THESIS

DEVELOPMENT OF A SAGEBRUSH STEPPE PLANT COMMUNITY 33 YEARS AFTER SURFACE DISTURBANCE

Submitted by

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ABSTRACT

DEVELOPMENT OF A SAGEBRUSH STEPPE PLANT COMMUNITY 33 YEARS AFTER SURFACE DISTURBANCE

The sagebrush steppe ecosystem is the most endangered ecosystem in North America due to sagebrush eradication, weed invasions and energy development. Restoration of sagebrush steppe plant communities damaged by these disturbances is extremely important to the survival of endangered or threatened sagebrush dependant species such as the sage-grouse and Columbia Basin pygmy rabbit. In the fall of 1976 a field experiment was initiated in the Piceance Basin of northwestern Colorado to study the effects of six seed mixes and three fertilizer treatments on the restoration of a sagebrush steppe plant community after surface disturbances associated with oil shale development. We revisited these study plots during 2008 and 2009 to determine the long-term effects of these treatments on plant community development.

Results from this 33-year study indicate that seed mix has long-term effects on the plant community production and composition. The composition of the plant community in all seeded plots was very similar to that of the seed mix used in 1976. The late-seral dominant shrub species in this system, sagebrush

(*Artemisia tridentata*), which was not seeded in any of the treatments, did not recover as the dominant shrub species. An initial fertilizer treatment had short-term effects on the plant community but its effects have become insignificant over time. A seed mix containing native species with no fertilizer addition appears to be the best long-term treatment for restoring a native sagebrush steppe plant community in this study.

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Introduction

Big sagebrush *(Artemisia tridentata)* is the dominant and arguably the most important plant species of the sagebrush steppe ecosystem in western North America (Prevey et al. 2010). It grows primarily in the intermountain west, situated between the Sierra Nevada and the Cascades Mountains to the west and the Rocky Mountains to the east. It once covered an area of approximately 44.8 x 10^6 hectares (West 1983) but is now estimated that as much as half of this ecosystem has already been lost (McIver 2010).

The sagebrush steppe has undergone many intense changes since European settlement brought livestock and agriculture. Land managers have removed sagebrush by prescribed burning, herbicides and mechanical methods to make room for forage species and farmland. With the introduction of cheatgrass (*Bromus tectorum*) in the late eighteen hundreds, the fire regime in some areas has increased to a frequency to which sagebrush is not well adapted (Baker 2006). Energy development is also contributing to the degradation and destruction of suitable sagebrush habitat. A model created by Walston et al. (2009) indicates that 1750 hectares of sagebrush in Wyoming have been directly impacted by natural gas infrastructure and that more than 50% of sagebrush habitat has been degraded.

Many sagebrush obligate animal species are also in direct danger of extinction due to habitat loss. The Columbia Basin pygmy rabbit is listed as endangered by the US Fish and Wildlife Service (U. S. Fish & Wildlife Service 2010) along with the highly visible Gunnison sage-grouse, which is a conservation species of concern in Colorado (Colorado Division of Wildlife 2010) and is listed as an endangered species in Canada (Committee on the Status of Endangered Wildlife in Canada 2010). One model predicts a 7-19% decrease in sage-grouse populations due to future oil and gas development (Copeland et al. 2009). With predicted rising temperatures and decreasing snow fall due to climate change, sagebrush populations and cover are predicted to decline (Poore et al. 2009) making the sagebrush steppe the most endangered ecosystem in North America (Knick et al. 2003).

The sagebrush steppe in the Piceance Basin of Northwestern Colorado is part of the larger Green River Basin that extends into southwestern Wyoming and eastern Utah. Oil shale was discovered in this region during the late 1800's and contains an estimated 1 trillion barrels of oil (Dyni 2002) lying underneath approximately 36,000 km^2 (13,900 mi^2) of land area. Many attempts over the last century have been made to efficiently extract the oil shale, but none to date have proven to be profitable. In the future, it is likely that this oil deposit will be extracted resulting in a large-scale disturbance. Revegetating these disturbed areas with native species is paramount for the survival of the sagebrush ecosystem, sagebrush dependant species and to meet the standards set by the federal Surface Mining Control and Reclamation Act of 1977[1].

A large research project, consisting of 10 separate studies, was initiated in the Piceance Basin of northwestern Colorado in 1976 to provide information for the reclamation of a sagebrush steppe plant community disturbed by oil shale development. One of the studies, Successional Study on Surface Disturbed Soils (SSSDS), was designed to examine the effects of seed mixes and fertilizer treatments on plant community recovery following surface disturbances associated with ancillary mining activities, such as access roads and staging areas (Cook and Redente 1980). During the installation of this study aboveground plant biomass and topsoil were removed, leaving the study site in a state similar to the early stages of primary succession (Bradshaw 1997).

The species that are first to arrive at such disturbances have priority and therefore may become dominant in the plant community (Young et al. 2001). In addition to being dominant, these species also set the trajectory of the subsequent and final plant communities (Egler 1952, Drake 1991). Such an effect is often referred to as initial floristics (Egler 1952) or, more recently as priority effects (Drake 1991).

