Restoration Research At The Rocky Mountain Arsenal National Wildlife Refuge

Fifth Year Report
The Rocky Mountain Arsenal National Wildlife Refuge
U. S. Fish and Wildlife Service

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EXECUTIVE SUMMARY

Three studies were implemented in 1995 on the Rocky Mountain Arsenal National Wildlife Refuge (Refuge) to identify restoration techniques that can be used to restore portions of the Arsenal to native prairie. The following objectives were addressed by the research: 1) determine if supplemental water improves establishment and production of perennial and seeded species, 2) determine if supplemental water, in combination with sucrose, accelerates the establishment of native prairie species by reducing the time that weedy species dominant a revegetated site, 3) determine the effect of mulch or a cover crop on native, seeded, and perennial species establishment and production, 4) determine the effect of seeding technique (drill vs. broadcast) on native, seeded, and perennial species establishment and production, and 5) determine the effect of carbon additions (sucrose), and nitrogen additions, on native species in weed infested areas.

The Crested Wheatgrass Replacement Study (CWRS) site is located in the SW quarter of Section 3. This study included ten treatments arranged in a 5-way randomized nested design with four replications. There are four irrigation treatments that span the months from May to August, and one control treatment. Sucrose was applied to half of each replicate. The second half of the replicate was not treated with sucrose. Six subtreatments were nested within each irrigation treatment and included: mulch, no mulch, cover crop, broadcast seeding and drill seeding. The seed mixture consisted of native grasses, forbs, and shrubs.

The Nitrogen Sucrose Study is located in the SW quarter of Section 3 in an area that is heavily infested with cheatgrass (*Bromus tectorum*). This study includes ten treatments arranged in a completely randomized design with four replications. Irrigation treatments were identical to the CWRS. Half of each replicate received sucrose, while the other half received nitrogen.

The Sucrose Only Study tests the effectiveness of applying sucrose on sites dominantd by an exotic annual grass, cheatgrass (*Bromus tectorum*). The following two communities were selected for this study: (1) heavy invasion by cheatgrass, (2) light to moderate invasion by cheatgrass. The study includes four different sucrose application rates arranged in a completely randomized design with four replications.

Each study was assessed for plant community development over a five year period between 1995 and 1999. Results after five years in the Crested Wheatgrass Replacement Study showed that irrigation in the first two growing seasons improved establishment and production in two lifeform categories, perennial grasses and perennial forbs. In addition, establishment and production of seeded species improved with irrigation. Perennial grasses were most improved by irrigation in May, June, July, and August (MJJA). However, the largest sequential irrigation increase in perennial grass establishment and production was between the M and MJ treatments. The broadcast seeding technique increased establishment and production of perennial grasses and forbs and decreased establishment and production of annual forbs. Broadcast seeding also significantly improved seeded species production and shrub establishment. The no mulch treatment had the greatest production of perennial grasses and the greatest relative production of seeded species compared to the other mulch treatments. The mulch treatment had the greatest perennial forb production, however, the cost of mulch may be a deterrent for its use given the success of the no mulch treatment. The cover crop treatment was not an effective revegetation practice. Sucrose applications showed no benefit to perennial or seeded species production, and shrub densities declined with sucrose application.

The Nitrogen Sucrose Study showed some response to irrigation, but the pattern was inconsistent. The control and MJJA treatments had the greatest production by perennial grasses, while the MJ treatment had the lowest perennial grass production. Annual forbs had the least production in the control and MJJA treatments and the greatest production in the MJ and MJJ treatments. Nitrogen applications greatly increased annual forb production and decreased perennial grass production compared to the application of sucrose. Sucrose decreased annual forb production and increased perennial grass and forb production. In addition native species production was over forty percent higher in the sucrose amended plots.

The Sucrose Only Study had differing responses depending upon the site. Increased sucrose application rate decreased the production of cheatgrass and improved the production of perennial grasses in the heavy cheatgrass sites. In the light to moderate cheatgrass sites, increased sucrose application rate decreased perennial grass production and did not appear to affect cheatgrass production.

INTRODUCTION

The U.S. Fish and Wildlife Service (Service) at the Rocky Mountain Arsenal National Wildlife Refuge is charged with managing wildlife and wildlife habitat during and following cleanup of contaminants. This management includes the conversion of sites currently dominated by exotic species to native prairie to provide diverse habitat for the variety of wildlife that reside on the Refuge. Restoration research was implemented at the Refuge in 1995 and continued through 1999. The research was designed to provide information on restoration practices that could accelerate the restoration process through the establishment of late seral species. The ultimate goal was to develop restoration information that could be used by the Service in restoring sites dominated by exotic species or disturbed during cleanup activities. In order to accomplish this goal, three restoration studies were implemented at the Refuge. The studies are the: Crested Wheatgrass Replacement Study, Nitrogen Sucrose Study, and the Sucrose Only Study. A number of research objectives were developed to provide specific restoration information. The following objectives were addressed by the research: 1) determine if supplemental water improves establishment and production of perennial and seeded species, 2) determine if supplemental water, in combination with sucrose, accelerates the establishment of native prairie species by reducing the time that weedy species dominant a revegetated site, 3) determine the effect of mulch or a cover crop on native, seeded, and perennial species establishment and production, 4) determine the effect of seeding technique (drill vs. broadcast) on native, seeded, and perennial species establishment and production, 5) determine the effect of carbon additions (sucrose), and nitrogen additions, on native species in weed infested areas. This report summarizes the methods and results of these studies in the fifth year (1999).

DESCRIPTION OF EACH STUDY

Crested Wheatgrass Replacement Study Experimental Design

The study site is located in the SW 1/4 of Section 3. This study includes ten treatments arranged in a 5-way randomized nested design with four replications (Figure 1). There are four irrigation treatments and a control. The first irrigation treatment begins in May, the last irrigation treatment ends in August. The irrigation treatments were applied during the first two years of the study (1995 and 1996).

The following irrigation schedule was followed:

1. Irrigation in May (2 inches)
2. Irrigation in May and June (2 inches/ month)
3. Irrigation in May June & July (2 inches/ month)
4. Irrigation in May June, July & August (2 inches/ month)
5. No irrigation (control)

Each irrigation treatment measures 60 ft. x 60 ft. and is separated by a 3 foot buffer strip within irrigation subtreatments and a 10 foot buffer strip between irrigation treatments.

Half of each replicate received sucrose at a rate of 1,429 lbs sucrose/acre/yr. For the first three years. The fourth and fifth year received twice the rate of 2858 lbs sucrose/acre/yr. The second half of the replicate was not treated with sucrose. Sucrose applications were divided into eight equal increments, applied every two weeks, beginning in May.

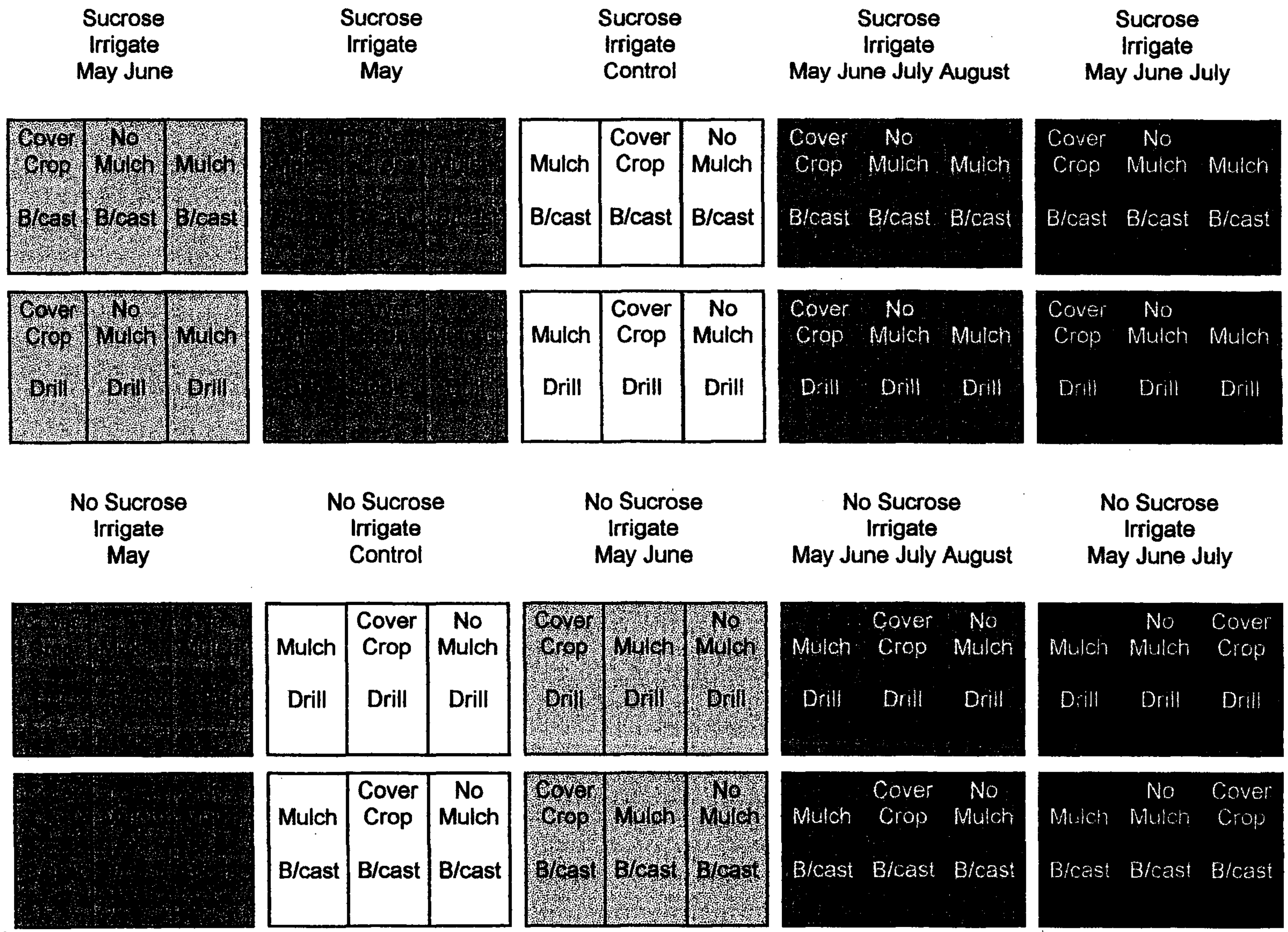

Figure 1. Experimental design for one replicate of the Crested Wheatgrass Replacement Study.

Six subtreatments are nested within each irrigation treatment. These subtreatments include: mulch, no mulch, cover crop (sorghum), broadcast seeding, and drill seeding. Each sub-treatment measures 15 ft x 28 ft. The seed mixture used in the study consisted of native grasses, forbs and shrubs (Appendix Table 1). Seeding of the native mixture in the mulch and no mulch subtreatments was completed in May of 1995. The cover crop treatments were planted with sorghum in May 1995. The cover crop, after being mowed and lightly harrowed, was seeded with the native mixture in April the following year (1996). Plant community development on the cover crop treatment was therefore one year behind the remaining treatments.

Nitrogen Sucrose Study Experimental Design

This study is also in the SW 1/4 of Section 3 in an area that is heavily infested with cheatgrass *(Bromus tectorum)*. The study includes ten treatments arranged in a completely randomized design with four replications. As in the CWRS, there are four irrigation treatments and a control. Each treatment measures 30 ft x 30 ft and is separated by a 10 foot buffer strip between irrigation treatments and a 10 foot buffer strip between the nitrogen (N) and sucrose treatments. Half of each replicate received sucrose while the other half received N (Figure 2). The sucrose was applied at the same rate and schedule as in the CWRS. Nitrogen was applied as ammonium nitrate at a rate of 89 lbs N/acre/year. The application of N

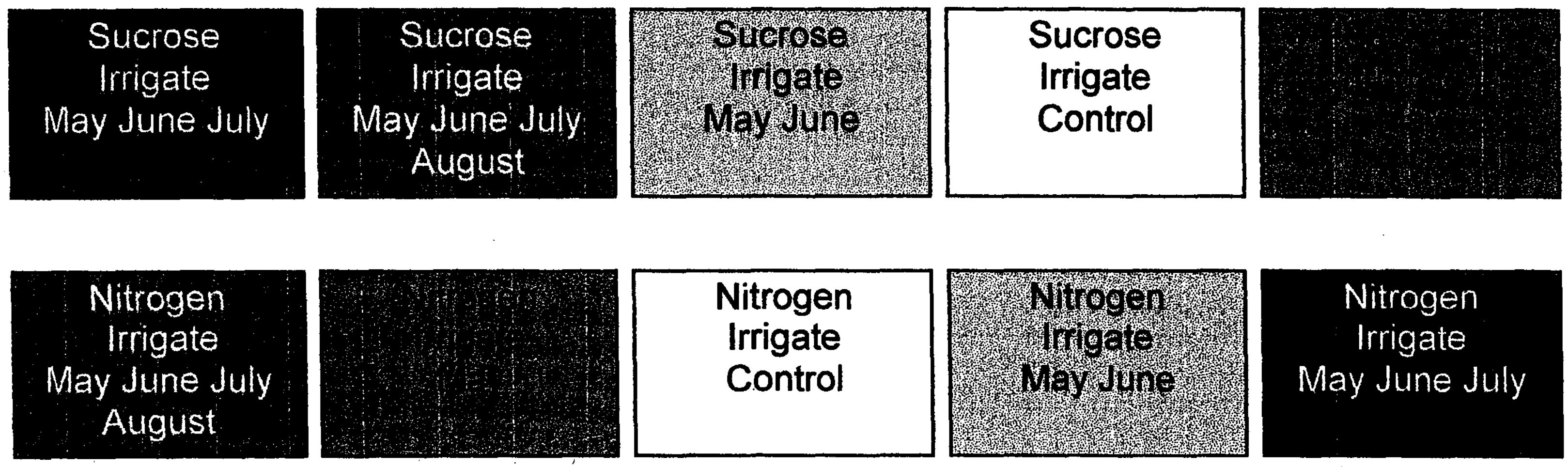

Figure 2. Treatment arrangement design for one replicate of the Nitrogen Sucrose Study.

was divided into three equal increments and applied in May, July and August. The following are the treatments included in this experiment.

1. Irrigate in May (2 inches) and apply sucrose
2. Irrigate in May & June (2 inches/month) and apply sucrose
3. Irrigate in May, June, & July (2 inches/month) and apply sucrose
4. Irrigate in May, June, July & August (2 inches/month) and apply sucrose
5. Apply sucrose no irrigation (control)
6. Irrigate in May (2 inches) and apply nitrogen
7. Irrigate in May & June (2 inches/month) and apply nitrogen
8. Irrigate in May, June, & July (2 inches/month) and apply nitrogen
9. Irrigate in May, June, July & August (2 inches/month) and apply nitrogen
10. Apply nitrogen (89 lbs N/a/yr) no irrigation (control)

Sucrose Only Study Experimental Design

The final study tests the effectiveness of applying sucrose on sites dominantd by exotic weeds. Two sites were selected for this study and include the following: 1) heavy invasion by cheatgrass (*Bromus tectorum*), 2) light to moderate invasion by cheatgrass. Both cheatgrass sites were located in the SE 1/4 of Section 8. The study includes four treatments arranged in a completely randomized design with four replications. Each treatment measures 30 ft x 30 ft and is separated by a 3 foot buffer strip between treatments (Figure 3).

The following are the treatments applied in the first three years of this

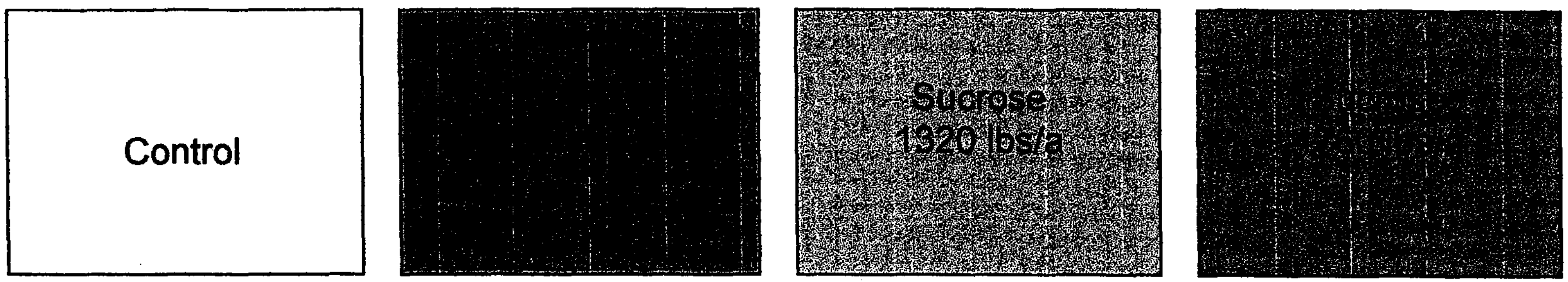

Figure 3. Treatment arrangement design for one replicate of the Sucrose Only Study.

experiment:

1. Control--no sucrose
2. Sucrose at 880 lbs sucrose/a/yr
3. Sucrose at 1320 lbs sucrose/a/yr
4. Sucrose at 1760 lbs sucrose/a/yr

The following are the treatments applied in the fourth and fifth year of the study:

1. Control--no sucrose
2. Sucrose at 1760 lbs sucrose/a/yr
3. Sucrose at 2640 lbs sucrose/a/yr
4. Sucrose at 3520 lbs sucrose/a/yr

METHODS

Crested Wheatgrass Replacement Study (CWRS)

Sampling was conducted in July and August of 1995, 1996, 1997 and 1999. All treatments were sampled every year except the cover crop treatment, which was not sampled in 1995. The fifth year data will be presented in this report except where noted. For previous years' data see Arthur and Redente USFWS Final Report document 1998.

Aboveground biomass was measured by clipping all vegetation inside randomly placed 0.25 m^2 quadrats. Five quadrats in each subtreatment were sampled for a total of 30 quadrats per irrigation treatment. A total of 800 quadrats were sampled in 1995 and 1200 quadrats in 1996, 1997 and 1999. Fewer quadrats were sampled in 1995 because the cover crop treatment consistently established in all subtreatments and therefore were not sampled. Vegetation was clipped at ground level and separated by species. All plant samples were oven dried and weighed.

The statistical analysis was based on a multilevel experimental design of a split-plot, a split-split-plot, and a strip-plot design. A mixed model analysis was used to include both fixed and random effects in the analysis. Analysis of variance (ANOVA) mean separation was determined at a maximum $p \leq 0.05$ significance level unless otherwise noted. All potential interactions among treatments were considered during the analysis. No significant interactions were found among the various treatment combinations. Studentized residual plots were generated to determine if the data fit the model assumption of homogeneous variance. The biomass data were log transformed to stabilize the variance. Statistical significance was then determined from the transformed data. Aboveground biomass means are presented graphically in the original scale.

Shrub data were only collected in 1999. All shrubs were counted and recorded by species in each subtreatment. The statistical analysis was based on the same multilevel experimental design of a split-plot, a split-split-plot, and a strip-plot design as noted above. Analysis of variance (ANOVA) mean separation was determined at a maximum $p \leq 0.05$ significance level unless otherwise noted. Studentized residual plots were generated to determine if the data fit the model assumption of homogeneous variance. Log transformation was not necessary. The data is presented as number of shrubs per treatment (shrub density).

Nitrogen Sucrose Study

Sampling was conducted in July of 1995, 1996, 1997 and 1999. All treatments were sampled each year, however, only the fifth year will be presented unless otherwise noted. Vegetation in randomly placed 0.25 m^2 quadrats was clipped by species, oven dried and weighed for biomass determination. Five quadrats in each treatment were sampled for a total of 200 quadrats. The statistical analysis was based on a split-plot design. A mixed model analysis was used to include both fixed and random effects. Analysis of variance (ANOVA) mean separation was determined at a maximum $p \leq 0.05$ significance level unless otherwise noted. As in the CWRS study no significant treatment interactions were found. Studentized residual plots were generated to determine data variability. As in the CWRS, the assumption of homogeneous variance was met by log transforming the data. Statistical significance was determined through analysis of the transformed data. Aboveground biomass means are presented graphically in the original scale.

Sucrose Only Study

Sampling was conducted in July of 1995, 1996, 1997 and 1999 . All treatments were sampled in all years at both sites. As mentioned above only the fifth year will be presented in this report. Aboveground biomass was measured by clipping all vegetation (by species) inside randomly placed 0.5 m^2 quadrats. The samples were then oven dried and weighed. Five quadrats in each treatment were sampled at all sites. A total of 160 quadrats were sampled for both cheatgrass sites. The statistical analysis was based on a randomized complete block design. Production was analyzed for significant trends within lifeform and between treatments using a general linear model. Analysis of variance (ANOVA) mean separation was determined at a maximum $p \leq 0.05$ significance level. As in the previous two studies, no significant treatment interactions were found. Studentized residual plots were generated to determine if the data had normal variability. The model assumption of homogeneous variance was met by log transforming the data. Analysis was completed on the transformed data to determine statistical significance. Aboveground biomass production means are presented graphically in the original scale.

