

Examining the response of soil nutrients to mastication
treatments in Colorado's Front Range ponderosa pine
forests

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1. Introduction

As competition for land, resources, and space increases, forest management has become a pressing challenge and priority for land managers and policy makers. Due to the hotter, drier conditions predicted for Colorado by downscaled climate models (Schoennagel, 2004; Whitlock, 2003), there is high fire safety concern on both state and federal levels. Several critical factors, including higher temperatures, disease occurrence (e.g., pine bark beetle, white pine blister rust), earlier snowmelt, increasing carbon dioxide levels, albedo changes, amplified weather extremes, vegetation shifts, increased aerosols, and previous forest management methods are combining to produce the observed increase in wildfire activity. As a result, land managers are increasingly thinning forests to prevent wildfires that might endanger sites or homes in urban-wildland interfaces (Owen, 2009). Studies have shown that forests with dense tree stands are more prone to catastrophic wildfires, which can further accelerate the loss of forest resources (Owen, 2009). In order to mimic natural fire patterns and maintain forest diversity, forests are being thinned and will continue to be managed and regulated to a substantial extent.

In the mid 19th century, due to Euro-American settlement and increased climatic variability, there was a high level of fire occurrence (Colorado State). Thus, in the late 19th and early 20th centuries, land management practices began focusing on protection of natural resources. During this time, fires were viewed as a threat and an unnatural, human-caused event from which forests should be protected. As a result, fires were strictly managed by federal government agencies and effectively excluded. High fire suppression in the northern Colorado Front Range during most of the 20th century is believed to have caused changes in forest structure that had made forests more susceptible and led to a high hazard of catastrophic fire in ponderosa pine forests (Veblen, 2000). In many Colorado ponderosa pine forests, decreased occurrence of frequent surface fires resulted in unprecedented increases in stand densities and fuel accumulations (Veblen, 2000). This shift in forest stand structure shifting from an open savanna-like structure to one with high tree densities contributed to destructive forest fires such as the Hayman fire in 2002 (Graham, 2003). In addition, the relatively dry climate of much of the Southwestern United States and the high frequency of lightning has had a major influence on the montane and subalpine ecosystems (VanKat, n.d.). As a result, an increase in the duration and intensity of the wildfire season in the western United States has been observed (VanKat, n.d.). Today, resource managers are trying to restore such ecosystems to their pre-20th century structure and composition through forest management techniques (Veblen, 2000). Yet, mimicking the biodiversity and natural selection patterns that nature creates is no simple task. In order to appease the increasing wildfire activity caused by climate change, land managers and foresters are working to reverse current wildfire trends. Different fuels treatments and management strategies have been implemented through silviculture to control the establishment, growth, composition, health, and quality of forests.

Fire suppression as a forest management technique is mainly employed to address the issue of wildland-urban interfaces near populated areas. However, as a result of fire suppression, stand density and denser forests has increased dramatically. During the 20th century, average Ponderosa pine forests increased from 40-60 stems/acre to 600-800 stems/acre, which leads to intense, devastating crown fires and the volatilization of nutrients (McCullough, 1998). Fire suppression has also not been an ideal management technique because it results in increased drought sensitivity and affects the soil structure and nutrient recycling (Baker, 1992; Parsons, 1979).

Prescribed burning was implemented to reintroduce the natural process of fire back into the forests to reduce fuel loading. Burning, an effective treatment for reducing surface fuels, opens up growing space for residual trees and increases stand conditions favoring faster development of the more fire-resistant, large trees. Burning also maintains natural vegetation boundaries, helps sustain grazing grounds, and controls pests (Wilberly, 2009). Of the common forest management techniques, prescribed fires have the advantage of most closely mimicking nature. Their disadvantages include high fire risk and the release of carbon dioxide into the atmosphere (rather than promoting on-site carbon storage). To ameliorate such effects, forest thinning is another widely-implemented management technique, preferred for the low risk and greater control it affords managers. Tree-thinning can similarly help reduce crown-fire potential, and increase light and resources for understory vegetation (Owen, 2009).

Because forest management can be a challenging task, it is important to look closely at fire management options to see which leads to the optimal result. “While many management practices cause some level of ecosystem disturbance and can increase the abundance of exotic species, they often create fewer disturbances than a severe wildfire” (Owen, 2009). It is important to continue exploring management options in order to find the most appropriate technique for the specified region. Requirements for Colorado's major tree species are varied, as are the management approaches that are appropriate for these forest types. For instance, management practices that encourage healthy forest conditions in ponderosa pine in the montane zone will not be appropriate for lodgepole pine, spruce-fir, piñon-juniper or aspen forests (Colorado State). The needs of forest types are vastly different, and therefore, effective management strategies to encourage healthy forests in these various types also will vary.

One type of thinning that has been less-studied for forest management is mastication, where approximately 50% of the trees are tagged, chopped down, and shredded into large chips that are distributed across the topsoil. Mechanical mastication employs hydro-mow equipment, similar to a large mulching lawnmower that uses rotating blades to shred live trees into large wood chips (Owen, 2009). Mastication as a forest management practice is gaining in use and popularity, especially among land owners: “on federal, state and private forestland in the Rocky Mountain West, mechanical fuel reduction treatments are widely prescribed, but very little information exists on mastication treatment effects for the Rocky Mountains and the Colorado plateau” (Stromberger, 2008).

There are several impacts that mastication may have on forest dynamics. “The simultaneous disturbance of adding chipped biomass to the forest floor and the opening of tree canopy may create a unique set of circumstances” (Wolk, 2008). A less studied aspect, but equally as important, is the impact of mastication on the soil structure and ecosystem. For example, Owen (2009) states, “Mechanical mastication is a newer fuel treatment and its impact to soil properties and above- and belowground communities is unknown.” While most similar to the thinning method of forest management, mastication may lead to different ecological responses due to the addition of the wood chips to the topsoil. While research has been done on the understory community changes post-mastication (Kane, 2009; Miller, 2009; Owen, 2009; Wolk, 2008), less is known about the effects on soil, which can have significant impacts on the microorganisms and biota. Furthermore, mastication, and the removal of trees and their carbon input, will likely alter the soil and fungal ecosystems, as aboveground biomass plays a strong role in soil ecosystem cycling. In a study examining nitrogen demand based on stand densities, results showed that at different levels of stand density, the subsequent demand for nitrogen needed to produce the various components also changed (Dicus, 1999). Changes in above-

ground nitrogen demand were subsequently reflected in corresponding changes in fine-root biomass. The combined effects of thinning and addition of fresh woodchips to the soil will likely have significant impacts for the system. Therefore, our research is one of few to explore mastication as a new forest management technique with regard to soil characteristics, interactions, and responses.

To determine the effects of mastication, we first examined soil physical properties, including moisture, temperature, and bulk density, in two pairs of control-treatment plots. Wolk reviews several studies that indicate that chipped biomass may increase soil moisture and moderate soil temperature variation, which may create more favorable plant growing conditions (Wolk, 2008). We similarly hypothesize that mastication will increase soil moisture, resulting in changes in microbial activity. Soil temperature is expected to decrease in response to mastication, as studies from a few years post-mastication found similar trends (Kobziar, 2007; Neal, 2007; Owen, 2009). Deenik (2006) found that microbial activity is limited at soil temperature near freezing, and increases with rising soil temperature. Therefore, we hypothesize that soil temperature will moderate, or decrease, in response to mastication, and will correspond with an increase in soil microbial activity. By examining soil moisture and temperature hourly over several months, our results provide insight into the microbial response and viability to changes in such parameters.

In addition to soil physical properties, we also considered changes in soil biological and chemical properties, including pH, soil fungal biomass, carbon and nitrogen content, nitrogen mineralization, ammonification, and nitrification. Because the addition of fresh woodchips will alter nutrient availability for microorganisms, we hypothesize that mastication will alter the rate at which organic matter decomposes and nutrients are either oxidized into plant-accessible forms (mineralization) or absorbed by microorganisms (immobilization). In mineralization, organic nitrogen (N) from decaying plants is converted into the bioavailable inorganic forms of ammonium (NH_4^+) and ammonia (NH_3), which can be further oxidized to nitrate (NO_3^-) as a result of soil microbial activity. Though some plants uptake organic forms of N directly (Nasholm, 2009), microorganisms (fungi and bacteria) most often convert organic N into more readily available inorganic forms. This process of mineralization is associated with microbial death. In immobilization, the opposite of mineralization occurs: NH_4^+ and NO_3^- are taken up by microbes or plants, resulting in microbial or plant growth. We expect an increase in microbial action (immobilization) after mastication when there is an increase in limiting nutrients, followed by a decrease (mineralization) once the microbes have used up the additional labile carbon forms such as sugars and carbohydrates from the woodchips.

Another important parameter we measured was soil carbon (C) and nitrogen (N). Forest soil scientists have long been concerned with soil C and N because these are often the limiting nutrients determining soil fertility relative to the more abundant nutrients of phosphorus and potassium (Johnson, 2000). Additions of organic carbon and nitrogen from mastication is expected to increase C in the soil and C:N ratios. These elevated C:N ratios are predicted to increase microbial activity by accelerating litter and soil organic matter decomposition (Ma, 2004). Because decomposing microorganisms derive their energy from carbon compounds in soil organic matter, the interaction of the N mineralization and immobilization processes is closely tied to the carbon cycle (Deenik, 2006). Because of this relationship, the C:N ratio can be used as an indicator of which step in the nitrogen cycle is occurring in the soil ecosystem. We expect that when N is limited shortly after mastication (high C:N ratios), net immobilization will occur with a loss of N from the bioavailable N pool. It is well established that, given a sufficiently large

carbon pool, soil microbes will immobilize plant-available N (Blumenthal, 1991). Therefore, the addition of organic C is expected to induce soil microbes to immobilize available nitrogen. In contrast, when N is abundant, we have a low C:N ratio which we expect to predominate six to nine months following mastication, with a net increase in mineralization (NO_3^- and NH_4^+).

While both fungi and bacteria are necessary for decomposition of organic matter, they degrade plant residues (fresh woodchips in our case) differently and have unique roles in the recycling of nutrients. Fungi are generally much more efficient at assimilating and storing nutrients than bacteria. Because fungi need a greater amount of carbon to grow and reproduce than bacteria, fungi will collect the required amount of carbon from soil organic material and plant sugars. Because the soils at our study sites are nitrogen-limited (not carbon-limited) (McKinley, 2011), the addition of woodchips from mastication is not likely to increase fungal populations. Bacteria, however, require more nitrogen than fungi, and therefore may benefit from the increase in nitrogen.

Additionally, because nitrification typically occurs only when there is an excess of nitrogen, we expect low nitrification rates compared to ammonification. This hypothesis is supported by a study by Neal (2007) who found that mastication plots had significantly higher concentration of NH_4^+ compared to NO_3^- . Determining these rates will reveal whether mineralization or immobilization is the dominant process and at which stage of the post-treatment process. Mineralization is associated with microbial death, and immobilization is associated with microbial growth. By examining net mineralization/immobilization as well as their rates we can determine not only the size of the bacterial pool, but also, and perhaps more importantly, how the pool is changing over time.

Because not much is known about the soil response to mastication and the effect of different parameters, our study is designed to examine soil responses and interactions. By examining soil properties, we can get to the, appropriately-named, “root” or source of subsequent changes in forest structure. Our study focuses on Ponderosa pine forests, of which historic management techniques have consisted of mostly suppression and thinning. Mastication, however, may prove to be a more efficient option for providing nutrients and restoring forests to their natural stand dynamics. By examining these ten parameters comprehensively, we may provide insight into how the interactions amongst soil properties lead to changes in forest structure. Our primary hypotheses conclude that mastication will lead to an increase in soil moisture and a decrease in soil temperature, which will facilitate more microbial activity. High microbial activity and immobilization will likely result shortly after mastication, following by mineralization and microbial death once the microbes have consumed the mulched trees. The subsequent stabilizing of microbes may facilitate the rejuvenation of forests back to historic frequency and severity. If long-term patterns follow this prediction, mastication may likely be a management technique that can beneficially manage the forests while allowing for forests to return to their ideal historic patterns.

