FINAL REPORT
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Effects of Forest Thinning and Chipping on Soil Properties and Understory Vegetation at Heil Valley Ranch

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Abstract

Boulder County Parks and Open Space utilizes mechanical forest thinning for wildfire mitigation. The purpose of this research project was to determine how mechanical thinning and chipping affect soil properties and understory regeneration at Heil Valley Ranch. Thinning creates significant physical disturbance to soil and vegetation, creating conditions that are favorable for the establishment of early seral plant species, including undesirable exotic weeds. Thus, forest management for fire mitigation frequently leads to management for exotic species invasions. One fire mitigation practice utilized by BCPOS is the conversion of unmerchantable timber into woodchip biomass, which may be spread on-site as mulch. The ecosystem effects of woodchip mulch applications to thinned forest remain largely unstudied. In this project, I tested the abiotic and biotic effects of woodchip amendments in a thinned forest, within the context of experimentally-manipulated gradients of soil nitrogen and phosphorus availability. Here, I will summarize the findings of the 2006 growing season. I found that woodchip mulch did not significantly alter soil pH or plant-available nitrogen and phosphorus, but did significantly affect the species richness, composition, and percent native cover of understory plant species. The differential effects of woodchip mulch on understory plant species indicate that the application of woodchip mulch in thinned forest may not be a one-size-fits-all management treatment, but it may promote forest restoration under certain circumstances.

Introduction

The Eastern Slope of Colorado's Front Range is a high-priority area for fire mitigation efforts. Due to decades of fire suppression, lower montane forests have expanded in density and range such that conditions now favor severe, stand-replacing fires in many areas[1]. In an effort to reduce the threat of wildfire to human communities, land managers such as BCPOS utilize mechanical thinning in surrounding forest. Mechanical thinning, however, alters the physical structure and the ecological functioning of the site[2,3].

One management concern is that thinned forests are especially susceptible to exotic species invasions. Ecological research has shown that exotic plant species are most likely to invade ecosystems where the availability of resources exceeds the level of use by resident species[4-11]. A mechanically thinned forest has ample light, space, and substrate for the establishment of understory plants, both native and exotic. However, a common fire mitigation practice is to chip and spread excess wood on-site, a procedure that alters the soil substrate. Additionally, woodchips may introduce novel chemical effects to the soil[12-15]. Other studies have found that carbon-based soil amendments (i.e. sugar, sawdust) reduce soil nitrogen availability, which in some cases inhibits the relative success of non-native plants[16-25]. The purpose of this project is to identify how wood chip amendments affect soil properties and understory species richness, composition, and diversity.

An additional factor that affects ecosystems along the Eastern Slope of Colorado's Front Range is the chronic, inadvertent "fertilization" effect of atmospheric nitrogen pollution and long-term fire suppression[26-31]. Since the native grasses and forbs of the Front Range evolved under conditions of low nitrogen availability, the current regime of nitrogen enrichment undermines the competitive strategy of native species while releasing potential invaders from prior nutrient limitations. Furthermore, in ecosystems that have experienced nitrogen (N) enrichment due to atmospheric deposition, phosphorus (P) availability has been found to be an important factor in the distribution of native and exotic species[32,33]. The role of P availability in determining patterns of plant invasion in N-enriched ecosystems is a topic that deserves more exploration. Thus, a component of this project is to investigate how nutrient availability in a thinned forest affects its relative invasibility.

I hypothesized that wood chip amendments would interact with gradients of nutrient availability to affect the diversity and abundance of native and exotic understory species in thinned lower montane forest. The specific objectives of this project were as follows:

Objective 1: To elucidate how mechanical thinning, with and without the spreading of wood chip mulch, affects understory vegetation and soil properties at Heil Valley Ranch.

Objective 2: To identify how physical and chemical disturbances influence the pattern of establishment of native plants and exotic weeds.

The results of this project are anticipated to be of use in future fire mitigation and vegetation management decisions by BCPOS.

Methods

Study site

The research site is within Stand 4, Unit A at Heil Valley Ranch. This lower montane site (elevation 2070m) was densely covered by ponderosa pine (*Pinus ponderosa*) prior to thinning in the summer of 2004. Understory vegetation was minimal or absent throughout, although several non-native weed species of priority management concern (including *Carduus nutans*, *Cirsium arvense*, and *Linaria dalmatica*) were present in meadows surrounding the site. Classified as one of the high-priority fire risks on BCPOS property, the site was mechanically thinned for fire mitigation purposes by BCPOS from August 2004 to June 2005. All stems smaller than 7" dbh were removed, reducing basal area from ~197 sq. feet/ac to ~ 104 sq. feet/ac.

Experimental Design

Following thinning, I set up 90 experimental plots in a blocked 3x3x2 factorial design to experimentally alter soil nitrogen and phosphorus availability in the presence and absence of wood chips. Nitrogen availability was manipulated at three levels (addition, ambient, and reduction), phosphorus availability at three levels (addition, ambient, and reduction), and application of woodchip mulch at two levels (present or absent). Thus, there were 18 possible combinations, or treatment types. Each treatment type was randomly assigned to a plot within a block, with 5 replicate blocks. Plots measure 1.5m x 1.5m square, with a 1m buffer on all sides.

For plots receiving woodchip applications, I applied woodchips by hand to an average depth of 3” in the appropriate plots (depth is standard silvicultural practice). Chemical nutrient amendments were then applied monthly during the growing seasons of 2005 and 2006. The rates of chemical nutrient amendments were determined in accordance with previously successful nutrient manipulations in Front Range ecosystems (Seastedt, unpublished data).
Table 1 indicates the nutrient amendments used and their rates of application.

Treatment	Soil Amendment	Rate
Nitrogen Addition	ammonium nitrate	10g N/m^2/y
Nitrogen Reduction	sucrose	500g C/m^2/y
Phosphorus Addition	super phosphate	2g P/m^2/y
Phosphorus Reduction	gypsum	10g Ca/m^2/y

Table 1.

