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Introduction

More than 50% of the original wetland area in the contiguous U.S. has been lost to development (Dahl 2000). Wetland losses have been particularly severe in the Willamette Valley in western Oregon. Wetland prairies were historically one of the dominant ecosystems, but today less than 1% remain, making it one of the most endangered habitats in the Pacific Northwest (Noss et al. 1995).

Historically, conversion to agriculture has been the primary mode of wetland loss in the U.S., with agriculture responsible for 70% of all wetland losses in the last half century (Frayer et al. 1983, Dahl and Johnson 1991, Dahl 2000). Similarly in the Willamette Valley, 70% of wetland losses from the 1980s to the 1990s were due to agriculture (Bernet et al. 1999). Grass seed is one of the most important agricultural products in the Willamette Valley, which is the world's largest producer of grass seed. Given their imperiled status, wetland prairies are the focus of extensive restoration efforts in the Willamette Valley, and much of the potentially restorable wetland area is currently in grass seed production.


Wetland Prairie

Despite the large amounts of money spent on wetland restoration, it is a relatively new field with little accumulated knowledge to draw from in planning and implementing restoration activities (National Research Council 2001). Moreover, restoration provides a challenging venue to test basic ecological principles within an important applied framework. Restoration of wetlands has focused primarily on the establishment of native plant communities, despite a national agenda of no-net-loss of overall wetland function (National Research Council 2001). However, many wetland functions may still be significantly deteriorated from natural wetlands even with successful native plant establishment (Simenstad and Thom 1996, Zedler 2003). Additionally, restorations are not always successful in establishing a native plant community, and both natural and restored wetlands often are dominated by exotic plant species (National Research Council 2001, Kellogg and Bridgham 2002).

Site preparation is one of the most important steps in establishing successful wetland restorations, although there have been very few comparative studies of different site preparation techniques. Elimination of the soil seed bank of exotic plants is an especially important goal of site preparation. However, site preparation may also have important impacts on soil processes, and there is potentially a trade-off between the effectiveness of a particular site preparation technique in removing the exotic seed bank and soil functioning.

We examined the effectiveness of a variety of site preparation techniques used for restoring native plant biodiversity and soil functioning in two studies conducted on wetlands restored by the West Eugene Wetland (WEW) Partnership:

- A large replicated field experiment with fifty 15-meter by 15-meter test plots in which the outcomes of ten different site preparation combinations were studied over three years in a former annual ryegrass field.
- A retroactive study of six past restoration sites restored from 1999-2004.

We also compared the results of both studies to the plant communities and soil attributes of three high- quality, local, remnant wetland prairies. These *reference sites* served as benchmarks for assessing the performance of the restored wetland prairies.

Replicated Field Experiments

Study Objective

The primary objective of this study was to inform and guide future restoration activities in the West Eugene Wetlands and to enhance the knowledge of wetland restoration in general by assessing commonly used site preparation techniques in an experimental setting.

More specifically, we asked:

- Which treatment combinations maximize native plant success and minimize invasion by non-indigenous species?
- How do different treatment combinations affect a variety of functional, chemical and physical soil attributes, and how do these soil attributes compare to reference sites and to adjacent areas that are still actively farmed?

Selection of Site Preparation Techniques and Experimental Design

The Lane Council of Governments facilitated a half-day *Wetland Restoration Site Preparation Forum* on January 22, 2004 to allow participants to share their experience using various site preparation techniques and to identify the most promising techniques to be considered for inclusion in the replicated field experiment. Approximately 50 people participated in the forum, representing a wide array of expertise, including soil scientists, farmers, botanists, extension agents, natural resource maintenance workers, landscape architects, and wetland restoration ecologists. Two additional public forums were held on November 15, 2005 and May 24, 2007 to share preliminary results of the study with the public and interested stakeholders.

Based on the results of the *Site Preparation Forum* and previous experience of the WEW Partners, a total of ten site preparation treatments were selected for the experiment. They included various combinations of tilling, herbicide application, solarization, and thermal weed control. Each treatment was replicated five times, resulting in a total of 50 experimental plots. The plots measured 15 meters by 15 meters and were separated by 10-meter mowed buffer strips. The relatively large size of the experimental plots was necessary so that typical large agricultural equipment could be used to implement the treatments.

A 4.5-hectare site west of Eugene near Coyote Creek was selected for implementation of the experiment. This site was in agricultural use for annual ryegrass (*Lolium multiflorum*) production until the spring of 2004. Based on interpretation of the Soil Survey of Lane County (SCS 1987) and historic vegetation mapping (Christy et al. 1999), the site was most likely historically dominated by a wetland prairie plant community. The soil type is mapped as Natroy silty clay loam. Farming of the site did not involve significant hydrological alterations, and it was seasonally inundated with approximately 5-8 cm of standing water, which is excellent wetland prairie hydrology. Site preparation was conducted between May and October 2004 and included the following techniques in various combinations (Table 1):

Solarization Treatment

<u>Solarization</u>: This technique involved placing a layer of 6 mil. clear plastic over the entire plot beginning in mid-July. A trench was dug around the perimeter to bury the edges of the

plastic and create a tighter seal. The plastic was then removed in early October. This treatment creates high soil temperatures which kills the existing vegetation and the soil seed bank.

Tilling

Tilling: This involved making two passes over the plots with a large field disk in alternating directions as soon as the soil was sufficiently dry (late June). This was followed by another round of tilling about two weeks later to further break up the soil and vegetation, this time using a harrow and culti-mulcher. This is a common restoration technique that kills the existing vegetation and turns over the soil seed bank, but does not necessarily destroy it.

Thermal Treatment: A propane burner (*Sunburst*) was pulled in a single pass over the test plots to burn off vegetation and seed near the soil surface. The machine applies a thin film of water to the vegetation and then subjects the plants and seeds to intense heat that is transferred to them through infrared energy, turbulent hot air and boiling water. This was done in mid-August.

Thermal Treatment

Herbicide Application: This involved spraying the vegetation in the test plots with a glyphosate-based herbicide (Roundup). A first treatment was applied in mid-July, with a second follow-up treatment to selected plots in early October after the seed bank germinated.

Herbicide Application

The plots were planted with a broadcast seeder on October 28, 2004 with a wetland prairie seed mix consisting of 15 species of native grasses and forbs. The seed came from the City of Eugene and included the following species: *Agrostis exerata; Aster hallii; Camasia quamash; Carex densa; Danthonia californica; Deschampsia cespitosa; Grindelia integrifolia; Epilobium densiflorum; Juncus tenuis; Madia glomerata; Microseris laciniata; Plagiobothrys figoratus; Potentilla gracilis; Prunella vulgaris* ssp. *lanceolata; and Wyethia augustifolia.* The seed was carefully weighed and divided into fifty identical batches to ensure consistent distribution on each of the plots.

The ten treatment combinations are listed in Table 1 below. However, the first (summer) herbicide application had no detectable effect on the plant communities ($p>0.6$) or soil response variables ($p>0.3$). The herbicide was applied in July and at this time plants had senesced for the growing season. For ease of interpretation, this treatment has been lumped with its similar counterpart (e.g., till, summer herbicide has been combined with till), reducing the total treatment combinations from ten to seven.

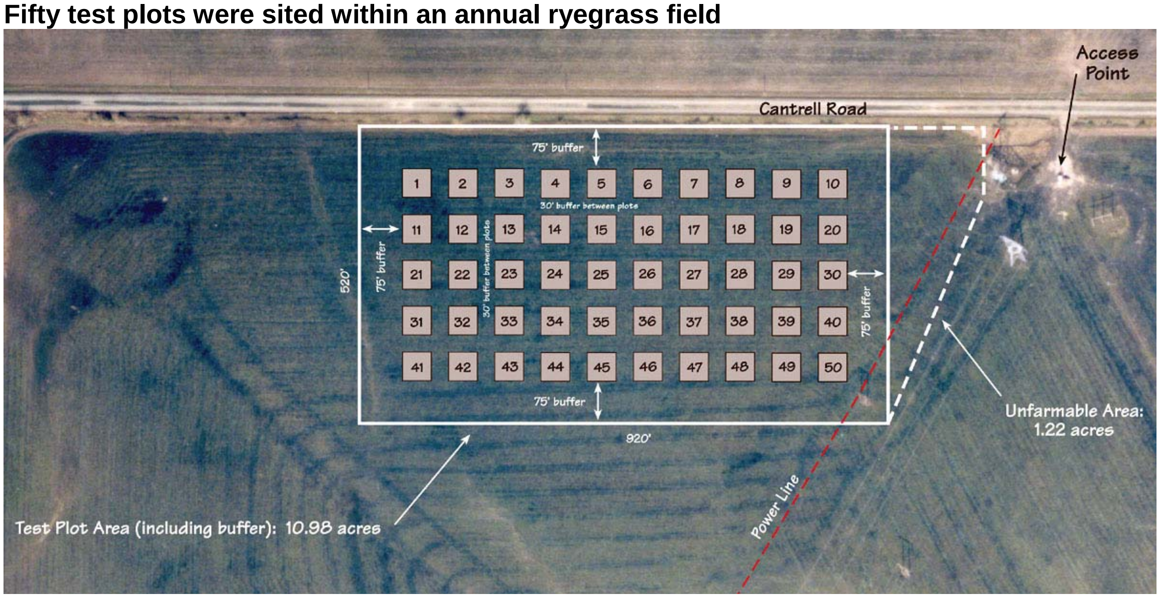
Table 1. Ten experimental treatment combinations, followed by the seven collapsed treatments due to the non-significant effect of the summer herbicide application.