2. Methods

2.1 Study sites

Our hypotheses were tested through soil sample collection and field analyses at two study sites: Sanborn Nature Center near Florissant, Colorado and Dome Rock near Divide, Colorado. Five treatment and five control plots were sampled at each study site, for a total of 20 plots (See Appendix 1).

In the Rocky Mountains of central Colorado, Sanborn Nature Camp (Latitude: 38°54'11.69" N; Longitude: 105°19'46.13" W) is located at an elevation of 8700 feet. The camp comprises more than 6,000 acres of open Ponderosa pine forest, wildflower meadows, and rocky bluffs underlain by Precambrian Pikes Peak Granite (Sanborn Western Camps, 2008). The forest is dominated by ponderosa pine (*Pinus ponderosa*). The site is characterized by gently sloping hills, with similar terrain and topology for control and treatment plots. Though roads traverse the property, all sampling sites are at least 20 feet from roads or walking trails.

Dome Rock (Latitude: 38°50'06.00" N; Longitude: 105°13'14.00" W) is a 640-acre scenic area located in Teller County, Colorado on the western slope of Pikes Peak. The site is owned by the Colorado Division of Wildlife and is located at an elevation of 9,044 feet. The area is dominated by massive, exfoliating outcrops of Pikes Peak granite, beaver ponds, and river bottom meadows (Colorado State Parks, 2011). Along with ponderosa pine, other common native plants in this area include limber pine (*Pinus flexilis*), Douglasfir (*Pseudotsuga menziesii*) and montane grassland plant communities. The area provides winter browse and lambing grounds for a herd of bighorn sheep. The study site is exposed to human traffic for trail hiking or nature walks during late summer and fall. The site is characterized by a 10° slope south, grassy hills, and similar topography and aspect for control and treatment plots. All samples sites are at least 20 feet away from roads and trails.

In general, winters in the montane and subalpine ecosystems of the southern Rockies tend to be cold, with an average minimum temperature in Colorado Springs of 35.4° F, summers warm to cool with an average maximum temperature of 61.6° F, and precipitation bimodal with peaks in winter and mid-summer, with an average annual precipitation of 16.2 inches (Climate Zone). Winter precipitation falls as snow, and a substantial snowpack develops an annual monthly snowpack of 42.7 inches (Climate Zone). Precipitation decreases as temperatures warm in the spring, and early summer tends to be the driest time of the year. With the beginning of the monsoon season in early July, precipitation increases. After the monsoon season ends in late August or early September, precipitation decreases and temperatures cool (VanKat, n.d.).

The soils at our study sites originated from gravelly alluvium and outwash of Pikes Peak granite and are classified as loamy mixed Eutroboralfs or Aridic Haploborolls (Moore, 1992). Pikes Peak granite consists of potassium feldspar (KAlSi_3O_8), quartz (SiO_2), and biotite ($\text{K}(\text{Mg,Fe})_3\text{AlSi}_3\text{O}_{10}(\text{F,OH})_2$), so soils will not be potassium (K) limited. Soils within this particular area are approximately 66% sand, 21% silt, and 13% clay with bulk densities that usually increase with depth and range between 1.1 and 1.5 g cm^{-3} . Soil organic material comprises about 1–2% of the soil by volume (Stromberger, 2008).

2.2 Sampling design

Five masticated “treatment” plots and five control plots of untreated intact-forest were selected at each site. Sites were chosen where pre- and post-treatment analysis could be done for comparison, matching control and treatment plots for similar elevation, slope, soil, vegetation, and overstory tree canopy cover. GPS coordinates were used to ensure that soil samples were collected from the same area each time (see Appendix 1). Within each of the 20 plots, five soil sub-samples were collected: one at the center of the plot and four from 20 meters away in each of the cardinal directions. These five samples were composited to ensure a representative sample at each plot. A 20 meter buffer zone between the samples and any roads or obstructions and other treatment boundaries was maintained.

Prior to mastication (in December 2010), plots were designated and initial samples were gathered at treatment sites. Initial samples at control sites were gathered after mastication to make sure samples were not in masticated areas. Mastication was conducted by the Colorado State Forest Service to mechanically shred 50% of the basal area of the treatment forest, focusing on the small and dead trees. Mastication resulted in scattered mulched material ranging from <2 to 15 cm in size, in areas roughly 15-20 m² in size. The average depth of chips on the forest floor was 2 cm. (Notes: the contractor at Sanborn Nature Camp was Kory Weaver of K & K Tree Service and at Dome Rock, the Contractor was Cody Neff of West Range Reclamation). Post-mastication soil samples were collected at the designated control and treatment plots throughout the summer and early fall a total of seven times (see Appendix 2). Initial samples were gathered in November/January, and post-mastication samples were gathered in early June, late June, early July, late July, mid-August, and mid-September.

2.3 Soil sampling and analyses

Soil samples were collected with a 3 cm diameter soil core to a depth of 15 cm. Two HOBO Micro Station Data Loggers with an EC-5 Soil Moisture Smart Sensor and a 12-Bit Temperature Smart Sensor (Onset Computer Corp., Bourne, MA) were installed on June 10th, 2011 at each site, one within the control plot and one within the treatment plot, for a total of four probes. With exception of the probe tip, the rest of the probe and probe equipment were encased in a plastic container and piping to protect from animal disturbance, and buried at a depth of 10 cm. The probes were set to record soil moisture and temperature on an hourly basis.

Soil temperature was also measured in the field using an Omega HH314A Handheld Temperature Humidity Meter (OMEGA Engineering Inc, Stamford, CT). By doing paired comparisons of the temperature and soil moisture data between the two methods (HOBO vs handheld), we calibrated the probes.

Soil for bulk density, a measure of soil compaction, was collected post-mastication by taking a core of known volume from each plot and dividing the dry weight by the volume of soil. Dry weights were determined using a Mettler-Toledo top loading balance.

Once soil samples were collected, they were placed in a cooler and brought to the Colorado College laboratory for analyses of soil moisture, pH, soil fungal biomass, total carbon, total nitrogen, mineralization, nitrification, and ammonification. In the laboratory, the fresh soil samples were homogenized and sieved to remove coarse material, using a 2 mm sieve. To supplement the soil moisture data from the HOBO probe, soil moisture was calculated in the lab from the loss in mass due to soil moisture of the dry soil after heating at 70°C for 12 hours. Soil pH was determined from fresh soil samples, using an Orion 550A pH meter and equal volumes of soil and water.

Ergosterol determination following the procedure of Hobbie et al. (2010) was used to provide an estimate of the living fungal biomass in the soil. First soil subsamples (0.5 g) were saponified by heating for 90 minutes at 70°C in 2 mL of methanol and 0.5 mL of 2 M NaOH after brief vortex mixing. After cooling, 1 mL methanol and 3 mL pentane were added, and samples were vortexed for 20 seconds. Samples were briefly centrifuged to eliminate emulsions and the upper pentane phase, containing ergosterol, was collected. The pentane addition, vortexing, centrifugation, and extraction was then repeated twice to extract residual ergosterol, using 2 mL of pentane per extraction step. The pentane (upper) phase was collected and combined with previous extracts. The combined pentane extracts were dried under nitrogen flow until completely evaporated, and the residue was redissolved in 1 mL of HPLC grade methanol

(Fisher Scientific, Pittsburgh, PA). This was passed through a 0.45 micron nylon syringe filter (Whatman), and injected into a Waters Acquity ultra performance liquid chromatography (UPLC) system (Waters Acquity, Milford MA). Ergosterol concentrations were calculated by calibration with external, gravimetrically prepared ergosterol standards (Fluka). The amount of ergosterol per gram of dry soil was calculated as the product of the ergosterol and the final methanol volume of the ergosterol solution per gram of dry mass of soil.

For determination of total carbon and nitrogen concentrations and C:N ratios, subsamples of dried, sieved soil were first ground in a jar mill for at least 12 hours. Approximately 20 mg of the powdered soils were transferred into small tin capsules and wrapped carefully using forceps. Filled and weighed tin capsules were then combusted in a ThermoQuest NC2100 elemental analyzer (CE Elantech, Lakewood, NJ) for determination of total carbon and total nitrogen. Carbon and nitrogen content were calculated by external calibration of an atropine standard (CE Elantech, Lakewood, NJ).

Nitrogen mineralization rates were determined by field incubation rather than the standard lab incubation. Subsamples of freshly sieved soil (10g) subsamples were shaken for 1 min in 50 mL 2 M KCl, set aside for 18-36 hours, filtered through pre-leached Whatman #42 filters into duplicate Lachat tubes (Hach, Loveland, CO), and processed for NO_3^- and NH_4^+ in a Lachat QuickChem 8000 flow injection analyzer (Lachat QuickChem 8000). Concentrations were calculated by external calibration with NH_4Cl and KNO_3 standards. Soil concentrations were compared between each respective sampling period. Net N mineralization was calculated as the difference between the sum of NH_4^+ and NO_3^- concentrations between each sampling period. Net nitrification was calculated as the difference between NO_3^- concentrations between sampling periods. Net ammonification was calculated as the difference between NH_4^+ concentrations between sampling periods. Comparing these parameters to the control group allowed us to determine whether mastication alters the rate at which nutrients are consumed by microorganisms and plants.

In addition to the N mineralization method we employed, mineralization rates can also be determined through an *in situ* method of measuring net absorption of ammonium and nitrate from resin bags, or by measuring the amount of NO_3^- and NH_4^+ that is released during incubation. A disadvantage of the field methods for measuring mineralization is the potential for other variables to confound the result, and thus attributing changes in NH_4^+ and NO_3^- to the microorganisms is less definitive. On the other hand, field methods have the advantage of being less removed from the actual site and undisturbed field conditions (soil temperature, moisture, porosity, and bulk density), so results can be more accurately attributed.

2.4 Statistical analyses

Statistical analyses (SPSS Statistics for PC v. 17.0) were used to examine differences among parameters for control and treatment groups. All comparisons were set with significance at the 0.05 probability level (95% confidence interval). Two-way ANOVA was used to test for differences in response variables among sites and treatments, and the post hoc Bonferroni HSD test was used for subsequent pair-wise comparisons, this being the most conservative approach when a small number of means are tested. If variables failed to meet assumptions of normality (p-p plots) and homogeneity of variances (Levene's Test of Equality of Error Variances), natural log transformations were applied or the nonparametric Kruskal-Wallis test was used. Linear regression was used to assess the correlations among soil moisture, soil temperature, N mineralization, and C:N ratios.

3. Results

Short-term changes in soil physical, biological, and chemical properties were recorded and analyzed. Our data examines results six to nine months post-mastication. Control and masticated sites were compared and are described here in accordance with the different parameters measured, including soil moisture, soil temperature, soil pH, soil microbial activity, soil nutrient pools, and microbial metabolism.

3.1 Soil Moisture

Soil moisture was analyzed gravimetrically in the lab (Figure 1) and with a HOBO probe in the field (Figure 2). Gravimetric soil moisture was found to be almost always higher for the masticated site than the control site throughout the summer. The difference in soil moisture was significant between the masticated and control areas at both sites. Using a two-tailed t-test, we found Sanborn treatment soil moisture was significantly higher than Sanborn control ($p=0.034$) and Dome Rock treatment soil moisture was significantly higher than Dome Rock control ($p=0.034$).

Similar to our results of gravimetric soil moisture at Dome Rock and Sanborn, the HOBO soil moisture probe data shows that masticated sites have higher soil moisture compared to control sites throughout almost all of the analysis. Running a paired t-test, we find this result to be significant. Dome Rock control soil moisture is significantly different from Dome Rock masticated ($p<0.0005$) and Sanborn control soil moisture is significantly different from Sanborn masticated ($p<0.0005$).

Despite the similar trend in soil moisture pattern, examining the HOBO soil moisture graph (Figure 2), it appears that the Sanborn control soil moisture data does not match the pattern of the other three sites, possibly because it is less sensitive to moisture changes than the other three probes. Therefore, in order to use our HOBO soil moisture data, we calibrated the measured HOBO soil moisture to the true gravimetric soil moisture via linear regression, taking an average of five points. The r^2 values between the measured and true soil moisture are: Sanborn Treatment $r^2=0.88$; Sanborn Control $r^2=0.35$; Dome Rock Treatment $r^2=0.85$; Dome Rock Control $r^2=0.51$ (See Appendix 3).

