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The Effects of Logging, Fire and Blowdown on Colorado Subalpine Forest Soil

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The Effects of Logging, Fire and Blowdown on Colorado Subalpine Forest Soil

By

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B.A., Rochester Institute of Technology 2005

A thesis submitted to the Faculty of the Graduate School of the University of Colorado in partial fulfillment of the requirement for the degree of Masters of Arts Department of Ecology and Evolutionary Biology

University of Colorado, Boulder

2009
This thesis entitled:

The Effects of Logging, Fire and Blowdown on Colorado Subalpine Forest Soil

Written by Kendra Morliengo-Bredlau
Has been approved for the Department of Ecology and Evolutionary Biology

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Date

The final copy of this thesis has been examined by the signatories, and we find that both the content and the form meet acceptable presentation standards of scholarly work in the above mentioned discipline.
Disturbance ecology is a growing field within ecology, and while studies of individual and discrete disturbances are increasing in number, there is a paucity of studies on the ecological effects of disturbance interactions. The goal of this project was to analyze how fire, blowdown and logging affect nitrogen cycling and other critical soil properties both independently and when they occur in rapid succession. The study site was located in the Routt National Forest where the forest sustained the largest windthrow ever recorded in the Southern Rocky Mountains in 1997. Of the 10,000 hectares affected by the blowdown, 935 were subsequently salvaged logged from 1998-2001. In 2002, portions of the intact, logged and blowdown were burned by the Hinman fire leaving a matrix of both individually and multiply disturbed sites. From 2005-2009 soil samples were acquired from intact, burned, blowdown, logged, burned logged, and burned blowdown and analyzed for available ammonium and nitrate; nitrification and mineralization potential; total extractable phosphorous; and percent calcium, potassium and magnesium. Multiple analysis of variance was used to evaluate how the different disturbance combinations affected the soil properties evaluated in this study. The main effects of blowdown and logging disturbances showed that the treatment type significantly affected the soil’s total phosphorous, ammonification potential and available nitrate. Evaluation of the effects of burned versus non-burned sites showed that burning significantly affected total extractable phosphorous, bulk density, soil organic matter content, available nitrate and ammonium, and C, N, Ca and Mg content.
Analyzing the interaction of the main effects of treatment and burning demonstrated that disturbance interactions do not have a synergistic effect in degrading soil properties. Instead, the reduction of fuel in the logged plots appeared to lower the fire intensity and preserved many soil properties to levels found in the undisturbed sample plots. Continued studies on the effect of disturbance interactions are critical for providing managers with the appropriate tools to manage forest landscapes after disturbances.
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Introduction

The burgeoning field of disturbance ecology is relatively new as compared to other related earth science fields. The iconic definition of disturbance was only put forth slightly over three decades ago by Pickett and White who described disturbance as “any relatively discrete event in time that disrupts ecosystem, community, or population structure and changes resource, substrate availability, or the physical environment” (Pickett and White 1985). The commonly accepted definition of the field of ecology was proposed only fourteen years prior by Odum as “the study of the structure and function of nature” (Odum 1971). Collectively, these definitions describe a field which seeks to address the impacts of natural and anthropogenic environmental alterations on ecosystem form and function.

The forests of the Colorado Rocky Mountains play host to a wide variety of anthropogenic and natural disturbances such as windthrow, beetle outbreaks, salvage logging efforts, and fire. The effects of these individual disturbances on forest stand structure (Stahelin 1943; Ehile and Baker 2003; Kulakowski and Veblen 2006; Veblen and Donnegen 2006) and soil properties (Hart, DeByle et al. 1981; Bormann, Spaltenstein et al. 1995; Foster, Aber et al. 1997) have been well documented; however, the effects of these disturbances when they occur in rapid succession is comparatively unknown. The importance of understanding the potentially synergistic effects of compounded, discrete disturbances has been emphasized in disturbance ecology literature (Paine, Tegner et al. 1998; Scheffer, Carpenter et al. 2001), yet very little research has been done to document the effects that compounded disturbances can have on a landscape. The small body of literature which does examine compounded forest disturbances has shown that, beyond delayed conifer regeneration (Donato, Fontaine et
al. 2006), entire ecosystem shifts are possible (Paine, Tegner et al. 1998; Payette and Delwaide 2003). The goal of this research is to evaluate how blowdown, fire and logging disturbance affect soil properties when they occur individually and in suite in a Colorado sub-alpine forest.

At the scale of the forest stand, blowdowns are typically more heterogeneous than those of fire and logging due to their highly patchy nature. Most fires rarely create more than a few patches in the affected landscape, whereas a large blowdown can create hundreds of individual patches of varying severity, as shown in the 2002 blowdown in the Routt National Forest (Colorado, USA) (Lindemann and Baker 2001). Within affected patches, blowdowns can cause significant alterations to understory vegetation and soils through dramatic redistribution of biomass and disruption of soil (Cooper-Ellis, Foster et al. 1999), however, these changes appear to be short lived (Rumbaitis-del Rio 2004). Seedling studies in the Routt N.F. also suggested that affected stands would eventually return to a composition similar to that which existed prior to the blowdown (Rumbaitis-del Rio 2004). A related study in the Harvard Forest LTER (Massachusetts, USA) was designed to test whether a 1938 hurricane or the salvage logging effort that followed was responsible for the significant changes in recovering stand structure. Researchers created an artificial blowdown and demonstrated that while there was significant stand structure reorganization, compositional shifts were minimal. Further, the soil environment showed negligible changes as well; reorganization of the aboveground biomass did not translate into alterations of important biogeochemical processes. Nitrogen mineralization and soil emissions of CO$_2$ and methane all remained unchanged after the experimental blowdown (Foster, Aber et al. 1997). Researchers concluded that the evident shift in forest structure after the hurricane was due to the
modification of the landscape during salvage logging efforts that drastically altered the soil environment and prevented the rapid recovery of vegetation which was observed in the experimental blowdown (Foster, Aber et al. 1997). Collectively, these studies suggest that blowdowns do not have long term effects on stand composition or on soil nutrient cycling.