	Seven Collapsed Treatments	**Ten Treatment Combinations**
1	Control : Summer Herbicide	Summer Herbicide
2	Till	Till Till, Summer Herbicide
3	Thermal	Summer Herbicide, Thermal
4	Till, Thermal	Till, Thermal Till, Summer Herbicide, Thermal
5	Fall Herbicide	Summer and Fall Herbicide
6	Till, Fall Herbicide	Till, Summer and Fall Herbicide
7	Till, Solarization	Till, Solarization Till, Summer Herbicide, Solarization

Three years of post-treatment data were collected in each of the 50 experimental plots, the adjacent farm field, and three high quality remnant prairies (reference sites) to assess how the various site preparation techniques impacted the following four categories of response variables:

- establishment of native Willamette Valley wetland plant species relative to non-native plant species in terms of percent cover and species diversity;
- aboveground and belowground productivity of the vegetation;
- functional soil ecosystem attributes, including nitrogen, phosphorus, and carbon cycling rates, and microbial biomass and respiration;
- physical and chemical properties of the soil.

Fifty test plots were sited within an annual ryegrass field



Effectiveness of Treatments in Reducing Seed Bank

Several of the treatments, including solarization, the fall herbicide application, and thermal weed control, were designed to specifically target the seed bank. Therefore in the winter of 2005, we quantified the seed bank in the various treatments by collecting soil cores from every plot and the adjacent farm field and allowed the seeds to germinate for three months in a greenhouse. Below, we present the results of this study.

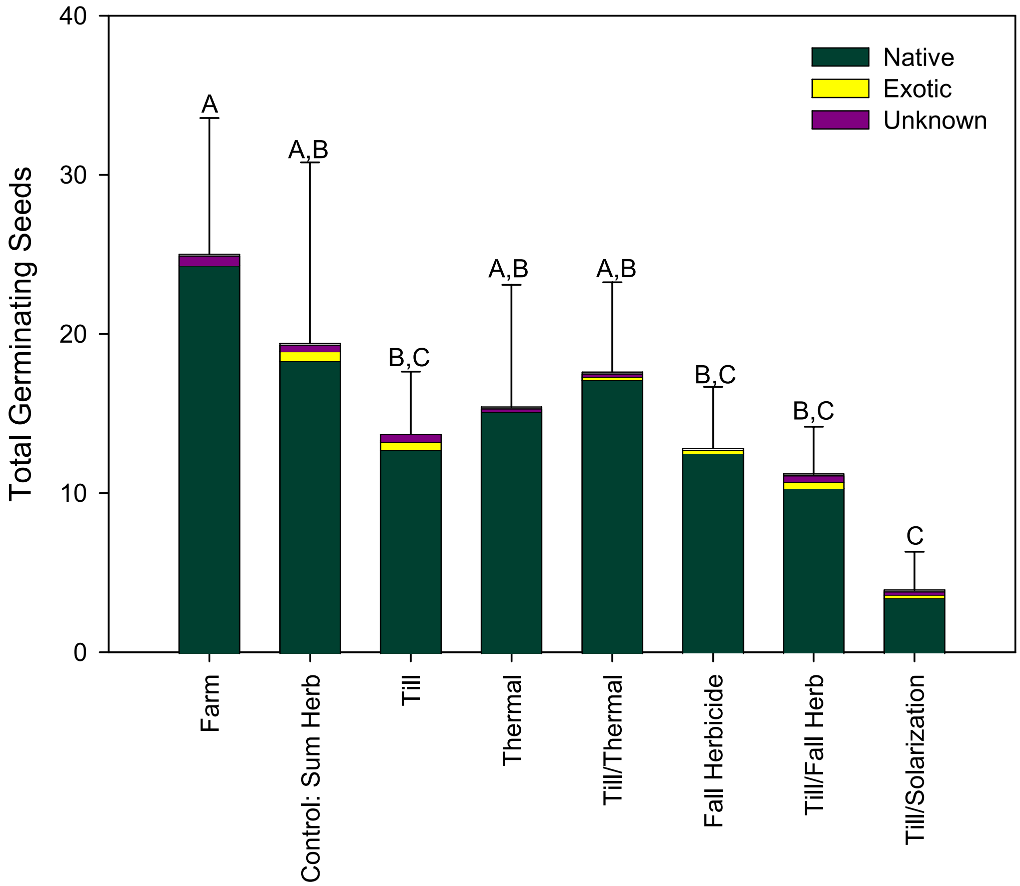


Figure 1. Total germinating seeds partitioned by native and exotic species in the seed bank study. Error bars represent 95% confidence intervals. Upper case letter differences indicate significant effects ($p < 0.05$) of treatment.

Summary of seed bank study:

- Solarization successfully reduced the seed bank from that in the farm field and the control (summer herbicide) treatment. There was also a trend for a reduction in the seed bank by the second herbicide application.
- Thermal weed control did not significantly reduce the seed bank.
- Surprisingly, a greater proportion of the germinating seeds were native than exotic in all treatments and in the farm field. However, it is important to note that soil cores were collected in the winter after some species had germinated. *Lolium multiflorum* typically germinates in the fall and as a result, we underestimated the *Lolium* in the seed bank.

Response of the Plant Communities

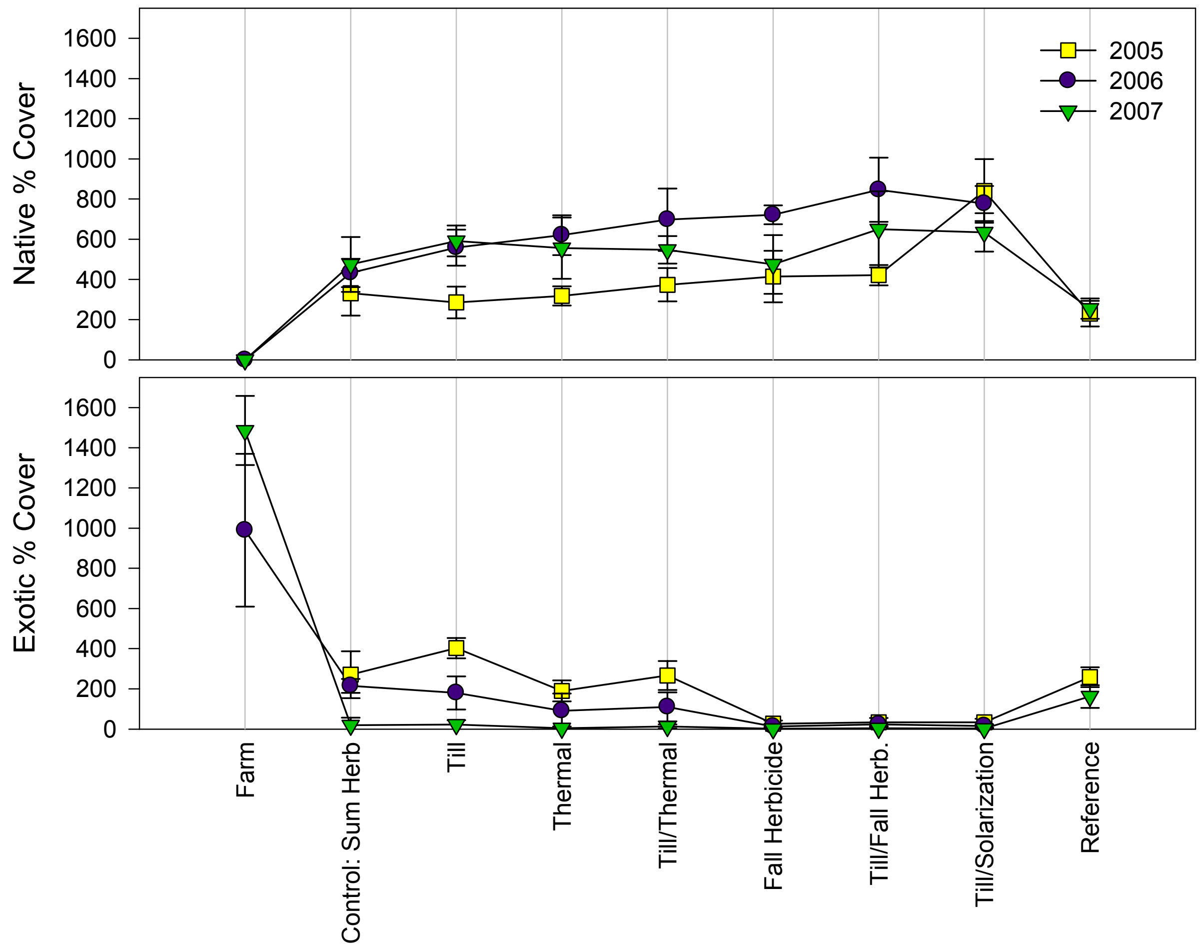


Figure 2 Mean native % cover and exotic % cover for different treatment combinations in 2005, 2006, and 2007. Percent plant cover was measured in three 1-m x 1-m sub-plots within each main plot, and the results from the sub-plots were averaged. We used the point-intercept method to determine cover, where 25 metal pins per sub-plot were dropped vertically from a frame to the ground. Any vegetation touching the pin was counted as a "hit", allowing for total cover to be greater than 100%. Error bars represent 95% confidence intervals.