Comparing the two different soil moisture techniques (HOBO and gravimetric), we find the gravimetric soil moisture method appears to be more representative than the HOBO probe, likely because the gravimetric method indicates the average soil moisture from five plots within each of the four sites, whereas the HOBO probe only measures the soil moisture in one location at each of the four sites. Also the location of the buried HOBO probe allows for site-specific factors to influence the data such as slope aspect, soil type, and local topography more than the gravimetric soil moisture method. However, the HOBO results are useful to examine high frequency changes in soil moisture at a single site.

FIGURE 1: Gravimetric soil moisture measured at each site location versus time

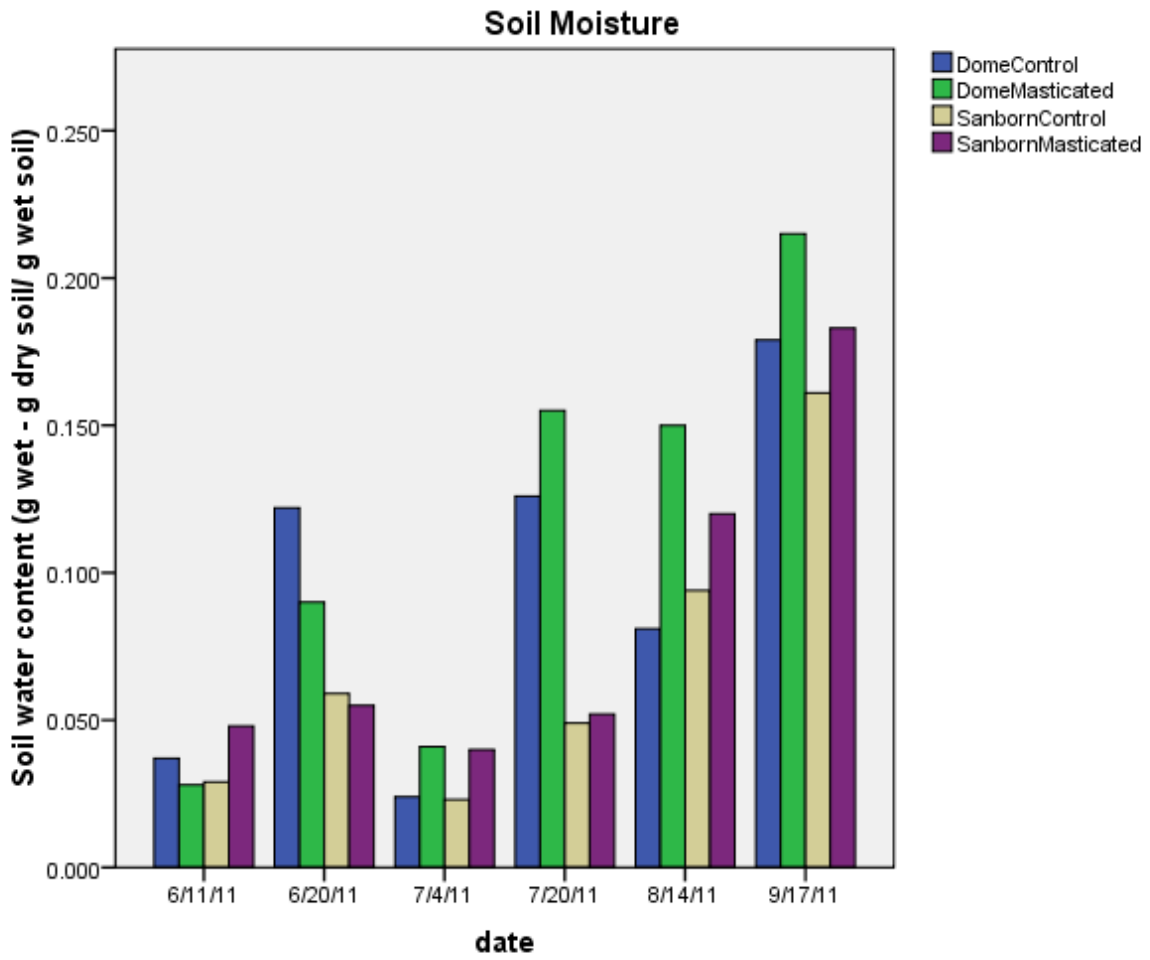
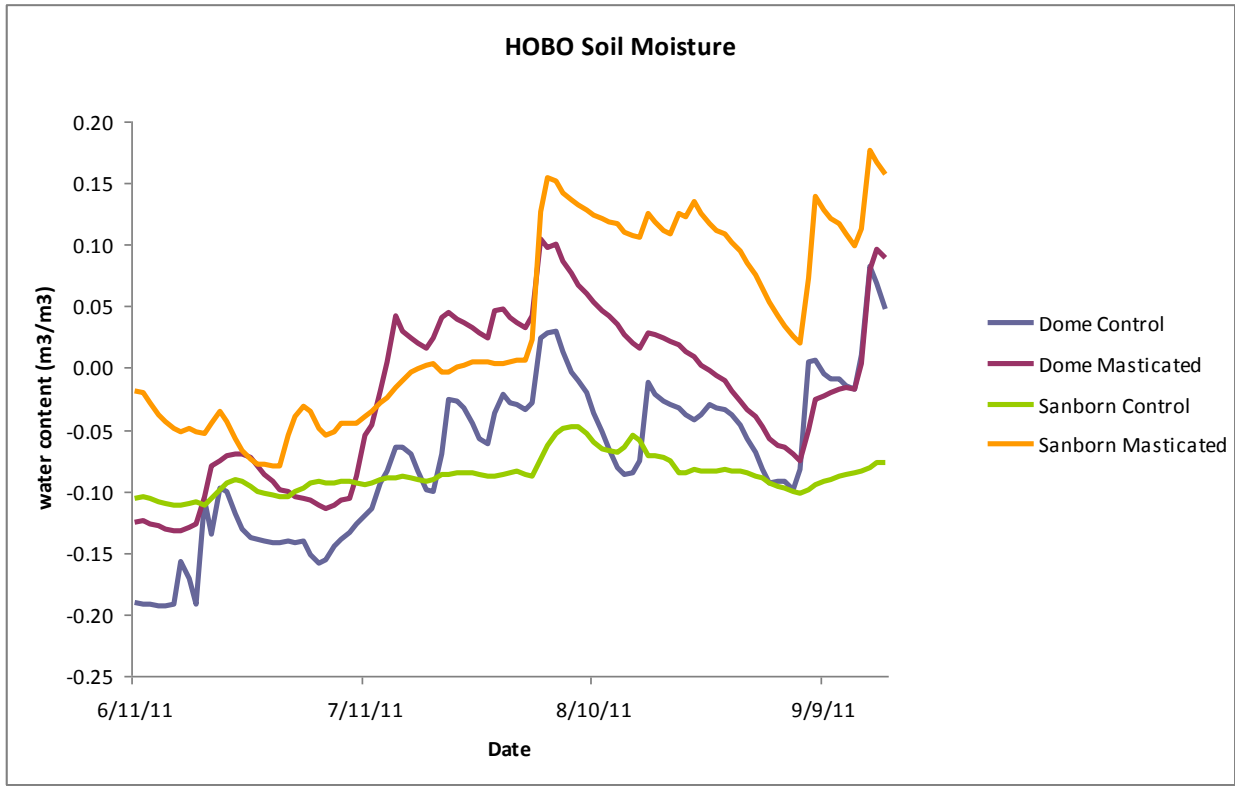


FIGURE 2: Soil moisture (measured by a HOBO probe) versus time



3.2 Soil Temperature

In order to analyze soil temperature effects, we examined the difference between masticated soil temperature and control soil temperature (Figure 3). Whenever the temperature difference is positive, the masticated site was warmer than the control site, and whenever the change is negative, the control site was warmer than the masticated site. Our data (Figure 4) shows conflicting results: at Dome Rock, the masticated site is consistently warmer than the control site, whereas at Sanborn, the control plot is almost always warmer than the masticated plot. The similar pattern in soil temperature for all four sites demonstrates precise but possibly inaccurate probe readings. This result suggests greater site averaging is required to elucidate temporal soil temperature patterns on a regional scale. Additionally, despite initial calibration, conflicting results may be a reflection of calibration differences between the two sets of probes. In examining Figure 4, we estimate a $\sim 4^{\circ}$ F calibration difference among Dome Rock HOBO probes and -2° F difference among Sandborn HOBO probes.

Soil temperatures were also recorded using a handheld temperature humidity meter (Figure 5) in the field each time soil samples were pulled. Taking field measurements at each plot and averaging the five plots for each site avoids site-specific variables such as canopy cover, albedo, and soil type from influencing the data. When the difference is positive, the masticated site has a higher soil temperature (warmer) than the control site, and when the difference is negative, the masticated site has a lower soil temperature (colder) than the control site. Examining Figure 5, Dome Rock and Sanborn soil temperatures follow the same trend. During the heat of the summer, the masticated sites have cooler soil temperatures than the control sites, whereas in early summer and in fall, the masticated sites have warmer soil temperatures.

FIGURE 3: Change in soil temperature (measured by the HOBO probe) versus time

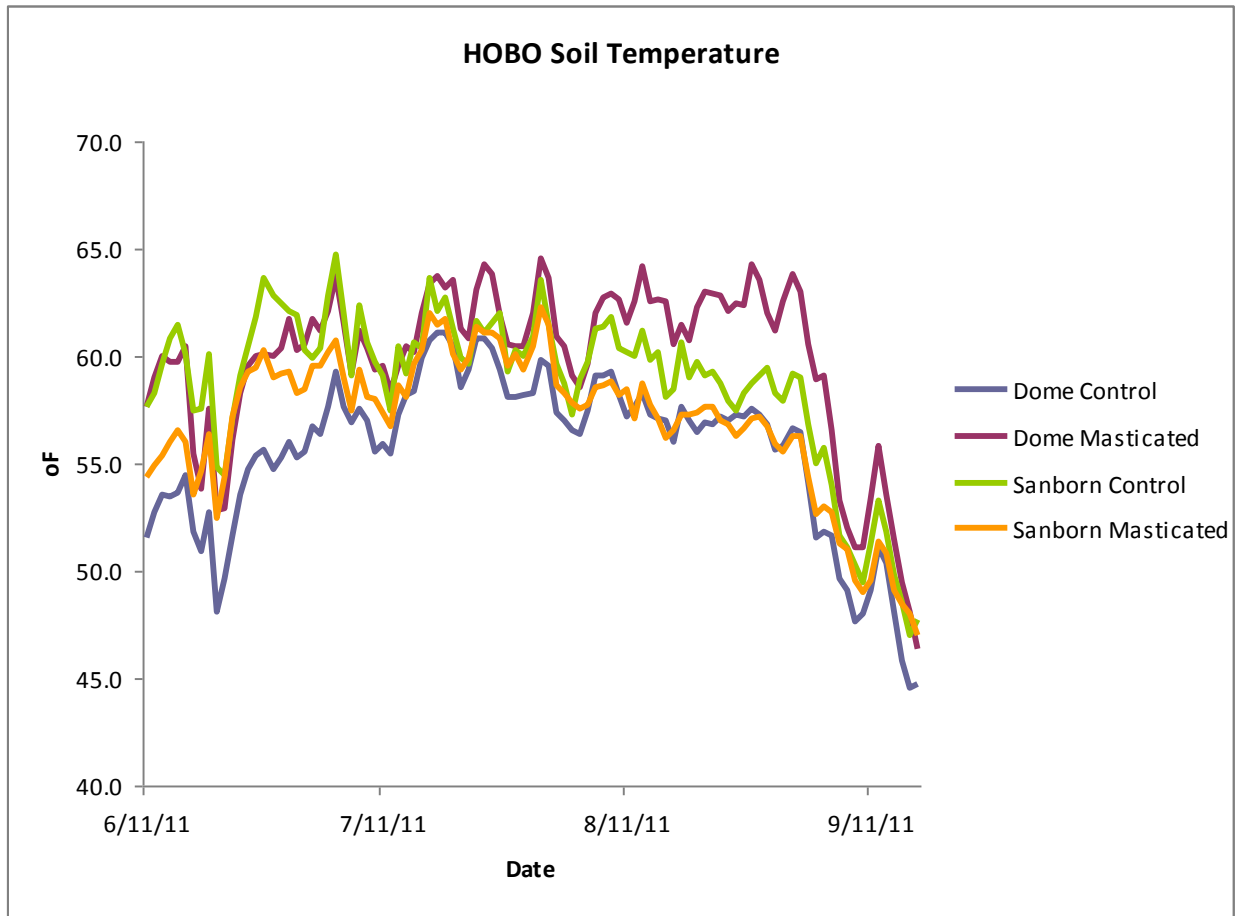


FIGURE 4: Difference in soil temperature (measured by the HOBO probe) between treatments versus time

