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RESEARCH ARTICLE

The Use of Seedbed Modifications and Wood Chips to Accelerate Restoration of Well Pad Sites in Western Colorado, U.S.A.

Joshua D. Eldridge,[1,2] Edward F. Redente,[1] and Mark Paschke[1]

Abstract

Semiarid ecosystems of Western North America are experiencing a boom in natural gas development. However, these systems are slow to recover from the disturbances created. The purpose of this study was to develop improved restoration techniques on natural gas well pads in Western Colorado. This study examined effects and interactions of seedbed modifications, soil amendments, seed mixtures, and seeding methods. The experiment was conducted in pinyon-juniper and semidesert shrub plant communities on five natural gas well pads beginning in 2006. Soil and plant cover data were collected to assess the effectiveness of 16 different treatment combinations. After two growing seasons, we found that patches of soil salinity (>4 dS/m) reduced plant cover to less than 20% on 55 of our 240 experimental plots. These patches of salinity, such as where reserve pits were buried, may need to be treated to completely restore cover on the total gas pad area, although causes of salinity patches needs further investigation. After removing the 55 saline plots from our data analyses, we found that wood chips (WC) as a soil amendment increased organic matter content and reduced non-native species. Rough seedbed modifications increased the establishment of native species, especially during years of below average precipitation. Island broadcasting resulted in an increase of noxious plant cover during the second growing season. From these findings we recommend that disturbed well pads in a similar environment be restored by seeding native species on sites that are amended with WC and physically modified to create a roughened seedbed.

Key words: **ecological processes, microcatchments, native plants, natural gas, revegetation techniques, soil amendments.**

Introduction

Natural gas exploration and extraction has grown considerably in Western Colorado in recent years (Colorado Oil and Gas Conservation Commission 2008). Construction of well pads, access roads, and pipeline right-of-ways removes existing vegetation and contributes to fragmentation of wildlife habitat (Bureau of Land Management [BLM] 1991, 1999). The semiarid conditions also make restoration more difficult as water can be a limiting factor in plant establishment without implementing some management or technology assistance (Allen 1995; Bainbridge 2007).

Activities related to drilling result in soil compaction and introduction of drilling related chemicals (BLM 1999). Like much of the arid and semiarid lands in the Western United States, Garfield County in Western Colorado has large amounts of non-native weeds like *Bromus tectorum* L. (cheatgrass) that surround areas of natural gas development (Allen 1995; Monsen & McArthur 1995). The interaction of disturbance, semiarid conditions, and weedy species produces an environment where successful restoration is more challenging.

The objective of this research was to identify successful autogenic restoration strategies for natural gas development on the Western Slope of Colorado and more widely, all semiarid ecosystems. Hypotheses that relate to soil amendments, seedbed modifications, seed mixtures, and seeding methods were tested. The first hypothesis was that wood chips (WC) as an incorporated soil amendment would reduce cover of weedy species. The second hypothesis was that a rough seedbed formed by the creation of microcatchments (Whisenant 1999; also called pits by Bainbridge 2007) would produce a higher cover of desired species. The third hypothesis was that a seed mixture with native annual and perennial species would provide better cover and facilitate establishment of perennials better than a seed mixture with only native perennials. The final hypothesis was that island broadcasting, a technique using two separate seed mixes broadcast in separate areas to create vegetative islands of shrubs and forbs with the interspaces seeded with grasses, facilitates better shrub and forb establishment than the traditional broadcast method of a single seed mix spread homogenously over the entire area.

[1] Department of Forest, Rangeland and Watershed Stewardship, Colorado State University, Fort Collins, CO 80523, U.S.A.
[2] Address correspondence to J. D. Eldridge, email eldridge6@hotmail.com

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This research project integrated ecological processes and modifying factors (Krueger-Mangold et al. 2006) into techniques that can be applied not only to the restoration of natural gas well pads, but also to the restoration of surface disturbances in most any arid or semiarid environment. In this study, we did not separate seedbed modifications, soil amendments, seed mixtures, and seeding method into independent factors, because in practice these are all performed together for the purpose of successful revegetation. It is important to know how these different practices of restoration interact and affect plant establishment.