[1] Surface Mining Control and Reclamation Act of 1977, title 30, chapter 25, subchapter V, δ 1265.b19

The objective of this thesis was to document the priority effects of the initial six seed mixtures and initial three fertilizer treatments. I hypothesize that a seed mixture containing native grasses, forbs and shrubs with no fertilizer treatment is the best for creating a productive, diverse native plant community in a disturbed sagebrush steppe in northwestern Colorado compared to the other five native and introduced seed mixes.

Materials and Methods

The study site is situated on 2.5 hectares in a sagebrush steppe community in the Piceance Basin of northwestern Colorado, 60 km NW of Rifle, CO (39°54'13'' N, 108°24'02'' W). Climate of the area is semiarid with a mean annual temperature of 8.7°C and mean annual precipitation of 294 mm with about half being received as snow during the winter and spring months (November-April) (National Weather Service 2007).

To examine the effects and interactions of seed mixture, fertilizer and mulch, the vegetation, along with the top 2-6 cm of soil, was removed with a bulldozer. Soil was then ripped to a depth of 30 cm. The study site was divided into 108, 9-m X 18-m plots in a split-plot design with six seed mixtures comprising the main plots and three fertilizer treatments comprising the subplots (Figure 1). Study plots were surrounded by a healthy sagebrush ecosystem situated on level ground at an average elevation of 2020 m. Hydro-mulch was applied to the 54 perimeter plots (grey plots in Figure 1), but its effects were considered insignificant (Johnson 1981) and therefore, those plots were not included in the present study. Six different seed mixtures of native and introduced grasses, forbs, and shrubs were drill seeded on the site (Table 1) in September of 1976. Winterfat (*Krascheninnikovia lanata*) was broadcast seeded prior to drilling because it has a tufted seed that could not be drill seeded evenly in the study plots.

