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SPECIAL INSTRUCTION SHEET

1. QA: N/A
Page: 1 of: 1

Complete Only Applicable Items

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2. Record Date 02/23/2001	3. Accession Number MOL.20010227.0039
4. Author Name(s) JAY P. ANGERER	5. Author Organization N/A

6. Title
USE OF IRRIGATION TO EXTEND THE SEEDING WINDOW FOR FINAL RECLAMATION AT YUCCA MOUNTAIN, NEVADA

7. Document Number(s) TDR-MGR-EV-000007	8. Version REV 00
9. Document Type REPORT	10. Medium OPTIC/PAPER

11. Access Control Code
PUB

12. Traceability Designator
DC # 23954

13. Comments
THIS IS A ONE-OF-A-KIND DOCUMENT DUE TO THE COLORED GRAPHS ENCLOSED AND CAN BE LOCATED THROUGH THE RPC

QA: N/A

Civilian Radioactive Waste Management System
Management and Operating Contractor

Use of Irrigation to Extend the Seeding Window for Final Reclamation at Yucca Mountain, Nevada

TDR-MGR-EV-000007 REV 00

August 2000

Prepared for:

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Under Contract Number
DE-AC08-91RW00134

TRW Environmental
Safety Systems Inc.

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ACKNOWLEDGMENTS

Many employees of the M&O Environmental Sciences Department contributed to this report. The names of these people are too many to mention individually; however, we thank every person who endured long hours and monotonous tasks during the implementation of these studies and the collection of data. Without their individual efforts, this report would not have been possible.

Disclaimer

Civilian Radioactive Waste Management System
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Use of Irrigation to Extend the Seeding Window for Final Reclamation at Yucca Mountain, Nevada

TDR-MGR-EV-000007 Rev 00

August 2000

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EXECUTIVE SUMMARY

The U.S. Department of Energy has implemented a program to investigate the feasibility of various techniques for reclaiming lands disturbed during site characterization at Yucca Mountain. As part of this program, two studies were conducted in 1997 to assess the effects of combinations of seeding date (date that seeds are planted) and supplemental irrigation on densities of native plant species at Yucca Mountain. Study objectives were to 1) determine whether the traditional seeding window (October-December) could be extended through combinations of seeding date and irrigation date, 2) determine which combination of seeding date and irrigation was most successful, and 3) assess the effects of irrigation versus natural precipitation on seedling establishment. In the first study, a multi-species seed mix of 16 native species was sown into plots on four dates (12/96, 2/97, 3/97, and 4/97). Irrigation treatments were control (no irrigation) or addition of 80 mm of supplemental water applied over a one month period. Plant densities were sampled in August and again in October, 1997. In the second study, *Larrea tridentata* and *Lycium andersonii*, two species that are common at Yucca Mountain, but difficult to establish from seed, were sown together into plots in January and August, 1997. Half the plots were irrigated with approximately 250 mm of water between August 18 and September 11, while the remaining plots received no irrigation (control). Plant densities were sampled in October, 1997.

The August census for the multi-species mix study showed irrigated plots that were sown in February, March and April had higher plant densities and more species than plots that were not irrigated. Irrigation had no effect on plant densities on plots that were seeded in December.

Plots were censused again in October following 18 mm of precipitation in September. Densities of three species, *Ambrosia dumosa*, *Hymenoclea salsola*, and *L. tridentata*, (warm-season species) were lower on irrigated plots sown in December, February, and March, and showed no response to irrigation on plots sown in April. Therefore, early spring irrigation did not facilitate establishment of warm-season species. These results suggest that these species are dependent upon precipitation while temperatures are warm in late summer or fall. However, control plots that were seeded in December had acceptable densities of these species. A more practical approach might be to avoid irrigation costs by seeding in December and waiting for fall precipitation.

The remaining species (cool-season species) showed an opposite response to supplemental water with greater densities on irrigated plots sown in February, March, and April, and no response to irrigation on plots sown in December. While these results show that irrigation can extend the seeding window for cool-season species should it be necessary, it was also apparent that if seeds are sown by late December, irrigation is not necessary to achieve acceptable plant densities.

In the two-species mix study, *L. tridentata* densities were highest on plots that were seeded and irrigated in August. Lower densities on irrigated plots sown in January could be due to mortality following early emergence triggered by precipitation, competition from weedy annuals, or reduced seed viability caused by high soil temperatures. There was no difference in *L. tridentata* densities between irrigated and control plots that were seeded in January, indicating that irrigation will not improve establishment of *L. tridentata* when it is seeded within the traditional seeding window. August seeding combined with irrigation could be used to remediate sites on

which *L. tridentata* has not previously established; however, adequate densities are achieved if seeded earlier and allowed sit in the seedbank until proper conditions for germination occur.

Lycium andersonii also had higher densities on plots that were irrigated and seeded in August. Lower densities on irrigated plots sown in January could be due to the same reasons mentioned above for *L. tridentata*. Irrigated plots sown in January had greater densities of *L. andersonii* than control plots sown in January, indicating that late summer irrigation could enhance establishment for seeds sown within the traditional seeding window.

Both *L. tridentata* and *L. andersonii* emerged at higher densities in the two-species mix than have been observed in other Yucca Mountain studies or final reclamation efforts. This could be due to several factors including 1) competition by cool-season species that establish earlier in the season and use resources before *L. tridentata* and *L. andersonii* germinate, 2) allelopathy, or 3) other interspecific interactions that affect the soil environment making it unsuitable for establishment of these two species.

Results of these two studies suggest improved planting techniques to enhance reclamation success in the future. First, it is always better to plant within the seeding window because higher plant density and diversity (success) is achieved without the additional cost of irrigation. Second, irrigation can be used to extend the seeding window if required. Without irrigation, seeding outside of the seeding window is dependent upon precipitation when it is least likely. Irrigation improves plant density, species richness, and diversity. Third, results from the multi-species mix study showed that timing of irrigation is more important than timing of planting for emergence of a group of species. Fourth, the two groups of species, warm-season and cool-season, may interfere with the other's establishment. This is demonstrated by the poor performance of warm-season species in the multi-species mix study, while at least one warm-season species (*L. tridentata*) did better when planted with only one other species. Using a seedmix that minimizes competition between these two groups of species may enhance density and diversity.

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1.0 INTRODUCTION

1.1 Applicability of the QA program

This report has been determined to be non-Quality Affecting in accordance with QAP-2-0, *Conduct of Activities*. This report is covered by the Activity Evaluation for Terrestrial Ecosystem Monitoring (CRWMS M&O 1997). The information will not be used to support any quality affecting activities. Therefore, this report is not subject to the requirements of the *Quality Assurance Requirements and Description* (QARD) document (DOE 2000). The development plan identified that the development of this report is exempt from any special requirements for the control of the electronic management of data.

1.2 Project Overview

As required by the Nuclear Waste Policy Act (NWPA) of 1982 and the Nuclear Waste Policy Amendments Act of 1987, the U.S. Department of Energy (DOE) is characterizing Yucca Mountain in Nye County, Nevada for the potential development of a monitored geologic repository for spent nuclear fuel and high-level radioactive waste. In keeping with requirements in the NWPA to conduct these investigations in an environmentally sound manner, DOE developed an Environmental Management Plan for the Yucca Mountain Site Characterization Project (YMP 1998). DOE implemented a habitat reclamation program to help speed the recovery of lands disturbed by site characterization activities (DOE 1989). Because of the difficulties associated with establishing vegetation in arid environments (i.e., high temperatures, limited moisture availability, low soil fertility) like Yucca Mountain, one of the components of the reclamation program included a series of studies to investigate the feasibility of various reclamation techniques. These studies were focused on identifying methods and improving the effectiveness of site preparation, revegetation, soil stabilization, and topsoil stockpiling techniques (CRWMS M&O 1998a, 1999a, and 1999b). One suite of studies investigated effects of various supplemental water treatments and planting date on seedling emergence and establishment in order to increase the success of revegetation efforts. This document reports the results of the last of these studies which were completed in 1997.

1.3 Previous Research

Soil moisture availability is one of the primary limiting factors for plant growth in arid environments. Perennial plant establishment under natural conditions in the Mojave Desert usually occurs only during favorable rainfall years (Wallace and Romney 1972, Beatley 1975). The difficulties with establishing plants during drought years in the Mojave Desert has led to the use of supplemental irrigation in several revegetation studies and implementation projects. These efforts have produced mixed results. For example, the use of irrigation during aqueduct and roadside revegetation in California did not improve seedling establishment (Graves et al. 1978, Kay 1979, Clary 1983). Similarly, in a study on the Nevada Test Site (Winkel et al. 1995), irrigation generally did not increase densities of seeded species; however, this result may have been due to above-average precipitation during the study that reduced the need and effectiveness of irrigation. In contrast with these studies, irrigation applied during summer months at Yucca Mountain increased plant survival and led to additional emergence of seeded species (CRWMS

M&O 1999a). Results of another study at Yucca Mountain showed that supplemental water added to recharge soil moisture in early February prior to seedling germination generally resulted in lower densities of seeded perennial species and higher densities of non-seeded annuals than on plots that received no water (CRWMS M&O 1999b). However, plots that received supplemental water later in the season (March 4 - 28) had higher perennial plant densities and higher species diversity than those that were not irrigated. The lower perennial densities observed on plots that received the February irrigation may have been due to early germination followed by frost kill, competition with annual weedy species, or a combination of both. However, these hypotheses were not explicitly tested.

The Yucca Mountain area receives an average of 128 mm of annual precipitation. The amount of annual precipitation at Yucca Mountain is, in general, related to El Niño events (Piechota and Dracup, 1996), but precipitation amounts generally are unpredictable. Therefore, planning to revegetate only during wet years would be impractical. Results of reclamation feasibility studies at Yucca Mountain indicated that direct seeding of native plant species could be successful if seeding was completed between October and the end of December, especially during years with above-average precipitation (CRWMS M&O 1999a). The combination of environmental conditions (soil moisture and temperature, day length, etc.) during this time period provide dormancy breaking and/or germination conditions required for seedling emergence for many of the native species that are seeded at Yucca Mountain. If seeding occurs later (i.e., January - April) there is a greater risk that germination and/or dormancy breaking conditions will not be met. Also, growing conditions following seedling emergence are critical to successful establishment. Seedlings that emerge later in the spring or summer are more likely to desiccate due to lack of soil moisture in the upper soil surface. For many species, early emergence allows seedlings to grow roots to deeper soil zones where moisture is available for longer periods into the summer.

Each species has slightly different requirements for breaking dormancy, germinating and establishing, and the presence of multiple species in a seed mix may affect these characteristics for each individual species in the mix. Generally, seed is sown early (October - December), heavily (up to 40 kg of pure live seed ha^{-1}), and with 13 - 16 species in the mix.

At Yucca Mountain, situations may exist where reclamation of all sites scheduled for reclamation cannot be completed during the recommended seeding window (October to December). Therefore, it may be necessary to conduct final reclamation after this period. Because of the risks involved (i.e. loss of applied materials and labor), it was important to determine whether the risk could be reduced by extending the seeding period through the use of irrigation. In 1997, two field studies were implemented to assess establishment of seedlings that were sown after the recommended seeding window and irrigated.

1.4 Objectives

Study objectives were to 1) determine whether the traditional seeding window (October-December) could be extended through combinations of seeding date and irrigation date 2) determine which combination of seeding date and irrigation was most successful, and 3) assess the effects of irrigation versus natural precipitation on seedling establishment. Two studies were implemented to meet these objectives. The first examined responses of a typical suite of species that would be sown on a disturbed site at Yucca Mountain (multi-species mix), the second examined responses of just two species, *Larrea tridentata* and *Lycium andersonii* (two-species mix). Soil temperature and moisture were monitored in both studies to help assess soil conditions that could affect germination and establishment. The information from these two studies will be used in land management decisions regarding revegetation efforts in drought years, and in years when seeding must occur later than December.

This report is organized into a General Methods section and two additional sections, one for each study. The study site, irrigation system, meteorological measurements, and vegetation sampling methods were the same for both studies and are presented in Section 2.0. Results, and discussion for the multi-species and two-species mix studies are presented in Sections 3.0 and 4.0, respectively. Section 4.0 also contains a discussion regarding some important differences in responses for *L. tridentata* and *L. andersonii* between the two studies. Section 5.0 presents conclusions regarding both studies.