Salvage logging is a common management technique employed to recoup economic losses, reduce fuel loads, control insects, improve seed beds and ameliorate the appearance of disturbed forests (Hart, DeByle et al. 1981; Gorte 1996; Cooper-Ellis, Foster et al. 1999). However, implementation of salvage logging after a blowdown can cause dramatic alterations to biotic controls and lead to alternative successional trajectories. Research completed on the effects of salvage logging in the 1997 Routt N.F. blowdown demonstrated that post-blowdown salvage logging significantly changed structural, physical and chemical properties that existed after the blowdown (Rumbaitis-del Rio 2006). Salvage logging the blowdown caused increased soil compaction, decreased N stocks and reduced the soil organic horizon. Further, there was significant alteration to understory composition of the recovering forest; instead of secondary succession dominated by seedlings which existed under the canopy of the forest, logging stands were dominated by grasses (Rumbaitis-del Rio 2006). Another study completed in the salvage logged sections of forest burned by the 2002 Biscuit Fire (Oregon, USA) documented a 71% decrease in seedling regeneration in logged tracts as compared to non-logged sections. The decrease was attributed to the soil disturbance associated with the logging operation and through physical burial of seedlings by woody debris (Donato, Fontaine et al. 2006). As shown in the Routt N.F. disturbance study, salvage logging can be particularly damaging to biogeochemical processes, especially that of nitrogen cycling.
Nutrient retention and the creation of nutrient pools within an ecosystem are strongly linked to the amount of existing aboveground biomass and are also related to the amount of soil organic matter (Vitousek and Reiners 1975; Aber, Nadelhoffer et al. 1989; Goodale, Aber et al. 2000). Dead and downed logs present in forests after a disturbance can serve as a sink for N through the uptake of soil N by wood-rotting fungi. Provided these harbored nutrients are released in time with the revegetation of a disturbed forest, there should be minimal losses of N from the disturbed site (Vitousek and Melillo 1979; Vitousek and Matson 1985). However, these nutrient storage pools in aboveground biomass are extremely vulnerable to severe losses in the event of salvage logging (Likens, Bormann et al. 1970). In coniferous forests, where a majority of nutrients are stored in aboveground biomass (Boerner 1982), the removal of aboveground biomass not only leads to net N loss, but reduces the ability of the system to retain N which becomes available after disturbance. While both fire and logging are disturbances which significantly decrease carbon stocks in affected forests, C losses through logging are often greater than C losses from a fire (Johnson, Murphy et al. 2005).

Ecologists’ view of the role of fire in ecosystems is no longer that of a pervasive disturbance (Clements 1916), but as an important part of the dynamics of forest ecosystem form and function (Boerner 1982). As fire intensity and frequency have increased over the past decade due to recent climate change (Westerling, Hidalgo et al. 2006), attention is directed at the effects of severe, stand-replacing fires on biogeochemical processes, as most prior research focused on low severity and/or prescribed burns (Turner, Smithwick et al. 2007). Since nitrogen is commonly accepted as the most limiting nutrient in young terrestrial soils and is rapidly lost through
volatilization during fire (Johnson, Murphy et al. 2005; Turner, Smithwick et al. 2007),
there have been many recent studies which focus on fire’s effect on N cycling. Nitrogen
loss can be detrimental to a recovering forest as it can decrease post-disturbance soil
fertility and negatively impact the litter quality of initial regrowth (Wilson, Mitchell et al.
2002). Nonetheless, recent publications have had mixed results regarding the impact of
fire on N cycling (Wilson, Mitchell et al. 2002; Smithwick, Turner et al. 2005; Turner,
Smithwick et al. 2007). Theories regarding fire’s ability to sterilize soils, or act as an
ecological “re-set” mechanism, have recently also come under criticism. Severe fires
have been associated with being able to homogenize a post-disturbance landscape,
ecologically “setting the clock back”. However, recent research has called that
assumption into question; a decade after the 1988 Yellowstone (Wyoming, USA) fires,
sites which had initially been subject to the most intense pockets of fire are showing
significant conifer regeneration (Baskin 1999), not reflecting the sterile, seedless soils
which were expected. Yellowstone soils affected by high severity fires also show high
variability in ammonification rates, likely resulting from heterogeneity in residual soil
organic matter (Turner, Smithwick et al. 2007). Interestingly, research completed in the
Routt N.F. in the first year following the large, stand-replacing “Hinman” fire showed
that pre-fire disturbances of blowdown and logging had minor effects on post-fire soil
properties and N cycling (Rumbaitis-del Rio 2004). The results of that study also
contradicted the commonly held assumption that mineralization rates increase after fire
and other disturbances (Vitousek 1979; Vitousek and Melillo 1979; Aber, Nadelhoffer et
al. 1989; Wan, Hui et al. 2001). Though the research supports that the fire appeared to
“erase” the previous disturbances, Rumbaitis-del Rio cautioned that this may not be
supported in later years of succession (Rumbaitis-del Rio 2004). This evident
homogenization after the fire was surprising as there is a large body of literature suggesting that previous disturbances can influence later seral stages (Turner 1989; Everham III and Brokaw 1996; Franklin, Spies et al. 2002).

Although the effects of disturbances that occur in rapid succession may be a frontier for future disturbance ecology research, ecologists and foresters have long appreciated the impact that less frequent disturbances can have on recovering stand structure and composition (Franklin, Spies et al. 2002; Kulakowski and Veblen 2002). Understanding how biological legacies influence later successional pathways has been touted as critical for developing silvicultural techniques which maximize economic gains while minimizing the impact on managed forest stands (Franklin, Spies et al. 2002). It has been argued that even high intensity disturbances rarely erase all previous structural remnants of the affected forests, and these are paramount for future reorganization. Both fires and blowdown increase the amount of snags and downed logs in the post-disturbance landscape, whereas salvage logging dramatically differs in the types, levels and patterns of the post-disturbance structural legacy. No overstory trees remain and there is a large decrease in coarse woody debris (Franklin, Spies et al. 2002). Beyond the influence of biological legacies on physical stand structure, research is emerging on the impacts of various disturbances on forest biogeochemical processes (Vitousek 1979; Vitousek and Melillo 1979; Smith, Coyea et al. 2000), however results vary widely. The study of a disturbance’s influence on ecosystem processes is challenging, especially when separating the impacts between stand structure dynamics and biogeochemical processes. A study by Smith et al. (2000) in a Canadian black spruce forest suggested that the differences between the immediate biogeochemical impacts of low impact logging and naturally occurring wildfires become negligible after a decade has passed (Smith, Coyea
et al. 2000). This observation supports the concept of anthropogenic emulation of natural disturbance through logging; however studies of high-impact logging following disturbance have demonstrated the potential to dramatically alter forest recovery (Hart, DeByle et al. 1981; Donato, Fontaine et al. 2006).