Methods

Site Description

The town of Parachute (39°27′07″N 108°03′08″W) is located on the Western Slope of Colorado, United States at an elevation of 1551 m above sea level. This area receives approximately 300 mm of precipitation a year with a highly variable distribution of precipitation throughout the year (Western Region Climate Center 2007).

The plant community in the valley bottom has largely been converted to cropland, but what native plant community remains is a semidesert shrub community, dominated by *Artemisia tridentata* Nutt. (big sagebrush) with lesser amounts of *Sarcobatus vermiculatus* (Hook.) Torr. (greasewood) and *Atriplex canescens* (Pursh) Nutt. (four-wing saltbush) (BLM 1991; West & Young 2000). The semidesert shrub community transitions into a pinyon-juniper community as elevation increases, followed by a mixed mountain shrub community near the top of the Roan Plateau (BLM 1991, 1999). This research was conducted in the pinyon-juniper and semidesert shrub plant communities. Research plots were placed on five well pads located between Parachute and Rifle, CO (Table 1). These pads were chosen because they were unlikely to be redisturbed by future drilling and were located in the plant communities that were most problematic to restore.

The Roan Plateau and underlying Green River Formation dominate soil formation of this area. These soils are formed from semi-consolidated shales that are easily weathered and produce loamy soils. The main soil types in the area of investigation include: Arvada–Torrifluvents–Heldt, Torriorthents–rock outcrop–Camborthids, and rock outcrop–Torriorthents (Harman & Murray 1977).

Experimental Design

The experiment was arranged as a split–split plot design. Well pads were considered as blocks and on each block there were six whole-plots. There were three replications of both seedbed modification types randomly assigned to the whole-plots. The experiment uses a 2 × 2 × 2 × 2 factorial design that resulted in 16 different treatment combinations. There are three replicates for each treatment at each well pad (Fig. 1). Therefore, each well pad has 48 sub-sub-plots for a total of 240 sub-sub plots (referenced from here on as plots) across all five well pads. Each of the 16 treatments has 15 total replicates. Plot dimensions are 6 m × 12 m. There are eight plots to a whole plot, making whole plot dimensions 25 m × 27 m. This includes a 1-m buffer strip between plots. This plot arrangement was replicated three times for each seedbed type on each well pad.