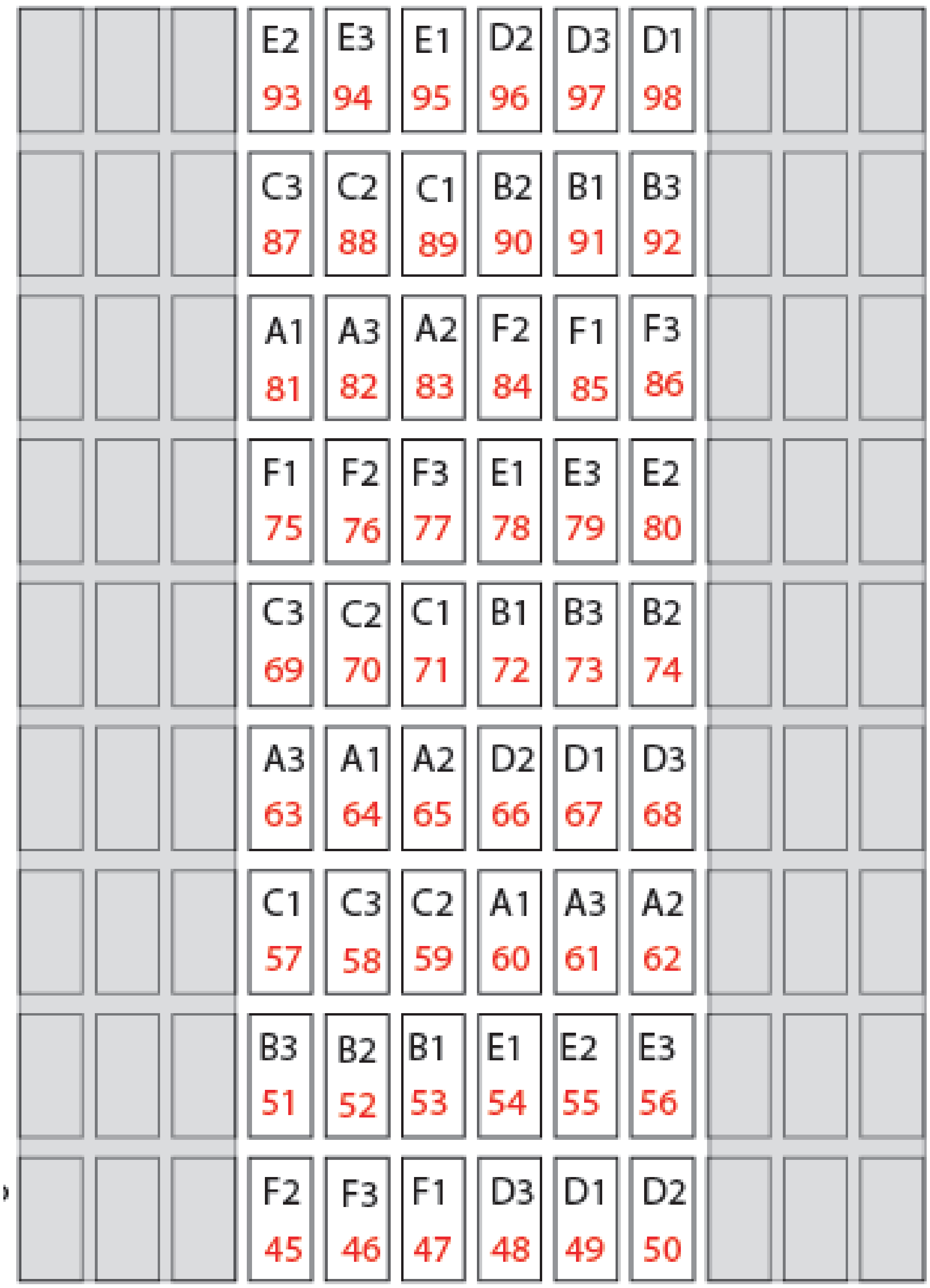

Figure 1. Plot layout at the Successional Study on Surface Disturbed Soils in the Piceance Basin of northwest Colorado. Alphanumeric code indicates seed mix and fertilizer treatment combination (A=native grass, C=native grass forb, E=native grass forb shrub, B=introduced grass, D=introduced grass forb, F=native & introduced grass forb shrub, 1=112 kg N ha^{-1} and 56 kg P ha^{-1}, 2=56 kg N ha^{-1} and 28 kg P ha^{-1}, and 3=no fertilizer) and the number is the plot number (45-98). The grey shaded plots had hydro-mulch applied and were determined not to be significant after 3 years and therefore were not included in the present study.

Table 1. Seed mixes used in 1976 at the Successional Study on Surface Disturbed Soils in the Piceance Basin of northwestern Colorado (LF=life form; G=grass, f=forb and S=shrub). Species with a star (*) were included in the seed mix but were not found in any quadrats sampled in 2008 or 2009.

Scientific name	Common name	Seeding Rate (kg ha^{-1})	LF	Nativity
Mixture A - Native grasses				
Pseudoroegneria spicata	Bearded bluebunch wheatgrass	3.4	G	N
Pascopyrum smithii	Western wheatgrass 'Rosana'	4.5	G	N
Elymus lanceolatus	Streambank wheatgrass 'Sodar'	3.4	G	N
Nassella viridula	Green needlegrass	3.4	G	N
Achnatherum hymenoides	Indian ricegrass	2.2	G	N
Mixture B - Introduced Grasses				
Agropyron cristatum	Crested wheatgrass 'Nordan'	3.4	G	I
Thinopyrum intermedium	Intermediate wheatgrass 'Oahe'	9.0	G	I
Psathyrostachys juncea	Russian wildrye 'Vinal'	3.4	G	I
Mixture C - Native grasses and forbs				
Elymus lanceolatus	Thickspike wheatgrass 'Critana'	5.6	G	N
Pseudoroegneria spicata	Bearded bluebunch wheatgrass	2.2	G	N
Nassella viridula	Green needlegrass	2.2	G	N
Achnatherum hymenoides	Indian ricegrass	1.1	G	N
Hedysarum boreale	Sweetvetch	1.1	F	N
**Coronilla spp.*	Crownvetch	1.1	F	N
Linum lewisii	Lewis flax	1.1	F	N
Penstemon palmeri	Palmer penstemon	1.1	F	N
Mixture D - Introduced grasses and forbs				
Psathyrostachys juncea	Russian wildrye 'Vinal'	3.4	G	I
Agropyron cristatum	Crested wheatgrass 'Nordan'	3.4	G	I
Thinopyrum intermedium	Pubescent wheatgrass 'Luna'	3.4	G	I
Medicago sativa	Alfalfa 'Ladak'	1.1	F	I
**Saponaria officinalis*	Bouncing bet	1.1	F	I
**Sanguisorba minor*	Small burnet	1.1	F	I
**Astragalus cicer*	Cicer milkvetch 'Lutana'	2.2	F	I

Table 1. Continued.

Scientific name	Common name	Seeding (kg/ha^{-1})	LF	Nativity
Mixture E - Native grasses, forbs and shrubs				
Table 1 continued				
Achnatherum hymenoides	Indian ricegrass	2.2	G	N
Pseudoroegneria spicata	Bearded bluebunch wheatgrass	2.2	G	N
Pascopyrum smithii	Western wheatgrass 'Rosana'	4.5	G	N
**Coronilla spp.*	Crownvetch	1.1		N
Hedysarum boreale	Sweetvetch	1.1	F	N
**Purshia mexicana*	Stansbury cliffrose	1.1	S	N
Ephedra viridis	Green Ephedra	1.1	S	N
Atriplex canescens	Fourwing saltbush	2.2	S	N
Krascheninnikovia lanata	Winterfat	1.1	S	N
Mixture F - Native and Introduced grass, forbs and shrubs				
Nassella viridula	Green needlegrass	2.2	G	N
Pseudoroegneria spicata	Bearded bluebunch wheatgrass	2.2	G	N
Agropyron cristatum	Crested wheatgrass 'Nordan'	2.2	G	I
Thinopyrum intermedium	Pubescent wheatgrass 'Luna'	2.2	G	I
**Astragalus cicer*	Cicer milkvetch 'Lutana'	1.1	F	I
Hedysarum boreale	Sweetvetch	1.1	F	N
**Purshia mexicana*	Stansbury cliffrose	1.1	S	N
Ephedra viridis	Green Ephedra	2.2	S	N
Krascheninnikovia lanata	Winterfat	1.1	S	N

The three fertilizer treatments were: high) 112 kg N ha^{-1} and 56 kg P ha^{-1}; low) 56 kg N ha^{-1} and 28 kg P ha^{-1}; and no fertilizer. Phosphorus was applied as triple superphosphate and roto-tilled into the soil prior to seeding. Application of nitrogen fertilizer, as granulated ammonium nitrate, was postponed until the end of the first growing season to avoid stimulating annual weed growth. Each seed mix and fertilizer combination was replicated three times. A 3-meter high wildlife fence was erected around the entire study area.