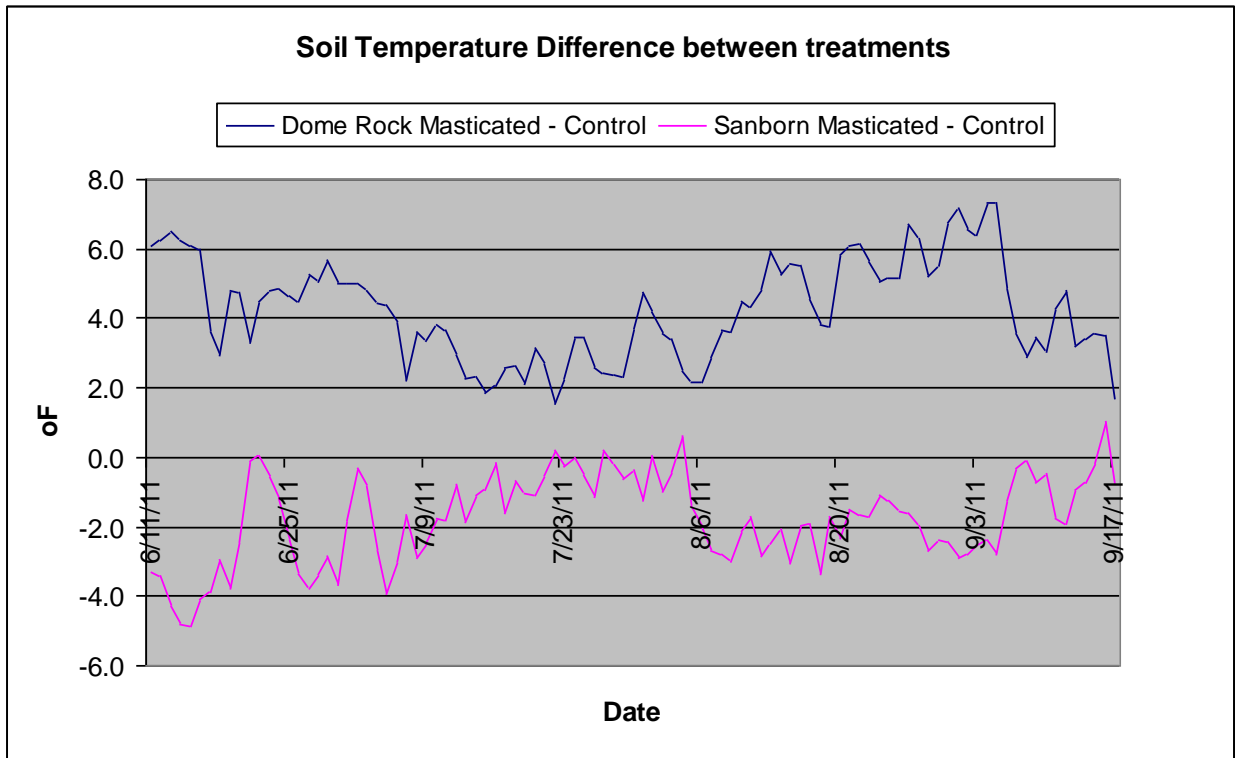
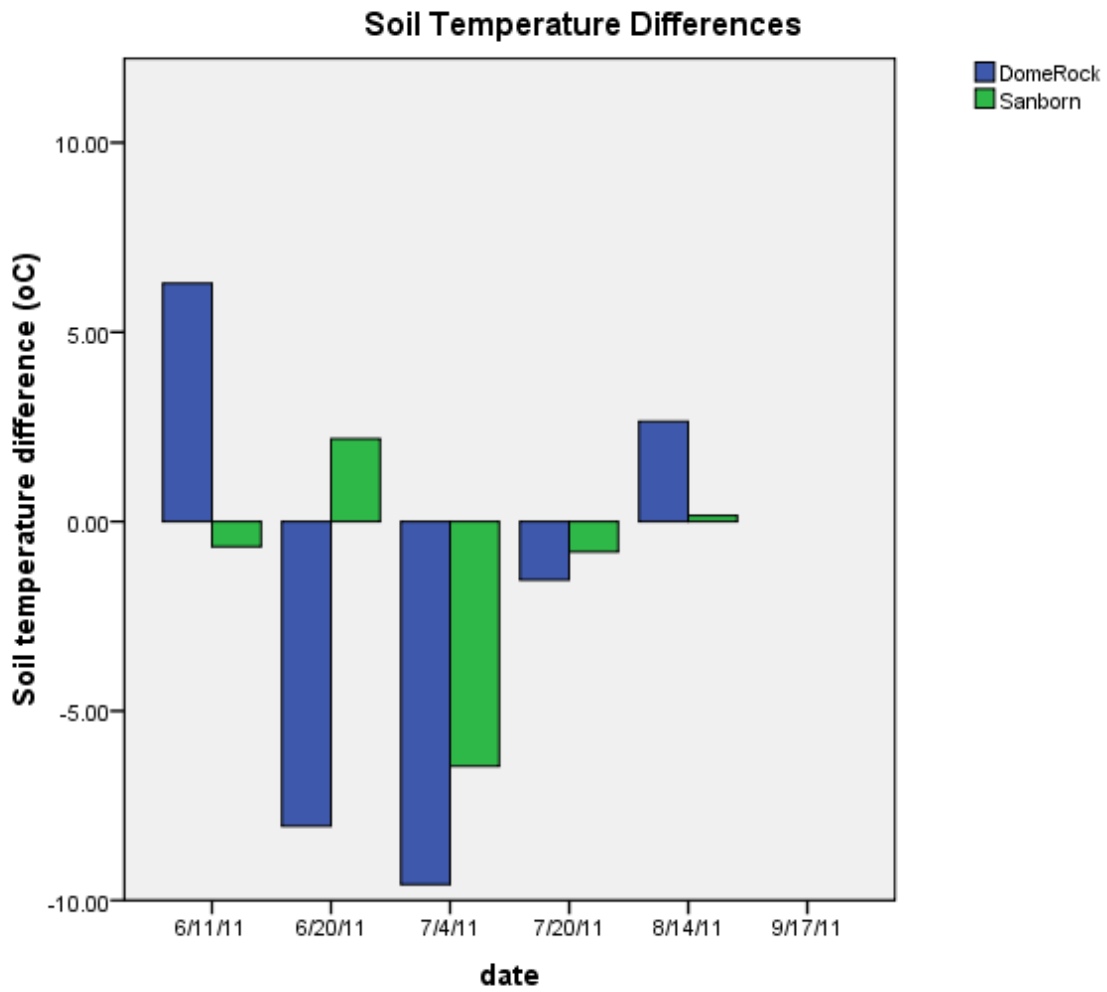


FIGURE 5: Differences in soil temperature between treatments versus time

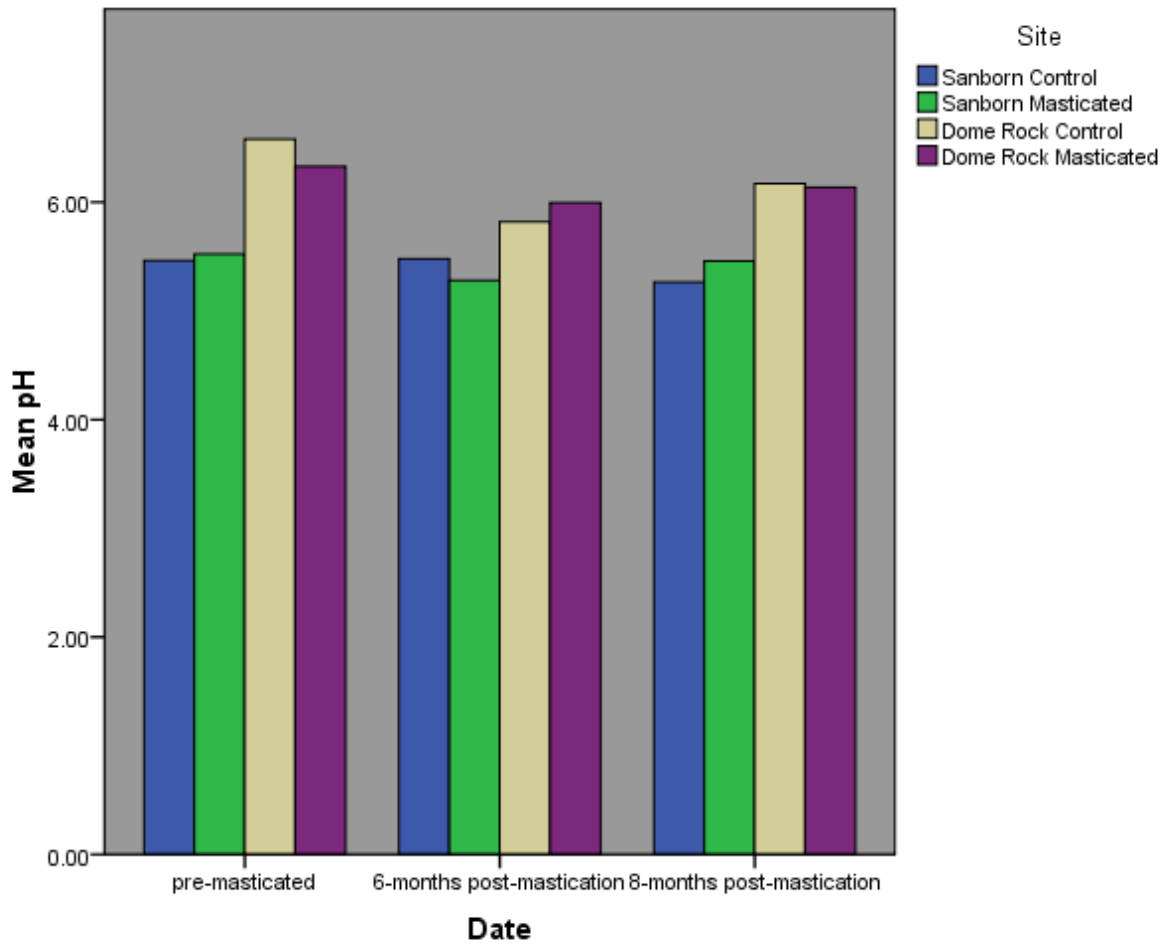


3.3 Soil pH

Running a two-way ANOVA, with the Bonferroni HSD post hoc test for pair-wise comparisons, we find pH is significantly higher ($p < 0.0005$) at Dome Rock (mean pH = 6.04) than Sanborn (mean pH = 5.37). Within each site Dome Rock and Sanborn, the masticated and control sites have the same soil pH ($p = 1.000$).

Soil pH was significantly different by date ($p = 0.045$) between pre-mastication and early June (6-months post-mastication) at Dome Rock and Sanborn sites (Figure 6). During the summer months, however, there is no statistical difference in pH between the control and treatment samples at Dome Rock or Sanborn.