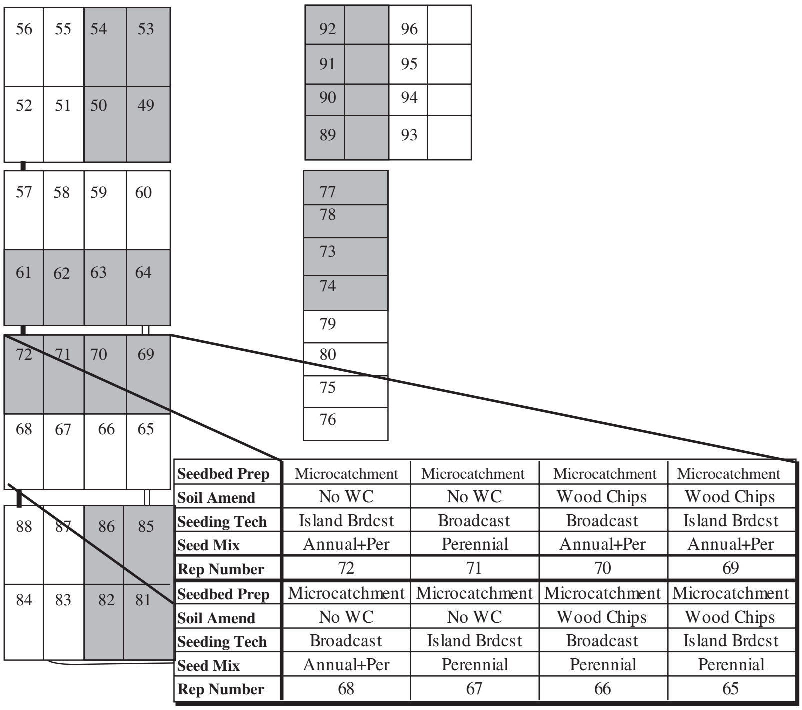
Treatment Descriptions

Research plots and all associated treatments were installed in late October and early November of 2006. The entirety of each well pad (see Table 1 for well pad surface areas) was ripped to 30 cm using a chisel plow and fertilized with 45 kg/ha of granulated 0:45:0 (N:P:K) broadcast from an all-terrain vehicle before treatments were applied. State certified weed-free straw mulch was applied at 4.5 Mg/ha after plot construction using a straw blower and crimper across all plots.

Seedbed Modification. There were two seedbed modification treatments tested, one that had a rough soil surface with microcatchments and the other that had a smooth soil surface. There were four microcatchments, measuring approximately 4.25 m^2 including the pit and mound in each plot, with one in every 18 m^2 or approximately 25% of the plot. The catchments were created by lowering the bucket on the front end of a tractor into the soil approximately 20–30 cm and driving forward 1 m, then dumping the excavated soil on the opposite

Table 1. Characteristics of natural gas well pads used for restoration research in Colorado, United States.

Pad	*Coordinates*	*Plant Community*	*Elevation (m)*	*Area of Disturbance (ha)*
GM 13-2	Latitude 39°27′53″N Longitude 108°05′02″W	Semidesert shrub	1618	0.65
PA 324-26	Latitude 39°29′23″N Longitude 107°58′13″W	Pinyon pine-juniper	1693	0.62
PA 42-29	Latitude 39°29′46″N Longitude 108°00′55″W	Pinyon pine-juniper	1792	0.78
RMV 215-21	Latitude 39°30′32″N Longitude 107°53′41″W	Semidesert shrub	1628	0.47
RMV 40-20	Latitude 39°30′44″N Longitude 107°54′50″W	Semidesert shrub	1661	0.61



Seedbed Prep	Microcatchment	Microcatchment	Microcatchment	Microcatchment
Soil Amend	No WC	No WC	Wood Chips	Wood Chips
Seeding Tech	Island Brdcst	Broadcast	Broadcast	Island Brdcst
Seed Mix	Annual+Per	Perennial	Annual+Per	Annual+Per
Rep Number	72	71	70	69
Seedbed Prep	Microcatchment	Microcatchment	Microcatchment	Microcatchment
Soil Amend	No WC	No WC	Wood Chips	Wood Chips
Seeding Tech	Broadcast	Island Brdcst	Broadcast	Island Brdcst
Seed Mix	Annual+Per	Perennial	Perennial	Perennial
Rep Number	68	67	66	65

Figure 1. Example of experimental design on a natural gas well pad in Colorado, United States. The whole plots (group of eight plots) are based on the seedbed modification type (rough or smooth) and split by the soil amendment type (WC [shaded region] or no WC). The remaining treatments (seeding technique and seed mix) were randomly placed within each whole plot.

side of the catchment. Primary orientation of the microcatchments was perpendicular to prevailing wind direction on flat surfaces or to the slope on steeper surfaces. The pile of soil was placed on the windward or downhill side of the catchment. The soil surface in between the microcatchments was rougher than the non-pitted smooth soil treatment, which was created using a harrow attached to a tractor.

Soil Amendments. There were two soil amendment treatments: WC versus no WC. An application rate equal to 90 Mg/ha of WC was applied to half of the sub-plots on all well pads (Schuman & Belden 1991). The WC were *Pinus* sp. acquired from a saw mill in Grand Junction, CO, and varied in size from saw dust to 15-cm-long chips. WC were incorporated into the top 15 cm of the soil using multiple passes with a chisel plow and harrow. Incorporation of the WC was intended to reduce plant available nitrogen, improve infiltration, increase soil moisture capacity, increase organic matter (OM) content of the soil, and stimulate microbial activity in the soil (Brady & Weil 1999).