RESULTS AND DISCUSSION

Crested Wheatgrass Replacement Study

Results

Irrigation Treatments

Life-form group

Production by life-form group differed significantly among irrigation treatments in both the annual and perennial grass categories (Figure 4 and Appendix Table 2). Annual grass production was greatest in the control and May (M) treatments, and was approximately twice that of the May June (MJ) and May June July August (MJJA) treatments, although, these treatments were not significantly different (33 g/m^2, 43 g/m^2, 14 g/m^2, 16 g/m^2, respectively). The May June July (MJJ) treatment had significantly less annual grass production than all other treatments. The largest contributor to annual grass production was *Bromus tectorum.*

Perennial grass production showed a strong trend of increasing production with increased irrigation. Perennial grass production was greatest in the MJJ and MJJA treatments (468 g/m^2, 499 g/m^2, respectively) and were significantly greater than the control, M, and MJ treatments (373 g/m^2, 389 g/m^2, 437 g/m^2, respectively). The control, M, and MJ treatments showed the same trend of increasing production with increased irrigation but were not significantly different from each other. The largest contributors to perennial grass production were three seeded species including sand bluestem (*Andropogon halli*), blue grama

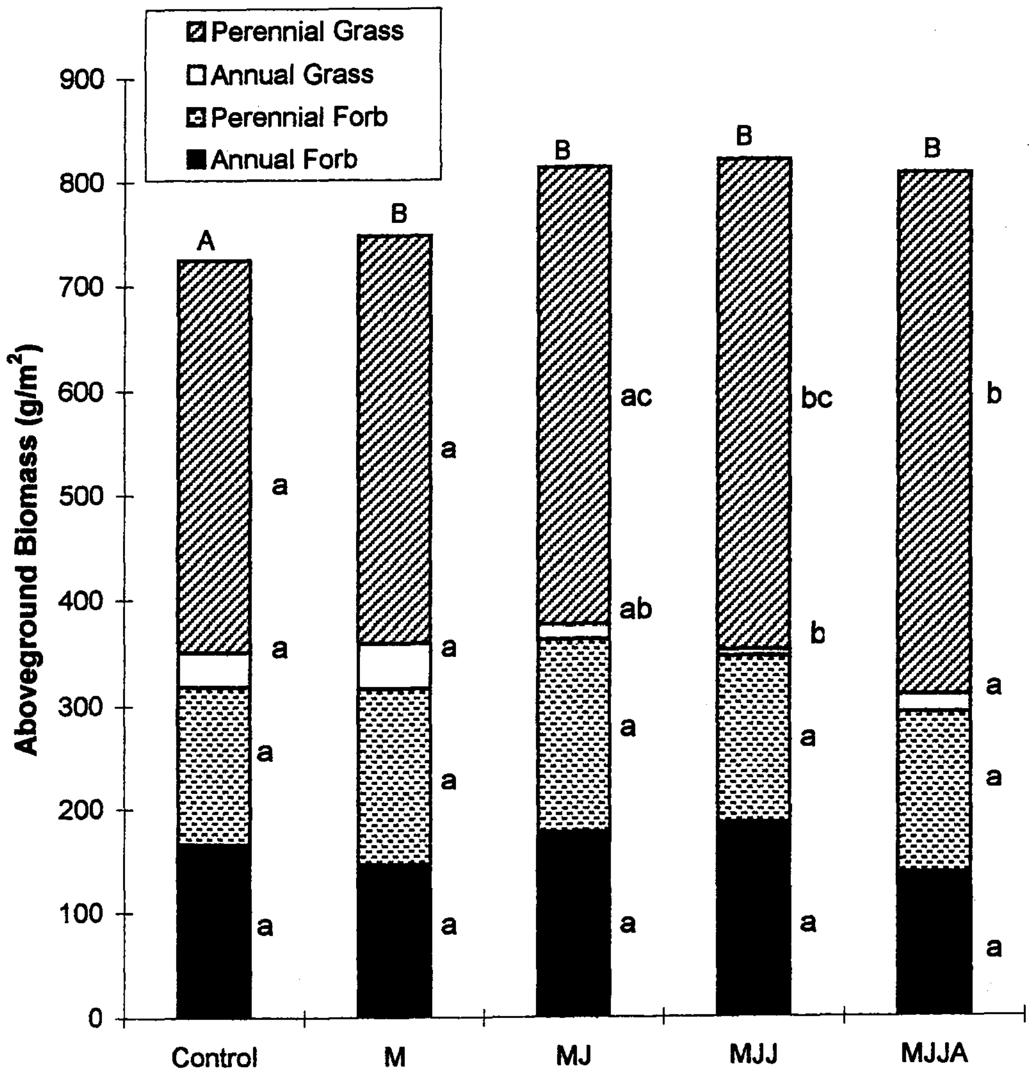

Figure 4. Mean aboveground biomass among irrigation treatments on the Crested Wheatgrass Replacement Study in 1999. Irrigation: Control=no irrigation, M=May Irrigation, MJ=May+June Irrigation, MJJ=May+June+July Irrigation, MJJA=May+June+July+August Irrigation. Different lower case letters within life-form groups and across treatments indicate significant differences ($p \leq 0.05$). Different upper case letters indicate significant differences in total production across treatments ($p \leq 0.05$).

(*Bouteloua gracilis*) and prairie sandreed (*Calamovlifa longifolia*), (means 163 g/m^2, 69 g/m^2, 67 g/m^2, respectively).

There were no significant differences among irrigation treatments in perennial and annual forb production. In addition there was no obvious trends among irrigation treatments and biomass production. Perennial forbs in the MJ treatment had the most production while the control treatment had the least (184 g/m^2, and 151 g/m^2, respectively). Annual forb production was greatest in the MJJ treatment and least in the MJJA treatment (185 g/m^2, and 137 g/m^2, respectively).

Native versus introduced species

Increased irrigation resulted in increased production by native species (Figure 5 and Appendix Table 3). Native species production was greatest in the MJ, MJJ, MJJA treatments (702 g/m^2, 692, g/m^2 and 677 g/m^2, respectively). The control and M treatments had significantly less production by native species than the other three treatments noted above (572 g/m^2 and 592 g/m^2, respectively).

Production by introduced species decreased with increasing irrigation. Introduced species production was significantly less in the MJJA than all other treatments (105 g/m^2). The M treatment had the greatest production by introduced species, however, it was not significantly different from the control, MJ, and MJJ treatment (156 g/m^2, 152 g/m^2, 120 g/m^2, and 141 g/m^2, respectively).

Seeded versus non-seeded species

The seeded versus the non-seeded analysis showed a linear response to irrigation as did the native versus introduced species analysis

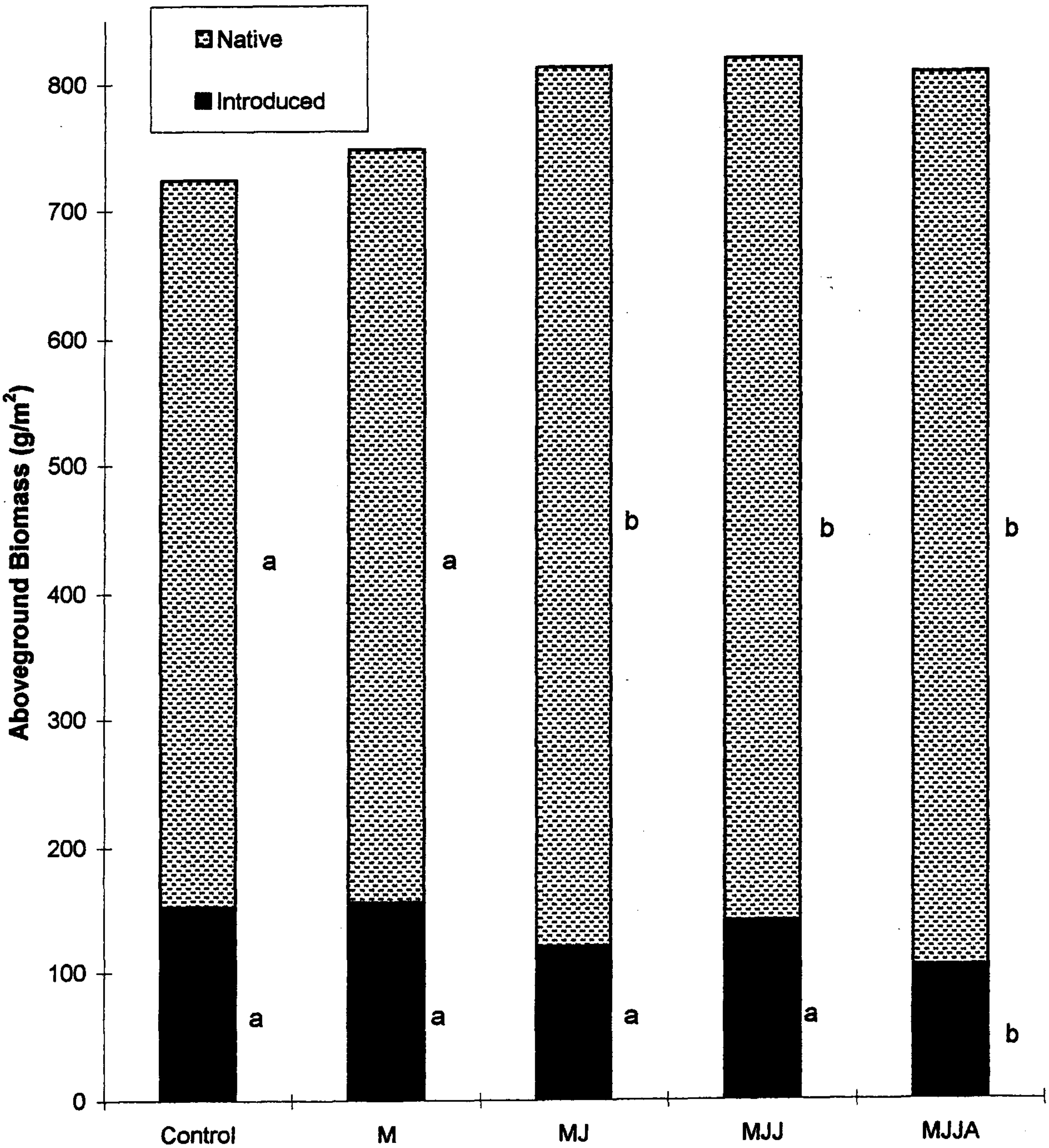

Figure 5. Mean aboveground biomass among irrigation treatments on the Crested Wheatgrass Replacement Study in 1999. Irrigation: Control=no irrigation, M=May Irrigation, MJ=May+June Irrigation, MJJ=May+June+July Irrigation, MJJA=May+ June+July+August Irrigation. Different lower case letters within native verses introduced species groups and across treatments indicate significant differences ($p \leq 0.05$).

(Figure 6 and Appendix Table 4). Seeded species production linearly increased with increasing irrigation. The MJJA treatment had the greatest production by seeded species however, it was not significantly different from the MJJ treatment (502 g/m^2, and 439 g/m^2, respectively). The dominant seeded species was a perennial grass, sand bluestem (*Andropogon halli*). The control treatment had the least production by seeded species and was significantly different from all treatments except the M treatment (310 g/m^2 and 338 g/m^2, respectively).

There was a linear decrease in non-seeded species production with increasing irrigation. The MJJA treatment had significantly less production by non-seeded species than all other treatments (304 g/m^2). The control and M treatments had the greatest production by non-seeded species (415 g/m^2, and 410 g/m^2, respectively). The MJ and MJJ treatments both had significantly less production by non-seeded species than the control treatment (376 g/m^2, and 380 g/m^2, respectively).

Seeding Technique

Life-form group

Production by life-form group between the broadcast and drill treatments was significantly different for perennial grasses and annual forbs (Figure 7 and Appendix Table 5). Perennial grass production in the broadcast treatment was significantly greater compared to the drill treatment (450 g/m^2 and 416 g/m^2, respectively). Annual forb production was significantly lower in the broadcast treatment than in the drill treatment (131 g/m^2 and 194 g/m^2, respectively). Annual grass production was a small component of the total production however, the

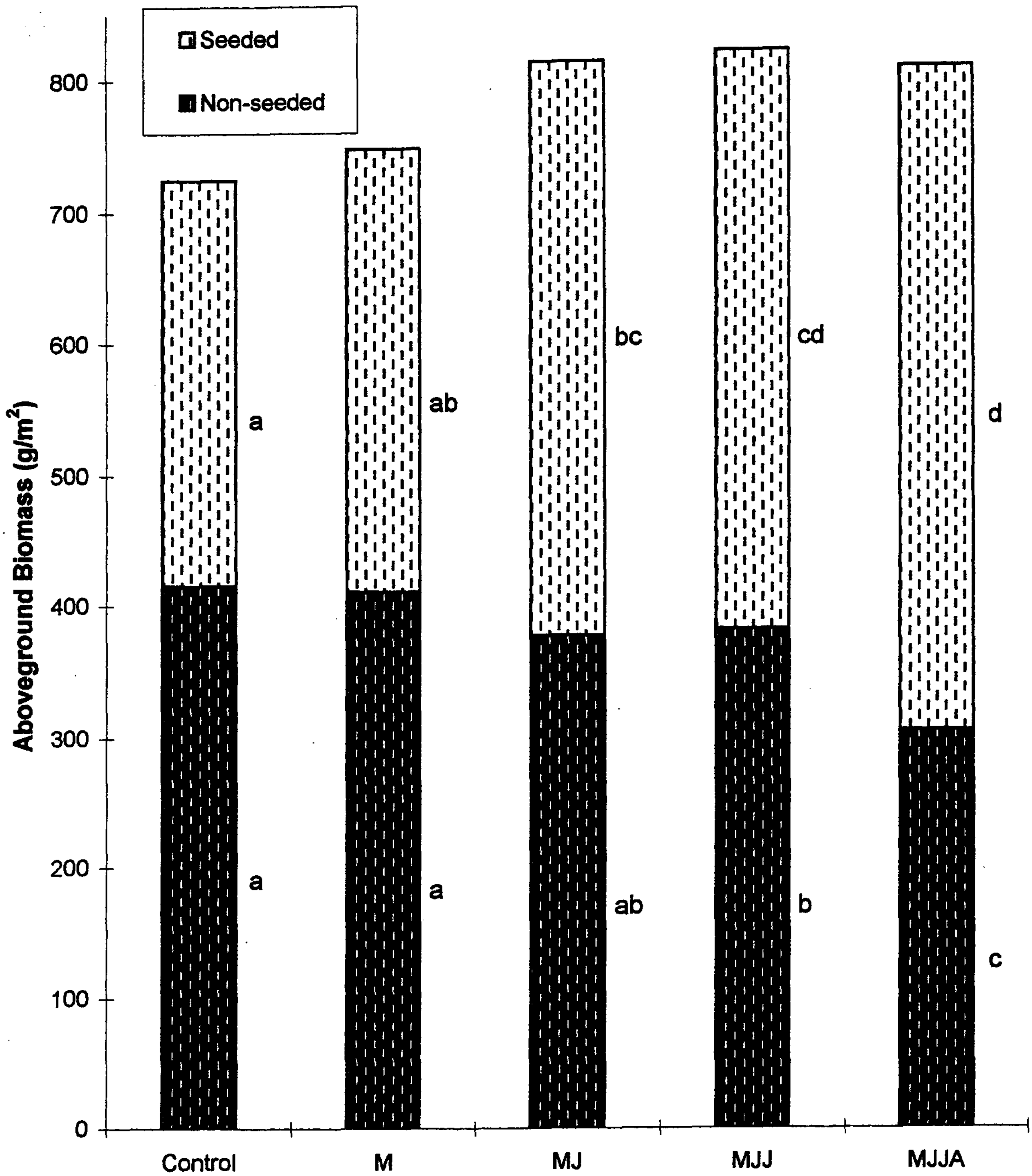

Figure 6. Mean aboveground biomass among irrigation treatments on the Crested Wheatgrass Replacement Study in 1999. Irrigation: Control=no irrigation, M=May Irrigation, MJ=May+June Irrigation, MJJ=May+June+July Irrigation, MJJA=May+ June+July+August Irrigation. Different lower case letters within seeded verses non-seeded species groups and across treatments indicate significant differences ($p \leq 0.05$).

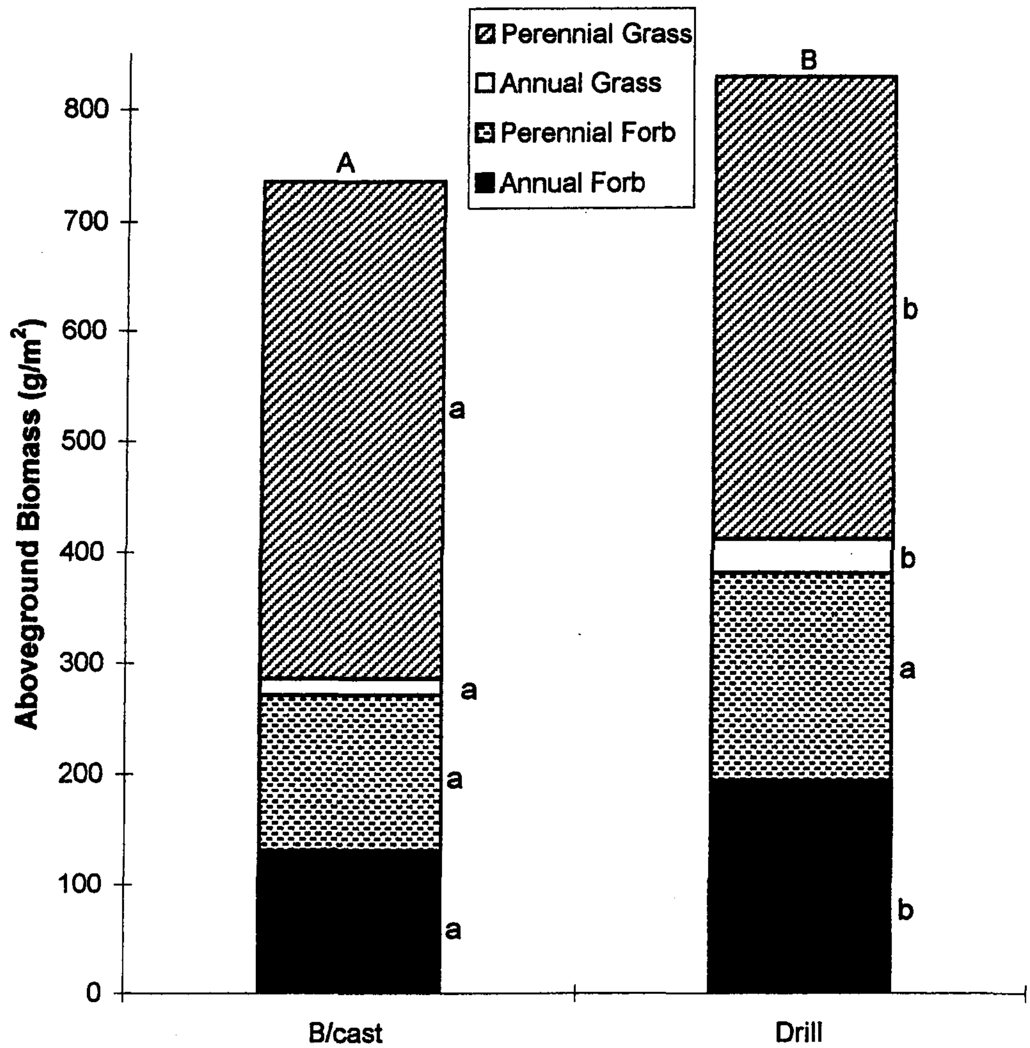

Figure 7. Mean aboveground biomass between seeding techniques on the Crested Wheatgrass Replacement Study in 1999. Seeding techniques, B/cast=broadcast seeding, Drill=drill seeding. Different lower case letters within life-form groups and between treatments indicate significant differences ($p \leq 0.05$). Different upper case letters indicate significant differences in total production across treatments ($p \leq 0.05$).

broadcast treatment had significantly less annual grass production than the drill treatment (15 g/m^2, and 31 g/m^2, respectively). Perennial forb production was greater in the drill treatment, however it was not significantly different from the broadcast treatment (188 g/m^2 and 140 g/m^2, respectively). The dominant perennial forb was not a non-seeded species, *Mentzelia nuda,* which had a mean production of 84 g/m^2.

Native versus introduced species

Production by native species was not significantly different between seeding technique. Introduced species production was significantly different between seeding treatments (Figure 8 and Appendix Table 3). The drill treatment had the greatest production by native species (628 g/m^2 and 666 g/m^2, respectively). The greatest mean production by native species was one seeded species and one non-seeded species, *Andropogon halli* and *Heterotheca villosa* (163 g/m^2, and 84 g/m^2, respectively). Introduced species production was significantly greater in the drill treatment compared to the broadcast treatment (107 g/m^2, and 163 g/m^2, respectively). The introduced species with the greatest mean production was *Salsoa iberica,* 32 g/m^2.