The aim of this project was to focus on fundamental questions in compound disturbance ecology that are relatively unaddressed or poorly understood by further studying the recovering soil properties in the multiply disturbed Routt National Forest (Colorado, USA). The disturbances present in the Routt N.F. study site are presented in Figure 1.

**Fig 1: Disturbance combinations present in the Routt N.F. Study**

The research goals for this current Routt N.F. investigation further a study completed in 2004 on the effect of blowdown and logging on various soil properties and regeneration composition. In the last year of the study, the 2002 Hinman fire burned portions of the logged and blowdown stands. Initial post fire data were collected on various aspects of N cycling, providing an important baseline for the immediate soil
response of the affected stands. The study concluded that, while blowdown sites still tightly controlled key biotic processes 5 years after the disturbance, fire appeared to homogenize the soil across sites with recent disturbance history. This current Routt N.F. study follows up on some of the critical questions addressed in that initial study: 1) **what are the effects of individual disturbances on soil properties, and 2) how does fire interact with logging and blowdown disturbances?** The goal of this project was to address the hypothesis that sites affected by compounded disturbances (blowdown, windthrow and logging) will show more highly degraded soils than sites affected by singular disturbances due to the additive effects of each individual disturbance. Although these questions are similar to the goals of the original study, it is important to readdress them as this current study was initiated 5 years after the fire and a decade after the first disturbance, the 1997 blowdown. Panarchy theory suggests that during the renewal stage of the adaptive cycle there is continual and rapid reorganization of resources (α stage) which lead to the more stable state of growth and exploitation (r stage) (Holling, Gunderson et al. 2002). The original study occurred within 5 years of the blowdown, and immediately after the fire; therefore the conclusions drawn from that time period may not reflect what is occurring as reorganization continues years later. Furthermore, this soil-centric study expands upon the data collected in the original study by including soil mineralization and nitrification potentials; available ammonium and nitrate, total phosphorous and analyses of other important cations (Ca⁺, Mg⁺, K⁺). Inclusion of these data, along with follow-up of some of the analyses performed in the original study will give a better sense of how these soils have changed since the original study during the α stage and provide a multi-faceted biogeochemical summary for continued research.
The goals of this research serve to not only fill gaps in understanding regarding the effects of compounded disturbance on soil properties, but may also serve to guide future management decisions. Understanding the biogeochemical and abiotic soil response of a forest after combinations of disturbances is of the utmost importance for managers who are charged with the conflicting goals of recovering economic losses while protecting forest health after a landscape scale disturbance. One of the more important management issues this project addresses is the potential effects of salvage logging on nitrogen cycling in a forest with a documented history of high intensity wildfires (Veblen and Donnegen 2006). Due to the harsh environment found at higher elevations, Colorado sub-alpine forests may be less resilient as compared to other forest types, such as in mixed deciduous forests. Therefore, they are an excellent study system to understand the effects of compounded disturbance; effects that may be less clear and muted by the greater resilience of more temperate ecosystems. With this in mind, there is a potential for the implications of this research to influence management decisions in other ecosystems beyond the Colorado subalpine. By investigating which processes are causing such dramatic differences in recovery patterns in the disturbances in Routt National Forest, this research may provide land managers with a variety of tools to help lessen the impact of their post disturbance management plans and also assist with the remediation of disturbance affected landscapes.

Methods

Study site

The study site is located within the Routt-Medicine Bow National Forest in Colorado. The forest is dominated by subalpine fir (*Abies lasiocarpa*), Englemann spruce
(Picea englemannii), lodgepole pine (Pinus contorta) and quaking aspen (Populus tremuloides Michx.). The soils are classified as loamy skeletal typic Cryochrepts and typic Dystrochrepts (Service 1999) and are derived from Precambrian granites, gneiss and glacial deposits (Snyder, Patten et al. 1987). The continental climate has a mean annual temperature of 3.8˚C, ranging from -9.5˚C in January and 16.6˚C in July (Center 2008). Mean annual precipitation is 60.9 cm (Center 2008) in the form of summer monsoons and winter snow pack.

On October 25, 1997, the forest sustained the largest windthrow ever recorded in the Southern Rocky Mountain region (Wesley, Poulos et al. 1998). The blowdown affected approximately 10,000 hectares (ha) of the forest, resulting in over 400 patches of downed trees ranging from <1ha to 310 ha with a mean patch size of 25 ha (Lindemann and Baker 2001). From 1998-2001, the U.S. Forest Service salvage logged 935 ha of selected sections of the blowdown using tractor-cable and helicopter harvesting methods. This combination of disturbance was the focus of a study initiated by Rumbaitis-del Rio in 1997 who documented the disturbance effects on soil biogeochemical properties, understory composition and seedling survival in logged, blowdown and intact forest stands (Rumbaitis-del Rio 2004). In 2002, lightning ignited the Mt. Zirkel Complex fire (consisting of the Burn Ridge and Hinman fires) which swept through the Routt N.F., affecting a total of 12,500 ha of forest. While the fire primarily burned the stands previously affected by the blowdown, it also burned sections of the salvage logging sites, despite significant fuel reduction efforts (Rumbaitis-del Rio 2004). The fire occurred in the final year of Dr. Rumbaitis-del Rio’s study, which provided important baseline data on the immediate effects of fire combined with the prior disturbances. This series of both natural and anthropogenic effects occurring on a
landscape in such a short period (five years) defines the concept of compounded disturbances as it relates to this study. Following the fire, the following combination of individual and compounded disturbances existed: burn, blowdown, logged blowdown, burned blowdown, and burned logged blowdown.

In 2006, a study was initiated to examine the different effects that these singular and compounded disturbances had on various soil properties and on critical aspects of nitrogen cycling. Three 15m by 15m plots were established in each of the five disturbance types, along with three plots in undisturbed forest stands (n=18). All plots were selected to minimize the amount of variation introduced by each disturbance. After the Hinman fire, the U.S. Forest Service documented the spatial heterogeneity of the fire severity, which we utilized to select plots that fell within the most severe burn category. Additionally, we utilized Forest Service mapping of blowdown severity to select the blowdown plots that fell within the most severe category of blowdown (90-100% of the trees were down). While the Forest Service used a combination of methods to perform the salvage logging effort, plots selected for this study were harvested only by tractor and cable. This method was the most common method of harvest as it was used on 75% of the salvaged logged areas (Service 1999). Additionally, all plots were selected to minimize differences in slope, aspect, and elevation as much as possible.