Four undisturbed reference plots, located in the adjacent native shrubland, were added as a 7th seed mix and 4th level of fertilizer so it could be compared against the other 6 seed mixes and 3 fertilizer treatments respectively. With a few exceptions, undisturbed reference plots were usually significantly different than test plots.

Plant community composition was measured by harvesting aboveground biomass in 7 0.5-m^2 quadrats in each of the 54 plots and 8 0.5-m^2 quadrats on the 4 adjacent undisturbed, control plots. The harvested biomass was sorted by species for each plot and dried at 55°C for 72 hours. Biomass was harvested in 2008 and 2009 to account for annual climatic variation such as drought and twice during each year (June and August) to coincide with the two growth pulses that occur during a single growing season (Carpenter et al. 1990). Litter was collected in each quadrat in 2009. Data from each year was combined and the greater biomass value of each species was used for the analysis. Shannon-Weiner diversity indices were calculated for each subplot using the formula outlined by Begon et al. (1996) where: H=Shannon diversity index, s=total number of species in the community, and P_i=proportion for the *i*th species:

$$H = -\sum_{i=1}^{s} P_i \ln P_i$$

Soil samples were collected in fall of 2008. In each plot, 36 2-cm X 10-cm samples were collected on a 2-m X 2-m grid pattern and mixed together for homogeneity. The samples were sent to AgSource Harris Laboratory and analyzed for NO_3^- and P using cadmium reduction and Bray I extraction, respectively. Soil nitrogen mineralization was analyzed using the Potential Net Nitrogen Mineralization method as described by Drury and Beauchamp (1991).

Statistical analyses were run as a split-plot design with repeated measures over two years. Since the year effect was almost always significant and large, and the year by seed by fertilizer was significant for about half of those responses, it was decided to analyze each year independently. The analysis of each year was run as a randomized block design with a split plot effect. Replications were the block effect, seed mix was the whole plot effect and fertilizer was the split plot effect.

The glimmix procedure in SAS 9.2 was used to calculate the analysis of variance, least square means and pairwise comparisons between years, seed mixes and fertilizer treatments. The tabulate procedure was then used to calculate standard errors of the means since there was not a significant block effect and the variance differed between seed mixes.

Results

Native plant biomass (Figure 2) and species diversity (Figure 3) were greatest in plots originally seeded with native species. However, the natives were only producing 39.6%-64.8% of the above ground production in these plots. Native species had limited invasion into plots seeded with introduced species and only produced 10% of the biomass in those plots (Figure 2). In the native & introduced grass, forb and shrub (N&IGFS) seed mix, where natives and introduced species were seeded together, native species had significantly lower biomass production as compared to introduced species. Introduced species produced 92% of the biomass in the N&IGFS seed mix with crested wheatgrass producing nearly 59% of the total production. The number of different native species in plots planted with N&IGFS mix was similar to that of other seed mixes even though native production was relatively low.

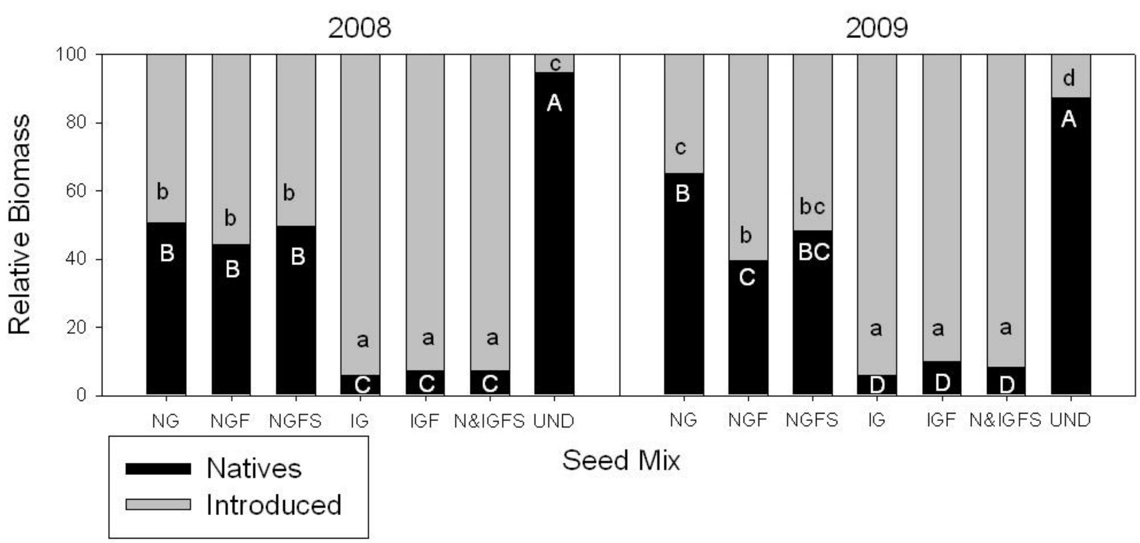

Figure 2. Relative aboveground native and introduced plant biomass production by year and seed mix (NG=native grass, NGF=native grass forb, NGFS=native grass forb shrub, IG=introduced grass, IGF=introduced grass forb, N&IGFS=native & introduced grass forb shrub, UND=undisturbed) 33 years after disturbance in northwestern Colorado. Letters on the bars represent significant similarities/differences among seed mixes within nativity and years using a Least Significant Difference test (N = 9, $\alpha = 0.05$).

