phase extraction techniques. Inorganic N concentrations in soil extractions and soil solution have been observed to shift between NH_4^+ and NO_3^- species after timber harvests of varying intensities and slash amounts without altering the size of the overall inorganic pool (Jerabkova et al., 2006; Mahendrappa et al., 2006). Soluble and extractable pools of N are readily available for plant uptake but also susceptible to loss or retention in the soil. Soluble organic nitrogen (SON) is also susceptible to leaching, but SON is more frequently mineralized into ionic N species and may be utilized by plants (Chen et al., 2005). Jerabkova et al. (2006) observed SON amounts to decrease with increasing biomass removal possibly indicating SON loss not reflected in the inorganic pool or simply a shorter N residence time in SON forms due to increased mineralization rates.

The appearance of a correlation of treatment with one nutrient pool and not another reflects the complexity of nutrient cycling processes in forest soils.

Given the wide range of harvesting effects on soil N and the limiting nature N can have in terrestrial ecosystems, it becomes crucial to assess any influence clearcut or single tree harvesting may have on the soil. While it is anticipated that medium and high nutrient status contain sufficient pools of N in the stable and labile forms to buffer any harvest effect, low nutrient status soil may be quite susceptible to depletion. Severe depletion due to clearcutting should not be evident in the labile N pools as they actively cycle. However, large removals of biomass via clearcutting may reduce stable N pools and cause long-term fertility issues.

3.3 Materials and Methods

3.3.1 Soil Sampling and Experimental Protocols for Determining Soil N Pools.

Site selection and soil sampling was conducted according to the methods described in Chapter 2. Samples collected in the field were stored at 4°C, sieved through a 2 mm mesh sieve while still moist, and returned to 4°C until analyzed. The moisture content of each sample was determined after sieving (Burt, 2004, method 3D2) to calculate the oven-dried (105°C) equivalent soil mass. Subsequently, mass associated with moisture was accounted for when it was necessary to obtain oven-dry equivalent soil mass.

Samples were dried at 40°C for 24 hours, finely ground and analyzed by dry combustion (Burt, 2004, method 4H2a2a1) using a LECO Truspec C/N analyzer (LECO Corp., St. Joseph, MI). Labile and stable pools of N were examined using potassium permanganate extraction (Westerhof et al., 1998). In brief, samples containing 25 ± 2 mg

C were extracted in 37.5 ml of 333 mM KMnO_4 for one hour in the dark at room temperature. Samples were centrifuged at 12,000 rcf ($\times g$) for 5 minutes, and the supernatant aspirated. The soil pellet was washed by resuspending the soil in Barnstead nanopure water three times or until KMnO_4 was no longer observed in solution. Caution was taken at all steps to ensure that no soil was lost via aspiration of supernatant solution. Centrifuge tubes containing soil were then placed in the oven at 40 ° C until dry. This residual, extracted soil was ground and analyzed for TN to measure the stable N pool (SN). Labile N (LN) is defined as the difference between total N before extraction and total N after extraction.

Another labile N fraction, water extractable N (WEN), was extracted in ultrapure water (Chen et al., 2005). Fifteen grams (oven-dry weight equivalent) of field moist soil were reacted in 37.5 ml ultrapure water, vigorously agitated on an end-to-end shaker for 1 hour, and centrifuged at 3,400 rcf ($\times g$) for 30 minutes. The supernatant was filtered through a 0.45 μm (nominal pore size) Whatman polypropylene syringe filter directly into 24 ml glass vials and analyzed for total soluble N with a Shimadzu TOC analyzer equipped with a total N module (TNM) and ASI autosampler (Shimadzu Corp., Kyoto, Japan).

Soils from the 0 – 10 cm and 10 – 20 cm depths were analyzed to determine relative, potentially mineralizable N (PMN) using an aerobic leaching procedure (Bundy and Meisinger, 1994; Motavalli et al., 1995; Mungai et al., 2006). Fifty grams (oven-dried equivalent) of field-moist, sieved soil was mixed with 50 g sand to increase drainage. The sand was combusted at 550 ° C for 1 hour prior to use to remove residual organic

carbon, and the mass of the sand was removed from future calculations of PMN. The soil-sand mixtures were incubated at 30°C in filter units equipped with cellulose acetate membranes (0.02 µm nominal pore size) and glass fiber prefilters. A glass fiber filter was also placed on top of the soil sample to avoid dispersion upon addition of solution. The filter units were leached immediately prior to incubation (0 day) with 100 ml N-free nutrient solution (Nadelhoffer, 1990) and with 50 ml solution on the following days after start of incubation: 1, 3, 7, 14, 21, 28, 42, 56, 70, and 84 d. Vacuum pressure of 47 kPa was applied to each filter unit for 1 hour during leaching. Leachates were collected in 60 ml HDPE bottles, were weighed, and stored at 4°C until analyzed for NH_4^+ and NO_3^- using Quikchem Lachat colorimetric methods 12-107-062-A (19 July 1993 revision) and 12-107-04-1-B (12 Nov. 1992 revision), respectively (Lachat Instruments - Hach Company, Loveland, CO). Filter units were weighed on a weekly basis prior to leaching to monitor moisture loss. Ultrapure water was added, as necessary, to maintain moisture content and to prevent concentration of nutrients in the soil due to addition of leaching solution. Rapidly mineralized N is representative of the labile N pool and N mineralized after the rate of mineralization has stabilized is indicative of N mineralized from the stable N pool (Mungai et al., 2006). The incubations were conducted for 84 d to hopefully capture the full PMN labile pool, however, the rate of mineralization never truly stabilized. Figure 3.1 displays a conceptual diagram of the relative sizes and proportions of the N pools studied.

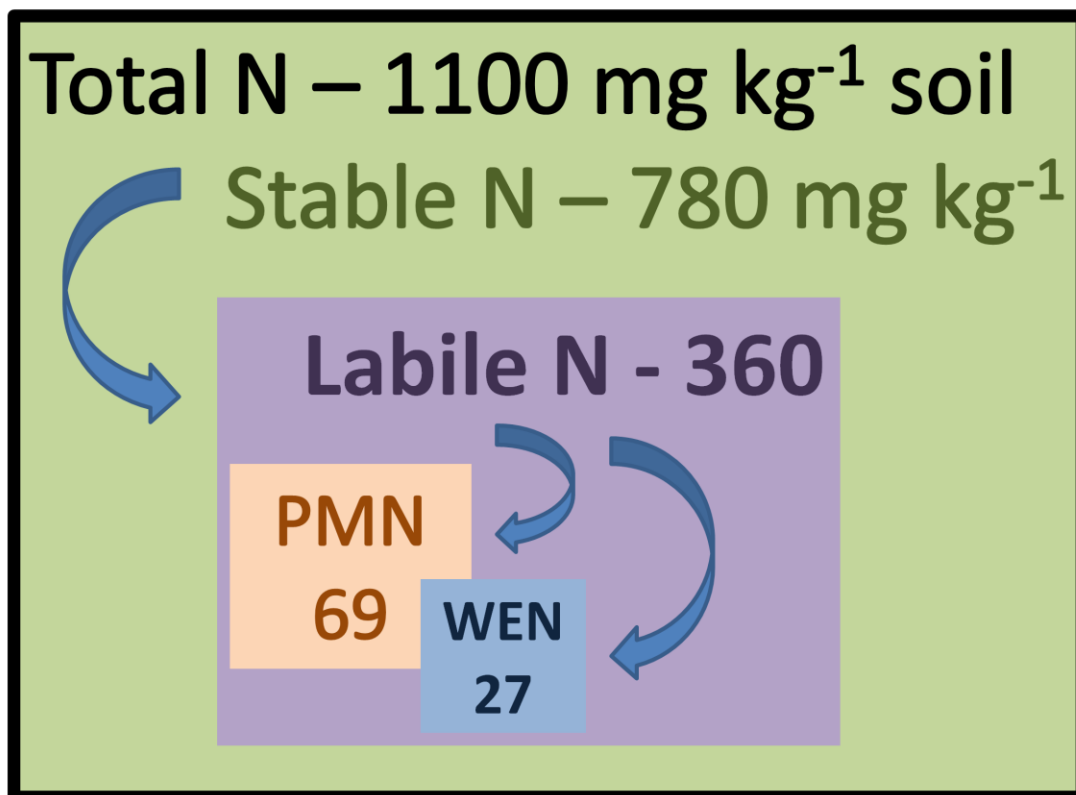


Figure 3.1. Conceptual diagram of soil nitrogen pools studied, relative proportions and overlap. WEN is water extractable N; PMN is potentially mineralizable N.

3.3.4 *Data Analysis.*

All experimental data was managed and analyzed with the data discussed in Chapter 2. In brief, calculations performed in both Access and MS Excel 2007 with statistical analysis performed on difference values in SAS Enterprise Guide software using PROC Mixed (Version 4.2, Copyright © 2006-2008, SAS Institute Inc., Cary, NC, USA). The properties of identified soil nutrient status field locations was evaluated via statistical analyses of all non-harvested samples. The same split-plot analysis of variance model was utilized with the split occurring by soil nutrient status as in Chapter 2 (Table 2.2). The same spatially-repeated split-plot analysis of variance model was utilized to determine significance in harvest treatment difference values, the split occurring by soil nutrient status and each depth class was considered as a spatially repeated sampling (Table 2.3). Since potentially mineralizable N was only determined for two depth classes, both models were slightly altered to account for this change (Tables 3.1 and 3.2). Significance ($\alpha = 0.1, 0.05, 0.01$ and 0.001) between mean values was determined using Tukey-Kramer adjusted values due to sample imbalance.

3.4 Results and Discussion

3.4.1 *Control Soil Properties.*

Analysis of all no harvest samples and harvest site controls revealed differences between soil nutrient status classes. In general, soil N pools were greater in high nutrient status soils than in medium or low nutrient status soils (Table 3.3). Potassium permanganate extractions partitioned nitrogen into significantly greater pools of SN in high nutrient status soils compared to medium ($p = 0.035$) and low ($p = 0.037$) nutrient

Table 3.1. Split-plot design analysis of variance table for determination of soil nutrient status (SNS) assignment main effect and error due to possible interactions with fixed effects depth, replicate, and treatment sampling location identifiers on potentially mineralizable N.

Source	Degrees of Freedom
SNS	2
Depth	1
Rep	2
Treatment	2
SNS*Depth	2
SNS*Rep	4
SNS*Treatment	4
Depth*Rep	2
Depth*Treatment	2
Rep*Treatment	4
SNS*Depth*Rep	4
SNS*Depth*Treatment	4
SNS*Rep*Treatment	8
Depth*Rep*Treatment	4
SNS*Depth*Rep*Treatment	8

Table 3.2. Split-plot design analysis of variance table with treatment main effect for potentially mineralizable N evaluation, each site split by soil nutrient status (SNS), each sampling repeated by depth.

Source	Degrees of Freedom
Treatment	2
SNS	2
Treatment*SNS	4
Depth	1
Treatment*Depth	2
SNS*Depth	2
Treatment*SNS*Depth	4

Table 3.3: Average soil N properties for no harvest management (NHM) and non-harvested, paired control soil samples associated with different nutrient status soils.

Soil Nutrient Status	TOC [†]	TN [‡]	C:N [§]	SN [¶]	LN [#]	WEN ^{††}	PMN ^{‡‡}
	--- (g kg ⁻¹ soil) ---	(ratio)	-- (mg N kg ⁻¹ soil) -	- (mg N kg ⁻¹ soil) -			
High	21 a ^{§§}	1.6 a	13.4 a	1200 a	460 a	40 a	74 a
Medium	13 b	0.9 b	14.4 a	600 b	300 b	23 b	60 a
Low	14 b	0.9 b	14.3 a	600 b	320 b	20 b	72 a
Significance Level ^{¶¶}	*	*		*		**	

[†] TOC, total organic carbon.

[‡] TN, total nitrogen.

[§] C:N, ratio of TOC to TN.

[¶] SN, stable nitrogen pool not oxidized by potassium permanganate.