2.0 GENERAL METHODS

2.1 Study Site

Yucca Mountain is located in southwestern Nevada, approximately 150 km northwest of Las Vegas, Nevada, and 26 km north of Amargosa Valley (formerly Lathrop Wells). A portion of the Exploratory Studies Facility (ESF) topsoil stockpile was selected for the study area. This area is approximately 0.4 ha with dimensions of 40x100-m. The depth of the stockpile ranged from 0.5-1.0 m. The stockpile is located in the southern part of Midway Valley approximately 800 m south of the southern tip of Exile Hill (Nevada grid coordinates N 758,830; E 567,720). The stockpile is constructed from topsoil salvaged from the muckpile storage area in Midway Valley and the South Portal road and pad area east of Boundary Ridge. The soils of the stockpile are predominantly sandy loams. The elevation of the site is 1,158 m (3,800 ft), the slope of the stockpile surface was 2-4% with a southeast aspect. The stockpile is situated in the *Larrea-Ephedra* vegetation association. Major plant species are *Ephedra nevadensis* (Nevada ephedra), *L. tridentata* (creosotebush), *L. andersonii* (Anderson desert thorn), *Hymenoclea salsola* (white burrobrush), and *Ericameria cooperi* (Cooper goldenbush). The climate is characterized by hot summers and cool winters. Average annual precipitation is approximately 128 mm and falls primarily as rain during the winter and early spring.

2.2 Irrigation System

The irrigation system for both studies was a solid-state system with a single, wobbler-head sprinkler placed on each plot. Each sprinkler produced a 360-degree-diameter distribution pattern that reached 12 m, thus ensuring that the entire seeded area was covered by the irrigation. The system was designed to ensure that each sprinkler applied equal amounts of water at equal pressure. Application amounts were monitored by metering out the same amount of water on each plot.

2.3 Air Temperature and Precipitation

A datalogger system (Campbell CR10) was used to collect continuous meteorological data at the site. Precipitation was measured with a tipping-bucket rain gauge (model TE525, Campbell Scientific, Inc.), and each 0.01 inches of precipitation was recorded by the datalogger system. Air temperature was measured every 60 seconds with a thermocouple thermometer (model 107, Campbell Scientific, Inc.) housed in a radiation shield. Daily maximum and minimum air temperatures were recorded by the datalogger system, and then the 60 second data were deleted to conserve storage space.

2.4 Soil Temperature and Moisture

Soil temperature data were collected at a depth of 2 cm using soil temperature cells constructed from corrosion-resistant stainless steel plates separated by a fiberglass binding with a small thermistor (model MC-310A, ELE International, Lake Bluff, Illinois, USA). Measurement protocol for soil temperature was the same as described above for air temperature with daily maximum and minimum temperatures recorded by the datalogger system. For the multi-species mix, 2 soil temperature cells were placed in one irrigated plot. For the two-species mix, 2 cells were placed in one irrigated plot and two cells were placed in a control plot. The control plot was about 200 m from the multi-species mix study plots and was used for both studies. All soil temperature cells were installed in January, 1997.

Soil moisture cells that measure resistance (Kohms) were buried at depths of 2 cm and 15 cm. These cells were constructed from corrosion-resistant stainless steel plates separated by a fiberglass binding that provided a coupling that varied with soil moisture content (model MC-314, ELE International, Lake Bluff, Illinois, USA). Resistance (Kohms) was measured every 60 seconds. Daily averages were calculated from the resistance data and stored on the datalogger system. The 60 second data were then deleted from the system. For the multi-species mix, three soil moisture cells were placed at 2 cm, and three at 15 cm in one control and one irrigated plot for each seeding date. For the two-species mix, two soil moisture cells were placed at depths of 15 cm and 2 cm in one irrigated and one control plot. Soil moisture cells were installed directly after completion of seeding and mulching for each date.

A laboratory calibration was used to determine the relationship between soil moisture content and soil cell resistance. Intact soil cores were collected from the study sites, and a saturation and progressive drying procedure was used during which soil weight and resistance measurements were made. Soil weights were converted to soil water volume, and a second order polynomial equation was fitted to the resistance and volume data and used to calculate soil moisture.

2.5 Vegetation Sampling

For the multi-species mix, seedling density was measured on August 25-26, 1997 and on October 21-23, 1997 (Table 1). Two 1x8-m belt transects were located in each replicate plot. Eight 1 m^2 quadrats were located within each belt transect (a total of 16 m^2 quadrats). Plant density was determined by counting the number of live seeded species, annual grasses, and annual forbs that were rooted within each 1 m^2 quadrat.

For the two-species mix, seedling density was measured on October 20, and 21, 1997. Plant density was measured as described for the multi-species mix study. Seedlings of *L. tridentata, L. andersonii*, annual grasses, and annual forbs that were rooted in the quadrats were counted.

Table 1. Design of multi-species and two-species experiments and when pertinent treatments were applied for each experiment.

	MULTI-SPECIES				TWO-SPECIES	
DESIGN						
Irrigation	Control	Irrigated			Control	Irrigated
Seeding Date	12/04/96	2/3/97	3/19/97	4/29/97	1/97	8/97
Replication	4				4	
Data Collection	8/25-26/97 and 10/21-23/97				10/20-21/97	
TREATMENTS						
Plot Size	10 x 10-m (10-m buffer)				5 x 10-m (10-m buffer)	
Ripping Date	immediately prior to seeding				immediately prior to seeding	
Mulching Date	immediately following seeding				immediately following seeding	
Mulch Amount	3500 Kg/ha				3500 Kg/ha	
Seeding Rate	25 PLS/m^2/species (400 PLS/m^2 total)				200 PLS/m^2/species (400 PLS/m^2 total)	
Date of Irrigation (total days)	2/25-3/18 (21)	2/25-3/18 (21)	3/26-4/14 (19)	5/5-5/29 (24)	8/18-9/11 (24)	8/18-9/11 (24)
Amount per irrigation	-	-	-	-	32 mm once / 3-5 days	32 mm once / 3-5 days
Total amount of water applied	78 mm	78 mm	95 mm	160 mm	250 mm	250 mm

3.0 MULTI-SPECIES MIX STUDY

In most revegetation efforts at Yucca Mountain, seeds of several species are mixed and sown together into prepared sites in an effort to revegetate the site with a diversity of species similar to that in adjacent areas. In this study, a typical multi-species seed mix (see Appendix A, Table A-1 for species list) was planted into prepared plots at the study site on four dates (December 4, 1996, February 3, 1997, March 19, 1997 and April 29, 1997) and water was added to half the plots.

3.1 Methods

3.1.1 Site Preparation

In the fall of 1996, 32 10x10-m study plots were identified within the study area. A 10-meter buffer zone was established around each plot to avoid contamination of control plots with water from irrigated plots. Treatment combinations were assigned randomly to each plot.

On each seeding date, the appropriate plots were ripped to relieve compaction and prepare a seedbed. Following ripping, a mixture of native seed was broadcast over the plot with a drill seeder with its disk openers raised above the soil. Plots were seeded with 25 PLS/m^2 of each of 16 native perennial species (Appendix A, Table A-1). One species, *Lycium andersonii,* did not establish and was removed from the analysis. After seeding, wheat straw mulch was applied at a rate of 3500 kg/ha and then anchored to the soil with a mixture of organic tackifier and wood fiber.

3.1.2 Irrigation

Approximately 78 mm of water was applied to half the plots. Amounts of water were adjusted to compensate for greater evapotranspiration as air temperatures increased at later seeding dates, resulting in roughly equal amounts of effective irrigation at each date (Table 1). With the exception of plots that were seeded in December, water was applied shortly after seeds were sown (Table 1).

3.1.3 Statistics

A two-way analysis of variance (ANOVA) was used to examine the effects of seeding date and irrigation on seedling density for the August and October census periods. Data sets were examined for homogeneity of variance and normality prior to analysis. Density data were transformed [(log (y + 1.0)] to meet the assumptions of ANOVA for the October census data and 1/(Y+1) transformed for the August census data. Main effects and interactions were computed with the ANOVA procedure in SYSTAT (SPSS, Inc. 1997). Effects were considered significant if $P < 0.050$. Post-hoc tests were performed using Fisher's least significant difference (LSD) mean separation procedure (Steel and Torrie 1980).

Upon examination of the data it became apparent that *A. dumosa*, *H. salsola*, and *L. tridentata* responded differently from the remaining species to seeding date and irrigation, indicating differential germination requirements. Plots of density means of individual species showed that *A. dumosa*, *H. salsola*, and *L. tridentata* tended to increase as seeding date progressed while the remaining 12 species showed the opposite response (see Tables A-1 through A-5 for species means). Additionally, these three species tended to have lower densities on irrigated plots, while the remaining species had higher densities on irrigated plots. Because of this pattern, these three species were analyzed separately from the remaining species. The former group was designated as warm-season and the remaining species as cool-season based on apparent differences in germination/emergence requirements. This designation does not reflect differences in photosynthetic metabolism (i.e., C_3, C_4, or CAM). The combined densities from each replicate of warm-season, cool-season, annual forbs, and annual grasses were used as dependent variables in the ANOVAs. For the August census period, densities of annual forbs and grasses were extremely low (means across treatments were 0.46 and 0, respectively) and no statistical analysis was performed.

In addition to ANOVAs, the Shannon-Wiener diversity index was calculated for each census date and treatment, and the total number of species present was determined for each treatment combination to examine the effect of irrigation and seeding date on species diversity and richness.

3.2 Results

3.2.1 Air Temperature and Precipitation

Maximum and minimum air temperatures fluctuated daily and cycled with seasonal patterns. Maximum temperatures were generally above 30° C from May through mid-September with few exceptions. Maximum air temperatures ranged from 35° to 40° C in July and August. Minimum air temperatures were as low as 5° C in January but were generally above 15° C from May through mid-September. Minimum air temperatures ranged from 16° to 25° C in July and August.

A total of about 10 mm of precipitation was recorded in mid-January (Figure 1). This was followed by an extremely dry period of over four months during which only trace amounts of precipitation were recorded. Over 21 mm fell over a two day period in June, followed by another dry spell of about three months. Throughout the month of September, 18.8 mm of precipitation was recorded.

3.2.2 Soil Moisture and Temperature

During the study, there were several natural precipitation events that affected soil moisture. These occurred on January 12 through 15, June 12 and 13, and September 2 and 25 (Figure 1). During precipitation events there was generally a decrease in maximum and minimum soil temperatures (Figures 1 and 2). These events increased soil moisture at a depth of 2 cm in all plots to approximately 17% (Figure 3).

Soil at a depth of 2 cm dried out quickly following irrigation and precipitation events (Figure 3). The permanent wilting point for crop species (-1.5 Mpa) was used as an indicator for periods when the upper 2 cm was likely too dry for germination to occur. For control plots, soil moisture at 2 cm was at or above the permanent wilting point for three intervals on average of 4.75, 4.5, and 7.5 days from June to October, while irrigated plots were above -1.5 Mpa for an average of 5.75, 4.75, and 6.25 days during the same period. Irrigation increased the number of days of favorable soil moisture at 2 cm by 42, 17, 37, and 22 days at the 12/4/96, 2/3/97, 3/19/97, and 4/29/97 seeding dates, respectively (Figure 3). Prolonged soil moisture above the wilting point following natural precipitation in the control plots seems to be responsible for the small difference between the 2/3/97 irrigated and control plots.

Soil moisture at 15 cm showed a similar response pattern to precipitation and irrigation as that at 2 cm except that the dry down curve was less steep and soil moisture remained above the permanent wilting point for a longer period of time (Figures 4 and 5). Soil moisture at 15 cm was above the wilting point for an average of 48 and 117 days in the control and irrigated plots, respectively. During the hottest period (July and August), soil moisture was below the permanent wilting point for 51 and 54 days in control and irrigated plots, respectively (Figure 4).