Monitoring Soil Response

Prior to thinning, I collected 30 soil samples from the site to obtain baseline values for soil pH, KCl-extractable nitrate and ammonium, resin-extractable inorganic P, and bicarbonate-extractable inorganic and total P. I repeated those soil collections and nutrient analyses in the spring of 2005 and 2006. Bulk density cores were collected in July 2006. Bulk density was not found to vary significantly throughout the site.

To monitor the flux of N and P over time, I installed 3 resin bags (J.T. Baker Mixed Bed Exchange Resin) in each plot for the growing season of 2005. This measure was repeated over the winter of 2005-2006 and the growing season of 2006. Resin bags contained 10g of mixed ion resin each and were installed at a depth of 5-10cm. Soil cores were also collected in May 2005. Soil cores and resin were analyzed for KCl-extractable NO_3^-, NH_4^+ and HCl-extractable inorganic P. The nutrient responses to treatments were analyzed via regression. Due to the logarithmic nature of the results, nutrient results were analyzed using log-transformed data; however, actual values are presented in the results section. Nutrient analyses of the resin bags from summer 2006 are currently in progress.

Monitoring Vegetative Response

Prior to thinning, I surveyed the understory species composition of each experimental block. Understory cover was minimal, due to the dense canopy and thick duff layer. Following thinning, understory plant establishment was abundant. In August 2005, June 2006, and August 2006, I recorded post-thinning species composition, richness, and diversity using point-intercept sampling of the central 1m^2 of each plot. Treatment effects on species diversity, distribution of individual species, and distribution of functional groups were analyzed using regression and ANOVA. For all figures in this report, values represent the mean +/-1 standard error.

Danthonia Seeding Experiment

To explicitly test how woodchip amendments affect the establishment of desirable understory vegetation, I broadcast-seeded native Poverty Oatgrass (*Danthonia spicata)* into a subset of plots in April 2006. The seed used for this study was donated by BCPOS. It was locally collected on BCPOS property in 2005 and had been analyzed to be 90% PLS. I utilized a seeding rate of 1300 PLS/m^2 (2g per half-plot), a rate at the upper limit of restoration seeding. The plots used for the Danthonia seeding experiment were those receiving phosphorus additions (6 plots per block, 30 plots total). I seeded only the north half of each plot so that the south half could serve as a control for comparison when measuring seedling establishment.

However, when I measured the Percent Cover of *Danthonia* seedlings in August, I found that the seeded halves of the plots did not have significantly greater *Danthonia* cover than the unseeded halves, indicating that germination was unsuccessful. Therefore, the *Danthonia* seeding experiment will not be discussed.

Results and Discussion

Abiotic Results: Soil Moisture and pH

Average percent soil moisture was significantly greater in woodchipped plots (29%) than in unchipped plots (24%; $p=0.02$; Figure1). As expected, nutrient amendments did not affect soil moisture.

Woodchips did not alter soil pH (Figure 2). Two nutrient treatments slightly altered soil pH: In plots treated with ammonium nitrate and/or gypsum, the average pH was ~5.35, as compared to an average pH of ~5.5 in all other plots. Although statistically significant ($p<0.004$ in each case), an alteration of pH of this magnitude is unlikely to be ecologically significant.

Figure 1. Woodchip plots had greater percent soil moisture than unchipped plots, on average.

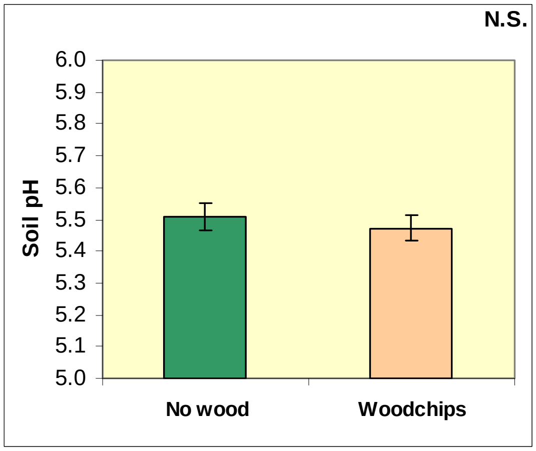

Figure 2. Woodchips did not significantly affect soil pH.

Abiotic Results: Soil Nutrients

In the first summer of the experiment, plant-available nitrogen (as measured by summer 2005 resin bag absorption of ammonium (NH_4) and nitrate (NO_3)) was significantly increased by nitrogen fertilization treatments ($p<0.0001$ for both NH_4 and NO_3), but was not significantly affected by either sugar or woodchip treatments.

Over the following winter, however, the effects of the summer's nutrient treatments became apparent: In sugar plots, winter resin bags collected ~1/10th the ammonium and nitrate as compared to control plots. In nitrogen fertilized plots, winter resin bags collected ~10 times the ammonium and nitrate as control plots ($p<0.0001$ for both NH_4 and NO_3; ammonium results shown in figure 3). Furthermore, in plots where nitrogen had not been chemically manipulated, woodchip amendments significantly reduced ammonium and nitrate availability by ~50% ($p<0.0001$ for both NH_4 and NO_3). In sugar and N-fertilized plots, this trend is absent, suggesting that the presence of woodchips initially interacted with the chemical soil amendments. Due to the logarithmic scale of the effects, these results were statistically analyzed using log-transformed data.

By May 2006, however, the effect of woodchips on plant-available nitrogen was prevalent throughout all treatment types: In spring soil cores, average nitrogen availability was significantly lower in all woodchip plots, as compared to all unchipped plots ($p<0.03$ for both ammonium and nitrate; results for nitrate shown in figure 4).