[#] LN, labile nitrogen pool determined by the difference between TN and SN after extraction with potassium permanganate.

^{††} WEN, water extractable nitrogen.

^{‡‡} PMN, potentially mineralizable nitrogen as determined over 84 day-aerobic incubation.

^{§§} Letters indicate significant differences between values within a column as determined using the Tukey-Kremer adjusted test of means.

^{¶¶} Asterisks under each column indicate significance levels: no asterisk, $\alpha=0.1$; *, $\alpha=0.05$; **, $\alpha=0.01$; and ***, $\alpha=0.001$.

status soils. Labile N followed the same pattern as SN with greater pools in high nutrient soils compared to medium and low nutrient status soils ($p = 0.069$ and 0.096 , respectively). Water extractable nitrogen also differed within the soils studied and greater WEN concentrations were found in high nutrient soils compared to both medium and low ($p = 0.008$ and 0.005 , respectively). No significant differences were evident between medium and low nutrient status soils for SN, LN or WEN ($p > 0.1$). No significant differences in PMN were observed between the soils after 84 days of incubation and soil carbon to nitrogen (C:N) ratios were similar as well. All N pools were significantly greater in the 0-10 cm depth relative to deeper sampling depths for all soil nutrient status (Table 3.4, p-values ranging from < 0.001 to 0.1). While the definition of soil nutrient status was initially based on subsoil base saturation, surface soil N pools prove to follow a similar correlation with assigned nutrient status as soil base cations, TOC and TN (See Chapter 2, section 2.4.1).

Greater concentrations of N pools in the surface 10 cm of non-harvested soils continue the suggestions that N cycling across all soils is influenced by surface deposition of materials (e.g. atmospheric, litter, slash, etc.) rather than cycling throughout the soil profile, regardless of stable or labile fraction. Continued decreases of soil N pools, particularly WEN indicate labile N leached from litter and A horizons is not accumulating to a depth of 30 cm. Unlike BS, Ca, and K concentrations, SN and LN pools in low nutrient soils continue to decrease significantly to the third depth class. Low nutrient status soils SN and LN concentration in 20-30 cm unharvested samples was not only significantly lower than 0-10 cm samples (both $p < 0.001$), but also the 10-20 cm

Table 3.4. Average soil N properties for no harvest management (NHM) and non-harvested, paired control soil samples associated with different nutrient status soils and each depth class.

Sampling Depth (cm)	TOC [†] -- (g kg ⁻¹ soil) --	TN [‡]	C:N [§] (ratio)	SN [¶] -- (mg N kg ⁻¹ soil) --	LN [#]	WEN ^{††} ---- (mg N kg ⁻¹ soil) ----	PMN ^{‡‡}
<u>High Nutrient Status</u>							
0-10	32 a ^{§§}	2.3 a	15 a	1500 a	780 a	58 a	105 a
10-20	17 b	1.4 b	15 b	1000 b	350 b	34 b	43 b
20-30	12 c	1.2 b	11 b	900 b	250 b	27 b	--
Significance Level ^{¶¶}	*	***	*	***	***	***	**
<u>Medium Nutrient Status</u>							
0-10	22 a	1.4 a	17 a	900 a	520 a	42 a	81 a
10-20	11 b	0.8 b	15 a	600 b	250 b	16 b	40 b
20-30	6 c	0.5 c	12 b	400 c	120 b	10 b	--
Significance Level	*		*		**	***	**
<u>Low Nutrient Status</u>							
0-10	25 a	1.5 a	17 a	900 a	590 a	39 a	101 a
10-20	11 b	0.8 b	15 a	500 b	250 b	14 b	43 b
20-30	6 c	0.5 c	12 b	400 c	110 c	7 b	--
Significance Level	*	*	*			***	**

[†] TOC, total organic carbon.

[‡] TN, total nitrogen.

[§] C:N, ratio of TOC-to-TN.

[¶] SN, stable nitrogen pool not oxidized by potassium permanganate.

[#] LN, labile nitrogen pool determined by the difference between TN and SN after extraction with potassium permanganate.

^{††} WEN, water extractable nitrogen.

^{‡‡} PMN, potentially mineralizable nitrogen as determined over 84 day-aerobic incubations.

^{§§} Letters indicate significant differences between values within a column as determined using the Tukey-Kramer adjusted test of means.

^{¶¶} Asterisks under each column indicate significance levels: no asterisk, $\alpha=0.1$; *, $\alpha=0.05$; **, $\alpha=0.01$; and ***, $\alpha=0.001$.

samples ($p = 0.099$ and 0.073 , respectively). The significant decrease with depth highlights the requirement for trees and other forest vegetation to obtain N from surface horizons. In these surface horizons, any observable deleterious effect of harvest will have greater control on N cycling. Surface deposition appears to control N cycling in all nutrient status soils. Greater N pools in high nutrient status soils probably derive from increased productivity in these sites and resulting biomass contributing N to the soil on a regular basis. Type 3 Test of Fixed Effects in unharvested soils are reported in Table 3.5.

3.4.2 Effect of Harvest on Soil N Pools.

Standard characterization analysis revealed significant differences ($\alpha \leq 0.1$) in TOC and TN difference values between clearcut and single-tree selection soils (see Chapter 2, also Type 3 Tests of Fixed Effect in Table 3.6). Increases were observed in clearcut treated soils were significantly different from decreases observed in single-tree selections across all soils and depth classes ($p = 0.048$ for TOC, and $p = 0.052$ for TN), though neither harvest treatment differed from values associated with non-harvest sites. The pattern of positive difference values and negative difference values associated with clearcuts and single-tree selection sites, respectively, was repeated for SN across all soils ($p = 0.066$), in high nutrient status soils ($p = 0.011$), the 0-10cm depth across all soil nutrient status categories ($p = 0.005$), and within high nutrient soils at 0-10 cm and 10-20 cm depths ($p = 0.001$ and 0.008 , respectively) (Fig. 3.2a-d). The majority of TN is comprised of SN in each soil type and depth class. High nutrient status soils and the 0-10 cm depth class generated the largest difference values in harvested soil TOC and TN, thus it was anticipated that SN would behave similarly. Kaye et al. (2003) observed a

Table 3.5. Type 3 Tests of Fixed Effects, evaluating soil nutrient status (SNS) identification in unharvested locations, including depth, replicate identification (Rep) and MOFEP treatment. Tukey-Kramer adjusted p-values of soil properties and nutrient concentrations from split-plot statistical design.

Source	----- p-values -----						
	TOC [†]	TN [‡]	C:N [§]	SN [¶]	LN [#]	WEN ^{††}	PMN ^{‡‡}
SNS	0.050	0.058	0.561	0.058	0.130	0.010	0.292
Depth	<0.001	0.001	0.018	0.002	0.002	0.001	0.008
Rep	0.431	0.646	0.776	0.631	0.662	0.216	0.663
Treatment	0.332	0.287	0.431	0.318	0.277	0.020	0.396
SNS*Depth	0.379	0.296	0.629	0.560	0.390	0.999	0.205
SNS*Rep	0.410	0.538	0.119	0.680	0.424	0.448	0.840
SNS*Treatment	0.066	0.182	0.935	0.200	0.264	0.444	0.447
Depth*Rep	0.964	0.899	0.472	0.997	0.620	0.823	0.940
Depth*Treatment	0.987	0.749	0.7464	0.707	0.793	0.004	0.308
Rep*Treatment	0.122	0.347	0.423	0.528	0.456	0.271	0.991
SNS*Depth*Rep	0.947	0.991	0.677	0.780	0.425	0.727	0.520
SNS*Depth*Treatment	0.387	0.442	0.815	0.717	0.309	0.934	0.947
SNS*Rep*Treatment	0.887	0.652	0.936	0.405	0.883	0.490	0.807
Depth*Rep*Treatment	0.960	0.956	0.423	0.947	0.497	0.631	0.766
SNS*Depth*Rep*Treatment	0.954	0.988	0.184	0.878	0.379	0.338	0.964

[†] TOC, total organic carbon.

[‡] TN, total nitrogen.

[§] C:N, ratio of TOC to TN.

[¶] SN, stable nitrogen pool not oxidized by potassium permanganate.

[#] LN, labile nitrogen pool determined by the difference between TN and SN after extraction with potassium permanganate.

^{††} WEN, water extractable nitrogen.

^{‡‡} PMN, potentially mineralizable nitrogen as determined over 84 day-aerobic incubation.

Table 3.6. Type 3 Tests of Fixed Effects for changes in soil TOC and nitrogen pools.

Tukey-Kramer adjusted p-values of soil properties and nutrient concentrations from split-plot spatially repeated statistical design with harvest treatment main effect, each site split by soil nutrient status (SNS), each sampling repeated by depth.

Source	----- p-values -----						
	TOC [†]	TN [‡]	C:N [§]	SN [¶]	LN [#]	WEN ^{††}	PMN ^{‡‡}
Treatment	0.049	0.059	0.335	0.071	0.097	0.334	0.375
SNS	0.048	0.068	0.444	0.068	0.234	0.451	0.761
Treatment*SNS	0.021	0.035	0.517	0.029	0.176	0.425	0.078
Depth	0.130	0.029	0.880	0.309	0.021	0.322	0.012
Treatment*Depth	0.024	0.001	0.591	0.005	0.002	0.004	0.121
SNS*Depth	0.702	0.586	0.708	0.184	0.218	0.001	0.280
Treatment*SNS*Depth	0.284	0.032	0.826	0.071	0.054	0.004	0.141

[†] TOC, total organic carbon.

[‡] TN, total nitrogen.

[§] C:N, ratio of TOC to TN.

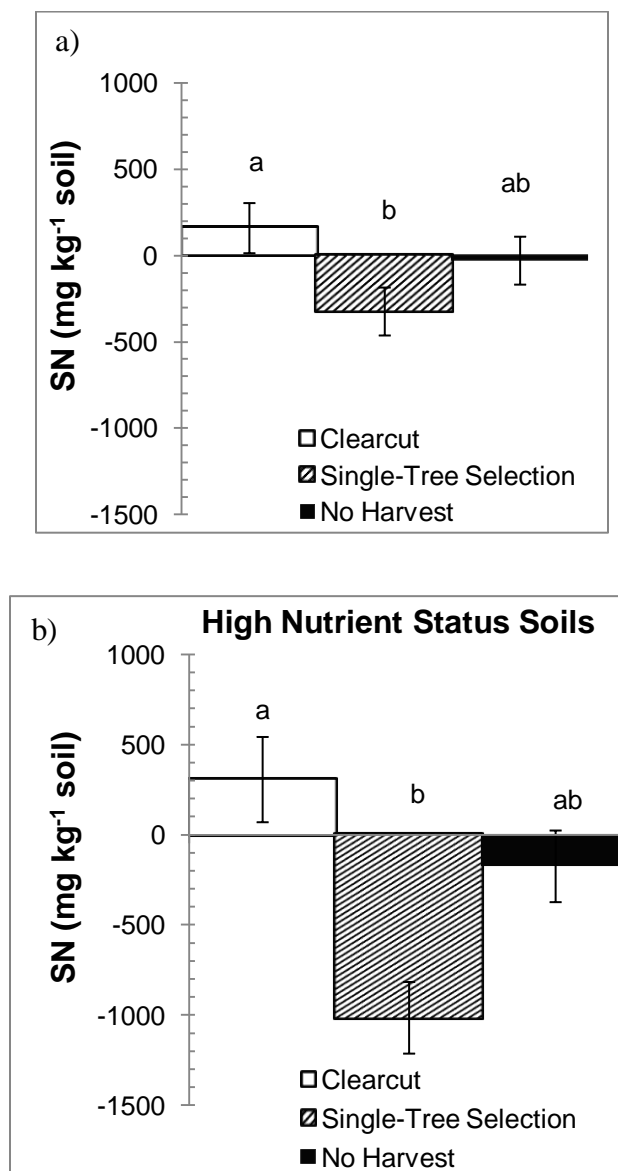
[¶] SN, stable nitrogen pool not oxidized by potassium permanganate.