Soil Property Analysis

In June 2007, five soil cores in each plot (n=90) were collected to a depth of 10cm. The duff layer was not included in the sample; the top of the core started at a distinguishable A horizon. Sampling was randomized by pacing out to pre-selected grid coordinates generated by a random number table. Samples were transported back to the
University of Colorado at Boulder in ziplock bags, sieved in a 2mm sieve, weighed, dried for 16hrs at 105°C, then reweighed. Soil cores were analyzed for bulk density, soil organic matter (SOM), and texture. Bulk density was calculated after drying field moist samples in a drying oven at 100°C for 24hours. SOM was calculated using subsamples of the dried bulk density soil. Ten gram subsamples of soil were placed into crucibles which had been in a 105°C oven for 1 hr prior to soil addition, and then placed in a drying oven for 8hrs at 105°C. The crucibles were transferred into a muffle furnace at 600°C for 8hrs. SOM was calculated by mass lost by ignition. Texture was calculated using the ashed SOM samples following the Boyoucous method (Boyoucous 1936). All within-plot samples were combined, and texture analyses were completed for each site (n=18). pH values were acquired using field moist soils from a July 2007 sampling trip, obtained in the identical manner as the June sampling (n=90). Soil slurries were made from a 2:1 deionoized water to soil ratio and measured using a Accumet AP62 pH/mV meter (Fisher Scientific).

Percent elemental carbon and nitrogen were analyzed using an Edger 1108 CHN Elemental Analyzer. Five 10cm soil cores were collected in each plot (n=90) in August 2007, sieved in a 2mm sieve, dried at 105°C for 18hrs and ground using a rock mill (Cianflone Scientific Instruments Corp.) for three minutes prior to processing.

Total extractable forms of phosphorous were analyzed using a modified version of Bray’s acid fluoride extraction (Bray and Kurtz 1945). In July 2008, four soil samples were collected in each of the plots (n=72) to a depth of 10cm. Soils were kept on ice and transported back to the lab where they were sieved in a 2mm sieve and extracted within 48hrs of collection. Extraction was completed by placing a 10g subsample in a bottle to which 50mL of Bray’s extraction solution was added. Samples were shaken
vigorously for three minutes and allowed to settle for 57 min, for a total of 1 hr. Concurrently, another 10g sub sample was extracted with 100ml 1M ammonium acetate as described by Robertson et al. (Robertson, Sollins et al. 1999) and analyzed for K, Mg and Ca. Phosphorus samples were filtered using Fisher brand Q2 filters and the ammonium acetate extraction was filtered using Whatman GF/A glass filters. Both extracts were analyzed at Colorado State University’s Soils Lab (Fort Collins, CO) using a flow injection autoanalyzer (Flow Solution 3000, OI Analytical). A separate 10g subsample was weighed and dried at 105°C for 18 hrs to calculate the moisture content of the soils and used to adjust the reported values from CSU. All values are reported in Appendix 1 and graphically represented in Appendix 2.

**Nitrogen Cycling Dynamics**

Soil cores for nitrogen mineralization and nitrification potential were collected to a depth of 10 cm in June 2008. Four samples were randomly obtained in each plot (n=72) by pacing out to coordinates generated from a random number table. The samples were kept at approximately 10°C during collection and transported back to Boulder where they were processed within 48 hrs of collection. All soil was sieved using a 2mm sieve prior to extraction. Ten gram sub-samples were immediately extracted with 100ml 2M KCl to determine initial ammonium and nitrate concentrations. Reported values were adjusted for background ammonium and nitrate in the KCl extract and adjusted for moisture content using a separate 10g sub-sample which was dried at 105°C for 16 hrs. Two more 10g sub-samples were placed in specimen containers and incubated in a dark, controlled temperature chamber for 28 days at 25°C. Incubated soils were kept at initial field moist conditions by periodic deionized water additions.
every 2-3 days. After 28 days, one incubated sample was extracted using 100ml of 2M KCl and the other was dried at 105°C to measure moisture content of the incubated samples which were used to adjust the reported ammonium and nitrate values. All extractions were gravity filtered using Fisher brand Q2 filters and frozen until analyzed at Colorado State University’s Soils Lab (Fort Collins, CO) using a flow injection autoanalyzer (Flow Solution 3000, OI Analytical). Mineralization and nitrification rates were calculated by subtracting the initial soil ammonium and nitrate concentrations from the incubated concentration and adjusted for moisture content.

Resin bags were used to establish the relative availability of ammonium and nitrate in each site using a modification of the method described by Binkley and Matson (Binkley and Matson 1983). Bags were constructed using commercial grade nylon filled with approximately 5g of mixed bed exchange resin and tied off with zip ties. Constructed bags were soaked for 20min in 2M NaCl and washed thoroughly with deionized water. The resin bags were placed in the field in late June 2008 and collected in early September 2008. Ten bags were placed in each of the plots (n=180) by removing a small, diagonal soil core at a depth of 10cm, placing the bag at the base of the hole and replacing the soil core. At the end of the season, the bags were collected and extracted with 50ml 2M KCl. Extracts were gravity filtered using Whatman 40 filters and frozen until analyzed at Colorado State University’s Soils Lab (Fort Collins, CO) using a flow injection autoanalyzer (Flow Solution 3000, OI Analytical). Results were adjusted for background ammonium and nitrate in the KCl extract and were also adjusted for the 28 days in the field. All values are reported in Appendix 1 and graphically represented in Appendix 2.
Statistical Analysis

Analyses were completed by combining all data points from the three plots within each disturbance. Raw data were natural log-transformed prior to analysis. Factorial multivariate analysis of variance (MANOVA) was used to analyze for differences in pH, bulk density, % soil organic matter (SOM), %C, %N, C:N ratio, ammonification potential, available nitrate and ammonium, phosphorous, magnesium, calcium and potassium in the top 10cm of soil in each disturbance. To examine the impact of disturbance on a range of soil properties, the parameters were divided into two groups prior to MANOVA evaluation. “Soil properties” refers to the grouping of the relatively static soil properties that were studied, specifically excluding those parameters associated with faster N cycling. These included pH, bulk density, % SOM, % C, percent N, P, K, Mg and Ca. The variables incorporated into the MANOVA for addressing differences in nitrogen cycling dynamics were the available ammonium and nitrate data from the resin bags and ammonification potential data from the 28-day incubation. The incubation did not demonstrate any nitrification potential, which may be in part due to the early season in which the soils were collected. Additionally, initial ammonium and nitrate extraction values which were collected at the onset of the incubation were not used in the MANOVA analysis because the resin bags were left in for a full season and are a more accurate indicator of seasonal nitrogen cycling dynamics. The data were analyzed to evaluate the significance of “treatment effects” (defined as the pre-burn conditions present: blowdown, logged and intact) and “burn effect” on selected soil parameters. In addition to these two main effects, interaction effects were also analyzed to evaluate whether burning affected each disturbance similarly. If significant differences were
found, the Tukey-Kramer HSD post hoc test was used to evaluate differences ($\alpha=0.05$).