Seeding Methods. Seeding methods included island broadcasting and traditional broadcasting. Island broadcasting separated forb and shrub species from grass species in the seed mix. The forbs and shrubs were hand broadcast in islands with the interspaces seeded with grasses. On the rough seedbed plots the forb and shrub mix was hand broadcast over and around the microcatchments. On the smooth seedbed plots the shrub and forb mix was hand broadcast in approximately the same spatial locations as the microcatchments. Traditional broadcast method had all plant life forms combined in one seed mix and hand broadcast homogenously over the entire plot.

Seed Mixes. There were two different seed mixes tested in each plant community; one seed mix contained only native perennials and the other contained native annuals and perennials. The species composition of the seed mixes were slightly modified based on the plant community type. Table 2 lists the species that were used in this experiment. Because of modifications for plant community type, the seeding rate varied from 44 to 66 kg pure live seed (PLS) ha^{-1}.

Data Collection

Plant cover was collected in July 2007 and July 2008. Plant cover was estimated using the point intercept method along line-transects. There were nine 12-m long transects spaced 61 cm apart per plot with hits recorded every meter. There were a total of 108 points sampled per plot. Aerial cover was estimated for each point, so any plant part from current year's growth, bare ground, litter, or rock that intercepted the line was recorded

Soil samples were collected during the summer of 2007 following the first growing season. A composite soil sample was collected from each plot. The composite sample consisted of three sub-samples from the top 15 cm of soil. Soil analyses included pH, electrical conductivity (EC), sodium absorption

Table 2. Native species planted on natural gas well pads in Colorado, United States.

Scientific Name	*Common Name*	*PLS/m²*	*Seeding Rate (PLS kg/ha)*
Juniperus osteosperma	Utah juniper	3	2.2
Artemisia tridentata var. *vaseyana*	Mountain big sagebrush	248	0.6
Ericameria nauseosus var. *nauseosa*	Rubber rabbitbrush	151	1.1
Atriplex canescens	Fourwing saltbush	54	4.7
Hesperostipa comata	Needle and thread	108	3.4
Achnatherum hymenoides var. *Paloma*	Indian ricegrass	118	3.4
Pascopyrum smithii var. *Ariba*	Western wheatgrass	86	3.4
Elymus trachycaulus var. *Revenue*	Slender wheatgrass	108	3.4
Elymus elymoides	Bottlebrush squirreltail	140	3.4
Sporobolus airoides	Alkali sacaton	215	0.6
Pleuraphis jamesii	James' galleta	118	3.4
Pseudoroegneria spicata	Bluebunch wheatgrass	97	3.4
Sphaeralcea coccinea	Scarlet globemallow	248	2.2
Penstemon strictus	Rocky Mountain penstemon	215	3.4
Linum lewisii	Lewis flax	226	3.4
Heliomeris multiflora	Showy goldeneye	194	0.8
Vicia americana	American vetch	32	4.5
Hedysarum boreale	Utah sweetvetch	32	3.4
Helianthus annuus	Common sunflower	24	2.2
Cleome serrulata	Rocky Mountain bee plant	43	3
Vulpia octoflora	Six weeks fescue	162	0.8

ratio (SAR), texture, and percent OM. Soil pH, EC, and SAR analyses were all done using a saturated paste extract. The EC was measured using a 1 cm conductivity cell and the SAR was measured by inductively coupled plasma. Texture was determined using an ASTM 152H hydrometer. OM content was determined using a modified Walkley–Black procedure (Spark 1996).