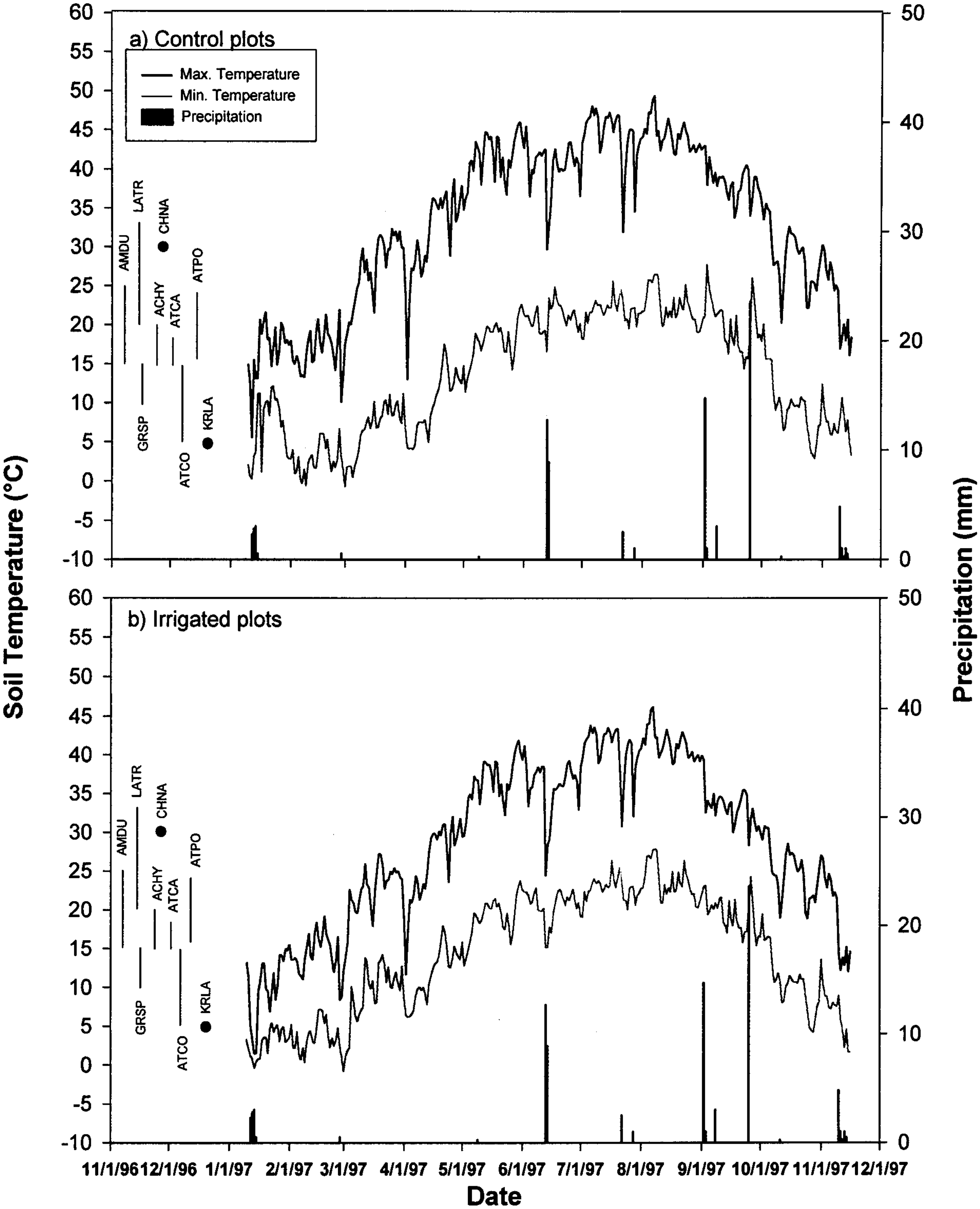

Figure 1. Maximum/minimum soil temperatures (lines) and precipitation (bars) in a) control plots, and b) irrigation plots for multi-species mix study. Note: control data was collected approximately 200 meters away from irrigated plots. Lines to the left are ranges of adequate temperatures for germination of seeded species. Species are represented by four letter codes. See Table A-1 for code description. DTN: MO0006SEPSOILT.004

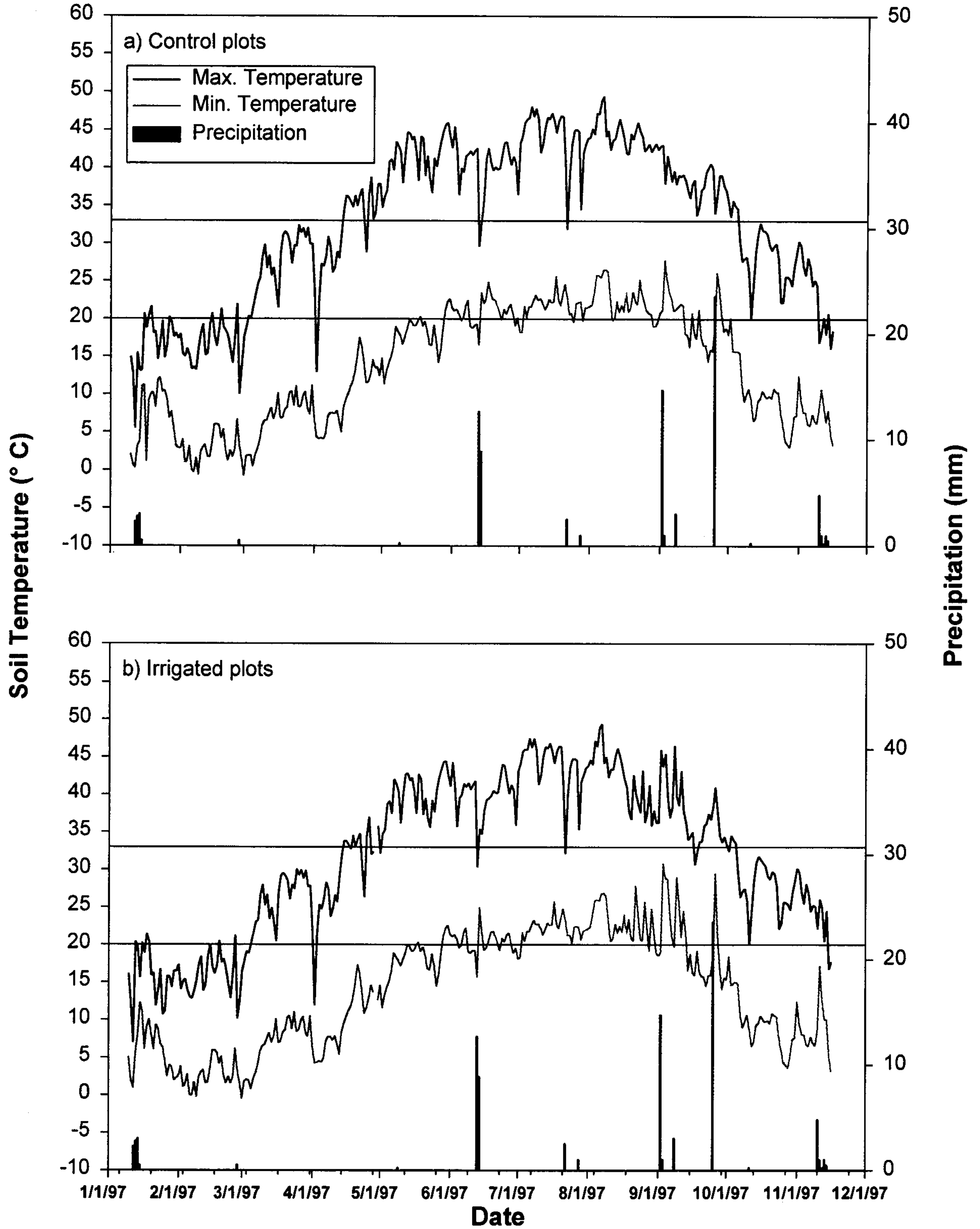

Figure 2. Maximum/minimum soil temperatures (lines) and precipitation (bars) in a) control plots, and b) irrigation plots for the two-species mix study. The lower reference line is the optimal germination temperature for *Lycium andersonii* and the lower limit for germination for *Larrea tridentata* (20° C). The upper reference line is the the maximum germination temperature for *Larrea tridentata* (33° C).
DTN: MO0005STMP1997.001

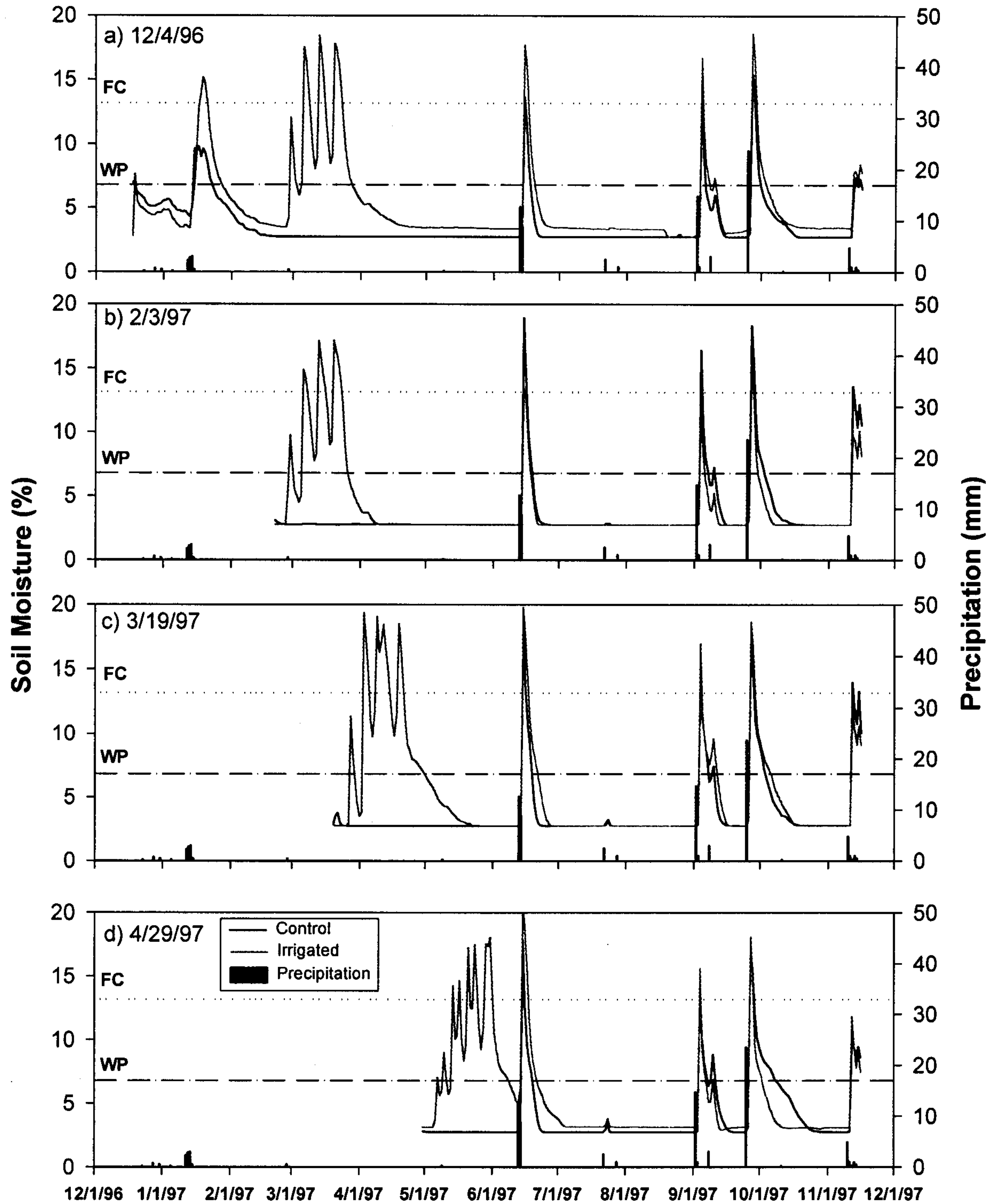

Figure 3. Soil moisture and precipitation for multi-species mix study. Lines are maximum and minimum means of three soil moisture cells buried at 2 cm (left Y axis). Bars are natural precipitation received during the study period (right Y axis). Separate graphs are for a) 12/4/96, b) 2/3/97, c) 3/19/97, and d) 4/29/97 seeding dates. FC is field capacity (-0.03 Mpa), and WP is wilting point (-1.5 Mpa). DTN (Soil Moisture): MO0006SEPRSM96.006, DTN (Precipitation): MO0006SEPPAATD.003