Introduced species biomass was greatest in plots seeded with introduced species (Figure 2). Diversity of introduced species, while lower than native species, was not significantly different between all seed mixes. However, overall species diversity was lower in plots seeded with introduced species (Figure 3). Introduced species were more successful at colonizing neighboring native plots relative to native success at colonizing neighboring introduced plots. Introduced species did not colonize undisturbed reference plots where natives were well established.

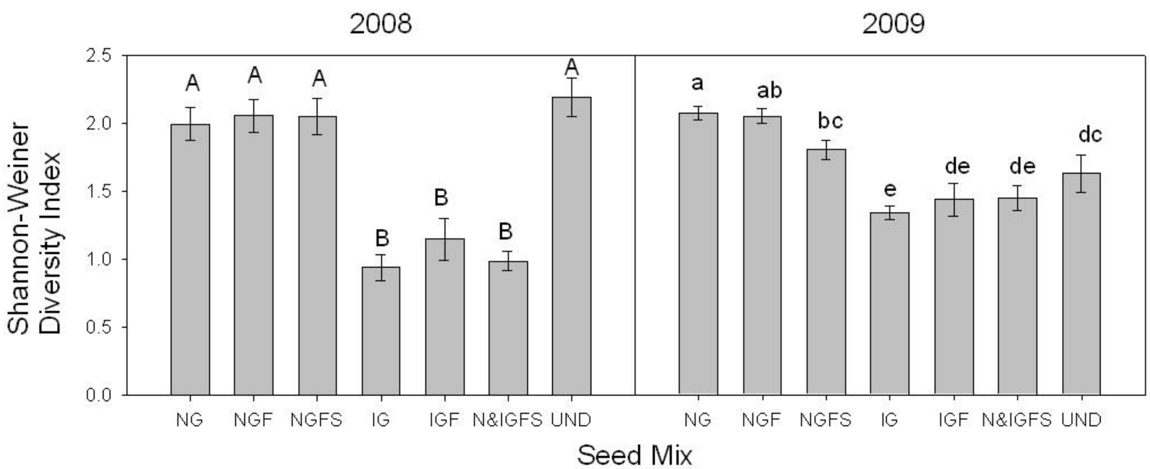

Figure 3. Shannon-Weiner diversity index by year and seed mix (NG=native grass, NGF=native grass forb, NGFS=native grass forb shrub, IG=introduced grass, IGF=introduced grass forb, N&IGFS=native & introduced grass forb shrub, UND=undisturbed) 33 years after disturbance in northwestern Colorado. Thin bars represent the standard error of the mean (N = 9). Different letters within a year represent significant differences among seed mixes using a Least Significant Difference test (α = 0.05).

Total above ground production for 2008 and 2009 was greatest in the plots seeded with the native and introduced grass-forb-shrub mixture followed by plots seeded with the introduced grass seed mixture (Figure 4).

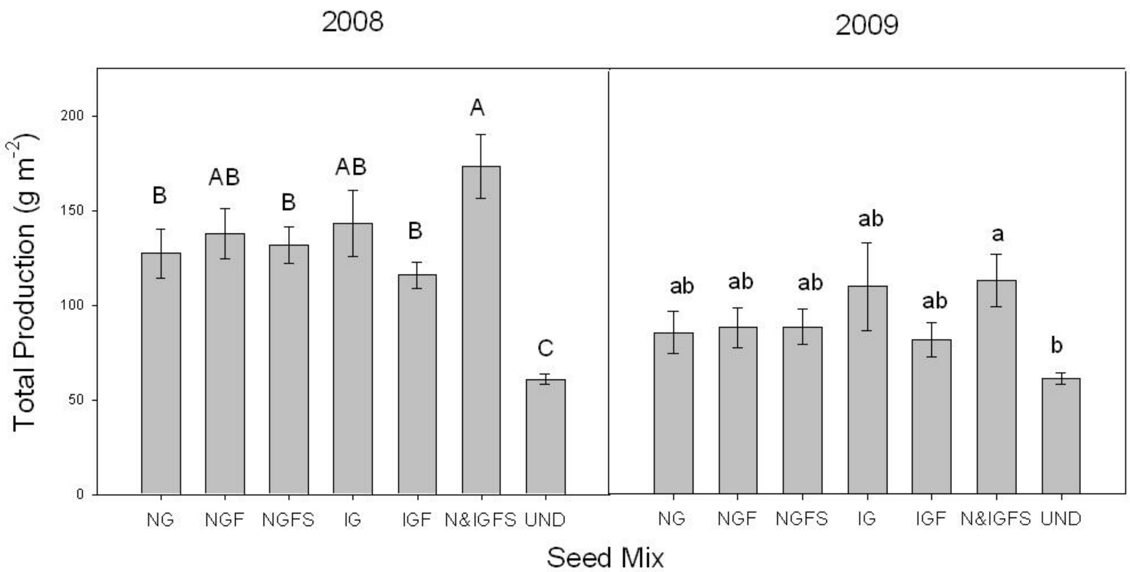

Figure 4. Mean total aboveground plant biomass production by year and seed mix (NG=native grass, NGF=native grass forb, NGFS=native grass forb shrub, IG=introduced grass, IGF=introduced grass forb, N&IGFS=native & introduced grass forb shrub, UND=undisturbed) 33 years after disturbance in northwestern Colorado. Thin bars represent the standard error of the mean (N = 9). Different letters within a year represent significant differences among seed mixes using a Least Significant Difference test (α = 0.05).