Summary of plant cover results:

- In 2005, the till+solarization treatment had high native cover and low exotic cover. The two fall herbicide treatments also had low exotic cover.
- Over time, the exotic cover decreased in all treatment combinations, and by 2007 no differences in exotic cover were evident among treatments.
- In 2007, the exotic cover in the treatments was lower than the reference sites, and native cover was higher.
- The farm field had higher total plant cover than any treatment combination or reference site due to the dense growth of *Lolium multiflorum*.

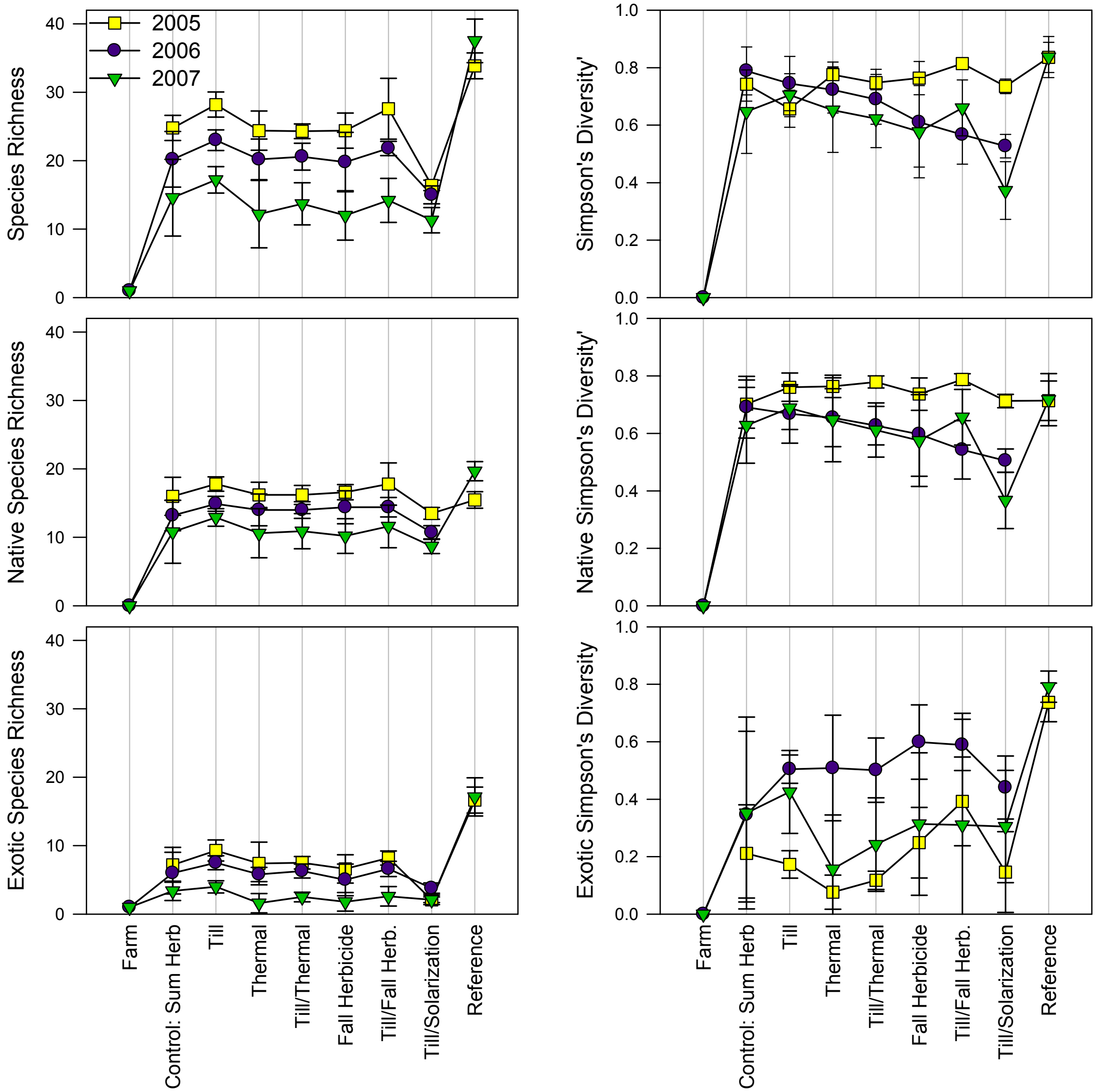


Figure 3. Mean species richness, Simpson's diversity, native species richness, native Simpson's diversity, exotic species richness, and exotic Simpson's diversity per m^2 for different treatment combinations in 2005, 2006, and 2007. Note that species richness is the number of species present, and that Simpson's diversity includes both richness and the relative evenness of the abundances of the species. Error bars represent 95% confidence intervals.

Summary of richness and diversity results:

- In 2005, solarization had lower total (native + exotic) species richness than all other treatments.
- Each year species richness declined in the treatments, resulting in lower native and exotic richness than the reference sites.
- In 2005, Simpson's diversity was not significantly different among treatments. However, by 2007, solarization had lower native and overall diversity, and the tilling treatment had the highest exotic diversity.

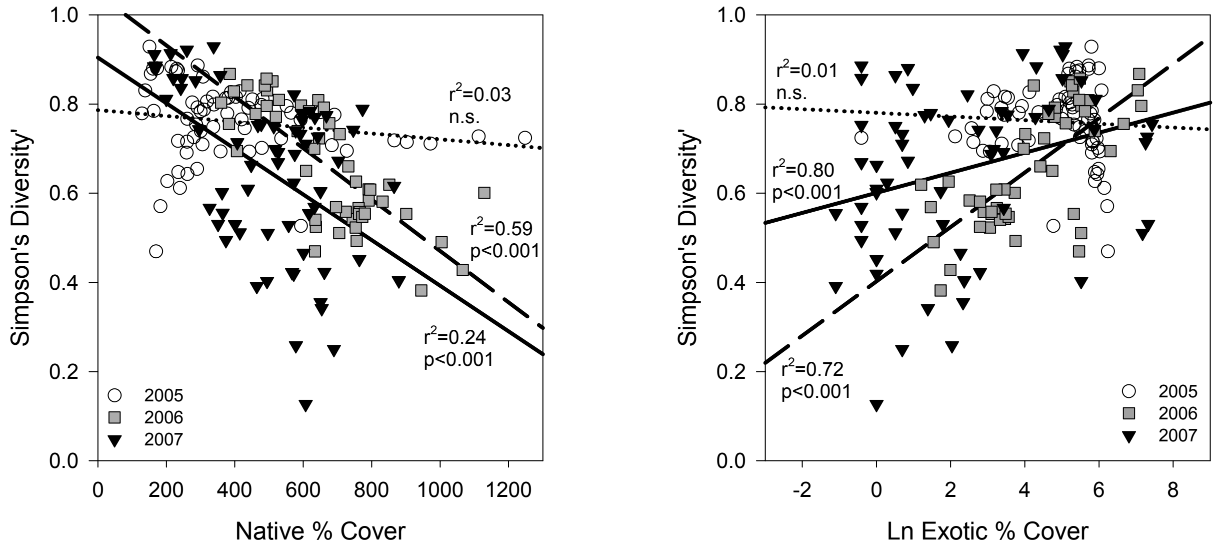


Figure 4. Simpson's diversity' vs. native and exotic % cover in the experimental treatments. Regression lines are drawn for each year (2005 dotted, 2006 dashed, and 2007 solid), and r^2 values are reported.

An apparent trade-off between native % cover and diversity:

- There was a strong tradeoff between native % cover and diversity that became apparent in 2006 (R^2=0.59) and to a lesser extent 2007 (R^2=0.24). Plots that had high native % cover tended to be dominated by highly competitive native perennial bunchgrasses, which resulted in lower overall diversity.
- Exotic % cover showed a positive correlation with diversity in 2006 and 2007 suggesting that within this site none of the exotic species present were competitively dominant and thus, increasing exotic cover actually increased overall diversity.