All data were analyzed using JMP IN 5.1.2 (SAS 2004) and Statistica (StatSoft 2005).

**Results**

**Soil Properties**

There was a significant main effect by the type of pre-fire disturbance, from here on referred to as “treatment”, (Wilks lambda $= 0.47$, $F_{18,108}=2.79$, $p<0.001$) as a result of the blowdown treatments having significantly lower amounts of total extractable phosphorous than the intact ($p=0.01$) and logged ($p=0.001$) treatments by 55% and 64% respectively. Burned sites were significantly different than unburned sites (Wilks lambda $= 0.49$, $F_{9,54}=6.23$, $p<0.001$) driven primarily by decreases in %SOM ($F=19.83$, $p<0.001$), %C ($F=18.98$, $p<0.001$) and %Ca ($F=12.63$, $p<0.001$) of 35%, 37% and 45% respectively. Burning contributed to a 148% increase in total phosphorus ($F=18.05$, $p<0.001$) and a 21% increase in bulk density ($F=7.89$, $p=0.006$). Burning had a relatively uniform effect on soil properties, regardless of previous disturbance (Burn by treatment interaction: Wilks lambda $= 0.47$, $F_{18,108}=2.73$, $p<0.001$), with notable interaction effects caused by a significant decrease of %SOM ($F=19.83$) in the burned intact forest and the burned blowdown as compared to the other four treatments. SOM content in the burned intact and the burned blowdown was close to half (46% and 48% respectively, see Appendix A for means and standard errors of all soil properties) of what was recorded in the burned logged ($p=0.052$ and $p=0.047$ respectively).

**Nitrogen Cycling Dynamics**

Treatment had a significant effect on the ammonification potential and available nitrate (Wilks lambda $= 0.56$, $F_{6,28}=7.24$, $p<0.001$). Available nitrate contributed the
most to the treatment effect ($F=11.54$) with significantly higher levels found in the logged treatments as compared to intact ($p<0.001$) and blowdown ($p=0.003$) by 10% and 7% respectively. The blowdown treatments had the lowest capacity for ammonification of all three treatments studied, 27% lower than the logged treatments ($p=0.001$) and 14% lower than the intact soils. Burned sites significantly differed from unburned sites ($F_{3,64}=10.89$, $p<0.001$) with 12% decrease in available ammonium ($F=7.74$, $p=0.007$) and 8% decrease in nitrate ($F=23.87$, $p<0.001$) after burning. There was no significant interaction between burning and treatment.

Discussion

*Individual Disturbance Effects: Blowdown, Logging and Fire*

The purpose of this study is to understand the effects of single and compounded disturbances on soil properties, with an expectation that the disturbances which occur in rapid succession would result in the most highly degraded soils. We anticipated variations in recovering soil properties between treatments due to the different effects that each type of disturbance have on a landscape. Landscapes affected by blowdowns show the greatest resilience and have been shown to maintain tight control over many biogeochemical cycling processes (Foster, Aber et al. 1997; Cooper-Ellis, Foster et al. 1999; Rumbaitis-del Rio 2004). Burned soils are typically characterized by having decreased organic matter, loss of N through volatilization, loss of other cations (P, K, Ca) through convection of ash (Boerner 1982), and it can be assumed that bulk density in the top soil horizons should increase with the combustion of lighter weight SOM content. Although burning can cause a sharp reduction in the C and N content of soils, studies have shown that post-burn soils have lower C:N ratios as compared to
undisturbed forests (Gonzalez-Perez, Gonzalez-Vila et al. 2004). Post-logging soils have shown high levels of available N in soil solution immediately after logging (Hart, DeByle et al. 1981), but this pulse may be short-lived as nitrate can be quickly lost from a landscape if there is minimal plant uptake (Parsons, Knight et al. 1994) or microbial immobilization (Vitousek and Matson 1985). Although logging can substantially decrease the natural O horizon, woody debris incorporated into the soil may contribute to a restocking of lost SOM and soil C content (Donato, Fontaine et al. 2006).

The expectation of variation between treatments was only partly fulfilled; out of all the variables addressed in this study only total phosphorous, ammonification potential, and available nitrate showed any treatment effects. Of these three variables, the blowdown showed the lowest capacity for ammonification (even in the presence of a considerable amount of SOM), the lowest amounts of total phosphorous, and low amounts of nitrate. However, aside from total phosphorous which was significantly lower than what was found in the logged and burned treatments, the blowdown treatments didn’t display any significant differences in the soil properties variables when compared to the intact treatment. One of the important characteristics separating the blowdown from the burn and logging is the retention of aboveground vegetation and associated live root networks. Landscape scale disturbances that result in the extensive loss of vegetative cover cause marked changes in nutrient cycling that range from accelerated nutrient cycling in soils (Vitousek and Melillo 1979) to high potential losses of nutrients through leaching (Vitousek and Reiners 1975) and erosion in some settings. However, in other experiments, and notably in simulated hurricane disturbance at Harvard Forest, nutrient losses are relatively unaffected by disturbances which retain aboveground vegetation, suggesting that some systems retain the capacity for nutrient
retention despite reduced rates of net primary productivity and alterations to stand structure and composition following disturbance. Our results follow this pattern with limited evidence that there is potential for nutrient loss increases following the blowdown disturbance. The mechanism of conservation of these biogeochemical cycling processes may be partly attributed to the preservation of intact root networks and above ground vegetation similar to what is found in an undisturbed forest. The importance of this mechanism is best displayed through understanding how their loss affected nitrogen cycling processes in the logged stands.