Annual species biomass was greatest in plots seeded with native species while introduced seed mixes had the lowest annual biomass (Figure 5). Plots seeded with native mixtures had the highest species diversity but many of those species were annual grasses and forbs, which together comprised more than 17% of the biomass production in plots seeded with the native grass and grass-forb mixes. When shrubs were included in the native seed mixture the resulting plant community resisted annual invasion, with annuals only accounting for 3.3% of the biomass production. All seed mixes that included introduced species resisted colonization by annual plant species with annuals accounting for less than 3.7% of the biomass in such plots. Plots seeded with introduced grass-forb seed mixtures had the lowest biomass production by annual species.

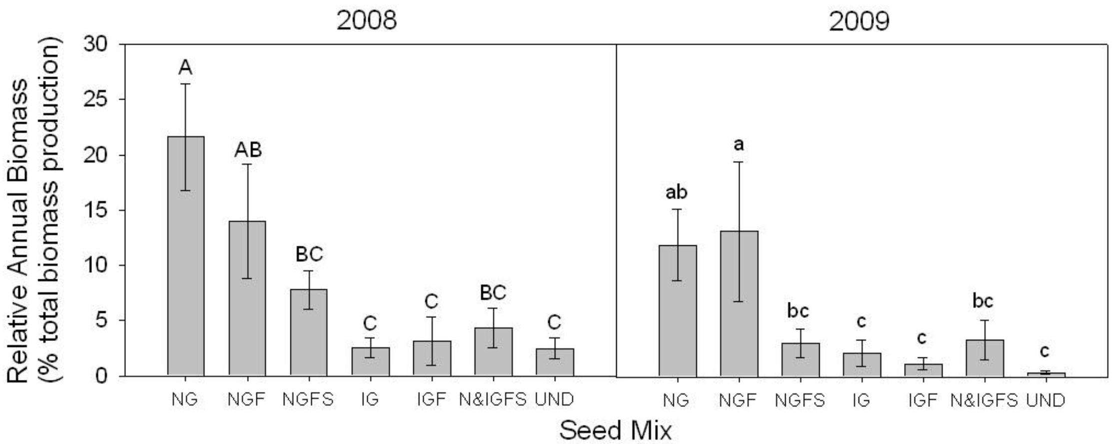

Figure 5. Mean aboveground annual plant biomass production by year and seed mix (NG=native grass, NGF=native grass forb, NGFS=native grass forb shrub, IG=introduced grass, IGF=introduced grass forb, N&IGFS=native & introduced grass forb shrub, UND=undisturbed) 33 years after disturbance in northwestern Colorado. Thin bars represent the standard error of the mean (N = 9). Different letters within a year represent significant differences among seed mixes using a Least Significant Difference test ($\alpha = 0.05$).

Sagebrush had limited colonization in plots seeded with native species, and was not observed in plots that were seeded with only introduced species (Figure 6). Overall, there was no statistical difference in sagebrush production between any of the seed mixes or fertilizer treatments.