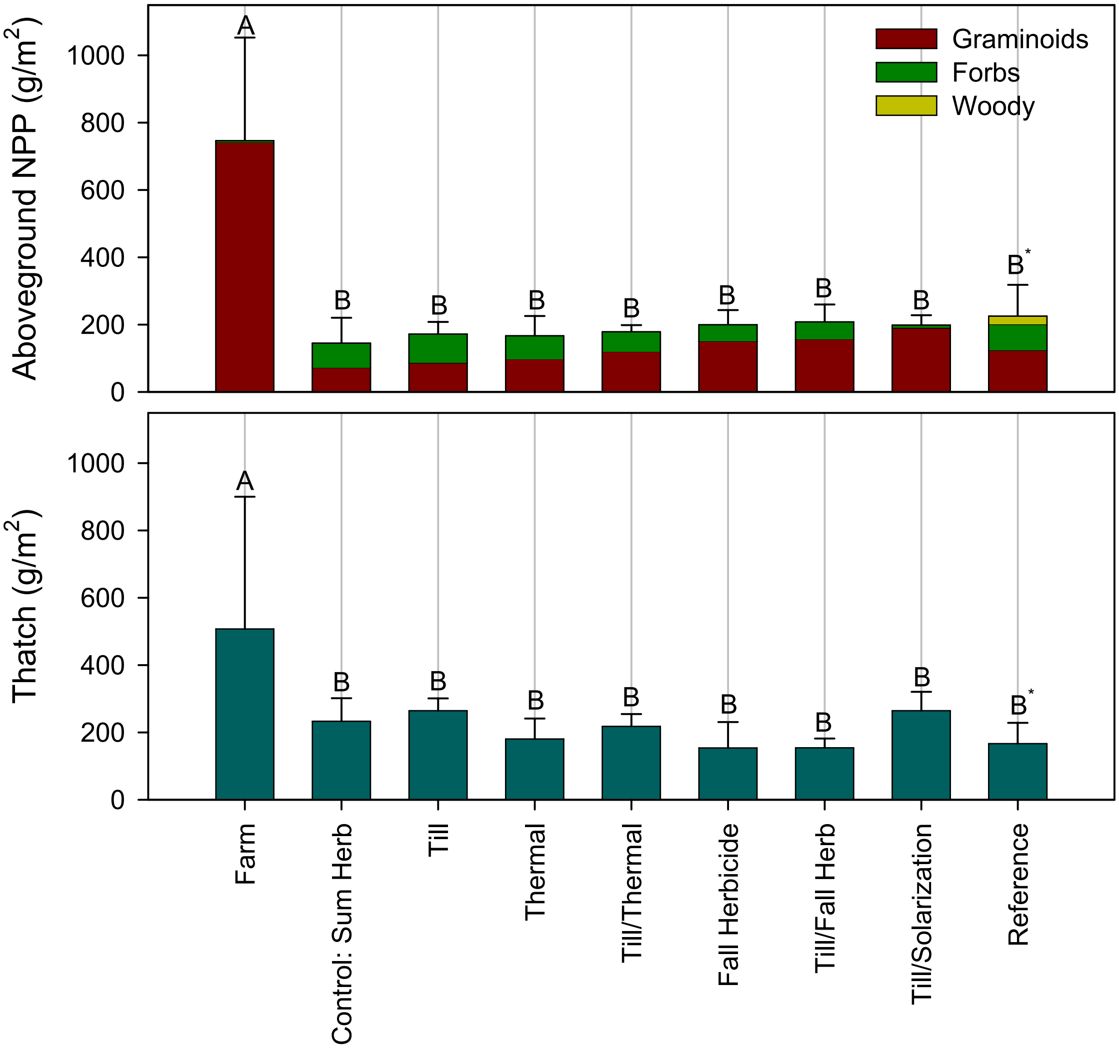


Figure 5. Aboveground net primary productivity (estimated from peak standing biomass) in the experimental treatments, farm field, and reference sites. Error bar represent 95% confidence intervals.

* Biomass data in the farm and experimental treatments were collected June of 2006 and biomass data for the reference sites were collected in June of 2005.

Summary of net primary productivity (NPP) and thatch results:

- Aboveground NPP and thatch was more than double in the farm than in the experimental treatments and reference sites. However, it is important to remember the farm is harvested and so biomass is not returned to the ecosystem.
- The biomass in the solarization treatment was almost entirely graminoid species, whereas the other six treatments were more evenly divided among plant functional groups.

Ordination of the treatments, farm, and reference sites:

The relationship among the three years of plant data in all treatments, reference sites, and the farm field were examined with a multivariate statistical technique called nonmetric multidimensional scaling (NMS). This technique 'ordinates' community structure so that a few axes are identified (composed of different combinations of ranked species cover) that allows one to visually examine how similar or dissimilar plant communities are from another. The plant community structure of each treatment is represented by a point, and the closer points are, the more similar treatments are in community structure and vice versa.

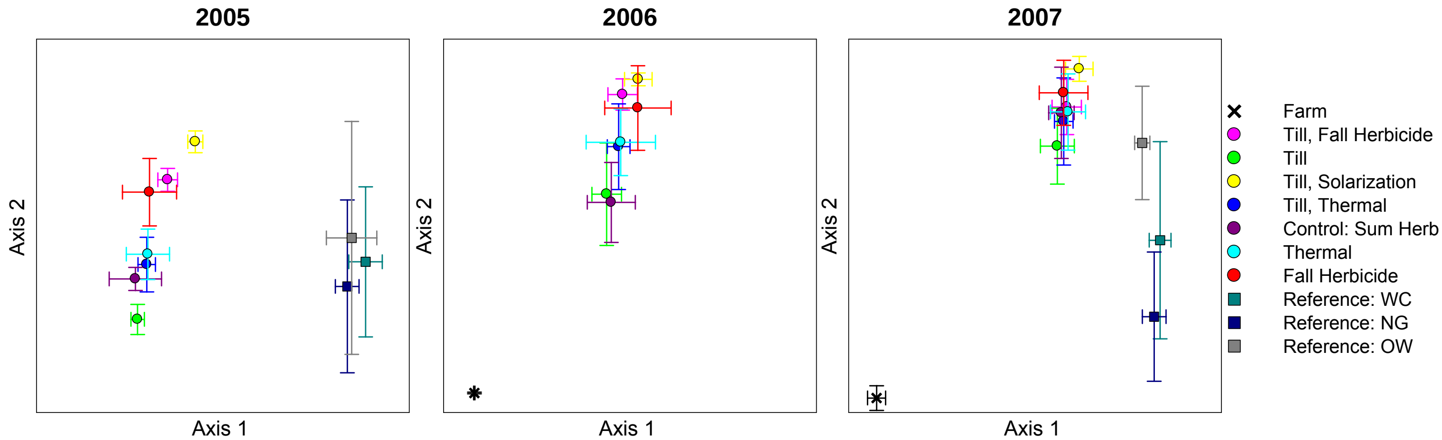


Figure 6. Nonmetric multidimensional scaling of plant communities in the treatments, farm field, and reference sites using relative Sorensen distance (A= 0.52, $p<0.0001$). All three years of plant data were ordinated together, but are split for visual clarification (i.e., the axes are the same for all three panels). Axis 1 explains 62% and axis 2 explains 21% of the variation in plant community structure. Error bars represent 95% confidence intervals. Data are not shown for the reference sites in 2006 because they were not censused in that year.

Summary of plant ordination results:

- The experimental treatments were more similar to one another in plant community structure than to either the reference sites or the farm field.
- Over time, plant community structure in the experimental treatments became more similar to the reference sites, that is, along axis 1 they progressed further right each year.
- Initially, differences in treatments were apparent, with till+solarization and till only being the most different; however, over time, the differences in treatment effects were dampened (i.e., points came closer together).
- The variance (as shown by the size of the error bars) in the experimental plots never approached the variance in the reference sites. This suggests that within each of the reference sites, the replicate plots were very different from one another (i.e., they had a high beta diversity), whereas the treatments had much more similar plant communities among the replicate plots.

Ordination of only the experimental treatments:

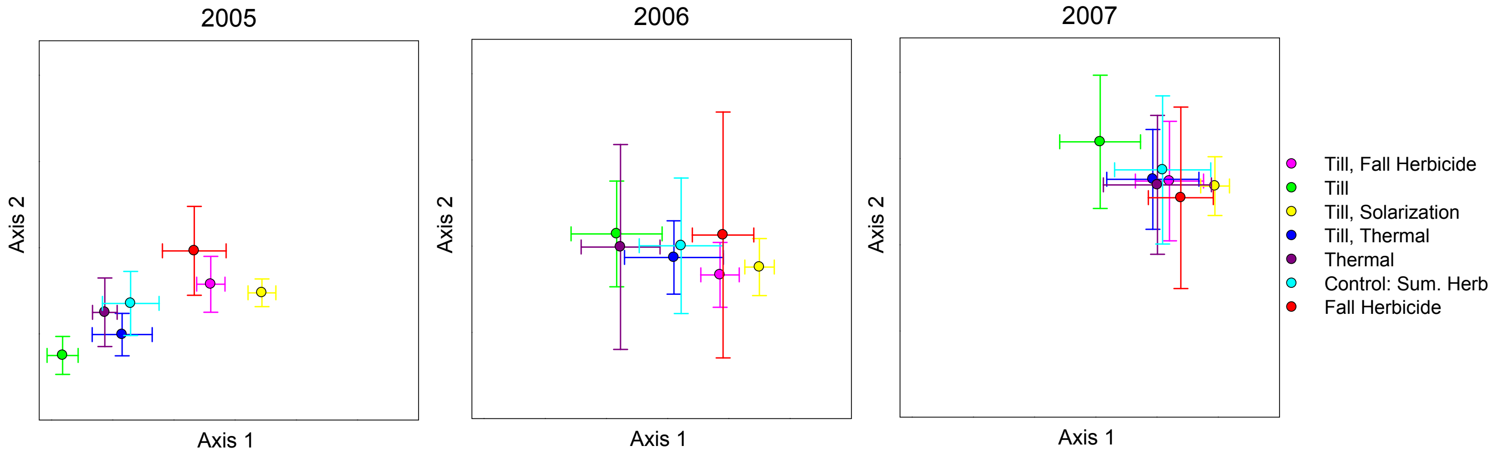


Figure 7. Nonmetric multidimensional scaling of plant communities only from the experimental treatments using relative Sorensen distance (A= 0.46, p<0.0001). All three years of plant data were ordinated together, but are split for visual clarification. Axis 1 explains 66% of the variation and axis 2 explains 14% of the variation in plant community structure. Error bars represent 95% confidence intervals.

Table 2. Species axis loadings for NMS ordination (see Fig. 3). Only significant (p<0.05) indicator species are reported. Native (N) and exotic (E) origin, annual (A) and perennial (P) life history, and functional group (G: graminoid, F: forb, and W: woody) are given.