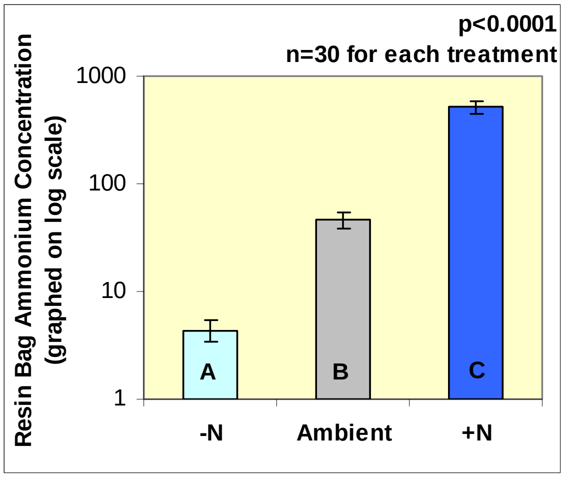

Figure 3. Winter 05-06 Resin Bag concentrations of ammonium. Soil nitrogen manipulations had the intended effect: There were 10-fold differences in ammonium availability for sugar, control and N-fertilized plots. Nitrate availability, not shown here, followed the same trend.

Figure 4. Spring 2006 Soil Cores. One year after the inception of the experiment, average nitrate availability was ~50% lower in woodchip plots than in unchipped plots, across all treatment types. The same trend was found for ammonium availability.

Vegetation Results 2006

Species Diversity, Richness, and Evenness

Species diversity was significantly reduced in woodchip plots ($p<0.0002$; Figure 3). Diversity is a measure of species richness and evenness; in this case, the lower diversity in woodchip plots can be attributed to poor species richness. On average, woodchip plots contained about half the number of plant species as unchipped plots (average richness in woodchip plots was 8.7, whereas average richness in unchipped plots was 4.4; $p<0.0001$). In contrast, evenness of species distributions was consistent throughout all plots, regardless of treatment type ($p>>0.05$ for ANOVA). Species diversity was not significantly affected by nitrogen or phosphorus availability.

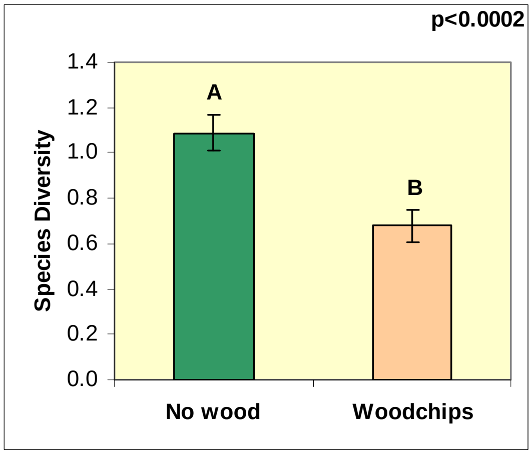

Figure 5. Plant understory species diversity was significantly greater in unchipped plots than in plots receiving woodchip amendments.

Percent Vegetative Cover

Increased species richness was also consistently associated with increased percent of ground covered by vegetation (Percent Cover) in the experimental plots ($R^2=0.50$, $p<0.0001$; Figure 4). In other words, greater percent cover was largely attributable to greater recruitment of species rather than to the increased size or abundance of a few dominant species. Overall, Percent Cover was significantly lower in woodchip plots than in unchipped plots ($p<0.0001$; Figure 5).

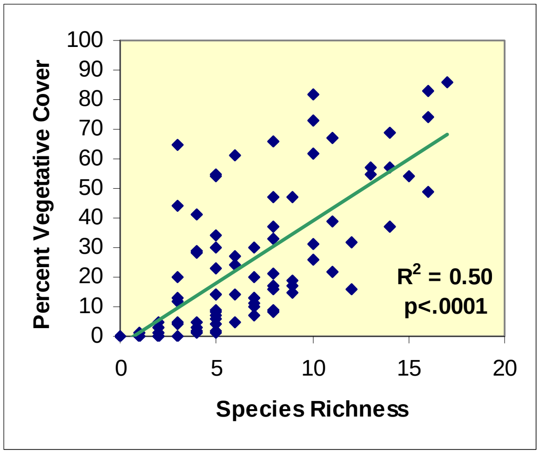

Figure 6. Percent cover is positively associated with species richness.

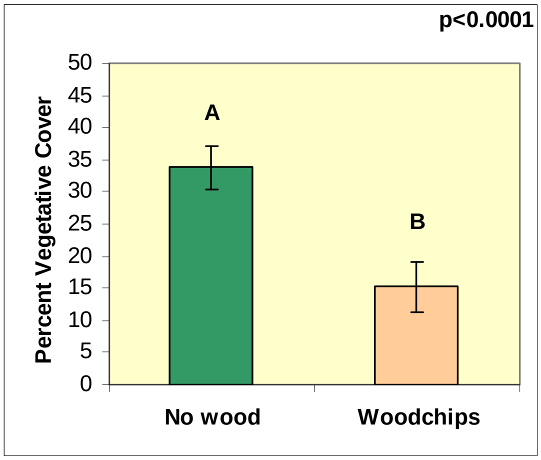

Figure 7. Average percent vegetative cover was 34% in unchipped plots and 15% in chipped plots.

Percent Cover was also significantly greater in plots fertilized with nitrogen, as compared to plots with ambient or reduced levels of nitrogen (p=0.0015; Figure 6). In other words, plant growth was more abundant when more nitrogen was available, indicating that nitrogen is a primary limiting nutrient for understory establishment in this area. In contrast, phosphorus manipulations did not affect Percent Cover, which implies that phosphorus must not be a limiting nutrient for the understory plants at Heil Ranch.

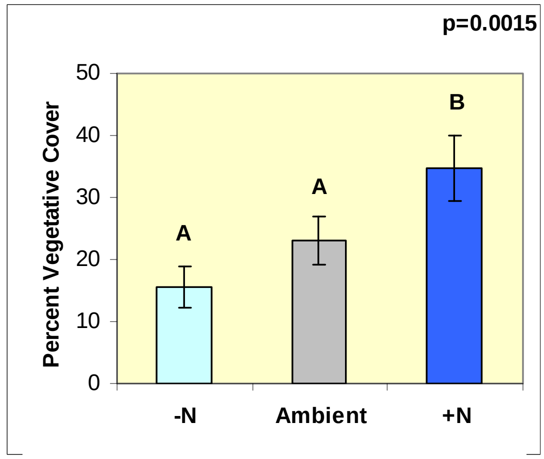

Figure 8. Nitrogen enrichment significantly increased the average percent cover of vegetation.