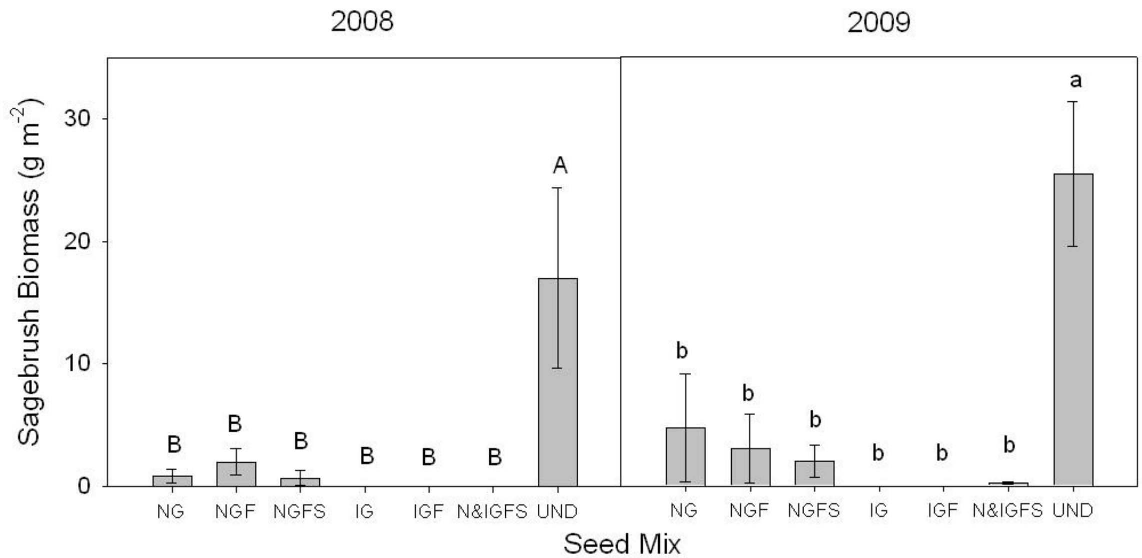

Figure 6. Mean sagebrush (*Artemisia tridentata*) biomass production by year and seed mix (NG=native grass, NGF=native grass forb, NGFS=native grass forb shrub, IG=introduced grass, IGF=introduced grass forb, N&IGFS=native & introduced grass forb shrub, UND=undisturbed) 33 years after disturbance in northwestern Colorado. Thin bars represent the standard error of the mean (N = 9). Different letters within a year represent significant differences among seed mixes using a Least Significant Difference test (α = 0.05).

After 33 growing seasons, the initial fertilizer treatments had few lasting effects on plant community production or composition. Native biomass production and species richness were not significantly different between fertilizer treatments, either in 2008 or 2009 (Figures 7 & 8).

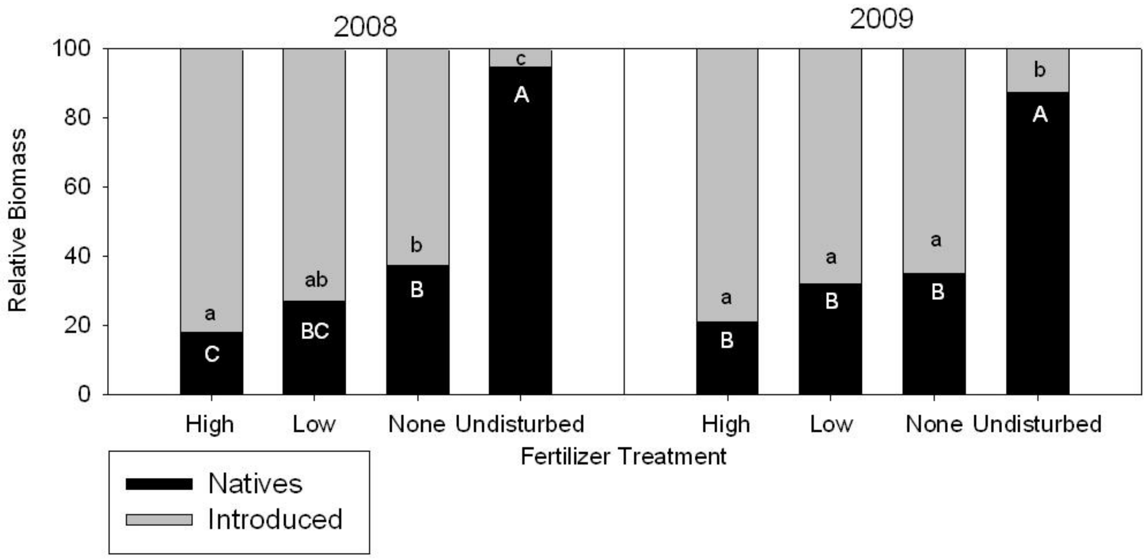

Figure 7. Mean native plant biomass production, 33 years after disturbance, by year in plots fertilized with either high (112 kg N ha^{-1} and 56 kg P ha^{-1}), low (56 kg N ha^{-1} and 28 kg P ha^{-1}), or no fertilizer in northwestern Colorado. Thin bars represent the standard error of the mean (N = 18). Letters on the bars represent significant similarities/differences among fertilizer treatments within nativity and years using a Least Significant Difference test (α = 0.05).

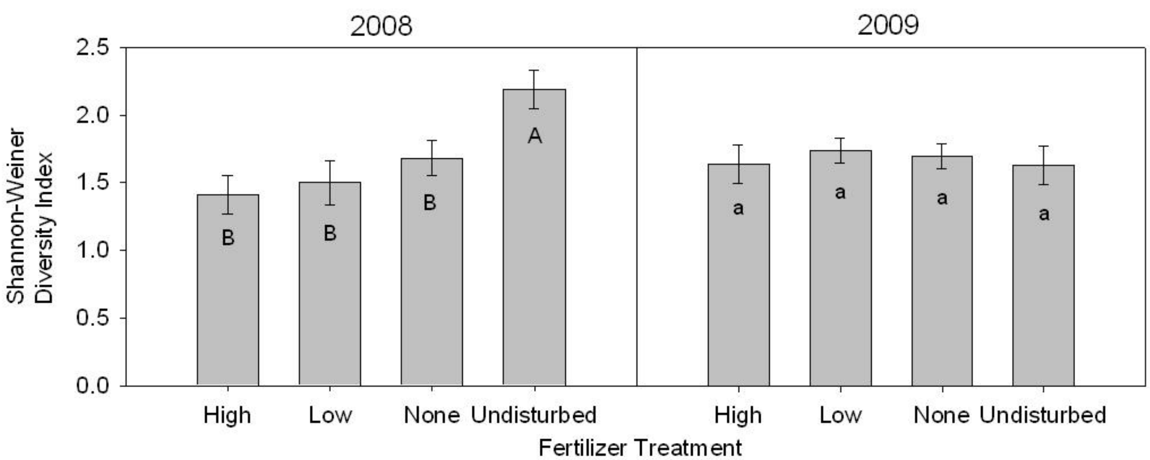

Figure 8. Shannon-Weiner species diversity index, 33 years after disturbance by year in plots fertilized with either high (112 kg N ha^{-1} and 56 kg P ha^{-1}), low (56 kg N ha^{-1} and 28 kg P ha^{-1}) or no fertilizer in northwestern Colorado. Thin bars represent the standard error of the mean (N = 18). Different letters within a year represent significant differences among fertilizer treatments using a Least Significant Difference test (α = 0.05).