Initially, logging resulted in considerable losses of surface soil horizons along with increases in bulk density (Rumbaitis-del Rio 2004); however, despite these obvious changes to the landscape structure, most of the soil properties measured in this later study were relatively unaffected by logging. Furthermore, the initial differences in bulk density and SOM were apparently ameliorated over the five-year recovery time, as there were no significant differences found in this study. We had expected to see evidence of reduced nitrogen cycling in these sites due to the removal of the organic horizon and increase in the amount of recalcitrant fine woody debris (Rumbaitis-del Rio 2004). Instead, the logged treatments had significantly greater available nitrate than the blowdown or intact treatment, and had the highest ammonification potential as well; significantly greater than what was found in the blowdown treatment. The explanation for the considerable amount of nitrogen cycling present in the logged soils, in the absence of an O layer, may be partly due to the reincorporation of woody debris into the soil during the logging process. Similar results were found in a Northern Rocky Mountain logging study which suggested high nitrate levels found six years after a skid-logging operation on lodgepole pine were a result of increased soil temperatures and
rapidly decomposing fine woody debris which had been incorporated into the soil, accelerating nitrification and moving nitrate readily into soil solution (Hart, DeByle et al. 1981). Because there was no significant difference in the %SOM in any of the treatments, the spike in available nitrate may be driven primarily by increased soil temperature in these plots (Wessman, unpublished data). Increased temperature has been shown to be significantly related to nitrogen mineralization in a variety of forest types (Reich, Grigal et al. 1997; Wilson, Mitchell et al. 2002; Hart, DeLuca et al. 2005; Yermakov and Rothestein 2006).

Along with increased soil temperatures in the logged treatments, the reduction in live root networks may also have contributed to the noted alterations in nitrogen cycling. The prominent spike in available nitrate could be explained by decreased plant uptake, as logging sites had the lowest amount of plant cover of all the treatments (personal observation), so available nitrate would be more likely to be adsorbed by resin bags since there is no competition with other plant roots. Plant roots can dramatically alter the amount of available nitrate, as demonstrated by Parsons et al. (1994) who showed significantly lower nitrate concentrations in lodgepole pine forests which had been thinned (40% removal) as compared to stands which had been clear cut (Parsons, Knight et al. 1994). This explanation is further supported by research completed by Likens et al. in the Hubbard Brook Experimental Forest which showed increased stream nitrate after a clear cut was subsequently treated with herbicide (Likens, Bormann et al. 1970). Vitousek and Matson (1985) conducted a comparable study in a loblolly pine plantation and reported similar results after clear cutting and herbicide treatment (Vitousek and Matson 1985). The logging site did not significantly differ in available ammonium from either the intact forest or blowdown site, suggesting that most available
ammonium was rapidly converted to nitrate, as plant uptake would be minimal in these relatively bare plots. Overall, the lack of vegetation and live root networks in the logged plots, combined with increased soil temperatures, may explain the high ammonification potential and high available nitrate content. Interestingly, these results directly counter contentions that high soil C:N ratios should exert a negative control on mineralization (Booth, Stark et al. 2005), as the logging sites had a significantly higher C:N content and ammonification potential than the other two treatments.

Analysis of the burned treatments supported our expectations of the effects of high severity fires on soil properties. Burning increased bulk density and total extractable phosphorous, and decreased SOM, C content, N content, Ca and Mg. These types of losses are common in burned forested ecosystems and support that we selected sites which fell within a high severity fire classification. Nitrogen volatilizes at a relatively low temperature (~200°C) whereas the volatilization of other important cations such as phosphorous, potassium and calcium occurs when temperatures are higher (>500°C) (Boerner 1982). While losses of SOM are expected in fires of any intensity, losses of organic C are indicative of high severity fires (Gonzalez-Perez, Gonzalez-Vila et al. 2004). The reported loss of C, Ca and Mg suggest that the fire in the burned sites was relatively intense, and support that the burned areas were within a high severity burn zone. These losses, either through volatilization or ash convection, can be particularly damaging for prompt vegetative recovery, as a majority of nutrients stored in pine forests are aboveground (Boerner 1982), leaving the soils nutrient poor and possibly hindering vegetative recovery. Five years after the fire, decreased amounts of available nitrate and ammonium are still apparent. The burn sites have significantly lower concentrations of these nutrients; notably, there is no difference in ammonification
potential between burned and unburned sites. This suggests that the microbial population in the burned sites has rebounded, but the nitrate and ammonium released by the population is either being immobilized or quickly taken up by emerging vegetation. Consistent with many other post-fire soil studies (see review by Gonzalez-Perez 2004), the C:N ratio in the burned sites was lower than unburned sites. One possible explanation is that the litter from herbaceous plants which commonly recolonize post-fire landscapes has a lower C:N ratio than the litter of unburned pine forests which dominates mature, unburned forest soils (Hart, DeLuca et al. 2005). This incorporation of nutrient rich litter evidently has lowered the C:N ratio in the burned soils in this study and, five years later, the burned soils are showing a considerable rebound in soil N content but are still lagging in incorporation of C. Soil N content in burned sites is 82% of what is present in unburned sites, while soil C in burned sites is 63% of what is present in unburned sites. Similar to what was seen in the logged treatments, burning resulted in a significant change in the C:N ratio of the soils, however there was no significant change in rates of N mineralization.