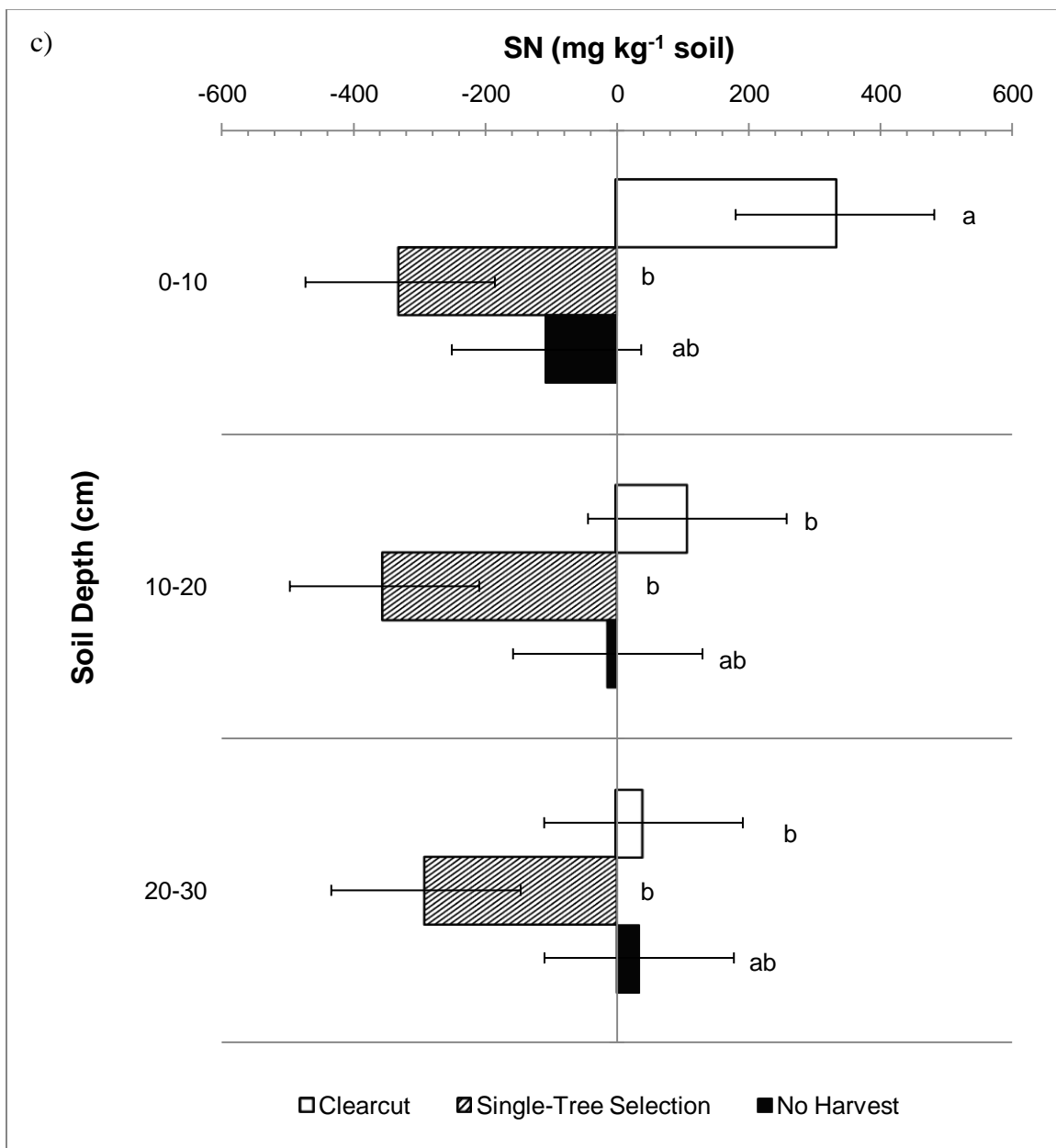
[#] LN, labile nitrogen pool determined by the difference between TN and SN after extraction with potassium permanganate.

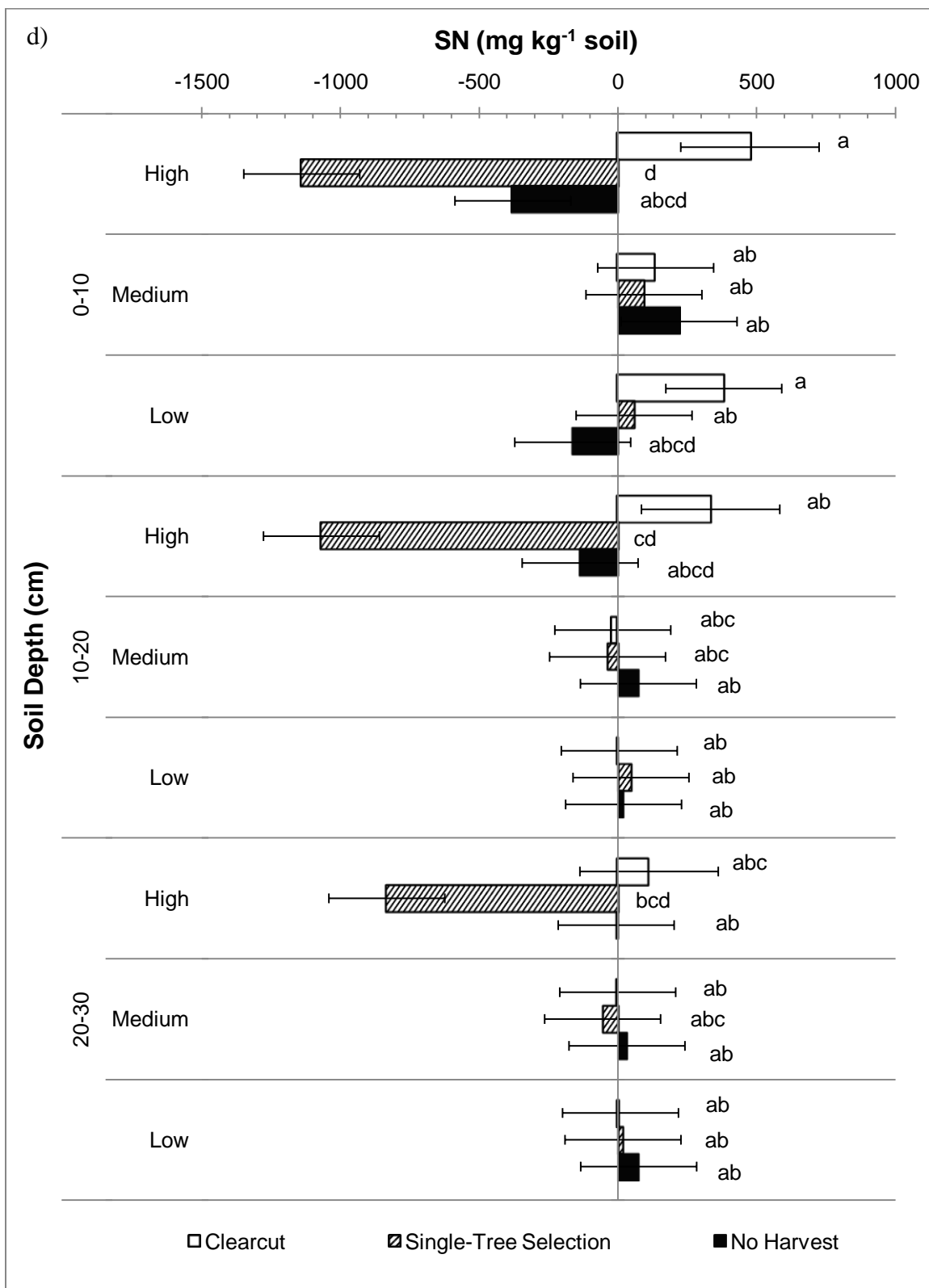
^{††} WEN, water extractable nitrogen.

^{‡‡} PMN, potentially mineralizable nitrogen as determined over 84 day-aerobic incubation.

Figure 3.2. Comparison of stable nitrogen (SN) mean difference values between harvest treatments (a) across all soils and depths, (b) in high nutrient status soils, (c) by soil depth, and (d) by soil depth and nutrient status using the Tukey-Kramer adjusted values test of means ($\alpha = 0.05$). Significant differences between all values in each figure are represented by the presence of different letters. Error bars represent one standard error.





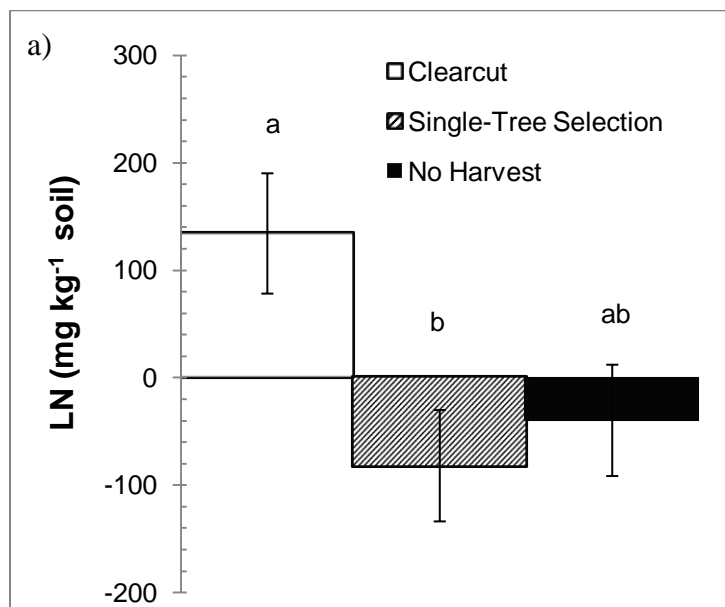


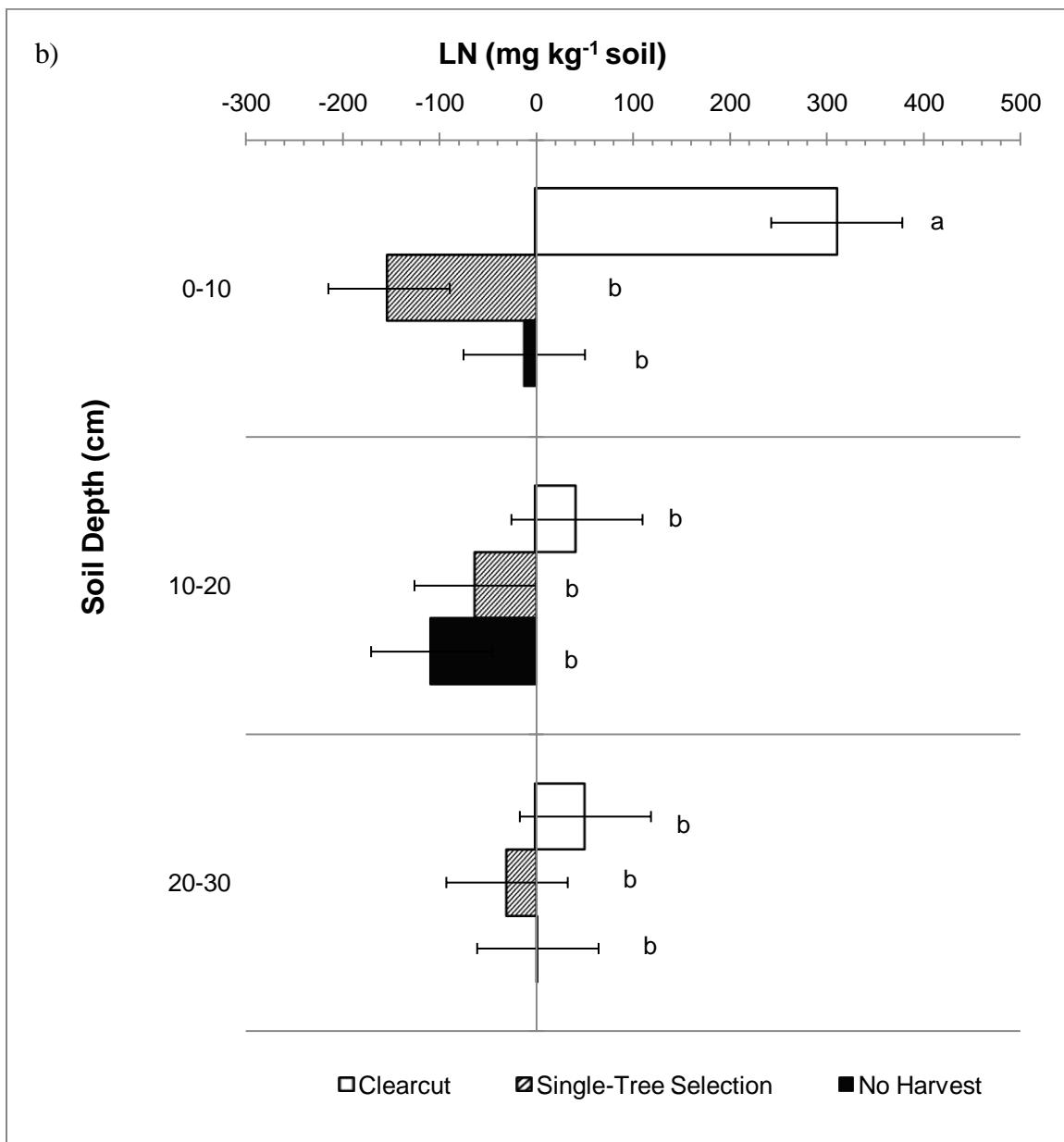
strong correlation between C and SN in forest soils of varying establishment stages in a floodplain succession as determined via long-term aerobic incubations.