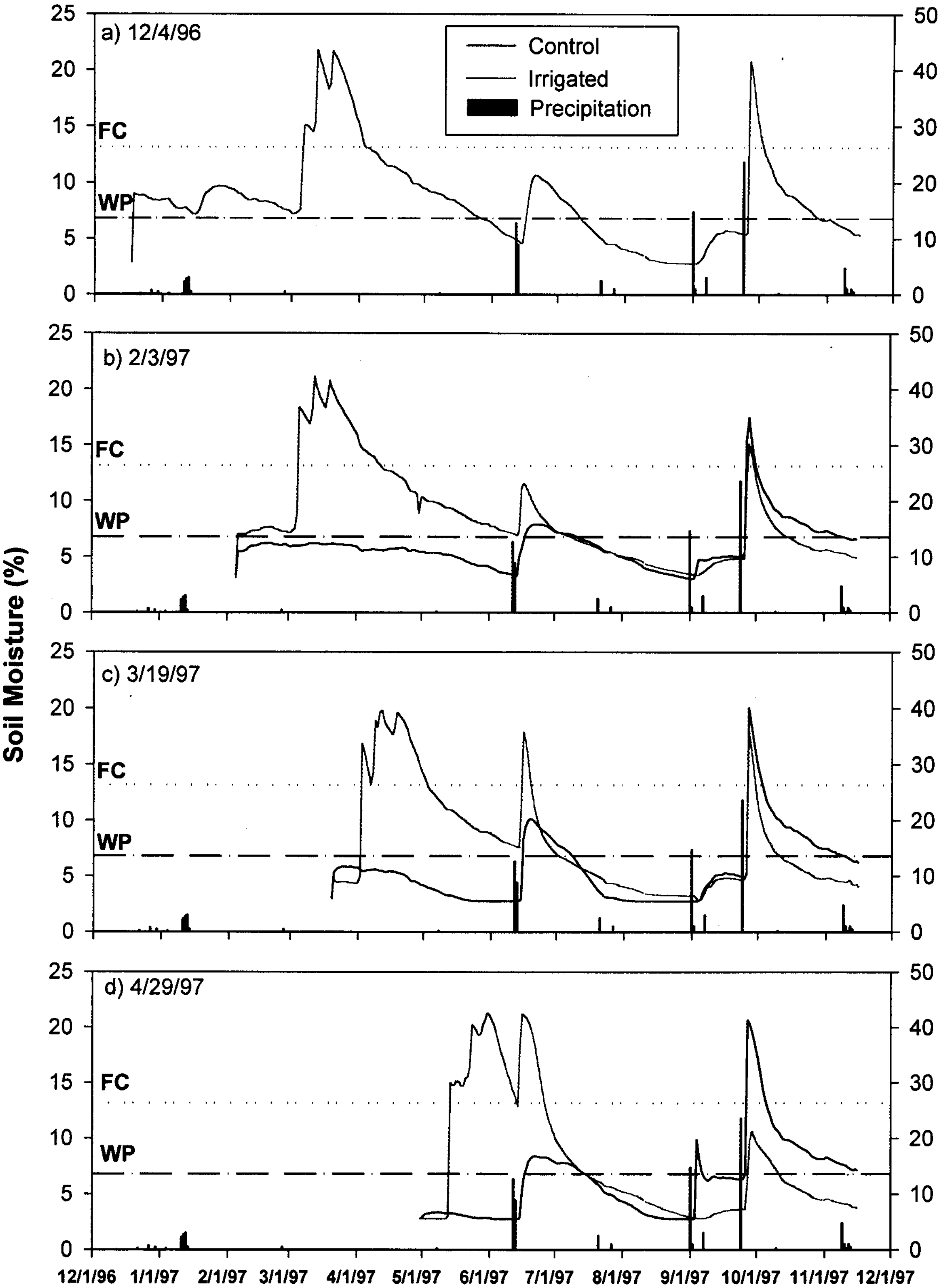

Figure 4. Soil moisture and precipitation for multi-species mix study. Lines are maximum and minimum means of three soil moisture cells buried at 15 cm (left Y axis). Bars are natural precipitation received during the study period (right Y axis). Separate graphs are for a) 12/4/96, b) 2/3/97, c) 3/19/97, and d) 4/29/97 seeding dates. FC is field capacity (-0.03 Mpa), and WP is wilting point (-1.5 Mpa). Note: Defective control soil probe in the 12/4/96 seeding date plot. DTN: MO0006SEPRSM96.006

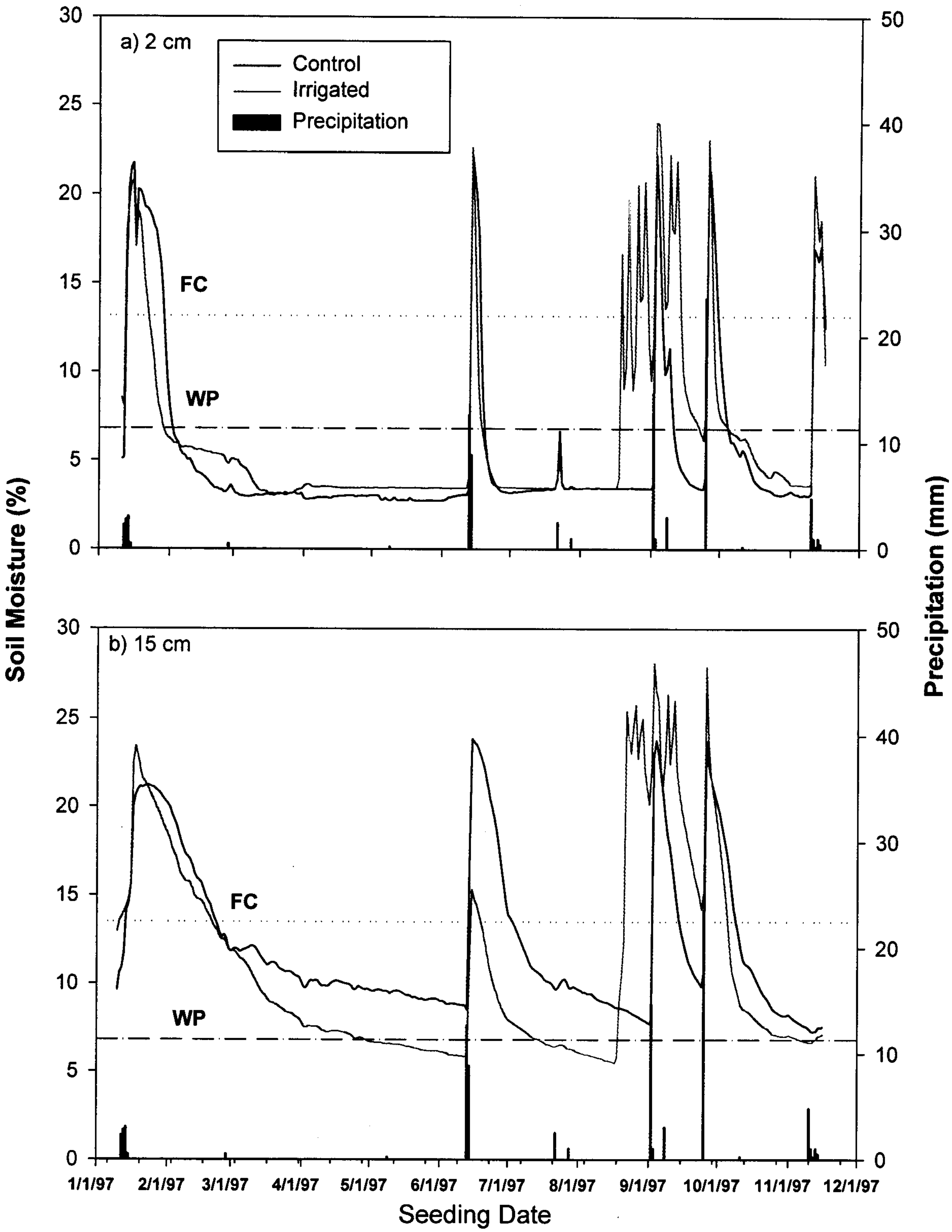

Figure 5. Gravimetric soil moisture (%) within irrigated and non-irrigated plots at a) 2 cm, and b) 15 cm depths in the two-species mix study. Lines are maximum and minimum means of two soil moisture cells buried at 15 cm (left Y axis). Bars are natural precipitation received during the study period (right Y axis). FC is field capacity (-0.03 Mpa), and WP is wilting point (-1.5 Mpa). DTN: MO0006SEPERSMD.005

Soil temperatures in irrigated plots were several degrees cooler than those in control plots (Figures 1 and 2). Mean monthly maximum soil temperatures were consistently lower in irrigated than in control plots throughout the study, even several months after irrigation was applied (Table 2).

Table 2. Mean monthly maximum soil temperatures (in ° C) at a depth of 2 cm on the multi-species mix plots. DTN: MO0006SEPSOILT.004

Month	Control	Irrigated
December (12 days)	NA*	7.8
January (21 & 31 days)	16.7	9.9
February	16.6	14.3
March	27.1	22.4
April	31.2	25.6
May	41.4	36.4
June	40.3	35.9
July	44.2	40.6
August	44.4	41.4
September	38.3	33.4
October	28.8	25.0
November (16 days)	23.1	19.3

*Soil temperature probes for the control plot were installed on January 9, 1997. Therefore, no soil temperature data were recorded for the control plot in December.

3.2.3 August Census

For the August census period, plant densities (all species combined) were greater on irrigated plots at all seeding dates except for December (Fisher's LSD test for December, P = 0.600, Table 3, interaction between seed date and irrigation). Density in the irrigated plots declined with progressively later seeding dates (Figure 6a). For control plots seeded in February, March, and April, seedling density was on average less than 0.8 plants/m^2 with no plants present on plots seeded in February (Figure 6a). On irrigated plots, relatively high plant densities (ranging from 14.5 - 28.6 plants/m^2) were observed (Figure 6a). Cool-season plant densities were higher than those of warm-season plant densities and primarily responsible for the trend observed when species were combined (Figures 6a, b and c). When observed separately, warm-season plant densities increased with later seeding dates and were higher on irrigated plots (Figure 6c).

Table 3. Results of a two-way analysis of variance examining the effects of seeding date and irrigation on density of all perennial plants for the August 1997 census date on multi-species mix study plots at Yucca Mountain. Data were 1/(Y+1) transformed for this analysis. Note: one replicate for both the irrigated and control treatments for the 4/29/97 seeding date were removed from this analysis. DTN: MO0006SEPPLDEN.002

Source	Sum of Squares	df	Mean Square	F-ratio	P
Seed date	1.242	3	0.414	394.2	< 0.001
Irrigation	3.367	1	3.367	3206.2	< 0.001
Seed date x Irrigation	1.130	3	0.377	358.7	< 0.001
error	0.023	22	0.001		

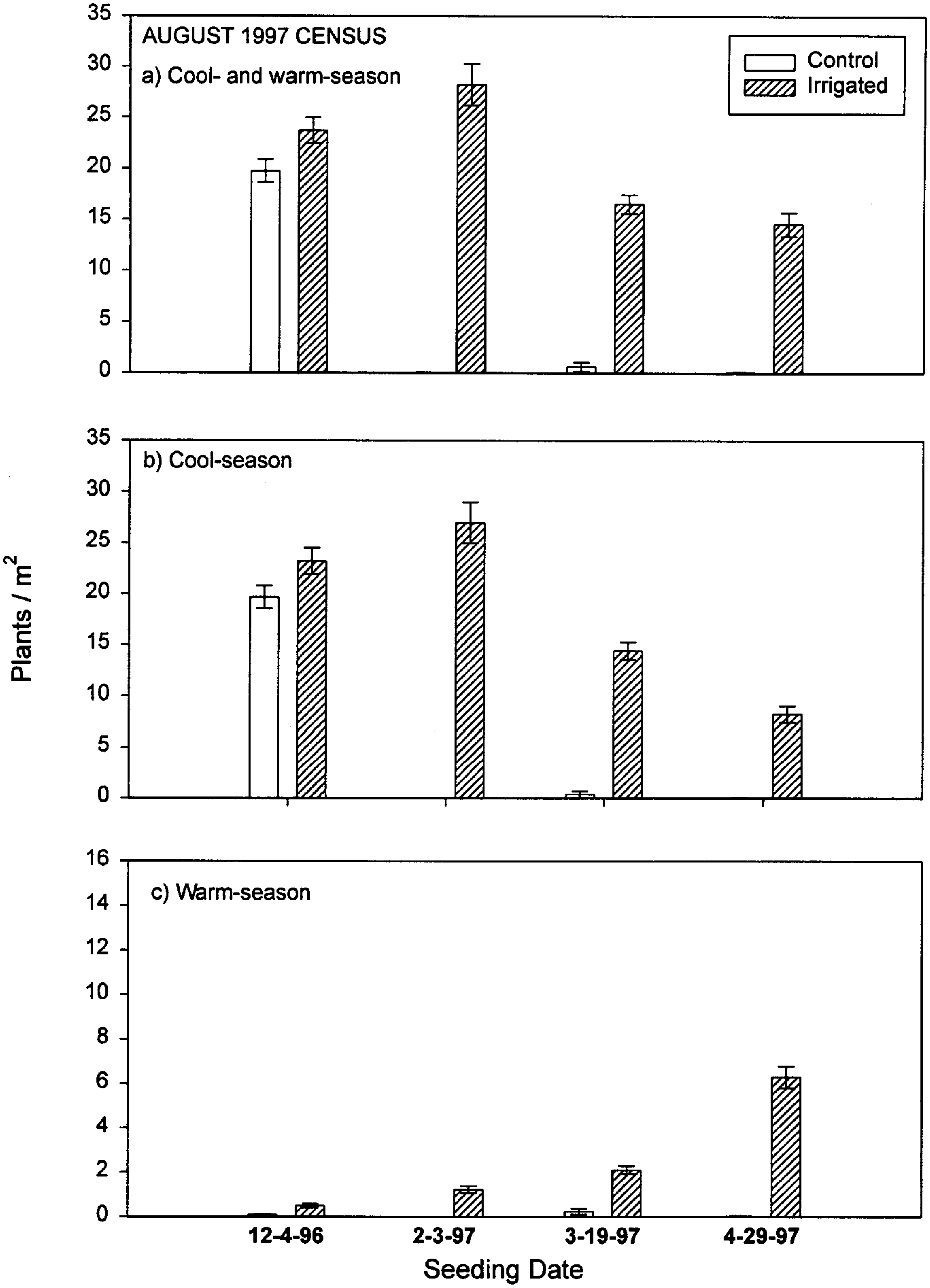

Figure 6. Means (±SE) for seedling densities of a) cool-season and warm-season, b) cool-season only, and c) warm-season only perennials in response to seeding date and irrigation at the August 1997 census date. Means are combined densities of plants in each treatment combination (n=4) for the August 1997 Census date. Note: different scale used in c). DTN: MO0006SEPPLDEN.002

3.2.4 October Census

For cool-season species at the October census, irrigated plots had significantly higher plant densities than control plots with the exception of those seeded in December (Table 4a, interaction between seeding date and irrigation, Figure 7a). Irrigated and control plots that were seeded in December had similar plant densities (Figure 7a). Densities decreased on irrigated plots that were seeded in March and April compared to those seeded earlier (Table 4a, Figure 7a). Plant density was about 3 plants/m^2 on control plots that were seeded in February, March and April. Without irrigation, cool-season species achieved a high density only when planted in December. These results are similar to those observed at the August census for cool-season species (Figure 6a and b).