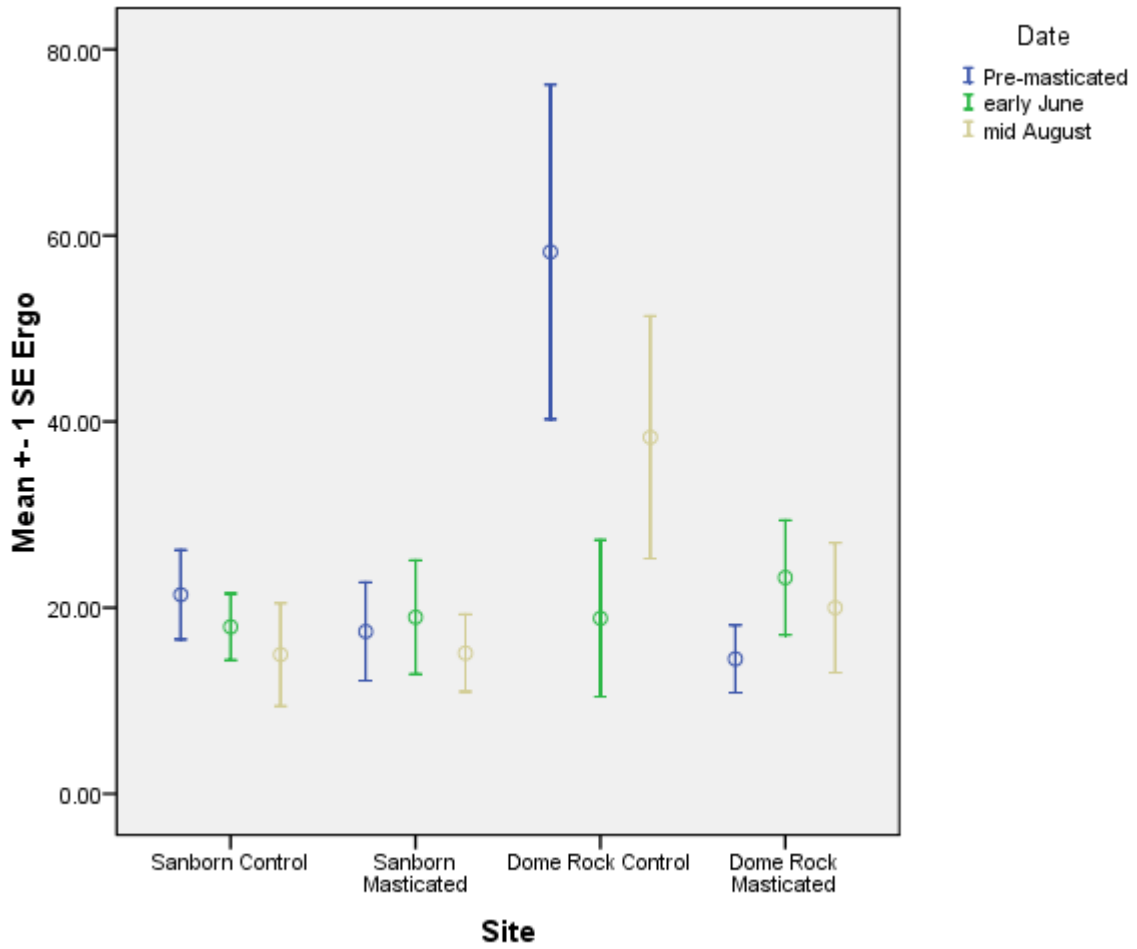
FIGURE 6: Mean pH at each site over time



3.4 *Soil microbial activity*

Ergosterol concentrations were used as a proxy for examining soil fungal biomass, as fungal biomass is proportional to the mean ergosterol concentration (mg/g soil). No consistent trend was found from data pre-mastication (November 2010) to post-mastication (June and August 2011 dates) although significant site-to-site variability is observed (Figure 7). Because the control sites are not masticated, any changes in ergosterol at control sites are not attributed to woodchip addition, but rather to natural fungal biomass change over time.

FIGURE 7: Changes in ergosterol concentration over time at each site



3.5 Soil nutrient pools

Carbon and nitrogen levels were examined to determine how mastication affected soil nutrient pools. Data does not include the initial samples collected pre-mastication to ensure results are reflecting post-mastication data only. The C:N ratios are much higher in the masticated sites compared to the control sites (Figure 8).

In order to examine the correlation between carbon and nitrogen percentages, regressions of nutrient levels were generated for each site (Figure 9). At all four sites, there are strong correlations between total organic carbon and nitrogen percentages, as seen by high r^2 values. At Dome Rock Masticated, $r^2=0.9403$; at Dome Rock Control, $r^2=0.9552$; at Sanborn Masticated, $r^2=0.89$; and at Sanborn Control, $r^2=0.8732$. The statistical Q test was used to identify and reject outliers from the data.

In Figures 10 and 11, carbon and nitrogen are analyzed separately to determine whether the increase in C:N ratios shown in Figure 8 are due to an increase in carbon or a decrease in nitrogen percentages. Relative to the control sites, the masticated sites show a greater increase in carbon percentage for the summer (dates 2-5) and a decrease in fall (date 6). Similar to the trend we found with soil percent carbon, Figure 11 shows a greater increase in the percent organic nitrogen in the soil in the masticated areas compared to the control sites for the summer (dates 2-5) and a leveling off in fall (date 6).

FIGURE 8: Carbon:Nitrogen ratios for each site based on the 95% confidence interval error bars