Species	Axis 1 Loading	Axis 2 Loading	Species Origin	Life History	Functional Group
Juncus bufonius	-1.09	-0.55	N	A	G
Lolium multiflorum	-0.96	-0.41	E	A	G
Montia linearis	-0.80	-0.48	N	A	F
Rubus armeniacus	-0.79	-0.29	E	P	W
Cirsium vulgare	-0.76	0.10	E	B	F
Cicendia quadrangularis	-0.73	-0.43	N	A	F
Gnaphalium palustre	-0.71	-0.30	N	A	F
Sonchus asper	-0.71	-0.13	E	A	F
Camassia quamash var. maxima	-0.67	-0.22	N	P	F
Hypochaeris radicata	-0.51	0.14	E	P	F
Epilobium densiflorum	-0.47	-0.20	N	A	F
Briza minor	-0.46	0.05	E	A	G
Plagiobothrys figuratus ssp. figuratus	-0.39	0.32	N	A	F
Veronica peregrina var. xalapensis	-0.36	-0.35	N	A	F
Cerastium glomeratum	-0.32	-0.07	E	A	F
Parentucellia viscosa	-0.29	0.11	E	A	F
Centaurium erythraea	-0.24	-0.20	E	A/B	F
Madia glomerata	-0.17	0.50	N	A	F
Juncus tenuis	0.29	0.58	N	P	G
Agrostis exarata	0.33	-0.07	N	P	G
Deschampsia cespitosa	0.52	0.14	N	P	G
Schedonorus arundinaceus	0.55	0.05	E	P	G

The axis loadings given in Table 2 help interpret the differences in plant communities in Figure 7. For example, *Lolium multiflorum* (annual ryegrass), loaded negatively on axis 1 and 2. Therefore, plots with a high abundance of *Lolium* would be found closest to the lower, left-hand corner of the figure. In 2005, all plots were closer to this corner showing they had a higher abundance of *Lolium* early on, but that over time, this species became less abundant. Also, one can use these loadings to understand difference among treatments. For example, in 2005, the till treatment had more *Lolium* present than the till+solarization treatment and this remained true over the following two years.

Summary of plant ordination results:

- Over time, treatments became more similar in plant community structure; however, the relative ordering or treatments remained the same.
- Solarization plant communities had a higher abundance of perennial grasses and lower abundance of annual grasses, whereas tilling and thermal treatments had higher abundances of forbs and the annual exotic grass, *Lolium multiflorum*.
- Over time, many early successional species (e.g., *Plagiobothrys figuratus, Juncus bufonius, and Gnaphalium palustre*) decreased in abundance and perennial grasses began to dominate plant communities.

Response of the Soils

Our second objective was to to examine how different treatment combinations affect a variety of functional, chemical and physical soil attributes, and how these soil attributes compare to reference sites and to adjacent areas that are still actively farmed.

Table 3. Overall significance of site preparation techniques on various soil attributes in test plots over four seasons of sampling beginning in fall 2005 through summer 2006, p-values are reported (n.s. =not significant). Explanations of significant effects are given.

	Comparison within treatments only				Treatments vs. Farm Field			
Response Variable	Season	Treatment	Season* Trtmt	explanation	Season	Treatment	Season* Trtmt	explanation
Bulk Density	n.s.	n.s.	n.s.		0.0001	0.002	n.s.	Bulk density was lower in the farm.
Carbon/ Nitrogen Ratio	n.s.	0.027	n.s.	The till, solar treatment had a higher C/N ratio than the till only trtmt.	n.s.	n.s.	n.s.	
Total Carbon (g C/m^2)	n.s.	n.s.	n.s.		0.001	n.s.	0.014	In the summer, the treatments had more total C.
Total Nitrogen (g N/m^2)	n.s.	n.s.	n.s.		0.003	n.s.	0.016	In the summer, the treatments had more total N.
pH	0.0001	n.s.	n.s.		0.002	0.0001	n.s.	The farm was more acidic than the treatments.
Nitrate (µg N/g soil)	0.0001	0.0001	0.022	In the fall and summer, till/solar was lower than all trtmts. except fall herb. and thermal.In the winter, the thermal trtmt. had higher nitrate availability.	0.0001	0.0001	0.0001	In the fall and summer, there was more nitrate in the farm. In the winter, there was more nitrate in the treatments.
Ammonium (µg N/g soil)	0.0001	n.s.	n.s.		0.0001	n.s.	0.0001	In the fall, there was more ammonium in the farm.
Phosphate (µg P/g soil)	0.0001	n.s.	n.s.		0.0001	n.s.	n.s.	
Microbial biomass C (µg C/g soil)	0.0001	0.007	n.s.	The till, solar treatment was lower than the fall herbicide, thermal, and till only trtmts.	0.0001	n.s.	n.s.	
Microbial biomass N (µg N/g soil)	n.s.	n.s.	n.s.		n.s.	n.s.	n.s.	
Microbial biomass P (µg P/g soil)	n.s.	n.s.	n.s.		n.s.	n.s.	n.s.	
Net N Mineralization (µg N/g soil/day)	0.0001	n.s.	n.s.		0.001	0.0001	0.001	In the fall and winter, mineralization rates were higher in the farm.
Net Nitrification (µg N/g soil/day)	0.012	n.s.	n.s.		0.0001	0.0001	0.001	In the fall and summer, net nitrification rates were higher in the farm.
Soil Respiration (mmol CO_2/m^2/day)	0.0001	n.s.	n.s.		0.0001	0.0001	0.0001	In the fall, winter, and spring, soil respiration was higher in the farm.
% Moisture	0.0001	n.s.	n.s.		0.0001	0.020	n.s.	On average, the farm field was wetter.
Root Biomass (g)	0.0001	0.015	0.009	In the fall, the fall herb. trtmt. had more biomass than the till, thermal trtmt. In the winter, the till,solar trtmt had more biomass than the fall herb, or till only trtmts.	0.0001	0.0001	0.0001	In the winter, spring, and summer, there was more bg biomass in the farm.

Overall summary of soil results:

- Of the 16 response variables, only four significantly differed among site preparation techniques. This suggests treatments had a minimal effect on soil responses.
- The experimental treatments and the farm field significantly differed for 11 of the 16 response variables. In general, the farm had higher nutrient levels, mineralization, nitrification, and respiration rates, and more belowground biomass. Two of the nutrient variables are examined in more detail in Figure 8.

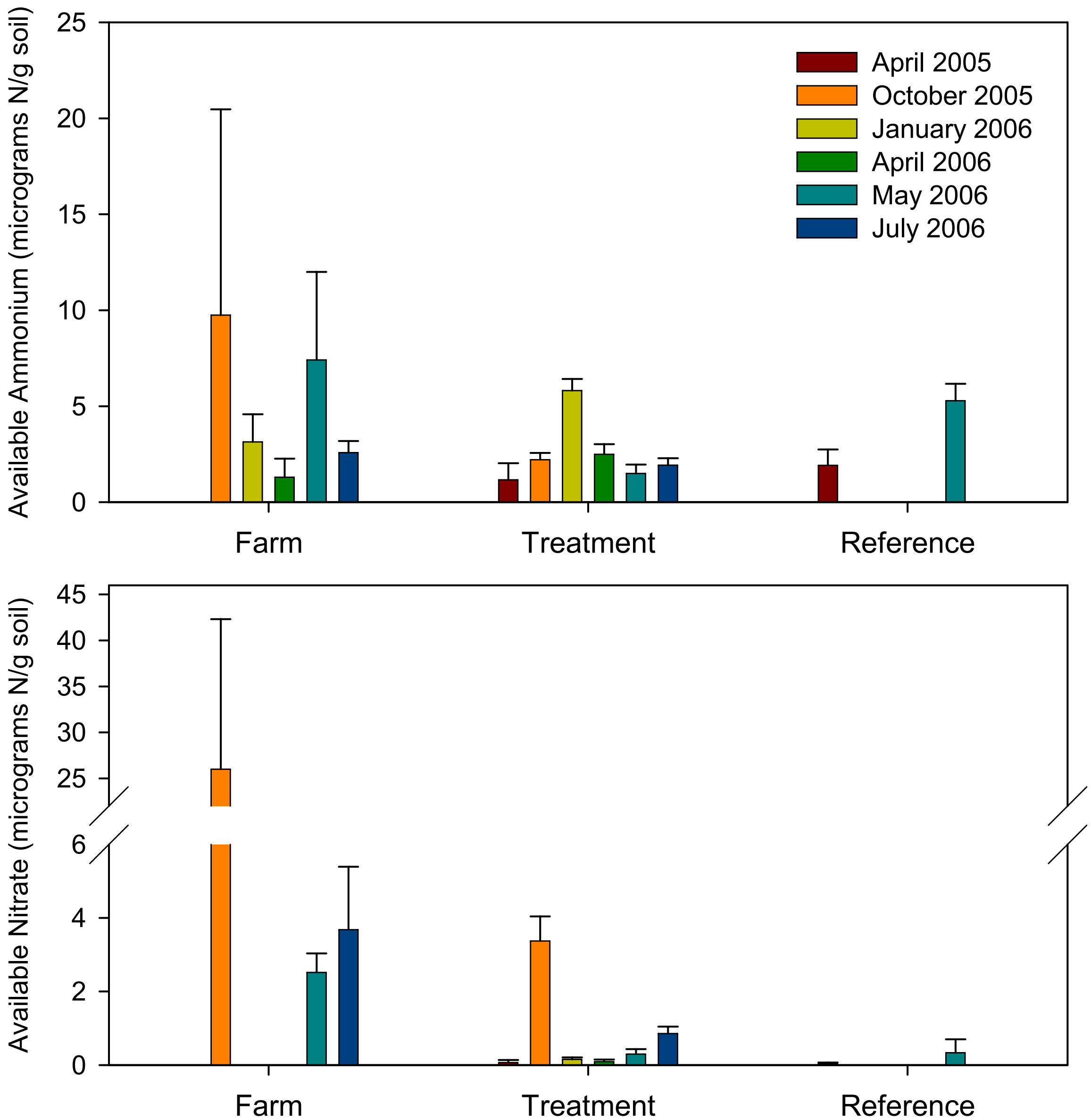


Figure 8. Available ammonium and nitrate in the farm field, treatment plots, and reference sites. Data were collected in the treatments during all sampling periods. In the farm, data were not collected April 2005. In the reference sites, data were not collected October 2005, January 2006, April 2006, or July 2006. Error bars represent 95% confidence intervals.