Seeded versus non-seeded species

Seeding technique significantly influenced production by seeded and non-seeded species (Figure 9 and Appendix Table 4). Production by seeded species was significantly greater in the broadcast treatment compared to the drill treatment (439 g/m^2 and 371 g/m^2, respectively). As mentioned above, the seeded species with the greatest mean production were *Andropogon halli,* followed by

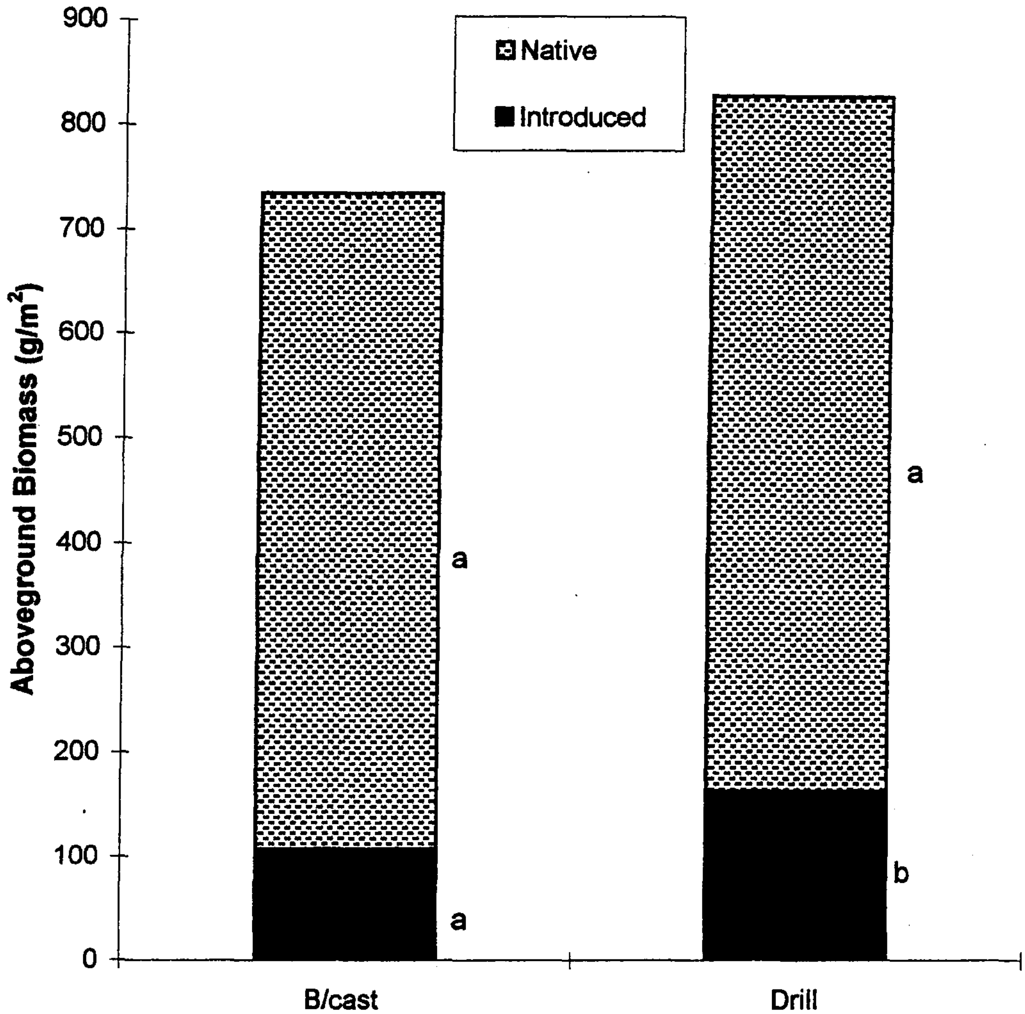

Figure 8. Mean aboveground biomass between seeding techniques on the Crested Wheatgrass Replacement Study in 1999. Seeding techniques, B/cast=broadcast seeding, Drill=drill seeding. Different lower case letters within native versus introduced species groups and between treatments indicate significant differences ($p < 0.05$).

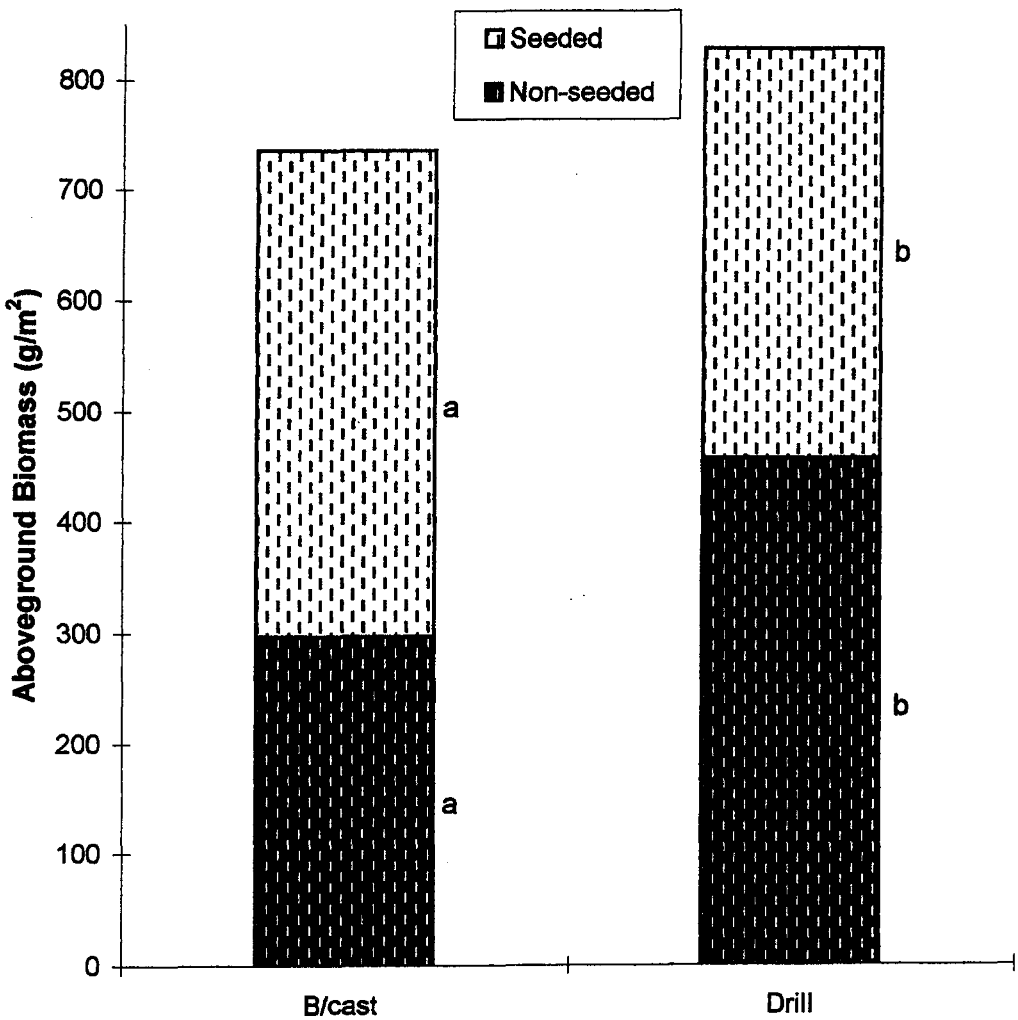

Figure 9. Mean aboveground biomass between seeding techniques on the Crested Wheatgrass Replacement Study in 1999. Seeding techniques, B/cast=broadcast seeding, Drill=drill seeding. Different lower case letters within seeded versus non-seeded species groups and between treatments indicate significant differences ($p < 0.05$).

Bouteloua gracilis and *Calamovilfa longifolia,* and these seeded species were also the largest contributors to perennial grass production (163 g/m^2, 69 g/m^2, and 67 g/m^2, respectively).

Production by non-seeded species was significantly less in the broadcast treatment compared to the drill treatment (297 g/m^2 and 457 g/m^2, respectively). The greatest mean production by non-seeded species was from *Heterotheca villosa* and *Helianthus petiolarus* (84 g/m^2 and 63 g/m^2, respectively).

Mulch Treatments

Life-form group

Analysis by life–form group among the three mulch treatments showed significant differences in production in all life-form categories (Figure 10 and Appendix Table 6). Perennial grass production was significantly greater in the no-mulch and mulch treatments compared to the cover crop treatment (564 g/m^2, 539 g/m^2, and 197 g/m^2, respectively). The cover crop treatment had significantly greater annual forb production than both the no-mulch and mulch treatments (293 g/m^2, 87 g/m^2, and 107 g/m^2, respectively). All mulch treatments were significantly different from one another in the perennial forb life-form group. The mulch treatment had the greatest perennial forb production followed by the cover crop treatment (213 g/m^2 173 g/m^2, respectively). The no-mulch treatment had the least production by perennial forbs (107 g/m^2). Annual grasses production was greatest in the cover crop treatment and least in the mulch treatment (45 g/m^2 and 7 g/m^2, respectively).

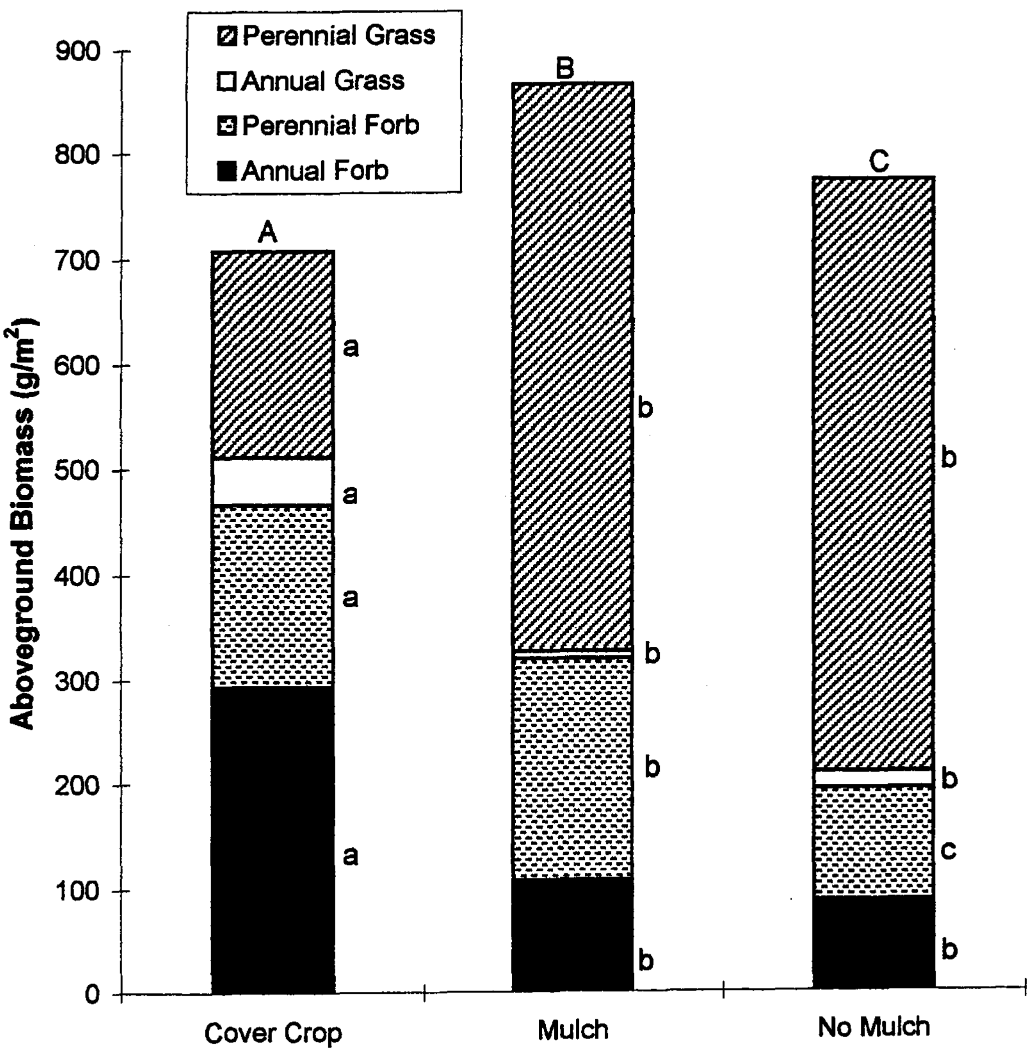

Figure 10. Mean aboveground biomass among mulch treatments on the Crested Wheatgrass Replacement Study in 1999. Different lower case letters within lifeform groups and across treatments indicate significant differences ($p < 0.05$). Different upper case letters indicate significant differences in total production across treatments ($p < 0.05$).

Native versus introduced species

Production by native and introduced species was significantly different among mulch treatments (Figure 11 and Appendix Table 3). Production by native species was greatest in the mulch treatment followed by the no-mulch and cover crop treatments (783 g/m^2, 691 g/m^2, and 467 g/m^2, respectively). All treatments were significantly different from one another.

Introduced species production was least in the mulch and no-mulch treatments and significantly greater in the cover crop treatment (82 g/m^2, 84 g/m^2, and 240 g/m^2, respectively).

Seeded versus non-seeded species

There was no significant difference in seeded species production between the mulch and no-mulch treatments (Figure 12 and Appendix Table 4). However, the mulch treatment did have greater seeded species production compared to the no mulch treatment (554 g/m^2 and 516 g/m^2, respectively). The cover crop treatment did poorly when comparing seeded versus non-seeded species production with only 145 g/m^2 seeded species production and 562 g/m^2 non-seed species production. The mulch and no-mulch treatments had significantly less production by non-seeded species, 311 g/m^2 and 258 g/m^2 respectively, than the cover crop treatment. The mulch and no-mulch treatments were not significantly different in both the seeded and non-seeded categories.

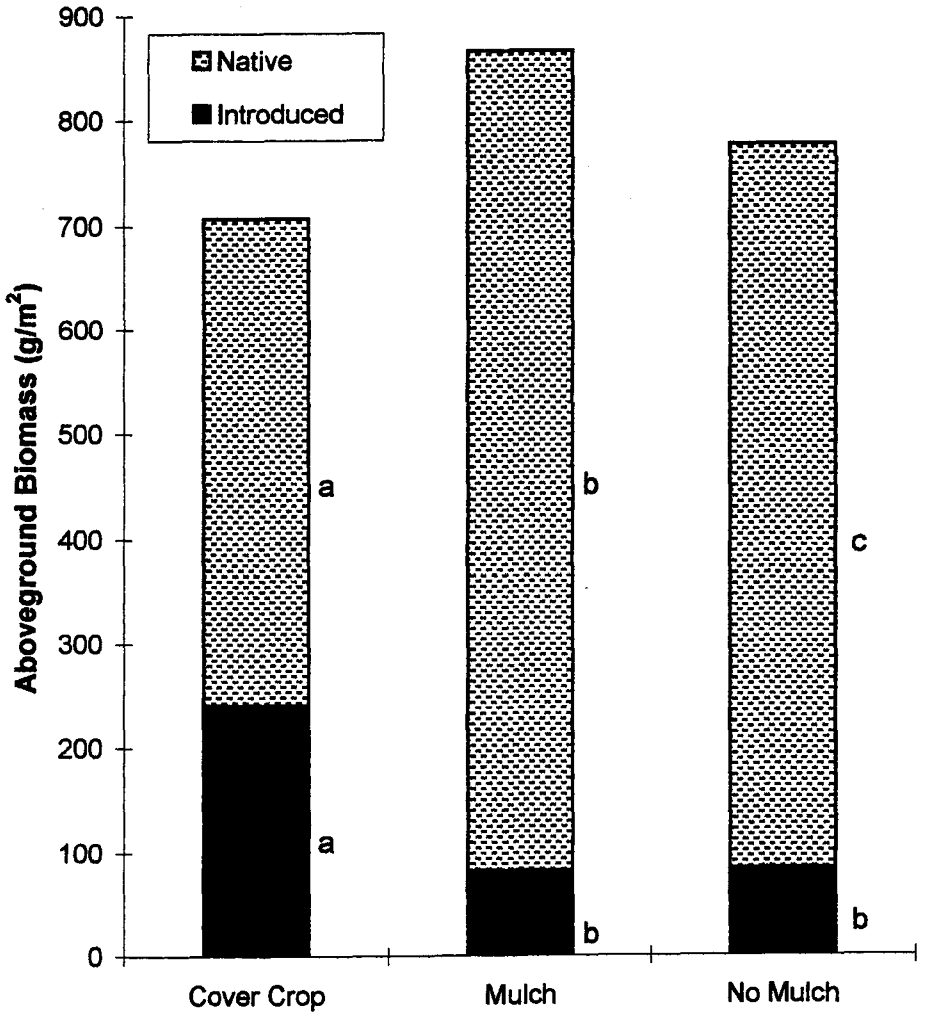

Figure 11. Mean aboveground biomass among mulch treatments on the Crested Wheatgrass Replacement Study in 1999. Different lower case letters within native versus introduced species groups and across treatments indicate significant differences ($p < 0.05$).

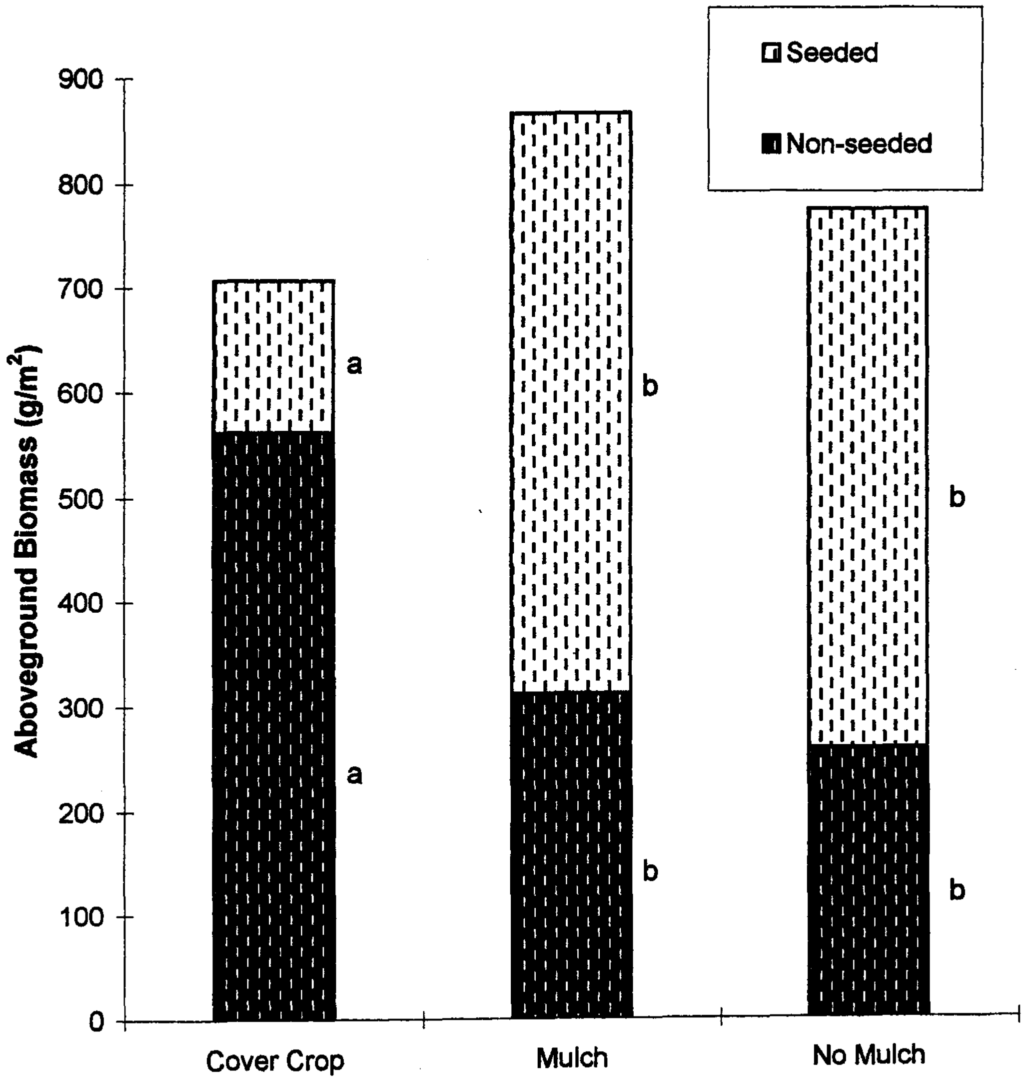

Figure 12. Mean aboveground biomass among mulch treatments on the Crested Wheatgrass Replacement Study in 1999. Different lower case letters within seeded versus non-seeded species groups and across treatments indicate significant differences ($p < 0.05$).

Sucrose Treatments

Life-form group

Analysis between sucrose treatments showed no significant differences in any life-form category (Figure 13 and Appendix Table 7). Perennial grass production was 447 g/m^2 in the no-sucrose treatment compared to 419 g/m^2 in the sucrose treatment. Annual forb production was slightly greater in the no-sucrose treatment than in the sucrose treatment (169 g/m^2 and 155 g/m^2, respectively). There were very small production differences between sucrose treatments in both annual grass and perennial forb production.

Native versus introduced species

No significant differences were found between sucrose treatments when analyzed by native versus introduced species production (Figure 14 and Appendix Table 3). Sucrose treated plots had 619 g/m^2 native species production and 140 g/m^2 introduced species production. The no-sucrose treatments had 675 g/m^2 native species production and 131 g/m^2 introduced species production.

Seeded versus non-seeded species

As with the previous two analysis, no significant differences were found between the sucrose treatments within seeded versus non-seeded species (Figure 15 and Appendix Table 4). The sucrose treated plots had 386 g/m^2 seeded species production and 372 g/m^2 non-seeded species production. Production by seeded species in the no-sucrose treated plots was 423 g/m^2 and production by non-seeded species was 382 g/m^2.