Data Analysis

We present results of soil sampling and four plant cover dependent variables: native seeded, non-native, noxious, and total plant cover. The native seeded variable includes those species that were seeded into the plot and referenced in Table 2. Non-native species were those plants that are not native to the area. Noxious species are plants that aggressively invade or are detrimental to economic crops or native plant communities; are poisonous to livestock; a carrier of detrimental insects, diseases, or parasites; or the direct or indirect effect of the presence of this plant is detrimental to the environmentally sound management of natural or agricultural ecosystems (Colorado Department of Agriculture 2003). Total plant cover is the combination of all dependent variables. The variables were not normally distributed and did not have homogenous variances by treatment due to high variability both within and between well pads. Based on visual observations and the results of the soil and plant sampling, it was determined that soil salinity may have reduced plant cover and caused interference with the treatments. Therefore, it was determined that plots with EC greater than 4 dS/m and plant cover less than 20% would be removed from the analysis.

Fifty-five plots were removed based on the above criteria, but the remaining 185 plots had highly skewed distributions for all variables, except for the total plant cover, which had a near normal distribution. No transformation normalized the distributions or made the variances of the remaining variables homogenous by treatment. In order to account for the non-normal distributions and unequal variances of data, a generalized linear mixed model was fit using the statistical software SAS proc GLIMMIX (SAS Institute Inc., Cary, North Carolina, 2006). This procedure combines a generalized linear model and a mixed model, which allowed statistical models to be fit to data with unequal variances and non-normal distributions. In this case a negative binomial distribution model was determined to be the most suitable. Proc GLIMMIX also accounted for the multiple error terms created by the experimental design. The data were analyzed individually by year. The soils data were analyzed using the same GLIMMIX model that was used for the cover data. Log transformations were found to provide normal distributions and homogenous variances by treatment for the OM and EC values.

Results

Soils

The results of soil sampling in 2007 showed that 135 of the 240 plots were saline ($pH < 8$, $EC > 4$ dS/m, $SAR < 15$) or saline–sodic ($pH < 8$, $EC > 4$ dS/m, $SAR > 15$). The average pH, EC, OM, and SAR values across all treatments were 7.6, 5.4 dS/m, 1.6%, and 7.1, respectively. The removal of plots due to soil salinity and low plant cover changed the EC and SAR averages to 4.0 dS/m and 5.8, respectively. The addition of WC was the only treatment that had a significant effect on any of the soil parameters. The WC addition significantly increased OM 38% from 1.3 to 1.8% (Fig. 2).

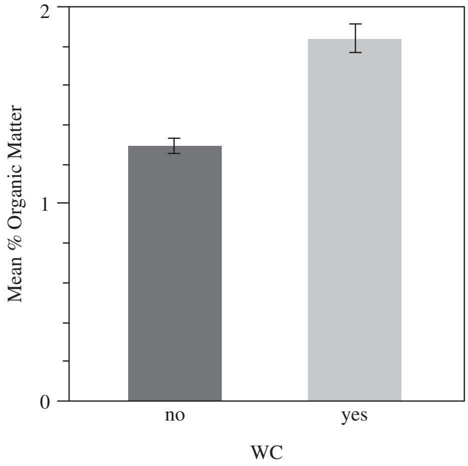


Figure 2. Effects of WC on percent OM of soils on natural gas well pads in Colorado, United States (p value 0.01).

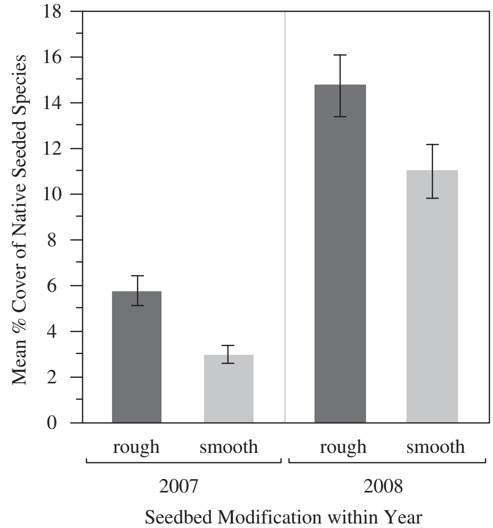


Figure 3. Effects of seedbed modification on native seeded species on natural gas well pads in Colorado, United States separated by year. (2007 p value 0.01, 2008 p value 0.09).