<u>Relative Abundances of Plant Groups and Weed Species</u>

Relative Abundance is defined as the percentage of the plant cover that is comprised of a certain species or group. Here, I will report first on the overall relative abundances of broad groups of plants (native and non-native graminoids and forbs) for the entire site, and then will itemize the responses of plant groups and weed species to the experimental manipulations.

Overall, native plants comprised 28% of the total vegetative cover in experimental plots, whereas non-natives made up the remaining 72%. This trend supports the expectation that non-native, weedy pioneer species are especially likely to invade following physical disturbance. Non-native forbs were the most abundant vegetation type. Non-native graminoids and native graminoids were roughly equally abundant and, combined, made up approximately half of the vegetative cover. Native forbs and shrubs were minimally abundant (Figure 7).

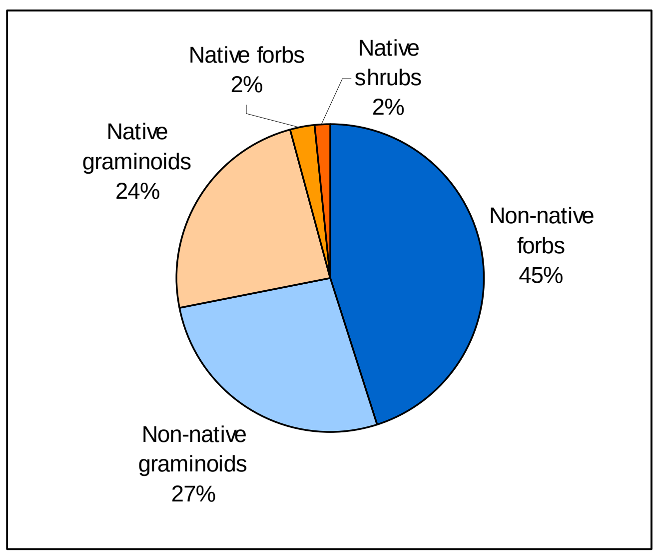

Figure 9. Overall, non-native plants made up nearly ¾ of the total plant cover in the experimental plots. Non-native forbs were the most abundant vegetation type. Native and non-native graminoids were approximately equally abundant. Native forbs and shrubs were rare.

Altogether, nearly 80% of the total vegetative cover was made up of the following seven species: Canada Bluegrass (*Poa compressa*), Canada thistle (*Cirsium arvense*), Kentucky bluegrass (*Poa pratensis*), mullein (*Verbascum thapsus*), poverty oatgrass (*Danthonia spicata*), sedge (*Carex spp.*), and ticklegrass (*Agrostis scabra*). Of these, Canada thistle and Kentucky bluegrass were most abundant, each comprising 20% of the total vegetative cover (Figure 8).

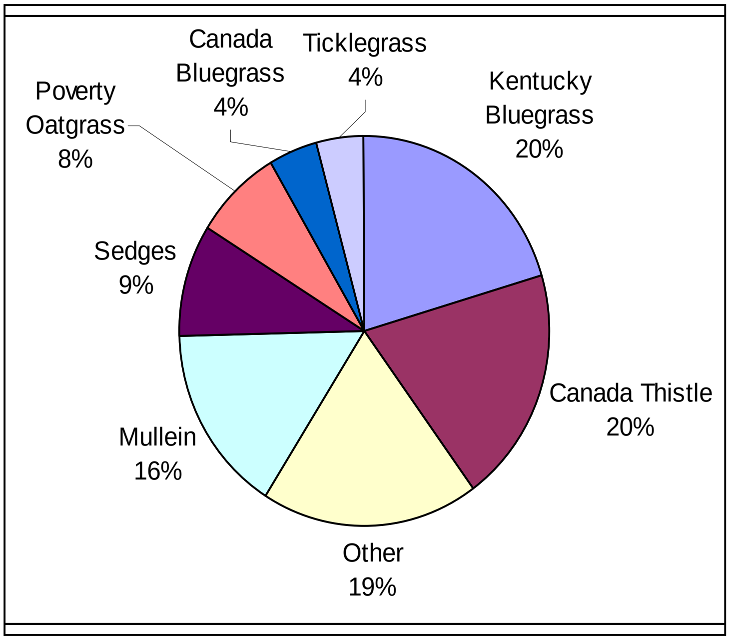

Figure 10. Species breakdown of percent vegetative cover, for all experimental plots combined. Shown here are the 7 most abundant species. The remaining category of "Other" was made up of 45 species.

Responses to Experimental Manipulations

Native Plants

The relative abundance of native plants was unaffected by woodchip treatments; that is, native plants comprised approximately the same percentage of the vegetation in chipped and unchipped plots. However, the relative abundance of natives was strongly sensitive to levels of N availability. Native plants comprised a significantly greater percentage of the vegetation in plots with reduced-N, as compared to ambient- or enriched-N plots ($p=0.01$; Figure 9). This trend supports the concept that native species are especially well-adapted to low soil nitrogen availability and are constrained in their ability to respond to nitrogen fertilization. Reciprocally, non-native species made up a greater portion of the vegetation in ambient- and enriched-N plots, but it is worth noting that nitrogen fertilization did not further increase the relative abundance of non-native plants above and beyond ambient levels. Phosphorus manipulations did not affect relative abundance of natives, indicating that phosphorus does not limit the establishment or survivorship of natives or non-natives.

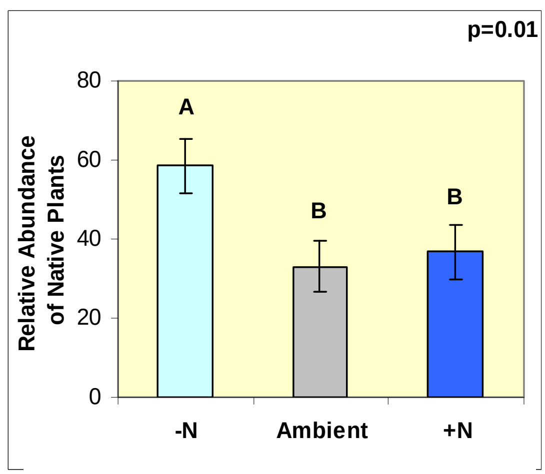

Figure 11. Native plants comprised 59% of the vegetation in reduced-N plots, on average. In ambient and enriched-N plots, natives comprised a significantly smaller portion of the vegetation.