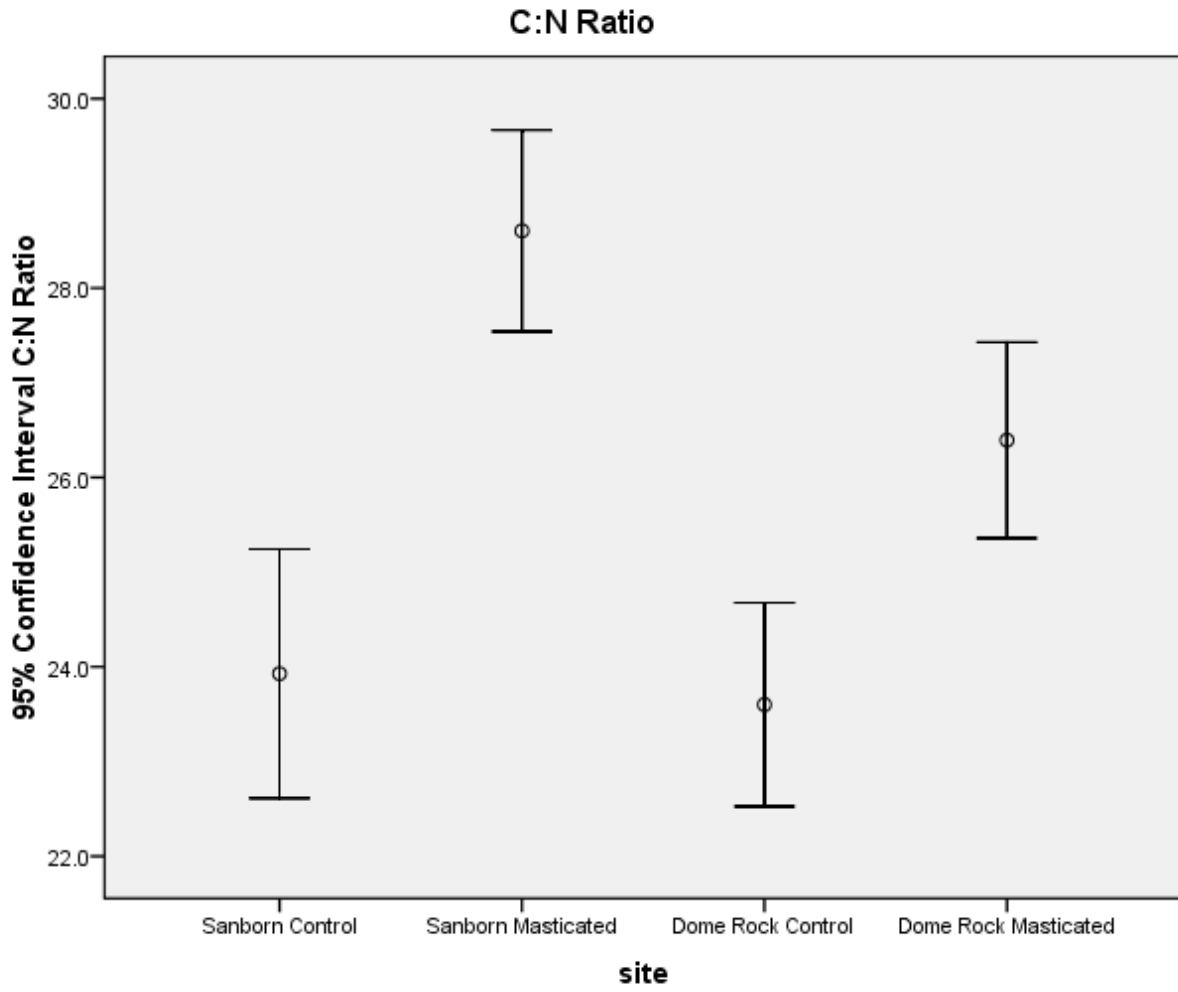


FIGURE 9: Carbon and nitrogen regressions at each site

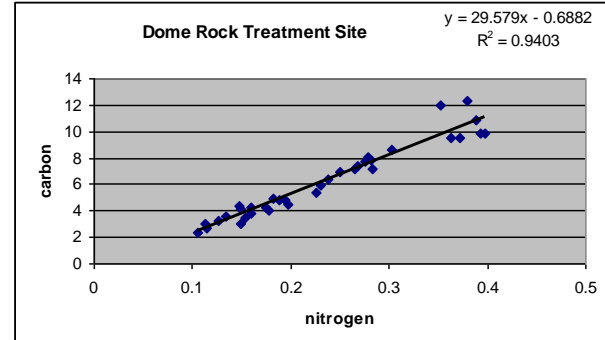
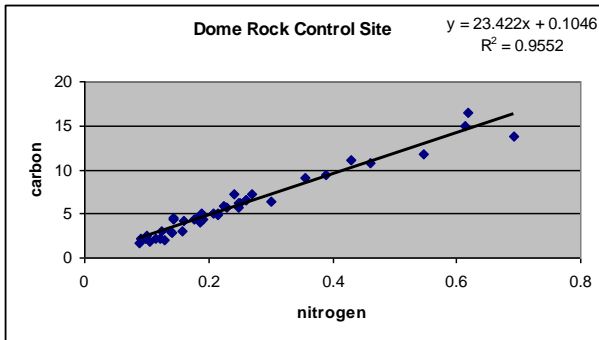
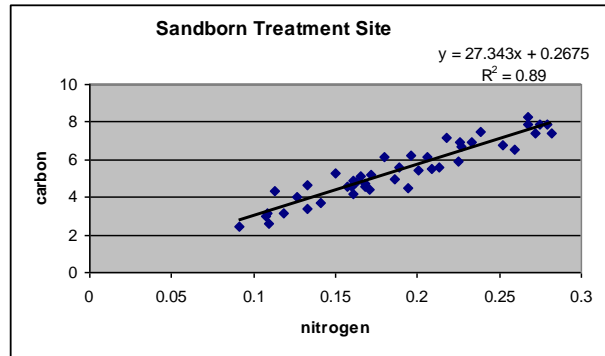
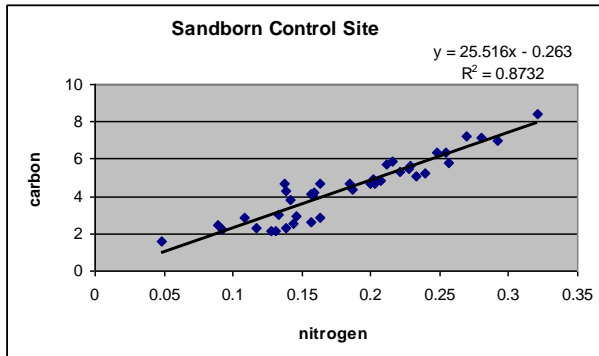
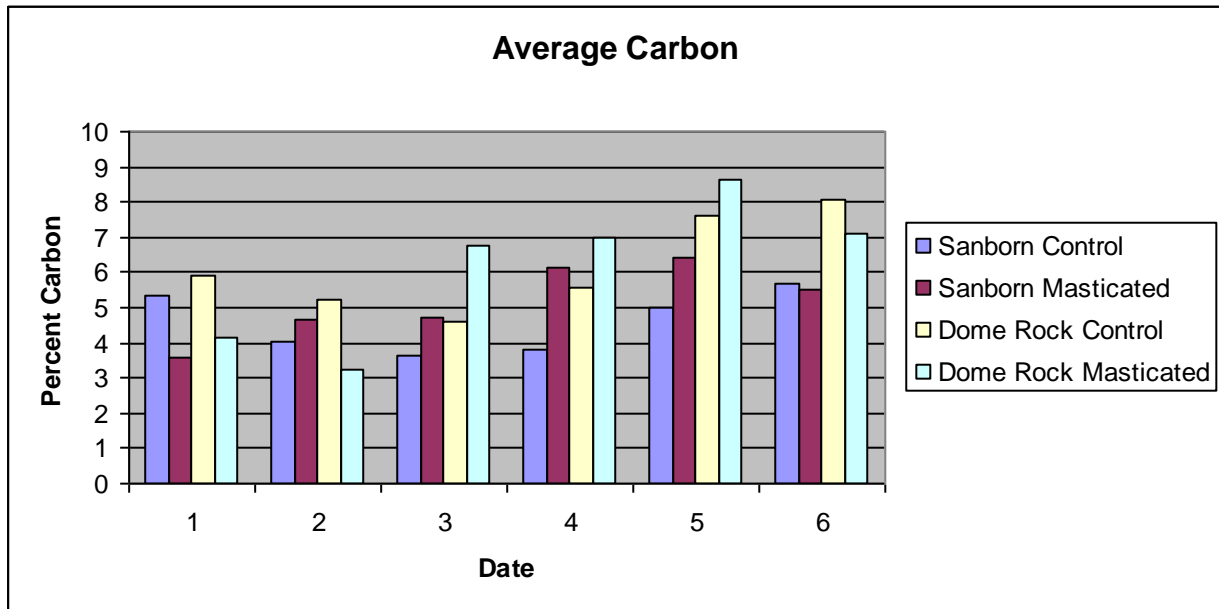
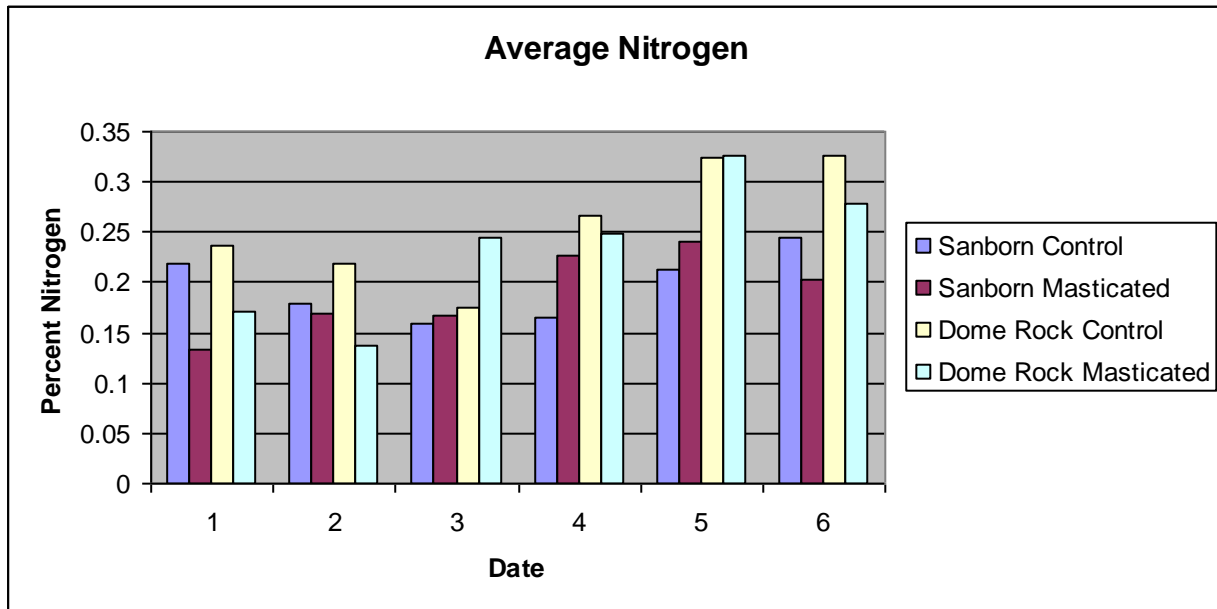


FIGURE 10: Average carbon percentages at each site versus time



Corresponding dates: 1= pre-mastication (December 2011); 2= 6/7/11; 3=6/21/11; 4=7/4/11; 5=7/20/11; 6=8/14/11

FIGURE 11: Average nitrogen percentages at each site versus time



Corresponding dates: 1= pre-mastication (December 2011); 2= 6/7/11; 3=6/21/11; 4=7/4/11; 5=7/20/11; 6=8/14/11

3.6 *Microbial metabolism*

Mineralization, ammonification, and nitrification rates were established for each sampling period to determine the increase or decrease in microbial metabolism and/or death since the previous sampling time. The mineralization rate is associated with the oxidation of nutrients into plant-accessible forms and subsequent microbial death. At each site, mineralization is determined by the amount of NH_4^+ and NO_3^- produced as a result of microorganism death per day (Figure 12). Across all sites, an S-shape pattern results, which is associated with an increase in microbial death in June/early July followed by microbial growth in late July/August, and an increase in death again in September.

Analyzing the differences in mineralization between control and mastication sites, the sites that underwent mastication experienced a decrease in microbial death earlier (in July compared to August), and then a subsequent moderation. This same trend is seen for ammonification: there is a larger decrease in ammonification earlier in the summer, followed by a leveling out of activity (Figure 13). There is relatively little nitrification contributing to mineralization compared to the other N sources (Figure 14). Nitrification, which occurs only when there is an excess of nitrogen, most strongly influenced mineralization during late July (seven months post-mastication).

FIGURE 12: Mineralization rate at each site measured by the change in nitrogen in the soil per day

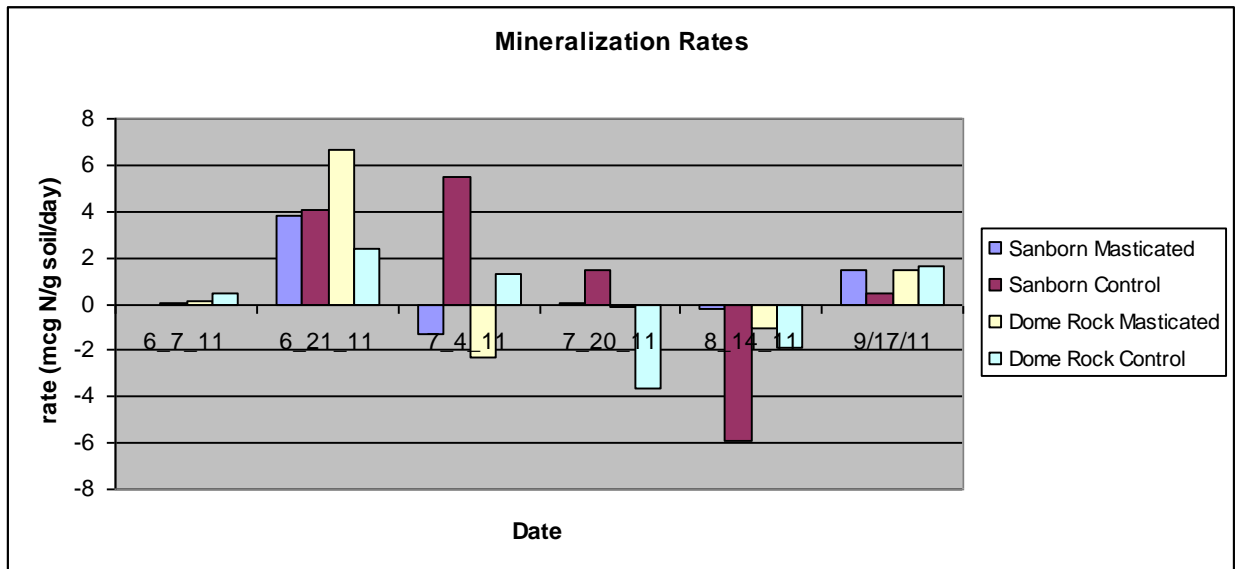


FIGURE 13: Ammonification rate at each site measured by the change in NH_4^+ in the soil per day

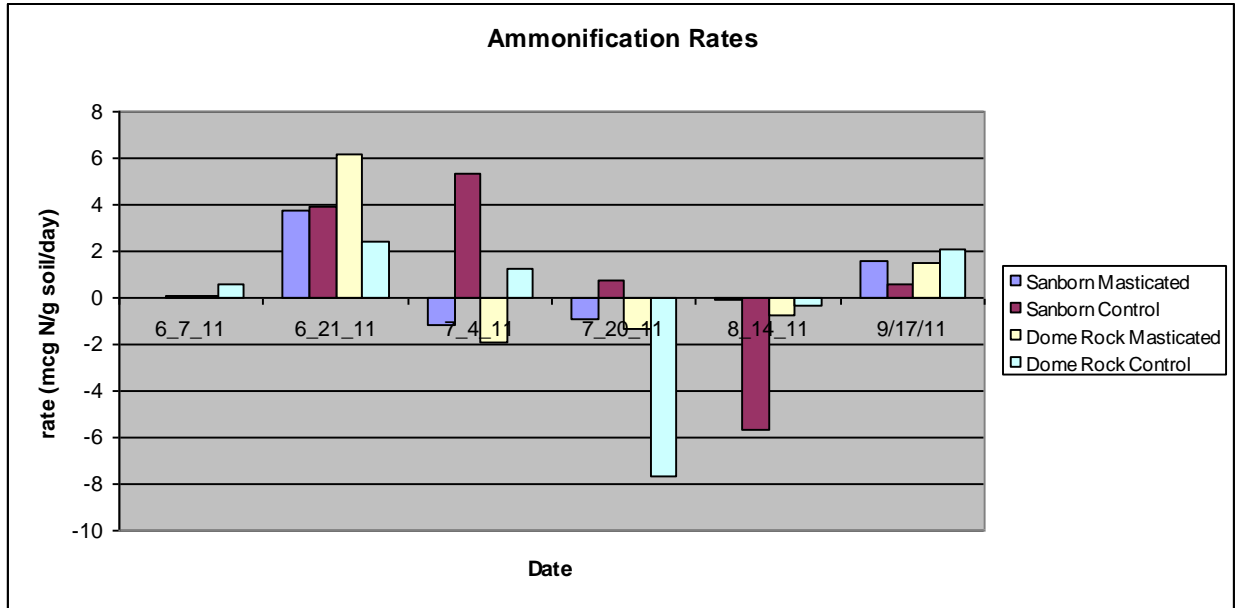
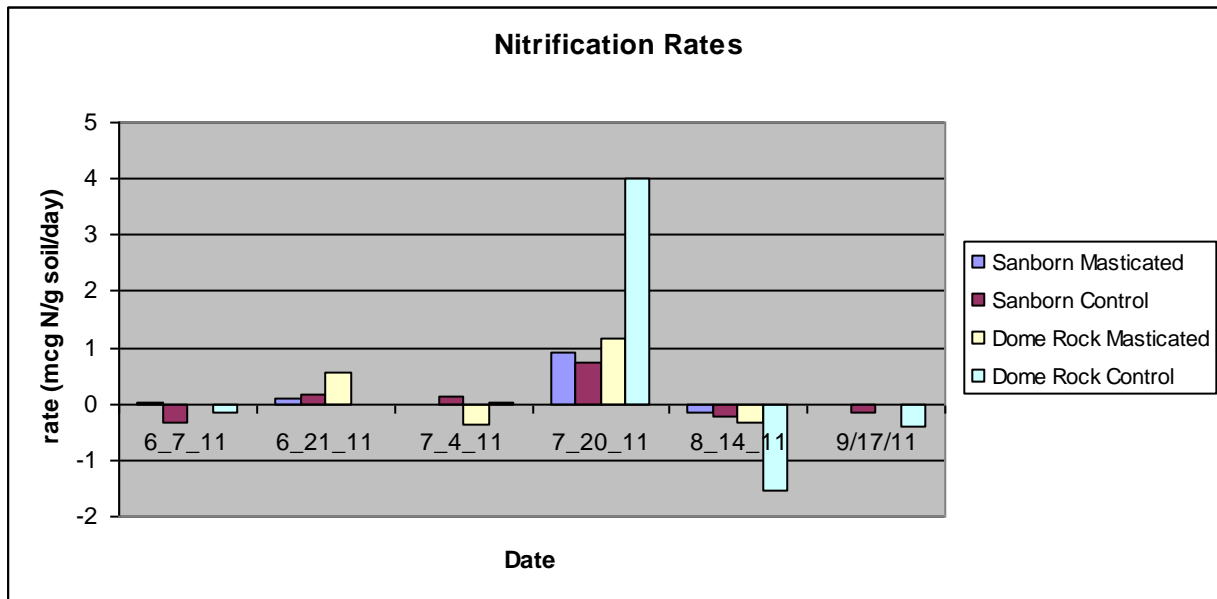