Labile nitrogen also followed the same pattern overall as SN, TN and TC. Significant differences were observed between positive difference values in clearcut clearcuts and negative difference values in single-tree selections across all soils ($p = 0.098$; Fig. 3.3a). However, high nutrient status soil LN exhibited no significant difference between treatments ($p > 0.1$). In the top 10 cm, positive LN difference values were observed in soils within clearcuts compared to negative difference values in single-tree selections ($p < 0.001$; Fig. 3.3b). Similar differences between the single tree and clearcut sites were also observed in the top 10 cm of high and low nutrient soils ($p = 0.068$ and 0.005 respectively) due to the large positive difference values in soils within clearcuts. However, this trend was not observed in the surface 10 cm of medium nutrient status soils ($p > 0.1$) (Fig. 3.3c). This is the first appearance of a significant difference in N pools in low nutrient status soils in this data set and could indicate sufficient deposition of slash in clearcuts relative to single-tree selections to enhance LN at the surface of low nutrient status soils. The finding of significant differences in high and low but not medium nutrient status soils remains to be explained.

While PMN followed a similar pattern of positive difference values in soils within clearcuts compared to negative difference values in single-tree selections, the results were not significantly different from each other except in the 0 - 10 cm depth of high nutrient status soils ($p = 0.041$) (Figs. 3.4a-c). Since PMN is another measure of a labile N pool (Kaye et al., 2003), it should be noted that the significance observed between clearcuts

Figure 3.3. Comparison of labile nitrogen (LN) mean difference values between harvest treatments (a) across all soils and depths, (b) by depth class across all soils, and (c) by soil depth and nutrient status using the Tukey-Kramer adjusted values test of means ($\alpha = 0.05$). Significant differences between all values in each figure are represented by the presence of different letters. Error bars represent one standard error.





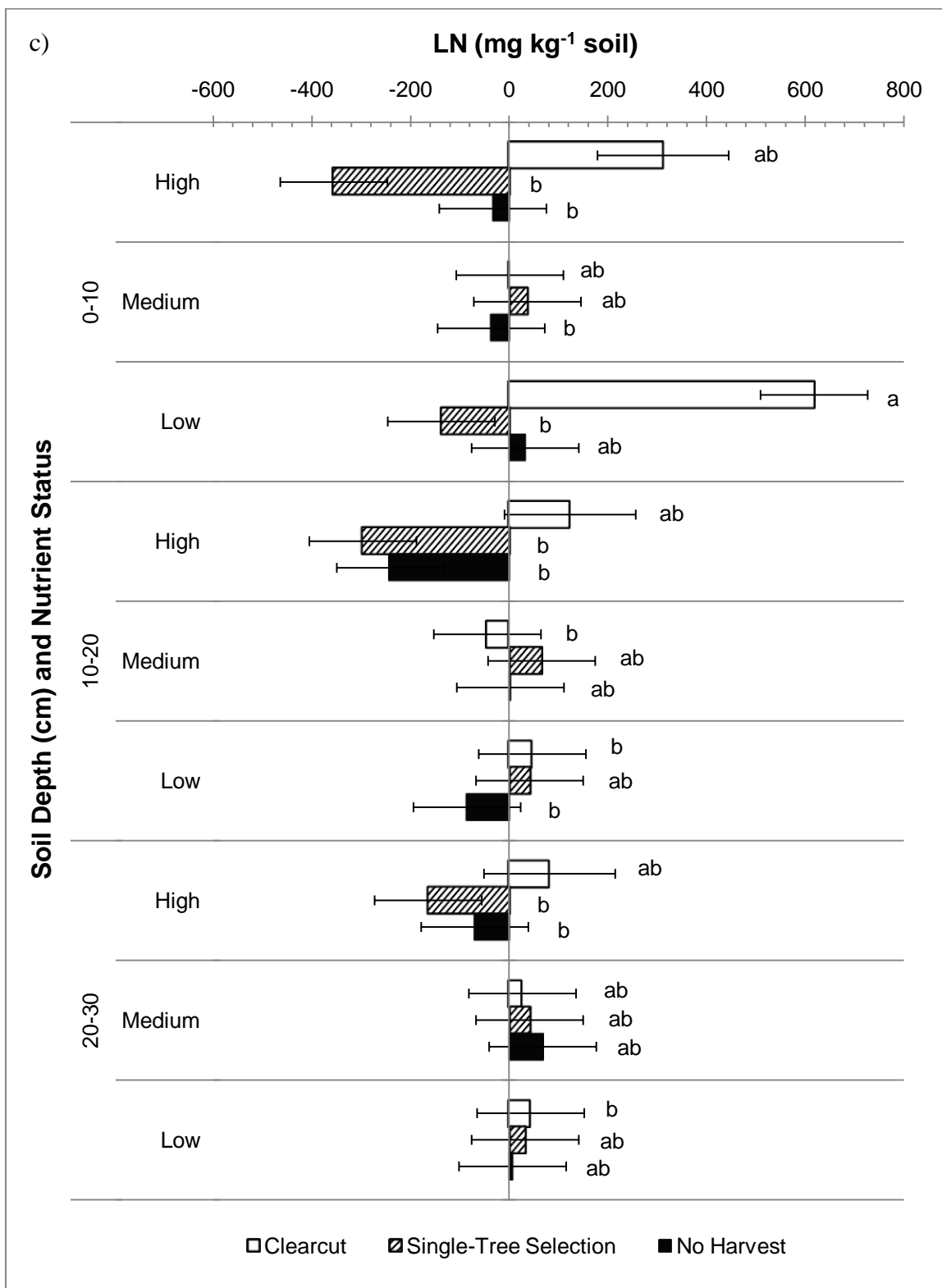
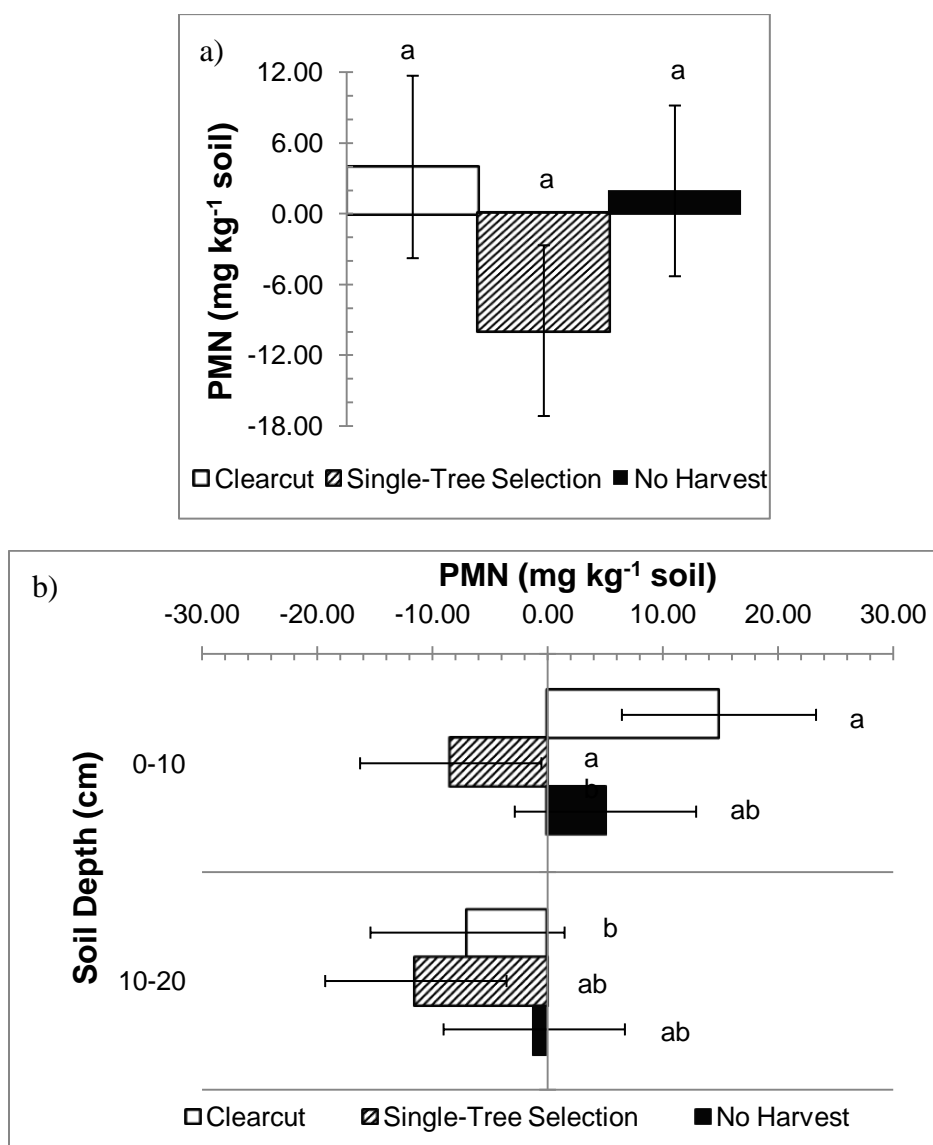
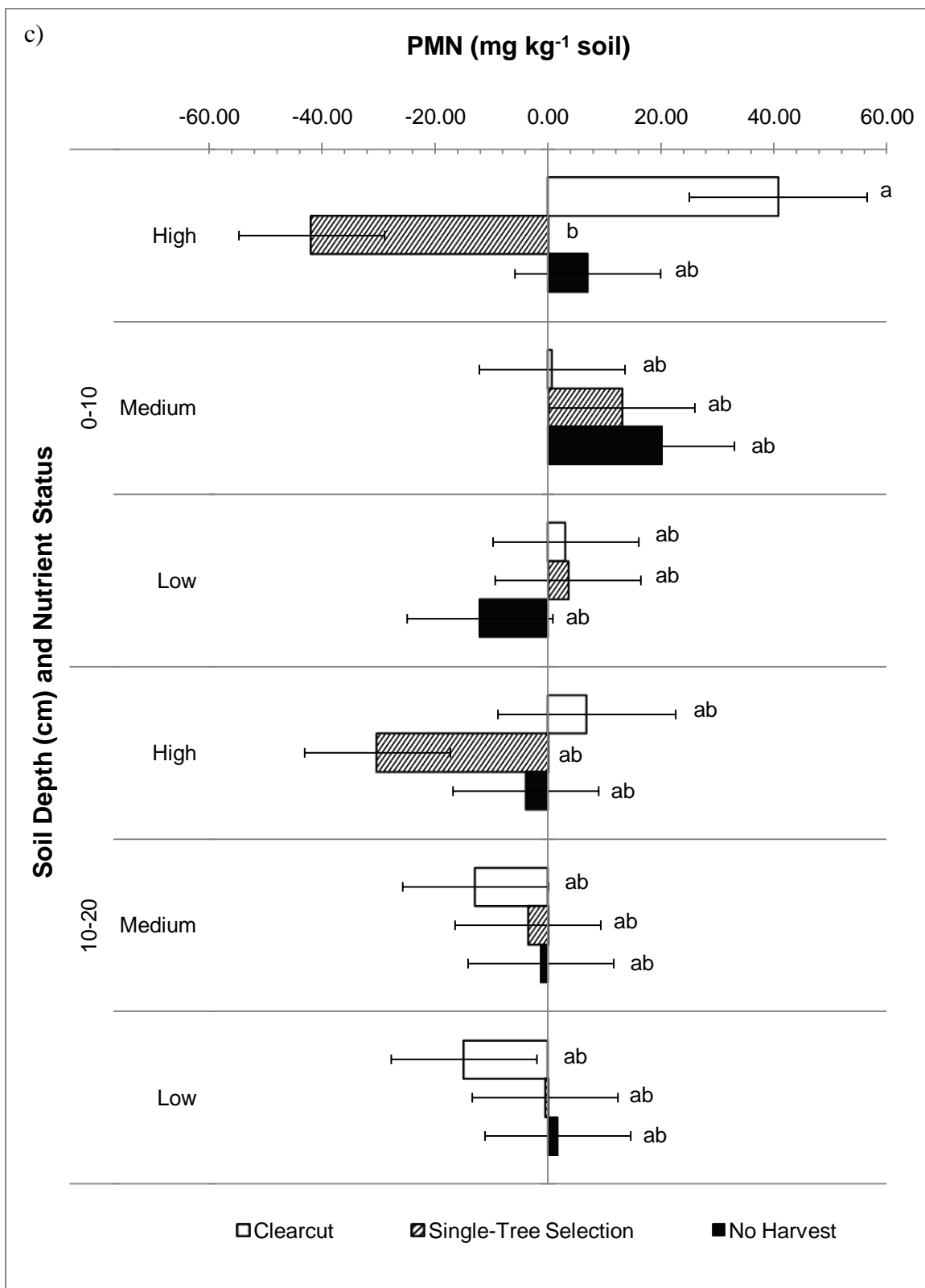