Native Grasses, Sedges, and Rushes

This group is comprised of Foxtail Barley *(Hordeum jubatum)*, Junegrass *(Koelaria macrantha)*, Muttongrass *(Poa fendleriana)*, Poverty Oatgrass *(Danthonia spicata)*, Sedges *(Carex spp.)*, Squirreltail *(Elymus eymoides)*, Ticklegrass *(Agrostis scabra)*, and Woodrush *(Luzula spp.)*.

Woodchips had a negative effect on the relative abundance of native graminoids (grasses, sedges, and rushes) at a marginal level of significance (p=0.07; Figure 10). Thus, woodchip applications in thinned forest appear to suppress the subsequent establishment of the historical understory vegetation type: native graminoids.

Where nitrogen was manipulated, native graminoids comprised a significantly greater percentage of the plant cover in reduced-N plots, as compared to ambient- or enriched-N plots (p=0.02; Figure 11). These results indicate that native graminoids are well-adapted to low nitrogen levels but are limited in their ability to respond to nitrogen enrichment. Due to the history of fire suppression in the area and ongoing atmospheric nitrogen deposition, current ambient levels of soil nitrogen are likely to be enriched in comparison to historical levels. Thus, nutrient status may further hamper efforts to re-establish native graminoids in thinned forests. Phosphorus availability did not affect the relative abundance of native graminoids.

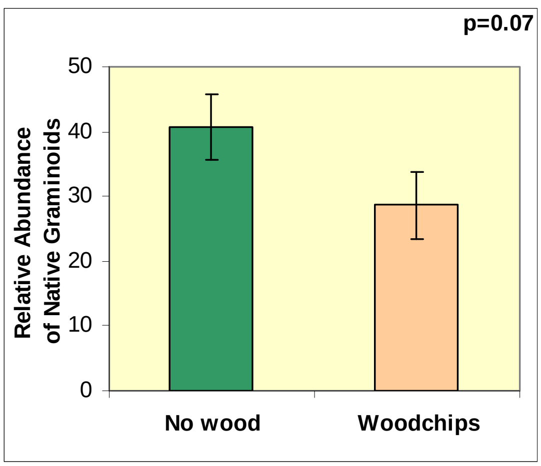

Figure 12. The average relative abundance of native graminoids was 41% in unchipped plots and 29% in woodchip plots.

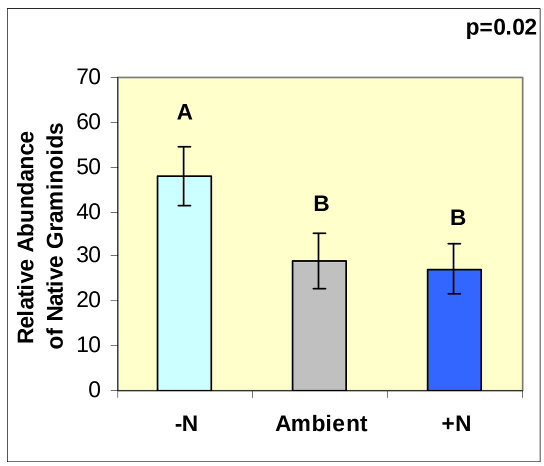

Figure 13. The average relative abundance of native graminoids was 48% in reduced-N plots and ~28% in ambient and enriched-N plots.

Non-Native Grasses

This group is comprised of Canada Bluegrass *(Poa compressa)*, Cheatgrass (*Bromus tectorum)*, Japanese Brome (*Bromus japonicus)*, Kentucky Bluegrass (*Poa pratensis)*, and Timothy (*Phleum pretense)*.

Relative abundance of non-native grasses was not affected by woodchips or nitrogen availability, but it was affected by phosphorus availability at a marginally significant level (p<0.07). The relative abundance of non-native grasses was significantly reduced in plots where phosphorus availability had been altered in either direction. This trend suggests that non-native grasses, as a group, may be especially sensitive to N:P ratios, such that their establishment is inhibited when that ratio is altered.

Native Forbs

The relative abundance of native forbs was uniformly low (an average of 2% of the vegetative cover) across all treatment types. There were no direct effects of N, P, or wood manipulations on the relative abundance of native forbs. A list of the native forbs found at the site can be found in Appendix 1.

Non-Native Forbs

As a group, the non-native forbs comprised the largest percentage of vegetation cover and demonstrated significant sensitivity to nitrogen levels. The relative abundance of the non-native forbs was significantly lower in N-reduced plots, as compared to ambient- and enriched-N treatments ($p<0.02$, Figure 12). This trend suggests that N reduction can inhibit the establishment of non-native forbs. Phosphorus and woodchip manipulations did not affect the relative abundance of non-native forbs.

A list of the non-native forbs counted in this study can be found in Appendix 1.

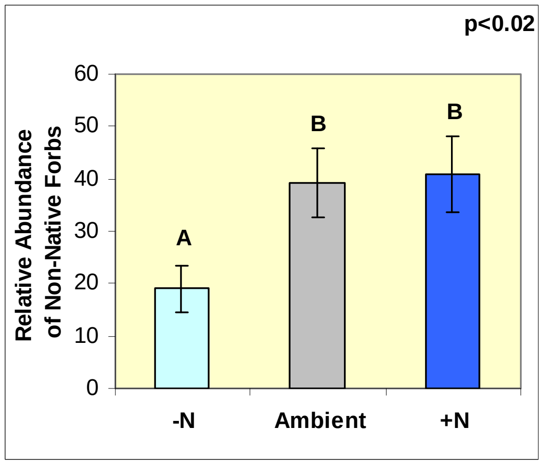

Figure 14. The average relative abundance of non-native forbs was significantly less in reduced-N plots.