FIGURE 14: Nitrification rate at each site measured by the change in NO₃⁻ in the soil per day



4. Discussion: Ecosystem responses to mastication

4.1 Soil Moisture

Analyzing the soil moisture content gravimetrically from our soil samples (Figure 1) and from the HOBO probe data (Figure 2), we find that, for both methods, soil moisture is almost always higher in the masticated areas compared to the control areas, suggesting that the woodchips are trapping moisture in the soil rather than allowing it to evaporate from the soil-air interface. In similar studies focusing on the effect of mastication on soil, it was found that soil in mastication treatments had higher soil moisture than untreated plots (Neal, 2007; Owen, 2009). In a study where woodchips were added to the ground surface, moisture content was also found to be significantly greater in the woodchip treatment compared to other treatments (Matson, 1992). In a study of soluble carbon addition to soil, water content was found to increase at treatment sites (Blumenthal, 1991). Additionally, a report examining the effects of mastication in the nearby Manitou Experimental Forest found a significant increase ($p=0.01-0.03$) in soil moisture in the chipped treatment compared to control plots (Marchand, 2006). Our data provide consistent results with these studies. In our study, the only time when soil moisture is lower in the masticated areas is in early June at Dome Rock, when the least amount of time had passed since mastication had been completed. This lower soil moisture is likely due to woodchips initially preventing precipitation from entering the soil. For the rest of the data, mastication leads to greater soil moisture, with the woodchips preventing evaporation. By increasing soil moisture, mastication may allow greater microorganism activity as the organisms would not be as water limited.

4.2 Soil Temperature

Soil temperature was analyzed with a HOBO probe (Figure 3) and a handheld temperature meter (Figure 5). Because we hypothesized that mastication would reduce temperature extremes by cooling summer soils and warming winter soils, we expected the difference in soil temperature within sites to be negative, as we see with Sanborn (Figure 4). Studies examining mastication and soil temperature found that soil at the masticated sites had lower temperatures than at the control sites (Neal, 2007; Owen, 2009). While we see this trend at Sanborn, we see an opposite trend at Dome Rock. Because the location of the probe and the variable insulation influence soil temperature data, we suspect that the probe location may influence the data to a greater extent than the mastication treatment. Prior to installation of the HOBO probes, both probes were calibrated at the same place. However, to account for this possible confounding variable of locality, we also recorded soil temperature readings at each of the twenty sites with a handheld meter during each sampling date. To examine the difference between control and mastication sites, we looked at the difference (mastication - control) at the two study sites (Figure 5). Our results show that during the heat of the summer, masticated sites have cooler soil temperatures than control sites, whereas in early summer and in fall, masticated sites have warmer soil temperatures. Thus, our results from the meter show that woodchips may be acting as a thermal blanket, insulating the soil when the air is cooler, and shading the soil from the sun when air temperatures are warmer.

Comparing the two methods for determining soil moisture and temperature, we find that the HOBO probes provide accurate and extensive data. However, because we were limited to one probe per site, site specific variables may influence the data and possibly overshadow the treatment effects. In future studies, placing more than one HOBO probe at each site would

reduce the site specific effects and show higher frequency changes in soil moisture and temperature.

4.3 Soil Bulk Density

TABLE 1: Soil bulk density measured at each site, post-mastication

Site	Bulk density (g/mL)
Dome Rock Masticated	0.7637
Dome Rock Control	0.2792
Sanborn Masticated	0.4040
Sanborn Control	0.5267

The average bulk density (g/mL) at each site was examined post-mastication. Because mastication requires heavy equipment, studies have found soil compaction resulted in a higher bulk density in masticated plots, which decreases soil aeration, and restricts root growth and microbial activities (Ma, 2004). Moghaddas (2008), on the other hand, found that no significant compaction due to mastication was observed. Our results show no consistent trend in bulk density between masticated and control sites, suggesting the hydro-mow equipment did not increase soil compaction or limit microbial activity. Based on the highly variable location of the heavy equipment at different sites, this mixed result is reasonable. Three bulk density samples were gathered per site, so the small sample size may contribute to the large variance in bulk density across our study sites. Additionally, rather than comparing bulk density between control and masticated sites, comparisons pre and post-mastication would provide more concrete effects of the mastication work.

4.4 Soil pH

Soil pH was analyzed in samples from pre-mastication and then twice post-mastication (early summer and late summer). There was no significant difference in soil pH between the treatment and control sites (Figure 6). For both Sanborn and Dome Rock, the same pH was observed between masticated and control sites. Therefore, differences in soil acidity do not appear to contribute a confounding variable nor influence the nutrient content or cycling. Furthermore, the two sites, Sanborn and Dome Rock, had statistically different pHs from each other ($p < 0.0005$), suggesting that our results are not unique to soils only with a certain pH.

pH was also found to be statistically different by date ($p=0.045$). This difference is due to the change in pH from pre-mastication to 6-months post-mastication. However, because pH does not change significantly by date and site, this alteration in pH is not attributed to the addition of woodchips, since pH changes across all sites (masticated and control) between dates. From December to June, soil pH overall became more acidic, from an average of 5.95 (+- 1.15) to 5.64 (+- 0.75). Because this change in pH is seen uniformly across all sites, this soil acidification may be attributed to climatic conditions (i.e. temperature or snowmelt) or to aboveground community changes, such as the addition of organic acids associated with photosynthesis and respiration. Because the pH of an environment affects bacterial growth and plant communities, a pH change could lead to a shift in the dominant soil species. Plant uptake of NO_3^- can raise pH, and uptake of NH_4^+ can lower pH (because NH_4 is a weak acid), by up to two units (Ehrenfeld, 2005). Therefore, if mastication resulted in changes in pH, alterations in species and resource competition may also result. Such changes are not seen as favorable, because shifts in plant community dynamics may encourage the growth of non-native species. In our study, we can

conclude that although pH varies slightly by date, mastication is not the direct cause of pH changes.

4.5 Soil fungal biomass

Ergosterol concentrations were utilized as a proxy for soil fungal biomass. We found no significant trend in soil fungal biomass (Figure 7), determined by the log base 10 of the ergosterol concentration, with site ($p=0.832$) or date ($p=0.406$). This lack of significance suggests that the fungi are not responding to the mastication treatment in the short term. This lack of change in soil fungal biomass may be attributed to counter-balancing processes. Though forest thinning reduces soil fungal biomass, mastication adds woodchips to the site and may increase soil fungal biomass, resulting in no change in ergosterol overall. Additionally, we predict the lack of change in ergosterol results from the continued presence of tree roots, allowing fungi to continue to thrive at the same rate. It appears that despite mastication treatment, the microbial population is relatively constant. Because we find no change in ergosterol concentration, we attribute changes in microbial processes to reflect changes in the bacterial pool size and metabolic activity rather than fungal activity. Additionally, no correlation was found between ergosterol concentration and soil temperature or moisture, suggesting the physical parameters are not limiting soil fungal biomass. Our study analyzed soil fungal changes six to nine months post-mastication, so while there was no change in fungal biomass within the study period, ergosterol concentrations may show greater change over a longer time period.

4.6 Carbon to Nitrogen Ratios

The soil carbon to nitrogen (C:N) ratio provides insight into nutrient availability for microorganisms and plants, and can determine which species are able to establish. Our results show an significant increase in the C:N ratio in both the masticated sites compared to the control sites (Figure 8). Because the sites are significantly different between treatment and control, this increase in C:N is likely correlated to mastication. Examining only post-mastication C:N results, we found the difference between masticated and control sites was statistically significant, $p < 0.0005$ (Sanborn) and $p = 0.003$ (Dome Rock). The mastication treatment led to significant increases in the C:N ratio of the soil. Additionally, the C:N ratio provides insight into which microbial processes are taking place. The C:N ratios at our sites range from 16-34, with an average ratio of 26:1. When C:N ratios are between 20-30, there is typically no net gain or loss of N from the active N cycle (Dennik, 2006). While the mastication treatment resulted in a higher C:N ratio at our study sites, the ratios are still within the 20-30 range, suggesting there is not a substantial change in net mineralization or immobilization from the organic carbon and nitrogen pools.

To further examine the relationship between soil nutrients, we used linear regression to measure the correlation between carbon and nitrogen at our sites. We found strong correlations at all four sites ($r^2 = 0.87-0.95$) (Figure 9). In a study examining the short-term effects of thinning in an old-growth mixed-conifer forest, a similarly strong correlation ($r^2 = 0.92$) between soil total C and N was found (Ma, 2004). This strong correlation suggests that mechanisms within the soil self-regulate to their optimal C:N ratio despite the addition of wood chips on the soil surface. Fungi and bacteria are the likely source regulating the C:N ratio, consuming the organic nutrients and converting them into inorganic forms for plant uptake.

In order to determine whether the increase in C:N ratios is due to an increase in carbon or a decrease in nitrogen, we examined the change in nutrients separately. By making the nutrients

from the thinned trees more accessible to the soil through mastication, we expected an initial influx of both C and N into the soil. In line with our hypothesis, examining percent carbon in the soil at the Sanborn masticated site compared to the control site, we found that carbon percentage increases throughout the summer with a slight decline during our last sampling (Figure 10). This decrease in late summer (8 months after mastication) may be because the stimulated microbes, “primed” with a large amount of accessible carbon from the chips, continue to consume carbon at a high rate. The bacterial community can quickly grow in population and consume the available carbon at a high rate, resulting in carbon depletion through time if more chips are not added. Thus, the end result is a decrease in carbon. Because we are not seeing changes in fungal biomass, changes in soil carbon are not likely linked to an increase or decrease in the fungal population, but rather to bacterial growth and consumption. A subsequent decrease in fungal population may be expected with decreasing carbon. Generally, if the symbiont trees are removed, the fungi will have no host, but if nitrogen becomes scarce, fungi compete better than bacteria. To test this scenario, continued monitoring of ergosterol is necessary.

At Dome Rock, our results show an initial decrease in carbon percentage in the masticated site, followed by a large spike two weeks later during our next sampling. This delayed response in carbon to mastication could be because of the associated delay in soil incorporation. Once the carbon reaches the soil, however, this elevated amount of carbon in the masticated site compared to the control continues throughout summer, until, similar to Sanborn, there is a decrease in carbon in mid-August, our last sampling date. This similar pattern of an increase in carbon in response to mastication with a slight decline toward the end could suggest interesting long-term results. Because microorganisms typically convert C into organic matter through immobilization, with hypothesize C:N ratios, C, and N would decrease over time until they match levels found at the control sites.

Examining the soil nitrogen percentages (Figure 11), we find the same trend as we saw among soil carbon levels. At Sanborn, there is an increase in soil nitrogen percentage at the masticated site, with a decrease at the last sampling date. At Dome Rock, after an initial decrease, there is a spike in soil nitrogen, which remains high until the last sampling date, where there is a slight decrease. The drop in nitrogen may be attributed to the uptake of N by fungi and bacteria, needed for regulation. These closely matched results between carbon and nitrogen percentages explain the high r^2 values between carbon and nitrogen seen in Figure 9. Continued statistical examination of nutrient percentages, C:N ratios, and ergosterol would be useful for determining long-term impacts. A multi-year study of the changes in nutrient availability of a thinned vs. masticated site found that total organic C and total N levels decreased two and three years after mastication was imposed (Stromberger, 2008). The decreased nutrient levels were attributed to a priming effect from additional decomposition by stimulated soil microorganisms. Extended research at our study sites would help confirm or reject the priming hypothesis.