Figure 3.4. Comparison of potentially mineralizable nitrogen (PMN) mean difference values between harvest treatments (a) across all soils and depths, (b) by depth class across all soils, and (c) by soil depth and nutrient status using the Tukey-Kramer adjusted values test of means ($\alpha = 0.05$). Significant differences between all values in each figure are represented by the presence of different letters. Error bars represent one standard error.





and single-tree selections for LN in 0-10 cm low nutrient status soil is distinctly lacking.

No discernable pattern was observed for WEN due to harvest treatment. An extremely negative difference value was observed in the top 10 cm of low nutrient status, no harvest soil (Fig. 3.5). This is not due to an outlier but the result of the high variability of soil properties across the landscape and random assignment of sampling locations in no harvest sites (Table 3.7). Ideally, random assignment of “treated” and “control” would result in paired sampling locations with very similar concentrations, and the resulting differences between two samples would be close to zero. In the event soil properties are quite different within pairing, equal probability of either “control” or “treated” samples having greater concentrations would still produce mean differences of all pairs approaching zero although the error or deviation would be large. In the case of WEN, each surface replicate from the randomly assigned “control” locations in low nutrient status soils of the no harvest site in each block was at least two fold greater than the paired “treated” soil.

Interestingly, while a slightly negative value is observed for PMN of the top 10 cm of unharvested low nutrient status soil, the lack of a strong negative value for LN suggests very little connection between WEN and LN. Potentially mineralizable N appears to be an intermediately labile pool between LN, as determined by potassium permanganate extraction, and WEN. Permanganate extraction for LN determination by was first applied by Westerhof et al. (1998) for use in conjunction with a 1-week laboratory incubation and inorganic N extraction for the development of an N management index. Potassium permanganate oxidizes certain C compounds in organic matter, simultaneously

Figures 3.5. Comparison of total water extractable nitrogen (WEN) mean difference values between harvest treatments by soil depth and nutrient status using the Tukey-Kramer adjusted values test of means ($\alpha = 0.05$). Significant differences between all values in each figure are represented by the presence of different letters. Error bars represent one standard error.

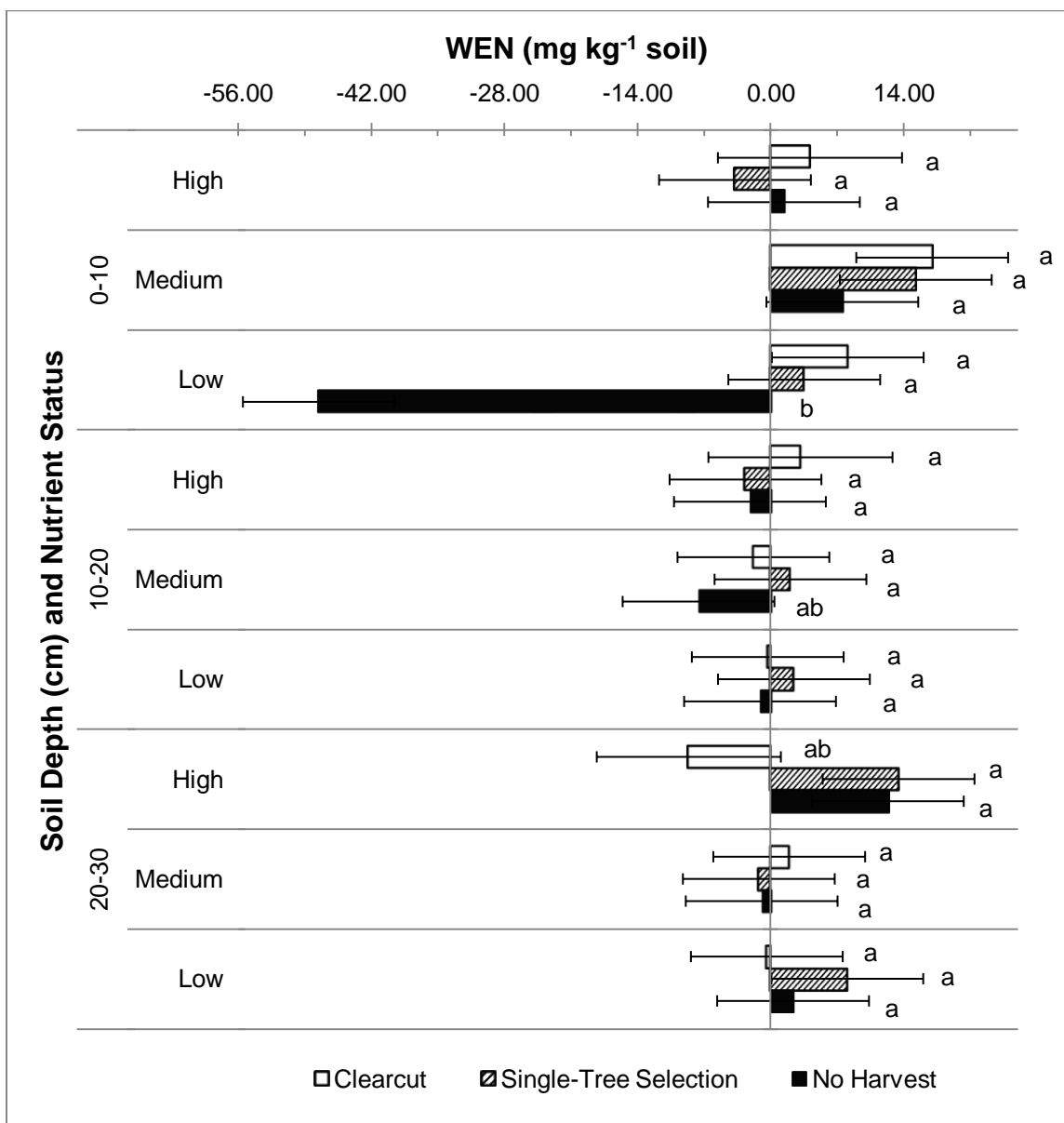


Table 3.7. Actual measurements of water extractable nitrogen (WEN) in 0-10 cm depth samples for each control site replicate. “Treated” and “Control” are random assignments made to locations in the field in order to sample non-harvested MOFEP sites 1, 6, and 8 in a manner similar to harvested sites.

Block	Site	Map Unit	Replicate	"Treated"	"Control"	Difference Value
				WEN (mg N kg ⁻¹ soil)		
1	1	80	1	60.57	135.29	
			2	25.62	93.22	
			3	58.55	115.99	
			Mean[†]	48.25	114.84	-66.59
2	6	80	1	21.25	53.69	
			2	17.31	57.41	
			3	30.46	55.16	
			Mean	23.01	55.42	-32.41
3	8	63	1	29.13	86.70	
			2	21.11	73.49	
			3	39.22	60.04	
			Mean	29.82	73.41	-43.59
				Overall Mean		-47.53

[†] Arithmetic means are calculated for field replicates and their respective difference values which are then averaged creating the large negative value for 0-10 cm no harvest treatment.

releasing N. However, the N mineralized during incubations results from the inherent soil microbial community and organic matter substrate quality. Previous studies have indicated that PMN and WEN may be initially affected by harvest and recover to pre-harvest or control levels within 10 years (Bradley and Parsons, 2007; Holmes and Zak, 1999; Idol et al., 2003; Jerabkova et al., 2006; Mahendrappa et al., 2006).

3.5 Conclusions

Clearcutting and single-tree selections have very different impacts on soil N pools consisting of complex organic compounds. Ten years after harvest, soil TN, SN, and LN concentrations are greater in clearcut sites and smaller in single-tree selection sites. In the surface 10 cm of high nutrient status soils, these altered N pools also resulted in greater PMN in clearcuts and smaller PMN in single-tree selections. While the variability of soil properties is very high resulting in no significant difference between either harvest and NHM soil properties, the consistent occurrence of positive values in soils within clearcuts and negative values in single-tree selections resulted in statistical significance between the treatments. No consistent effects of harvest method were observed in WSN. Interestingly, soil types and depth classes with the largest N pools in non-harvested control locations (high nutrient status, 0-10 cm depth) were the most sensitive to harvest effects. Larger TN, SN and LN in clearcuts is likely the direct result of slash deposition during harvest. Single-tree selections separate the slash deposition away from the location of biomass removal, i.e. the stump. These altered soil nutrient properties are unlikely to persist over a full 100 year rotation in the Ozarks, but implications for more intensive harvest removal are unknown.

3.6 References

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CHAPTER 4: CONCLUSIONS

4.1 Summary

The overall objective of this study was to elucidate the impacts of forest regeneration methods on Missouri Ozark Highland soil nutrient concentrations, pools and chemical properties ten years after harvest. To meet this objective, the effects of forest harvest on soil nutrients and chemical properties were investigated for clearcut and single-tree selections and no harvest control sites in high, medium and low nutrient status soils found within the Missouri Ozark Forest Ecosystem Project (MOFEP). Ten years after harvest, bulk soil samples were collected using a paired sampling technique that consisted of sampling treated and non-harvested areas within the same contiguous soil unit. When the soil map unit being sampled was encompassed within a harvested area, the nearest representative non-harvested unit was sampled. Upon return to the laboratory, samples were analyzed for exchangeable cation concentrations, base saturation (BS) of soil cation exchange capacity, extractable acidity (EA), pH, total organic carbon (TOC), total nitrogen (TN), and nitrogen pools.