Table 4. Results of a two-way analysis of variance examining the effects of seeding date and irrigation on plant density of a) cool-season species, b) warm-season, c) annual forbs, and d) annual grasses on multi-species mix study plots for the October 1997 census date at Yucca Mountain. Data were log transformed for these analyses. DTN: MO0006SEPPLDEN.002

a) Cool-season

Source	Sum of Squares	df	Mean Square	F-ratio	P
Seed date	10.636	3	3.545	31.950	< 0.001
Irrigation	12.379	1	12.379	111.601	< 0.001
Seed date x Irrigation	4.573	3	1.524	13.743	< 0.001
error	2.662	24	0.111		

b) Warm-season

Source	Sum of Squares	df	Mean Square	F-ratio	P
Seed date	0.252	3	0.084	1.256	0.312
Irrigation	2.066	1	2.066	30.834	< 0.001
Seed date x Irrigation	0.994	3	0.331	4.943	0.008
error	1.608	24	0.067		

c) Annual forbs

Source	Sum of Squares	df	Mean Square	F-ratio	P
Seed date	1.824	3	0.608	1.882	0.161
Irrigation	9.826	1	9.826	30.408	< 0.001
Seed date x Irrigation	12.939	3	4.313	13.348	< 0.001
error	7.432	23	0.323		

d) Annual grasses

Source	Sum of Squares	df	Mean Square	F-ratio	P
Seed date	17.426	3	5.809	4.716	0.010
Irrigation	12.754	1	12.754	10.355	0.004
Seed date x Irrigation	6.483	3	2.161	1.754	0.183
error	29.562	24	1.232		

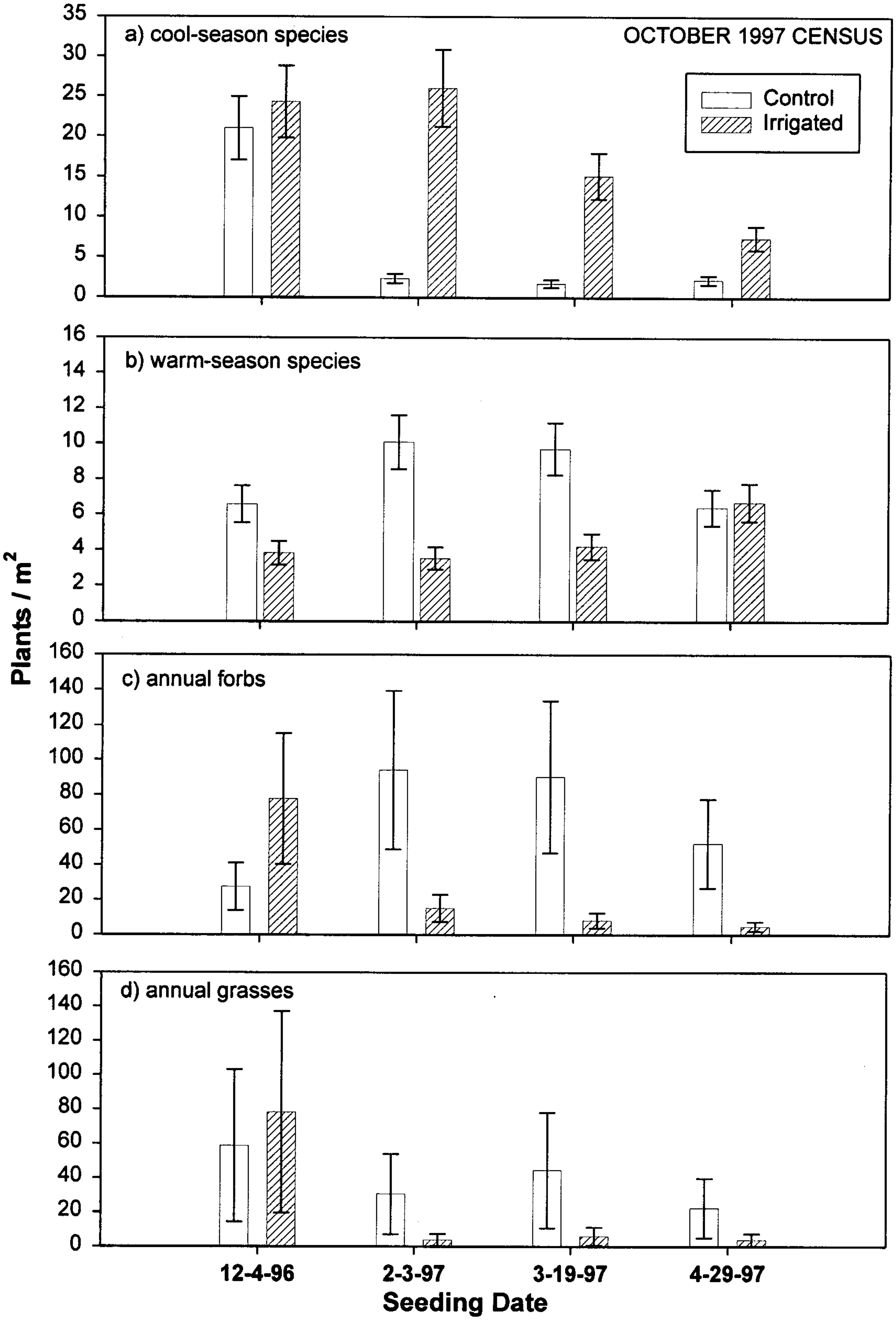

Figure 7. Means (± SE) for seedling densities of a) cool-season species, b) warm-season species, c) annual forbs, and d) annual grass species in response to seeding date and irrigation. Means are combined densities of plants in each treatment combination (n=4) from data taken at the October 1997 census date.
DTN: MO0006SEPPLDEN.002

For warm-season species at the October census, the interaction between seeding date and irrigation was significant with higher plant densities on control plots compared to irrigated plots for the first three seeding dates (Table 4b, Figure 7b). For plots seeded in April, irrigation had no effect on plant density (Fisher's LSD test, $P = 0.800$). Additionally, there was no difference in plant density among seeding dates ($P = 0.312$, Table 4b). In general, without irrigation, warm-season species achieved the highest densities on plots seeded in February and March. With irrigation, plant density was lower for plots seeded in December, February, and March than for plots that received no irrigation (Figure 7b). These results differ from those observed in August when plant densities were higher on irrigated plots compared to control plots.

The interaction between seeding date and irrigation was significant for annual forbs ($P < 0.001$, Table 4c) with an increase in forbs in response to irrigation on plots seeded in December and a decrease in response to irrigation on plots that were seeded later (Figure 7c). There was no effect of seeding date on annual forbs ($P = 0.161$, Table 4c). There was no interaction between seeding date and irrigation for annual grass density ($P = 0.183$, Table 4d). Annual grasses had lower densities on irrigated plots compared to control plots for those seeded in February, March, and April (Figure 7d). Plots seeded in December had the highest annual grass densities (Table 4d, Figure 7d).

For both census dates, the Shannon-Wiener diversity index was calculated for each treatment combination, and the total number of species was determined to examine the effect of irrigation and treatment date on diversity (Figure 8). Diversity and richness were essentially equal on irrigated and control plots that were seeded in December. Generally, irrigation increased species diversity and richness on plots that were seeded in February, March, and April. For the control plots, species diversity and richness declined from the December to March seeding dates, and increased slightly on the plots seeded in April.

3.3 Discussion

3.3.1 August Census

At the August census, there was little response in the control plots seeded outside the traditional seeding window. This is because there had been only one precipitation event in June of about 15 mm that was either not sufficient to stimulate germination, or germination was followed by seedling mortality prior to the census.

With irrigation, these results suggest that seeding at Yucca Mountain could occur as late as April 30th to meet density requirements. The end goal for reclamation at Yucca Mountain is to re-establish sustainable native plant communities on disturbed sites that have densities similar to undisturbed areas. Reclaimed sites are monitored and remediated if necessary until an established success criteria is met, at which time the sites are released from further monitoring. Previous studies at Yucca Mountain (CRWMS M&O 1998b) indicate that plant densities on reclaimed sites decreases over time. However, sites that begin with high initial densities (32-72

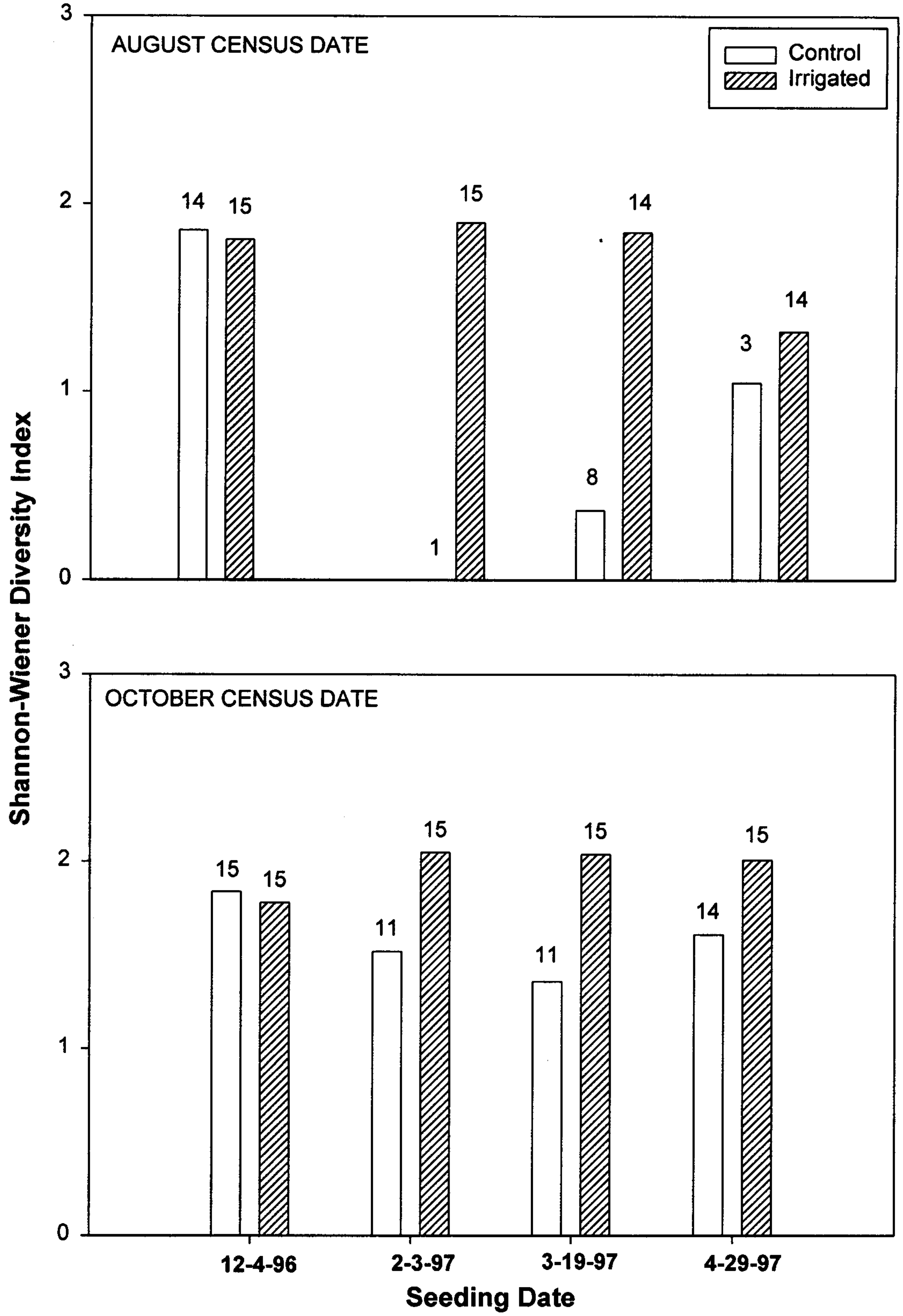

Figure 8. Shannon-Wiener diversity indices for plots by seeding date and irrigation treatment at the August 1997 census date. This index includes the number of species present on a site as well as the proportional abundance to present one number which estimates diversity. Both warm-season and cool-season species are included in this index. Counts of the number of species present are given above each treatment combination bar.

plants/m^2) tend to have higher percent losses (49-70%) in the first year than those with lower initial densities (5-15 plants/m^2). Evidence from previous studies at Yucca Mountain suggest that initial plant densities as low as 4.9 plants/m^2 are high enough to maintain densities that pass the success criteria goals. Thus, plots seeded in April, with a mean of 14.5 plants/m^2, likely have enough plants to maintain densities over the years to pass the success criteria.