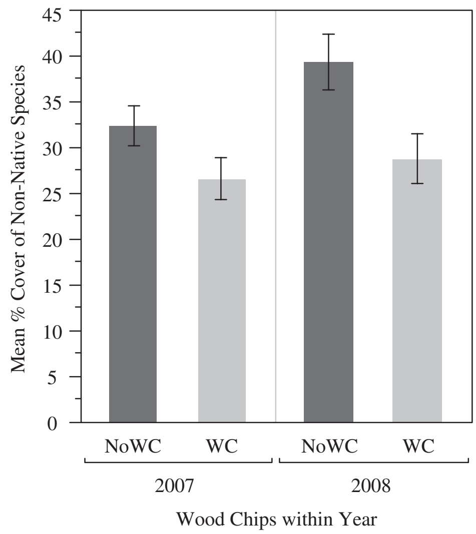


Figure 4. Effects of WC on non-native species cover on natural gas well pads in Colorado, United States (2007 p value < 0.001; 2008 p value 0.01).

Native Seeded Species

Native seeded species had different responses to treatments, depending on the year. Precipitation during the first growing season was 53% of average (100 mm) from November 2006 to June 2007, whereas precipitation during that same span in 2008 was 104% of average (193 mm). Native seeded cover in 2007 averaged 4.5% across all treatments with a standard deviation of 5.6 and ranged from 0 to 31%, with an average of six species present. Native seeded cover in 2008 showed a significant increase (Fig. 3) with an average of 13.0% across all treatments, a standard deviation of 12.5 and a range of 0–74% with an average of nine species. The most successful shrub, forb, and grass species were: *Atriplex canescens* (four-wing saltbush), *Hedysarum boreal* (Utah sweetvetch), and *Pascopyrum smithii* var. Arriba (western wheatgrass).

The most significant treatment effect seen on the native seeded species was that the rough seedbed exhibited increased cover compared to the smooth seedbed treatment in both years (Fig. 3). As previously mentioned, 2007 had significantly less than average precipitation and 2008 had about average. This treatment effect was consistent in both plant communities and at sites that were flat or had topographic relief.

Seed mixture had a significant influence on plant community development in 2007, but the effect was short lived. The first growing season showed significantly higher cover (p value 0.02) with the annual and perennial seed mix (5.5 vs. 4.0% cover), but 2008 showed no statistical difference (p value 0.17) between seed mixtures, 13.0% for the annual and perennial seed mix versus 15.2% with just perennials.

Non-Native Species

Non-native species cover in 2007 was 29.5% when averaged over all treatments, with a standard deviation of 21.7 and a range of 0–73% with an average of five species. Non-native cover in 2008 was 34% averaged over all treatments, with a standard deviation of 28 and a range of 0–90% with an average of six species. The three most common non-native species were *Sisymbrium altissimum L.* (tall tumble mustard), *Salsola tragus* L. (prickly Russian thistle), and *Eremopyrum triticeum* (Gaertn.) Nevski (annual wheatgrass). WC had a significant negative effect on non-native plant cover in both years (Fig. 4). In 2007, WC reduced non-native cover by 18% and 2008 showed an even greater effect with a 27% decrease in non-native cover when compared to the no WC treatment.