In general, it was observed that nutrient values increased in clearcuts relative to single-tree selection sites, although harvested sites did not generally differ from samples collected under no harvest management. Difference values between treated and non-harvested paired samples were used to statistically compare treatment effects on

measured parameters. The difference between harvested or treated soil properties and the paired control samples was typically positive for soil base saturation, Ca, K, TOC, total N (TN), stable N, labile N, water extractable N, and potentially mineralizable N within clearcuts. Soil differences due to harvest were typically negative in single-tree selection sites for base saturation, Ca, Mg, K, extractable acidity, [H⁺], TOC, total N (TN), stable N, labile N, and potentially mineralizable N. Many of these positive values for clearcuts were significantly different ($\alpha = 0.05$) from the negative single-tree selections, particularly TOC and N pools in the top 10 cm and in high nutrient status soils. Difference values associated with no harvest treatment (control) sites were highly variable resulting in a range of positive and negative values. Additionally, parameter values from no harvest sites were not significantly different from clearcut or single-tree selection values.

The influence of harvest on the measured parameters is generally attributed to the deposition of slash during timber removal. Typically, clearcuts are viewed as an intense disturbance since all or near-all trees in a stand are felled. However, the broad application of a clearcut across an entire stand enhances the likelihood of broad slash distribution which mitigates nutrient loss after timber harvest. Single-tree selections are a less intense, more disperse disturbance of removing or felling individual trees throughout a stand. However, the individual removal of trees results in slash deposition approximately one whole tree height away from the actual site of removal (i.e., where the stump remains). Though the slash will contribute to soil nutrient pools wherever it is

deposited, the slash will not directly mitigate nutrient loss in a zone immediately surrounding the stump.

It remains to be determined whether or not nutrient depletion in zones influenced by single-tree selection will adversely affect tree regeneration and species composition over the long-term. In the short-term, this practice mimics whole-tree harvest in a localized area, and whole-tree harvest has been observed and projected to reduce soil nutrient pools (Aherne et al., 2008; Belleau et al., 2006; Thiffault et al., 2006). However, it is postulated that as tree removal occurs over a 100 year rotation the overall deposition of slash on-site will be random. Subsequently, zones of nutrient depletion will be ameliorated during future harvest events as slash is deposited and mineralized.

In summary, significant differences were observed between clearcuts and single-tree selections particularly in the top 10 cm and in high nutrient status soils. However, neither harvest treatment was significantly different from the no harvest control sites due to high soil variability inherent in the landscape. These results suggest that clearcuts induce an increase and single-tree selections induce a decrease in soil nutrients within 10 years after harvest; however over the course of a one hundred year rotation few if any harvest effects may be especially in low and medium nutrient status soils.

4.2 Future Research

This project ultimately supports the need for future research evaluating harvest effects on forest soils in the Ozarks. First, the sampling conducted represents one point in time 10 years after a harvest. It is most likely the soil parameters studied here are returning to environmental baseline levels after peak disturbance shortly after harvest. The

replication of this study either sooner or greater than 10 years post-harvest would confirm this presumption. Also, the potential losses occurring at the site of a single-tree selection is only accounting for the spatial area of the removal, not the area where deposition occurs. Across a landscape, these losses may be ameliorated by soil nutrient increases due to the slash deposition. In the discussion of this study it was assumed the distribution of slash across a clearcut is relatively uniform and single-tree selections are felled in random directions. These assumptions could be confirmed or disproven by evaluating both factors after the next harvest, i.e. record the distribution of slash across MOFEP clearcuts and the orientation of slash deposition from single-tree selection in the landscape with reference to the original tree location.

The unique sampling methodology employed by sampling directly around a single removed tree has revealed significantly lower nutrient pools in single-tree selection harvesting. Additional sampling methodologies would aid in determining the extent in the landscape of the influence of a single removal. A grid sampling approach could be undertaken surrounding a stump to determine directional influences and the circumference of the area influenced by harvesting. Also, a transect could be sampled from a removed tree to various surrounding non-harvested trees to determine the point of equal influence or possible “edge”.

Given the highly significant treatment effects in high nutrient status soils and surface depths, it is debatable whether to continue sampling to lower depths and both low and medium nutrient status soils. Transect sampling down the landscape may aid in identifying specifically where in the soil-landscape harvest effects become significant

rather than in these pre-determined nutrient status soils. Given the soil is experiencing changes due to harvest at MOFEP, it may be possible to correlate herbaceous and woody response to changes in soil nutrients. A thorough study examining whether any of the range of soil parameters measured here influence site index could also be undertaken.

4.3 References

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APPENDIX

APPENDIX A. FIELD SAMPLING LOCATIONS

Table A.1. World Geodetic System (WGS 84) coordinates of sampling locations in decimal degrees.

"Treated" Locations			"Paired" Non-harvested Locations		
Location	Latitude	Longitude	Location	Latitude	Longitude
1-74-T	N 37.17870°	W 091.12684°	1-74-P	N 37.17966°	W 091.12878°
1-80-T	N 37.17651°	W 091.12996°	1-80-P	N 37.17614°	W 091.12986°
1-82-T	N 37.17776°	W 091.12811°	1-82-P	N 37.17708°	W 091.12846°
2-74-T	N 37.15358°	W 091.11779°	2-74-P	N 37.15481°	W 091.11888°
2-80-T	N 37.15777°	W 091.15321°	2-80-P	N 37.15852°	W 091.15374°
2-82-T	N 37.15783°	W 091.15260°	2-82-P	N 37.15899°	W 091.15056°
3-74-T	N 37.13290°	W 091.08293°	3-74-P	N 37.13354°	W 091.08341°
3-80-T	N 37.13968°	W 091.08813°	3-80-P	N 37.14040°	W 091.08884°
3-82-T	N 37.14574°	W 091.09527°	3-82-P	N 37.14634°	W 091.09425°
4-80-T	N 37.14822°	W 091.07427°	4-80-P	N 37.14914°	W 091.07507°
4-81-T	N 37.14026°	W 091.08277°	4-81-P	N 37.13979°	W 091.08134°
4-82-T	N 37.14806°	W 091.07324°	4-82-P	N 37.14831°	W 091.07435°
5-80-T	N 37.16481°	W 091.04099°	5-80-P	N 37.16409°	W 091.04086°
5-81-T	N 37.15264°	W 091.04624°	5-81-P	N 37.15425°	W 091.04553°
5-82-T	N 37.15369°	W 091.04570°	5-82-P	N 37.15430°	W 091.04594°
6-74-T	N 37.17945°	W 091.04758°	6-74-P	N 37.17991°	W 091.04701°
6-80-T	N 37.16949°	W 091.04164°	6-80-P	N 37.16998°	W 091.04146°
6-82-T	N 37.17102°	W 091.03567°	6-82-P	N 37.17059°	W 091.03534°
7-63-T	N 37.01407°	W 091.20341°	7-63-P	N 37.01443°	W 091.20351°
7-81-T	N 37.00055°	W 091.19568°	7-81-P	N 37.00003°	W 091.19527°
7-82-T	N 37.02446°	W 091.20950°	7-82-P	N 37.02356°	W 091.21056°
8-63-T	N 37.00528°	W 091.17730°	8-63-P	N 37.00572°	W 091.17754°
8-81-T	N 37.00557°	W 091.17700°	8-81-P	N 37.00327°	W 091.17532°
8-82-T	N 37.00384°	W 091.17605°	8-82-P	N 37.00220°	W 091.17401°
9-74-T	N 37.07135°	W 091.11030°	9-74-P	N 37.07116°	W 091.10990°
9-80-T	N 37.07297°	W 091.13007°	9-80-P	N 37.07240°	W 091.13089°
9-82-T	N 37.07203°	W 091.12977°	9-82-P	N 37.07144°	W 091.13031°

APPENDIX B. STATISTICAL MODELS IN SAS

B.1. Code for split-plot, incomplete block design analysis of variance in SAS software for determination of soil nutrient status (SNS) assignment efficacy of soils from unharvested locations. Main effect SNS and error due to possible interactions with fixed effects by block: depth, replicate (rep), and assigned MOFEP treatment (trt, i.e. EAM, UAM, or NHM).

```
proc mixed data=CONTROL-DATASET;
  class block SNS depth rep trt;
  model DEPENDENT VARIABLE = SNS depth rep trt SNS*depth SNS*rep SNS*trt
    depth*rep depth*trt rep*trt SNS*depth*rep SNS*depth*trt SNS*rep*trt
    depth*rep*trt SNS*depth*rep*trt;
  random int SNS depth rep trt SNS*depth SNS*rep SNS*trt depth*rep depth*trt
    rep*trt SNS*depth*rep SNS*depth*trt SNS*rep*trt depth*rep*trt
    SNS*depth*rep*trt/subject=block;
  lsmeans SNS depth trt SNS*depth SNS*depth*trt/ pdiff;
run;
```

B.2. Code for split-plot, spatially repeated, incomplete block design analysis of variance in SAS software for determination of harvest treatment (trt) main effect; each plot split by soil nutrient status (SNS), each sampling repeated by depth.

```
proc mixed data=DIFFERENCES-DATASET;
  class block trt SNS depth;
  model DEPENDANT VARIABLE = trt SNS trt*SNS depth trt*depth depth*SNS
    depth*trt*SNS/outp=pred; *ddfm=kr;
  random int trt trt*SNS/subject = block;
  repeated depth/ type=sp(pow) (depths) subject=trt*SNS (block) r rcorr;
  lsmeans trt SNS trt*SNS depth trt*depth depth*SNS depth*trt*SNS/adjust=tukey
    pdiff;
  ods listing sge = on;
  ods output diffs=ppp lsmeans=mmm;
  ods listing exclude diffs lsmeans;
run;
*you will need to modify the next line to point where the pdmix800.sas file
  resides on your machine;
%include 'FILE LOCATION';
%pdmix800 (ppp,mmm,alpha=.05,sort=yes);
run;
```

APPENDIX C. ADDITIONAL FIGURES OF SIGNIFICANT RESULTS

Figure C.1. Comparison of least squares means of difference values by harvest treatment and soil nutrient status for (a) total nitrogen (TN) and (b) stable nitrogen (SN) using the Tukey-Kramer adjusted values test of means ($\alpha = 0.05$).