The effect of fire severity on soil is an important question, as high severity fires have been likened to a biological reset mechanism (Hart, DeLuca et al. 2005) associated with the ability to sterilize soils (Baskin 1999). Initially, it was the conclusion of the first Routt study that the severe fire “erased” the effects of the previous disturbances (Rumbaitis-del Rio 2004). Beyond looking at the trajectory of these sites five years after the burn, the importance of selecting high severity burned treatments in this study was three-fold: 1) differences in fire intensity can dramatically affect post-burn soil properties (Gonzalez-Perez, Gonzalez-Vila et al. 2004; Hart, DeLuca et al. 2005; Turner, Smithwick et al. 2007) 2) intense fires are characteristic of the historical burn regime of this
subalpine forest (Veblen and Donnegen 2006), and 3) much less is known about the effects of high severity fires on soil properties as a majority of post-burn N studies use low severity fire sites (see review by Smithwick et al. 2005). The results of this study support the results of other studies on the effects of high severity fires on soil properties. Studies on the effects of severe, stand replacing fires do not indicate a “reset” of the biological clock in affected ecosystems; instead there is mounting evidence that nutrient cycling after high severity burns is still quite active. While there are demonstrated losses of many critical nutrients after burning, the warming of the soil due to decreased canopy LAI leads to increased microbial activity (Smithwick, Turner et al. 2005) and can help lead to recover lost N via increased rates of mineralization. In the case of this study, soil N content has rebounded quickly within only 5 years. This may be a response of the increased microbial processing along with detritus contributions of *Epilobium angustifolium*, a high nitrogen uptake species (Brakenhielm and Liu 1998) which was found in a majority of the burned sites (personal observation). This study supports the contention that severe, stand replacing fires do not lead to significant changes in mineralization rates immediately after burning (Smithwick, Turner et al. 2005) and therefore may provide a strong platform for quick initiation of N cycling after burning. This evident resilience is also augmented by studies which demonstrate that coniferous forest in the Northern Rocky Mountains have substantial conservation mechanisms to retain N through microbial immobilization and plant uptake during the early succession after severe fires (Turner, Smithwick et al. 2007).

*Compounded Disturbance Interaction*

The primary goal of this study was to look at how these individual disturbances interact and to evaluate whether or not there were synergistic responses, which may
unexpectedly degrade soil quality to a degree greater than what was seen individually. This study focused on soil properties because they are a critical piece in understanding vegetative recruitment patterns and may serve to forecast the success of revegetation efforts. The initial hypothesis was that the lack of vegetation found in sites subjected to blowdown, logging and wildfire was a result of the synergistic interaction of the individual disturbances severely degrading soil properties. That hypothesis was not supported in the conclusion of this research. Statistical analysis of the interaction between burning and the three treatments did not demonstrate a significant trend of burning dramatically affecting the logged sites preferentially over the intact or blowdown sites. However, the soils of the burned logged sites showed more similarity to the soils of the intact forest than the burned intact or the burned blowdown. The SOM content of the burned logged sites was not significantly different than any of the unburned treatments and was significantly greater than the content in the burned intact and burned blowdown. This may be explained by logging serving to decrease available fuels, and therefore decreasing fire intensity or the duration of the burn in the logged sites as compared to the blowdown and intact stands where there was substantially more fuel. Further support for this hypothesis was the significant decrease in the levels of Ca and Mg in the burned intact and burned blowdown treatments as compared to the other four treatments. While their contribution to the overall interaction effect was small (F=4.62, 5.35 respectively), in combination with SOM results, these results suggest that the fires in the blowdown and intact treatments were more intense since losses of those cations are typically associated with higher intensity fires (Boerner 1982). Of the properties evaluated for interactions in N cycling dynamics, there was no evidence of burning
affecting the logged treatments preferentially over the intact and blowdown treatments, as there was no significant interaction effect.

Conclusions

Disturbance interaction is a relatively understudied field that deserves more attention in an era dominated by increasing desire to manage ecosystems. Forest managers are charged with developing appropriate management plans to aid quick recovery of landscape-level disturbances; however, there is a paucity of research from which to draw from in developing these plans. There are mounting studies which suggest that existing management practices designed to assist in post-fire recovery such as salvage logging, seeding and livestock grazing have contributed to degradation of soil and water quality delaying restoration and directly working against the restoration goals (Beschta, Rhodes et al. 2004; Donato, Fontaine et al. 2006). Continued research designed to understand the how disturbances interact is imperative for developing appropriate management plans.

The unexpected results of this study speak to the resilience of Colorado sub-alpine forests soils to retain nutrients even under multiple disturbance regimes. Optimistically, these results may suggest that manual revegetation efforts to reforest disturbed plots may be successful since it is evident that nitrogen cycling processes and other important base cations are still present, and in some cases, at levels similar to that of undisturbed forests. This research does not condone or condemn the act of salvage logging, it simply serves to reflect that the lack of vegetation in the compounded disturbance sites may not be due to degradation of soil properties due to logging. Implementation of salvage logging is not a decision which is made lightly; there has been
considerable research demonstrating the importance of standing dead and snags for preserving the heterogeneity of forests which is paramount for preserving biodiversity (Franklin, Spies et al. 2002). From a biogeochemical viewpoint, perhaps Colorado subalpine forests are more resilient than previously thought, and have a larger capacity for absorbing the impacts of disturbance. Boreal forest systems subjected to multiple disturbances of fire and harvest show a remarkable ability to regain almost all lost P, N and C within a few decades of disturbance (Smith, Coyea et al. 2000). However, these same forests have been shown to have significant vulnerability to ecosystem shift in the presence of the compounded disturbances of insect infestation, harvesting and fire; a shift that was not attributed to alterations to biogeochemical processes but rather the manual impacts of the harvesting techniques (Payette and Delwaide 2003).

The original question of what is driving differences in vegetation in these sites has become clearer. The initial study completed after the blowdown and logging suggested the reduced species richness, diversity and vegetation cover found in the logged sites was due to the extensive mechanical damage to surviving vegetation (Rumbaitis-del Rio 2006) with noted alterations to some N-cycling processes and soil properties (Rumbaitis-del Rio 2004). Since that study, five years after the last disturbance, many of the soil properties evaluated in this study have begun to reach predisturbance levels. Even the blowdown treatments, which were the most significantly degraded according to the parameters evaluated in this study, show more vegetative cover as compared to the logged treatments. These results suggest that alterations to biogeochemical cycling are not responsible for a shift in the successional trajectory of the burned logged sites. There are many more avenues for research to evaluate the hypotheses put forth in this thesis and in the original research. If, as suggested, the
biogeochemical processes are intact, then manual revegetation efforts should show substantial success in these multiply disturbed sites. A corollary to a manual seeding and survival study would be a seedbed study to evaluate whether the presence or absence of species in the logged sites is due to the lack of a nearby viable seed source. This research served to answer many of the questions posed in the conclusion of the first Routt study and has helped focus future research on disturbance interaction in this subalpine forest. Ultimately, continued research in this site will add to a larger body of research on ecological resilience and may aid in future management decisions on appropriate post-disturbance remediation plans by identifying factors which may hinder vegetative recovery. The continuation of biogeochemical studies in the Routt National Forest will provide an excellent overview of more than a decade of recovery in a multiply disturbed ecosystem; and, in light of the importance of long term ecological research, will contribute to further understanding the biogeochemical changes which occur during the succession of subalpine forests.
References


Appendix 1: All soil parameters evaluated in Routt study. Reported means are \( \pm 1 \) standard error.