Summary of available ammonium and nitrate results:

- In the farm nutrient levels were high in the fall and spring.
- High nutrient availability in the farm in the fall and spring was not mirrored in the treatment plots, with a particularly large difference in fall nitrate concentrations.
- Overall, the restored wetland plots (regardless of treatment) rapidly attained nutrient levels (and other soil attributes) that closely approximated the reference sites.

Summary of Key Findings from Replicated Field Experiment

Site Preparation Treatments

- Solarization and the fall herbicide application were the most effective treatments for decreasing the seed bank and exotic cover initially. However, over time all treatments had low exotic cover because *Lolium multiflorum* was not a dominant competitor over time and no other dominant exotic species colonized the plots during the course of the experiment. If the site chosen had a dominant exotic competitor, the outcome would likely be different.
- The solarization treatment gave high native plant cover in the first year and low exotic plant cover throughout the experiment, but this treatment also had low native and overall species richness and diversity due to the dominance of the native bunchgrasses *Deschampsia cespitosa* and *Agrostis exarata*. Thus, there was a trade-off between high abundance of competitive native bunchgrasses and species diversity in this treatment.
- The July herbicide application had no detectable effect on plants communities. If the herbicide could have been applied earlier in the growing season, it may have had a greater effect.
- The tilling treatment, which disturbs the soil and brings up the seed bank, yielded the poorest results in terms of decreasing the seed bank and exotic cover. To be effective, at a minimum it would need to be applied over multiple growing seasons.
- The thermal treatment did not decrease the seed bank, but instead acted more like a surface fire and was very effective at killing small seedlings. To reduce the seed bank, this technique would need to be applied at time of seed germination.
- In general, none of the treatments resulted in a significant change in the belowground responses after the first year, but as changes in plant composition and productivity feedback to the soil, we expect that differences are likely to become larger.
- Herbicide application had no detectable effect on soil variables measured.
- Although treatments had minimal effects on belowground responses, the soils were distinctly different from the annual ryegrass farm field, with soil characteristics becoming more similar to the reference sites.

Ecological Lessons Learned

It is important to take the ecological lessons learned from experiments such as ours so that they can be employed in other restorations. Some key findings are :

- Plant community structure converged among treatments and became more similar to the reference sites over time due to a reduction in the cover of *Lolium multiflorum*, a loss of early successional species (including those which were planted), and increasing dominance of perennial grasses. Thus, an understanding the successional dynamics of the plant species involved can be used to more quickly direct wetland restorations to a desired plant community condition.
- As a result of these successional dynamics, there was a decrease in overall and native plant species diversity over time in all treatments. Treatment plots never attained the overall or native plant diversity of the reference sites, despite the relatively high cover of exotic plant species in the reference sites.
- A trade-off was evident between native plant cover and diversity. These results suggest that future research efforts need to be focused on establishing and maintaining native plant diversity in wetland restorations.

Retroactive Study

Over the past 15 years, the West Eugene Wetland partnership has been actively restoring land using a variety of restoration techniques (e.g., sod removal, fill removal, solarization). However, no quantitative analyses have been conducted to examine the response of the plants and soils to these techniques. To address this gap, data were collected from three high quality wetland prairie remnants, which served as reference sites, and seven previously restored wetland prairie sties. At each site, 15 1-m^2 plots were randomly located and surveyed for percent cover, productivity, and species diversity using the same methods as for the replicated field experiment. Measurements were taken in July 2005 on a total of 150 plots. Five of the 15 plots at each site were randomly selected to examine the same soil variables measured in the replicated field study in April of 2005.

Study Objectives

- Establish baseline data on soil dynamics and plant communities, and the relationship between these two factors, in remnant wetland prairies
- Examine response of vegetation and soil for commonly used restoration techniques over the past 8 years

Table 4. List of retroactive study sites, year restoration was implemented, and the site history.

Site	Treatment	Year	Site History
Willow Corner	Fill Removal	2003	Filled Wetland Prairie
Beaver Run	Sod Rolling	2003	Abandoned Pasture
Turtle Swale Phase I	Sod Removal	2001	Pasture
North Greenhill	Sod Removal	1999	Ryegrass Field
North Greenhill	Sod Removal	2003	Ryegrass Field
North Greenhill	Solarization	1999	Ryegrass Field
North Greenhill	Solarization	2001	Ryegrass Field
Coyote Prairie	Solarization	2004	Ryegrass Field
Willow Creek	Reference	NA	NA*
North Greenhill	Reference	NA	NA*
Oxbow West	Reference	NA	NA*

* All three of the reference sites (Willow Creek, North Greenhill, and Oxbow West) have some limited history of grazing, but it is believed that they were never tilled or planted in an agricultural crop, which allowed native vegetation to persist. All three of these sites are in public or land trust ownership and managed for wetland prairie habitat.

As described in the replicated field experiment results, we used nonmetric multidimensional scaling (NMS) to assess the differences in overall plant community structure among the retroactive study site types. For this study, we performed three separate NMS analyses for all plants, native plants and exotic plants, respectively.

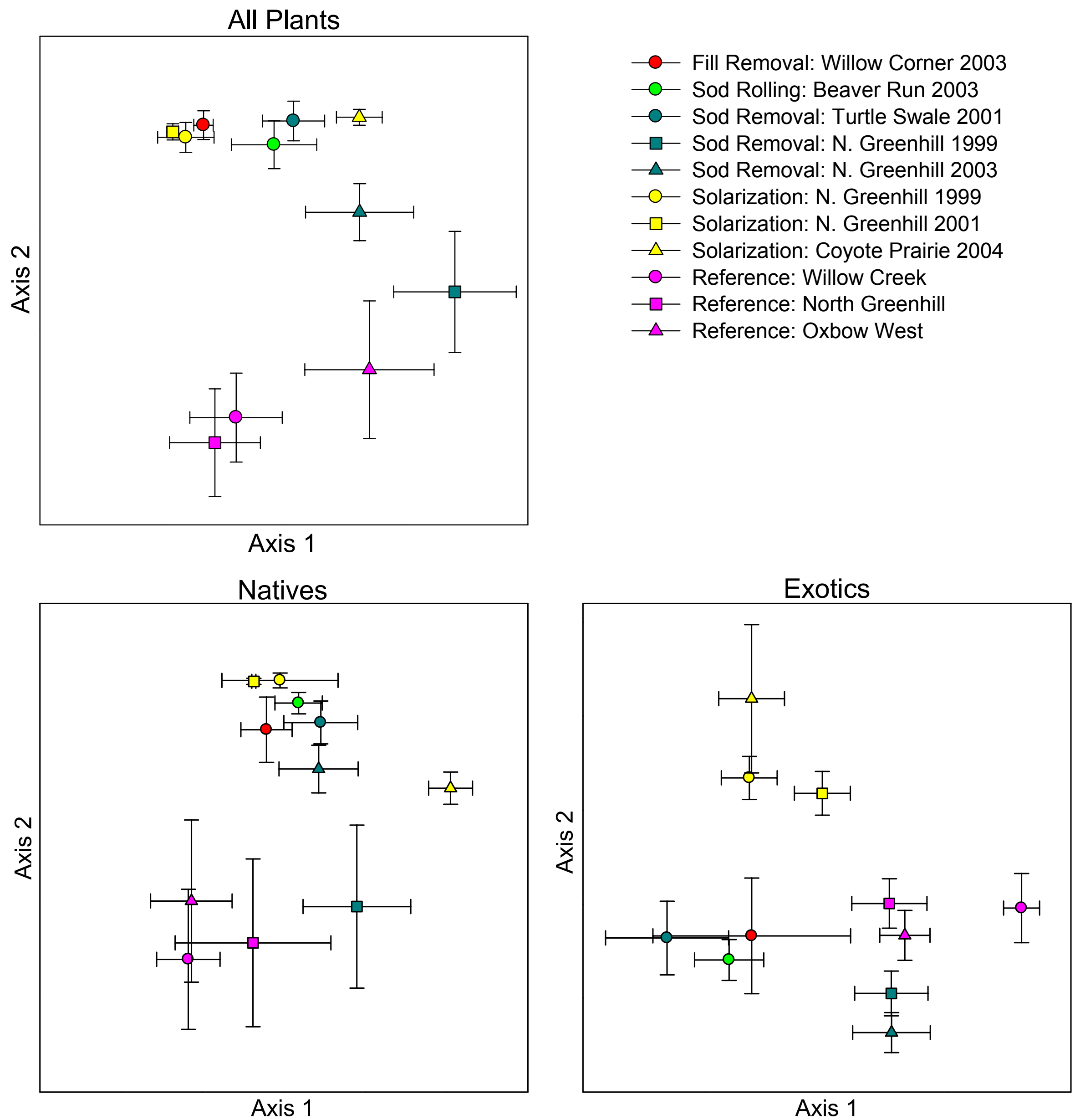


Figure 9. Nonmetric multidimensional scaling of total (A=0.34, p<0.0001), native (A=0.34, p<0.0001), and exotic (A=0.38, p<0.0001) plant communities for retroactive study using relative Sorensen distance. For all plants, axis 1 explains 25% and axis 2 explains 39% of the variation, for native plants axis 1 explains 48% and axis 2 explains 36% of the variation, and for exotic plants axis 1 explains 16% and axis 2 explains 23% of the variation in plant community structure. Error bars represent 95% confidence intervals.