Results from this census indicate that irrigation can extend the seeding window. They also suggest that, given adequate precipitation, costly irrigation inputs can be avoided if seeding is done within the traditional seeding window (October through December) at Yucca Mountain.

3.3.2 October Census: Cool-Season Species

Cool-season species had relatively high mean plant densities (approximately 25 plants/m^2, Figures 6b and 7a) on irrigated plots that were sown in December and February, and little change in densities were observed between the August and October census dates. Additionally, no change in plant densities were observed between census dates for irrigated plots sown in March and April. For control plots seeded in February, March and April, 2 - 3 plants/m^2 emerged between census dates. Apparently the 18 mm of precipitation that occurred in the interim between census dates had little effect on cool-season plant densities, indicating that these species are adapted to germinate under cool soil temperatures. Depletion of the seedbank on irrigated plots is a possible reason that additional plants were not observed at the October census. However, this is not likely since few plants on control plots emerged between census dates.

Irrigation caused an average decrease of 4.4° C (calculated from Table 2) in mean monthly maximum soil temperature during the course of the study. Irrigation, and possibly the resulting decrease in soil temperatures allowed cool-season species to emerge outside the traditional seeding window. Consistently lower mean monthly maximum soil temperatures on irrigated plots, even several months after irrigation was applied (Table 2), could have been due to shading by higher plant cover on irrigated plots compared to control plots.

Adequate plant densities for this suite of species (8 plants/m^2, Figure 7a) suggest that seeding could occur through April with the addition of water. While fall irrigation (as a mitigation measure) would not result in the response documented in the plots irrigated in the spring and early summer, combining the response of these species with that of the warm-season species would mostly likely result in plant densities sufficient to meet the success criteria. Thus, fall irrigation could be used as a mitigation measure if natural precipitation was lacking.

This suite of species established well without irrigation when planted in late fall. Mean plant densities were 20 and 22 plants/m^2 at the August and October census dates, respectively. Data on temperatures required for germination for seven of the cool-season species were found in the literature (Barbour 1968; Booth 1992; Chatterton and McKell 1969; Griffith and Booth 1998; Jones and Nielson 1992; Jordan and Haferkamp 1989; Kay et al. 1977a; Kay et al. 1977b; Meyer et al. 1998; Potter et al. 1986; Romo and Eddleman 1988; Sheps 1973; Wood et al. 1976). For these seven species, the number of days that soil temperatures were within a favorable range for germination decreased from the December seeding by an average of 8, 19, and 23 days for the three subsequent seeding dates, respectively. Thus, there was greater opportunity for germination when seeded in December compared to other seeding dates.

In addition to cooler temperatures, plants seeded in early December benefited from a longer growing season than the other three cohorts in this study. As a result of earlier planting, the December cohort was also the only one receiving any precipitation prior to, or during, the period when most germination is observed (mid-February to April). Seeding during December allowed plants to take advantage of the small amount of natural precipitation and adequate temperatures occurring in January. This in turn allowed more time for root growth deeper into the soil profile where moisture is available for longer periods of time following precipitation. Soil moisture at 15 cm remained above the wilting point for longer periods than soil at 2 cm. Therefore, plants seeded in December probably had access to soil moisture for longer periods than the other seeding dates.

3.3.3 October Census: Warm-Season Species

Significant changes in warm-season species densities were observed between the August and October census dates. These changes are primarily due to the precipitation received after the August census date and prior to the October census date. Therefore, the observed difference between August and October for control plots should be regarded as resulting from a combination of late summer rainfall and seeding date. In August, mean plant densities on irrigated plots ranged from 0.1 plants/m^2 for plots seeded in December to 6.2 plants/m^2 for plots seeded in April (Figures 6c and 7b). In October, mean plant densities increased to approximately 4 plants/m^2 on irrigated plots for all seeding dates except April where no change was observed. Even greater increases in mean plant densities between census dates were observed for control plots. Mean densities increased from an average of less than 0.2 plants/m^2 in August (all seeding dates, Figure 6c) to 6.1 (December), 10 (February), 9.9 (March), and 6.2 (April) plants/m^2 at the October census (Figures 6c and 7b).

These results suggest several things about warm-season species requirements. First, the 18 mm of precipitation that fell in September combined with higher soil temperatures seem to provide the best conditions for emergence of warm-season species. While earlier irrigation stimulated some establishment (particularly for plots seeded in April when soils were warmer) as observed in August, results suggest that irrigation in September would be more beneficial to establishment of this suite of species regardless of seeding date. Second, highest densities were observed on plots seeded in February and March suggesting that, ideally, these species should be planted during this time period and irrigated in September if no precipitation occurs. Third, these species can be seeded in December and achieve adequate (if not maximum) densities with either late fall precipitation or irrigation. Plant densities for warm-season species on irrigated plots were lower than those on control plots in October.

Results from the August census showed that very few cool-season plants were present on control plots seeded in February, March, and April, indicating that very few plants would have been present on these plots in September when precipitation occurred. It may be that low densities of cool-season species on these plots allowed greater opportunity (space, soil moisture and nutrients) for warm-season species to take advantage of September rains and establish compared to irrigated plots where high densities of cool-season plants were established. Cover of cool-season plants that were three to five months old could have reduced establishment opportunities for warm-season plants in September through competition for limiting resources. Formation of soil crusts through irrigation, early germination followed by mortality, or lower minimum and maximum soil temperatures on irrigated plots could also have affected warm-season plant establishment on irrigated plots. However, these alternatives are not supported by the August census data.

Results from this study suggest that warm-season species do not respond as well to early spring irrigation as they do to irrigation or precipitation when temperatures are warmer (late spring or fall). However, seeding during the traditional seeding window and waiting for fall precipitation would be economical and result in acceptable initial plant densities.

3.3.4 Species Diversity

Species richness and diversity was consistently higher in the irrigated plots compared to the control plots. This was primarily due to cool-season species which composed the bulk of the seedmix and responded well to irrigation. An increase in species diversity occurred in the control plots between the August and October census dates (Figure. 8). This is due to the late summer precipitation which caused emergence in control plots between the two census dates.

The diversity success criteria at Yucca Mountain is 60% of the number of species present in undisturbed areas. High relative diversity was achieved when seeding in the traditional window or irrigating outside of the seeding window. Species diversity requirements may not be met if seeding occurs outside the seeding window and irrigation is not used.

3.3.5 Weedy Annual Species

Weedy annual species can inhibit native species establishment through competition for resources and irrigation in arid environments can result in high densities of weedy species. The most common weedy forbs were *Sisymbrium altissimum*, *Amsinckia tessellata*, *Erodium cicutarium*, and *Salsola kali*. The most common weedy grasses were *Bromus rubens*, *Schismus arabicus,* and *Vulpia octiflora*. In this study, irrigation increased the emergence of annual species on plots seeded in December, and suppressed their emergence on plots seeded at later dates. There were very few annual forbs and grasses at the August census, probably because this census was past the growing period of the annual species and most would have died by this time. A second cohort of annuals emerged in response to September rains and were present at the October census. This pattern might be explained if spring irrigation stimulated germination and depleted the annual species seedbank. Fewer annuals on irrigated plots for three of the four seeding dates could indicate that fewer ripe seeds were present in the seedbank to respond to added moisture. The long term consequences of this pattern are difficult to predict. Irrigation could lead to greater reproduction and seed viability of annuals, resulting in increased densities of annuals in successive years.

3.3.6 Multi-species Study Conclusions

The results of this study indicate that irrigation can extend the seeding window for species that have cool-season germination requirements. Combined densities on irrigated plots were significantly higher than control plots during each seeding date outside the traditional seeding window. However, the benefit provided by irrigation decreases as temperatures increase. Therefore, if planting outside of the seeding window is required, planting as soon as possible is recommended. The data also show that if these species are seeded within the designated window, high densities are realized without the added cost of irrigation.

Warm-season species showed the opposite pattern as cool-season species in response to irrigation. For these species, it appears that emergence is highly dependent upon the combination of precipitation and warm temperatures. Neither irrigation or different seeding dates alone are sufficient to greatly increase establishment of warm-season species. However, these species are an important part of the plant community and seeds that do not germinate may remain viable in the soil for several years should conditions for germination occur.

4.0 TWO-SPECIES MIX STUDY

Larrea tridentata and *Lycium andersonii* are often dominant in the plant communities at Yucca Mountain, but direct seeding of these two species during final reclamation is rarely successful. *L. tridentata* seedlings sometimes appear two to three years after sowing, indicating delayed germination, a residual seed bank, or recruitment from shrubs in undisturbed areas. *L. andersonii* rarely establishes from seed and often must be transplanted onto reclaimed sites. Because these plants are important to plant community structure and are visually conspicuous in surrounding native vegetation, this study was implemented to see if germination requirements could be met.

4.1 Methods

4.1.1 Site Preparation

In the fall of 1996, 16 5x10-m plots were identified within the study area and treatments were randomly assigned. A buffer area of at least 10 meters was used between plots to avoid cross contamination between irrigated and non-irrigated plots. Prior to plot identification, the site was ripped to alleviate compaction and prepare a seedbed.

On January 8, 1997, plots assigned the January seeding date were broadcast seeded (by hand) with *L. tridentata* and *L. andersonii* seeds at a rate of 200 PLS/m^2. Both species were seeded into each plot. Seeds were covered using a drag harrow and then mulched with 3500 kg/ha of wheat straw. The wheat straw was anchored to the ground with a mixture of organic tackifier and wood fiber. On August 12, 1997, the remaining plots were seeded following the same procedure described above.

4.1.2 Irrigation

Irrigation application started on August 18, 1997 and continued every 3 to 5 days until September 11, 1997. Water was applied at a rate of 32 mm per irrigation with the exception of August 21 when 28 mm of water was applied. After seeding in January, the entire study area was enclosed with a poultry wire fence to exclude rabbits and hares.

4.1.3 Statistics

Significance of main effects and interactions was tested using a two-way ANOVA computed with the General Linear Model (GLM) procedure of the Statistical Analysis Software (SAS Institute, Inc. 1995). Effects were considered significant if $P < 0.05$. Post-hoc tests were done using Fisher's least significant difference mean separation procedure (Steel and Torrie 1980). Log transformations [log (y + 0.5)] of the response variables were used to improve normality and equality of variances when appropriate.

4.2 Results

4.2.1 Air Temperature and Precipitation

See section 3.2.1

4.2.2 Soil Moisture and Temperature

Soil moisture at a depth of 2 cm decreased quickly when irrigation was stopped and after precipitation events (Figure 5a). The permanent wilting point for crop species (-1.5 Mpa) was used as an indicator for periods when the upper 2 cm was likely too dry for germination to occur. Control plots were above -1.5 Mpa for 50 days from January to September while irrigated plots were above –1.5 Mpa for 77 days during the same period.

Soil moisture at 15 cm in the two-species study was above the permanent wilting point for the entire experiment in the control plots and below the wilting point for 79 days in the irrigated plots (Figure 5b). Soil moisture at 15 cm in irrigated plots remained above field capacity from August 19 through October 31. However, two significant precipitation events occurred during this time period causing soil moisture to increase for part of that time in control plots also.

Soil temperatures in irrigated plots were several degrees cooler than those in control plots (Figure 2). Mean monthly maximum soil temperatures were consistently lower in irrigated than in control plots throughout the study (data not shown but were similar to Table 2 for the multi-species mix study).

4.2.3 Vegetation

4.2.3.1 *Larrea tridentata*

Irrigation increased the density of *L. tridentata* for the August seeding date but not for the January seeding date (Figure 9a, Table 6a, interaction between seed date and irrigation, P = 0.032). The densities of *L. tridentata* irrigated in August were twice as great as the densities for the other three treatments.

The January and August seeding date treatments without irrigation had similar seedling densities indicating that regardless of planting date, conditions during the study period were adequate to promote germination (Figure 9a). From April until seedling density was measured, soil temperatures were in the range of optimal conditions for *L. tridentata* germination (Figure 2).