<table>
<thead>
<tr>
<th></th>
<th>Control</th>
<th>Control + Burn</th>
<th>Blowdown</th>
<th>Blowdown + Burn</th>
<th>Blowdown + Logging</th>
<th>Blowdown + Logging + Burn</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Bulk Density (g/cm(^3))</strong></td>
<td>1.14 ± 0.08</td>
<td>1.27 ± 0.07</td>
<td>0.99 ± 0.06</td>
<td>1.28 ± 0.05</td>
<td>1.08 ± 0.09</td>
<td>1.18 ± 0.09</td>
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<tr>
<td><strong>pH</strong></td>
<td>5.45 ± 0.11</td>
<td>5.72 ± 0.16</td>
<td>5.81 ± 0.11</td>
<td>5.37 ± 0.14</td>
<td>5.59 ± 0.07</td>
<td>5.66 ± 0.14</td>
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<tr>
<td><strong>% SOM</strong></td>
<td>9.93 ± 1.16</td>
<td>5.50 ± 0.50</td>
<td>13.19 ± 1.11</td>
<td>5.26 ± 0.34</td>
<td>9.12 ± 1.33</td>
<td>9.83 ± 1.08</td>
</tr>
<tr>
<td><strong>% C</strong></td>
<td>4.34 ± 0.40</td>
<td>2.64 ± 0.29</td>
<td>5.78 ± 0.90</td>
<td>2.61 ± 0.24</td>
<td>4.26 ± 0.55</td>
<td>4.00 ± 0.49</td>
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<tr>
<td><strong>% N</strong></td>
<td>0.22 ± 0.02</td>
<td>0.16 ± 0.01</td>
<td>0.3 ± 0.04</td>
<td>0.14 ± 0.01</td>
<td>0.17 ± 0.02</td>
<td>0.21 ± 0.02</td>
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<tr>
<td><strong>C:N Ratio</strong></td>
<td>19.83 ± 1.17</td>
<td>16.56 ± 0.57</td>
<td>18.78 ± 0.75</td>
<td>18.24 ± 0.50</td>
<td>24.47 ± 1.27</td>
<td>19.36 ± 1.11</td>
</tr>
<tr>
<td><strong>C Stock (g/m(^2) (10cm depth))</strong></td>
<td>4954.58 ± 468.54</td>
<td>3282.15 ± 310.22</td>
<td>5943.44 ± 1091.04</td>
<td>3342.83 ± 312.28</td>
<td>4538.61 ± 609.11</td>
<td>4654.11 ± 535.26</td>
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<tr>
<td><strong>N Stock (g/m(^2) (10cm depth))</strong></td>
<td>251.67 ± 20.68</td>
<td>193.74 ± 13.68</td>
<td>180.33 ± 13.13</td>
<td>179.55 ± 18.93</td>
<td>243.19 ± 28.77</td>
<td>19.56 ± 1.11</td>
</tr>
<tr>
<td><strong>Stock Ratio</strong></td>
<td>19.83 ± 1.17</td>
<td>16.56 ± 0.57</td>
<td>18.77 ± 0.75</td>
<td>18.24 ± 0.50</td>
<td>24.47 ± 1.27</td>
<td>19.36 ± 1.11</td>
</tr>
<tr>
<td><strong>Immediate Extractable NH(_4)</strong></td>
<td>8.62 ± 2.42</td>
<td>2.98 ± 0.35</td>
<td>4.74 ± 1.12</td>
<td>4.71 ± 1.14</td>
<td>7.14 ± 2.33</td>
<td>3.50 ± 0.90</td>
</tr>
<tr>
<td><strong>Ammonification Rates (µNH(_4)/g dry soil/day)</strong></td>
<td>0.39 ± 0.12</td>
<td>0.24 ± 0.06</td>
<td>0.19 ± 0.08</td>
<td>0.04 ± 0.03</td>
<td>0.77 ± 0.26</td>
<td>0.41 ± 0.08</td>
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<tr>
<td><strong>Available Ammonium (µNH(_4)/g resin)</strong></td>
<td>0.48 ± 0.14</td>
<td>0.17 ± 0.07</td>
<td>0.57 ± 0.18</td>
<td>0.19 ± 0.07</td>
<td>0.58 ± 0.17</td>
<td>0.17 ± 0.08</td>
</tr>
<tr>
<td><strong>Available Nitrate (µNO(_3)/g resin)</strong></td>
<td>0.37 ± 0.08</td>
<td>0.17 ± 0.05</td>
<td>0.79 ± 0.23</td>
<td>0.62 ± 0.22</td>
<td>0.85 ± 0.25</td>
<td>0.74 ± 0.34</td>
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<tr>
<td><strong>P (µP/g dry soil)</strong></td>
<td>20.28 ± 3.62</td>
<td>49.20 ± 8.06</td>
<td>11.94 ± 3.93</td>
<td>32.91 ± 8.70</td>
<td>29.39 ± 3.79</td>
<td>44.12 ± 6.33</td>
</tr>
<tr>
<td><strong>Ca (µCa/g dry soil)</strong></td>
<td>6044.12 ± 1142.54</td>
<td>2816.88 ± 378.61</td>
<td>7020.71 ± 1469.42</td>
<td>1671.41 ± 331.38</td>
<td>3190.43 ± 311.23</td>
<td>3432.09 ± 504.39</td>
</tr>
<tr>
<td><strong>K (µK/g dry soil)</strong></td>
<td>306.67 ± 72.21</td>
<td>155.89 ± 38.33</td>
<td>102.67 ± 22.40</td>
<td>189.69 ± 40.34</td>
<td>138.86 ± 16.88</td>
<td>187.16 ± 38.32</td>
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<tr>
<td><strong>Mg (µMg/g dry soil)</strong></td>
<td>306.53 ± 45.77</td>
<td>219.44 ± 20.34</td>
<td>455.53 ± 86.65</td>
<td>145.45 ± 31.07</td>
<td>237.96 ± 34.01</td>
<td>308.06 ± 51.19</td>
</tr>
</tbody>
</table>
Appendix 2: Graphs of selected soil parameters evaluated in this study. Bars denote ± 1 std error.

**Bulk Density**

**% Elemental Nitrogen**