Species-Specific Responses in Relative Abundance

Following are species-specific responses for four invasive non-native forb species that are of special concern for weed management at Heil Valley Ranch.

Mullein

Mullein abundance was strongly inhibited by woodchips ($p<0.0001$). Woodchip plots contained an average of 1% cover by mullein, as compared to an average of 19% in unchipped plots. Mullein abundance was also lower in N-reduced plots, both chipped and unchipped ($p<0.0001$; Figure 13). One trend that was not captured by the methods of this project but that was visually apparent was the abundant establishment of mullein along the edges of woodchip plots (Figure 14). Although these edges are an artifact of an experimental design, it is likely that mullein would exhibit similar establishment patterns in areas where woodchip mulch was applied at spatially variable depths. Gaps in woodchip application provide sunny spots for a seedling to establish, yet receive some of the temperature insulation and moisture-conserving properties of the surrounding mulch.

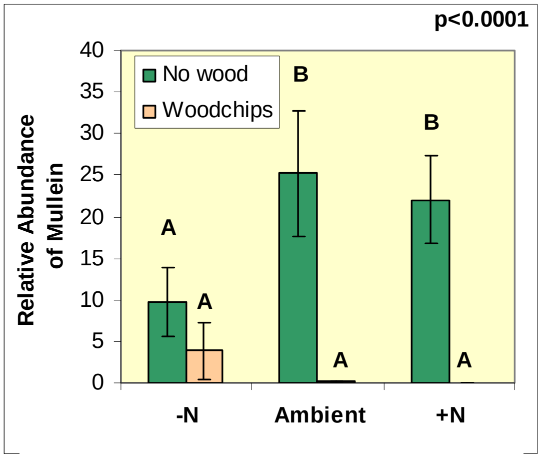

Figure 15. Mullein was scarcely abundant in woodchip plots. Nitrogen reduction also inhibited mullein abundance.

Figure 16. Along the edges of woodchip plots, mullein establishment was abundant.

Canada Thistle

The average relative abundance of canada thistle was three times greater in woodchip plots than in unchipped plots (p=0.02; Figure 15). Furthermore, there was a weak but significant positive relationship between the Percent Cover of Canada thistle with the Percent Cover of stumps (R^2=0.06, p=0.02; Figure 16). Stumps may create a "nurse" effect that promotes the survivorship of Canada thistle seedlings, due to the shading provided and the moisture-holding capacity of the decomposing wood.

Figure 17. The average relative abundance of Canada thistle was 7% in unchipped plots and 19% in chipped plots.

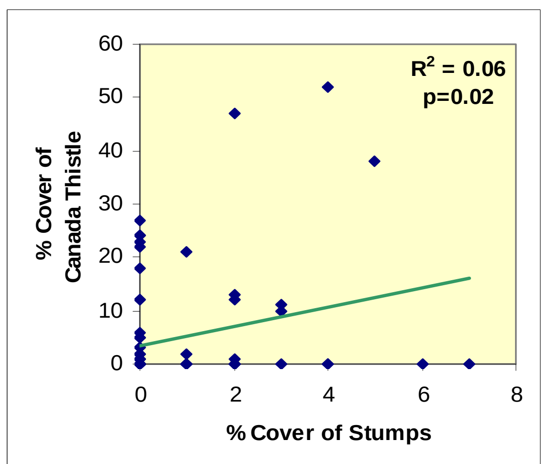

Figure 18. The percent cover of Canada thistle was positively associated with the percent cover of stumps.

Canada thistle also achieved its greatest relative abundance in enriched-N plots ($p<0.05$; Figure 17), indicating that it is disproportionately capable of responding positively to nitrogen fertilization, as compared to other species. Manipulations of phosphorus did not affect relative abundance of Canada thistle.

Thus, it appears that the effort of woodchip mulching in thinned forest, especially in areas that have experienced decades of fire suppression and ongoing atmospheric nitrogen deposition, creates conditions that are ideal for the subsequent establishment of Canada thistle.

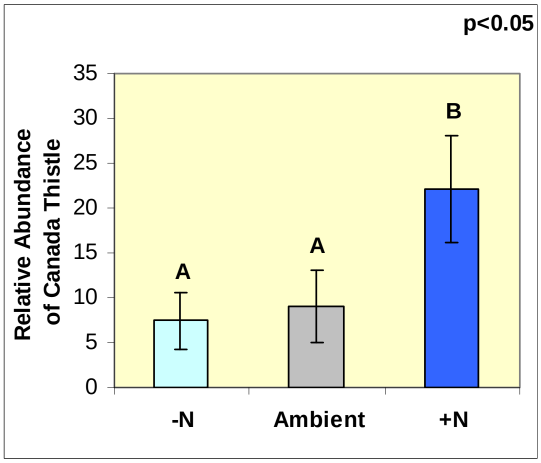

Figure 19. The relative abundance of Canada thistle was greatest, on average, in nitrogen-enriched plots.

Musk Thistle and Bull Thistle

In contrast to the establishment patterns of Canada thistle, the relative abundances of musk thistle and bull thistle were not affected by woodchip amendments. For musk thistle, there was a marginally significant trend that indicated strong inhibition in reduced-N conditions and moderate inhibition in enriched-N conditions ($p<0.10$; Figure 18). For bull thistle, abundance was low throughout all treatment types. It was especially scarce in N-reduced plots and P-enriched plots. Although its low levels of abundance led to large variability in trends, a marginally significant interaction effect between N and P availability suggested that bull thistle is most successful where the N:P ratio is high, either by increasing N with respect to P, or by reducing P with respect to N ($p<0.08$).