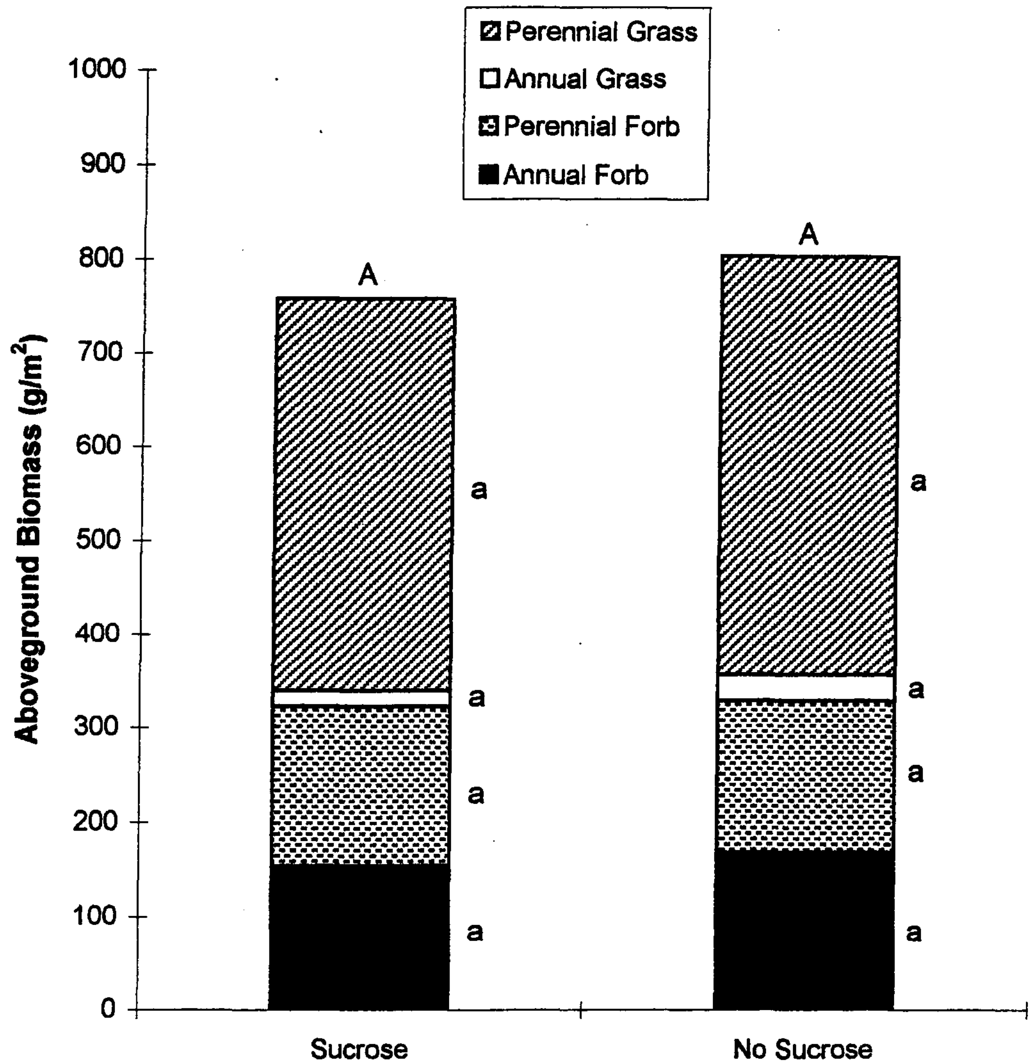

Figure 13. Mean aboveground biomass between sucrose treatments on the Crested Wheatgrass Replacement Study in 1999. Different lower case letters within lifeform groups and between treatments indicate significant differences ($p < 0.05$). Different upper case letters indicate significant differences in total production across treatments ($p < 0.05$).

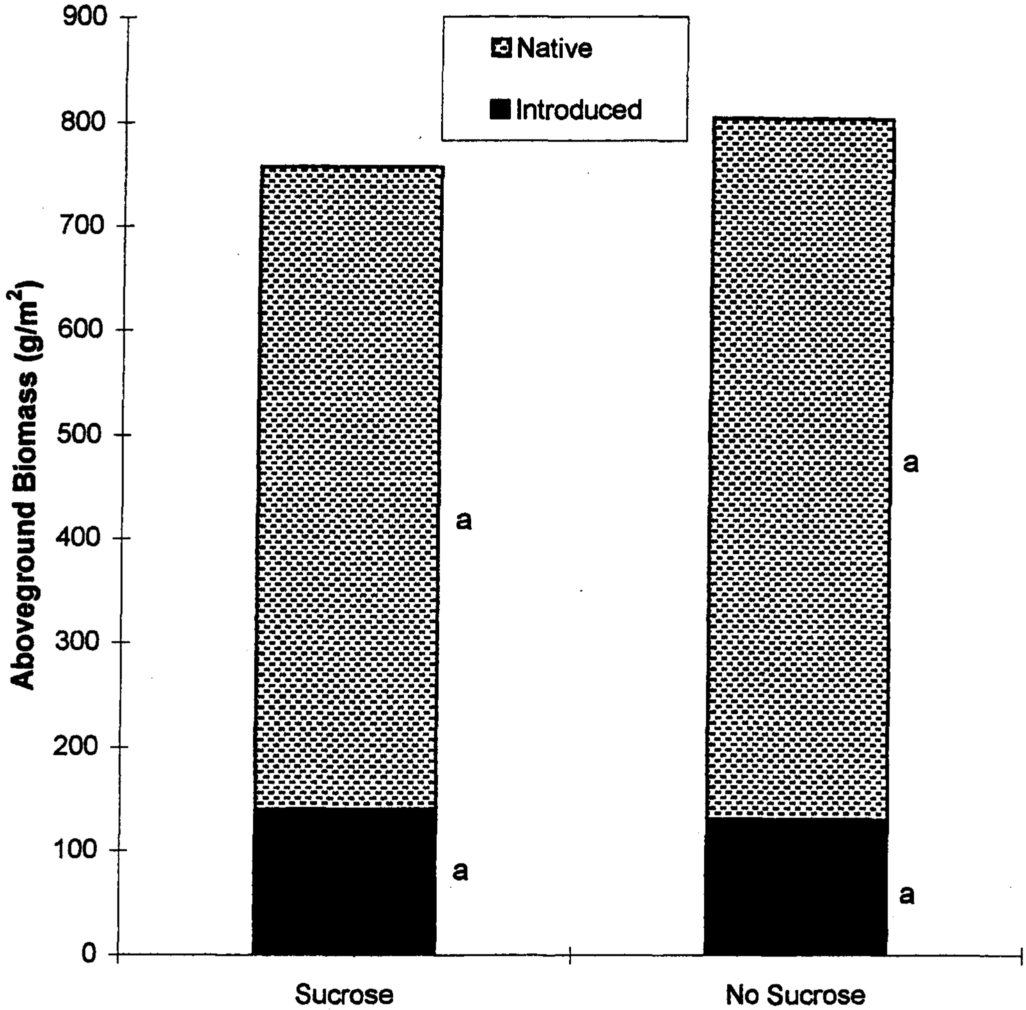

Figure 14. Mean aboveground biomass between sucrose treatments on the Crested Wheatgrass Replacement Study in 1999. Different lower case letters within native versus introduced species groups and between treatments indicate significant differences ($p < 0.05$).

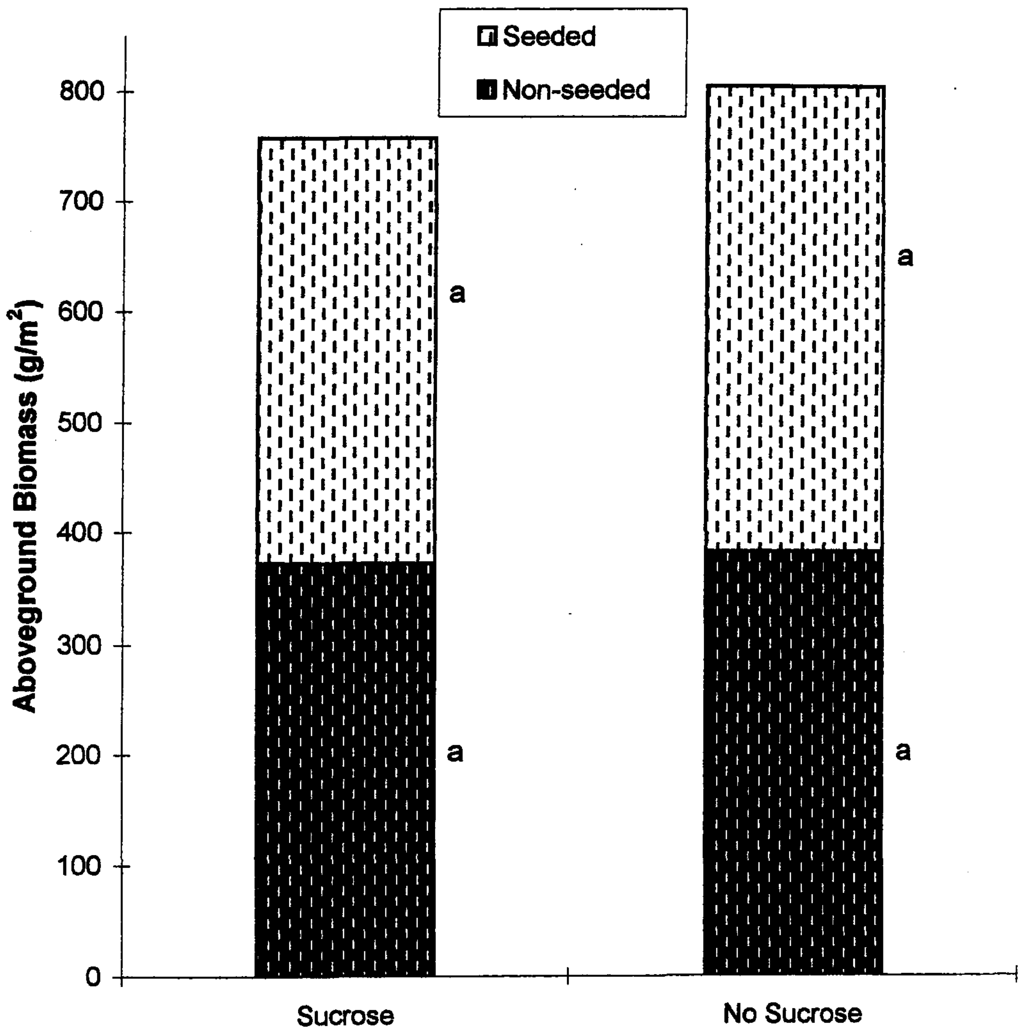

Figure 15. Mean aboveground biomass between sucrose treatments on the Crested Wheatgrass Replacement Study in 1999. Different lower case letters within seeded versus non-seeded species groups and between treatments indicate significant differences ($p < 0.05$).

Shrub Density All Treatments

Shrub densities among irrigation treatments were not significantly different (Figure 16). However, total number of shrubs did increase linearly with increasing irrigation. The MJJA irrigation treatment had the most shrubs with a total of 199 individuals. The fewest shrubs were in the control treatment with a total of 162 individuals.

Seeding technique greatly influenced shrub density (Figure 17). The broadcast treatment had significantly more shrubs than the drill treatment (700 and 167 shrubs, respectively).

Mulching treatment also significantly influenced shrub density (Figure 18). Both the no mulch and mulch treatments were significantly different from the cover crop treatment (459, 379, and 29, respectively). The no mulch treatment had the most shrubs and had significantly more shrubs than the mulch treatment at $p < 0.07$.

Shrub densities between the sucrose and no sucrose treatments were significantly different (Figure 19). The no sucrose treatment had significantly more shrubs than the sucrose treatment (508,and 359 shrubs, respectively).

Discussion

Irrigation Treatments

Irrigation had long-term effects on community composition in the fifth growing season, although irrigation water was only added for the first two growing seasons. The fifth year results showed that increased irrigation affected community

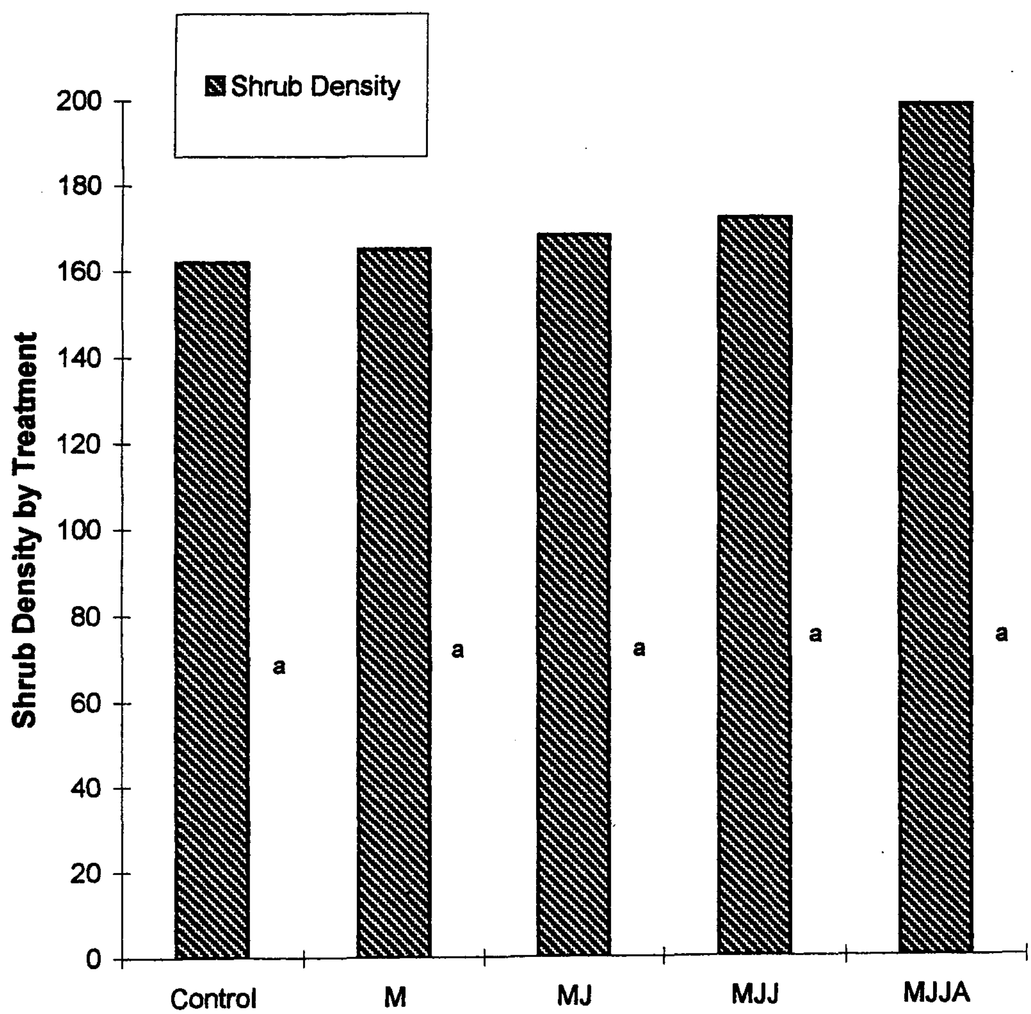

Figure 16. Total number of shrubs among irrigation treatments on the Crested Wheatgrass Replacement Study in 1999. Irrigation: Control=no irrigation, M=May Irrigation, MJ=May+June Irrigation, MJJ=May+June+July Irrigation, MJJA=May+ June+July+August Irrigation. Different lower case letters across treatments indicate significant differences ($p \leq 0.05$).

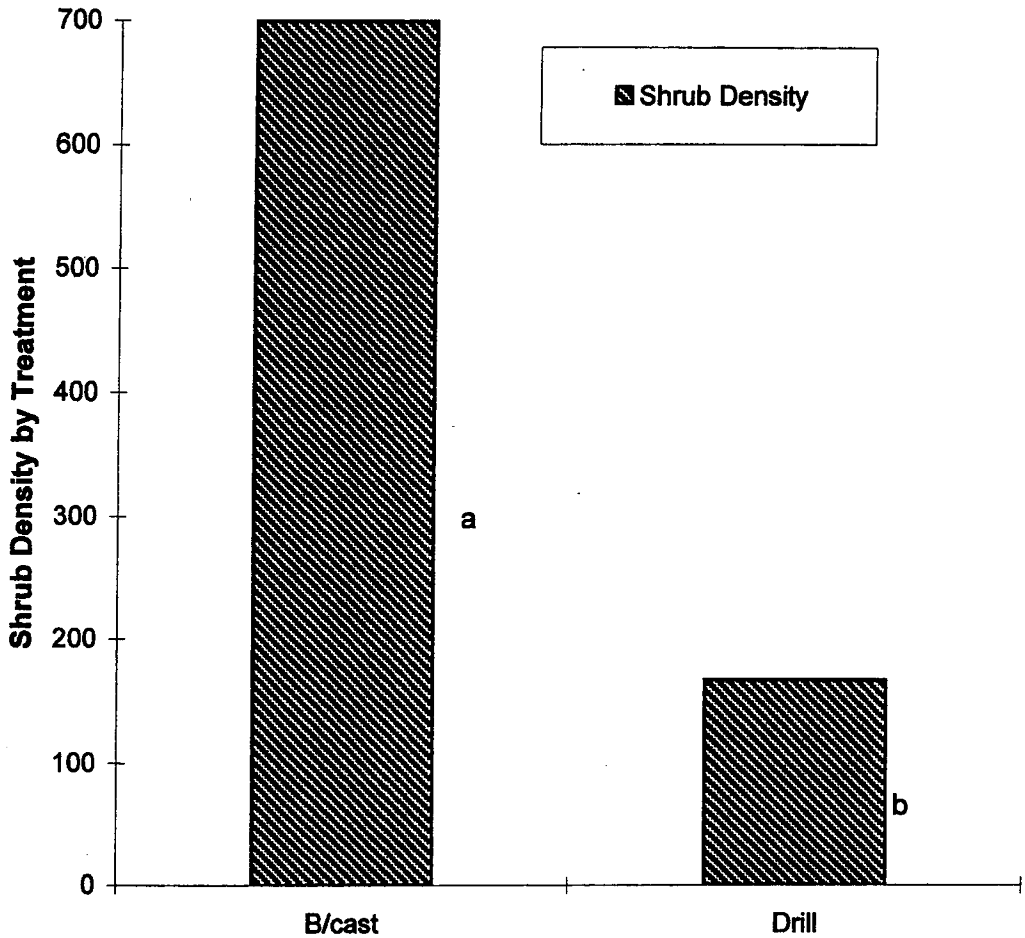

Figure 17. Total number of shrubs between seeding techniques on the Crested Wheatgrass Replacement Study in 1999. Seeding techniques, B/cast=broadcast seeding, Drill=drill seeding. Different lower case letters treatments indicate significant differences ($p < 0.0001$).

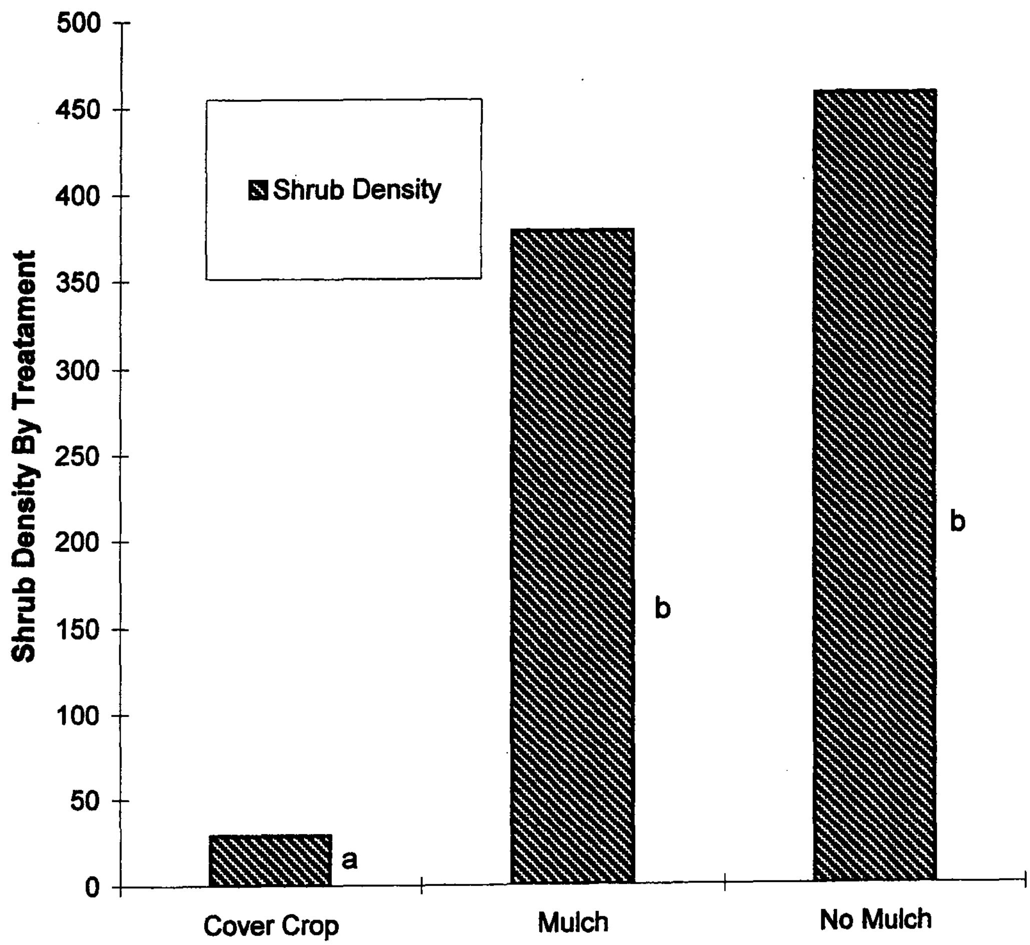

Figure 18. Total number of shrubs among mulch treatments on the Crested Wheatgrass Replacement Study in 1999. Different lower case letters across treatments indicate significant differences ($p < 0.0001$).