Noxious Species

Noxious species cover increased from 2007 to 2008. Noxious plant cover in 2007 was 0.2% when average over all

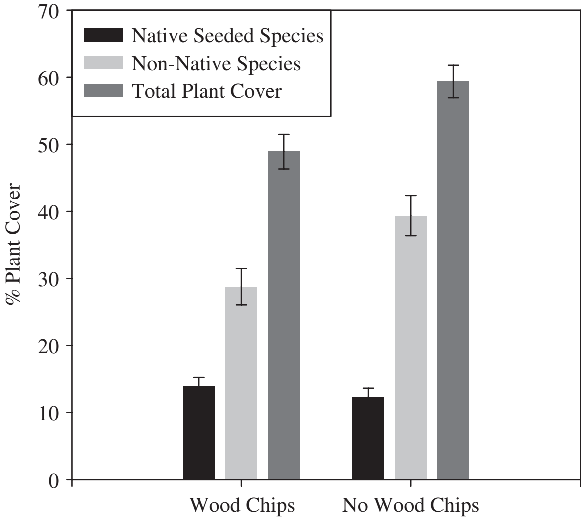


Figure 5. The effects of WC on native seeded species, non-native species, and total plant cover on natural gas well pad restoration in Colorado, United States.

treatments, with a standard deviation of 0.6 and a range of 0–4% with an average of one species. This increased to 4.5% in 2008, with a standard deviation of 6.2 and a range of 0–32% with an average of two species. The only noxious species encountered on the research plots were *Bromus tectorum* L. (cheatgrass), *Erodium cicutarium (L.) L'Hér.ex Aiton* (redstem filaree), and *Halogeton glomeratus (Bieb.) C.A. Mey* (saltlover).

There was a low incidence of noxious species in 2007 and no treatment influenced the cover of noxious plants. With the increase in noxious plants in 2008, the island broadcasting treatment (5.7% cover) showed a significant (p value 0.02) increase in noxious species cover when compared to the traditional broadcast method (4.1% cover).

Total Plant Cover

Total plant cover was significantly higher in 2008 than 2007. Total plant cover in 2007 averaged 36% cover across all treatments, with a standard deviation of 20.7 and a range of 0–80% with an average of 13 species. Total plant cover in 2008 averaged 54%, with a standard deviation of 24.6 and a range of 3–99% with an average of 19 species.

WC were the only treatment that had a significant effect on total plant cover and they significantly reduced total plant cover in both growing seasons. Total plant cover was reduced by 15.6% in 2007 and 18.0% in 2008. Although total cover was reduced with WC, the ratio of non-natives to natives actually improved from a 3:1 without WC to a 2:1 with WC (Fig. 5).

Discussion

The large disparity in moisture conditions between the 2 years of this study provided an opportunity to investigate how treatments affect plant community development in an average and below-average water year. Given the monthly and annual variability in precipitation for this and other semiarid areas, it is important to identify techniques that can assist the establishment of desired native species during less than average precipitation years.

WC as an incorporated soil amendment and the creation of a rough seedbed could have long-lasting effects on the establishment of viable native plant populations on surface disturbances caused by resource extraction in semiarid areas. The effects of these two treatments were the most consistent of all treatments across both growing seasons. The rough seedbed improved native plant cover regardless of moisture conditions, which is important when trying to reclaim areas in arid and semiarid environments. The WC treatment consistently reduced non-native species and significantly increased soil OM content. Newman and Redente (2001) found that initial restoration practices can have a long-term influence on plant community development, so if the trends from this experiment continue there is potential that these treatments would provide operators with additional strategies to establish viable native plant communities.

The rough seedbed modification improved all plant-cover variables in 2007, but in 2008 only the native seeded species displayed higher cover in the rough seedbed. There are several potential reasons why the rough seedbed improved plant cover. Rougher soil surfaces increase the number of safe sites for germinating seeds by providing improved seed/soil contact and better moisture and temperature conditions than smooth soil surfaces (Harper et al. 1965; Call & Roundy 1991; Winkel et al. 1991; Smith & Capelle 1992; Chambers 2000). These effects should persist as long as the microcatchments remain functional. Harper et al. (1965) stated that the number of individuals that become established is a direct function of the number of available safe sites provided on the soil surface. One concern with microcatchments in this study is that the pits accumulated large amounts of litter associated with windblown straw mulch and dead plant material. Over time, this could improve soil quality with an increase in OM, but accumulated litter may create an impediment to seedling emergence in some areas (Fowler 1988; Smith & Capelle 1992).