Summary of plant community analysis:

- The three reference sites had similar overall plant community structure, but had relatively high variance among plots (i.e., high beta diversity) for both the overall plant community and for the native plant component. In contrast, they had some of the lowest variability for the exotic plant component. This suggests that there tends to be a relatively consistent set of exotic species found in the reference plots, whereas the native species are more patchily distributed among reference site plots.
- Plant communities in the restoration treatments were all substantially different than the reference sites, even up to 6 years post-establishment.

- The solarization sites differed the most from the reference sites in plant community structure. Solarization sites grouped relatively close to one another and had low variance (i.e., plots within a site are similar to one another).
- Plant communities in the sod removal sites were intermediate in structure between the solarization and reference sites.
- Plant community structure in the fill removal site was most similar to the solarization sites.

With only one site, traditional statistics could not be done on the fill removal and sod rolling sites. Thus for the remaining graphs, only sod removal, solarization, and reference treatments are presented.

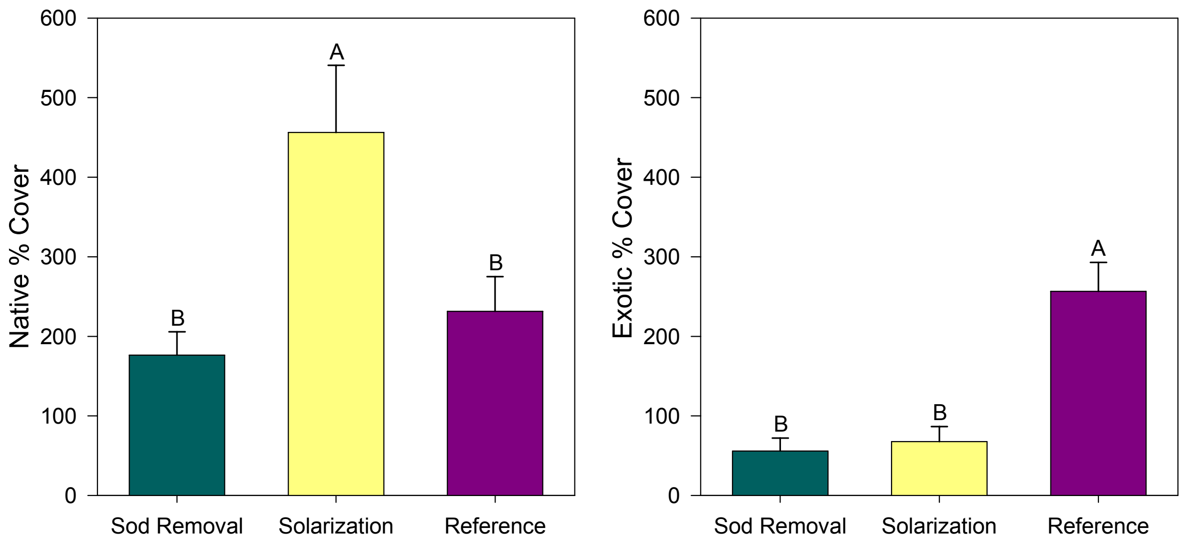


Figure 10. Mean native % cover and exotic % cover for sod removal, solarization, and reference sites. Error bars represent 95% confidence intervals.

Summary of cover data:

- Solarization sites had high native cover. This was due to the high cover of native perennial bunchgrasses (e.g., *Deschampsia cespitosa* and *Agrostis exarata*).
- Reference sites had three times the exotic cover of sod removal or solarization sites. This could partially reflect the post-management that occurs in the restoration sites (e.g., hand weeding of exotics).
- Overall, sod removal sites had the lowest total cover (adding native and exotic together).

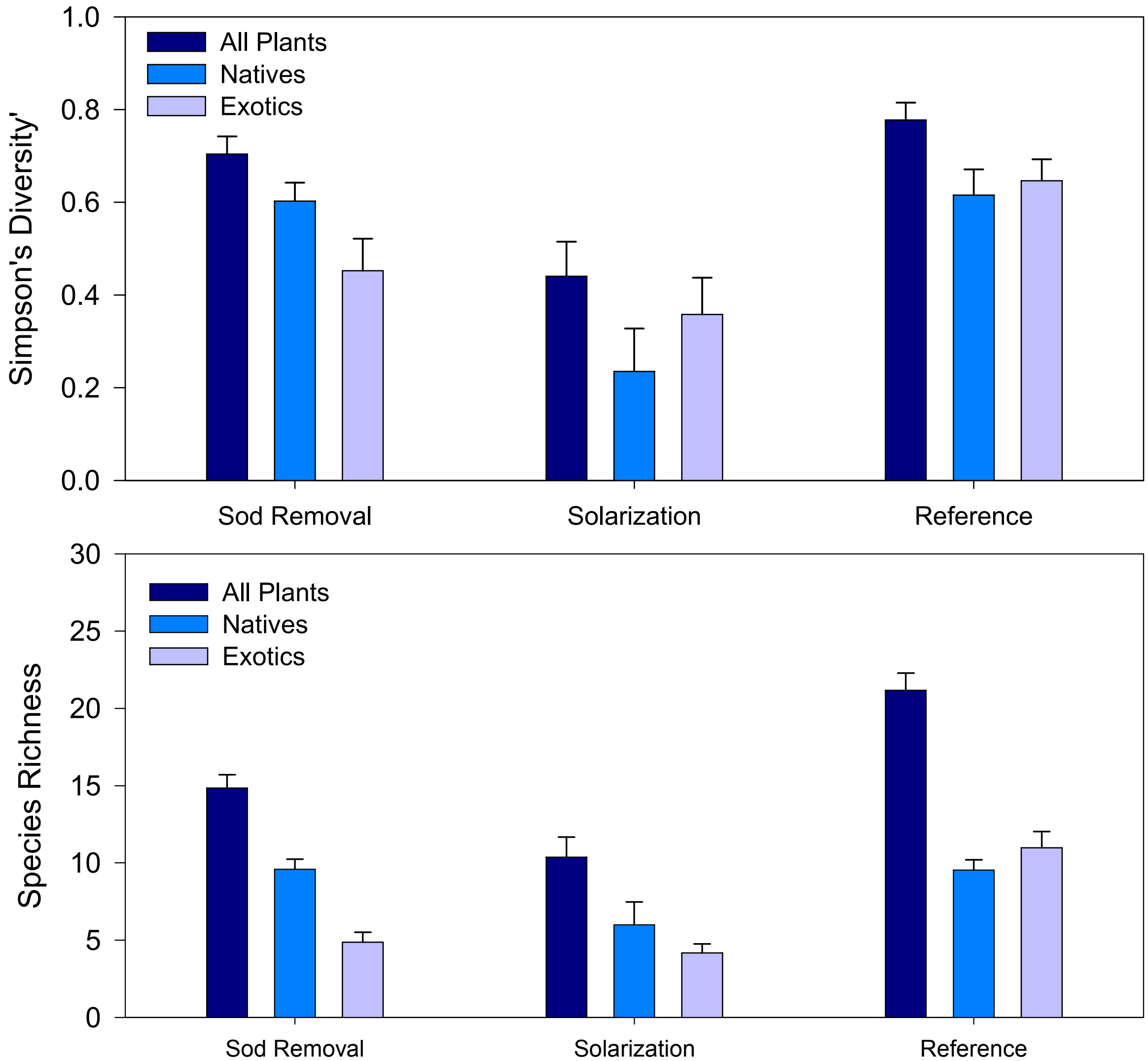


Figure 11. Mean total, native, and exotic Simpson's diversity' and species richness for sod removal, solarization, and reference sites. Error bars represent 95% confidence intervals.

Summary of richness and diversity:

- Solarization sites had lower Simpson's diversity than reference sites or sod removal sites. In particular, native diversity was very low.
- Overall, reference sites had the highest richness and diversity, which was to a great extent a consequence of their relatively high exotic species richness and diversity.
- Sod removal sites had intermediate total and native diversity and richness, but similar exotic diversity and richness to solarization sites.
- Reference sites had comparable native and exotic diversity and richness.