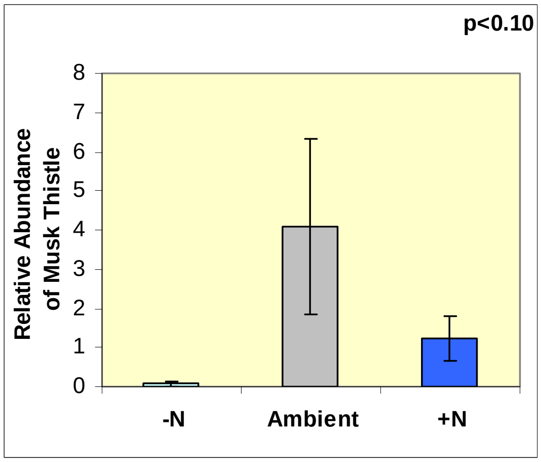

Figure 20. Musk thistle was nearly absent in reduced-N plots and scarcely abundant in N-enriched plots.

Conclusion

Mechanical forest thinning for fire mitigation is a fact of life for land managers throughout the West, including Boulder County Parks and Open Space. However, the physical disturbances of mechanical thinning create conditions that encourage the introduction and establishment of weeds. Overall, non-native plants were three times more abundant at the site than native plants in the second summer following thinning. In fact, over half of the total vegetative cover in the experimental plots was comprised of three non-native species (Canada thistle, Kentucky bluegrass, and mullein). Thus, it is clear that the physical reduction of forest density to historical levels leads to secondary ecological issues at the site.

Wood chip amendments introduce further novel chemical and physical effects that impact understory vegetation reestablishment. Within a year of the inception of the experiment, concentrations of plant-available nitrogen (ammonium and nitrate) were found to be 50% lower in woodchip plots, as compared to unchipped plots. Woodchips were not found to alter soil pH, but they did increase average percent soil moisture. These alterations to nitrogen and water availability are likely to be primary factors that explain the observed 50% reduction in understory species richness in woodchip plots; in other words, the chemical and physical effects of woodchip amendments seem to select for a certain suite of understory species.

Specifically, the native graminoids were significantly less abundant in woodchip plots, as was a weed species of local management concern, mullein. The non-native grasses were equally abundant in chipped and unchipped plots. Only one species was found to consistently achieve greater abundance in woodchip plots: Canada thistle. Thus, in sites where Canada thistle is a weed concern, woodchip application may compound the problem. On the other hand, if mullein is a primary concern, woodchips may be a useful treatment. Neither musk nor bull thistle demonstrated a response to woodchip amendments.

An additional factor to affecting weed management in thinned forests along the eastern slope of Colorado's Front Range is that of chronic soil nitrogen enrichment. Decades of fire suppression and chronic atmospheric deposition have likely led to a gradual accumulation of soil nitrogen. Since the native plants of the Front Range have evolved with low nitrogen availability, it was expected that ambient conditions would not be most favorable for the establishment of native species following the physical disturbance of forest thinning. In fact, I did find that native plants as a group, and specifically, native graminoids, achieved significantly greater abundance when I experimentally reduced nitrogen availability. In contrast, I found a dramatic inhibition of both mullein and musk thistle when nitrogen availability was chemically reduced. Canada thistle was not inhibited by reductions in nitrogen availability, but it demonstrated a dramatic increase in relative abundance in response to nitrogen fertilization.

Although woodchip treatments did effectively reduce soil nitrogen concentrations over time, the patterns of vegetation establishment in woodchip plots were profoundly different than those of chemically nitrogen-reduced plots. Thus, the physical effects of woodchip amendments appear to be more important than their effects on soil nutrient availability, in terms of their influence on understory vegetation establishment. Prescribed burning may be a useful tool to reduce total concentrations of soil nitrogen, although it does create a temporary flush of readily plant-available nitrogen in the ash layer (as demonstrated by the lush growth of musk thistle following the fire of 2004 at Heil Valley Ranch).

In conclusion, where the dual management concerns of fire mitigation and weed management coexist, the decision to apply woodchip mulch should be guided by existing weed management concerns. Woodchip amendments were shown to have differential effects on understory plant species. Notably, native graminoids and mullein were inhibited by woodchips, whereas Canada thistle increased in abundance where woodchips were applied. Furthermore, chronic accumulation of soil nitrogen may be undermining efforts to reestablish native graminoids and exclude non-native weeds in the understory.

APPENDIX 1: List of Native and Non-Native Forbs at Site.

List of Native Forbs:

Aster, Hairy Golden	*Heterotheca villosa*
Aster, Porters	*Aster porteri*
Broom Senecio	*Senecio spartioides*
Chiming Bells	*Mertensia lanceolata*
Cinquefoil - hairy green	*Potentilla spp.*
Cinquefoil, Wooly	*Potentilla hippiana*
Cudweed	*Graphalium uliginosum*
Fleabane, Early Bluetop	*Erigeron vetensis*
Goldenrod - rough	*Solidago nana*
Goldenrod - amooth	*Solidago simplex*
Gumweed, Curlycup	*Grindelia squarossa*
Harebell, Common	*Campanula rotundifolia*
Horseweed	*Conzya spp.*
Onion, Nodding	*Allium ceruum*
Parsley, Whiskbroom	*Harbouria trachypleura*
Ragweed	*Ambrosia psilostachya*
Rockcress, Drummond's	*Boechera drummondii*
Sage, Fringed	*Artemisia frigida*
Salsify	*Tragopogon spp.*
Sandwort, Desert	*Eremogone fendleri*
Willowherb, Tall Annual	*Epilobium brachycarpum*
Yarrow	*Achillea lanulosa*

List of Non-Native Forbs:

Dandelion	*Taraxacum officinale*
Dock, Curly	*Rumex crispus*
Knotweed, Erect	*Polygonum douglasii*
Lambsquarters	*Chenopodium album*
Mullein	*Verbascum thapsus*
Prickly Lettuce	*Lactuca serriola*
Sorrel, Red	*Rumex acetosella*
Thistle, Bull	*Cirsium vulgare*
Thistle, Canada	*Cirsium arvense*
Thistle, Musk	*Carduus nutans macrolepsis*
Toadflax, Dalmation	*Linaria dalmatica*
Vervain, Prostrate	*Verbena bracteata*