WC as a soil amendment shows promise as a viable strategy for improving restoration on surface disturbances. WC increased the OM content of the soils, which has been shown to improve microbial activity (Tisdall et al. 1978; Anderson & Domsch 1989), water holding capacity, aggregate stability, and lowers soil bulk density (Barzegar et al. 2002; Sanborn et al. 2004; Tahboub et al. 2008). These are all soil characteristics that affect plant establishment and are potential limiting factors to successful well pad restoration.

The addition of a carbon (C) source, in this case WC, and the anticipated change in nitrogen (N) availability (Paschke et al. 2000; Herron et al. 2001; Blumenthal et al. 2003; Baer et al. 2004) resulted in a shift in the plant community composition that favored the cover of native seeded species. It was expected that the addition of a C source would result in a reduction of overall plant growth because the additional C would stimulate soil microbial growth thus tying up available N in their biomass (Brady & Weil 1999; Blumenthal et al. 2003). This result was also expected because one of the most abundant non-native species was Russian thistle and Redente et al. (1992) found that Russian thistle was significantly reduced at low levels of available N. The positive response of native seeded species to WC, in conjunction with the rough seedbed modification, provides two strategies that, if early trends continue, would result in a higher cover and frequency of desired species (Harper et al. 1965; Eschen et al. 2007).

There were mixed results with the effect of seed mixtures on native seeded species. In the first growing season the annual plus perennial seed mix produced a higher cover of native species. This response was not observed in 2008. This may be explained by the majority of annual species germinating in the first growing season, but their inability to set seed under dry conditions in 2007 resulted in a lower number of annuals in 2008. Initially, it was thought that the native annuals would be able to compete against and reduce the cover of the non-native annuals (Fargione et al. 2003; Pokorny et al. 2005), which was observed in 2007, but not in 2008.

The increase in noxious plants associated with island broadcasting could pose a threat to successful restoration on these pads. Noxious species dominate the areas surrounding many of the well pads and one objective of restoration is to establish a plant community that can resist plant invasions. However, the island broadcast treatment, as implemented in this study, may actually provide an opening for noxious species to become established as the seeding rate with island broadcasting was lower than the traditional broadcast treatment. The increase in noxious species, especially cheatgrass, with this treatment may make it too risky in areas where noxious species are a problem. Future research should focus on increasing the seeding rate to provide more direct competition with noxious species.

The presence of saline and saline-sodic soils and their influence on plant community development was not fully explored in this study. More than half of the 240 research plots displayed saline or sodic-saline soil conditions. Cause of the salinity is unclear at this time, but the spatial relationship between the location of the majority of saline plots and the location of the buried reserve pit indicate that there may be a relationship between the two. Further investigation is needed to determine if there is a correlation between the buried reserve pit and soil salinity and sodicity.

The treatments tested were intended to restore disrupted ecological processes and initiate an autogenic repair process for restoration of surface disturbances in a semiarid environment, specifically natural gas well pads on the Western Slope of Colorado. The use of a rough seedbed and WC shows potential in manipulating plant community composition to favor native seeded species and help reduce non-native species cover. The treatments that influenced the seedbed and rooting zone appear to be driving the interactions and success of different restoration approaches and techniques.

Implications for Practice

- Extensive, systematic soil sampling and treatment of contaminated areas, such as patches of high salinity, before applying the restoration treatments will greatly improve chances for success.
- Do not assume that there were no spills or that salts have not moved into the rooting zone.
- Seedbed modifications should try to create rough microsites to improve seeding success and incorporate wood waste or similar material to increase soil OM.
- Use a diverse seed mix that matches local climate and meets post mining land use.

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