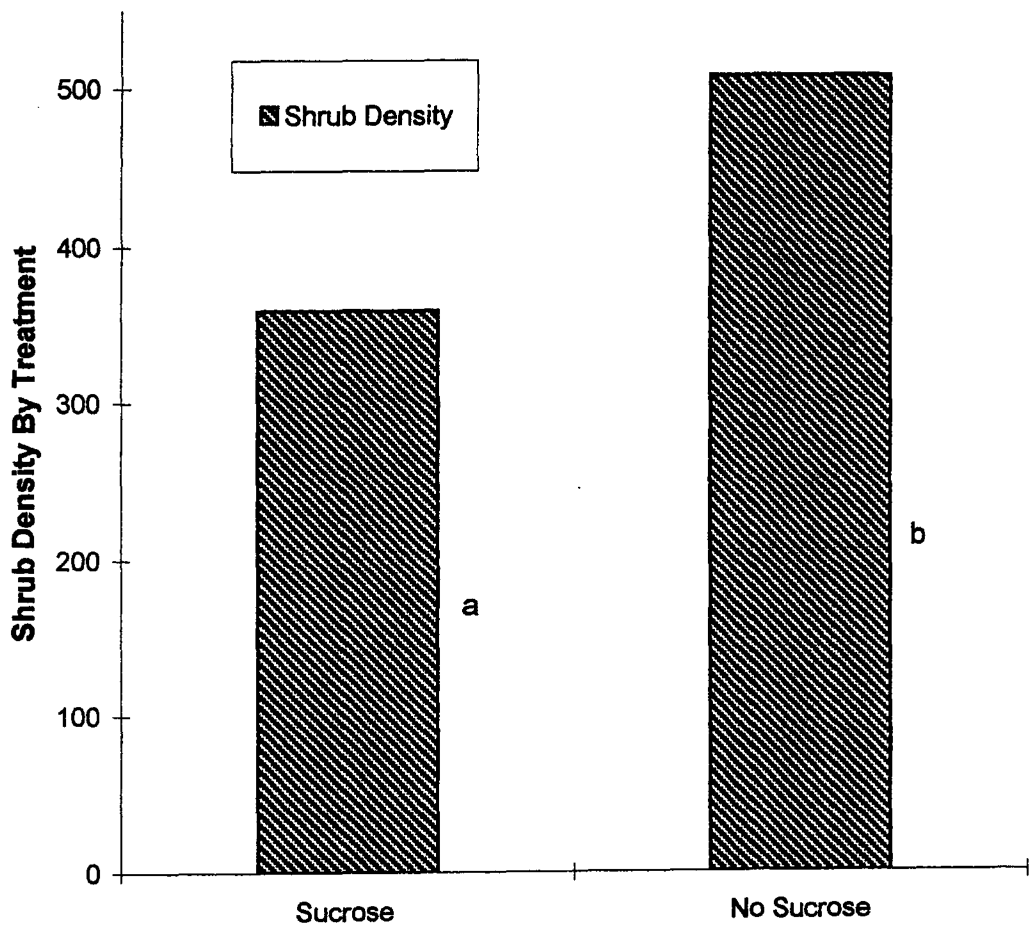

Figure 19. Total number of shrubs between sucrose treatments on the Crested Wheatgrass Replacement Study in 1999. Different lower case letters between treatments indicate significant differences ($p < 0.007$).

structure by increasing perennial grass production. Relative perennial grass production was 11 % greater in the MJJA treatment than in the control or 126 g/m^2 more production. There was a linear increase in production by perennial species with increasing irrigation however, only the control and MJJA treatments were significantly different.

Relative weedy annual forb production was 5 % lower in the MJJA treatment compared to the control treatment or 30 g/m^2 less production.

Within the perennial forb life-form group no obvious trends were observed. The MJ treatment had the greatest production by perennial forbs and there was only a 1% difference in relative perennial forb production between the MJJA treatment and the control treatment. Annual grass production was not a significant contributor to overall plant production in the fifth year. However, annual grass production generally decreased with increasing irrigation.

An over-all comparison between the fifth growing season and the third growing season revealed a reversal in community structure dominance (Appendix Figure A-1 and Appendix Table 4). There was a large increase in perennial species production and a large decrease in production by annual forbs during the fourth and fifth growing season (Figures 4 and Appendix Figure A-1). Annual forbs were the dominant life-form in the third growing season, while perennial species were the dominant life-forms in the fifth growing season. For instance, relative annual forb production in the MJJA treatment was 17 % in the fifth growing season compared to 63 % in the third growing season; while relative perennial grass production was 62 % in the fifth growing season compared to 29 % in the third growing season.

In addition to knowing how the community developed by life-form group, it is also important to know how native species responded to treatments. Therefore, in the fifth year analysis by native versus introduced species was performed. This analysis showed a linear increase in native species production with increasing irrigation and a trend toward decreased production by introduced species with increased irrigation. Native species comprised 87 % of the relative production in the MJJA treatment. By comparison relative production by native species in the control treatment was 79 % and had 130 g/m^2 less production by native species than the MJJA treatment.

Relative production by introduced species was least in the MJJA (8 %) and greatest in the M treatment (21 %). Introduced species production in the M treatment was 51 g/m^2 greater than MJJA treatment.

Some of the native species in the native versus introduced species analysis were not seeded, therefore it is also important to ask whether irrigation affected seeded species production. Therefore, an analysis by seeded versus non-seeded species was conducted. This analysis showed a linear response to irrigation for both seeded and non-seeded species.

Seeded species production increased linearly with increasing irrigation while non-seeded species decreased with increased irrigation. For instance, relative production by seeded species in the MJJA treatment was 62% while in the control treatment it was only 42 %. Production by seeded species in the MJJA treatment was significantly greater than all treatments except the MJJ. The MJJA treatment had 192 g/m^2 more production by seeded species than the control treatment.

Production by seeded species increased in a linear fashion from the control to the MJJA treatment however, watering through June had the greatest increase in seeded species production from the previous irrigation treatment. Therefore, if water is a limited resource, the MJ treatment would be the best minimum watering treatment.

Relative production by non-seeded species was least in the MJJA treatment (38 %) and greatest in the control (57 %). Relative production by non-seeded species was 111 g/m^2 more in the control treatment than the MJJA treatment. Production by non-seeded species steadily decreased with increasing irrigation, with the least production by non-seeded species in the MJJA treatment, which was 106 g/m^2 less than the control treatment. The MJJA treatment yielded the best ratio between seeded and non-seeded species with 62 % seeded species and 38 % non-seeded species.

Seeding Technique

All analyses performed showed that seeding technique had a long-term effect on community structure. In general, the broadcast treatment had a more favorable effect on community structure and had the best ratio between seeded and non-seeded species.

Relative production by perennial grasses in the broadcast treatment was 61 % compared to the drill treatment with 50 %. The broadcast treatment had 34 g/m^2 more production by perennial grasses. Annual forb production in the broadcast treatment had 63 g/m^2 less production than the drill treatment. Relative production by perennial forbs was 5 % greater in the drill treatment than in the broadcast treatment however, the difference in production was not significant. Annual grass production was not a major contributor to total production with 4 % relative production in the drill treatment and 2 % in the broadcast treatment.

A comparison of native versus introduced species showed that the drill treatment had significantly more production by introduced species than the broadcast treatment. Production by introduced species was 56 g/m^2 higher in the drill treatment than in the broadcast treatment . Native species production was higher in the broadcast treatment than in the drill treatment, however, the differences were not significant.

There were large differences in relative production by seeded versus non-seeded species between the drill and broadcast treatments. The broadcast treatment had 60 % relative production by seeded species compared to the drill treatment with only 44 %. In addition, the broadcast treatment had 16 % less relative production by non-seeded species. As is commonly practiced, the broadcast treatment was seeded at twice the drill seeding rate. Seeded species production in the broadcast treatment, with twice the seeding rate, resulted in an increase of 68 g/m^2 over the drill treatment. Total production was 94 g/m^2 higher in the drill treatment than in the broadcast treatment, but that increase was attributed to non-seeded species production. Non-seeded production was 160 g/m^2 greater in the drill treatment than in the broadcast treatment. Therefore, there may be an advantage to the use of broadcast seeding to reduce production by non-seeded species.

Mulch Treatments

Results indicate that mulch treatments had a long-term effect on plant community development. As with the first two treatments above, differences in plant production were still evident after the fifth growing season. The cover crop treatment was a poor treatment with 28 % relative production by perennial grasses compared to the mulch and no-mulch treatments with 62 % and 73 % relative perennial grass production, respectively. In addition, the cover crop treatment had the greatest relative annual forb production of 41 % compared to the mulch and no-mulch treatment with 12 % and 11 % respectively. The differences in production by the cover crop treatments did not seem related to the fact that it was planted with the native mixture one year after the mulch and no-mulch treatments The no-mulch treatment had the least production by perennial forbs, however, many of the perennial forbs present were non-seeded species.

The no-mulch and mulch treatments had the highest relative production by seeded species at 67 % and 64 %, respectively. The cover crop treatment did especially poor in this analysis at 21 % relative seeded species production.

The cover crop treatment had 66 % relative production by native species, however, many of the native species contributing to the native production were "weedy" natives, such as *Mentzelia nuda, Iva xanthifolia,* and *Physalis heterophylla.* The mulch and no-mulch treatments had a high percentage of relative production by native species (91% and 89 %, respectively) and included many seeded native species like *Artemisia ludoviciana* and *Gaillardia aristata.*

Clearly, there is no advantage to planting a cover crop before planting the native community. The differences between the mulch and no-mulch treatments were not significant enough to merit using mulch when irrigation is applied, considering the cost and effort involved in mulch application.

Sucrose Treatments

No differences were found between the sucrose treated and no sucrose treated plots. The lack of a community response in the fifth year may have resulted because the other revegetation treatments overwhelmed the effect sucrose may have had on community development, or the sucrose application rate may not have been high enough to invoke the expected response.

Shrub Density

Shrub density was influenced by all revegetation treatments except irrigation. Irrigation did not show any significant differences among treatments, but total number of shrubs did increase linearly with increased water application. The increase in shrub densities was small among the M through MJJ treatments with only a two to three shrub increase per treatment. However, the MJJA treatment increased by 27 shrubs compared to the MJJ treatment.

Seeding technique greatly influenced shrub densities with 81 % of the shrubs recorded growing in the broadcast treatment. There were 533 more established shrubs in the broadcast treatment than in the drill treatment. Therefore, shrubs may be particularly sensitive to planting depth. It appears that desirable shrub densities can be achieved if seeds are placed on the surface and lightly harrowed to increase seed soil contact. Rubber rabbitbrush (*Chrysothamnus nauseosus*) was the most successful of the three shrub species planted with a total of 797 shrubs for all treatments. The other two species, fourwing saltbush (*Atriplex canescens*) and yucca (*Yucca glauca*), had less success with 53 and 17 total shrubs for all treatments respectively. The broadcast treatment averaged 6 shrubs per 1260 ft^2, while the drill treatment averaged 1 shrub for the same area.

The cover crop treatment was not a successful treatment with respect to shrub establishment. The cover crop treatment had 430 fewer shrubs than the no-mulch treatment and 350 fewer shrubs than the mulch treatment. The no-mulch treatment had the most shrubs with 80 shrubs more than the mulch treatment. The broadcast mulch treatments had 46 fewer shrubs than the broadcast no mulch treatment. Therefore, mulch application may have inhibited shrub germination. In the first growing season, mulch may have caused a reduction in light reaching the first leaves. In addition, Russian thistle (*Salsola iberica*) was highly productive in the mulch treatment during the first growing season and still dominant in the second growing season, which would have reduced light penetration to the germinating seedlings. The weight of the mulch may also have been a factor in limiting the number of shrubs germinating through the mulch layer.

The plots not treated with sucrose had significantly more shrubs than those treated with sucrose. The non-sucrose plots had 149 more shrubs than did the sucrose treated plots. Rubber rabbitbrush was the dominant shrub, as mentioned above, and is considered an early to mid-seral shrub species and may be sensitive to reductions in plant available nitrogen from the sucrose applications. Therefore, reductions in plant available nitrogen may have reduced shrub germination and establishment.

Nitrogen Sucrose Study

Results

Irrigation Treatments

Life-form Group

Irrigation averaged over both nitrogen and sucrose treatments showed significant differences in all life-form groups except perennial forbs (Figure 20 and Appendix Table 8). Total production was greatest in the MJ treatment (814 g/m^2).

The irrigation treatments amended with sucrose showed no significant differences in production by life-form group at the $p \leq 0.05$ significance level (Figure 21). However, the MJJA irrigation and sucrose combined treatment had significantly less annual forb production than the MJ and MJJ sucrose treated plots at the $p \leq 0.06$ significance level (63 g/m^2, 231 g/m^2, and 231 g/m^2, respectively). The least production of annual forbs was in the control and MJJA treatments, and the most production in the MJ and MJJ treatments (70g/m^2, 63 g/m^2, 231 g/m^2, and 231 g/m^2, respectively). The perennial forb life-form group had a similar pattern to the annual forbs with the control and MJJA treatments with the least production and the MJ treatment with the greatest production (108 g/m^2, 69 g/m^2, and 188 g/m^2, respectively).

Annual grass production had an inverse relationship of decreasing production with increasing irrigation in the sucrose irrigation combined treatments. Annual grass production decreased from the control to the MJJA treatment in a

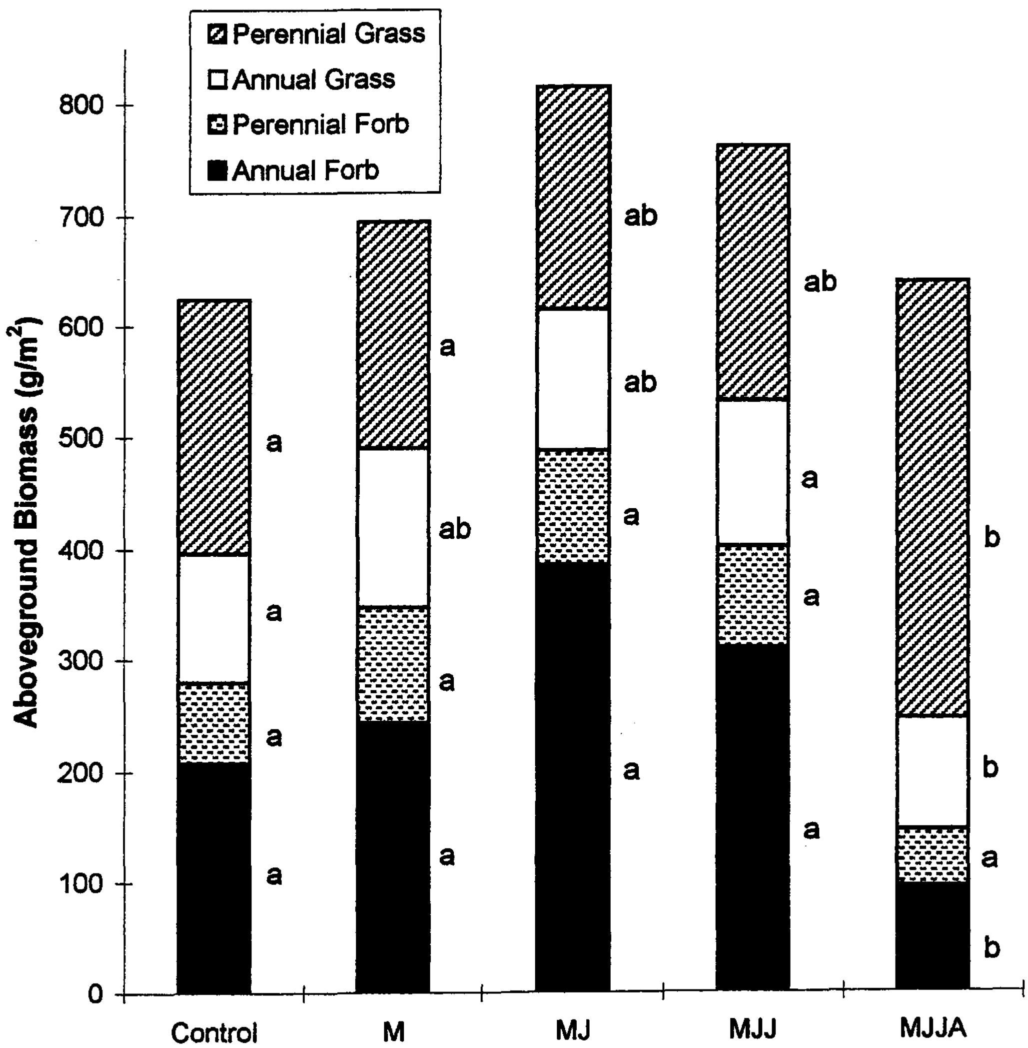

Figure 20. Mean aboveground biomass among irrigation treatments on the Nitrogen Sucrose Study in 1999. Irrigation, Control=no irrigation, M=May Irrigation, MJ=May+June Irrigation, MJJ=May+June+July Irrigation, MJJA=May+June+ July+August Irrigation. Different lower case letters within lifeform groups and across treatments indicate significant differences ($p \leq .05$).

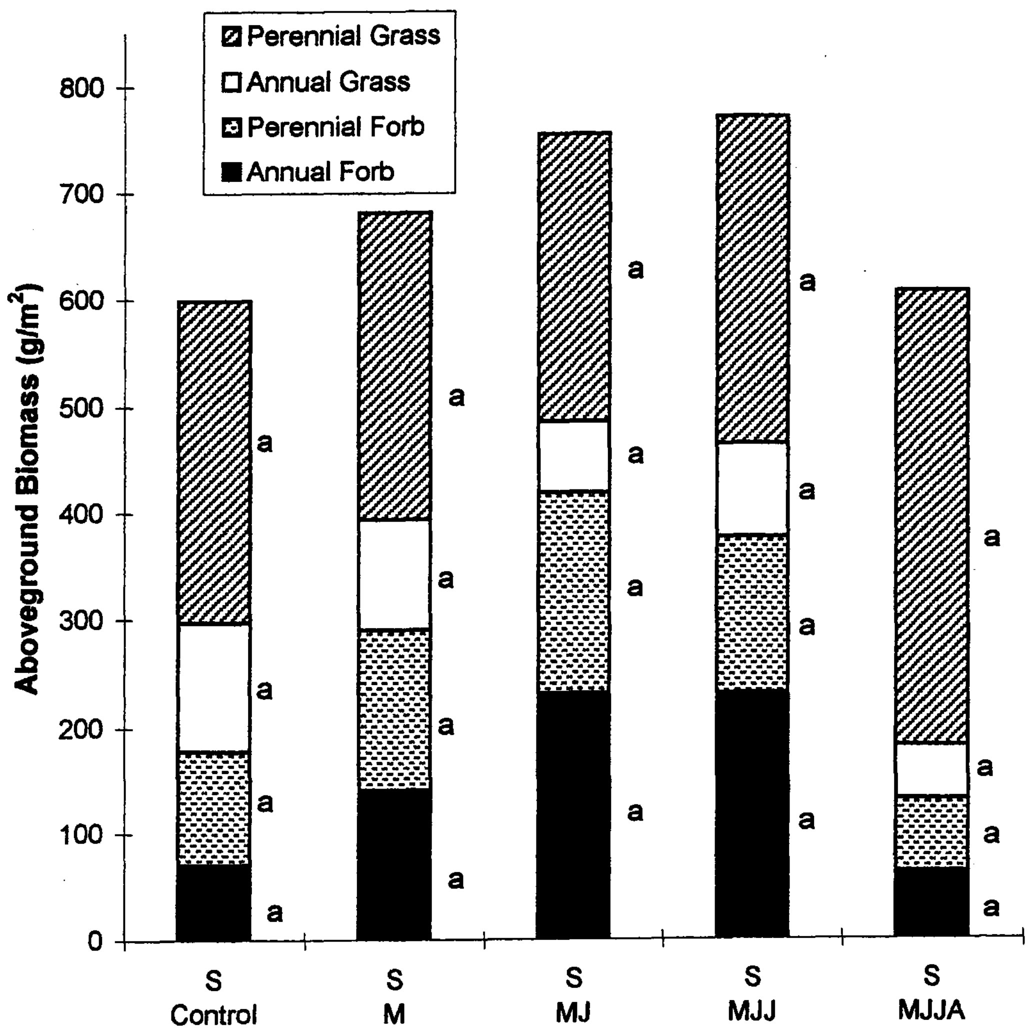

Figure 21. Mean aboveground biomass among irrigation treatments (with sucrose) on the Nitrogen Sucrose Study in 1999. Irrigation, Control=no irrigation, M=May Irrigation, MJ=May+June Irrigation, MJJ=May+June+July Irrigation, MJJA= May+June+July+August Irrigation. S=sucrose. Different lower case letters within lifeform groups and across treatments indicate significant differences ($p < 0.05$).

linear fashion however, differences were not significant (119 g/m^2 and 51 g/m^2, respectively).

Perennial grass production in the combined irrigation and sucrose treated plots was greatest in the MJJA treatment but was not significantly different from the least productive treatment MJ (424 g/m^2 and 269 g/m^2, respectively).

In the combined irrigation and nitrogen treated plots, significant differences were found in one life-from group, perennial grasses (Figure 22). The MJJA combined treatment had significantly more perennial grass production than the M combined nitrogen treatment (362 g/m^2 and 122 g/m^2, respectively).

There was a large fluctuation in production within the annual forb life-form group among treatments however, no significant differences were found. The greatest production by annual forbs in the combined nitrogen plots was the MJ treatment with 540 g/m^2 compared to the smallest production of 127 g/m^2 in the MJJA combined nitrogen treatment.

Production by perennial forbs in the combined nitrogen treatments was small compared to the other life-form groups. The greatest production in this category was in the M nitrogen combined treatment at 58 g/m^2, compared to the least production in the MJ treatment of 16 g/m^2.

Annual grass production in the combined nitrogen irrigation treatment was greatest in the MJ treatment and least in the control treatment (186 g/m^2 and 114 g/m^2, respectively).