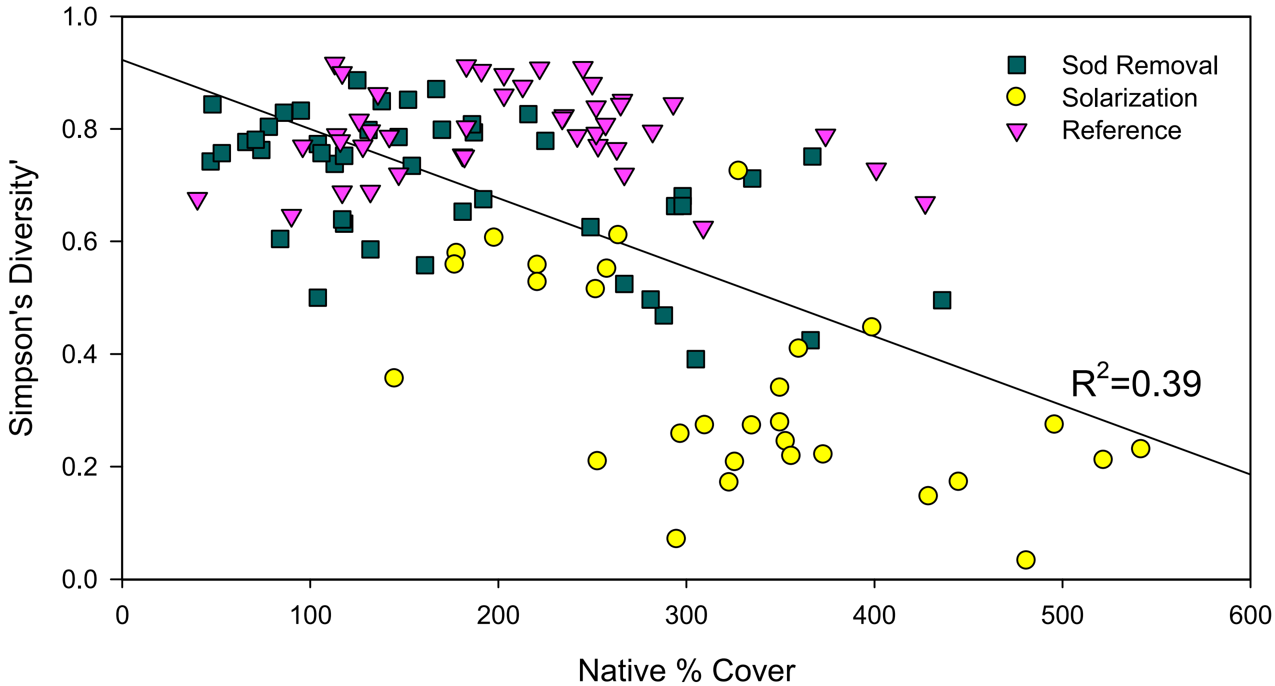


Figure 12. Simpson's diversity' vs. native % cover in the sod removal, solarization, and reference sites. Regression line is drawn for all treatments together and the R^2 is reported.

As seen in the replicated field experiment, there was a tradeoff between native % cover and diversity. Areas that had a high native cover tended to be dominated by perennial bunchgrasses with very few coexisting species.

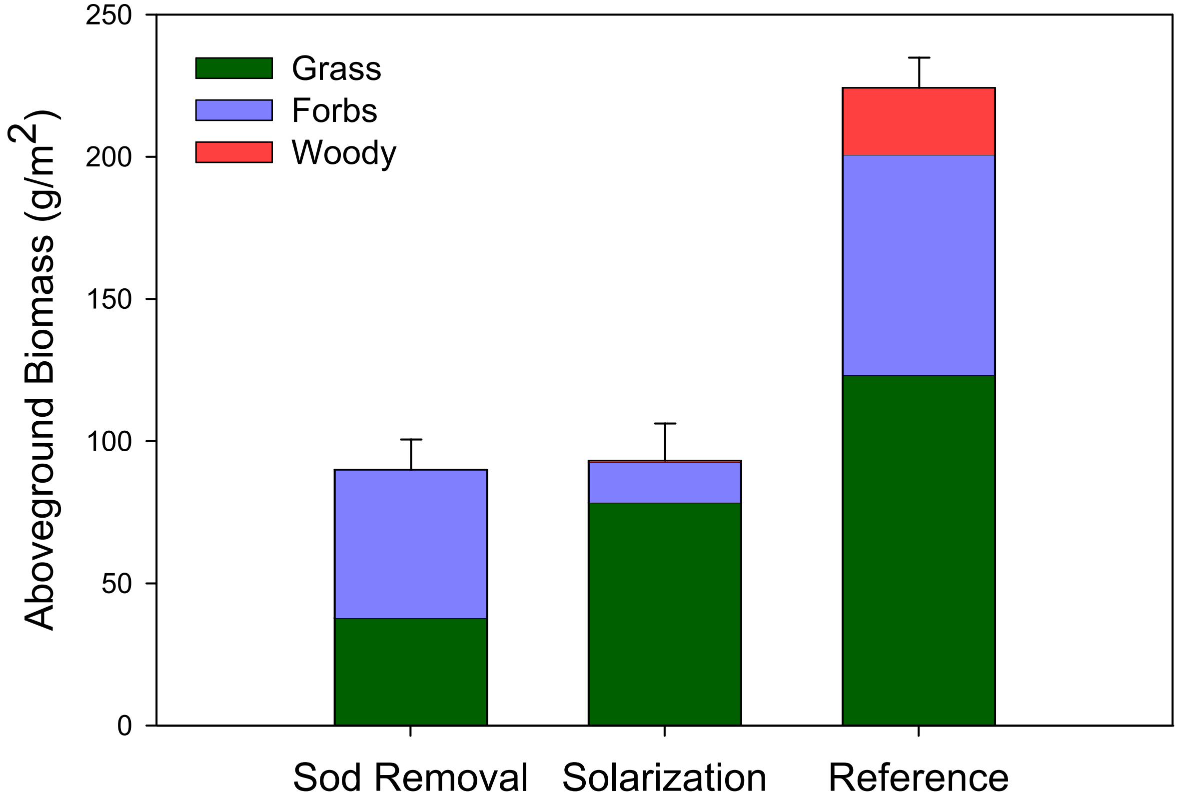


Figure 13. Mean aboveground biomass of sod removal, solarization, and reference sites. Biomass is partitioned into grasses, forbs, and woody biomass. Error bars represent 95% confidence intervals.

Summary of aboveground biomass results:

- Reference sites were the most productive areas.
- Solarization sites had a disproportionately large biomass of grasses compared to the other sites, whereas sod removal had the highest proportion of forb biomass.

Table 5. Overall significance of treatment (sod removal, solarization, and reference) on various soil attributes in retroactive study, p-values are reported (n.s. =not significant). Explanations of significant effects are given. All data was collected April 2005.

Response Variable	Treatment p-value	Explanation
Bulk Density	0.0001	Sod removal had a higher bulk density than solarization or reference sites.
Carbon/ Nitrogen Ratio	n.s.	
Total Carbon (g C/m^2)	0.0001	Sod removal sites had lower total C than solarization or reference sites.
Total Nitrogen (g N/m^2)	0.0001	Sod removal sites had lower total N than solarization or reference sites.
pH	0.0001	Solarization sites were more acidic than reference or sod removal sites.
Nitrate (µg N/g soil)	0.08	Sod removal had marginally more nitrate than reference sites.
Ammonium (µg N/g soil)	n.s.	
Phosphate (µg P/g soil)	0.0001	Solarization had higher phosphate availability than sod removal.
Microbial biomass C (µg C/g soil)	0.0001	Sod removal had less microbial biomass C than solarization or reference sites.
Microbial biomass N (µg N/g soil)	0.0001	Sod removal had less microbial biomass N than solarization or reference sites.
Microbial biomass P (µg P/g soil)	0.0001	Sod removal had less microbial biomass P than solarization or reference sites.
Ecosystem Respiration (mmol CO_2/m^2/day)	0.0001	Solarization had higher ecosystem respiration than sod removal or reference sites.
% Moisture	0.0001	Sod removal had lower % moisture than solarization or reference sites.
Belowground Biomass (g)	0.056	Sod removal had lower belowground biomass than reference sites.
Soil Texture	n.s.	
Denitrification Rate	n.s	
Mycorrhizae % Colonization	0.001	Mycorrhizal colonization was lowest in sod removal sites, intermediate in solarization sites, and high in reference sites.

Summary of soil results:

- In contrast to the replicated field experiment, there were significant differences in most soil variables among the treatment types. This may in part be due to the much larger differences in treatments (e.g., sod removal v. undisturbed soil horizons in the reference plots), to the fact that treatment was confounded with site (compared to the experiment, where all treatments were clustered in a single site), or with the longer term feedbacks of plant community to soils that may have occurred.
- In general, the sod removal sites were most different from the reference sites. With the removal of the topsoil, bulk density has increased, and microbial biomass, mycorrhizal colonization, organic matter, and belowground biomass have decreased.
- The solarization sites had higher ecosystem respiration and phosphate availability, but in general had similar soil attributes to the reference sites.

Summary of Key Findings from Retroactive Study

- Plant communities and soil properties are distinctively different among treatments. Plant community structure in the restored sites remains very different than in the reference sites.
- Reference sites had higher productivity, species richness, and in particular, exotic richness and cover than sod removal or solarization.
- Solarization sites had low richness and productivity (mostly grass), but high total cover. Soils approached reference conditions for most attributes except ecosystem respiration and PO_4^{3-} availability, perhaps due to the high thatch cover.
- Sod removal sites had low species richness and cover, but similar native species richness and native cover to the reference sites. Soils had dramatically different functional, chemical, and physical properties when compared to reference sites.
- A tradeoff exists between native cover and diversity. It is important to keep this in mind when considering the factors for a *successful* restoration.