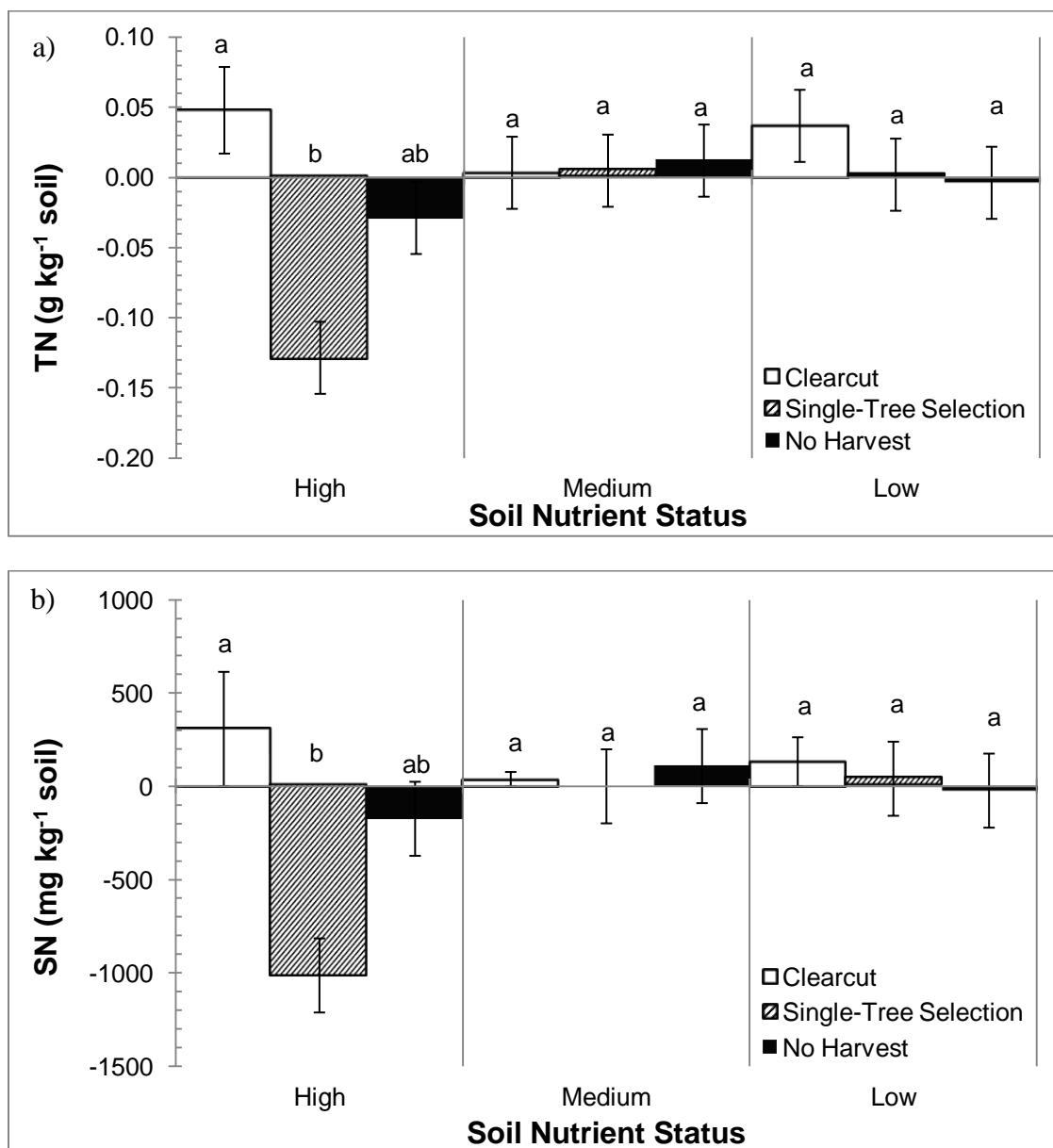
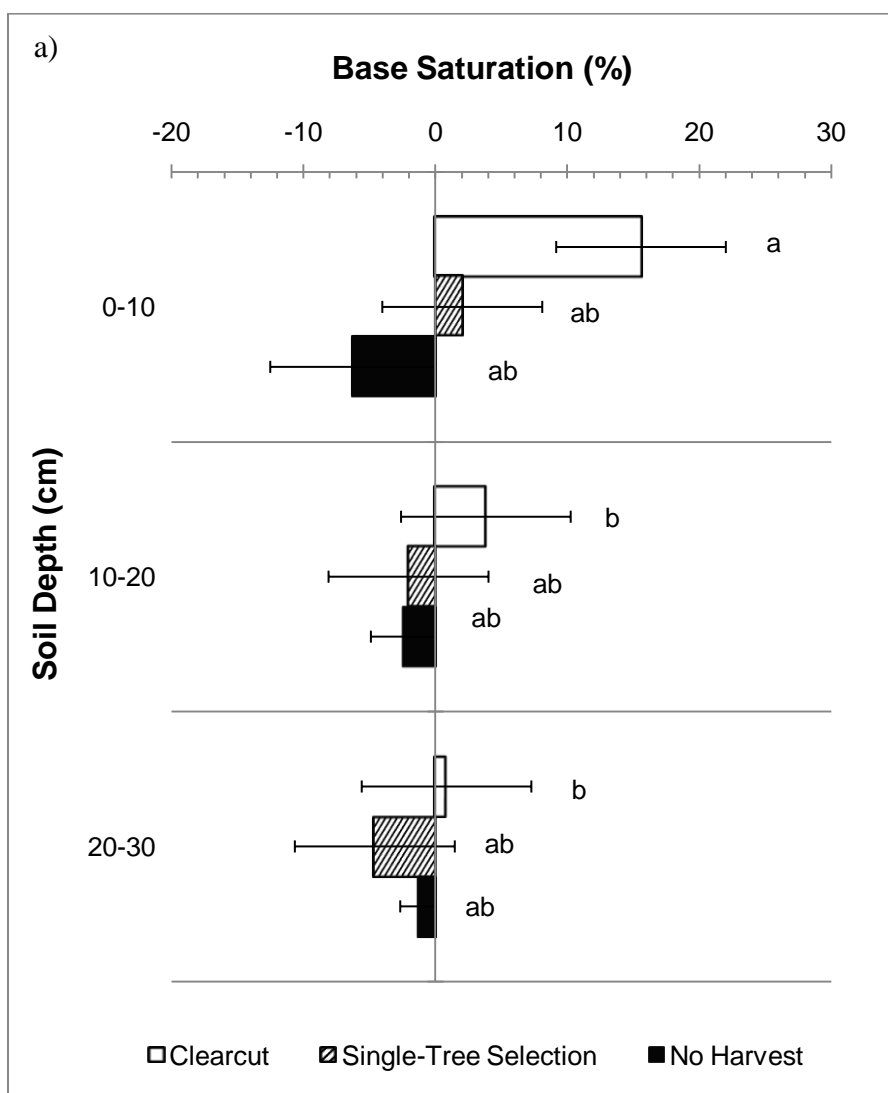
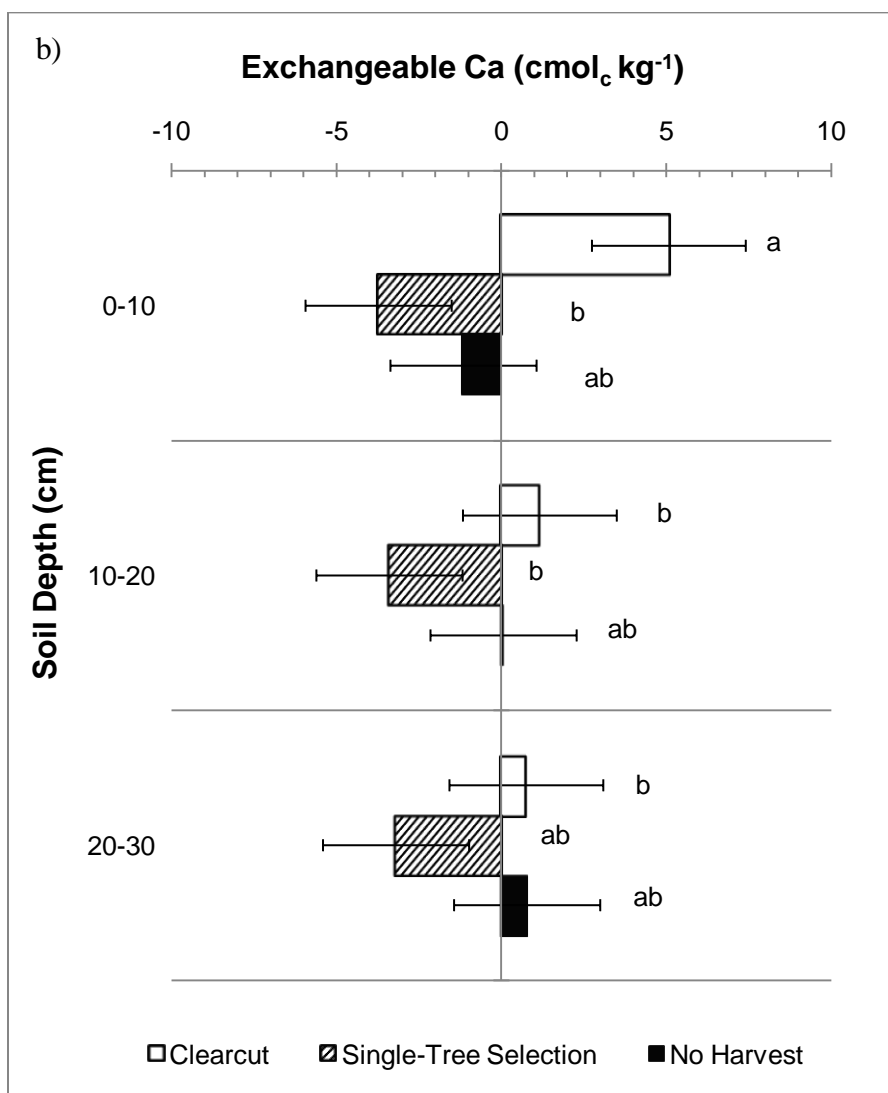
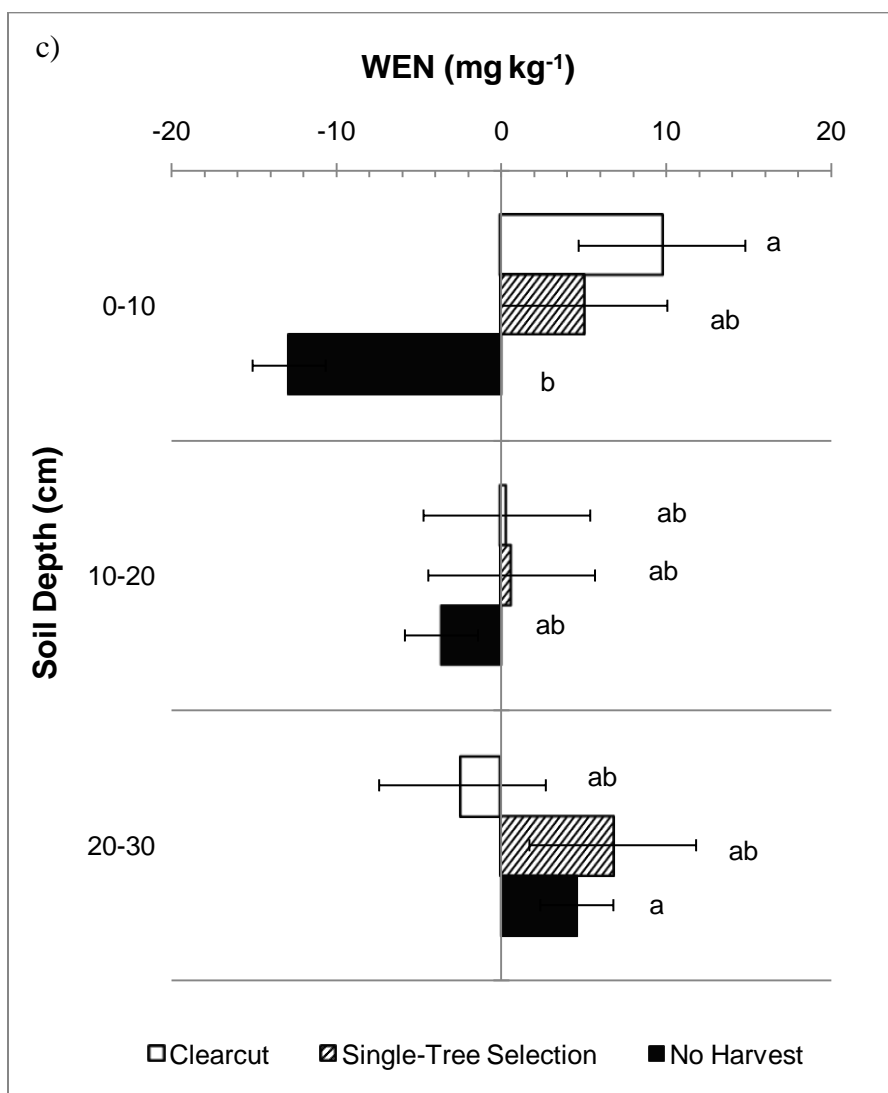


Figure C.2. Comparison of least squares means of difference values by harvest treatment and soil depth class for (a) soil base saturation, (b) soil exchangeable Ca and (c) water extractable nitrogen (WEN) using the Tukey-Kramer adjusted values test of means ($\alpha = 0.05$).







APPENDIX D. DETAILED PROCEDURES

Sample Preparation and Acid Washing Sand:

Sieving moist samples:

1. Bring samples in a cooler to room 27. Keep samples in cooler when not sieving them.
2. Place butcher paper on table. Sieve moist sample onto butcher paper. Remove any rocks or root fragments and throw away. Use rubber stopper to break large soil aggregates and force through sieve. Transfer sieved sample into new plastic bag. Write sample number on bag!
3. Use wire brushes to clean sieves between samples. Shop vac in 313 next to fume hood if needed for larger clean ups.
4. Clean up area, sweep table and floor and put all items away when finished.