Native versus introduced species

Within the combined irrigation sucrose treated plots there were no

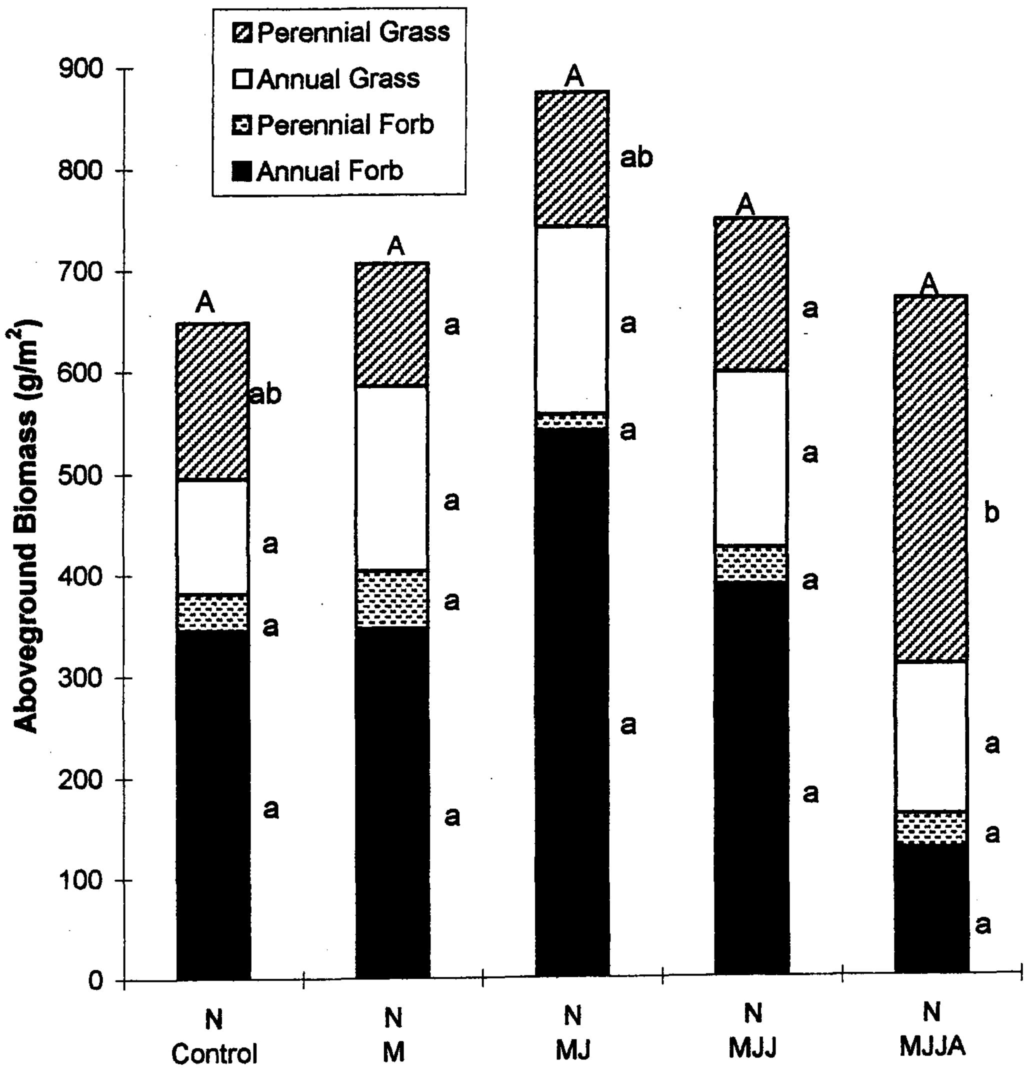

Figure 22. Mean aboveground biomass among irrigation treatments (with Nitrogen) on the Nitrogen Sucrose Study in 1999. Control=no irrigation, M=May Irrigation, MJ=May+June Irrigation, MJJ=May+June+July Irrigation, MJJA=May+June+July+ August Irrigation. N=nitrogen. Different lower case letters within lifeform groups and across treatments indicate significant differences ($p \leq 0.05$). Different upper case letters indicate significant differences in total production across treatments ($p \leq 0.05$).

significant differences in either native or introduced species production (Figure 23). The MJJ combined treatment had the greatest native species production and the control had the least native species production (487 g/m^2 and 388 g/m^2, respectively). Introduced species production in the combined sucrose irrigation treatment was inconsistent, with the least production in the M and MJJA treatments and greatest in the MJ treatment (133 g/m^2, 205 g/m^2, and 355 g/m^2, respectively).

Introduced species production in the combined nitrogen irrigated plots had a similar pattern as in the combined sucrose irrigated treatment, but with greater production (Figure 24). The control and MJJA nitrogen combined treatment had the least production, and the MJ treatment had the greatest production (475 g/m^2, 458 g/m^2, and 740 g/m^2, respectively). The native species production in the combined nitrogen irrigated plots was less than in the sucrose combined plots. The greatest native species production was in the MJJA combined nitrogen treatment and least in the MJ combined treatment (213 g/m^2 133 g/m^2, respectively).

Soil Amendment Treatments

Life-form Group

Soil amendment treatment with nitrogen or sucrose resulted in significant differences in all life-form groups (Figure 25 and Appendix Table 10). Annual forb production was significantly greater in the nitrogen treated plots than in the sucrose treated plots (349 g/m^2 and 147 g/m^2, respectively). Annual grass production was also greater in the nitrogen treated plots than the sucrose treated plots (160 g/m^2 and 86 g/m^2, respectively). Perennial species production was

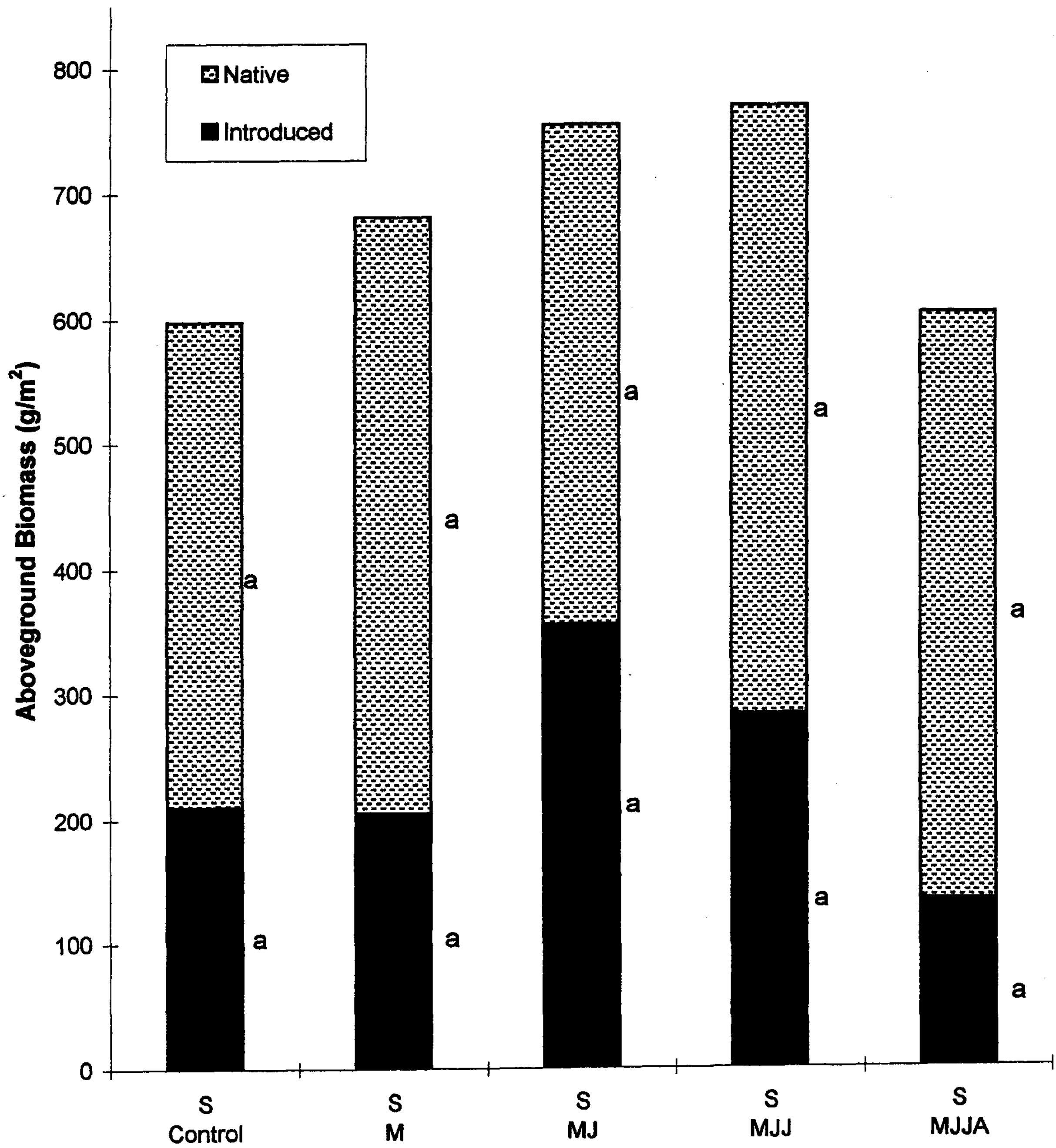

Figure 23. Mean aboveground biomass among irrigation treatments (with Sucrose) on the Nitrogen Sucrose Study in 1999. Control=no irrigation, M=May Irrigation, MJ=May+June Irrigation, MJJ=May+June+July Irrigation, MJJA=May+June+July+ August Irrigation. S=sucrose. Different lower case letters within Native or Introduced species and across treatments indicate significant differences ($p < 0.05$).

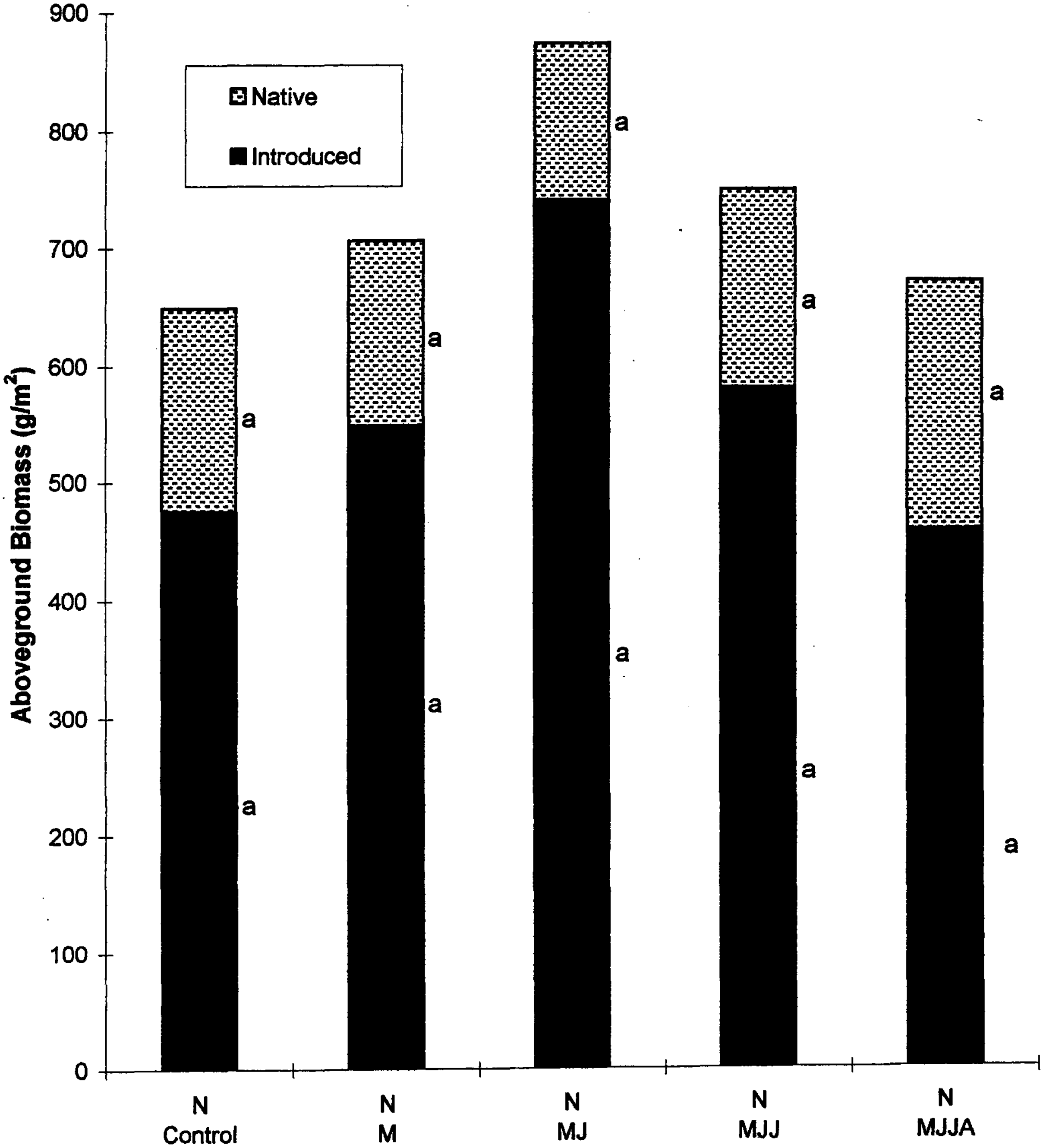

Figure 24. Mean aboveground biomass among irrigation treatments (with Nitrogen) on the Nitrogen Sucrose Study in 1999. Control=no irrigation, M=May Irrigation, MJ=May+June Irrigation, MJJ=May+June+July Irrigation, MJJA=May+June+July+ August Irrigation. N=nitrogen. Different lower case letters within Native or Introduced species and across treatments indicate significant differences ($p < 0.05$).

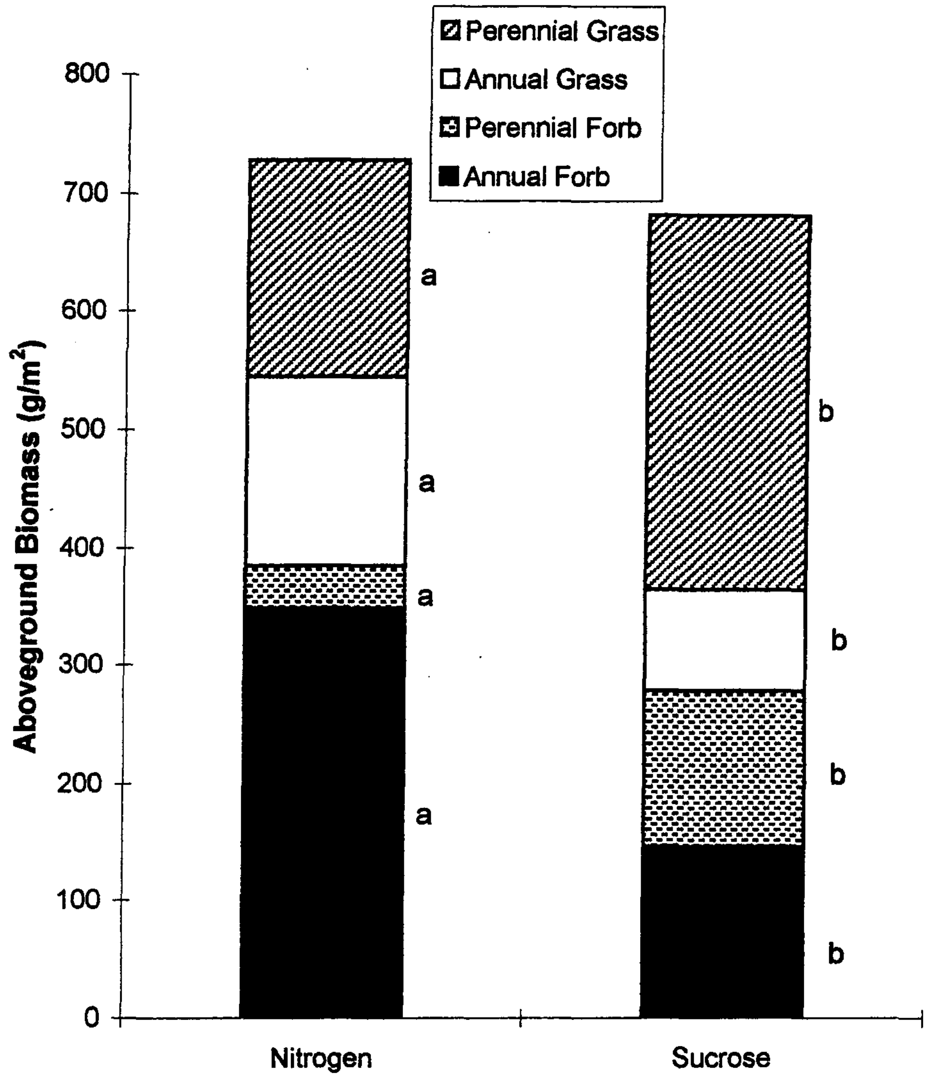

Figure 25. Mean aboveground biomass between nitrogen/sucrose treatments on the Nitrogen Sucrose Study in 1999. Different lower case letters within lifeform groups and between treatments indicate significant differences ($p \leq 0.05$). Different capital letters indicate significant differences in total production across treatments ($p < .05$).

significantly greater in the sucrose treated plots than the nitrogen treated plots (318 g/m^2 and 184 g/m^2, respectively). Perennial forb production in the sucrose treated plots had 132 g/m^2, compared to the nitrogen treated plots with 36 g/m^2 and was significantly different at the $p \leq .06$ level.

Native versus introduced species

Treatment with nitrogen and sucrose significantly influenced native and introduced species production (Figure 26 and Appendix Table 9). Sucrose treated plots had significantly greater native species production with 445 g/m^2 compared to the nitrogen treated plots with 169 g/m^2. Introduced species production was significantly greater in the nitrogen treated plots compared to the sucrose treated plots with 561 g/m^2 and 237 g/m^2, respectively.

Discussion

Irrigation Treatments

The linear response to irrigation observed in the third study year seemed to be fading after three years with no water applications. Total biomass production was greatest in the MJ treatment and least in the control and MJJA treatment. It is not clear why this pattern emerged, but it was consistent for both the nitrogen and sucrose combined irrigation plots. Annual forb production followed the same pattern regardless of amendment treatment. In addition, perennial forb production in the sucrose treated irrigation plots, and annual grass production in the nitrogen treated irrigation plots, exhibited the same pattern.

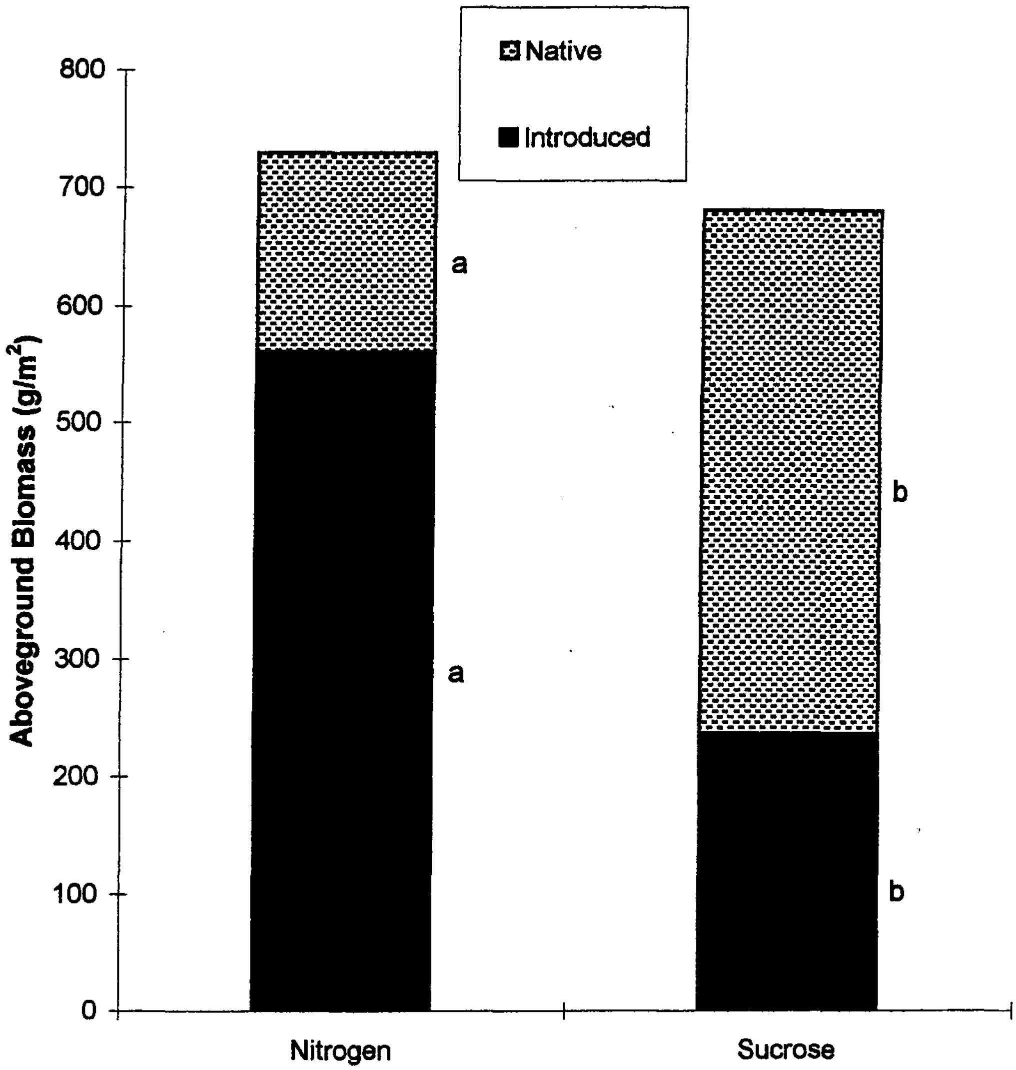

Figure 26. Mean aboveground biomass between nitrogen/sucrose treatments on the Nitrogen Sucrose Study in 1999. Different lower case letters within Native or Introduced species and between treatments indicate significant differences ($p < 0.05$).

Irrigating through August improved relative perennial grass production, however there was not a linear response to irrigation. Relative perennial grass production was 61 % in the MJJA treatment compared to 36 % in the control treatment. Irrigating through August also decreased production by annual forbs. Relative annual forb production was 14% compared to the greatest relative annual forb production of 47 % in the MJ irrigation treatment. There was no obvious linear pattern with regard to irrigation however, the MJJA treatment clearly had the most desirable species composition compared to all other treatments.