Literature Cited

1. Veblen, T. T. & Brown, P. M. in *Unpublished report to the regional office of the US Forest Service* (Denver, CO, 2001).
2. Harrod, R. J. The effect of invasive and noxious plants on land management in eastern Oregon and Washington. *Northwest Science* 75, 85-90 (2001).
3. Kizlinski, M. L., Orwig, D. A., Cobb, R. C. & Foster, D. R. Direct and indirect ecosystem consequences of an invasive pest on forests dominated by eastern hemlock. *Journal of Biogeography* 29, 1489-1503 (2002).
4. Hobbs, R. J. & Huenneke, L. F. Disturbance, Diversity, and Invasion - Implications for Conservations. *Conservation Biology* 6, 324-337 (1992).
5. Dukes, J. S. & Mooney, H. A. Does global change increase the success of biological invaders? *Trends in Ecology & Evolution* 14, 135-139 (1999).
6. Shea, K. & Chesson, P. Community ecology theory as a framework for biological invasions. *Trends in Ecology & Evolution* 17, 170-176 (2002).
7. Stevens, C. J., Dise, N. B., Mountford, J. O. & Gowing, D. J. Impact of nitrogen deposition on the species richness of grasslands. *Science* 303, 1876-1879 (2004).
8. Sher, A. A. & Hyatt, L. A. The disturbed resource-flux invasion matrix: a new framework for patterns of plant invasion. *Biological Invasions* 1, 107-114 (1999).
9. Stohlgren, T. J. et al. Exotic plant species invade hot spots of native plant diversity. *Ecological Monographs* 69, 25-46 (1999).
10. Elton, C. S. *The ecology of invasions by animals and plants* (John Wiley & Sons, Inc., New York, 1958).
11. Davis, M. A., Grime, J. P. & Thompson, K. Fluctuating resources in plant communities: a general theory of invasibility. *Journal of Ecology* 88, 528-534 (2000).
12. Binkley, D., Bird, S., Ryan, M. G. & Rhoades, C. C. in *Report to Interior West Center for the Innovative Use of Small Diameter Wood* (2003).
13. O'Connell, A. M., Grove, T. S., Mendham, D. S. & Rance, S. J. Impact of harvest residue management on soil nitrogen dynamics in Eucalyptus globulus plantations in south western Australia. *Soil Biology & Biochemistry* 36, 39-48 (2004).
14. Lalande, R., Furlan, V., Angers, D. A. & Lemieux, G. Soil improvement following addition of chipped wood from twigs. *American Journal of Alternative Agriculture* 13, 132-137 (1998).
15. Blumfield, T. J. & Xu, Z. H. Impact of harvest residues on soil mineral nitrogen dynamics following clearfall harvesting of a hoop pine plantation in subtropical Australia. *Forest Ecology and Management* 179, 55-67 (2003).
16. Corbin, J. D. & D'Antonio, C. M. Can carbon addition increase competitiveness of native grasses? A case study from California. *Restoration Ecology* 12, 36-43 (2004).
17. Perry, L. G., Galatowitsch, S. M. & Rosen, C. J. Competitive control of invasive vegetation: a native wetland sedge suppresses Phalaris arundinacea in carbon-enriched soil. *Journal of Applied Ecology* 41, 151-162 (2004).
18. Blumenthal, D. M., Jordan, N. R. & Russelle, M. P. Soil carbon addition controls weeds and facilitates prairie restoration. *Ecological Applications* 13, 605-615 (2003).
19. Lowe, P. N., Lauenroth, W. K. & Burke, I. C. Effects of nitrogen availability on competition between Bromus tectorum and Bouteloua gracilis. *Plant Ecology* 167, 247-254 (2003).

20. Kolb, A., Alpert, P., Enters, D. & Holzapfel, C. Patterns of invasion within a grassland community. *Journal of Ecology* 90, 871-881 (2002).
21. Alpert, P. & Maron, J. L. Carbon addition as a countermeasure against biological invasion by plants. *Biological Invasions* 2, 33-40 (2000).
22. Paschke, M. W., McLendon, T. & Redente, E. F. Nitrogen availability and old-field succession in a shortgrass steppe. *Ecosystems* 3, 144-158 (2000).
23. Morghan, K. J. R. & Seastedt, T. R. Effects of soil nitrogen reduction on nonnative plants in restored grasslands. *Restoration Ecology* 7, 51-55 (1999).
24. Zink, T. A. & Allen, M. F. The effects of organic amendments on the restoration of a disturbed coastal sage scrub habitat. *Restoration Ecology* 6, 52-58 (1998).
25. Morgan, J. P. Soil impoverishment: a little-known technique holds promise for establishing prairie. *Restoration and Management Notes* 12, 55-56 (1984).
26. Aber, J. D. & Melillo, J. M. *Terrestrial Ecosystems* (Saunders College Publishing, a division of Holt, Rinehart and Winston, Inc., Orlando, FL, 1991).
27. Seastedt, T. R., Briggs, J. M. & Gibson, D. J. Controls of Nitrogen Limitation in Tallgrass Prairie. *Oecologia* 87, 72-79 (1991).
28. Blair, J. M. Fire, N availability, and plant response in grasslands: A test of the transient maxima hypothesis. *Ecology* 78, 2359-2368 (1997).
29. Baron, J. S. et al. Ecosystem responses to nitrogen deposition in the Colorado Front Range. *Ecosystems* 3, 352-368 (2000).
30. Tilman, D. et al. Fire suppression and ecosystem carbon storage. *Ecology* 81, 2680-2685 (2000).
31. Rueth, H. M. & Baron, J. S. Differences in Englemann spruce forest biogeochemistry east and west of the Continental Divide in Colorado, USA. *Ecosystems* 5, 45-57 (2002).
32. Seastedt, T. R. & Vaccaro, L. Plant species richness, productivity, and nitrogen and phosphorus limitations across a snowpack gradient in Alpine Tundra, Colorado, USA. *Arctic Antarctic and Alpine Research* 33, 100-106 (2001).
33. LeJeune, K. D. & Seastedt, T. R. Centaurea species: the forb that won the west. *Conservation Biology* 15, 1568-1574 (2001).