In a meta-analysis on the effects of forest management on soil C and N storage, results from several studies indicate high C:N ratio residues incorporated into soils over the short-term, with soil carbon re-equilibrating to lower carbon and nitrogen levels and C:N ratios more similar to the background values with time (Johnson, 2000). As our research matches this trend thus far, the suggestion that soil nutrient content will re-equilibrate and C:N ratios will decrease to reflect ratios found at control sites seems a logical assumption.

4.7 Mineralization, Ammonification and Nitrification Rates

In addition to changes in soil carbon and nitrogen pools, mastication was predicted to alter the soil nitrogen cycle, including mineralization, ammonification, and nitrification rates. Matson (1992) and Perez (2004) both found that woodchips decreased nitrogen availability, and Blumenthal (2003) similarly found carbon additions to soil decreased N availability. Our results (Figure 12) show an increase in mineralization in the masticated sites compared to the control sites, followed by a decrease and a slight increase again in early fall. We expected an increase in microbial activity (immobilization) after mastication when there was an increase in carbon, followed by a decrease (mineralization) once the microbes consumed the additional, labile carbon. The large increase we see early in the study can be attributed to the increased mobilization of C and N from thinned trees. With greater microbial respiration due to the mobilization, there is high mineralization activity.

In a study examining the effect of a nitrogen fertilization treatment and a woodchip addition treatment, Matson (1992) showed a large increase in mineralization one year later in a fertilization site (168.7 ug/g) compared to a woodchip addition site (-0.5 ug/g) and a control site (-1.7 ug/g). Our study of mastication likely follows the results of the nitrogen fertilization experiment due to fresh, bioavailable nutrients being released after mastication. Once all the nutrients have been depleted from the fresh woodchips, however, our results are more likely to follow the trend of the woodchip addition from Matson's study. Two years post-mastication, Matson found fertilized plots to have more mineralization and nitrification than control plots, whereas the woodchip addition treatment had less mineralization and nitrification than control plots. Longer-term studies of mastication at different sites would reveal whether mastication follows similar trends to the fertilization or the woodchip treatment.

It has been found that factors that affect microorganisms, such as temperature and moisture, can affect the nitrogen conversion and mineralization rates (Deenik, 2006). To determine whether mineralization, nitrification, and ammonification are limited by such factors, we compared mineralization, nitrification, and ammonification rates to soil moisture and temperature.

Overall, few parameters were found to correlate significantly with nitrification, likely because the majority of the mineralization taking place is due to ammonification. Nitrification, a more energy-intensive process, occurs when bacteria in the soil convert NH_4^+ from decaying organic matter to NO_3^- . Although plants can use both NH_4^+ and NO_3^- as nitrogen sources, NH_4^+ is retained in soils by binding to negatively-charged mineral and organic particles. Thus it is reasonable that more ammonification (Figure 13) is taking place compared to nitrification (Figure 14).

Examining the ANOVA results, we found both mineralization and ammonification rates to be significantly different by date. To determine whether this significance is due to the nutrient content (C:N), soil temperature, or soil moisture, we ran linear regressions between the rates and other variables. We found moisture to be negatively correlated with ammonification, but no trend between moisture and mineralization or nitrification. This negative correlation (when moisture increased, ammonification decreased) was unexpected. Deenik (2006) found that in dry soils, N mineralization is low because soil microorganisms activity is limited by water availability. We hypothesized that more moisture would allow for more mineralization, ammonification, and nitrification to occur, because microbes would not be limited by water availability. Our results instead suggest that a low amount of moisture is not a limiting factor for mineralization, ammonification, or nitrification, and that excess moisture may be detrimental for ammonification in these soils. Deenik (2006) also found that in saturated soils, N mineralization is limited due to

the lack of oxygen, so only aerobic soil microorganisms are actively mineralizing. This oversaturation and lack of oxygen is a reasonable explanation for the negative correlation between soil moisture and mineralization.

Soil temperature was also surprisingly negatively correlated with mineralization ($p=0.036$) and ammonification ($p=0.012$). We expected a temperature decrease would reduce mineralization rates, but we observed increased mineralization instead. Typically, warm soils provide favorable conditions for nitrification, but perhaps microbes have a temperature maxima and have adapted to the colder temperatures in the Colorado montane climate. Thus, at warmer temperatures the mineralization rates do not increase. Overall, it appears that temperature and moisture did not have a large impact on mineralization rates.

5. Conclusion

While past ecological studies have focused on how mastication affects biological parameters such as aboveground response (Owen, 2009), understory growth (Kane, 2009; Neal, 2007), or biodiversity (Miller, 2009; Wolk, 2008), our study is unique in its examination of soil interactions. These interactions can be used as an index for the larger forest responses due to mastication. Our results indicate that bacteria, as opposed to fungi, have a larger impact on soil nitrogen and carbon cycling post-mastication. Contrary to our hypothesis, nutrient content, rather than soil temperature or moisture, was the limiting factor for N mineralization. This suggests that projected climate changes such as increased temperature and soil moisture content may not significantly impact soil processes compared to the applied forest management technique in the short-term, though there may be longer term cumulative effects still unknown. While several findings resulted from our short-term study, extending the study for multiple years would provide valuable feedback that is not evident in shorter time frames, including different treatment options over a greater number of sites and ecosystems. Additionally, the results of our study provide insight into which parameters would be most important to examine in future studies.

Examining the physical properties of soil responses to mastication, we analyzed soil moisture, temperature, and bulk density. Though our soil moisture results are consistent with similar studies (Owen 2009, Neal 2007, Marchand 2006, Matson 1992, Blumenthal, 1991), the impact of temperature is not as clear, and may have a negative correlation with nitrification rates. Because no trend of increased bulk density in treated areas due to soil compaction from the mastication equipment was found, we conclude that the mastication equipment has little effect on the soil physical properties and is not of great concern when considering the impacts of mastication as a forest management technique.

In addition, we analyzed soil biological and chemical parameters. While it was important to examine pH to ensure control sites did not differ in acidity from treatment sites (to not confound our results), no change in pH is expected over time, and does not appear to be a significant factor in soil response, but rather a potential indicator of soil respiration as a function of season. As fungi are a key player in soil-plant interactions, a long-term analysis of the soil fungal biomass via ergosterol concentrations would be valuable to determine whether the fungal pool is simply slow to respond or unresponsive to the forest management technique.

Because of the active response in mineralization, ammonification, and nitrification rates for both site and date, we recommend continued monthly monitoring of NO_3^- and NH_4^+ concentrations. Because there are multiple methods for measuring net N mineralization, with advantages and disadvantages for each one, continuing with the same procedure is suggested so that longer-term results can be compared to our short-term results. The bacterial N cycle was

observed to respond on weekly to monthly timescales, considerably more rapidly than the fungal community. Additionally, it would be interesting to compare with a lab incubation to affirm our results, as our variances may have been smaller had we done lab incubation.

Due to the complex biogeochemical processes occurring within the soil ecosystem, a close monitoring of soil and microorganism responses post-mastication is a valuable step towards understanding different forest management techniques. Plant-soil feedback processes are not only integral to many ecological processes, but they are also a prominent component of the ecological responses to global environmental changes. No system can remain immune from certain disturbances; in the future, few areas will be protected from direct human activity (Hobbs, 1992). Forests, like most natural resources, require proper management to be healthy and productive. Therefore, it is important to find the right regional management technique for a particular ecosystem. Our findings should be useful for forest managers assigned to assess and predict the consequences of alternative forest management techniques of ponderosa pine forest ecosystems of the Rocky Mountain region. If we aim for optimal native diversity at the landscape level, restoring forests so that disturbance occurs at its historical frequency, pattern, and severity is ideal. As with any forest management technique, it is important for results to be analyzed before the technique is widely implemented. Mastication may be a method that assists in the forest restoration process, and is a valuable management technique warranting further long-term research.

6. Acknowledgements

Many thanks and immense gratitude go to Howard Drossman for his guidance, project design, and advising; Matt Reuer for his invaluable assistance in the lab and his dedication throughout the project, and Janell Harvey her assistance in field sampling. Funding for this research has been supplied through the Coalition for the Upper South Platte (CUSP) and Catamount Center.

7. Appendices

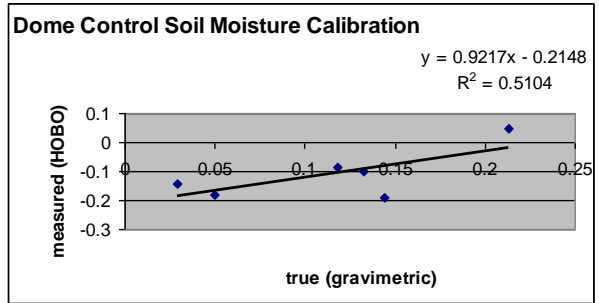
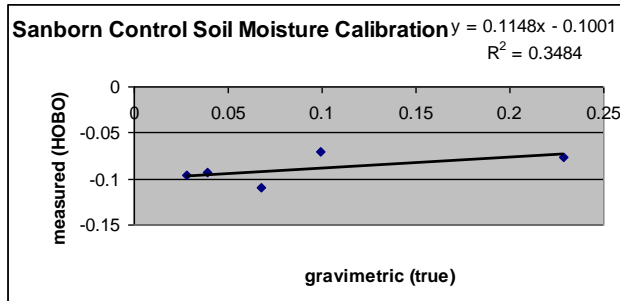
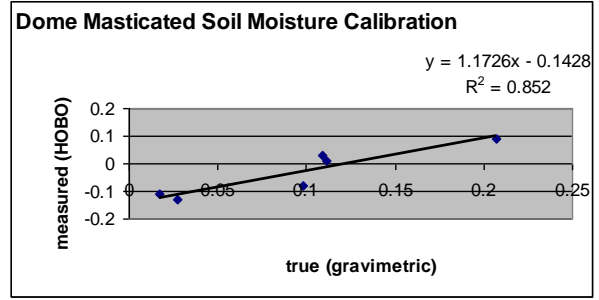
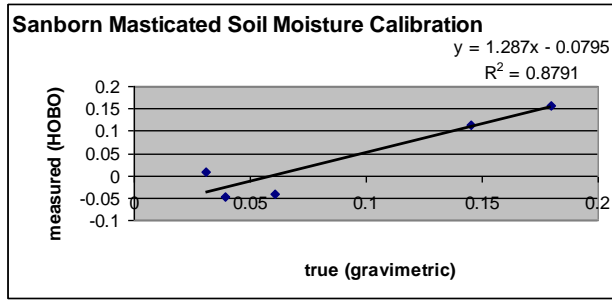
Appendix 1: GPS coordinates of control and masticated plots at Sanborn Nature Camp and Dome Rock

S1: 13S 047 913/ 4306191	CS1: 13S 0471943/ 4305962	D1: 13S 0408342/ 4303006	CD1: 13S 0480166/ 4303077
S2: 13S 0471835/ 4306191	CS2: 13S 0471890/ 4306043	D2: 13S 0480336/ 4302892	CD2: 13S 0480196/ 4303108
S3: 13S 0471817/ 4306232	CS3: 13S 0472045/ 4305887	D3: 13S 1480516/ 4302859	CD3: 13S 0480248/ 4303053
S4: 13S 0471828/ 4306275	CS4: 13S 0472119/ 4306031	D4: 13S 0480466/ 4302947	CD4: 13S 0480299/ 4303136
S5: 13S 0471934/ 4306240	CS5: 13S 0471986/ 4306073	D5: 13S 0480449/ 4303058	CD5: 13S 0480447/ 4303202

Appendix 2: Dates of soil sampling at each site

Sanborn	1/7/11	6/7/11	6/21/11	7/4/11	7/20/11	8/14/11	9/17/11
Control Sanborn	11/20/10	6/7/11	6/21/11	7/4/11	7/20/11	8/14/11	9/17/11
Dome Rock	1/7/11	6/10/11	6/21/11	7/4/11	7/20/11	8/14/11	9/17/11
Control Dome Rock	11/20/10	6/10/11	6/21/11	7/4/11	7/20/11	8/14/11	9/17/11

Appendix 3: Soil moisture calibration graphs at each site



8. References

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