Soil Amendment Treatments

Treatment with nitrogen and sucrose clearly had a significant effect on species composition. Relative production by perennial grasses in the sucrose treated plots was 47 %, compared to the nitrogen treated plots with 25 %. There was significantly more relative production by perennial forbs in the sucrose treated plots (19 %) compared to the nitrogen plots (5 %). Relative annual forb production, which was almost entirely from undesirable species, was 48 % in the nitrogen treated plots compared to 21 % in the sucrose treated plots. The plant community shifted toward an undesirable species composition with early seral species dominating the community in plots where nitrogen was applied. Nitrogen was added to determine if the existing perennial community could be enhanced by promoting increased biomass production by perennial species. Nitrogen did not enhance the perennial grass production but seemed to inhibit perennial species production by enhancing the production of weedy annual forbs. In addition, annual weedy species established in the community where they were not present before treatment application. The trend toward higher annual species production began after the second year of application (Arthur 2000, Arthur and Redente 1998) and continued into the fifth year.

Relative native species production in the sucrose treated plots was 42 % higher in the sucrose treated plots than in the nitrogen treated plots. Therefore, approximately three times more relative production by native species was achieved with sucrose treatment compared to treatment with nitrogen. The opposite was true for relative production by introduced species. Relative production by introduced species in the nitrogen plots was more than twice that of the sucrose treated plots.

Nitrogen application was not an effective treatment for shifting established native communities with weed infestation toward perennial species dominance. It is also likely that nitrogen applications would not be effective in enhancing perennial species during or after seeding in native soil. Sucrose applications in comparisons to nitrogen application shifted the community toward a more desirable community of native plant species and greatly enhanced the perennial community. The caveat is that an affordable source of carbon would have to be found to make comparable sucrose applications feasible at a large scale.

Sucrose Only Study

Results

Heavy Cheatgrass Site

Production by life-form group differed significantly among sucrose treatments in both the annual grass and perennial forb categories (Figure 27 and

Appendix Table 11). Annual grass production was significantly greater in the control group than in the 1760 (lbs/acre) treatment (250 g/m^2 and 135 g/m^2, respectively). In addition there was a linear inverse relationship between annual grass production and increasing sucrose treatment. The higher the amount of sucrose applied, the less annual grass production. Only two species made up the annual grass life-form group, which included *Bromus tectorum* (cheatgrass) and *Vulpia octiflora* (six weeks fescue). Cheatgrass was the most dominant of the two species with an average of 187 g/m^2 compared to six weeks fescue with 5 g/m^2.

Perennial forb production was significantly greater in the 1760 sucrose treatment than the control treatment (69 g/m^2 and 162 g/m^2, respectively). The control group had the highest perennial grass production and the 1320 treatment had the least, however no statistical differences were found (155 g/m^2, 107 g/m^2, respectively). Annual forb production was an insignificant component of the species composition at only 6 g/m^2 total average production and no significant differences were found. Total production was greatest in the 880 treatment but was not significantly different from the 1760 treatment (503 g/m^2 and 404 g/m^2, respectively).

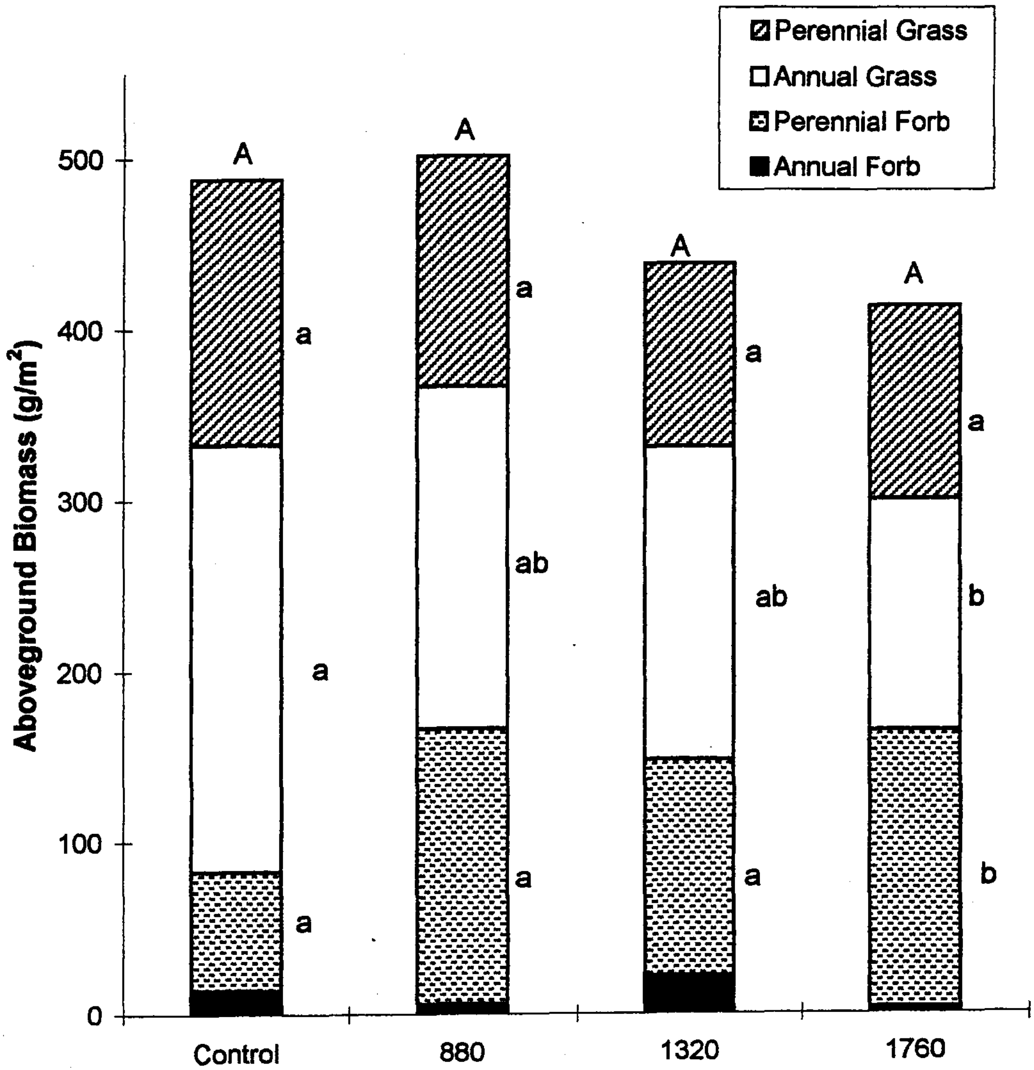

Figure 27. Mean aboveground biomass among sucrose treatments on the heavy cheatgrass site in the Sucrose Only Study in 1999. Control = no sucrose, 880 = 880 lbs/acre sucrose, 1320 = 1320 lbs/acre sucrose, 1760 = 1760 lbs/acre sucrose. Different lower case letters across treatments and within life-form groups indicate significant differences ($p < 0.05$). Different upper case letters indicate significant differences in total produion across treatments. No significant differences found in the annual forb life-form category.

Native species production was not significantly different among the sucrose treatments (Figure 28 and Appendix Table 12). Introduced species production was significantly less in the 1760 treatment than in the control treatment at the $p \leq .06$ level (262 g/m^2 and 134 g/m^2, respectively). The general trend was for higher sucrose applications to support less production by introduced species.

Light to Moderate Cheatgrass Site

Application of sucrose significantly influenced production by life-form group in one category, perennial grasses (Figure 29 and Appendix Table 13). Perennial grass production was significantly greater in the control treatment than in the 1320 and 1760 treatment (673 g/m^2, 490 g/m^2, and 424 g/m^2, respectively). There was an inverse relationship between increasing sucrose application and decreasing perennial grass production. Perennial grass production was the largest component of the plant community structure with an average of 530 g/m^2. Production by perennial forbs, annual grasses and annual forbs was relatively small compared to perennial grass production (49 g/m^2, 46 g/m^2 and 8 g/m^2, respectively). Annual grass production showed no discernable pattern resulting from sucrose treatment and was not significant among treatments. Perennial forb production was not significantly different, but had a linear pattern of increasing production with increased sucrose application amount. Annual forb production was an insignificant component of the community with an average of 8 g/m^2, as noted above.

Total production was significantly greater in the control group than the other three treatment groups. The control group had 763 g/m^2 total production

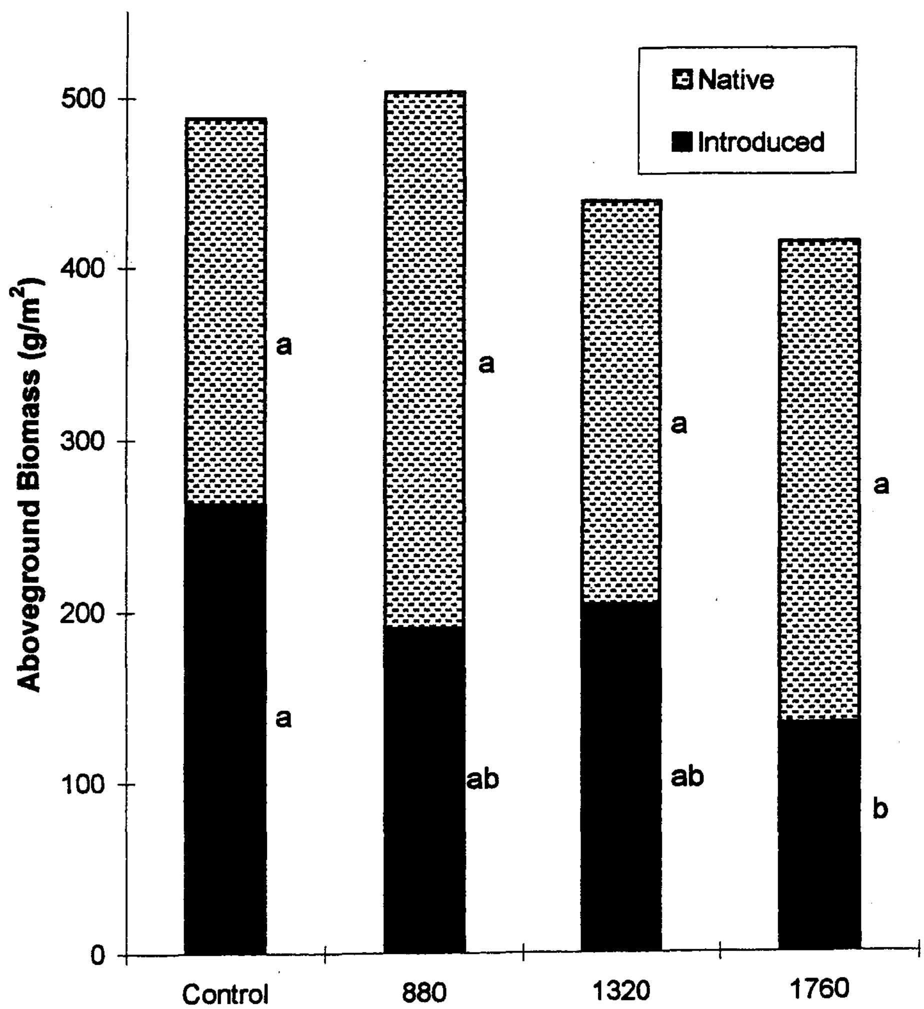

Figure 28. Mean aboveground biomass among sucrose treatments on the heavy cheatgrass site in the Sucrose Only Study in 1999. Control = no sucrose, 880 = 880 lbs/acre sucrose, 1320 = 1320 lbs/acre sucrose, 1760 = 1760 lbs/acre sucrose. Different lower case letters across treatments and within native or introduced species production indicate significant differences ($p < 0.05$).

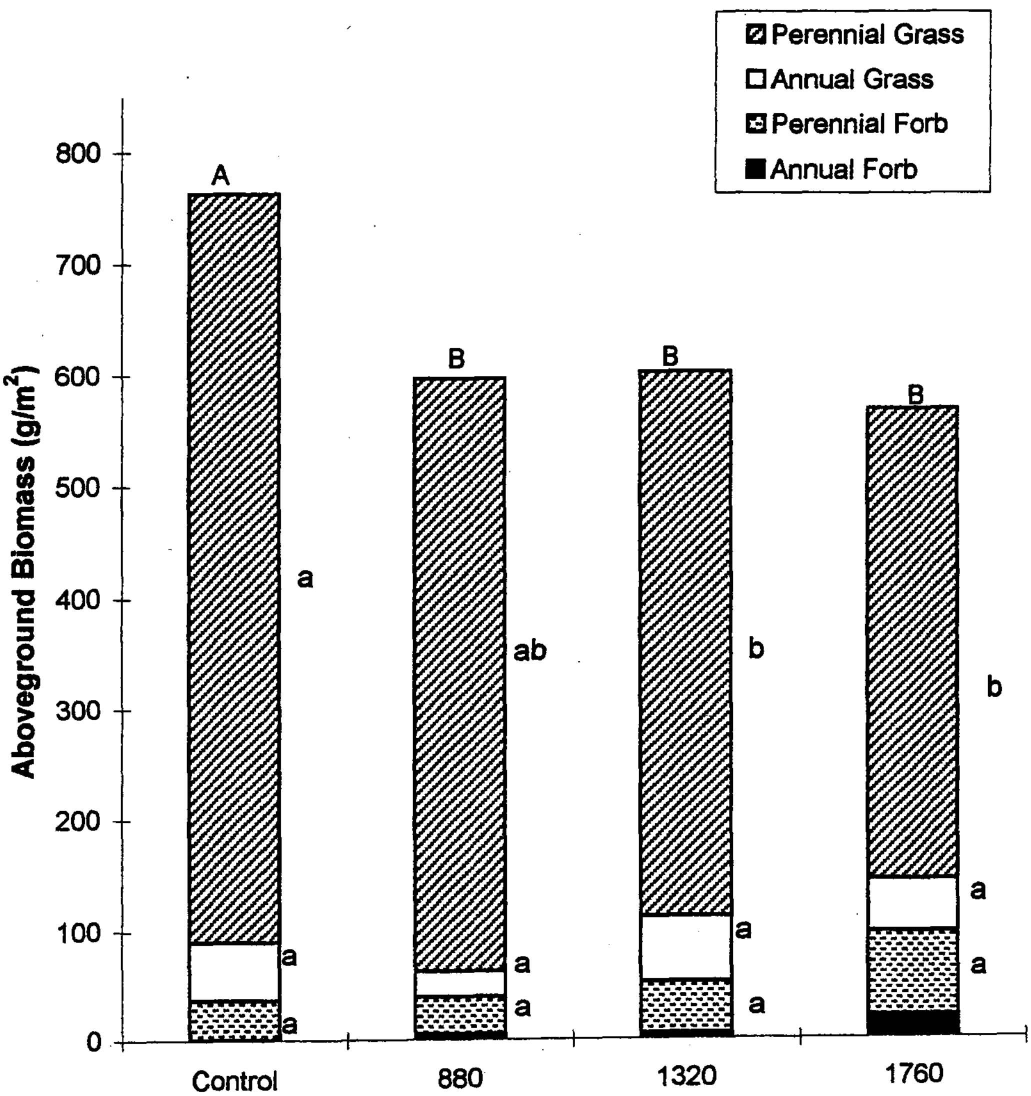

Figure 29. Mean aboveground biomass among sucrose treatments on the light/moderate cheatgrass site in the Sucrose Only Study in 1999. Control = no sucrose, 880 = 880 lbs/acre sucrose, 1320 = 1320 lbs/acre sucrose, 1760 = 1760 lbs/acre sucrose. Different lower case letters across treatments and within life-form groups indicate significant differences ($p < 0.02$). No significant differences were found in the annual forb life-form category.

compared to the least productive treatment 1760, with 568 g/m^2. Greater total production in the control treatment can be attributed to the contribution by perennial grasses.

Among all treatments, native species dominated the community with an average of 582 g/m^2 compared to introduced species with 48 g/m^2 (Figure 30 and Appendix Table 12). The control treatment had significantly greater native species production than both the 1320 and 1760 treatments (709 g/m^2, 538 g/m^2, and 508 g/m^2, respectively). Introduced species production was not significantly different among treatments. The greatest production by introduced species was in the 1320 treatment and the least production by introduced species was in the 880 treatment (63 g/m^2 and 25 g/m^2, respectively).

Discussion

Heavy Cheatgrass Site

One of the main objectives of this study was to see if a carbon amendment (sucrose) could be an effective control for cheatgrass infested rangelands. The carbon amendment was applied to experimentally lower the plant available soil nitrogen by increasing the C:N ratio and moving the system toward microbial N immobilization. Reductions in soil N should inhibit weedy annual plants, enhance perennial species, and theoretically shift the community toward perennial dominance.

Increased sucrose application in the heavy cheatgrass site resulted in a decrease in annual grass production. Significant drops in annual grass production

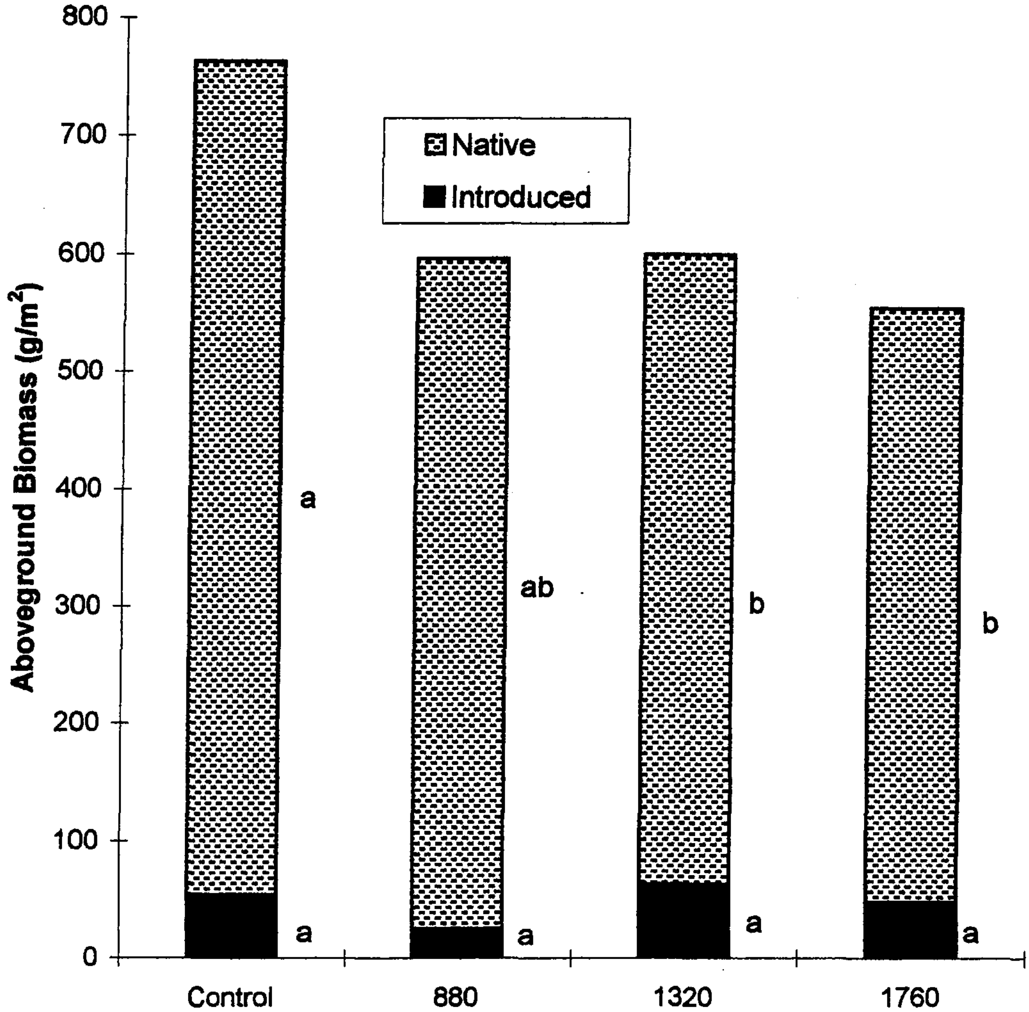

Figure 30. Mean aboveground biomass among sucrose treatments on the light/moderate cheatgrass site in the Sucrose Only Study in 1999. Control = no sucrose, 880 = 880 lbs/acre sucrose, 1320 = 1320 lbs/acre sucrose, 1760 = 1760 lbs/acre sucrose. Different lower case letters across treatments and within native or introduced species production indicate significant differences ($p < 0.03$).

were observed in the amended site compared with the control (non-amended) site after five years of applications. There was a linear decrease in production by annual grasses with an increase in amount of sucrose application. For instance, relative annual grass production in the 1760 lbs/acre treatment was 18 % lower than the control treatment. In addition, annual grass production in the control plots was 1.9 times higher than in the 1760 plots.

Relative production by perennial species was 68 % in the 1760 treatment group compared to the control treatment with 46 % relative production. In addition, both the 880 and 1320 treatments had higher relative production by perennial species than the control by an average of 10 %. Therefore, applying a carbon source did shift the community from annuals to perennials.

Annual forb production was a very minor contributor to the plant community and was not significantly different among treatments.

Total production generally decreased with increased sucrose application rates. In general, increased production was a result of greater cheatgrass growth in the control and 880 treatments . The control treatment had 489 g/m^2 total production compared to the 1760 treatment with 405 g/m^2 total production.

Relative production by native species was greatest in the 1760 sucrose treatment at 68 % and least in the control group with 46 % relative production. In addition the control group had 22 % more relative production by introduced species than the 1760 treatment. Generally there was a linear increase in native species production and a linear decrease in introduced species production with increasing sucrose treatment.

Light to Moderate Cheatgrass Site

Sucrose application significantly influenced perennial grass production in the light to moderate cheatgrass site. As the sucrose application rate increased, perennial grass production decreased. The control treatment had significantly greater production by perennial grasses than the 1320 and 1760 treatments. No other significant differences by life-form were found.