Table 5. Results of a two-way analysis of variance examining the effects of seeding date and irrigation on the density of a) *Larrea tridentata*, b) *Lycium andersonii,* c) annual forbs, and d) annual grasses on study plots at Yucca Mountain. Sums of squares are the same as mean square when there is only one degree of freedom (mean square = sum of squares/df). Data for *Lycium andersonii* and annual grasses were log transformed for this analysis. DTN: MO0005PDEN1997.000

a) *Larrea tridentata*

Source	Sum of Squares	df	Mean Square	F-ratio	P
Seed date	19.506	1	19.506	3.73	0.077
Irrigation	21.390	1	21.390	4.09	0.066
Seed date x Irrigation	30.710	1	30.710	5.87	0.032
error	62.732	12	5.227		

b) *Lycium andersonii*

Source	Sum of Squares	df	Mean Square	F-ratio	P
Seed date	2.908	1	2.908	13.59	0.003
Irrigation	7.011	1	7.011	32.75	< 0.001
Seed date x Irrigation	0.090	1	0.090	0.42	0.528
error	2.568	12	0.214		

c) Annual forbs

Source	Sum of Squares	df	Mean Square	F-ratio	P
Seed date	2058.890	1	2058.890	12.7	0.004
Irrigation	3.210	1	3.210	0.02	0.890
Seed date x Irrigation	393.361	1	393.361	2.44	0.144
error	1932.086	12	161.007		

d) Annual grasses

Source	Sum of Squares	df	Mean Square	F-ratio	P
Seed date	0.322	1	0.322	0.69	0.421
Irrigation	0.100	1	0.100	0.22	0.651
Seed date x Irrigation	0.164	1	0.164	0.35	0.564
error	5.580	12	0.465		

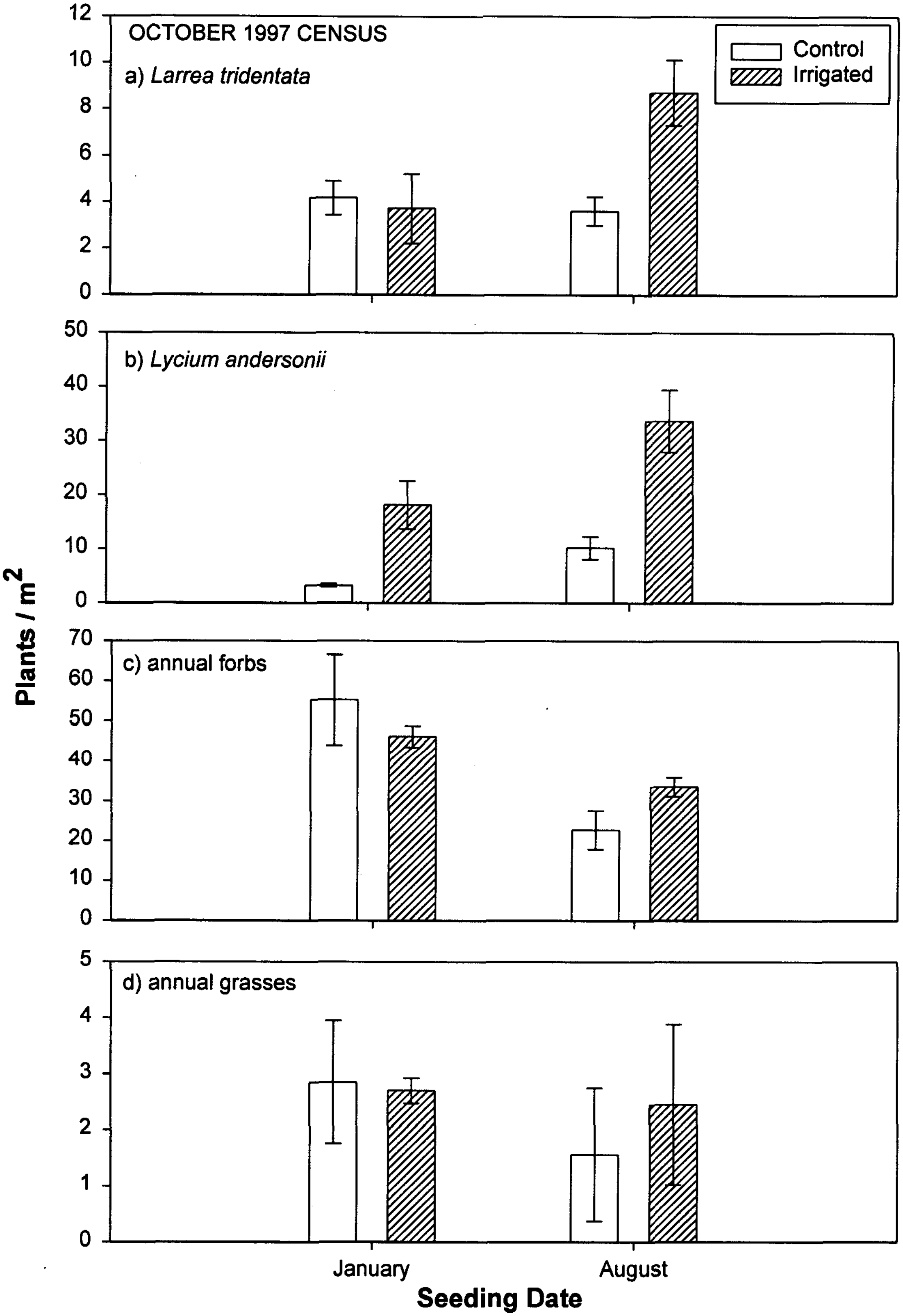

Figure 9. Mean (± SE) number of a) *Larrea tridentata*, b) *Lycium andersonii*, c) annual forbs and d), annual grasses emerging in each treatment during the two-species mix irrigation study. Data are means of densities of plants in each treatment combination (n=4) taken at an October 1997 census date.
DTN: MO0005PDEN1997.000

Soil moisture at 2 cm depth was quite low for the majority of the period between April and August; however, rainfall events during mid-June (22 mm) and September increased soil moisture beyond field capacity (Figure 5). These precipitation events, along with optimal temperatures, may have provided proper conditions for germination in plots that were not irrigated.

Seeding date alone was not statistically significant for *L. tridentata* densities. However, there was a general trend for plots planted in August to have higher seedling densities than those planted in January (6.17 ± 1.20 vs. 3.96 ± 0.79 plants/m^2 for the August and January seeding dates, respectively, Table 6).

Table 6. Mean seedling density (±SE) of *Larrea tridentata*, *Lycium andersonii*, annual grasses, and annual forbs in response to seeding date and late summer irrigation at Yucca Mountain, Nevada. DTN: MO0005PDEN1997.000

	Control		Irrigated	
Seeding Date	**January**	**August**	**January**	**August**
Larrea tridentata	4.18 (0.74)	3.63 (0.62)	3.73 (1.51)	8.71 (1.41)
Lycium andersonii	3.23 (0.31)	10.25 (2.07)	18.13 (4.45)	33.69 (5.75)
Annual Grasses	3.31 (1.09)	2.31 (1.19)	2.73 (0.22)	3.14 (1.44)
Annual Forbs	55.33 (11.20)	22.73 (4.84)	46.31 (2.60)	33.54 (2.36)

The effect of August irrigation alone did not effect the densities of *L. tridentata*. Irrigated plots had higher average densities, but the variability within the irrigated plots was greater (6.22 ± 1.34 vs. 3.91 ± 0.46 plants/m^2 for irrigated and control plots, respectively, Table 6). This variability resulted from the significant interaction between seeding date and irrigation treatment.

4.2.3.2 *Lycium andersonii*

Irrigation increased the density of *L. andersonii* for both seeding dates (Figure 9b, Table 5b, $P < 0.001$). Density for *L. andersonii* was also higher for the August seeding date than for the January seeding date ($P < 0.001$).

Soil temperatures were consistently near the reported optimal germination temperature for *L. andersonii* (20° C in Kay et al. 1977b) during April to June, and September to October, during the study period (Figure 2). Rainfall events in June and September provided adequate soil moisture for emergence of *L. andersonii* since plots receiving no irrigation showed emergence.

4.2.4 Non-seeded Weedy Species

Annual forbs in plots seeded in January had higher densities than forbs in plots seeded in August (Figure 9c, Table 5c, $P < 0.001$). Annual forbs had almost twice as many plants on plots seeded in January as plots seeded in August (Table 5). Densities of annual grasses showed no response to irrigation or seeding date (Figure 9d, Table 5d).

4.3 Discussion

For *L. tridentata,* the combination of an August seeding and late summer irrigation resulted in significantly higher numbers of seedlings when compared to no irrigation and the January seeding dates (Figure 9). This result is consistent with Barbour's (1968) findings that *L. tridentata* seeds need warm temperatures (20° to 33° C) and adequate soil moisture for germination. Temperatures at the study site were within this range during the period of irrigation application (Figure 2). Soil moisture during this period appeared to be adequate for germination (Figure 5). Lower densities of *L. tridentata* on plots seeded in January and irrigated in August is similar to the results observed in the multi-species mix study, and may have several possible explanations. First, seeds may have germinated after the rainfall events that occurred during June and later died because of lack of soil moisture after the soil dried out (Figure 5). Second, the viability of the seeds sown in January may have been reduced. Barbour (1968) found that dry seeds of *L. tridentata* exposed to unusually warm temperatures (37-71° C) exhibited reduced germinability. The implication is that seeds may lose viability in topsoils during the summer months (Barbour 1968). Temperatures above 37° C did occur at the study site occasionally in June, July, and August, thus increasing the likelihood that seed viability was reduced. Third, lower *L. tridentata* densities on plots seeded in January could have been due to high densities of annual forbs (Figure 9c). Annual forb densities were almost two times higher in these treatments which could have increased competition for soil moisture during the time when *L. tridentata* seeds were germinating and becoming established. Soil moisture at 15 cm was higher in control plots than irrigated plots from mid-June through mid-August due to natural precipitation. This may be an indication of greater competition for soil moisture, at least in the irrigated plots. Because seedling densities were not measured prior to August irrigation on plots seeded in January. Therefore, it is impossible to determine which factors may have contributed most to the reduced seedling numbers on these plots. However, all of the above factors could have influenced the observed seedling densities.

Regardless of seeding date and irrigation treatment, the seedling densities of *L. tridentata* were higher in this study than in previous studies at Yucca Mountain, and higher than densities observed in the multi-species mix study reported here. This may be in part due to higher seeding rates than previous studies (200 PLS/m^2). Densities of this species have been low at most revegetation study sites (< 1 plants/m^2) (CRWMS M&O 1998b) with the exception of one study to assess the effects of mulch and polyacrylamide gel application (CRWMS M&O 1999a). In that study, *L. tridentata* had significantly higher densities in plots with gravel mulch (3.3 plants/m^2) than in plots with straw mulch (0.3 plants/m^2). This difference was thought to be related to warmer temperatures beneath the gravel mulch compared to that of straw mulch when soil moisture was available (CRWMS M&O 1999a). Densities in the study reported here ranged from 3.6 to 8.7 plants/m^2 across treatments (Table 6). A possible explanation for the increased response at this site may be related to less competition from cool-season species that germinate earlier and use water and nutrient resources before *L. tridentata* germinates. Most studies previously conducted at Yucca Mountain used seed mixes containing 10 to 15 different species. In this study, only two species were seeded, thus reducing the probability of interspecific competition and other possible interactive effects, including chemicals spread seed to seed or seedling to seedling that may affect germination or seedling survival.

Seeding date influenced the emergence of *L. andersonii.* The reasons for the lower densities for *L. andersonii* in the January seeding date may be similar to those describe above for *L. tridentata*: plant mortality after germination, loss of seed viability during the summer months, competition from the greater number of annual forbs in these plots (Figure 9c), or a combination of all of these factors.

Soil moisture at 2 cm depth stayed above the permanent wilting point during the irrigation period indicating that soil moisture was adequate for germination of *L. andersonii.* Plots receiving no irrigation also exhibited some emergence of *L. andersonii.* Apparently, rainfall received during the study period was adequate to promote germination in these plots. Rainfall events in September resulted in soil moisture conditions that were above the permanent wilting point for periods of 5 to 10 days (Figure 5), which could have been long enough for the seeds to germinate and emerge.

As with *L. tridentata*, the emergence of *L. andersonii* in this study was much higher than that observed in previous studies at Yucca Mountain including the multi-species mix study presented here. In the majority of these studies, observed densities were low (< 1 plants/m^2) (CRWMS M&O 1998a). The lowest density observed in this study was 3.22 plants/m^2 on plots seeded in January that received no irrigation. As discussed previously for *L. tridentata*, the fact that only two species were seeded in this study and the seeding rates were higher than in previous studies may have reduced interspecific competition and other negative species interactions.

The higher plant densities of annual forbs on January seeded plots is not easily explained. One possibility is that when the August seeding date treatment was installed, soil disturbance created during harrowing and/or covering of the soil with mulch may have killed small seedlings of the annual forbs, thus reducing their densities on plots sown in August. Plots seeded in January had an extended period where emergence and growth of annuals could have occurred as opposed to the plots seeded in August. Late summer irrigation apparently did not influence densities of annual forbs which may provide further evidence that the forbs had germinated prior to start of the irrigation treatments.