Several additional variables were examined to generate possible insights into the long-term effects of seed mix and fertilizer treatment. These additional variables included: plant tissue nutrient content, nitrogen mineralization potential and seed bank composition. These studies did not reveal any significant conclusions; however, the results are included in Appendix A of this thesis.

Discussion

The results of this study indicate that initial seed mixture had long lasting effects on plant community composition and production after 33 years. Plots seeded with native species in 1976 were dominated by native species in 2009 and plots seeded with introduced species in 1976 were dominated by introduced species in 2009. Five years into the original study, Redente et al. (1984) reported that in all seed mix treatments, grasses dominated the plant communities with the introduced grass (IG) and introduced grass and forb (IGF) seed mixes having the greatest biomass production. Grass species still dominated biomass production through 2009 and the IG mixture still had the greatest biomass production of all the mixes followed by the N&IGFS.

It is generally recognized that plant species diversity contributes to resilience following disturbance (Walker 1995, Hector et al. 2010) as well as resistance to invasion (Naeem et al. 2000, Kennedy et al. 2002). In this study, species diversity was lowest after 33 years in plots seeded with introduced species relative to plots seeded with native species. Similar observations have been made in other studies at this site (Sydnor and Redente 2000, Newman and Redente 2001). The resulting lack of diversity in communities created by seeding introduced species may indicate a decrease in the overall health and stability of the resulting communities (Knops et al. 1999, Lehman and Tilman 2000).

The correlation of increased species richness to increased biomass production seen in other studies (Tilman et al. 2001, Biondini 2007) was not apparent in this study. Greater species richness in plots seeded with native species might be attributed to colonizing non-seeded species such as annual grass (*Bromus tectorum*), annual forbs (*Lactuca serriola, Descurainia pinnata*) and an introduced species from neighboring plots (*Agropyron cristatum*). Conversely, the introduced-seeded plots had lower species richness, with the species composition consisting of less colonizing species. This last point may have to do with competitive exclusion of colonizing species by crested wheatgrass (*Agropyron cristatum*), which was included in all of the introduced seed mixes. Introduced species are known to inhibit colonization of native species (Wilson 1989) and stands of crested wheatgrass in particular have been documented to have lower species diversity (Broersma et al. 2000).

Sagebrush did not recover to its pre-disturbance condition despite the fact that the study plots were surrounded by a sagebrush dominated community. There are several possible reasons for this slow recovery. Topsoil containing the soil seed bank and the aboveground shrub biomass was removed during plot installation in 1976. This presumably left the soil devoid of sagebrush propagules. It is also important to note that sagebrush was not included in the seed mix nor was it planted in this experiment. Sagebrush has been shown to successfully re-establish if seeded to desired densities (Hild et al. 2006) or if one-fourth to one-third of sagebrush biomass was left in tact (Ziegenhagen and Miller 2009), but our study shows that sagebrush can be a weak invader and natural invasion can take a long time.

While seed mix had lasting effects on plant community composition, the effects of a fertilizer treatment in this study were short lived. The fertilizer treatment had an initial effect on the plant community composition. In 1981, five years after the study was established, there was an inverse relationship between fertilizer treatment and species richness (Stark and Redente 1985). Grass production was greater and forb production was reduced in plots with fertilizer treatments relative to unfertilized plots (Redente et al. 1984). After 33 years, correlations between fertilizer treatment and species richness, grass production and forb production have become insignificant.

Although we did not find persistent differences in the plant community due to fertilizer treatments, two other long-term studies at the same site have shown that fertilizer treatments can have profound long-term effects on the plant community. Newman and Redente (2001) documented that an initial fertilizer treatment of N and P impacted early plant community development. They found that after 20 years the plant community production was still significantly different between fertilizer treatments. Similar results were seen in another 24-year study at the same site. Significant differences were observed among plant functional groups in plots treated with biosolids used as a slow release fertilizer on nutrient poor subsoils (Paschke et al. 2005). It is possible that the effects of initial fertilizer applications were not persistent in this present study compared to the other studies due to the additional 13 and 9 growing seasons, respectively.

Conclusion

Based on these long-term results, seed mixtures have lasting effects on plant community composition and production. Most of the species initially seeded in this study were still present in the plots where they were seeded and sagebrush, which was not planted, was only starting to get established in native seeded plots. The effects of the initial fertilizer treatments were short lived and neither native biomass production nor native species richness was greater in plots without fertilizer treatment as hypothesized.

Implications for Management

1. When restoring a sagebrush steppe plant community, use species native to the area and include sagebrush in the seed mix.
2. If a diverse native plant community is desired, introduced species should be used sparingly because they can reduce species diversity and prevent colonization of native species.
3. An initial fertilizer treatment may not be effective or necessary for meeting long-term restoration goals.

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