Relative production by perennial grasses decreased with increasing sucrose application. The greatest relative perennial grass production was in the control treatment and was 13% greater than the 1760 treatment. Relative production by perennial forbs showed the opposite trend as perennial grasses. Increased sucrose application rate supported increased relative production by perennial forbs. Relative production by perennial forbs was most in the 1760 treatment (14 %) and least in the control treatment (5 %). This pattern may have emerged because relative perennial grass production was most dominant in treatments with the lowest application rate. Therefore, competition from the perennial grasses in least amended treatments may have decreased production by the perennial forbs. Relative annual grass production did not appear to respond to the sucrose treatments.

Native species production followed the same trend as the perennial grasses, and it appeared that this life-form group was driving the differences between native and introduced species production. Relative production by native species was greatest in the control treatment with 93 % and least in the 1760 treatment with 89

% relative production. Introduced species production did not differ significantly.

It is clear that sucrose application in light to moderate cheatgrass infested areas is not recommended. The results from this study indicate that in areas where cheatgrass is not dominant, its production does not respond to decreases in plant available nitrogen. However, perennial grass production is significantly decreased by a reduction in plant available nitrogen, which was opposite of the intended objective.

RECOMMENDATIONS FOR FUTURE RESTORATION

- Irrigate 0.50 inches per week in May, June, and July for the first two years after seeding. The largest increase in perennial grass and seeded species production was present with irrigation through July.

- Broadcast seed rather than drill seed. Broadcast seeding increased production by perennial grasses and decreased production by annual forbs. In addition 60 % of the relative production in the broadcast treatment was from seeded species compared to the drill plots, which had 44 % relative production by seeded species. Shrub production was greatly improved with broadcast seeding.

- After broadcast seeding, use a light harrow or a medium to heavy chain to increase the seed soil contact. The light chain that attaches to the back of the broadcast seeder owned by the FWS was inadequate to cover the seed after broadcasting. During plot establishment a chain was connected to the harrow and good seed soil contact was achieved with the modified harrow system following broadcast seeding.

- Mulching in the spring is not necessary for successful restoration when combined with irrigation. Production by perennial forbs was higher in 1999 in the mulched treatment but perennial grass production was lower. Mulching only improved relative production of seeded species by 3 %. In addition, shrub density results indicate that mulch can inhibit shrub establishment. While mulching did improve perennial forb production and slightly improved overall seeded species production, it inhibited shrub establishment and perennial grass production therefore, it appears that the benefits of mulching do not out-weigh the disadvantages and additional cost.

- A cover crop prior to native seeding is not recommended. The cover crop treatment continued to do poorly after four growing seasons in all treatment combinations and in all analyses.

- Seedbed preparation in a crested wheatgrass dominated site should consist of first using a large moldboard plow to thoroughly uproot the root balls, followed by disking at least twice to reduce crested wheatgrass reestablishment. In 1999, the crested wheatgrass mean production did increase compared to 1997 however, it only averaged 27 g/m^2 across all treatments in contrast to the most dominant perennial grass, *Andropogon halli,* which averaged 163 g/m^2.

- Sucrose application is not recommended during the restoration process in the amount applied in the CWRS study for two reasons. First, it appears that other revegetation techniques outweighed the effect of the sucrose amendment.

Second, shrub densities were significantly lower in the plots that received sucrose.

- Nitrogen additions are not recommended. In the Nitrogen Sucrose Study nitrogen additions increased production by annual forbs and decreased perennial grass production. In addition, nitrogen additions are not recommended during the restoration process, even though nitrogen was not added to the CWRS. It is the opinion of the authors that nitrogen additions would maintain annual species dominance for a longer period than if nitrogen was not added.

- Two years of irrigation and five years of sucrose application in a weed infested native site shifted community structure toward perennial species and reduced annual weedy species production compared to sites irrigated and amended with nitrogen. However, further study would be required to recommend sucrose treatments with irrigation given the high cost of irrigation and amending with sucrose.

  - Application of sucrose alone can shift native communities that are heavily infested with cheatgrass toward a community dominated by perennial species. In addition, cheatgrass production was significantly reduced with increased sucrose application. The response was linear. If an affordable source of carbon can be found, carbon amendments can help reduce cheatgrass in heavily infested areas.

  - Application of sucrose alone is not recommended for sites with light to moderate cheatgrass infestation. The reduction in plant available nitrogen through the application of sucrose decreased production by perennial grasses and did not decrease cheatgrass production.

  - Long-term research is invaluable for evaluating how restoration techniques can influence community structure and restoration success. Notable differences did arise between the third and fifth year of the studies. An evaluation conducted ten years after the research inception is recommended to determine how restoration techniques continued to influence native community structure over the long term.

APPENDIX A

Figures and Tables

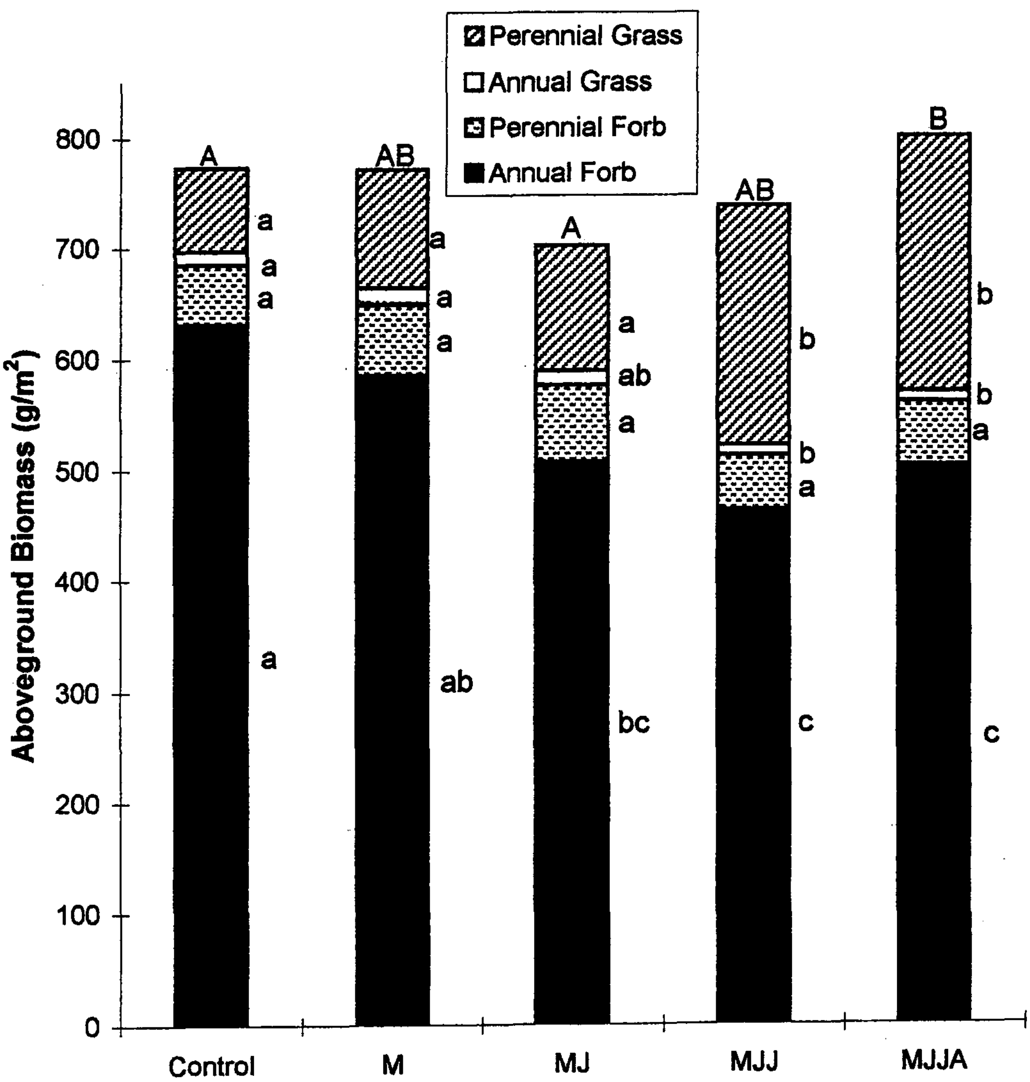

Figure A-1. Mean aboveground biomass among irrigation treatments on the Crested Wheatgrass Replacement Study in 1997. Irrigation: Control=no irrigation, M=May Irrigation, MJ=May+June Irrigation, MJJ=May+June+July Irrigation, MJJA=May+June+July+August Irrigation. Different lower case letters within lifeform groups and across treatments indicate significant differences ($p \leq 0.05$). Different upper case letters indicate significant differences in total production across treatments ($p \leq 0.05$).

Table 1. Seed mixture for Crested Wheatgrass Replacement Study

Scientific Name	Common Name	Variety	lbs PLS/A
Perennial Grasses			
Bouteloua gracilis	Blue grama	Hachita	0.14
Calamovilfa longifolia	Prairie sandreed	Goshen	1.74
Bouteloua curtipendula	Side-oats grama	Vaughn	0.20
Andropogon hallii	Sand bluestem	Woodward	5.09
Pascopyron smithii	Western wheatgrass	Arriba	0.20
Panicum virgatum	Switchgrass	Nebraska 28	0.41
Oryzopsis hymenoides	Indian ricegrass	Nezpar	0.38
Perennial Forbs			
Cleome serrulata	Rocky Mountain bee plant		0.10
Gaillardia aristata	Blanket flower		0.10
Linum lewisii	Blue flax		0.10
Helianthus annuus	Annual sunflower		0.10
Achillea lanulosa	Yarrow		0.003
Artemisia ludoviciana	Louisiana sagewort		0.03
Coreopsis tinctoria	Plains coreopsis		0.09
Artemisia frigida	Fringed sage		0.02
Shrubs			
Chrysothamnus nauseosus	Rubber rabbitbrush		0.15
Atriplex canescens	Fourwing saltbush		0.88
Yucca glauca	Yucca		0.10
TOTAL			9.833

Table 2. Mean aboveground biomass in g/m^2 among irrigation treatments on the Crested Wheatgrass Replacement Study in 1995, 1996, 1997, and 1999. Control=no irrigation, M=may irrigation, MJ=May+June irrigation, MJJ=May+June+July irrigation, MJJA=May +June +July+August irrigation, 1-SE=Standard Error.

	Irrigation Treatment					
	Control	May	MJ	MJJ	MJJA	1-SE
1995						
Annual Forb	188	173	170	135	169	19
Perennial Forb	0.6	1	0.3	1	1	0.4
Annual Grass	67	44	38	72	61	10
Perennial Grass	17	17	13	20	17	3
Total	273	235	221	228	248	19
1996						
Annual Forb	827	855	1159	1157	1166	111
Perennial Forb	35	42	76	79	52	13
Annual Grass	23	36	67	114	73	20
Perennial Grass	98	166	139	181	220	43
Total	983	1099	1441	1531	1511	123
1997						
Annual Forb	631	585	507	463	504	46
Perennial Forb	54	64	69	50	57	22
Annual Grass	3	6	3.7	0.3	0.3	2
Perennial Grass	77	108	113	216	232	31
Total	765	763	692.7	729.3	793.3	40
1999						
Annual Forb	166	146	176	185	137	29
Perennial Forb	151	169	184	159	155	41
Annual Grass	33	43	14	6	16	10
Perennial Grass	373	389	437	468	499	68
Total	724	748	812	819	806	44

Table 3. Mean aboveground biomass in g/m^2 (with 1 standard error) between Native and Introduced spcecies production among treatments on the Crested Wheatgrass Replacement Study in 1999. Control=no irrigation, M=may irrigation, MJ=May+June irrigation, MJJ=May+June+July irrigation, MJJA=May +June +July+August irrigation, B/cast = broadcast seeding, Drill = drill seeding, Mulch=mulch treatments, Sucrose=sucrose applied, No Sucrose=no sucrose applied.

	Native	1-SE	Introduced	1-SE
Irrigation				
C	572	36	152	30
M	592	36	156	30
MJ	692	36	120	30
MJJ	677	36	142	30
MJJA	702	36	105	30
Seeding				
B/cast	628	29	107	28
Drill	628	29	163	28
Mulch				
Cover Crop	467	32	240	29
Mulch	783	32	82	29
No Mulch	691	32	84	29
Sucrose				
Sucrose	619	37	140	29
No sucrose	675	37	131	29

Table 4. Mean aboveground biomass in g/m^2 (with 1 standard error) between Seeded and Non-seeded species production among treatments on the Crested Wheatgrass Replacement Study in 1999. Control=no irrigation, M=may irrigation, MJ=May+June irrigation, MJJ=May+June+July irrigation, MJJA=May +June +July+August irrigation, B/cast = broadcast seeding, Drill = drill seeding, Mulch=mulch treatments, Sucrose=sucrose applied, No Sucrose=no sucrose applied.

	Seed	1-SE	Non-seeded	1-SE
Irrigation				
C	310	49	415	34
M	338	49	410	34
MJ		49	376	34
MJJ	90.7	49	380	34
MJJA	502	49	305	34
Seeding				
B/cast	438	44	297	29
Drill	371	44	457	29
Mulch				
Cover Crop	145	46	562	31
Mulch	554	46	311	31
No Mulch	516	46	259	31
Sucrose				
Sucrose	386	51	372	29
No sucrose	424	51	382	29

Table 5. Mean aboveground biomass in g/m^2 (with 1 standard error) between seeding treatments on the Crested Wheatgrass Replacement Study in 1995, 1996, 1997 anmd 1999.

	Seeding Treatment		
	B/cast	Drill	1-SE
1995			
Annual Forb	144	189	12
Perennial Forb	1	1	0.3
Annual Grass	73	40	7
Perennial Grass	20	13	2
Total	238	243	13
1996			
Annual Forb	967	1095	102
Perennial Forb	72	43	10
Annual Grass	54	71	19
Perennial Grass	202	122	40
Total	1,295	1,331	116
1997			
Annual Forb	473	602	39
Perennial Forb	77	45	18
Annual Grass	2	3	1
Perennial Grass	197	103	27
Total	749	753	32
1999			
Annual Forb	131	194	25
Perennial Forb	140	188	38
Annual Grass	15	31	8
Perennial Grass	450	416	64
Total	735	829	38

Table 6. Mean aboveground biomass in g/m^2 (with 1 standard error) among mulch treatments on the Crested Wheatgrass Replacement Study in 1995, 1996, 1997 and 1999.

	Mulch Treatment			
	Cover	Mulch	No Mulch	1-SE
1995				
Annual Forb		189	145	12
Perennial Forb		1	1	0.45
Annual Grass		37	76	6
Perennial Grass		13	20	2
Total		240	242	12
1996				
Annual Forb	1356	1010	728	104
Perennial Forb	31	72	69	11
Annual Grass	21	51	116	19
Perennial Grass	29	200	257	41
Total	1,437	1,333	1,170	118
1997				
Annual Forb	735	452	426	42
Perennial Forb	44	84	56	20
Annual Grass	4	2	1	2
Perennial Grass	22	211	216	29
Total	805	749	699	35
1999				
Annual Forb	293	107	87	27
Perennial Forb	173	213	107	39
Annual Grass	45	7	16	9
Perennial Grass	197	539	564	65
Total	707	865	774	40

Table 7. Mean aboveground biomass in g/m^2 (with 1 standard error) between sucrose treatments on the Crested Wheatgrass Replacement Study in 1995, 1996,1997and 1999.

	Sucrose Treatment		
	Sucrose	No Sucrose	1-SE
1995			
Annual Forb	166	167	12
Perennial Forb	0	1	0.32
Annual Grass	49	64	8
Perennial Grass	15	18	2
Total	231	250	12
1996			
Annual Forb		1037	102
Perennial Forb	91	63	11
Annual Grass	61	64	18
Perennial Grass	143	181	40
Total	294	1346	115
1997			
Annual Forb	535	540	39
Perennial Forb	73	50	20
Annual Grass	3	3	1
Perennial Grass	146	154	29
Total	757	746	38
1999			
Annual Forb	155	169	28
Perennial Forb	168	161	38
Annual Grass	16	28	8
Perennial Grass	419	447	68
Total	758	806	42

Table 8. Mean aboveground biomass in g/m^2 (with 1 standard error) among irrigation treatments on the Nitrogen Sucrose Study in 1995, 1996, 1997 and 1999. Control=Control M=May Irrigation, MJ=May+June Irrigation, MJJ=May+June+July Irrigation, MJJA=May+ June+July+August Irrigation.

	Control	May	MJ	MJJ	MJJA	1-SE
1995						
Annual Forb	2	1	2	3	7	3
Perennial Forb	6	14	13	8	15	7
Annual Grass	112	107	121	101	104	14
Perennial Grass	34	29	32	51	91	17
Total	153	151	168	162	217	15
1996						
Annual Forb	21	99	247	88	185	69
Perennial Forb	63	52	41	83	63	34
Annual Grass	15	12	42	122	25	20
Perennial Grass	250	250	194	452	549	122
Total	349	413	524	745	822	144
1997						
Annual Forb	183	219	160	261	464	68
Perennial Forb	19	47	25	14	47	19
Annual Grass	82	92	92	81	16	20
Perennial Grass	182	155	197	247	312	70
Total	466	513	474	603	839	118
1997						
Annual Forb	70	141	231	231	63	91
Perennial Forb	107	149	188	146	68	69
Annual Grass	119	104	67	88	51	28
Perennial Grass	302	287	269	306	423	88
Total	598	682	756	770	606	96

Table 9. Mean aboveground biomass in g/m^2 (with 1 standard error) between Native and Introduced species production among treatments on the Nitrogen Sucrose Study in 1999. Control=no irrigation, M=may irrigation, MJ=May+June irrigation, MJJ=May+June+July irrigation, MJJA=May +June +July+August irrigation, Sucrose=sucrose amendment, Nitrogen=Nitrogen amendment.

	Native	1-SE	Introduced	1-SE
Irrigation				
C	90.7	81	211	84
M	477	81	205	84
MJ	401	81	355	84
MJJ	487	81	283	84
MJJA	473	81	133	84
Amendments				
Sucrose	445	36	237	38
Nitrogen	169	42	561	73

Table 10. Mean aboveground biomass in g/m^2 (with 1 standard error) between nitrogen/sucrose treatments on the Nitrogen Sucrose Study in 1995, 1996, 1997, and 1999.

	Nitrogen	Sucrose	1-SE
1995			
Annual Forb	2	3	3
Perennial Forb	9	13	7
Annual Grass	115	103	11
Perennial Grass	56	39	18
Total	182	158	15
1996			
Annual Forb	234	43	69
Perennial Forb	77	54	34
Annual Grass	76	20	23
Perennial Grass	472	409	122
Total	859	526	114
1997			
Annual Forb	394	121	53
Perennial Forb	12	49	12
Annual Grass	40	105	16
Perennial Grass	141	297	60
Total	587	571	89
1999			
Annual Forb	349	147	41
Perennial Forb	36	132	31
Annual Grass	160	86	13
Perennial Grass	184	318	39
Total	729	682	43

Table11. Mean aboveground biomass in g/m^2 among sucrose treatments on the heavy cheatgrass site in the Sucrose Only Study in 1995, 1996, 1997 and 1999. Control = no sucrose, 880 = 880 lbs/acre sucrose, 1320 = 1320 lbs/acre sucrose, 1760 = 1760 lbs/acre sucrose.

	Control	880	1320	1760
1995				
Annual Forb	15	17	11	7
Perennial Forb	19	12	21	12
Annual Grass	118	130	104	92
Perennial Grass	15	27	11	20
Total	166	186	148	131
1996				
Annual Forb	91	81	114	125
Perennial Forb	159	95	133	69
Annual Grass	16	17	25	30
Perennial Grass	144	186	186	96
Total	410	379	457	319
1997				
Annual Forb	119	34	422	57
Perennial Forb	137	203	195	161
Annual Grass	122	133	138	109
Perennial Grass	152	224	140	220
Total	530	593	895	547
1999				
Annual Forb	14	6	22	3
Perennial Forb	69	162	125	162
Annual Grass	250	200	183	135
Perennial Grass	155	135	107	113
Total	488	503	437	413

Table 12. Mean aboveground biomass in g/m^2 between Native and Introduced species production among treatments on the Sucose Only Study, heavy cheatgrass and light/moderate cheaatgrass sites in 1999. Control = no sucrose, 880 = 880 lbs/acre sucrose, 1320 = 1320 lbs/acre sucrose, 1760 = 1760 lbs/acre sucrose.

	Native	Introduced
Heavy Cheatgrass		
Treatment		
Control	226	262
880	313	190
1320		203
1760	90.7	134
Light/Moderate Cheatgrass		
Treatment		
Control	710	54
880	572	25
1320	538	63
1760	508	48

Table 13. Mean aboveground biomass in g/m^2 among sucrose treatments on the light to moderate cheatgrass site in the Sucrose Only Study in 1995, 1996, 1997 and 1999. Control = no sucrose, 880 = 880 lbs/acre sucrose, 1320 = 1320 lbs/acre sucrose, 1760 = 1760 lbs/acre sucrose.

	Control	880	1320	1760
1995				
Annual Forb	8	12	17	11
Perennial Forb	7	11	7	16
Annual Grass	41	47	61	44
Perennial Grass	106	101	83	116
Total	162	171	168	187
1996				
Annual Forb	91	1	1	14
Perennial Forb	29	47	20	18
Annual Grass	9	8	15	7
Perennial Grass	399	326	351	301
Total	526	382	387	339
1997				
Annual Forb	0	2	15	2
Perennial Forb	40	9	31	40
Annual Grass	60	27	44	28
Perennial Grass	482	444	409	366
Total	582	483	499	436
1999				
Annual Forb	1	5	5	20
Perennial Forb	36	34	47	77
Annual Grass	54	24	60	47
Perennial Grass	673	534	490	424
Total	764	597	602	568