4.4 Conclusions

The combination of an August seeding date and late summer irrigation resulted in significantly higher densities of *L. tridentata.* This combination may be a viable method for the establishment of *L. tridentata* on disturbances at Yucca Mountain, and may also be a viable alternative for the mitigation of previously revegetated sites that have extremely low densities of this species.

Lycium andersonii densities were strongly influenced by late summer irrigation application, and to a lesser extent, by seeding date. At Yucca Mountain, the application of late summer irrigation to areas seeded during the normal revegetation window (October to December) may be a viable alternative to improve establishment of this species. *Lycium andersonii* could also be combined with *L. tridentata* in an August seeding with late summer irrigation as described above.

Seeding during August reduced densities of annual forbs in the year of seeding. This reduction may have improved emergence of *L. tridentata* and *L. andersonii* by decreasing the competition for resources. Seeding date and later summer irrigation did not influence densities of annual grasses.

5.0 FINAL CONCLUSIONS

Results of these two studies suggest improved planting techniques to enhance reclamation success in the future. First, it is always better to plant within the seeding window because higher plant density and diversity is achieved without the additional cost of irrigation. Second, irrigation can be used to extend the seeding window if required. Without irrigation, seeding outside of the seeding window is dependent upon precipitation when it is least likely. Irrigation improves plant density, species richness, and diversity. Third, results from the multi-species mix study showed that timing of irrigation is more important than timing of planting for emergence of a group of species. For example, warm-season species planted in control plots in February, March and April responded similarly (6-10 plants/m^2) to natural precipitation in September. In the two-species mix study, timing of planting did seem to affect the performance of both *L. tridentata* and *L. andersonii,* possibly for reasons discussed earlier; but, plant densities of both species were still high compared to previous trials. This suggests that both warm-season and cool-season species can be planted together with the intent that they germinate at different times of the year, although, there may be some loss of seed viability for warm-season seeds planted in fall and winter and germinating the following summer.

Fourth, the two groups of species, warm-season and cool-season, may interfere with the other's establishment. This is demonstrated by the poor performance of warm-season species in the multi-species mix study, while at least one warm-season species (*L. tridentata*) did better when planted with only one other species. This may also be due to the higher seeding rate used per species in the two-species mix study. Using a seedmix that minimizes competition between warm and cool-season species may enhance density and diversity.

Each species in the multi-species mix study has unique germination requirements. While it is not possible to meet all these requirements for each species, it is possible to adjust seeding rates to optimize plant density and diversity. The dominant warm-season *L. tridentata* often has low densities in the first few years of a reclamation effort, following which its densities may increase. Whether this is due to seed that was previously planted, or if it is blown in from surrounding plant communities is not known. Perhaps by decreasing the seeding rate of cool-season species, thus reducing their initial competitive ability, and increasing the seeding rate of this warm-season dominant species, higher diversity will result and revegetation will better match the natural community in less time.

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7.0 DATA

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APPENDIX A

SPECIES CODES AND INDIVIDUAL SPECIES DENSITY IN RESPONSE TO IRRIGATION AND SEEDING DATE IN THE MULTI-SPECIES MIX STUDY

Table A-1. Four letter species codes for species seeded in irrigation studies at Yucca Mountain, Nevada. Scientific names are from Kartesz 1987. * = warm season species

Species Code	Scientific Name	Common Name
AMDU*	Ambrosia dumosa (gray) Payne	white bursage
ATCA	Atriplex canescens (Pursh) Nutt.	fourwing saltbush
ATCO	Atriplex confertifolia (Torr. & Frem.) S. Wats.	shadscale
ATPO	Atriplex polycarpa (Torr.) S. Wats.	desert saltbush
CHNA	Chrysothamnus nauseosus (Pallas ex Push) Britt.	stickyleaf rabbitbrush
CHVI	Chrysothamnus viscidiflorus (Hook.) Nutt.	rubber rabbitbrush
CORA	Coleogyne ramosissima (Torr.)	blackbrush
EPNE	Ephedra nevadensis S. Wats.	Nevada ephedra
ERFA	Eriogonum fasciculatum Benth.	California buckwheat
GRSP	Grayia spinosa (Hook) Moq.	Hopsage
HYSA*	Hymenoclea salsola Torr. & Gray ex Gray	white burrobush
KRLA	Krascheninnikovia lanata (Pursh) Guldenstaedt	winterfat
LATR*	Larrea tridentata (Sesse & Moc. ex DC.) Coville	creosote bush
LYAN	Lycium andersonii (Gray)	Anderson's desert thorn
ORHY	Oryzopsis hymenoides (Roemer & J.A. Schultes) Ricker ex piper	Indian ricegrass
SPAM	Sphaeralcea ambigua Gray	Desert Mallow

Table A-2. Mean (± SE) seedling density (plants/m^2) of each species seeded in the multi-species study by seeding date in the control plots from the August 1997 census date.

	Control			
Species	**12/4/96**	**2/3/97**	**3/19/97**	**4/29/97**
Ambrosia dumosa	0.05 (0.03)	0.0 (0.0)	0.1 (0.06)	0.02 (0.02)
Atriplex canescens	3.7 (0.3)	0.02 (0.02)	0.2 (0.15)	0.03 (0.02)
Atriplex confertifolia	0.8 (0.1)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)
Atriplex polycarpa	1.5 (0.2)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)
Chrysothamnus nauseosus	0.08 (0.1)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)
Chrysothamnus viscidiflorus	0.3 (0.08)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)
Coleogyne ramosissima	0.06 (0.04)	0.0 (0.0)	0.02 (0.02)	0.0 (0.0)
Ephedra nevadensis	7.8 (0.6)	0.0 (0.0)	0.08 (0.08)	0.0 (0.0)
Eriogonum fasciculatum	1.0 (0.2)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)
Grayia spinosa	1.2 (0.1)	0.0 (0.0)	0.02 (0.02)	0.0 (0.0)
Hymenoclea salsola	0.02 (0.02)	0.0 (0.0)	0.09 (0.08)	0.02 (0.02)
Krascheninnikovia lanata	2.4 (0.3)	0.0 (0.0)	0.05 (0.04)	0.0 (0.0)
Larrea tridentata	0.2 (0.02)	0.0 (0.0)	0.02 (0.02)	0.0 (0.0)
Oryzopsis hymenoides	0.1 (0.06)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)
Sphaeralcea ambigua	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)

Table A-3. Mean (± SE) seedling density (plants/m^2) of each species seeded in the multi-species study by seeding date in the irrigated plots from the August 1997 census date.

	Irrigation			
Species	**12/4/96**	**2/3/97**	**3/19/97**	**4/29/97**
Ambrosia dumosa	0.4 (0.08)	0.8 (0.1)	1.0 (0.1)	2.5 (0.3)
Atriplex canescens	5.0 (0.4)	7.0 (0.6)	4.5 (0.3)	3.1 (0.4)
Atriplex confertifolia	0.4 (0.01)	0.5 (0.1)	0.1 (0.04)	0.5 (0.03)
Atriplex polycarpa	1.3 (0.2)	3.9 (0.4)	2.0 (0.2)	1.9 (0.2)
Chrysothamnus nauseosus	1.6 (0.2)	0.5 (0.1)	0.3 (0.07)	0.08 (0.04)
Chrysothamnus viscidiflorus	0.8 (0.2)	0.2 (0.07)	0.2 (0.06)	0.1 (0.04)
Coleogyne ramosissima	0.2 (0.05)	0.1 (0.05)	0.02 (0.02)	0.0 (0.0)
Ephedra nevadensis	6.0 (0.5)	6.5 (0.7)	2.3 (0.3)	0.9 (0.2)
Eriogonum fasciculatum	3.3 (0.3)	2.9 (0.4)	2.4 (0.3)	0.6 (0.1)
Grayia spinosa	1.5 (0.2)	0.5 (0.1)	0.0 (0.0)	0.03 (0.02)
Hymenoclea salsola	0.08 (0.03)	0.3 (0.07)	0.7 (0.1)	2.2 (0.2)
Krascheninnikovia lanata	2.5 (0.2)	4.0 (0.4)	2.2 (0.2)	1.1 (0.2)
Larrea tridentata	0.05 (0.04)	0.3 (0.02)	0.4 (0.09)	1.7 (0.2)
Oryzopsis hymenoides	0.3 (0.08)	0.5 (0.1)	0.2 (0.07)	0.0 (0.0)
Sphaeralcea ambigua	0.2 (0.06)	0.3 (0.07)	0.3 (0.07)	0.4 (0.07)

Table A-4. Mean(± SE) seedling density (plants/m^2) of each species seeded in the multi-species study by seeding date in the control plots from the October 1997 census date.

	Control			
Species	**12/4/96**	**2/3/97**	**3/19/97**	**4/29/97**
Ambrosia dumosa	4.7 (0.4)	6.0 (0.4)	5.1 (0.3)	3.4 (0.3)
Atriplex canescens	3.8 (0.3)	1.5 (0.2)	1.4 (0.2)	1.5 (0.2)
Atriplex confertifolia	0.8 (0.1)	0.1 (0.03)	0.0 (0.0)	0.0 (0.0)
Atriplex polycarpa	1.5 (0.2)	0.05 (0.03)	0.0 (0.0)	0.02 (0.02)
Chrysothamnus nauseosus	0.7 (0.1)	0.0 (0.0)	0.0 (0.0)	0.2 (0.07)
Chrysothamnus viscidiflorus	1.4 (0.2)	0.03 (.02)	0.02 (.02)	0.03 (.02)
Coleogyne ramosissima	0.4 (0.9)	0.0 (0.0)	0.2 (0.2)	0.2 (0.2)
Ephedra nevadensis	9.6 (0.6)	0.9 (0.2)	0.5 (0.1)	0.4 (0.09)
Eriogonum fasciculatum	1.3 (0.2)	0.1 (0.06)	0.08 (0.04)	0.2 (0.06)
Grayia spinosa	1.5 (0.2)	0.0 (0.0)	0.0 (0.0)	0.02 (0.02)
Hymenoclea salsola	1.2 (0.2)	3.3 (0.2)	3.3 (0.3)	1.9 (0.2)
Krascheninnikovia lanata	2.4 (0.3)	0.0 (0.0)	0.02 (0.02)	0.02 (0.02)
Larrea tridentata	1.0 (0.2)	1.7 (0.2)	1.4 (0.2)	1.3 (0.1)
Oryzopsis hymenoides	0.3 (0.07)	0.1 (0.05)	0.1 (0.04)	0.2 (0.09)
Sphaeralcea ambigua	0.2 (0.08)	0.1 (0.05)	0.2 (0.06)	0.09 (0.04)

Table A-5. Mean (± SE) seedling density (plants/m^2) of each species seeded in the multi-species study by seeding date in the irrigated plots from the October 1997 census date.

	Irrigation			
Species	**12/4/96**	**2/3/97**	**3/19/97**	**4/29/97**
Ambrosia dumosa	3.1 (0.3)	2.4 (0.2)	2.2 (0.2)	2.6 (0.2)
Atriplex canescens	5.0 (0.4)	8.2 (0.6)	4.8 (0.3)	3.5 (0.4)
Atriplex confertifolia	0.7 (0.1)	0.8 (0.1)	0.1 (0.04)	0.1 (0.03)
Atriplex polycarpa	1.2 (0.2)	4.0 (0.4)	1.9 (0.2)	2.1 (0.3)
Chrysothamnus nauseosus	0.7 (0.1)	0.8 (0.2)	0.3 (0.07)	0.2 (0.05)
Chrysothamnus viscidiflorus	2.4 (0.3)	0.4 (0.2)	0.1 (0.05)	0.1 (0.05)
Coleogyne ramosissima	0.6 (0.1)	0.3 (0.09)	0.05 (0.03)	0.02 (0.02)
Ephedra nevadensis	6.9 (0.4)	6.7 (0.5)	3.1 (0.3)	1.0 (0.2)
Eriogonum fasciculatum	3.8 (0.3)	2.9 (0.3)	2.4 (0.2)	0.8 (0.1)
Grayia spinosa	1.3 (0.2)	0.6 (0.1)	0.02 (0.02)	0.02 (0.02)
Hymenoclea salsola	0.6 (0.1)	1.0 (0.1)	1.2 (0.2)	2.2 (0.2)
Krascheninnikovia lanata	2.5 (0.2)	4.3 (0.4)	2.3 (0.2)	0.02 (0.02)
Larrea tridentata	0.4 (0.09)	0.3 (0.07)	0.9 (0.1)	2.3 (0.2)
Oryzopsis hymenoides	1.1 (0.2)	1.7 (0.2)	0.6 (0.1)	0.3 (0.08)
Sphaeralcea ambigua	0.3 (0.08)	0.5 (0.09)	0.5 (0.09)	0.5 (0.09)