Determining soil moisture content

1. Write numbers on aluminum weigh boats or pans.
2. Place aluminum boats in the oven at 105°C for 24 h. Remove from oven with tweezers and allow to cool in desiccator for ~ 30 min.
3. Record pan number and mass to 0.0001 g on analytical balance (use tweezers to place boat on balance).
4. Weight 1.0 g soil into boat and record mass to 0.0001 g.
5. Place in oven at 105°C and dry for 24 h. Sign oven log sheet.
6. Allow samples to cool in dissector ~30 min before weighing sample.
7. Weigh boat + soil and record mass to 0.0001 g.

Acid washing sand:

1. Place enough sand in acid wash to cover the bottom of container (2-4 scoops). Let sit overnight.
2. Place rinse container next to acid wash in hood. Use strainer to scoop as much sand as possible out of acid bath and into rinse container.
3. Transfer rinse container to sink. Rinse thoroughly, filling container half way with DI water while agitating sand. Carefully pour water off sand into sink. Repeat rinse 6-10 times (more rinses for more sand). You may have to rinse for a whole hour or more. Check the pH of the sand to be sure it is close to DI water and no longer acidic.
4. Fill 6 large crucibles with wet sand $\frac{1}{2}$ - $\frac{3}{4}$ full. Wipe any water or sand off bottom and sides of crucibles. Place crucibles in an oven in 313 at 105 degrees Celsius until visibly dry (2 hours or more).
5. Place crucibles inside muffle furnace. Close door and turn on to ~550 degrees Celsius. Set point should be set already, keep an eye on it to be sure. After furnace has heated up to ~500 degrees, continue to heat samples for 1 hour. Turn off furnace. Let it cool down SEVERAL hours or overnight.
6. Place a piece of tape on the furnace door handle that says "IN USE!" When the oven is turned off, write on the tape "Cool down from 550 start [time]."
7. Turn on furnace briefly to check temperature. Wearing gloves, open furnace door SLOWLY. Using tongs, remove crucibles from oven and place on metal tray to finish cooling.
8. Once sand is cool, place in acid washed sand tub and use a paper towel to clean out crucibles.

Potentially Mineralizable Nitrogen Adapted from Motavalli et al. (1995) and Mungai et al. (2006)

1. Wet sieve soils.
2. Determine moisture content of soils and sand.
3. Prep sand.
4. Make nutrient solution. Make solutions by weight using analytical balance to check pipetting. Assume density of water = 1 g/ml. Check interferences with Lachat.

4.0 mM CaCl ₂	2.0 μM MnSO ₄
2.0 mM KH ₂ PO ₄	2.0 μM ZnSO ₄
1.0 mM K ₂ SO ₄	0.5 μM CuSO ₄
1.0 mM MgSO ₄	0.5 μM Na ₂ MoO ₄
25 μM H ₃ BO ₃	

5. Set up filter units.
 - a. Wet funnel with Barnstead ultra pure water. Using tweezers, place membrane, O-ring in order.
 - b. Ensure filters are wet and stable in place
 - c. Attach sample container and prefilter, ensuring prefilter is wet and makes good contact with membrane.
 - d. Attach bottom flow directing piece, and cap to funnel outlet.
6. Number units.
7. Fill assembled filter units with Barnstead ultra pure water. Leach by applying vacuum pressure 47 kPa or 13.88 in Hg. Calibrate pressure regulator at this time. Discard leachate, reuse 20 flasks, wash flasks when all units have been flushed.
8. Weigh 50.00 grams oven-dried equivalent of sand and 50.00 grams oven-dried equivalent of soil. Mix, add to filter units. **Record actual weight of sand and soil added.** Units 1, 34, and 67 should be sand only.

9. Place dispersion filter on top of sample and attach lid. **Record assembled weight.**
 - a. Place all units in refrigerator overnight. **Record side arm flask weights to be used next morning.** Turn on incubator to warm up.

THE NEXT DAY:

1. Make sure weights of side arm flasks are recorded. Attach filter unit to side arm flasks and vacuum manifold.
2. Using funnel in filter lid, burette and burette stand, add 100 ml nutrient solution to unit, controlling dripping.
3. Leach for 1 hour at 47 kPa suction.
 - a. If needed, manually create structure on soil to aid drainage.
4. Remove units from manifold. Record weights and place units in incubator at 30 degrees Celsius. Ensure container in bottom of incubator is full of DI water.
5. Reweigh side arm flasks. Transfer leachate from side arm flasks to square bottles. Store refrigerated.
10. Weigh units weekly and before and after each leaching to verify constant moisture content. Add ultra pure water if needed.
11. Repeat leaching on days 1, 3, 7, 14, 21, 28, 42, 56, 70, 84.
12. Add 50 ml nutrient solution, equilibrate 30 min, leach at 47 kPa (13.88 in Hg) for 1 hour.
13. Repeat weighing and sample collection.
14. Analyze leachates for $\text{NH}_4^{+}\text{-N}$ and $\text{NO}_3^{-}\text{-N}$ using Lachat QuikChem Analyzer.

Potassium Permanganate Extractable Nitrogen Method Adapted from Westerhof et al. (1998)

1. Make 0.333 M KMnO₄ solution in water. FW = 158.04 g. Need 2.5 L total solution.

0.333 M KMnO ₄
= 0.333 mole/L * 158.04 g/mole * 2.5 L = 131.5683 g KMnO₄
2500 ml – (131.5683 g / 2.7 g/ml KMnO ₄) = 2451.271 g H₂O

2. Label tubes and record tube weights. *Confirm sample IDs.

Sample	Label	Weight (g)	Sample	Label	Weight (g)
2-74-T-3-3	01		8-81-T-1-3	25	
2-82-T-2-3	02		8-82-P-1-3	26	
4-82-P-2-3	...		9-80-P-3-3	...	
6-80-P-3-3	24		9-80-T-2-3	48	

3. Calculate 25 mg C oven-dried equivalent of samples and record weight loaded into tubes:

Sample	Weight needed: (g)	Weight loaded in tubes:	Sample	Weight needed: (g)	Weight loaded in tubes:
2-74-T-3-3	9.4711	01	8-81-T-1-3	4.9054	25
2-82-T-2-3	3.8266	02	8-82-P-1-3	9.1018	26
4-82-P-2-3	7.3442	...	9-80-P-3-3	4.7136	...
6-80-P-3-3	13.8424	24	9-80-T-2-3	4.9392	48

4. Filter KMnO₄ solution to be used daily. Add 37.5 ml solution to tubes in sets of 8, record weight added. Break between each set of 8.

$$0.333 \text{ M KMnO}_4 = 37.5 \text{ ml} * (2451.271 \text{ g H}_2\text{O} + 131.5683 \text{ g KMnO}_4) / 2500 \text{ ml} \\ = \mathbf{38.7426 \text{ g solution}}$$

Tube	g solution:	Tube	g solution:
01		25	
02		26	
...		...	
24		48	

5. Shake tubes for 1 hr by sets of 8.

Tubes:	Time:	Start	End
01-08			
09-16			
17-24			
25-32			
33-40			
41-48			

6. Centrifuge 10,000 rpm or x g for 5 min.
7. Pour /pipette off KMnO₄ solution into waste container. Fill tube with Barnstead UP water, resuspend pellet. Spin 5 min. Pour/pipette off rinse water. Repeat rinse procedure until supernatant is clear.

8. Place open tubes in wire rack to dry in oven at 40 degrees C for a couple days. (Wash out oven ahead of time.) Can use vacuum oven as well to ensure complete drying.
9. Record final dried tube + soil weight once dry.

Tube	Weight	Tube	Weight
01		25	
...		...	
24		48	

10. Finely grind samples and run TN on LECO.

Water Extractable Nitrogen Method Adapted from Chen et al. (2005)

1. Label tubes MA001-MA486. Weigh 15 g ODE field moist, sieved soil into bottles recording final weight of soil.
2. Add 37.5 ml Barnstead Ultra-Pure distilled water to tubes recording final weight.
3. Shake end-to-end for 1 hour in sets of 16.
4. Use centrifuge to separate solid and liquid fractions, 30 minutes at 4,000 RPM. Make sure weight is balanced.
5. Filter directly into Shimadzu vials (same label as tubes) using 0.45 micrometer Whatman polypropylene filters (CAT# 6790-2504).
6. Measure total N concentration using Shimadzu TOC-VCSH Total Carbon Analyzer equipped with a TNM-1 nitrogen module and autosampler (TC/TN, sparge kit off, no acid addition).
 - a. Incorporate a standard in tray run every 15 samples.
 - b. Shimadzu runs vials at a time, approx 24 hours. Run at least one calibration curve at the beginning of analysis. Plan runs ahead of time and incorporate a triplicate run once every 30 samples or so to get an idea for variability.
 - c. Tray configuration:

12	<i>Calibration standards</i>
15	Samples
1	<i>Check Standard</i>
15	Samples
1	<i>Check standard</i>
2	triplicate
13	Samples
1	<i>Check standard</i>
15	Samples
1	<i>Check standard</i>
2	Samples
2	triplicate
11	samples
1	<i>Check standard</i>
1	<i>blank</i>
93 vials	71 samples per run

Example Weight Table:

Sample ID	Tube	g soil needed for 15 g ODE:	Actual Sample Weight (g):	Actual Water Weight (g):
6-82-P-1-3	1	17.7090		
6-82-P-2-3	2	18.3129		
6-82-P-3-3	...	17.8852		
...	71	18.0213		
Blank	Blank	Fill with water		

Example Shake Timing Table:

Tubes:	Shake Time:	Start	End
1-16			
17-32			
33-48			
49-64			
64-Blank			

Shimadzu run start time:

Shimadzu run end time:

Additional notes:.

FOREST HARVEST EFFECTS ON SOIL CHEMICAL PROPERTIES AND
NUTRIENT CONCENTRATIONS IN OZARK HIGHLAND SOILS

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PUBLIC ABSTRACT

Forests in southeast Missouri are managed by the Missouri Department of Conservation (MDC) using a variety of harvest methods. Both clearcutting (CC) and single-tree selection (STS) harvesting are utilized to achieve a variety of management goals for ecosystem diversity, wildlife, sustainability and quality timber. The Missouri Ozark Forest Ecosystem Project (MOFEP) was established to research how current MDC management guidelines are affecting various ecosystem traits and sustainability. This study indicates the different harvest used for forest regeneration is having an effect on nutrients in the surface soil. Ten years after harvest, soil samples were collected from 0- to-30 cm in each harvest type at MOFEP (CC, STS, and no-harvest removal sites) using a paired sampling approach (i.e., samples were collected in treated and nearby non-treated locations). This paired sampling revealed soil nutrients may be decreasing at STS sites and increasing at CC sites compared to their paired controls. However, soil properties and nutrients are so variable at MOFEP that sample pairs of neither harvest method are statistically different from sample pairs in entirely no-harvest MOFEP sites. This could change if forest rotations are shortened or greater amounts of biomass are removed in each harvest event.

VITA

Meredith Albers grew up immersed in natural resources while camping, hiking and floating on family vacations in southeast Missouri. Her interest and aptitude in science lead her to earn a Bachelor of Science in Biological Sciences with minors in Forestry and Soil Science from the University of Missouri. While undergraduate coursework and research experience was heavy in molecular biology and biochemistry, her experiences on the MU Collegiate Soil Judging Team enlightened her to pursue a career in Soil Science. As a master's student at MU, she was able to continue as Assistant and Co-coach of the Collegiate Soil Judging Team while volunteering for various educational and outreach activities related to soil education. Her enjoyment of traveling, being in the field learning about new ecosystems and working with diverse people has led her to leave academia after completion of her Master of Science degree in Soil, Environmental and Atmospheric Science. After graduation she will be employed with the United States Department of Agriculture's Natural Resource Conservation Service as a Soil Scientist in Fairfield, Iowa.